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Study for Incorporating Time-Synchronized Approach Control into the CH-47/VALT Digital Navigation System

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SUMMARY

A study of various techniques for obtaining time synchronized (4D) approach control in the NASA VALT research helicopter is described in this report. The study consisted of an examination of previously proposed 4D concepts and their compatibility with the existing VALT digital computer navigation and guidance system hardware and software. Modifications to various techniques were investigated in order to take advantage of the unique operating characteristics of the helicopter in the terminal area.

A 4D system is proposed, combining the Direct To Maneuver with the existing VALT curved path generation capability. Time of arrival is controlled by both path alteration and velocity control techniques. Various elements of the proposed system have been implemented through computer software generation. The operation of these elements have been checked out using the existing VALT software validation system in a flight simulation configuration.

INTRODUCTION

On January 9, 1976, NASA/LARC, Hampton, Virginia, awarded Contract No. NAS1-14238 to Sperry Flight Systems for a study of time-synchronized approach control techniques. The work performed under this contract is part of the NASA VTOL Approach and Landing Technology (VALT) program designed to determine the operating envelope and piloting procedures for VTOL aircraft in the terminal area.

In order to provide a viable intercity and intracity operating system, future VTOL aircraft will have to perform curved, decelerating time-constrained approaches under all flight conditions. This ability, referred to as a four dimensional (4D) approach capability, will require greater sophistication in many portions of the total operating system than is currently available. This is particularly true for the navigation, guidance and control areas where little research and development has been done relative to the 4D approach problem.

In order to provide the necessary data base for such future VTOL navigation, guidance and control systems, the Langley Research Center of the National Aeronautics and Space Administration initiated the VALT program. One of the program's goals is to define navigation, guidance and control concepts which would give VTOL aircraft the necessary 4D approach capability. The primary tool used in the VALT program is a specially equipped CH-47B research helicopter which is used to evaluate candidate concepts in an actual flight environment. The helicopter is equipped with a fly-by-wire control system and a programmable navigation and guidance system based on a general purpose digital computer.

This study was conducted to determine the feasibility of incorporating a 4D capability into the existing VALT system using the existing VALT software and hardware. The study was divided into the following four tasks:

TASK 1
ANALYSIS OF 4D TECHNIQUES

A literature search was conducted to examine various 4D techniques proposed for both fixed wing and helicopter applications. Published papers and reports were reviewed with a particular emphasis on those techniques that appeared most suitable for the VALT system. Modifications to published techniques were investigated in order to take advantage of the more flexible operating capability of VTOL aircraft.

TASK 2
ASSESSMENT OF SOFTWARE REQUIREMENTS

A preliminary estimate of the programming effort required to implement various 4D techniques was made. This estimate was combined with an evaluation of the operational aspects of the various techniques investigated as part of Task 1 in order to select a set of techniques suitable for a VALT 4D system.

TASK 3
EVALUATION OF 4D TECHNIQUES

Digital computer software was created to implement various concepts and techniques selected as part of Task 2. A fixed based simulation was used to verify the operation of the software.

TASK 4
DEFINITION OF A MAN/MACHINE INTERFACE

A fixed based simulation was used to identify interface problems between the pilot and the 4D system. An interactive graphics display capability was added to the simulation facility to allow visual presentation of the 4D approach situation to the pilot. Recommendations were prepared outlining additional information exchange concepts that would be suitable for operational use.

SYMBOLS

a	Acceleration Used for Airspeed Control
a_1	Acceleration for First Segment of Two Speed Change Profile
a_2	Acceleration for Single Speed Change Profile
a_3	Acceleration for Final Segment of Two Speed Change Profile
α	Ratio of Initial Radius to Final Radius
α_L	Initial Turn Angle to the Left for Symmetrical Delay Fan
α_R	Initial Turn Angle to the Right for Symmetrical Delay Fan
A	Acceleration Distance to T_1
ALEG	Distance on A side of Delay Fan
AP	Avoidance Point
B	Acceleration Distance after T_1
BLEG	Distance on B side of Delay Fan
β	Turn Angle for Symmetrical Delay Fan Arcs
CCD	Center to Center Distance between Avoidance Point and Second Turn
CLEG	Distance on C side of Delay Fan
D	Desired Time to Go
DBC	Center to Center Distance between Avoidance Point and First Turn
DTAN_	Tangent Distance from Turn 2 to Avoidance Area
d_{as}	Straight Line Acceleration Distance
d_f	Primary Decision Distance for Computing Direct To
d_i	Length of Straight Line Segment
d_o	Primary Decision Distance for Computing Direct To
g	Constant Acceleration of Gravity
γ	Angle between Inbound Heading and Heading to Second Turn Center
HTAN_	Heading of Tangent Lines from Turn 2 to Avoidance Area
i	Number of Segments
k	Ratio of Airspeed to Wind Velocity
K	Time Error Multiplier for Speed Control
L	Path Segment Length

L_1 Minimum Path Length for Single-Speed Change

L_2 Maximum Path Length for Single-Speed Change

P_f Final Point on Direct To

P_o Initial Point on Direct To

ϕ Bank Angle

R Radius of Circular Arc Segment

R_f Final Turn Radius on Direct To

R_o Initial Turn Radius on Direct To

RAV Avoidance Area Radius

RDELA Radii of Delay Fan Turns

S Offset Distance from Nominal Path

ψ Aircraft Heading

ψ_1 Initial Heading on Direct To

ψ_2 Final Heading on Direct To

ψ_c Heading of CLEG

ψ_f Final Heading on Delay Fan

ψ_g Ground Track Heading

ψ_i Initial Heading on Delay Fan

ψ_w Wind Heading

t Time

T Waypoint Section Time

T_c Section Clock Time To Go

t_1 Time for Initial Speed Change

t_2 Time for Final Speed Change

T_1 Time at Midpoint of Intermediate Speed Change

t_i Constant Velocity Time on Straight Segment

t_i' Constant Velocity Time on Circular Arc Segment

t_n' Circular Arc Acceleration Time Increments

Δt Time Error

TOA Time of Arrival

θ	Pitch Attitude
V_f	Segment Final Velocity
V_g	Ground Velocity
V_i	Segment Initial Velocity
V_m	Segment Maximum Velocity
V_n	Segment Minimum Velocity
V_u	Airspeed
V_w	Wind Velocity
V	Aircraft Ground Velocity
V_1	Initial Velocity on Direct To
V_2	Final Velocity on Direct To
V_{cmd}	Velocity Command
V_{max}	Aircraft Maximum Velocity Limit
V_{min}	Aircraft Minimum Velocity Limit
V_e	Intermediate Velocity for Two Speed Change Profile
V_{REF}	Velocity Reference from Profile
V_X	Waypoint Crossing Velocity
WP_	Waypoint Number
X	Aircraft X Position
XAV	X Position of Avoidance Point
XC2	X Center of Delay Fan Turn 2
XT1	X Center of Delay Fan Turn 1
Y	Aircraft Y Position
YAV	Y Position of Avoidance Point
YC2	Y Center of Delay Fan Turn 2
YT1	Y Center of Delay Fan Turn 1
Z	Altitude
z	Difference between Ground Track Heading and Wind Heading

VALT SYSTEM DESCRIPTION

The NASA VALT System is an integrated hardware and software package designed to provide a tool for investigating the problems associated with terminal area operations of VTOL aircraft. The system is built around a modified CH-47B helicopter and contains research oriented control, display, navigation and guidance subsystems. A block diagram of the VALT system is shown in Figure 1.

Research Aircraft

The NASA research aircraft is a highly modified CH-47B helicopter. The aircraft contains a research pilot station in the right side cockpit and a safety pilot station on the left side. The research pilot position instrument panel incorporates two video monitors for use with a ground-based, flight display research subsystem. The VALT engineers station is located in the main cabin area and provides the research engineer the capability to monitor and control the entire system. The aircraft is equipped with monitored, full authority, actuators in the pitch, roll, yaw, and collective axes.

Control System

The VALT CH-47B control system is a hybrid combination of analog and digital components. The analog elements of the system include the sensors, the actuation system, and the attitude stabilization portion of the control system. The digital elements include the digital navigation system and the air/ground telemetry data link. The digital navigation system contains the general purpose digital computer, a digital interface unit and two control/display units that provide the operator interface with the system. A complete description of the digital navigation system is contained in Reference 14.

Radar Tracking and Data Link

The primary navigational position information for the VALT system is provided through the use of an FPS-16 tracking radar combined with a laser ranging system located at the Wallops Flight Center. Radar information is processed on the ground with a digital computer in order to generate a three-dimensional coordinate fix. The X position, Y position, and Z position information is transmitted to the aircraft through the Telemetry Data System (TDS) data link.

A TDS Interface Unit (TIF) in the aircraft provides the interface between the data link and the digital computer. A computer program combines the raw position data with aircraft acceleration data to produce inertially smoothed position information for guidance computations. Reference 17 contains a description of the technique used.

Software

The functions that the VALT system performs are determined by the digital computer software. The primary flight system software consists of a real time executive routine and set of selectable subroutines called by the executive routine. The subroutines that are called during any particular real time cycle are a function of the mode of system operation selected by the pilot or by the flight test engineer.

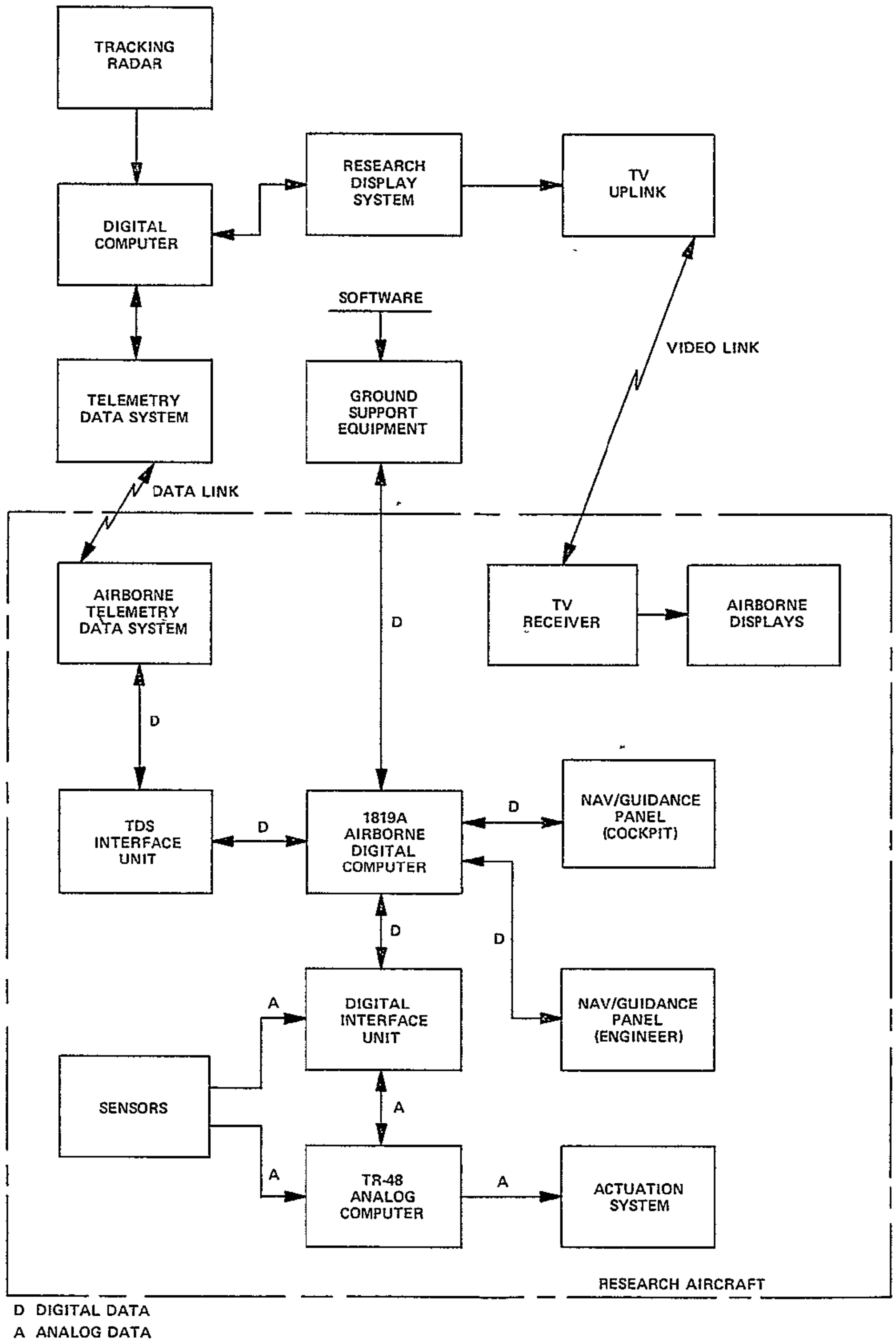

Figure 1
VALT Research System

The flight system software has the capability to generate arbitrarily shaped curved approach paths in both the lateral and vertical planes. The lateral curved path software is based on an elliptical curve fitting technique which is described in Reference 15. In addition, the software can generate curved deceleration profiles with velocity specified as a function of distance to go along the lateral path. Five lateral curved paths, five vertical profiles and five velocity profiles can be stored in the flight computer. Selection of any combination of curved paths and profiles can be made through the use of the control/display unit.

The flight system software generates all the necessary commands to fly the curved paths and profiles in either a fully automatic mode or in a pilot aided mode through the generation of flight director steering commands.

4D TECHNIQUES

Task I included the requirement to investigate, through a literature search, various 4-D approach techniques that have been proposed or implemented in other research projects. The literature search resulted in the collection of 44 articles and technical papers related to 4-D techniques. These articles are listed in the reference section and in the bibliography which is attached as Appendix F. The purpose of this section is to consolidate and summarize the information contained in these articles and to indicate whether or not the techniques presented are applicable to VTOL aircraft. In general, all the techniques investigated utilize path alteration or velocity control or a combination of both in order to achieve a predetermined time of arrival. It should be noted that none of the techniques that have been researched are specifically directed towards VTOL aircraft and that all the techniques provide time of arrival control to an approach gate and not to a touchdown. This section is divided into two major parts in order to cover the two broad areas of path alteration and velocity control.

2D, 3D and 4D Guidance

Aircraft guidance in the terminal area can be classified into 2D, 3D and 4D systems. 2D systems are primarily concerned with lateral guidance of the aircraft while controlling altitude and velocity with relatively gross changes to maintain separation. The recent development of Area Navigation (RNAV) has enhanced the ability of the ATC system to utilize precision 2D guidance in the terminal area. The addition of vertical path control to the 2D lateral system results in 3D approach control systems. The ability to incorporate vertical navigation waypoints into present day RNAV systems allows for precise control of both vertical and lateral position along the entire approach path and thus allows for more efficient utilization of the terminal area airspace.

A 4D approach system adds time control to a 3D system. Time controlled approaches can reduce the separation distance between aircraft down to a level that approaches the minimum separation standards, since the time of arrival dispersion at various 3D waypoints can be greatly reduced. A reduction in the separation of aircraft in the terminal area can result in an increase in the landing rate on any given runway and thus reduce landing delays. It should be noted that a reduction in arrival delays is not necessary if the runway capacity is in excess of the terminal area arrival rate for incoming aircraft since delays in the terminal area are not experienced under these conditions. It should also be noted that a 4D system must offer a reduction in the arrival dispersion at a time controlled waypoint when compared to the normal dispersion that would be experienced at the same waypoint with a 3D system. This reduction in arrival dispersion becomes a benchmark for evaluating the worth of a 4D system. A standard deviation of 20 seconds is often used in conjunction with fixed wing approaches using a 3 mile separation standard and approach speeds between 120 knots and 150 knots (Reference 8). A computer controlled 4D system should be able to reduce this type of deviation by 50 percent or more.

Path Alteration

The term Path Alteration is used to cover a wide variety of techniques that involve control of the lateral position of aircraft. In some ways the term is incorrectly applied since it is necessary to have generated some path before it can be altered. The generation of a flyable path is a subject of much discussion in the articles researched and will be covered first.

Path Generation Using the Direct To Concept - Assuming that some type of velocity control profile has been given or determined, it is necessary to know the shape and length of the desired lateral flight path in order to determine the time to fly that path. This is a problem similar to that which was encountered in the original VALT system design. It is necessary to

- generate a path that goes from point A to point B in a continuous manner,
- generate a path that can be flown by the aircraft in question,
- generate a path that can be synthesized within memory and time limits set by the on-board computer and
- generate a path that has a readily determined path length.

For the purpose of this discussion, it will be assumed that no winds exist. The problem of winds will be discussed in a later section. Since the papers that have been researched are directed primarily towards STOL or other fixed wing aircraft, it is not surprising to find that the path generation techniques presented are based on circular arc curved sections. This is the path best suited for relatively constant speed turns at steady bank angles. The problem to be solved is to find a path from point 1 to point 2 with a given initial heading at point 1, the desired final heading at point 2, and a radius to be used for circular arc curved sections of the flight path. Figure 2 shows the geometry for the problem to be solved, while Figure 3 shows the minimum path to solve the problem within the constraints given. Techniques for solving this problem are covered in References 2, 3, 4, and 5. This technique of using a turn, a straight segment and another turn is employed in many of the systems researched as a part of this study and will be referred to as the "Direct To" concept throughout the rest of this report.

A 4D System Using the Direct To Concept - The Direct To concept can be used as the basis for a 4D system. Assume that an approach path is specified by a series of waypoints such as shown in Figure 4. If the distance between the waypoints is known and if an aircraft is flying at a constant velocity (no wind condition), then the time to reach the approach gate from any waypoint is known. If an aircraft is located at some initial point (X_1, Y_1) with an initial heading ψ_1, then a Direct To path exists between the present aircraft position and each of the waypoints. The time to traverse the Direct To path to each waypoint can be determined and, subsequently, the time to arrive at the approach gate can be found for each of the possible flight paths. (This is shown in Figure 5.) By continuously calculating the Direct To distance to one or more waypoints while flying an "open loop" approach course, the time to arrive at the approach gate can be continuously predicted. When the predicted time of arrival and the desired time of arrival are in agreement, the system is instructed to lock onto the path and follow it to the approach gate. This type of system has been flown in a STOL aircraft using an on-board digital computer (References 13 and 16).

Modified Direct To Concept - The basic Direct To flight path as used in previous flight tests is directed towards fixed wing aircraft that fly at relatively constant speed. For use in a VTOL application, however, it may be desirable to use two different circular arc radii for the two turns, since the desired velocity may be significantly different at each of the turns. The mathematics and logic decision rules presented in References 2, 3, 4, and 5 can be modified to incorporate this type of change.

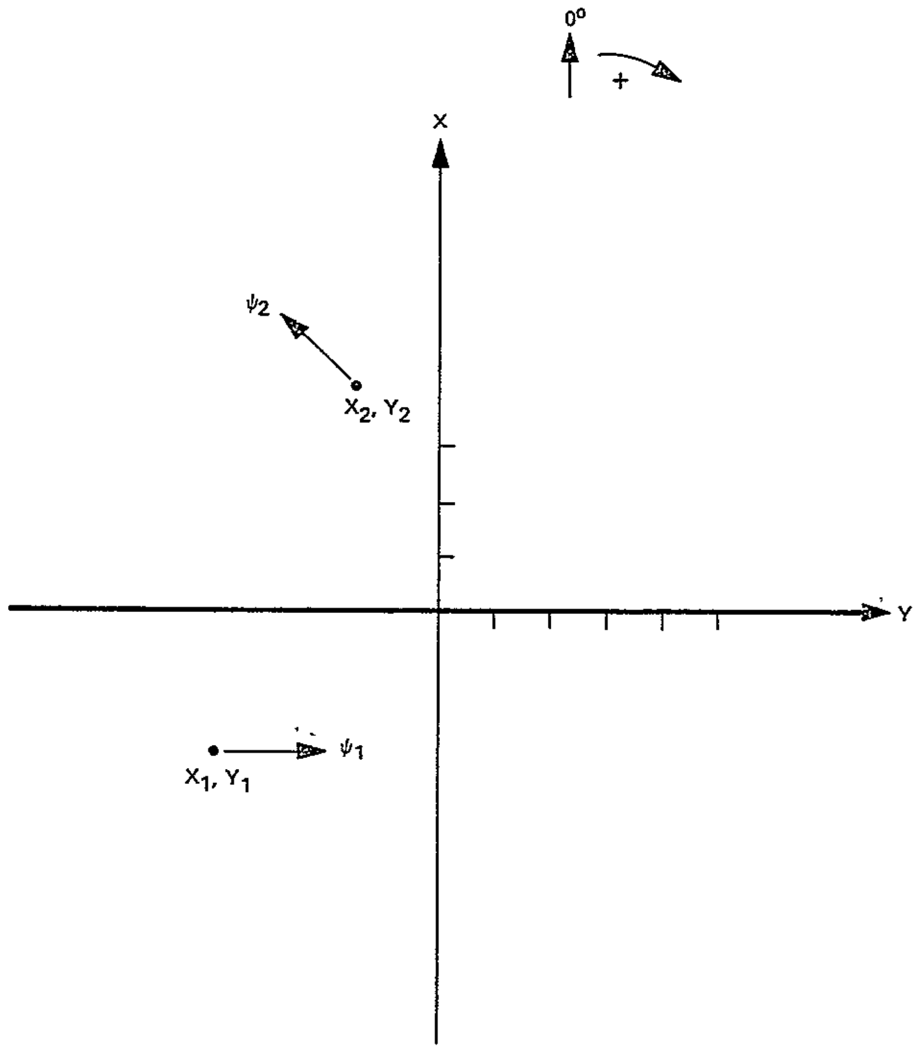

Figure 2
Path Generation Problem

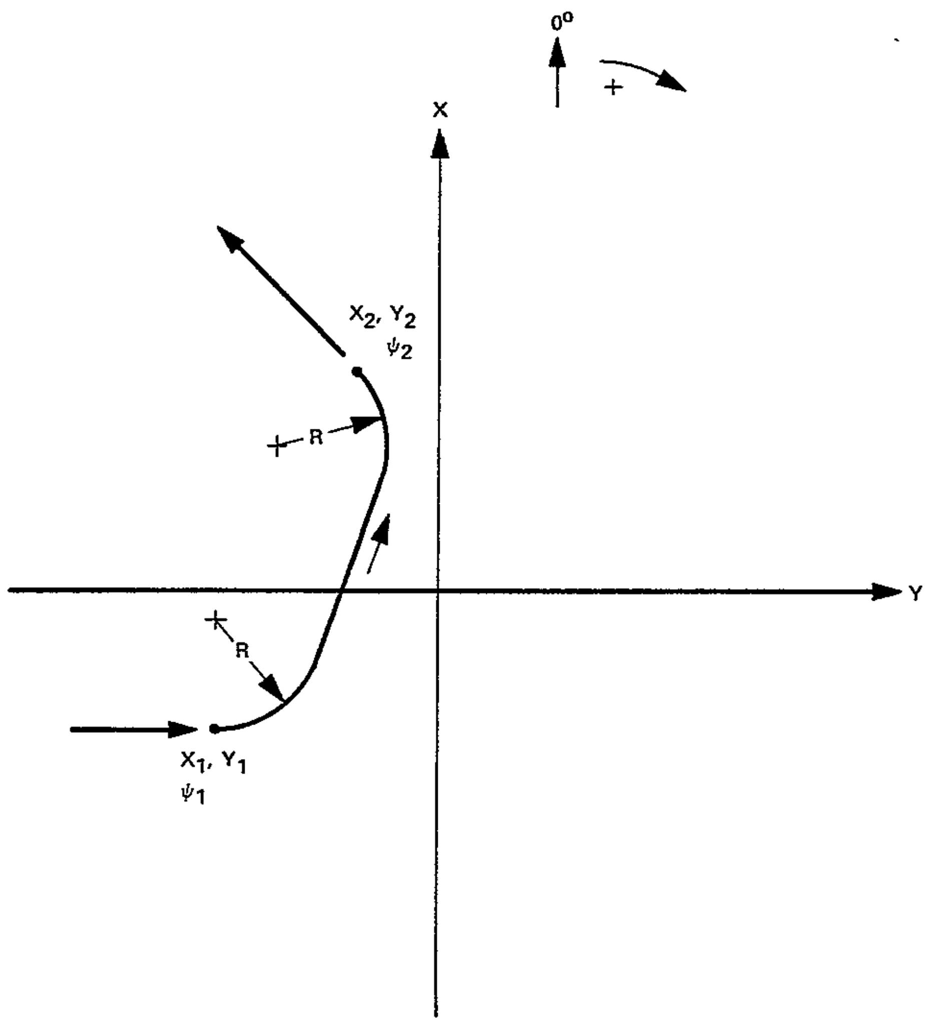

Figure 3
Direct To Flight Path

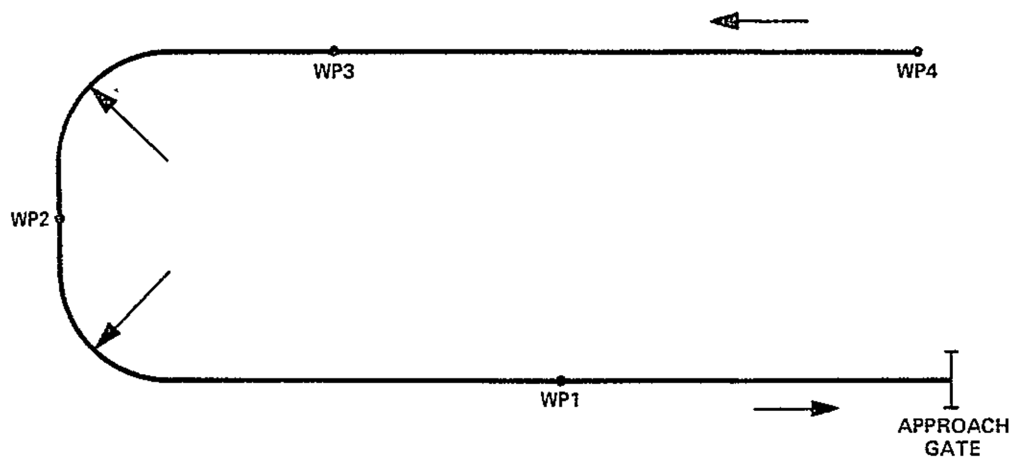

Figure 4
Fixed Approach Path With Waypoints

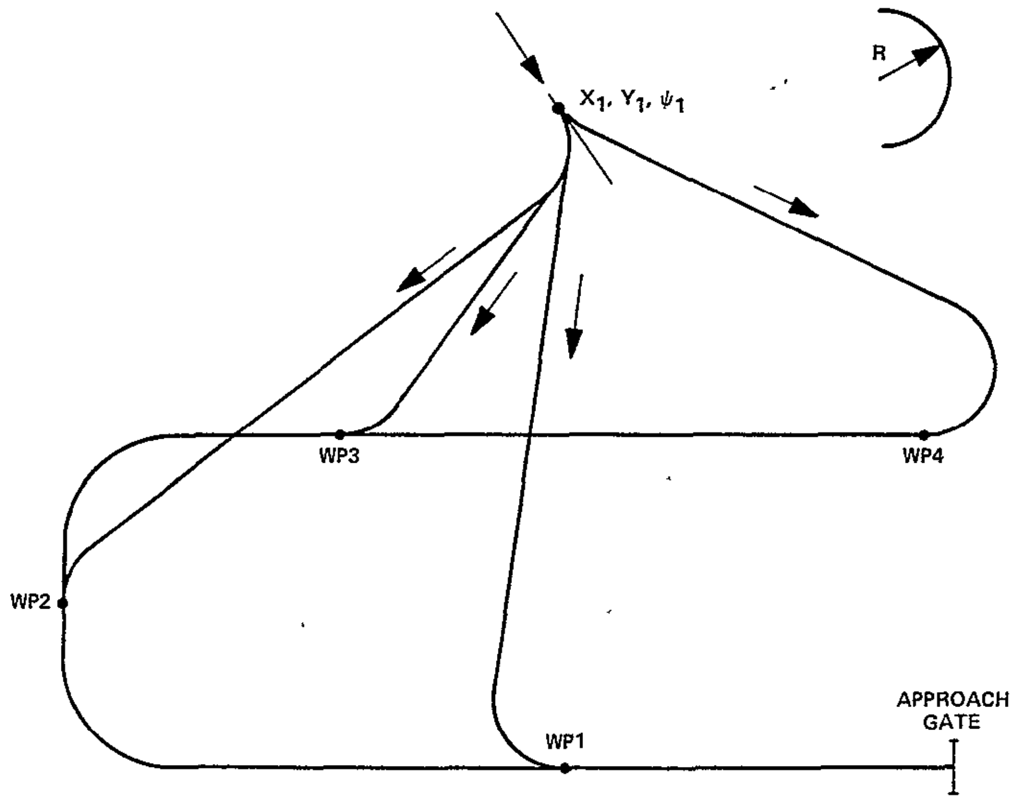

Figure 5
Direct To Approach Paths Through Approach Waypoints

Path Alteration With Delay Fans - One of the most easily visualized methods of path alteration is through the use of what are termed delay fans. A delay fan that is incorporated into an approach path provides a means of adjusting the total path length and, therefore, the time of arrival. The use of delay fans requires that the approach path contain areas where an inbound aircraft may deviate from the nominal flight path within some specified limits. A variety of delay fan forms can be used. Consider the path geometry shown in Figure 6 where WP1 is defined by X_1, Y_1, and ψ_1; and WP2 is defined by X_2, Y_2 and ψ_2. For the purpose of this discussion, ψ_1 and ψ_2 are equal, but this is not a necessary condition. A symmetrical delay fan path between WP1 and WP2 is shown in Figure 7 and the symmetry occurs about the nominal path bisector. Assuming that the same turn radius is used at both WP1 and WP2, and the aircraft is flying at a constant velocity, the amount of time to traverse the path is a function of the initial turn angle.

A parallel offset delay fan using the same nominal flight path is shown in Figure 8. If the assumption is made that the initial and final turns are equal and are fixed at some value, then the amount of time required to traverse the path is a function of the initial straight line distance S. Note that in the parallel offset delay fan, all turn angles are equal.

A third type of delay fan can be generated using the same maneuver that is employed in the Direct To Path generating technique. This type of maneuver, shown in Figure 9, consists of an initial turn to a straight segment and a Direct To path to the final waypoint. As in the case of the parallel offset technique, the value of the initial turn can be varied to suit the particular application. A good description of all the various delay fan maneuvers can be found in Reference 8.

A 4D System Using Delay Fans - A time controlled approach system utilizing delay fan maneuvers would be based on a fixed nominal approach path containing one or more turns. Areas of allowable path deviation are defined at the turns, and delay fan maneuvers are used to lengthen or shorten the path. Figures 10 and 11 show typical approach paths and areas of allowable maneuver. The use of maneuver areas as a time control technique is discussed in conjunction with the FAA Metering and Spacing geometry in References 1 and 8. Reference 10 describes a similar 4D technique that uses a series of time control waypoints to define a nominal approach path, where certain portions of the approach are designated as maneuver areas, while other portions are fixed. A typical approach path in this type of 4D system is shown in Figure 12. This type of multiple time waypoint approach path may be useful when VTOL and CTOL flight paths are intermixed in a common terminal area as described in Reference 9.

Path Control Using Maneuver Corridors - Reference 10 describes a path control technique that defines a maneuver corridor around a nominal flight path. Waypoints are defined at each point on the path where a turn occurs. Path adjustment is accomplished by moving the waypoints along the turn angle bisectors in a way to lengthen or shorten the flight path while maintaining the total flight path within the maneuver corridor. Typical gain time and lose time flight paths are shown as Figure 13. Creation of gain time or lose time path can be accomplished in one of two ways; a path could be generated that alters all the waypoints in order to keep the path deviation small at all points or a path could be created that returns to the nominal as soon as possible. These two types of paths are shown in Figure 14.

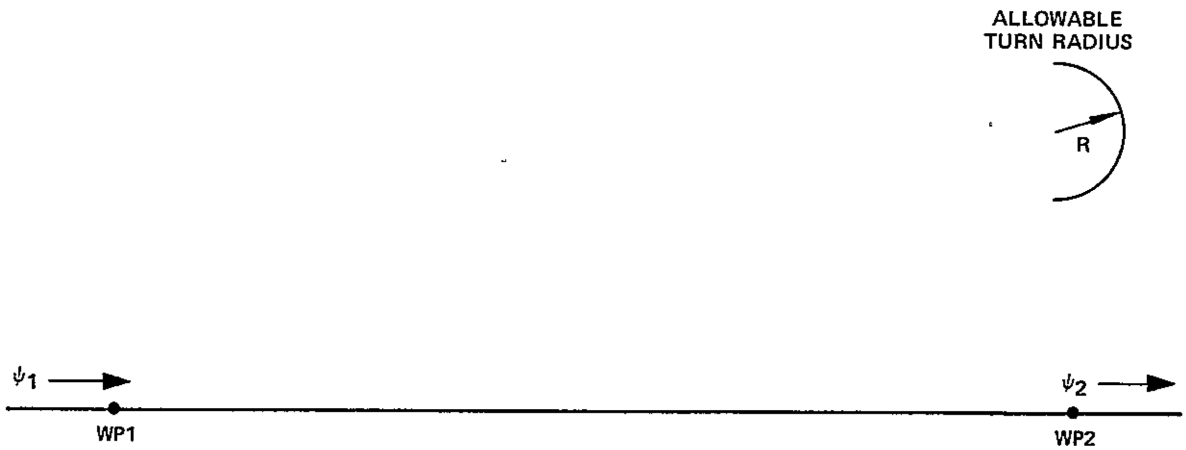

Figure 6
Delay Fan Geometry

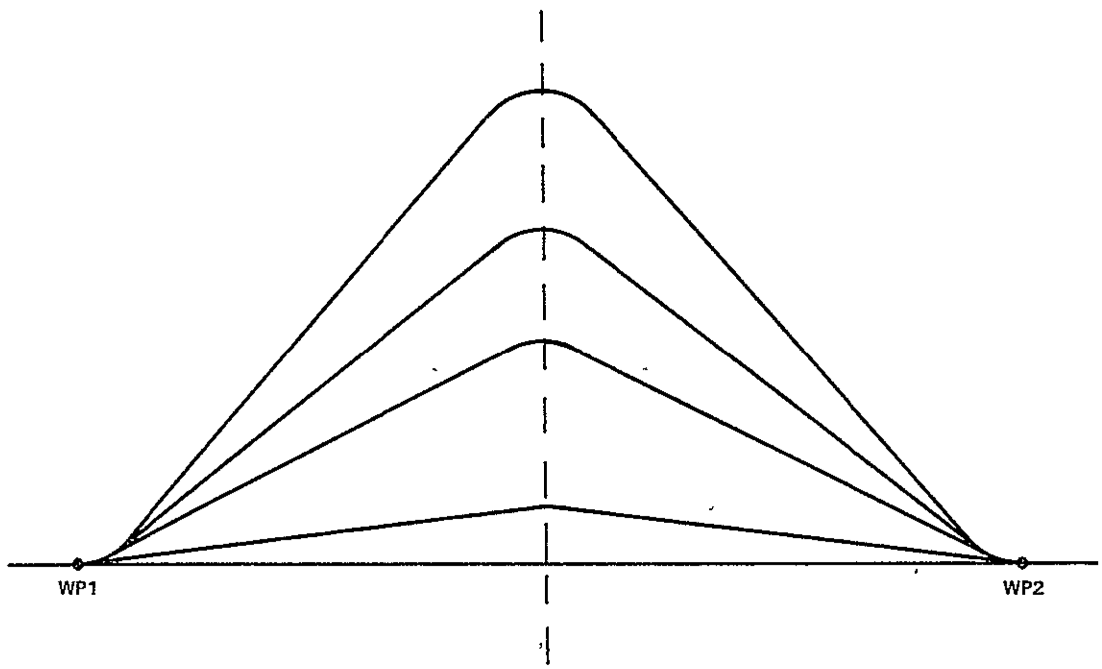

Figure 7
Symmetrical Delay Fan

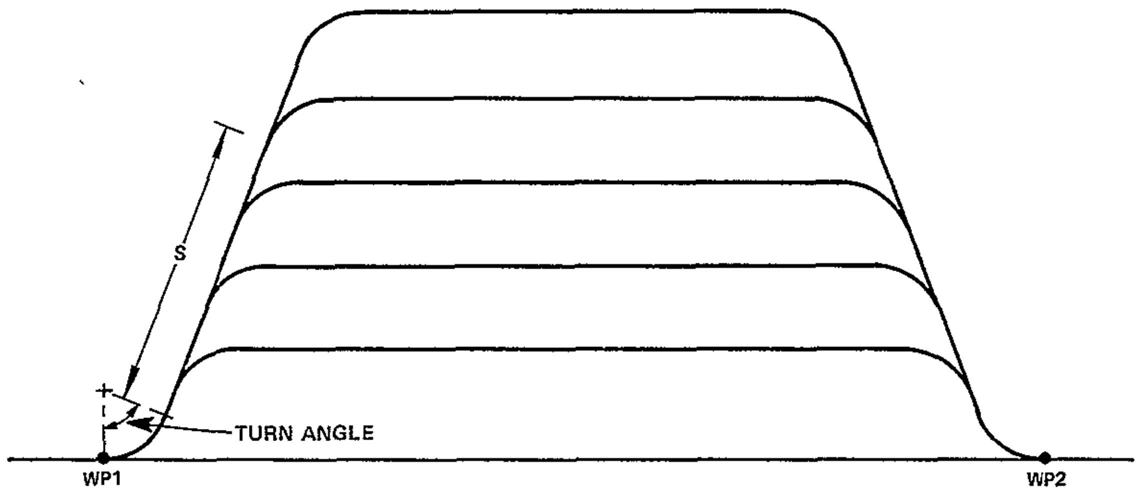

Figure 8
Parallel Offset Delay Fan

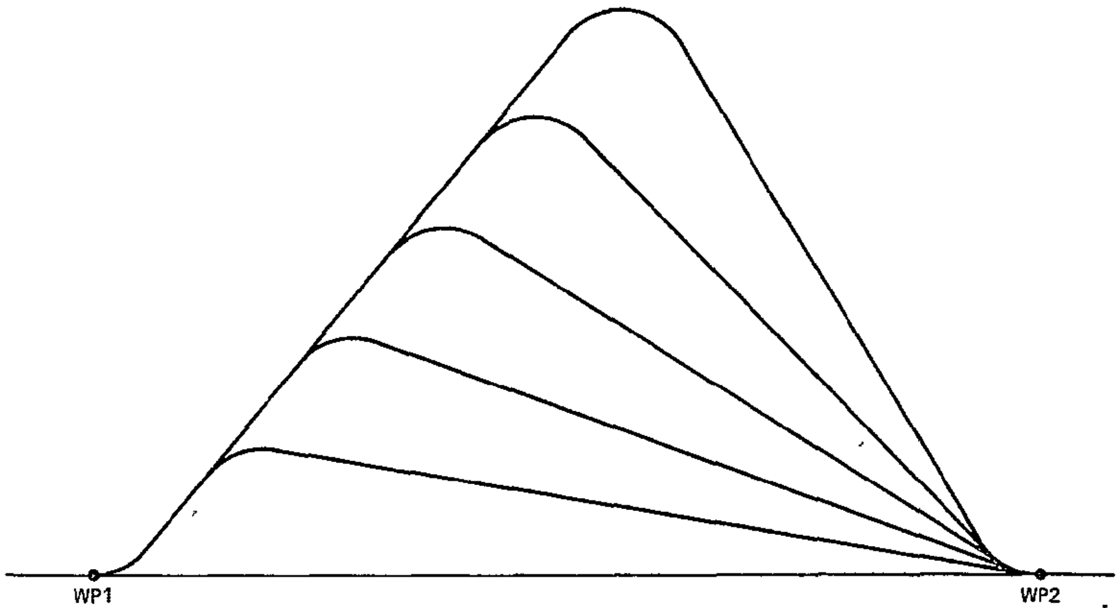

Figure 9
Direct To Delay Fan

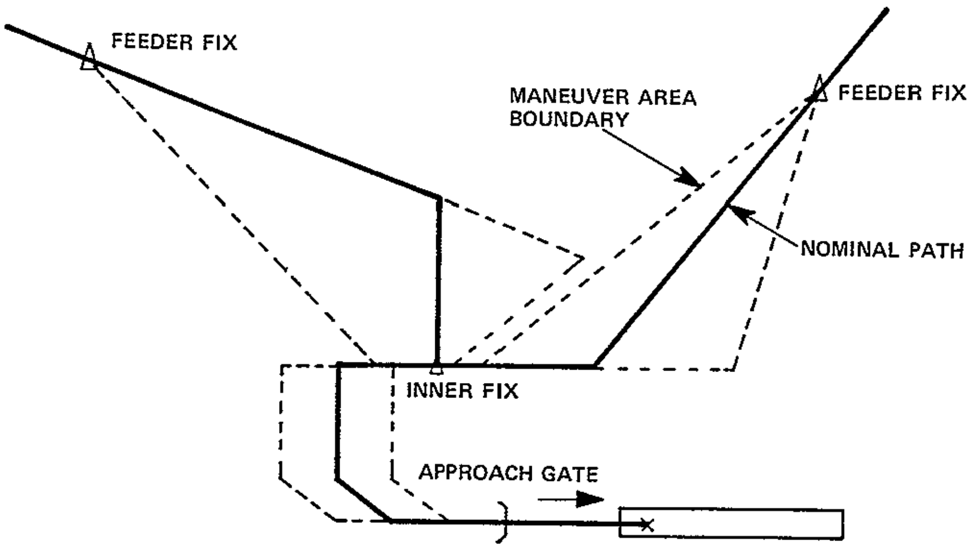

Figure 10
Maneuver Area With Feeder Fixes Off Runway Centerline

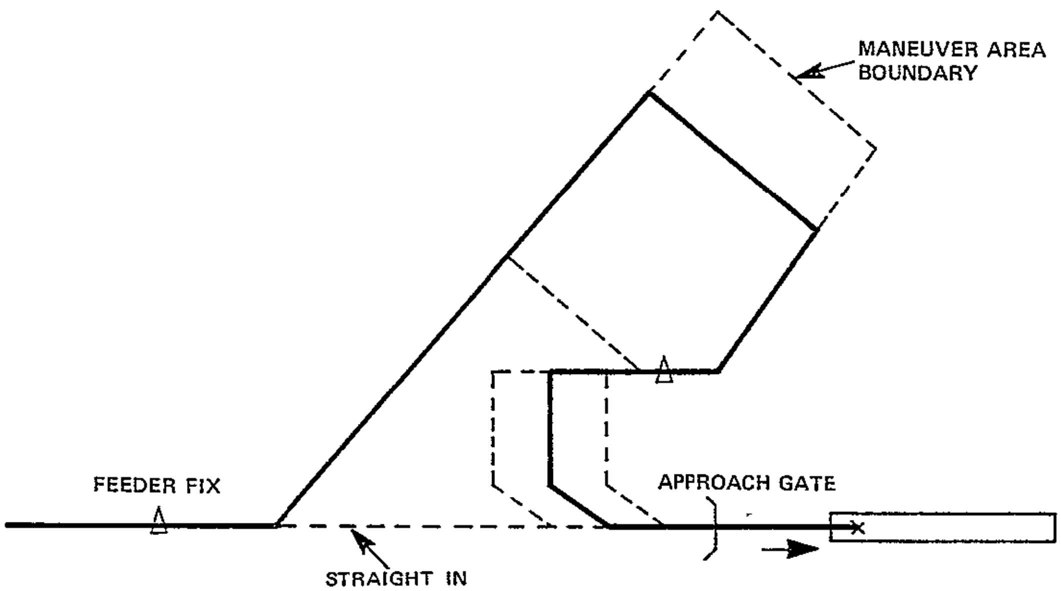

Figure 11
Maneuver Area With Feeder Fix on Runway Centerline

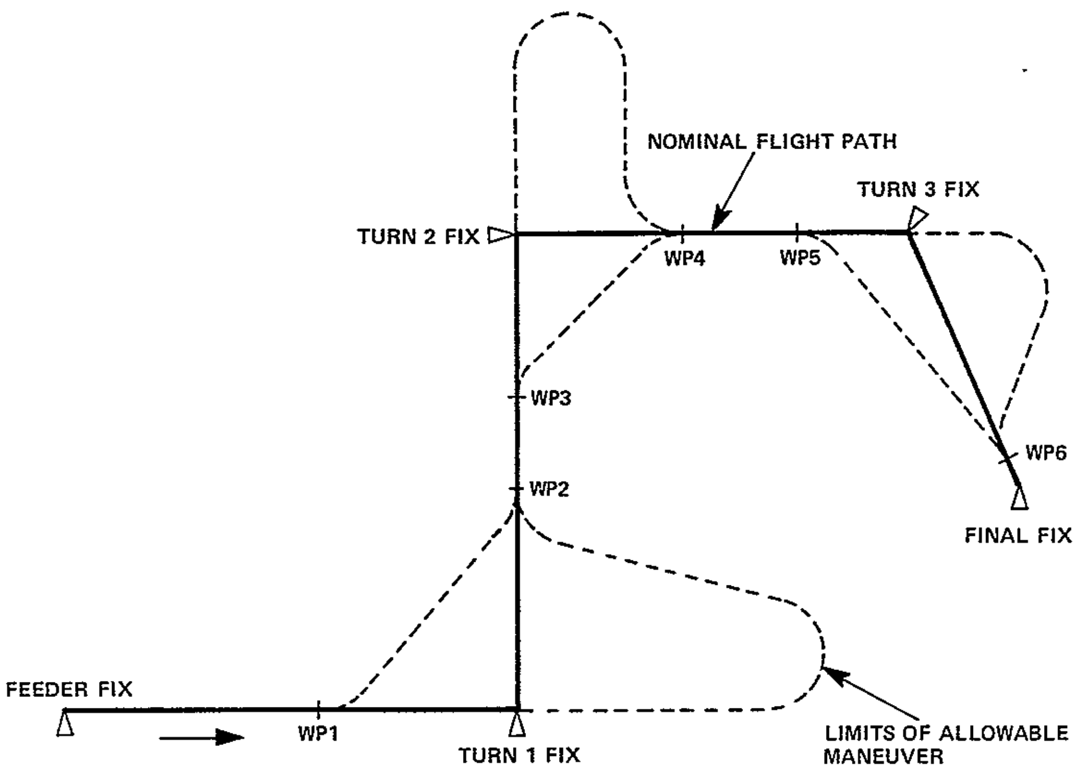

Figure 12
Multiple Time Waypoint 4D Approach Using Delay Fans

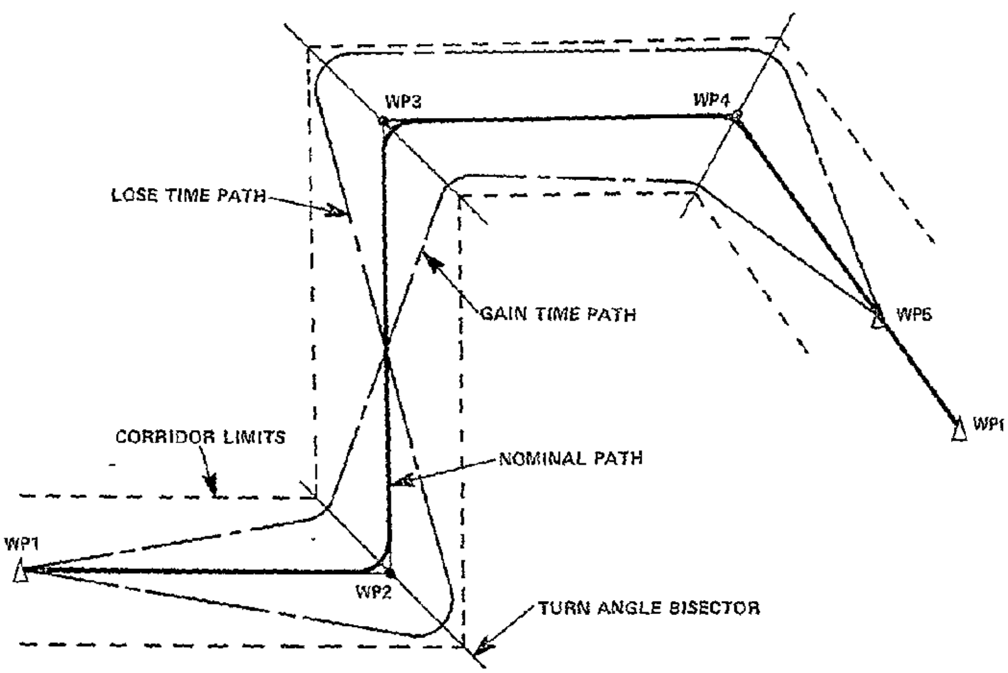

Figure 13
Path Control Using Maneuver Corridors

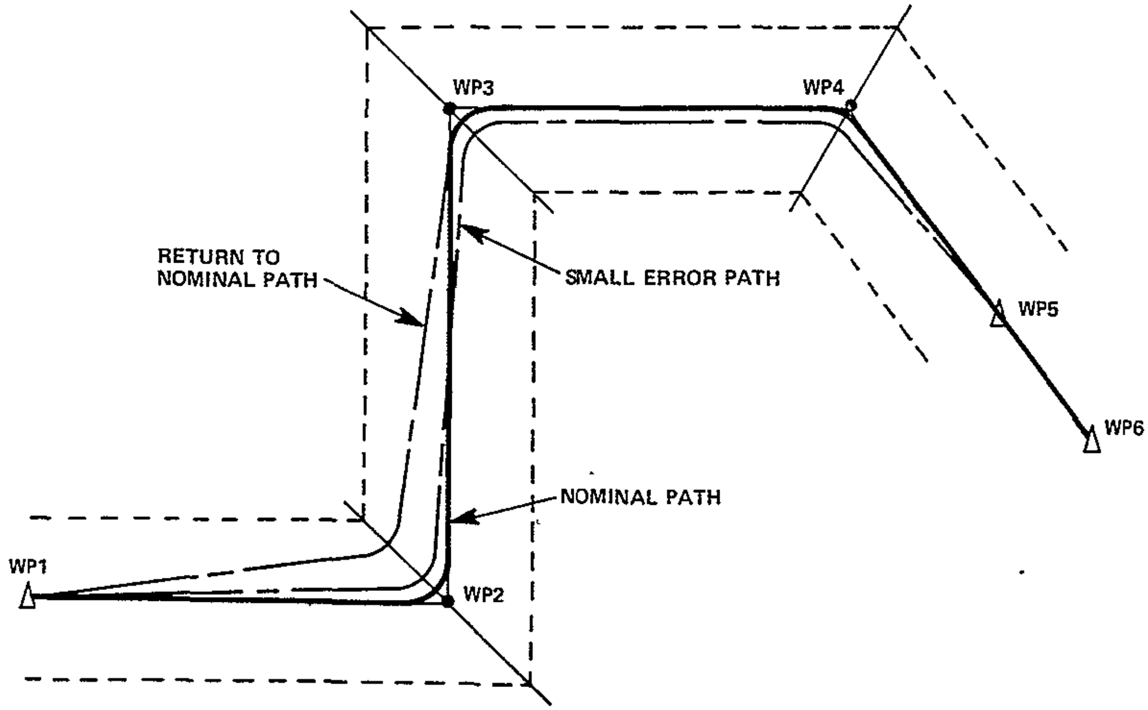

Figure 14
Alternate Path Reduction Techniques

Avoidance Areas - An interesting path generation idea is presented in Reference 19. A path is constructed through a series of data points using the Direct To technique described above. Path generation is further complicated, however, by the introduction of avoidance points. An avoidance point is defined as the center of a circle through which the flight path may not penetrate. The Direct To technique is modified to avoid these areas. A typical flight path is shown in Figure 15.

Multiple Approach Paths - One final technique in the area of path generation, that is of interest, is presented in Reference 18. A series of fixed approach paths are created that link together one or more source nodes (feeder fixes) and one or more sink nodes (approach gates) through a series of intermediate control points. Each aircraft that enters the approach system is placed into a classification that is based on its normal approach speed and its ability to increase or decrease speed. Time separation standards are established for the various nodes. Aircraft arriving at a source node are scheduled to the closest available sink node consistent with the aircraft classification and other traffic. The actual approach path is not known to the pilot until this decision is made. The scheduling problem is handled by a ground computer as part of the Air Traffic Control system. A typical approach situation is shown as Figure 16.

Velocity Control

The second major element of 4D approach systems is velocity control. Velocity control is necessary in order to ensure that the predicted time of arrival at a time waypoint can be attained. The extent to which velocity control is a coarse or a fine tuning device is, of course, a function of the speed range of the aircraft in question. Velocity control techniques are divided into two primary categories; ground speed (or zero wind) control and airspeed control.

Ground Speed Control - Speed control is one of the primary elements of a 4D approach system. The system must be able to calculate the velocity profile needed to traverse a known path within a given time, and must be capable of controlling the aircraft in a way to ensure that the desired profile is followed. In addition, the system must be able to determine the maximum and minimum time required to traverse a given path within the maneuver constraints that have been placed on the aircraft. A velocity control system that uses ground speed control tends to simplify the problem since the system may compensate for wind effects.

One technique that can be used to define the velocity profile, is to use a standard form of profile and adjust the parameters to suit the particular path and aircraft. Reference 12, for example, discusses the use of a profile consisting of an acceleration or deceleration segment followed by a constant velocity segment and then another acceleration or deceleration segment. This type of profile can then be fitted between two time control waypoints in order to establish the velocity commands needed to traverse the flight path segment in the allotted time. Degenerate cases of the standard profile can be used as required with the exception that all profiles must contain a constant velocity segment. The use of this type of general purpose profile is illustrated in Figure 17 where all accelerations and decelerations are constant, but not necessarily equal to each other, and the final velocity is less than the initial velocity. Under these conditions, the total path length is represented as the area under the profile. Distance L_1, for example, represents the shortest path that can

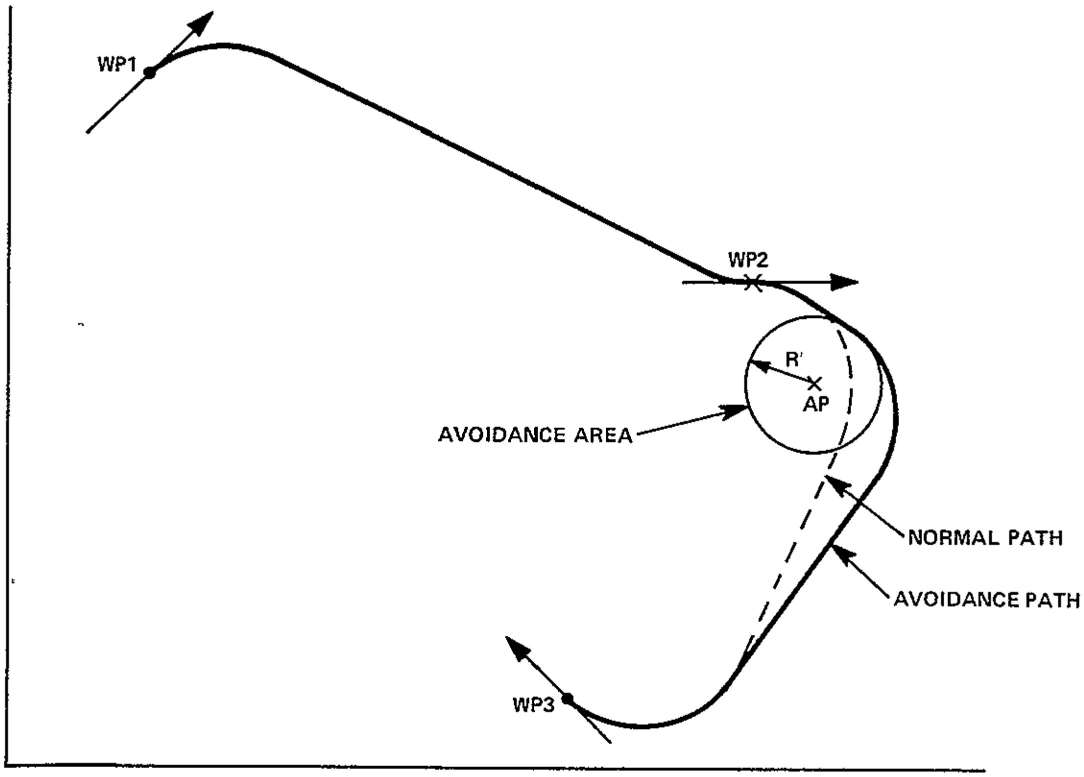

Figure 15
Path Generation Incorporating Avoidance Points

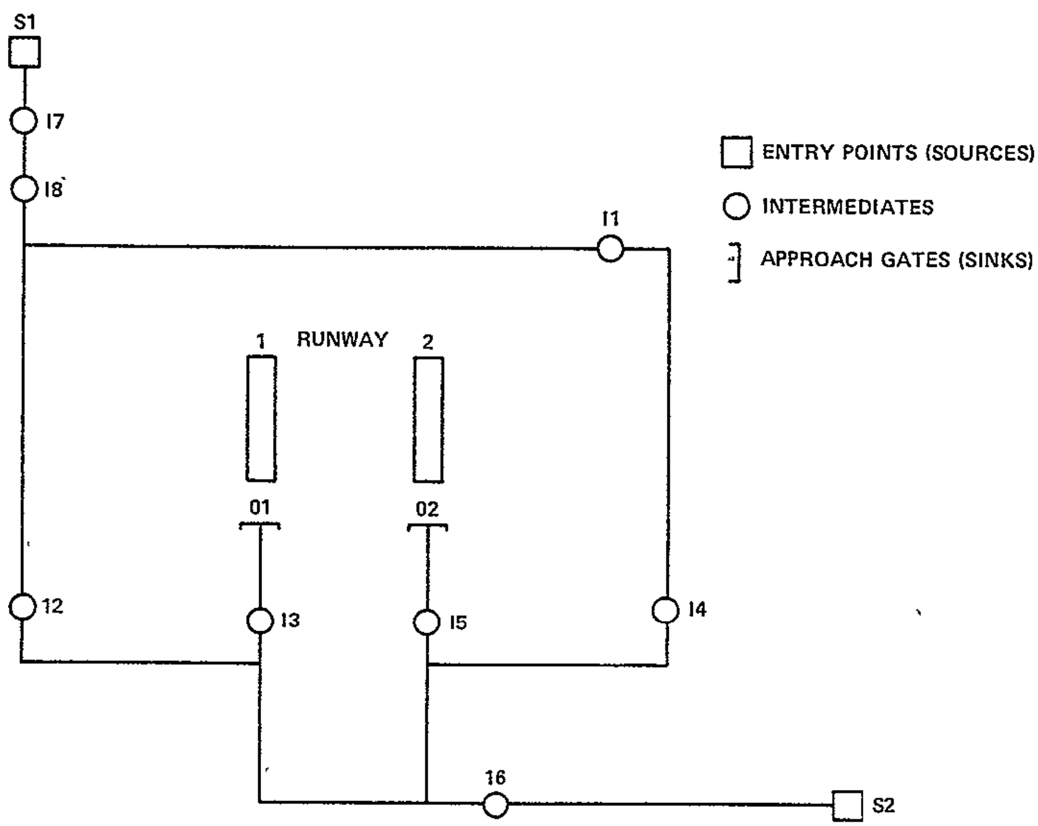

Figure 16
Multiple Approach Paths

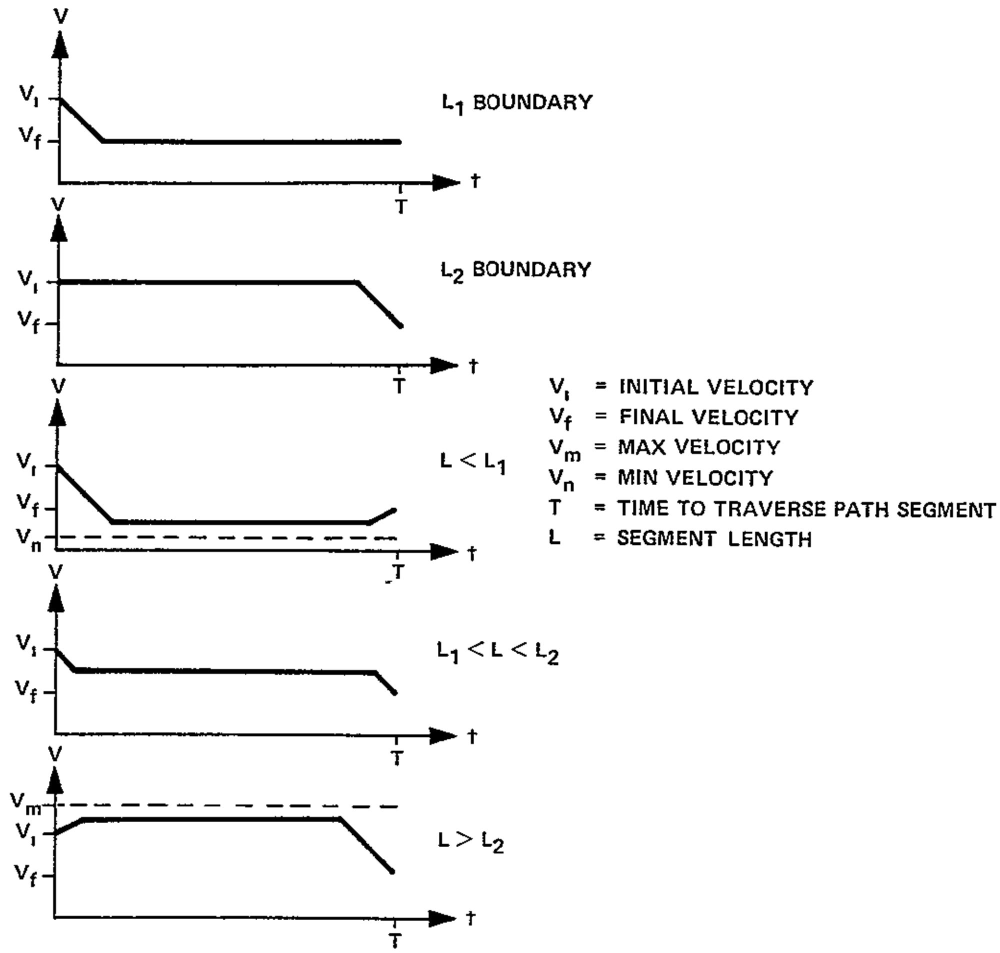

Figure 17
3 Segment Velocity Profile

be flown with a two segment profile. Similarly, L_2 represents the longest path that is possible with a two segment profile. These two distances represent the boundary conditions that define the type of the three segment profile that must be used to traverse a known path distance within a given time frame. If, for example, the desired path distance is less than L_1, a profile consisting of a deceleration, a constant velocity segment, and an acceleration is required. Similar analysis reveals the conditions which the other profiles shown in Figure 17 would be applied. If the final velocity is greater than the initial velocity, the same type of determination can be made. This type of analysis is important because it provides a mechanism that allows the on-board digital computer to make an unambiguous decision based on little input data. It should also be noted, that a simple analysis of this type can be used to determine the absolute minimum and maximum path distance that can be covered within the constraints such as acceleration, deceleration, maximum velocity, and minimum velocity that are imposed on the system.

The velocity profile generation techniques, discussed above, can be expanded to incorporate different baseline profiles. It may be advantageous, for example, to utilize a profile consisting of two constant velocity segments joined by a single acceleration or deceleration segment in conjunction with a Direct To lateral path. This type of profile would restrict velocity changes to the straight line segments of the lateral path, thus reducing pilot workload during turns. It may also be desirable, for example, to use a velocity profile that specifies the value of acceleration or deceleration as well as the value of the velocity that must be satisfied at a time waypoint. Such a constraint may even be required in order to avoid unacceptable pitch activity during the final phase of the approach.

In addition to defining the appropriate velocity profile, a 4D system must be able to determine when a given flight path or segment cannot be traversed in the time specified without exceeding one or more system limits and it must be able to correct velocity profile errors in a manner as to ensure that the desired time of arrival is attained. The first problem is a subset of the profile generation problem and can be handled during the profile initialization phase. Two common techniques are used to handle the control problem. First, a new profile can be generated on a repetitive time basis such as every 10 seconds. This technique was used in a STOL system described in References 13 and 16. Speed control in these flight tests was carried out with throttle motions and the use of the update technique resulted in unacceptable throttle activity in flight. A second technique that has been suggested involves the addition of a correction term to the velocity profile. Correction terms can be based on either time error at a position, or position error at a given time. In either case, a velocity bias proportional to the error is added to the nominal velocity commanded by the velocity profile. Limits and gain scheduling as a function of time to go are usually applied to the correction factors in order to prevent excessive velocity build-up when large errors exist. Empirical determination of the required bias was employed in the flight tests reported in Reference 13.

Phantom Aircraft Tracking - Given that a velocity profile can be generated through a scheme similar to that discussed above, the use of essentially open loop correction factors can be avoided if an appropriate control system is employed. A control system based on the positioning of a phantom aircraft along the 4D flight path is presented in References 12 and 13. In this system, the desired reference position of the aircraft at any time is computed and used to generate crosstrack and along track error signals based on the actual aircraft position. A moving coordinate system, with the original located at the phantom aircraft position and one axis tangent to the path is employed. Reference commands such as the nominal bank angle and the nominal velocity are computed based on the flight path. Correction commands derived from the crosstrack and along track errors are summed with the reference commands.

Airspeed Control - In all but the most ideal research conditions, 4D flights will be conducted in the presence of winds. Calculations of time to go or time to traverse a segment of the 4D flight path, are generally based on measurement of ground speed along a ground referenced track. If the flight path involves turning maneuvers, or if the wind magnitude or direction changes, then the airspeed required to maintain a certain ground speed profile will also vary. Attempts to maintain a reference ground speed under such conditions can result in a considerable increase in pilot workload, particularly in computer aided manual flight. In addition, the amount of pitch activity may be unacceptable to pilots or passengers during the approach portion of the flight. For these reasons, the use of airspeed based commands in a 4D system may be desirable.

The use of airspeed based references in a 4D system implies the capability to generate the ground based flight path and to then present commands to the pilot or autopilot in the form of required airspeeds. If, for example, the desired airspeed profile for a given path segment is a constant, it is necessary to be able to compute the value of the constant airspeed required to traverse the path in a given time increment. For curved flight paths in the face of steady winds, this will result in a non-constant ground speed profile. Similarly, it may be necessary to compute the time required to traverse a curved flight path at a given airspeed. For straight flight path segments in the face of steady winds, the problem simply becomes one of computing the heading and airspeed necessary to maintain a ground speed along a fixed ground track. For curved flight paths, however, the problem becomes much more difficult. In order to determine the time required to traverse a circular ground track in the presence of a steady wind for example, it is necessary to solve an elliptical integral. Various approximation techniques for solving such problems are presented in References 5, 6, and 7. Solutions for the problem involving curved flight paths, other than circular arcs, have not been found in the literature search.

Another problem that exists in the presence of winds, involves the computation of the nominal bank angle required to fly a circular ground track. Since most control systems would use the nominal bank angle as a reference, and since this angle will change as the path is traversed, the 4D system must be capable of solving this problem for the flight path in question. Techniques for solving this problem are presented in References 6 and 7 for circular paths with steady winds. Solutions for constant velocity as well as accelerating and decelerating speed profile conditions, are also contained in these references.

VALT 4D SYSTEM

The first question to be faced in formulating a 4D concept suitable for VALT involves the degree to which velocity control and path control are to be used. Since one of the objectives of the VALT program is to provide a data base for future navigation, guidance and control systems, a 4D system for VALT should incorporate both ideas. The inclusion of both path control and velocity control concepts will facilitate evaluation in both the simulation and flight test environment and will provide a broader data base for future efforts. The degree to which a particular technique is used can be governed by software limits placed on the parameters that define each technique. For example, if the area of maneuver allowed around a given portion of the approach path is quite restrictive, then the system will be forced to rely primarily on velocity control techniques. On the other hand, operational limits on the vehicle airspeeds at both the upper and lower ends may indicate that a path alteration maneuver is necessary in order to accommodate gross changes in waypoint arrival times or large time errors that may be induced into the system.

The configuration and capabilities of the existing VALT system have had a strong influence on the techniques and concepts selected for the VALT 4D system. The capability of the VALT system to generate arbitrarily shaped curved approach paths based on tabular position data indicated that path control techniques, based on well defined ground tracks, should be employed. The existing ground speed control and velocity profile generation software pointed to the use of ground speed velocity control techniques for the 4D application. Airspeed control techniques appear to offer some significant reductions in pilot workload, however, and the inclusion of these techniques in the system offers the opportunity to expand the basic system capabilities.

Based on an analysis, the 4D techniques reviewed and considering the nature and capabilities of the existing VALT system, the following framework for a VALT 4D system has been adopted:

- Multiple time control waypoints defined in tabular format similar to the existing lateral path data tables.

- A three part 4D approach path consisting of a Direct To maneuver to an initial waypoint, a fixed nominal path with areas of allowable maneuver bounded by time control waypoints, and a final deceleration to a hover.

- Velocity control based on a combination of airspeed and ground speed references. The approach path velocity profile is to be generated on a real time basis using two different three segment profile generation techniques.

- Direct To path generation capability from any point on or off the path to any time control waypoint on the path. Path selection and initialization procedures are modified versions of the existing VALT lateral path selection techniques.

- Path alteration on the nominal approach path based on the Direct To delay fan technique. Areas of allowable limits to be contained in the path generation software.

Multiple Time Control Waypoints

A time control waypoint in the VALT 4D system is defined by an X position, a Y position, and a desired heading in the horizontal plane and by a specified time of arrival at that point. Since the lateral flight path will be generated from the waypoint data by the existing VALT software in a manner that forces inclusion of all waypoints in the path, all VALT waypoints are similar to the final heading waypoints described in Reference 5.

Multiple time control waypoints are used to define time boundaries for various sections of the approach, thus providing a convenient method for separating and restricting the degree of path alteration or velocity control that can be used. In addition, the use of multiple time control waypoints will be necessary in an operational system to ensure aircraft separation in very high density terminal area operations involving intersecting flight paths.

4D Approach Path

The approach path consists of three separate sections: the path capture maneuver, the nominal approach path, and the deceleration to a hover. A time control waypoint is placed at the point where the deceleration phase begins and is used to define the approach gate and the final time of arrival. 4D control will not extend beyond the approach gate. A constant attitude deceleration profile will be used from the approach gate to the landing pad. This type of deceleration profile is described in Reference 11. Existing VALT software is used to provide the required velocity reference as a function of path distance to go during the deceleration.

The nominal flight path section is defined as that portion of the approach that starts at the initial time control waypoint and ends at the approach gate. Additional time control waypoints may be included in the nominal flight path. Areas of maneuver can be established between adjacent time control waypoints to provide a boundary on any path alteration decisions. Delay fan path alteration techniques are used to provide a path distance change capability. The decision to use a fixed nominal path and delay fan path alteration techniques was based on the capabilities and flexibility of the existing VALT path generation software. Implementation of 4D path techniques in this manner, requires only the generation of suitable data points and is much more readily accommodated than other techniques such as the use of maneuver corridors.

In conjunction with the delay fan path alteration techniques developed in this study, two maneuver area modification techniques are also being used. Delay fan boundaries determine the area of allowable path modification between two time control waypoints. Variable delay fan boundaries have been incorporated into the system to investigate the effect of boundary limits on the delay fan generation process. Avoidance points and avoidance areas have also been added in the delay fan maneuver areas. Avoidance points are defined as points in the approach area from which the specified flight path must be separated by a given minimum distance. The avoidance area is defined as a circular area with the avoidance point as its center and the minimum separation distance as the radius. When used in conjunction with the path alteration priority system defined for VALT 4D, the avoidance area may modify the lateral path in a way to force the velocity profile off the designated limits, and possibly produce simpler velocity profiles within the delay fan area. A complete description of the delay fan techniques and the delay fan area modification techniques to be used is contained in Appendix A.

The portion of the approach between the present aircraft position and the initial time control waypoint, is defined as the path capture maneuver section. A path must be defined from any point in the terminal area to the initial time control waypoint. This path is based on the position coordinates of these two points and the initial and desired final aircraft heading. The path capture phase of the approach will generally provide the greatest degree of arrival time control since subsequent phases of the approach are relatively constrained. For this reason the path capture maneuver should be well defined and have a known distance that can be used as a basis for velocity control. The Direct To technique described in Reference 3, satisfies this requirement and will be used for the path capture phase of the approach. The basic Direct To technique has been modified to allow the use of different radii on each of the two circular maneuvers. This change has been incorporated because of the greater range of operating speeds available with the helicopter, thus allowing turns of greatly differing radii to be made during a single Direct To maneuver without exceeding the system bank angle limit.

In addition to providing a well defined maneuver from the present aircraft position to the initial time control waypoint, the Direct To maneuver is also used to generate a flight path between the present aircraft position and any other time control waypoint including the approach gate. When combined with a suitable velocity control technique, the Direct To maneuver provides a powerful and flexible time control capability that can be readily incorporated into the existing VALT software. A complete description of the Direct To techniques developed for VALT is contained in Appendix B.

Velocity Control

Three different velocity reference generating techniques are used during the 4D approach. A constant attitude deceleration profile based on distance to go along the path is used from the approach gate to the touchdown point. Time control techniques are not employed during this portion of the approach.

On the nominal approach path, a ground speed profile is generated using the specified waypoint arrival times in conjunction with the distance between waypoints. Velocity changes are accomplished with constant acceleration and deceleration values using three segment velocity profile techniques similar to those described in Reference 12. Waypoint crossing velocities are detrmined by a weighted average technique based on the path length, the time allowed, and the minimum and maximum velocity limits for the segments. The ground speed velocity reference generated by the velocity profile is summed with an additional velocity term based on calculated time error to produce an instantaneous velocity command. This velocity command is then used with the existing velocity control software to control the aircraft. A complete description of the methods used for velocity profile generation and control are contained in Appendix C.

During the path capture phase, time control is maintained through the use of airspeed commands rather than ground speed commands. Airspeed control is incorporated during this maneuver in order to reduce the pitch commands that occur during curved flight in the presence of winds, to eliminate airspeed fluctuations which may be disturbing to the pilot, and to provide a smooth transition from the airspeed hold mode which is the primary pitch mode used prior to initiating the approach capture mode. The basic techniques for generating constant airspeed commands during curved path flight in the presence of winds are discussed in Reference 6. These techniques have been modified to allow independent selection of the entry and exit airspeeds thus allowing the system to generate an airspeed profile that transitions from the initial airspeed to the airspeed required to achieve the desired ground speed at the first time control waypoint. The time to traverse the path capture segment is determined by positioning the acceleration or deceleration at an appropriate point on the flight path. When using airspeed control two changes are incorporated into the lateral position control laws described in Reference 14. When flying in the presence of winds, it is necessary to hold some lateral error in order to fly a crab angle to the path. On the curved sections, a lateral offset is necessary in order to deviate from the nominal bank angle around the turns in the presence of winds. A crab angle lead term has been added to eliminate the errors on the straight sections of the path. For the circular turn segments, a bank angle lead term has been added which commands a changing bank angle for a given radius turn in the presence of prevailing winds. The nominal crab and bank angles are then related to wind magnitude and direction and will not generate lateral path errors. A complete description of the methods used to obtain airspeed velocity references and the related crab and bank angles is contained in Appendix D.

Displays and Controls

The conduct of successful curved, descending decelerating approaches with time constraints will require efficient, real-time exchange of information between the pilot and the aircraft systems. This information exchange can be divided into four principal areas:

- Flight Path Command Information
- Horizontal and Vertical Situation Information
- System Performance Monitoring Information
- Flight Path Control Information supplied by the pilot

The flight path command information includes flight director commands generated by the digital navigation computer as a function of aircraft position on a fixed approach path. As indicated in past flight operations, the pilot tends to lack full confidence in the flight director commands during curved approaches. To add credibility to the flight director system, information displays of horizontal and vertical situations need to be added to the system. Such displays would provide pictorial descriptions of aircraft position relative to a lateral flight path and altitude and velocity profiles. The displays would also show the prescribed flight path relative to significant terrain features, changes in the lateral path which may take place, and the aircraft position relative to some desired hover point. Displays are also necessary so that the pilot may monitor the quality of his progress along the flight path. Such performance monitors would include altitude and velocity profile tracking, altitude and time error displays, and heading or course indicators. All of this available information enables the pilot to more accurately evaluate his position on the approach and anticipate any action that will be necessary to successfully complete the approach.

It is also necessary to permit the pilot to actively take part in accepting or rejecting approach paths that are being displayed. In the past the pilot was not aware of the course of an approach path relative to the surrounding terrain. By superimposing the path over a terrain map, the pilot can accept or reject a specified approach path based on flyability in that terminal area. Several techniques can be used to produce this pilot-control capability. The existing technique in the VALT system is keyboard entry through the Navigation/Guidance Control Panel, but this form of data entry has been found to be somewhat inefficient while operating in a flight situation. Other techniques for pilot data entry need to be addressed to reduce pilot activity in this area. A method for the pilot to enter data directly from the display would be most desirable. Several different techniques are available for this type of data entry, such as joystick, data tablet, track ball, light pen or touch sensor screens. The graphics joystick was selected for data entry into the VALT simulation display system.

SOFTWARE

The software generated as part of this study consists of flow charts and digital computer programs. Flow charts have been generated for:

- The Direct To and symmetrical delay fans,
- The Direct To path capture maneuver including the use of two different turn radii,
- Velocity profile generation, using both single-speed change and two-speed change techniques,
- Determination of crossing velocities in a multiple waypoint path,
- Generation of curved path airspeed velocity profiles under steady wind conditions, and
- Interactive graphics displays for all phases of the 4D approach.

The flow charts are contained in Appendices A through E.

Digital Computer Programs

Digital computer programs have been generated to implement and verify selected portions of the flow charts. In order to incorporate those programs developed for 4D into the 1819A flight computer, certain modifications had to be made to the program structure described in Reference 14. The programs required strictly for flight test in the VALT CH-47B aircraft were eliminated for the simulation. The split-cycle inner loop structure was eliminated, and the loop time was set to 40 milliseconds. This provided the time and space needed to verify the operation of the 4D programs. The program organization is shown in Table 1.

TABLE 1

VALT COMPUTER ORGANIZATION

00000 - 00177	Reserved Interrupt and I/O Locations
00200 - 05671	Flight System Running Program
05672 - 07261	Time and Velocity Calculations
07262 - 07777	Direct To Axes Rotation
10000 - 15577	Extended Utility
15600 - 17777	Direct To Switching Diagram and Data Table Generation
20000 - 22747	Lateral Path Running Program
22750 - 23423	VALT Simulation
23424 - 24024	Direct To Parameter Computation
24025 - 25415	Lateral Path Data
30000 - 32650	Flight System Variables
33640 - 35073	DRO Routines
37000 - 37777	Constants

Direct To - The software developed for the Direct To maneuver is quite extensive. The degree of programming complexity is much greater than first anticipated, primarily due to the inclusion of the capability to use two different radii on the same path.

In all, about 1500 words of code have been generated to implement the Direct To capability. The majority of that coding is required to implement the switching diagram decision table. The estimated time to compute the Direct To capture maneuver, including generating a path data table, is five milliseconds. Coding has not been done for the cases where the initial and final points on the Direct To Maneuver have equal or opposite headings since the additional effort did not appear to be justified for this study. The Direct To program has been structured to allow the additional coding to be added at a later date.

Implementation of the Direct To program as a real-time prediction routine required that the program be defined as four major subroutines:

(1) Data transferral and coordinate transformation

(2) Switching diagram decision table

(3) Computation of Direct To path parameters such as headings, radii and segment lengths

(4) Generation of a path data table.

For the prediction process, the first three subroutines are called sequentially. The Direct To path parameters can be computed and compared with known time and distance requirements for automatic switching onto the maneuver. The fourth subroutine is not called until the system is commanded to switch onto the Direct To capture maneuver.

Delay Fans - The routines for generating Direct To delay fans have been coded and checked out. Two different techniques were developed for handling the Direct To delay fan. The first was a predictive-type generation; the other was a single fixed computation. For the first it was necessary to add about 100 words of coding to the Direct To subroutines to generate the delay fan maneuver. For the other, a routine of nearly 300 words was written.

The first program design is such that the aircraft flies a predetermined outbound heading from the entry waypoint while using the Direct To predicting capabilities to calculate the path parameters required to fly to the exit waypoint. When the time and distance constraints of the fan area have been satisfied, the system is automatically switched onto a Direct To capture maneuver. The computation time of this routine is approximately the same as that for the Direct To capture routine.

The second program design is such that when the time and velocity requirements are known, a distance is generated and then the delay fan maneuver is generated directly. This program has been coded and checked out for turns of the same direction only. The equations necessary for a maneuver of opposite turns require an iterative process to compute the maneuver. It was determined that this kind of flexibility was not necessary for this study, and therefore the effort required to code and check out such a routine was not justified. The program that was written, however, does generate the delay fan maneuver prior to flying the approach.

Only the flow charts have been completed for the symmetrical delay fan. Since there are many restrictions on this type of maneuver and, since it is in reality a special case of the Direct To delay fan, it was felt that the time to code and check out this routine could not be justified for this study.

Velocity Profile and Time Control - The velocity profile generation routine has been coded and checked out using the Sperry VALT Software Validation Facility (SVSVF). The routine at present runs in two different modes: off-line and real time. In the real-time configuration, the routine generates a profile for a single time section based on known entrance and exit velocities, section time, and distance. In the off-line configuration, the routine computes a velocity profile for up to seven time waypoint sections, using the weighted averaging technique for determining waypoint crossing velocities. In this configuration the routine takes approximately two milliseconds to generate a profile. In the real-time configuration it takes less than half a millisecond. The routine which generates the profiles is approximately 400 words in length.

The time-control routine which uses this velocity profile data has been coded and verified in conjunction with the flight system program. This program is used in place of the original VALT velocity profile routine whenever the system is operating in a 4D mode. Once the aircraft arrives at the approach gate, the system reverts to the constant attitude deceleration profile used for 3D approaches.

Airspeed Control - A flow chart was generated to define the procedure required to obtain an airspeed based velocity profile on a Direct To path with steady winds. In order to provide the most flexible capability, the implementation assumed that both the initial and final airspeed values were to be selectable. For programming simplicity, it was felt that acceleration and decelerations should be allowed to occur only on the straight portions of the flight path. The generation of a digital computer program to implement this concept required the programming of all of the basic time and distance equations listed in Appendix D as well as the generation of an incremental iteration routine to use these equations since no direct method of solution was found. The operation of the program under the special case constraint that accelerations and decelerations occur only on the straight-line portions of the flight path has been checked out. Modifications have been made to the velocity command control law routine to fly the airspeed profile generated. Routines have also been developed which generate the crab angle necessary to fly in winds, and a variable bank-angle lead term for flying circular arcs in winds. These programs have all been checked out, and are operational on the SVSVF simulation. Program coding of approximately 1500 words was required for these routines.

Interactive Graphics Display - A graphical representation of the horizontal situation was added to the SVSVF using a CRT display. The flight computer program for generating and outputting the appropriate data to the graphics host computer has been coded and checked out. The digital display program in the graphics host computer, primarily FORTRAN IV, has been coded and checked out. The capability now exists to build and manipulate horizontal and vertical situation displays and performance information displays based on data from the flight computer during flight simulation. The horizontal situation displays consist primarily of a moving map and a prescribed lateral approach path. The display configuration is changed, based on the position of the aircraft during the approach. For example, prior to capturing the approach path, the pilot would like to know what path he will follow and what relation it has to area landmarks. However, while hovering over the landing pad, the primary interest to the pilot is the pad itself and his vertical position. The performance information displays involve the graphical construction of velocity and altitude data profiles and various situation indicators, such as heading, time to go, and altitude.

The routine in the flight computer which generates and outputs data to the graphics system is straightforward, and consists of about 150 words and takes less than 300 microseconds. The programs in the graphics host computer are quite extensive. A great deal of the programs are written in FORTRAN and, when compiled, are about 20,480 words in length and may take up to 6 seconds to update. However, when the display that is to be manipulated is very simple (such as an aircraft symbol), the update rate increases to about 10 cycles per second. The slow update rates result from using a simple graphics system in the SVSVF, and are considerably slower than the update rates that would be obtained in a typical aircraft display system.

In addition to the data that is updated during the real-time simulation, a great deal of path data is preloaded into the graphics host computer. The preloaded data includes:

- Nominal Lateral Path Data
- Delay Fan Boundaries
- Waypoints and Waypoint Numbers
- Aircraft Symbols
- Scale Factors for Display Scale Changes
- Display Positioning Boundaries
- Runway and Terrain Feature Information in the Approach Area
- Performance Indicator Graphics

The data sent to the graphics host computer by the 1819A during a simulated approach includes:

- Aircraft Position and Heading
- Direct-To Capture and Delay Fan Data
- Direct To Predict Flag
- North-Up/Heading-Up Flag
- Display Mode Flags
- Approach Path Distance to Go
- Altitude Profile Data

- Velocity Profile Data
- Time to Go
- Capture Waypoint Number
- Error Codes
- Avoidance Area Data

Using the data provided by the 1819A in conjunction with the data preloaded in the graphics host computer, a moving map representation of the terrain features and lateral path, along with data monitoring displays, is generated.

The basic map display has two operating modes - heading-up and north-up. Selection of the operating mode is made by the pilot through the Navigation/Guidance Control Panel.

As part of the Direct To predict mode, the pilot has the option to select the initial capture point from among the various waypoints that define the prescribed nominal path. The selection of the capture waypoint is made through the use of the Navigation/Guidance Panel, or by a direct technique utilizing the display system's joystick. When the system is operating in the predict mode, the display shows the predicted Direct To path to the capture point and the predicted delay fan path. If the capture path is invalid due to the position or heading of the aircraft relative to the selected capture point, the Direct To path is deleted from the display.

When nearing the end of the approach path, the scale of the graphics display is varied so that less of the map is shown and greater displacement of the lateral and longitudinal flight path excursions is obtained. The scale change is made in six discrete steps based on distance to go along the flight path. When the distance to go is less than 100 feet, the display changes to the hover configuration and the scaling becomes a linear function of the altitude.

Since it is important to observe how the velocity profile is affected by alterations in the time and distance constraints, it was necessary to incorporate into the display system the ability to construct and display a graphical representation of the profile in the real-time flight simulation. The velocity versus time to go profile is constructed and displayed once an approach has been selected. The total profile consists of a series of three segment profiles which may include either one or two speed changes.

An altitude profile with a constant glideslope is also constructed, and may be directly changed by the pilot through the joystick. Alteration is accomplished by selecting a new breakpoint which may be done when on or off an approach. Both actual and commanded altitude are displayed to show altitude error.

Performance monitoring displays, both alphanumeric and graphical, are provided. A time to go graph and an altitude graph, both with actual and commanded parameters, are included in the displays. A heading indicator in the form of a bar graph is also provided. When in the hover display, an alphanumeric readout of the altitude is included.

Pilot Interface

Pilot performance during 4D curved path approaches depends on efficient information transfer between the pilot and the aircraft systems. To ensure that the pilot is better informed of the path he will be required to fly, displays of the flight path parameters will be necessary. More efficient data entry techniques must be developed for the pilot to have control over the path he wants to fly.

Flight Path Command Information - The flight director commands, sent to the pilot or autopilot, are generated as a function of aircraft progress along a fixed lateral path and the velocity and altitude profiles. The most significant interface problem observed was the pilot disorientation produced on the curved lateral path. This is a problem shared by non-time constrained curved path approach systems, however, the problem is more significant with 4D systems since real time path alteration may be taking place. The problem stems from the flight computer recognizing the along track progress and the pilot having very little information by which to monitor that progress. This tends to produce a lack of credibility in the system on the part of the pilot. The problem consists of two parts:

- Knowledge of present position relative to the touchdown point and any terrain obstacles
- Knowledge of the nominal flight path between the present position and the touchdown point.

A knowledge of the flight path directly influences the system performance in the manually piloted modes since it increases the pilot's acceptance and tracking of the computed flight director commands. Raw data displays such as bearing and distance to a known point are useful in establishing present position, but are not as effective for estimating the flight path as they are during straight in approaches. For these reasons, a number of CRT based displays have been incorporated into the VALT 4D system. These displays include such things as moving and fixed map horizontal situation displays, fixed axis velocity and altitude profiles, fixed and moving scale performance monitors, and alphanumeric readouts.

Flight Path Displays - The objective of the flight path display is to enable the pilot to quickly and accurately visualize and evaluate flight path information. From the display, the pilot is able to determine the present position of the aircraft relative to the touchdown point, the nominal approach path to the touchdown point, areas where path alterations may be allowed or required, and any significant terrain features. The graphics display is able to further define the present position of the aircraft by use of alphanumeric representations of such parameters as range and bearing to a known point. This display would be used in place of the conventional electromechanical Horizontal Situation Indicator (HSI) in the aircraft instrument panel and would contain some or all of the following elements:

- Nominal Lateral Path
- Time Control Waypoints
- Delay Fan Maneuver Boundaries

- Direct To Capture and Direct To Delay Fan Flight Paths
- Avoidance Areas
- Airport Runway System
- Landing Pad
- VOR or Radar Station
- North Indicator
- Aircraft Symbol
- Bearing, Range, and Altitude Readout
- Approach Plate Information

A typical display is shown as Figure 18. In this display the approach path and terrain features are translated about the aircraft symbol to ensure that the area immediately surrounding the present aircraft position is centralized on the display.

Rotation of the display is handled in two different modes: heading-up and north-up. In the heading-up mode, the aircraft symbol is fixed while the map rotates and translates about it. This mode is shown in Figure 19. In the north-up mode, the aircraft symbol rotates to track actual heading while the map is simply translated while being maintained in a north-up orientation. This mode is shown in Figure 20.

Elements which represent physical structures, terrain features, airport runways, the landing pad, and the VOR station and elements such as time control waypoints and the north indicator are not subject to real time modification. The nominal lateral path is modifiable in that those sections of the nominal path upstream of the capture waypoint selected by the pilot are not displayed. The upstream waypoints themselves, however, continue to be displayed so that the pilot can constantly observe and select those waypoints. Further, if the waypoint selected is downstream of a delay fan area, neither the delay fan nor the maneuver area boundaries are displayed.

In the predict mode the Direct To path capture maneuver is modified as a function of aircraft position and the capture waypoint selected. Once on an approach, however, the Direct To capture display is fixed. Likewise, while predicting a delay fan, the delay fan maneuver is variable until a path best suited to time and velocity requirements has been selected, at which time the delay fan becomes fixed for the remainder of the approach. This type of display is shown in Figures 21 and 22.

Other changes to the display are made in the alphanumeric readouts. As the aircraft position changes the bearing and range digital displays change. Bearing and range computations are made as a function of aircraft position relative to some fixed point, such as a VOR or radar station.

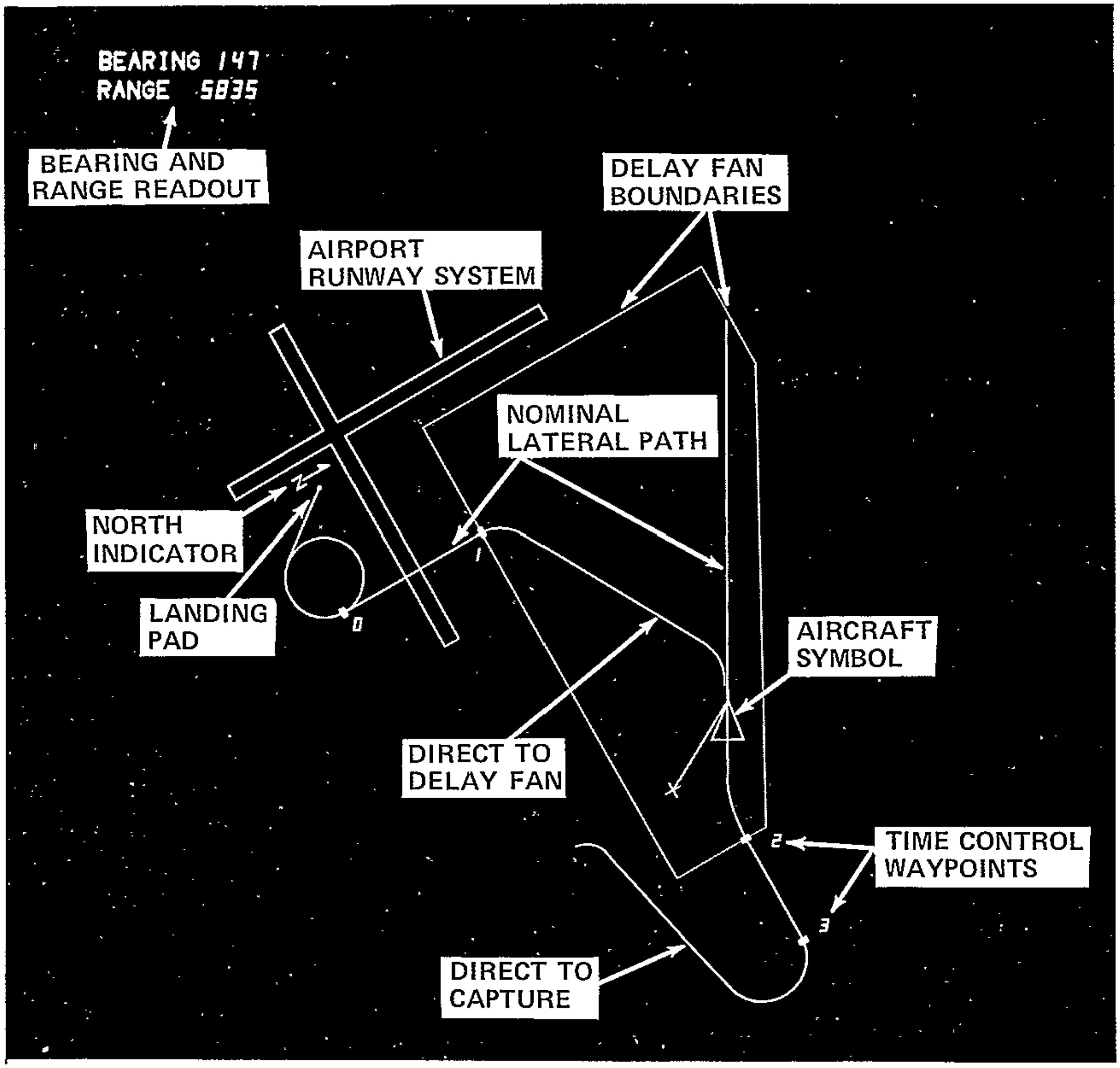

Figure 18
Typical Graphics Display

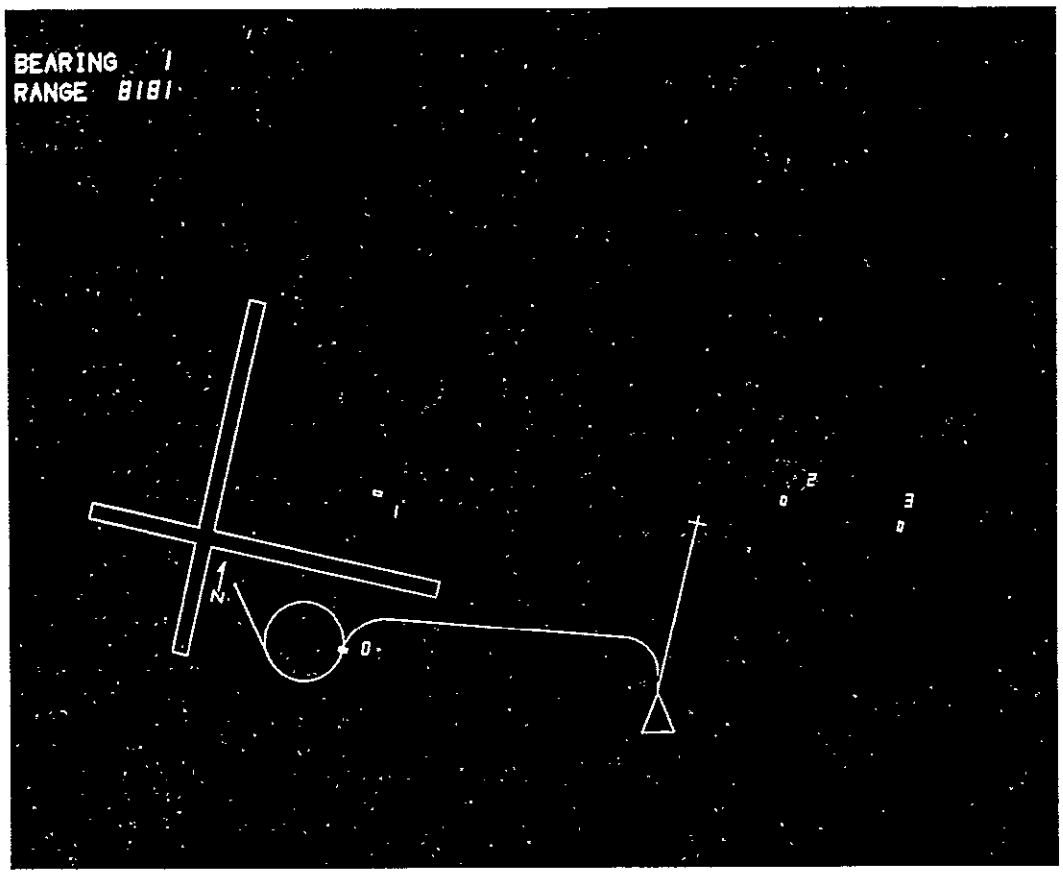

Figure 19
Heading Up Mode

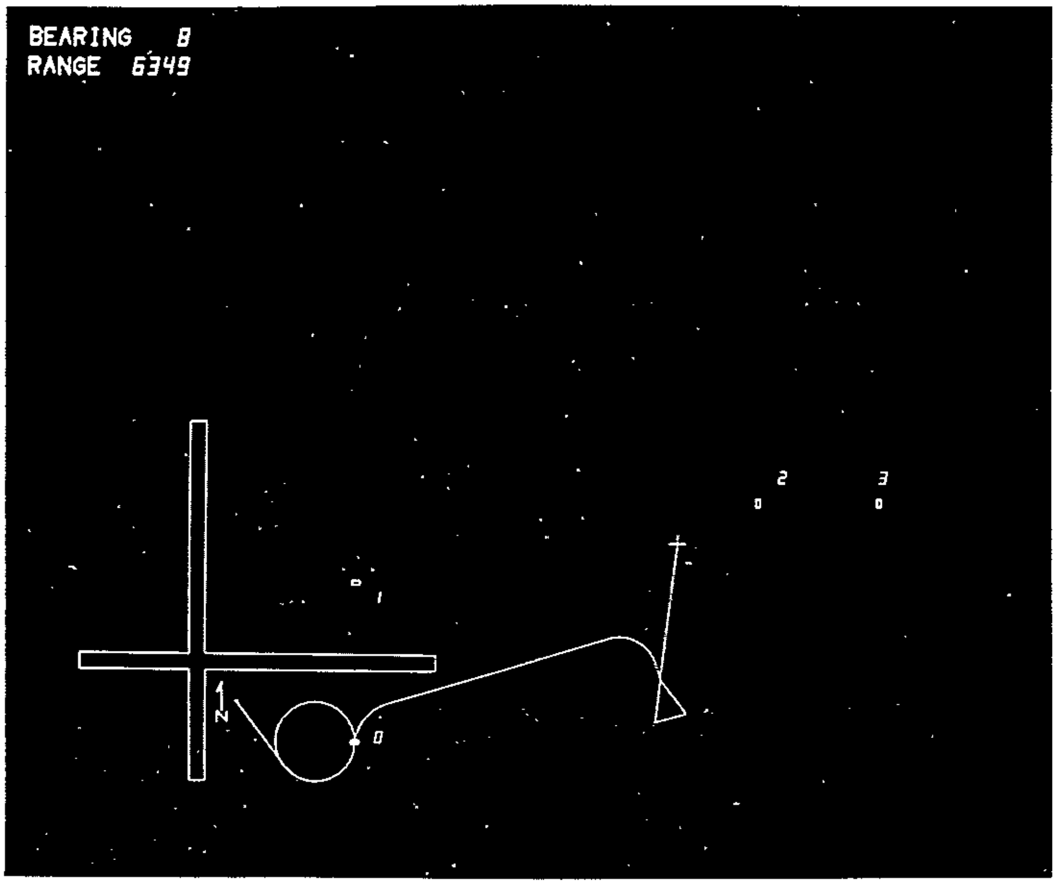

Figure 20
North-Up Mode

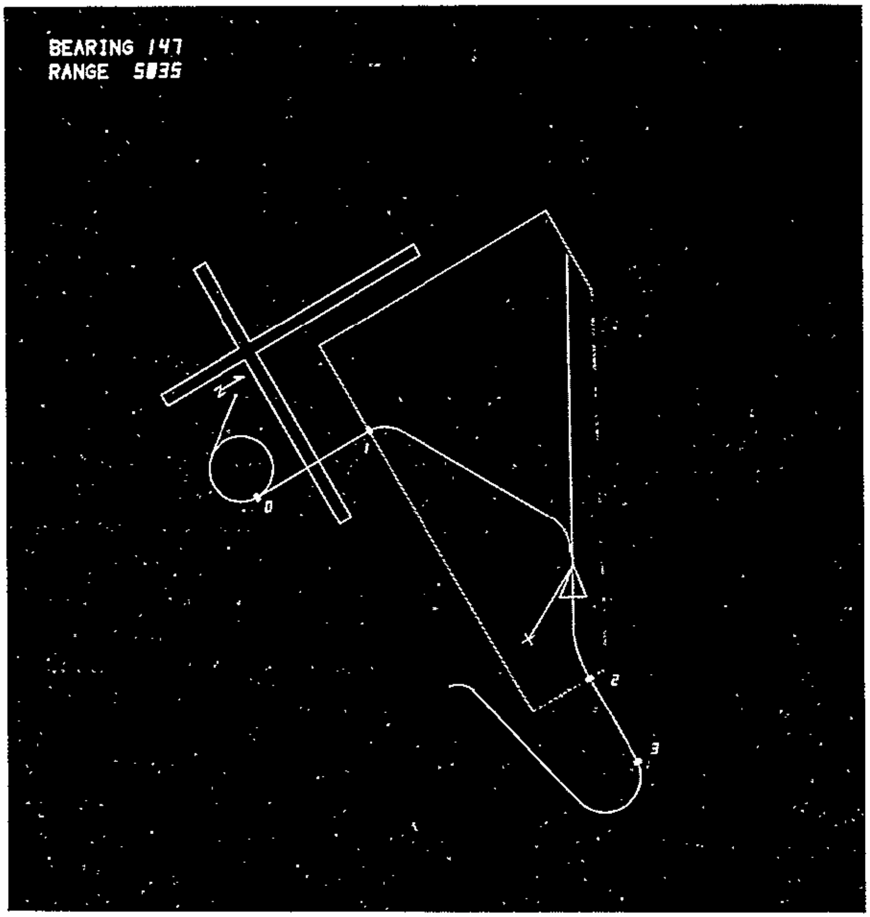

Figure 21
Predicted Delay Fan in Heading Up Mode

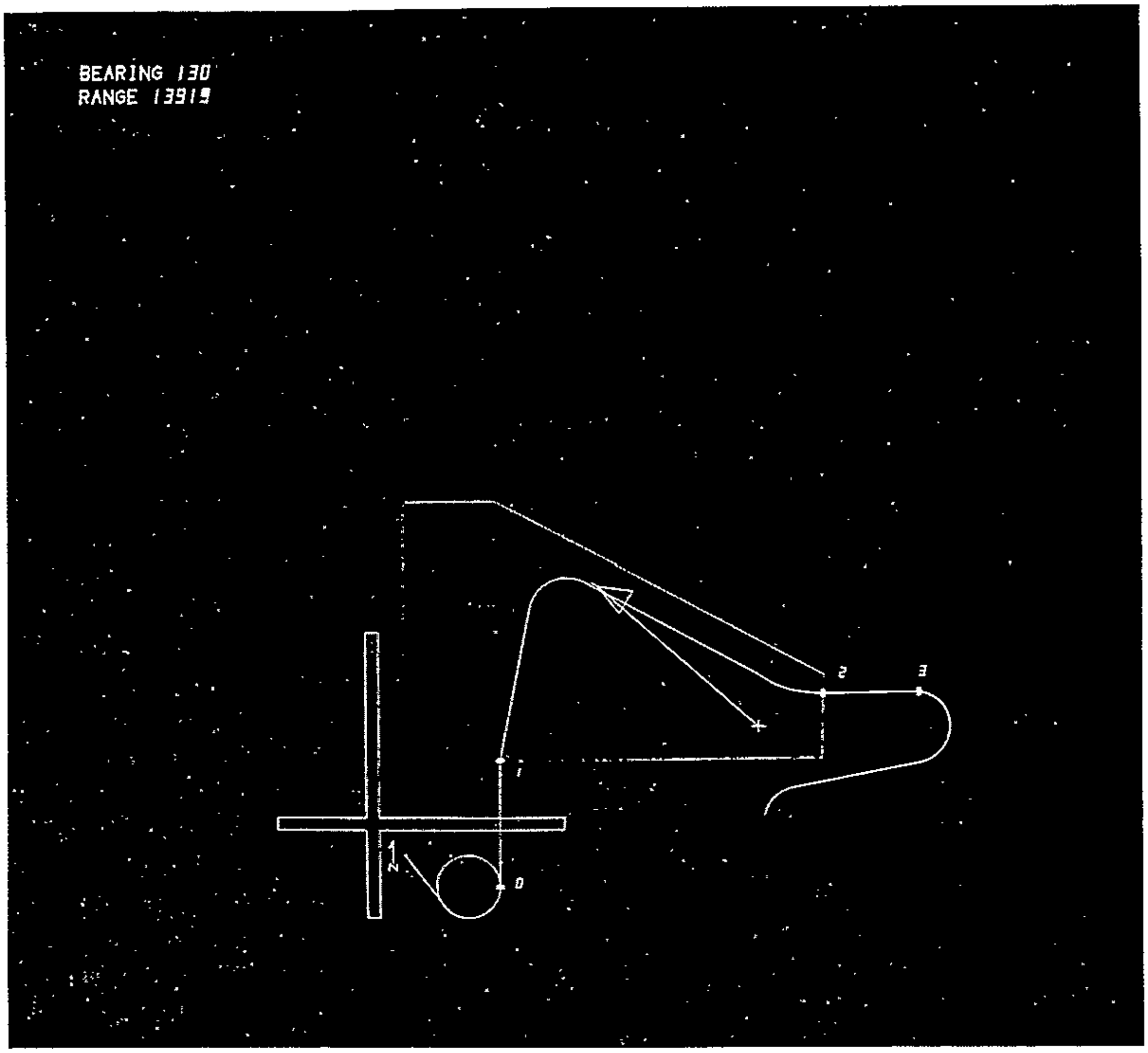

Figure 22
Predicted Delay Fan Captured in North-Up Mode

Finally, scale changes are made to the display so that more meaningful information can be presented to the pilot during various phases of the approach. During the initial phase of the approach the entire lateral path and terminal area are displayed giving the pilot an idea of his approach path relative to surrounding landmarks. However, as the aircraft nears the end of the approach, the display is "blown up" so as to show pertinent landing pad and hover position information. A typical scale change is shown in Figure 23.

The display could also be used to provide normal approach plate information, such as shown in Figure 24.

<u>System Performance Monitoring Displays</u> - The objective of the system performance monitoring displays is to allow the pilot to continually assess the actual aircraft situation relative to all the commanded parameters. From the display the pilot is able to determine the present aircraft position along the velocity or altitude profiles, the aircraft heading, and errors or lack of errors in tracking time, velocity, or altitude.

Two types of altitude profile monitoring are available to the pilot. In Figure 25 the scale on the right side shows two indicators which are translated up and down the scale. The two pointers represent commanded altitude and actual altitude. From this display the pilot can readily determine errors with respect to the nominal profile. From the graphical representation of the altitude profile shown at the bottom of Figure 25, the pilot can readily determine the present aircraft position on the altitude profile. The tracking indicator represents actual aircraft altitude and distance remaining along the path to the hover point. If an error exists between the altitude profile and the actual altitude, the indicator will be displaced off the profile by that amount. The pilot can, therefore, easily evaluate progress along the path and errors in altitude. Alphanumerics in this display indicate the maximum altitude of the profile in feet, the distance along the lateral path at which the glideslope begins, and the glideslope angle in degrees.

On the left side of Figure 25 a time-to-go monitor is displayed. The time-to-go displayed is the time remaining on the flight path to the approach gate. Two moving indicators on the scale allow the pilot to evaluate the difference in actual time-to-go and the time remaining as a function of path distance remaining and the nominal velocity profile. From this display the pilot can make judgments as to the acceptability of the approach. For instance, if the time difference between the actual and desired is relatively large, the pilot may decide to abort the approach and go around, or he may choose to adjust the time of arrival so as to eliminate the time error, or he may choose to fly the time capture velocity control. Other information which is available to the pilot includes aircraft heading at the top of the display, and a moving aircraft-fixed map display at the center. The heading indicator shows present aircraft heading at the center and extends 45 degrees to both sides. This is a fixed pointer-moving scale display.

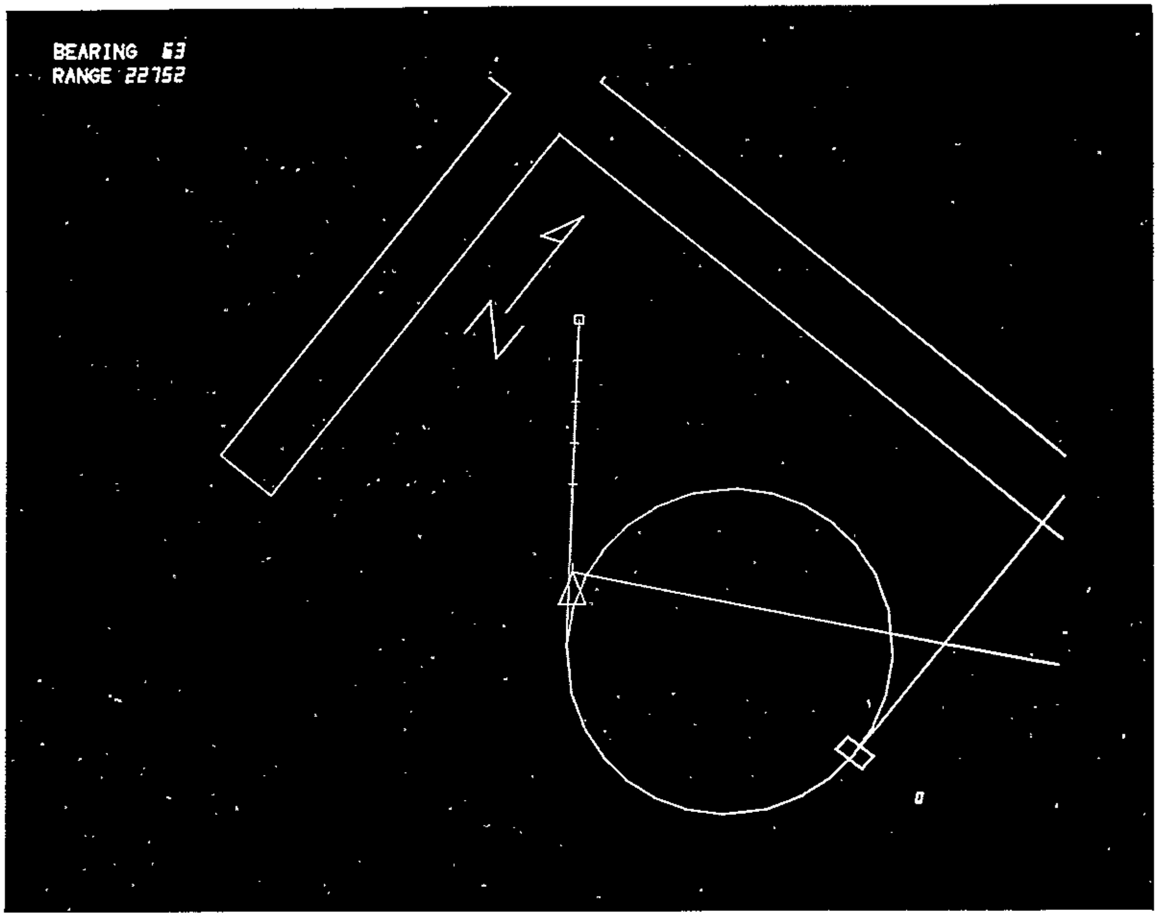

Figure 23
Scale Change 2 in Heading Up Mode

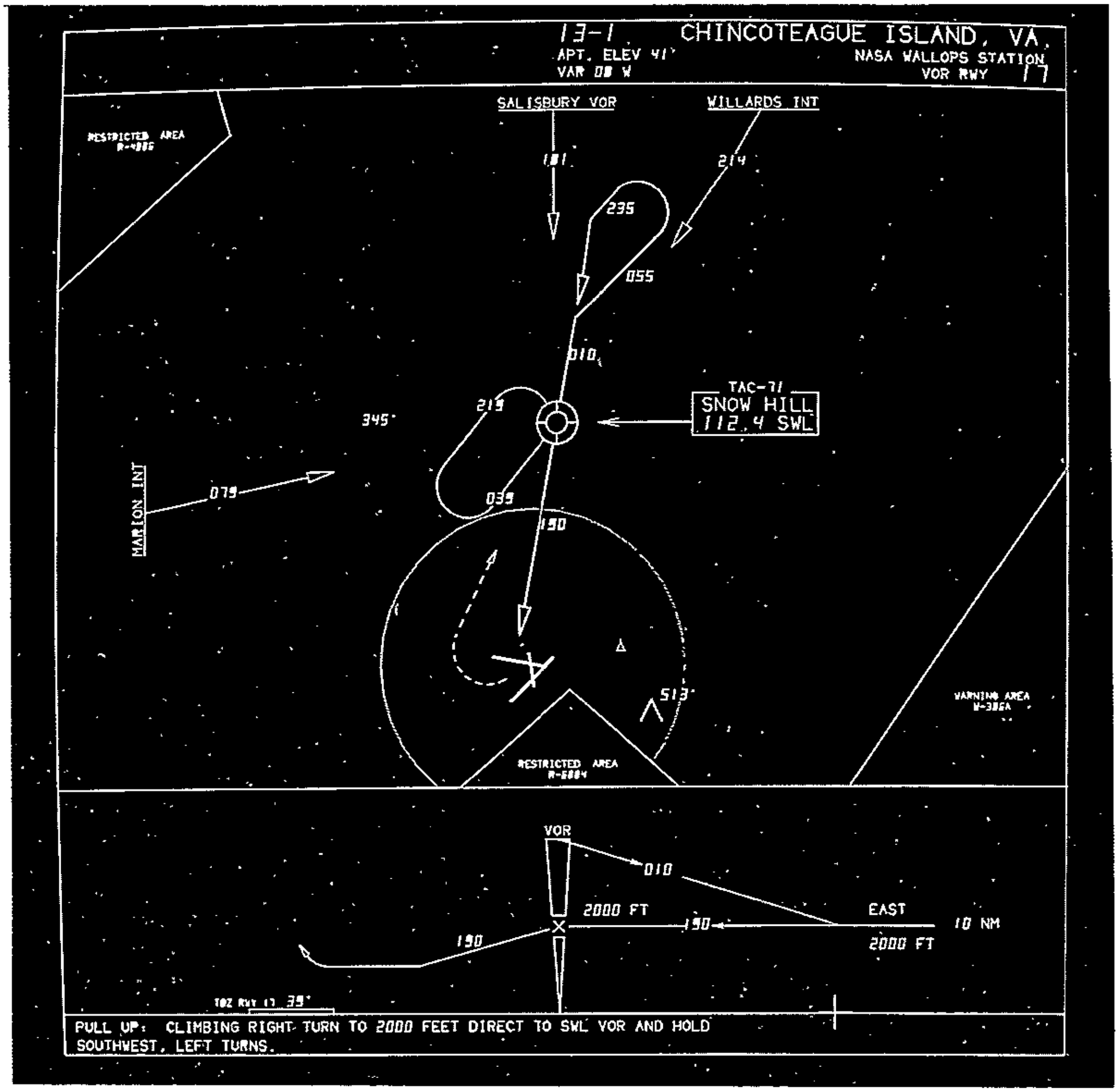

Figure 24
Approach Plate

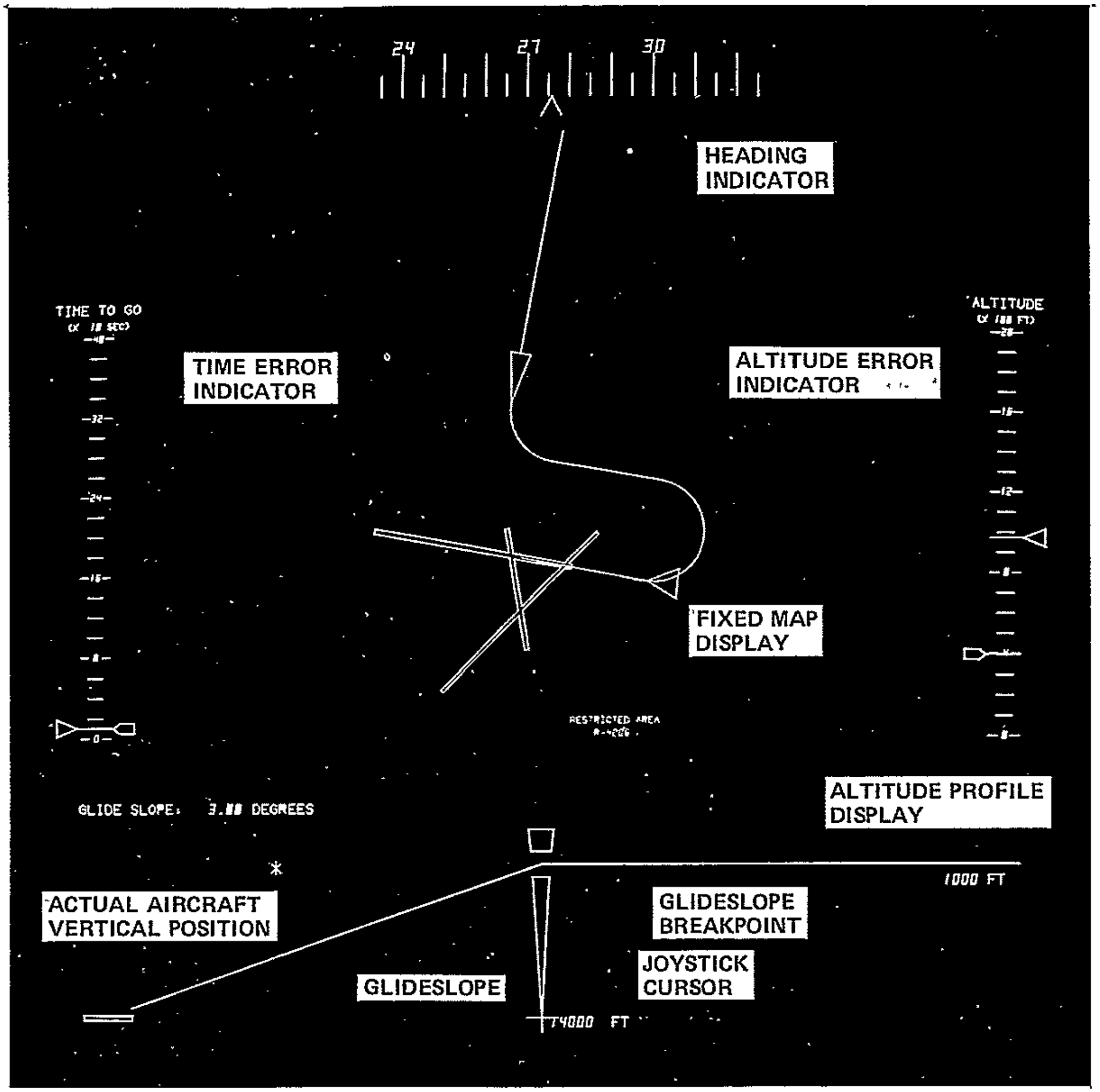

Figure 25
Altitude Profile Monitors and Time Monitor

The velocity display would be similar to the altitude display with the exception that the altitude scale on the right side of the display would be replaced by a velocity scale and the altitude profile at the bottom of the display be replaced by a velocity profile. The velocity profile has two configurations, one for ground speed only and one for airspeed/ground speed combinations. In Figure 26 a simple ground speed profile is displayed and an indicator shows the progress of the aircraft along the profile. It should be noted that for velocity profile tracking the indicator should show true time position and actual velocity. The nominal velocity profile indicates the speeds necessary to fly a designated lateral path if no perturbations are introduced into the system. If a time error does exist, for example, then the actual speed commanded will be different than the nominal velocity profile. Figure 27 shows a combination airspeed and ground speed profile display. A discontinuity exists about midway on the profile to indicate two things:

- The difference between airspeed and ground speed at that point

- A change from airspeed control to ground speed control

From the display the pilot can also see when he transitions from 4D flight to 3D flight at the approach gate.

Command and Control - In a time constrained environment, the aircraft performance required to accomplish a desired maneuver may exceed the performance limits set into the system. It is not desirable, therefore, to allow totally random combinations of waypoints and arrival times, since infeasible solutions may result. The use of stored nominal approach paths will probably be required for both terrain and traffic avoidance. Selected portions of the approach would be set up to accommodate path alteration maneuvers, however, such maneuvers would be limited by defined maneuver area boundaries. For fully automatic operations, the selection of the type and degree of path alteration or velocity profile modification would follow a fixed priority order. For less than fully automatic operation, the degree to which the pilot will be allowed to exercise his judgment in the selection of various path and profile maneuvers will dictate the level of interactive man machine interface that will be necessary. A system predictive mode has been incorporated into the VALT display to show the pilot the consequences of various contemplated actions. The selection and examination of these alternate approach paths will be paced by the ability of the pilot to quickly and clearly interrogate the system. Except for very simple cases, pilot commands to the system will require more efficient input devices than the VALT numeric keyboard and display panel.

As a minimum, alphanumeric data transfer capability could be added to the system, however, consideration has been given to more direct interactive techniques. The use of the graphics joystick has been incorporated into the VALT system for pilot modification of path maneuvers. As shown in Figure 28 the pilot uses the graphics joystick to move the cross shaped cursor to one of the five waypoints and selects that waypoint by depressing the joystick button. The path capture maneuver is predicted and displayed on the screen and the pilot can evaluate the flyability of the maneuver. By monitoring the scale on the left, the pilot can also reselect waypoints until one is found which is suited to the time requirements. Using this technique, the pilot can quickly evaluate the prescribed flight path without turning his attention to some other instrument or display. Another use of the joystick entry capability is in generating the altitude profile as shown in Figure 29. By moving the joystick cursor along the horizontal axis of the altitude profile, the pilot can select the desired glideslope or glideslope breakpoint. The usefulness of this could be in maintaining a high altitude over some height restriction and then making a sharp descent, thus making a previously unflyable path flyable. By using these techniques, the pilot can then take a more active part in decision making pertaining to selected approach paths.

A detailed description of the computer aided graphics techniques employed in this study is contained in Appendix E.

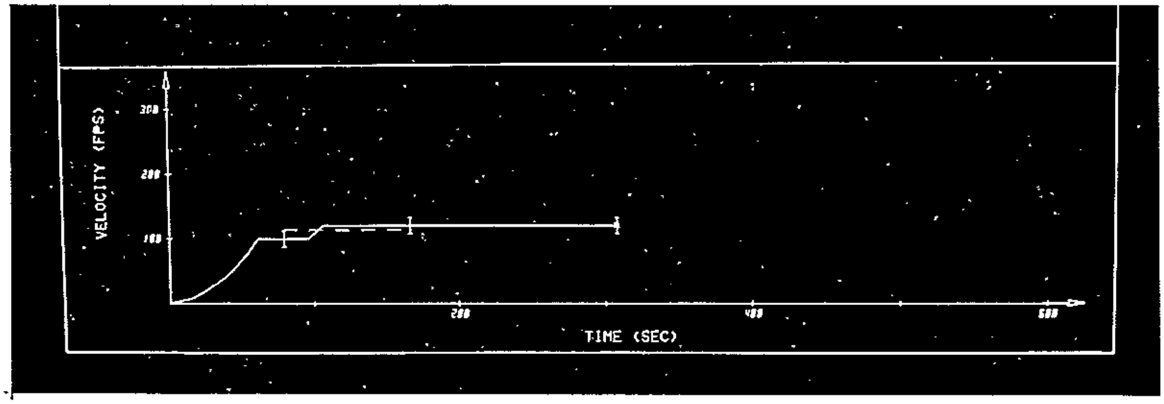

Figure 26
Ground Speed Profile Display

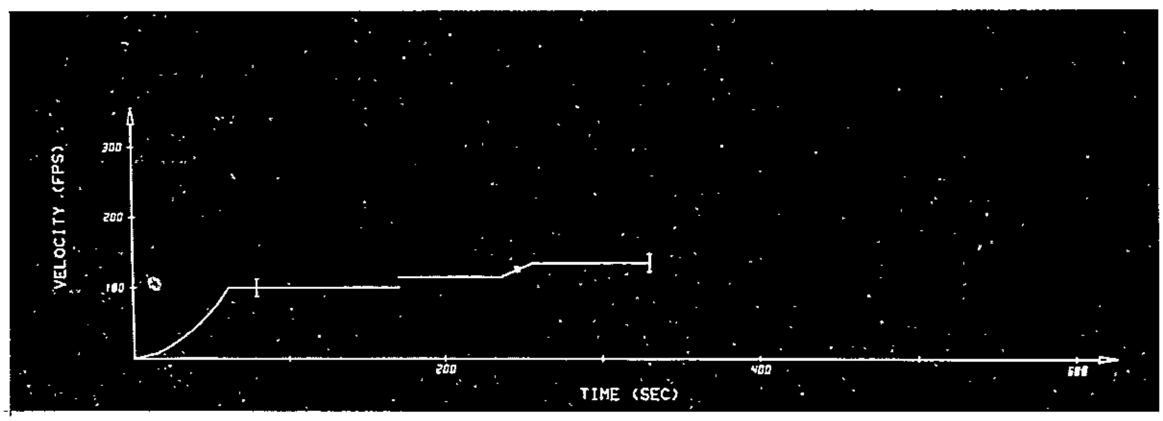

Figure 27
Airspeed Profile Display

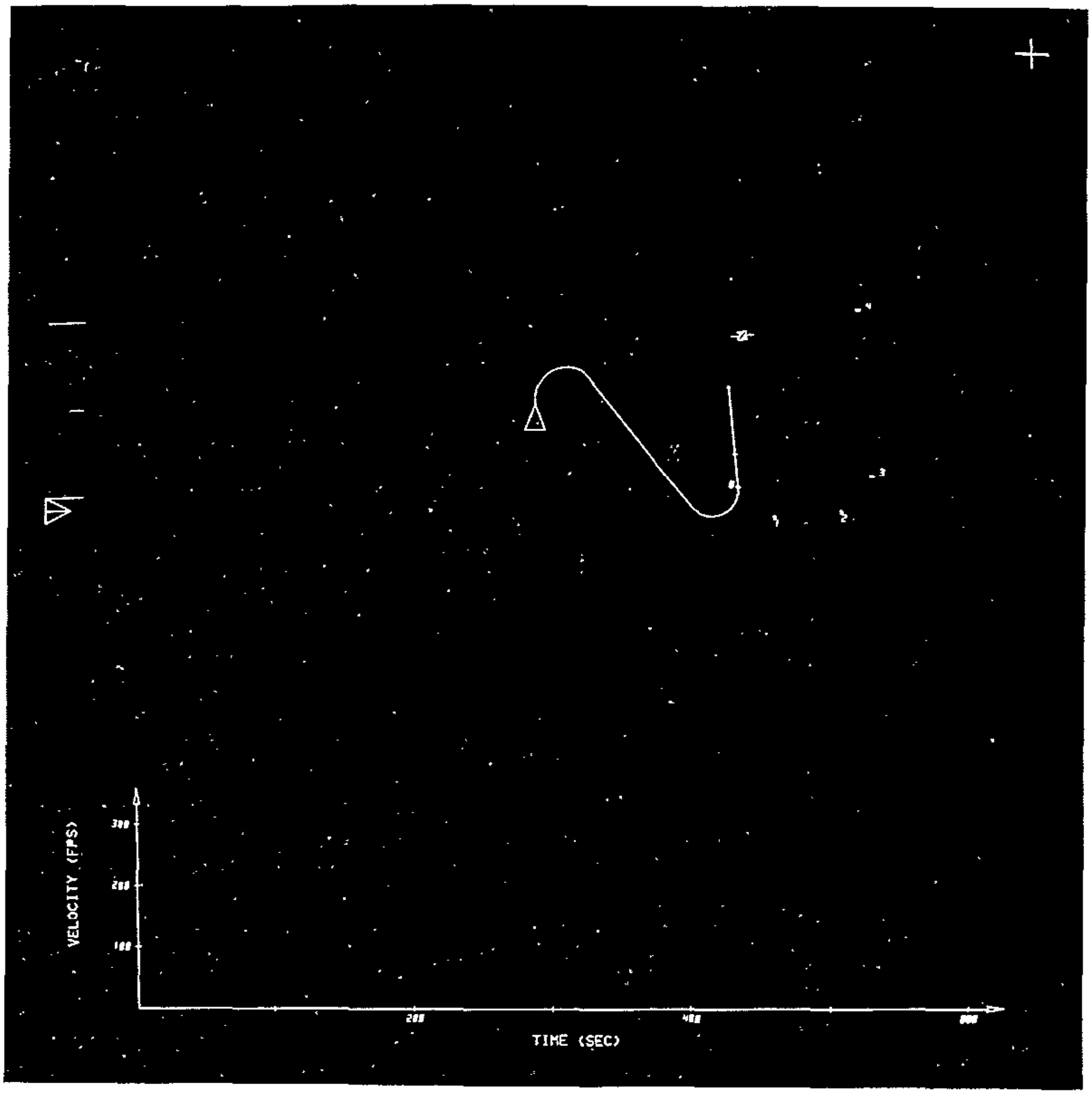

Figure 28
Airspeed Control Display With Cursor Selection of Waypoints

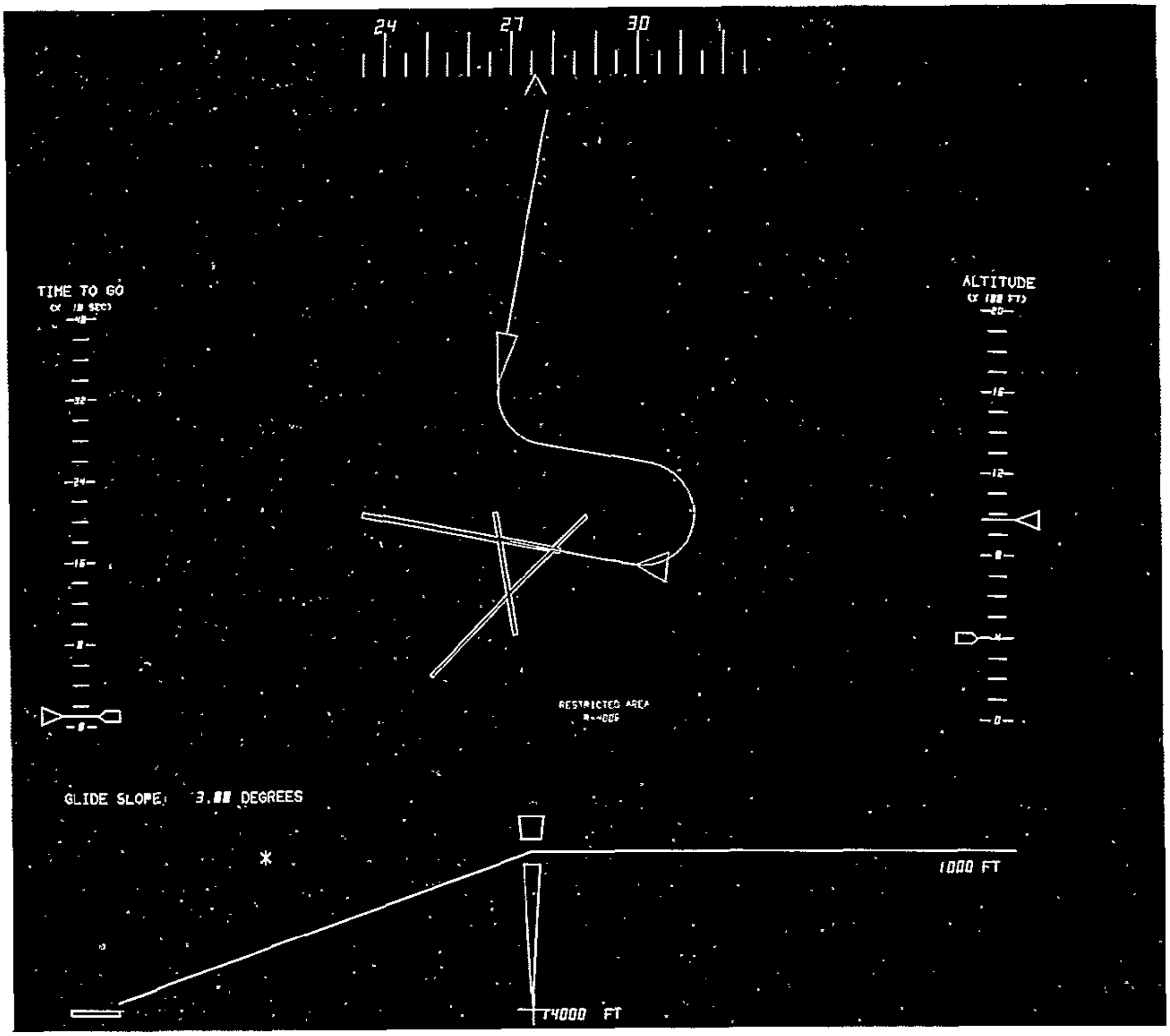

Figure 29
Altitude Profile Mods With Joystick

SOFTWARE VALIDATION

The Sperry VALT Software Validation Facility was used to verify the correct operation of the 4D software. The SVSVF consists of an analog computer and a fixed base helicopter cockpit simulator (Figure 30), the flight system digital computer and interface equipment and a graphics host computer and graphics display processor and monitor (Figure 31). The facility allows simulated 4D approaches to be conducted in both the automatic and flight director aided manual modes.

Cockpit Instruments and Displays

The SVSVF cockpit instrument panel, shown in Figure 32, contains the following instruments and displays:

1. Electromechanical Vertical Situation Indicator (VSI) used to display:
    - Pitch and Roll Attitude
    - Lateral Acceleration
    - Crosstrack Error
    - Height Error
    - Pitch, Roll, and Collective Flight Director Cues
    - Radar Altitude below 100 feet.
2. Electromechanical Horizontal Situation Indicator (HSI) used to display:
    - Magnetic Heading
    - Crosstrack Error
    - Time Error
3. Radar Altimeter
4. Vertical Speed Indicator
5. Airspeed Indicator
6. VALT Navigation Guidance Control Panel (Figure 33)
7. Digital Time Readout

The time error display was incorporated into the system through the use of a moving pointer on a fixed index on the right side of the HSI. The display indicates the difference between the computed time to complete the approach and the clock time to complete the approach. Clock time is based on present time of day and a fixed time of arrival at the approach gate. Computed time remaining is based on present velocity, present position on the lateral path, and distance referenced position on the nominal velocity profile. The computed time to go is then referenced to the time of arrival at the approach gate.

Figure 30
Analog Computer and Cockpit Simulation Equipment

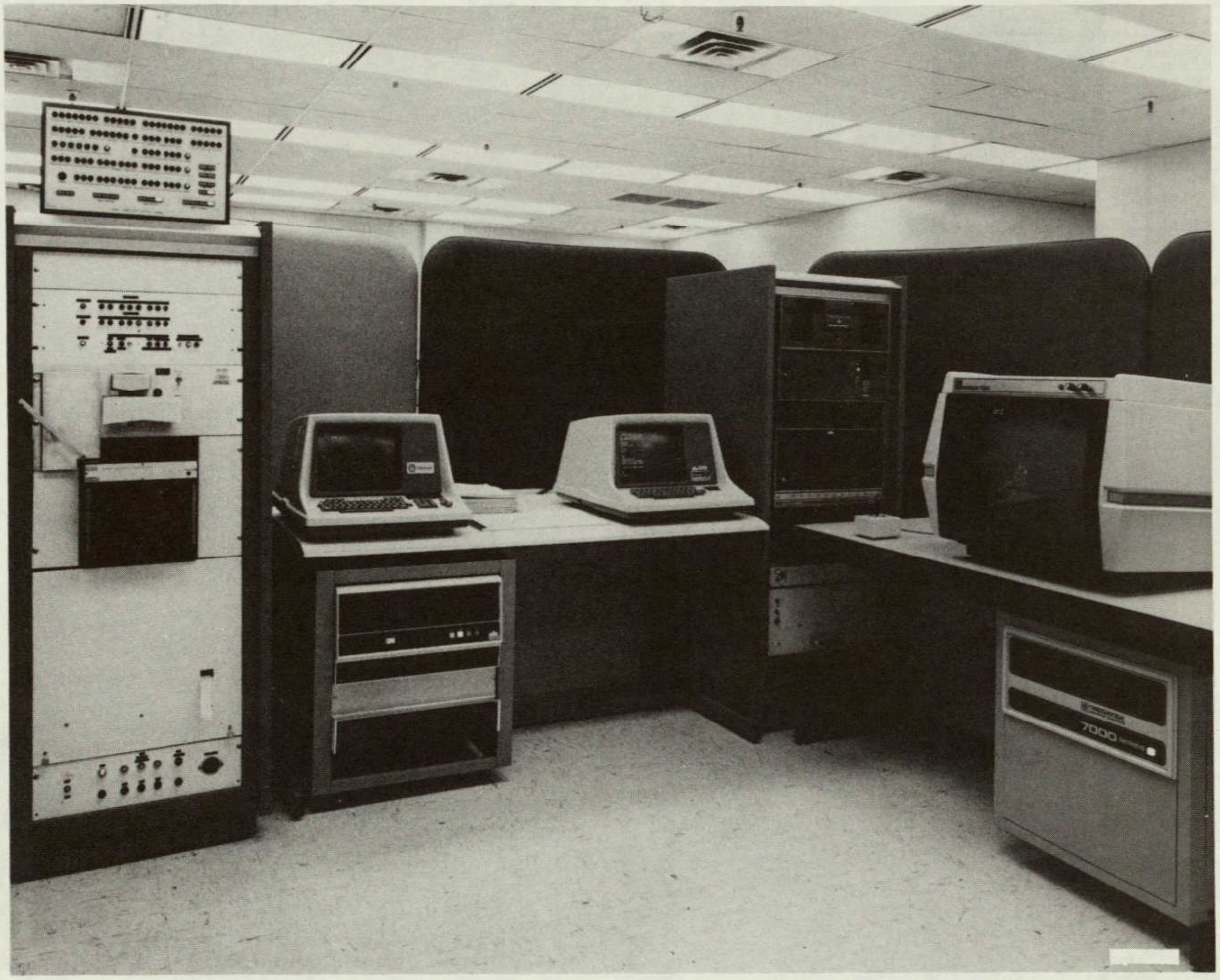

Figure 31
Flight Computer and Graphics Equipment

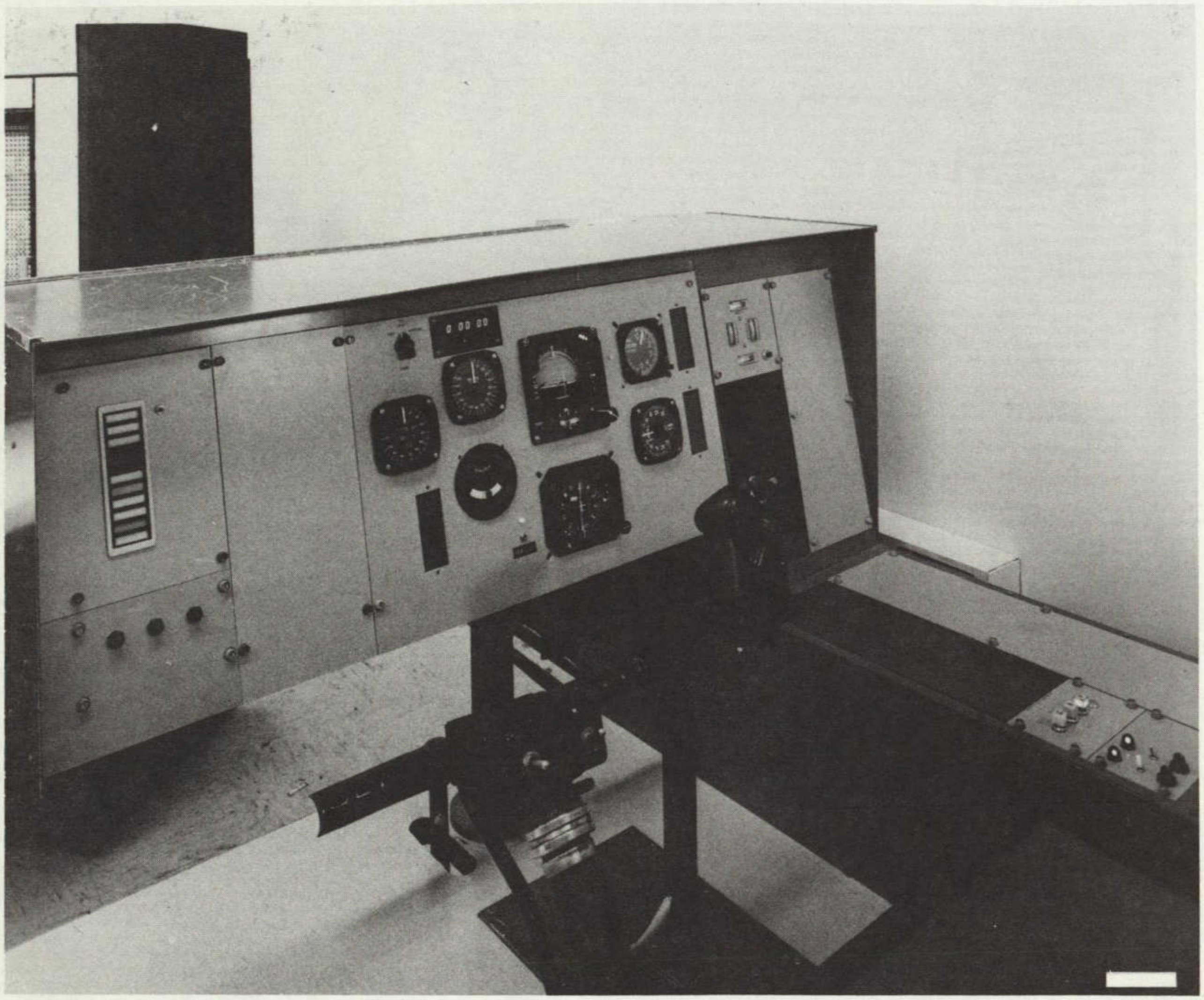

Figure 32
Cockpit Instrument Panel

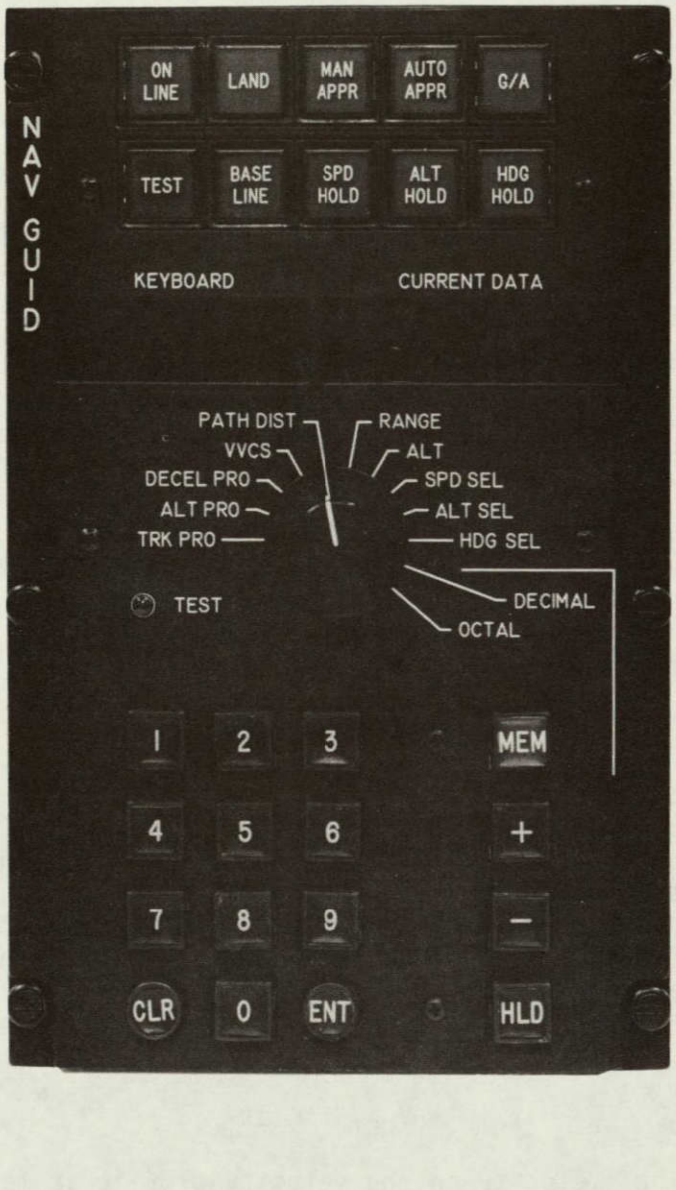

Figure 33
Navigation/Guidance Control Panel

The digital time readout was added to display time of day, time of arrival at the approach gate or time remaining to the approach gate. A rotary switch is used to select the parameter desired for display.

Electronic Horizontal Situation Indicator (Graphics Display)

The CRT graphics display terminal, shown in Figure 34, was added to the SVSVF for this study. A block diagram of the graphics system addition to the basic SVSVF is shown in Figure 35. The graphics system is used to display:

- The lateral flight path and terrain features on a moving map in north-up and heading-up configurations.
- Time Waypoints
- Velocity and Altitude Profile
- Time and Altitude Monitors
- Heading Indicator
- Approach Plate Information
- Avoidance Areas
- Delay Fan area boundaries
- Bearing and Range to a predetermined fix in both graphic and alphanumeric forms
- Landing pad representation.

Time Error Control Data

Time error control using velocity manipulation was checked out on the SVSVF. A time error is generated from the difference in actual time to go and desired time to go. In the example in Figure 36, actual time to go, or clock time remaining until time of arrival at the approach gate, is shown as Point T_C on the time axis. At that time there is a corresponding distance remaining on the lateral path equal to the area under the nominal velocity curve at Point D. The time D is then the desired time remaining on the lateral path. The difference between the times D and T_C is the time error Δt. A velocity command is then generated using the equation:

$$V_{cmd} = V_{ref} + K\ \Delta t$$

where V_{ref} is the nominal velocity on the velocity profile in meters per second corresponding to the present position on the flight path, K is a gain constant in meters per second per second to determine time error closure rate, and Δt is the time error in seconds. In addition, the magnitude of the $K\Delta t$ term is limited so as to prevent large velocity excursions from the nominal velocity profile. The limits are shown as the dashed boundaries around the nominal

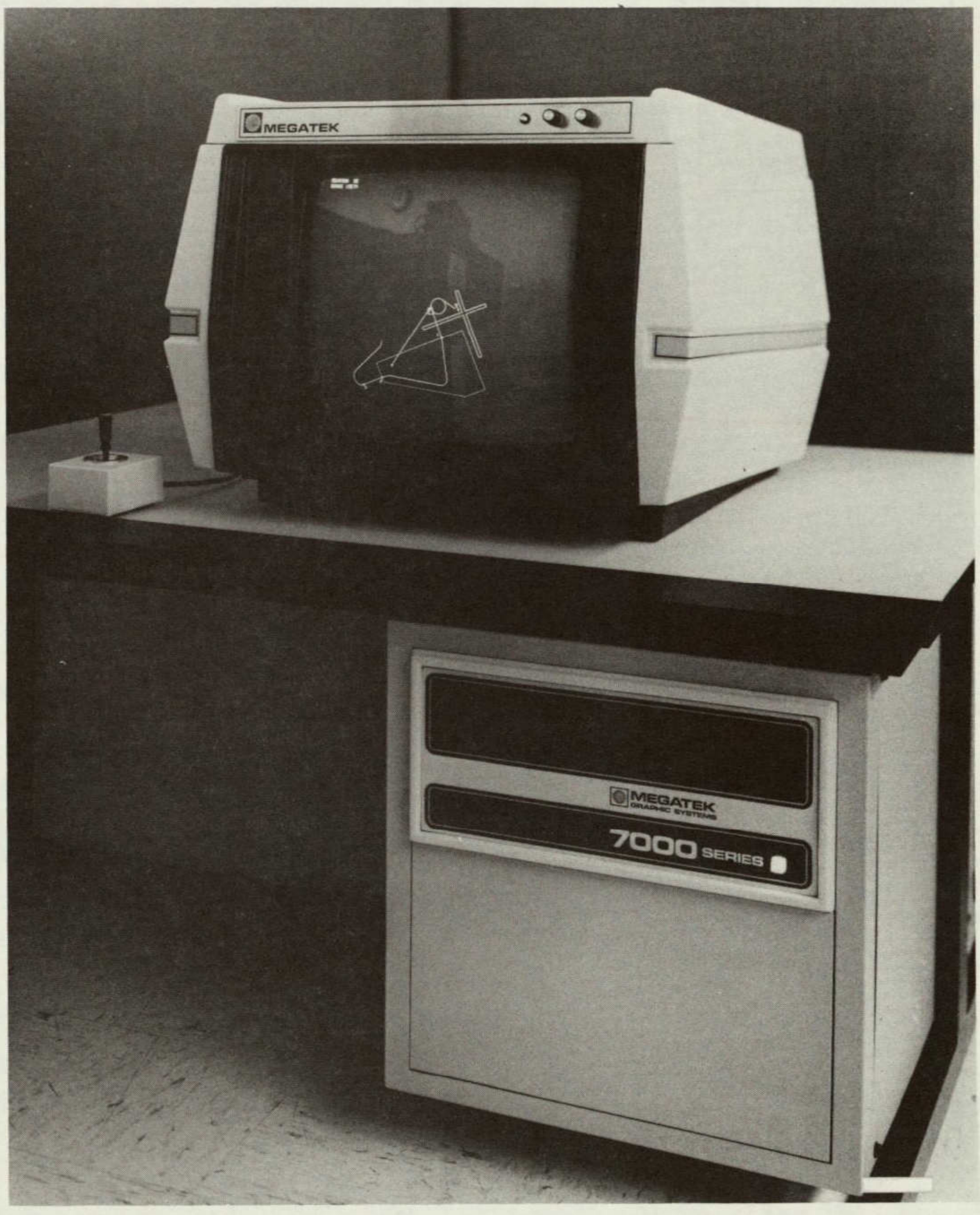

Figure 34
Graphics Display System

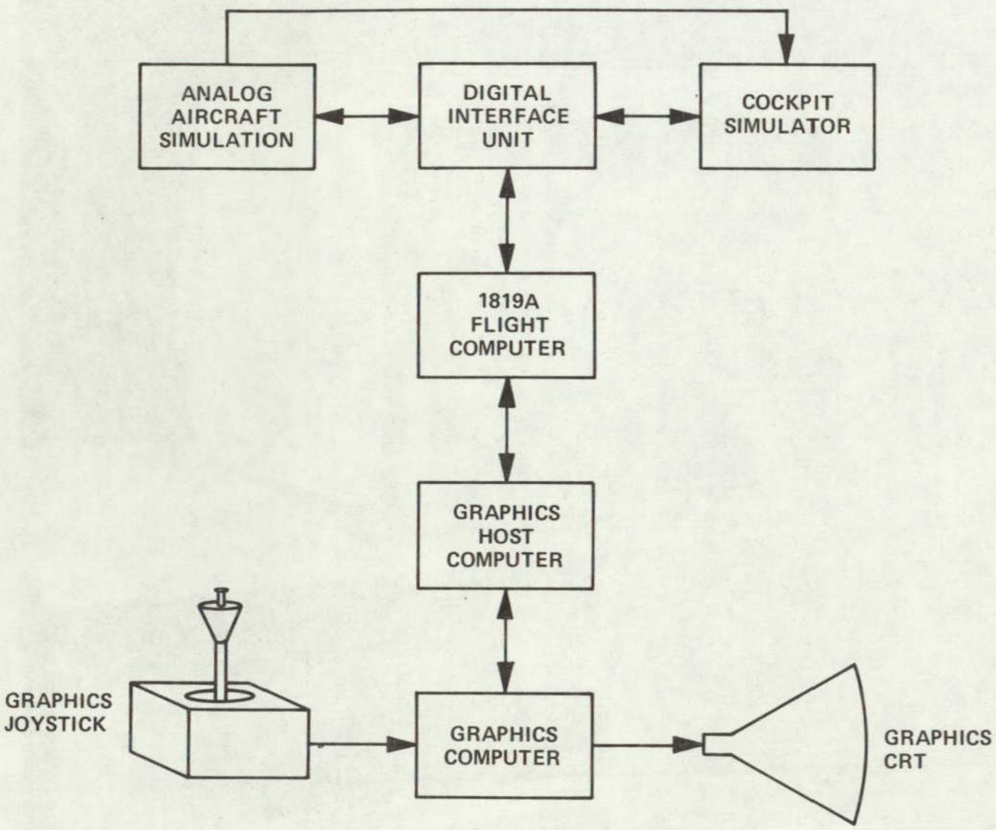

Figure 35
Block Diagram of SVSVF with Graphics

profile in Figure 36. Figures 37 through 40 show the simulated aircraft response to a 5 second time error step for the following gain and limit conditions:

Figure	K	Limit
37	6.10	6.10 m/s
38	6.10	3.05 m/s
39	3.05	6.10 m/s
40	3.05	3.05 m/s

The nominal velocity for each of these cases was 45 meters per second. The time required to close out the time error to less than .5 second varied from 32.5 seconds to 54.5 seconds. A value of K equal to 3.05 m/s^2 and a limit on $K\Delta t$ of 6.10 meters per second was selected for use on all simulated 4D approaches. This combination appeared to be a good compromise for both the automatic and the flight director aided manual approach modes.

Direct To Maneuvers

The Direct To maneuver can be characterized by the direction of the initial and final turns of the maneuver; i.e., Right Straight Left (RSL), RSR, LSR, and LSL. Maneuvers that contain only an initial or a final turn or do not have a straight line segment are considered to be degenerate cases of these basic maneuvers. Figure 41 shows the four basic Direct To maneuvers as generated by the Direct To software. These paths were flown on the SVSVF simulation at a constant velocity of 45 meters per second.

The variable radii capability of the Direct To software is illustrated in Figure 42. Five different Direct To maneuvers were flown to the same waypoint using different entrance velocities while holding the exit velocity constant. This condition created variable radii for the initial turn while holding the radius of the final turn constant.

The use of the Direct To maneuver to capture various waypoints on the nominal approach path is shown in Figure 43. The four paths shown were flown by commanding the system to generate a Direct To path to four different time control waypoints from the same initial point.

Direct To Delay Fan

The use of the Direct To maneuver to provide flight path alteration in a delay fan area is shown in Figures 44 and 45. The paths flown in Figure 44 were produced by varying the delay fan boundary times, thus changing the velocity profile and the path length to fly from the entry waypoint to the exit waypoint in the time specified. Table 2 gives a list of the time and velocity constraints put on each run to produce the different path lengths shown. Each of the paths flown in the delay fan area was generated using a nonpredictive mode. As the aircraft enters the delay fan area, the system calculates a Direct To maneuver to the exit waypoint, but continues flying the initial heading until the combined length of the Direct To manuever and the distance already flown

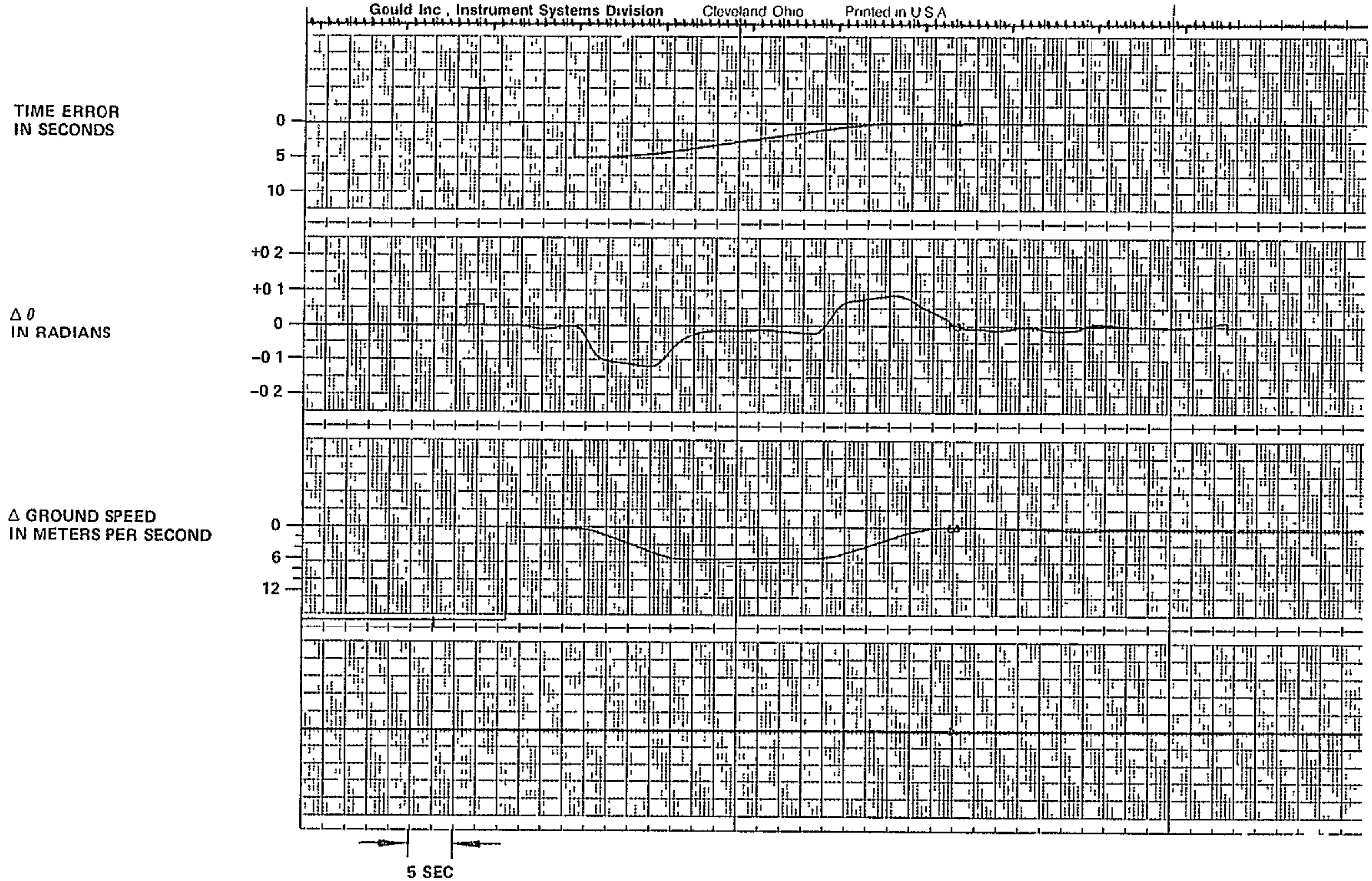

Figure 37
Time Error Response

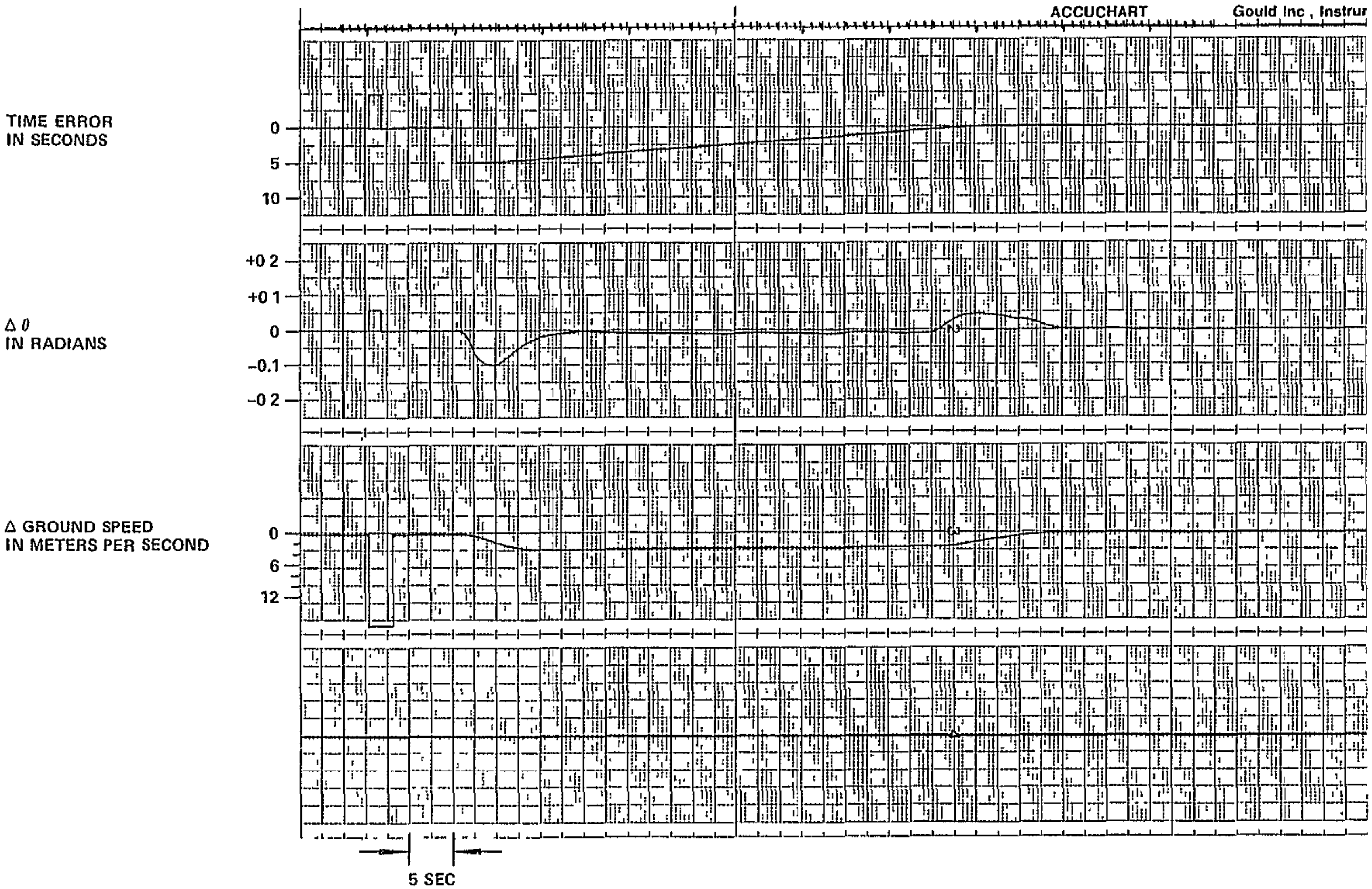

Figure 38
Time Error Response

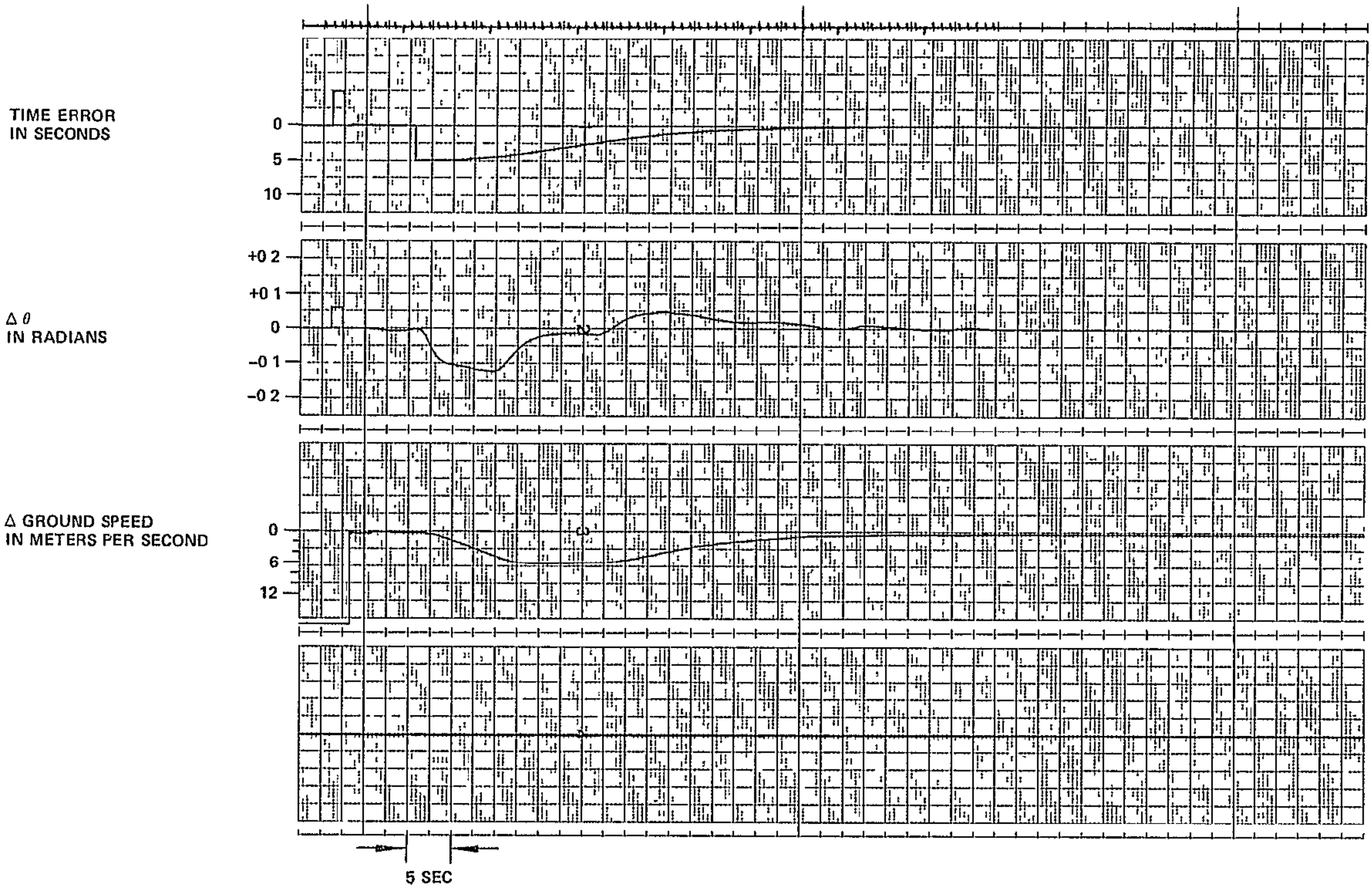

Figure 39
Time Error Response

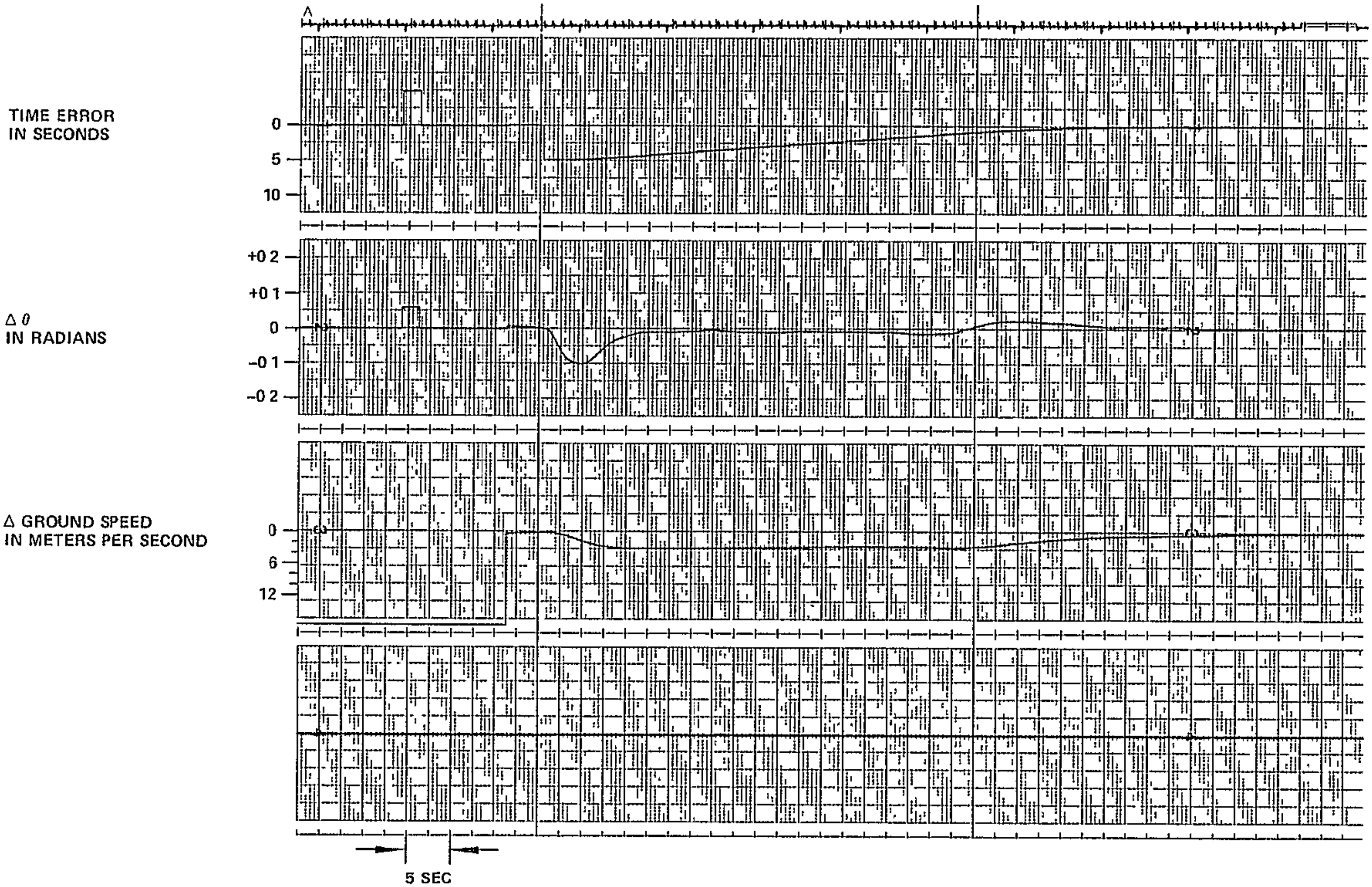

Figure 40
Time Error Response

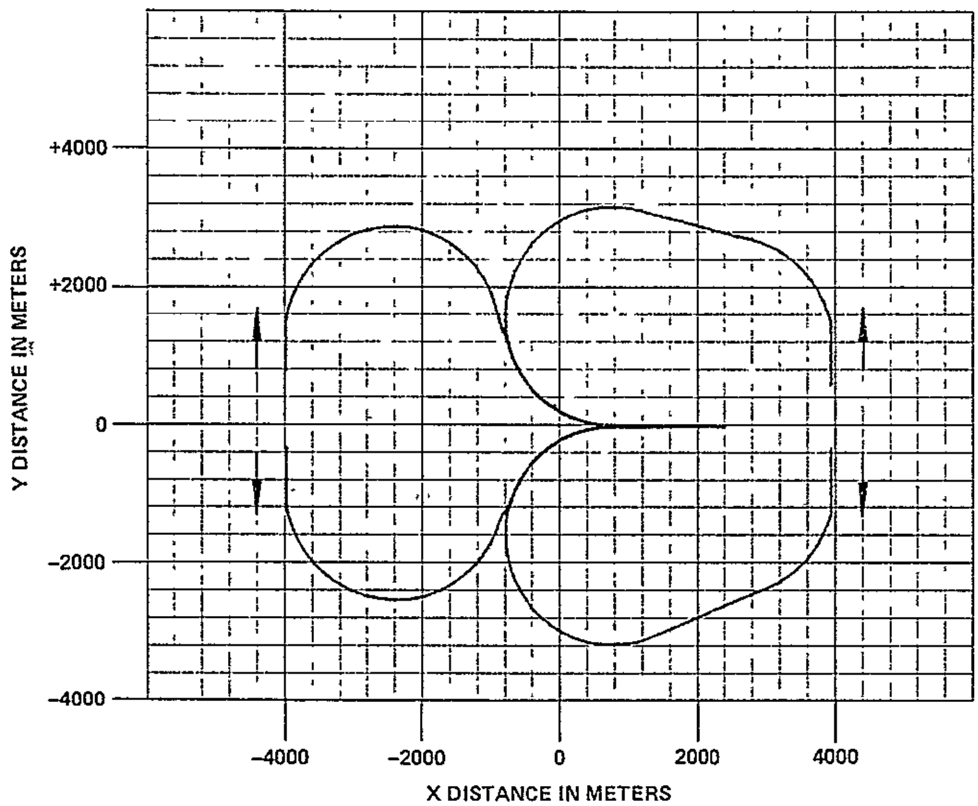

Figure 41
Four Types of Direct To Paths

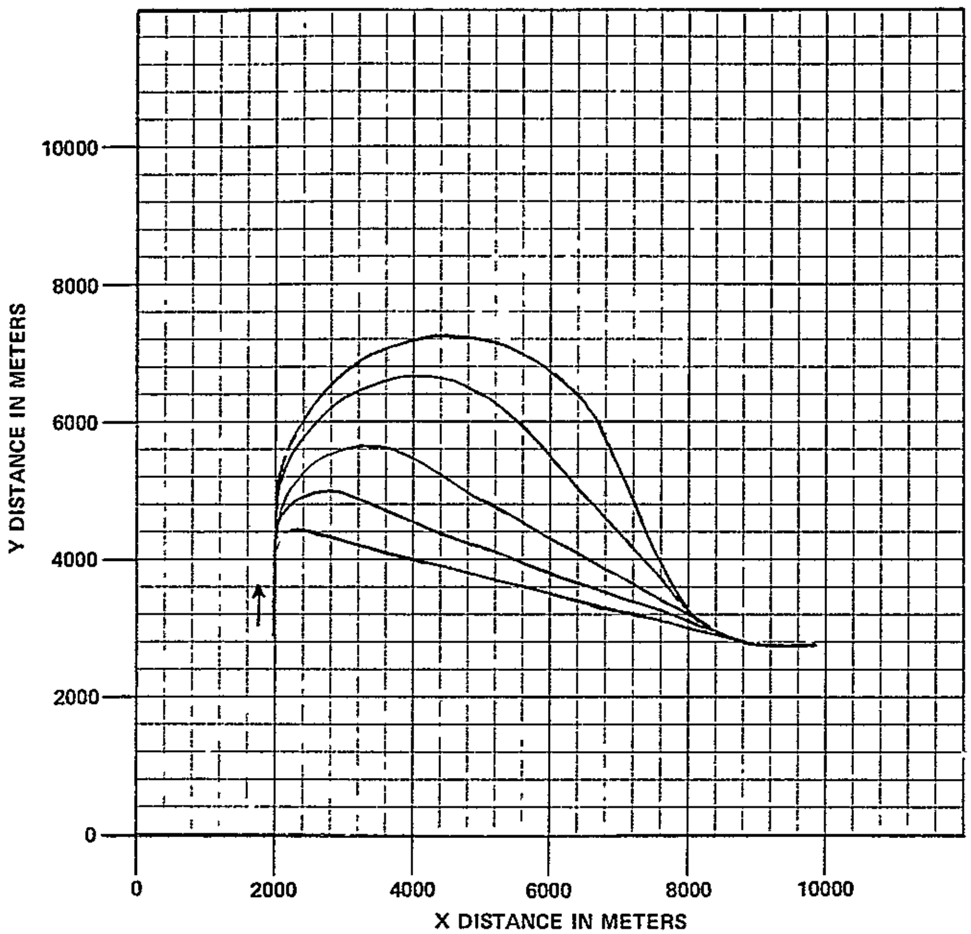

Figure 42
Direct To Path with Different Radii

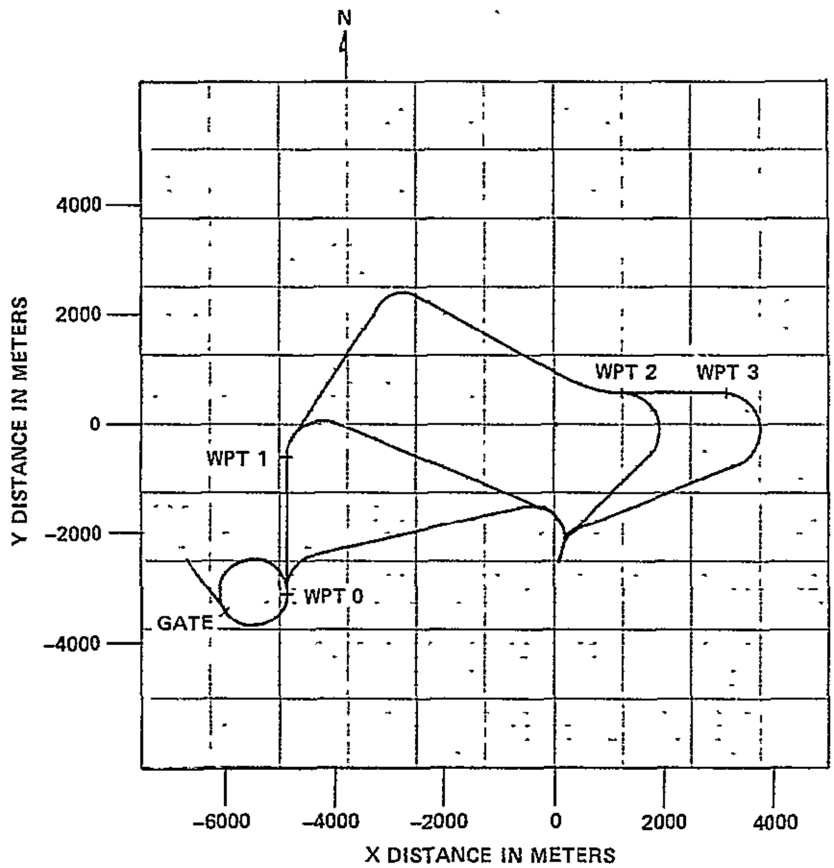

Figure 43
Direct To Flight to Different Waypoints

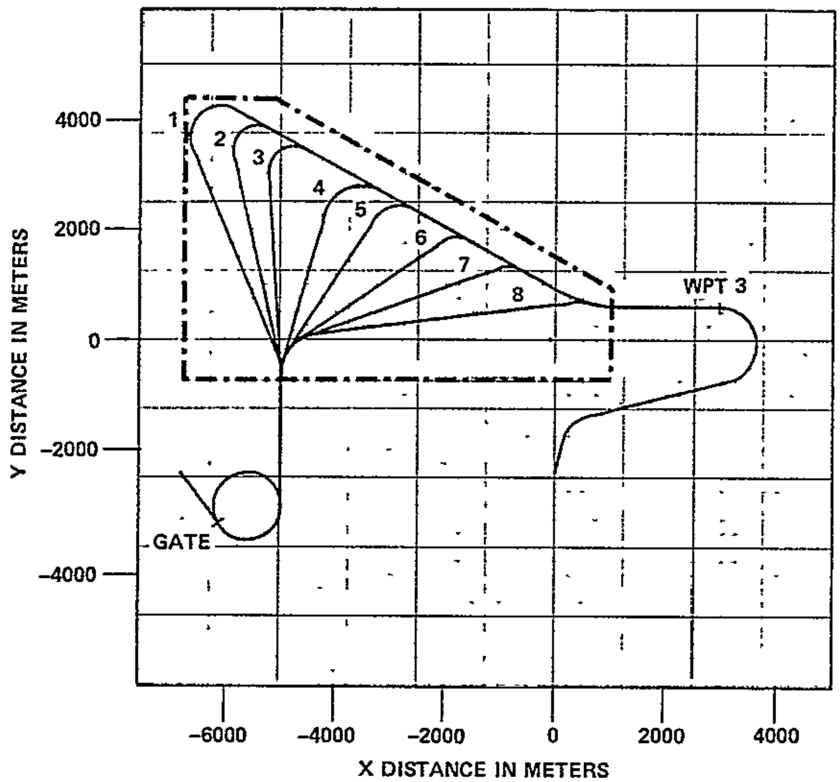

Figure 44
Path Alteration with Direct To Maneuver

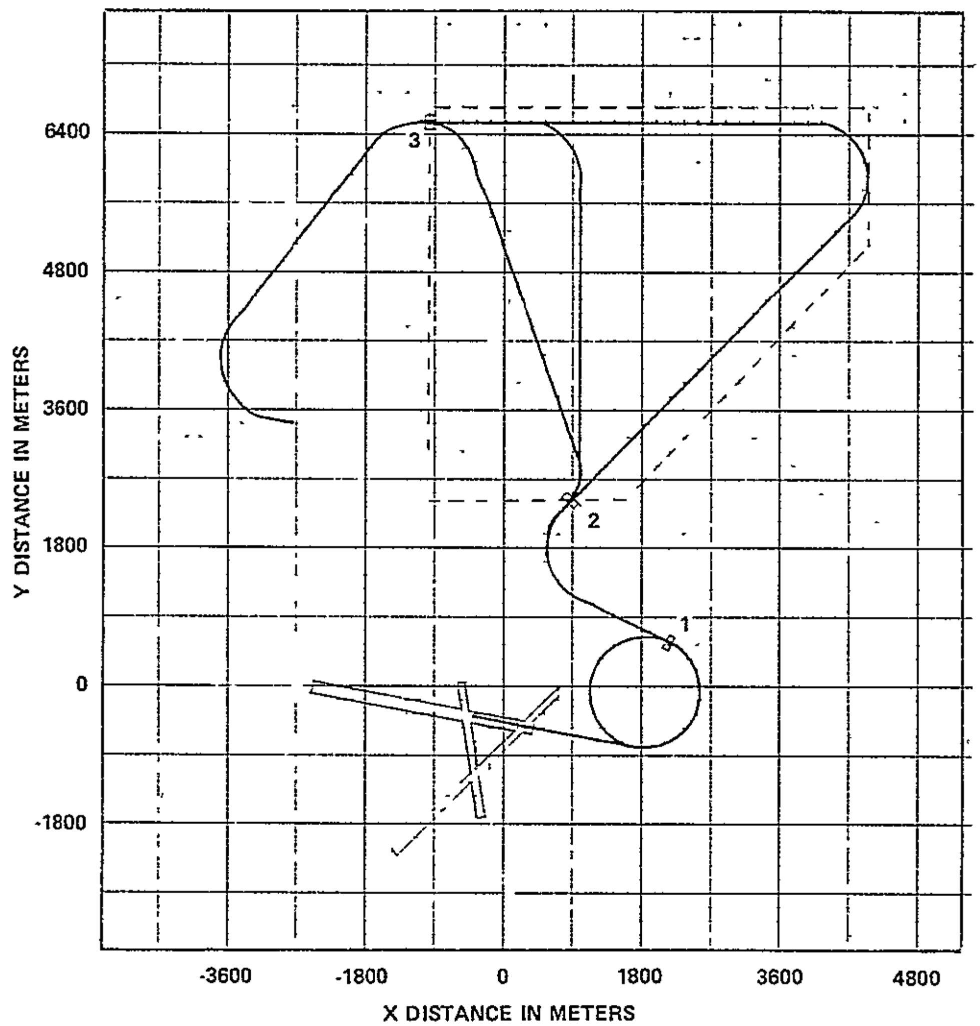

Figure 45
Delay Fans to Wallops

TABLE 2

VELOCITY PROFILE DATA FOR DELAY FAN GENERATION

Flight No.	Time at WPT 0	Time at WPT 1	Time at WPT 2	Time at WPT 3	Delay Fan Max Speed	Delay Fan Min Speed
1	165 sec	232 sec	610 sec	660 sec	35.7 m/s	35.7 m/s
2	165 sec	232 sec	610 sec	660 sec	35.7 m/s	31.9 m/s
3	165 sec	232 sec	610 sec	660 sec	35.7 m/s	28.6 m/s
4	165 sec	232 sec	460 sec	510 sec	39.5 m/s	31.9 m/s
5	165 sec	232 sec	460 sec	510 sec	35.7 m/s	31.9 m/s
6	165 sec	232 sec	460 sec	510 sec	31.9 m/s	31.9 m/s
7	165 sec	232 sec	445 sec	495 sec	31.9 m/s	31.9 m/s
8	165 sec	232 sec	435 sec	485 sec	31.9 m/s	31.9 m/s

in the area is equal to the path length generated by the change in boundary waypoint times. When this condition is satisfied, the aircraft switches to the Direct To path.

The different paths flown in Figure 45 were also produced by changing the boundary waypoint times. These paths, however, were predicted prior to flying the approach. By varying the boundary waypoint times, the path distance in the delay fan area was changed. The Direct To maneuver corresponding to that path length was then generated immediately. The delay fan maneuver can then be displayed for the pilot's acceptance or rejection. Using this technique the pilot is made aware of the path he will be required to fly prior to actually accepting an approach rather than waiting until he is committed to an approach and has already flown through part of the delay fan area. The plots of the different paths flown in the delay fan area show the flexibility of this maneuver and the ability of the maneuver to generate the path necessary to reach the next waypoint at a specified time and within given velocity constraints. The Direct To path alteration maneuver provides the same path stretching or shortening capability as the various fixed form delay fans in a manner that is readily incorporated into the VALT software.

Avoidance Areas

Where generating Direct To maneuvers in the delay fan area using the direct computation technique, avoidance areas can be taken into consideration. In order to demonstrate the flexibility of the avoidance area modification technique, a Direct To path, generated without consideration of the avoidance area, is shown in Figure 46. In this case, the path length was increased from the nominal path length so as not to violate the velocity limits placed on the velocity profile. Because the path intersects the avoidance area, the path length was again increased to bypass the avoidance area. The path around the avoidance area is shown in Figure 47. The new path has the effect of pulling the minimum velocity off the lower velocity limit as shown in Figure 48. The paths and profiles shown here were generated prior to accepting an approach. A discussion of the technique used to generate a path around an avoidance area is discussed in Appendix A.

Airspeed Control

A full predictive capability was used to evaluate the use of the airspeed control on the Direct To capture portion of the lateral path. Using the predictive mode, a keyboard entry through the Nav/Guidance Control Panel of the approach gate time of arrival was made. From the ground speed velocity profile generation routine, the time to fly from any selected waypoint to the approach gate can be determined thereby fixing the time to fly the Direct To capture maneuver from the present aircraft position to the selected waypoint. The airspeed profile along the Direct To capture path was generated using the program that places speed changes on the straight line segment of the capture path. From that routine, the minimum and maximum times required to fly the path capture maneuver were generated and then compared with the time available for the maneuver. This comparison was displayed on the left side of the graphics terminal as shown in Figure 49 with the maximum and minimum values as the end points of the scale and the pointer as the available clock time for the maneuver. Any time that the pointer was between the limit marks, the path was flyable from the standpoint of time, distance, and velocity. This gave the pilot the opportunity to determine the flyability of the lateral path due to terrain obstructions or other considerations. When all parameters were satisfied, the approach was selected and flown. The velocity profile for the fixed path and the resulting Direct To maneuver were displayed as shown in Figure 50. A trace of simulated aircraft responses while flying a combined airspeed and ground speed control law is shown in Figure 51. Comparison of the airspeed and ground speed traces demonstrates the changing ground speed in airspeed control and changing airspeed while in ground speed control on the various turns of the approach. A discussion of the techniques used for generating an airspeed profile and flying airspeed control is contained in Appendix D.

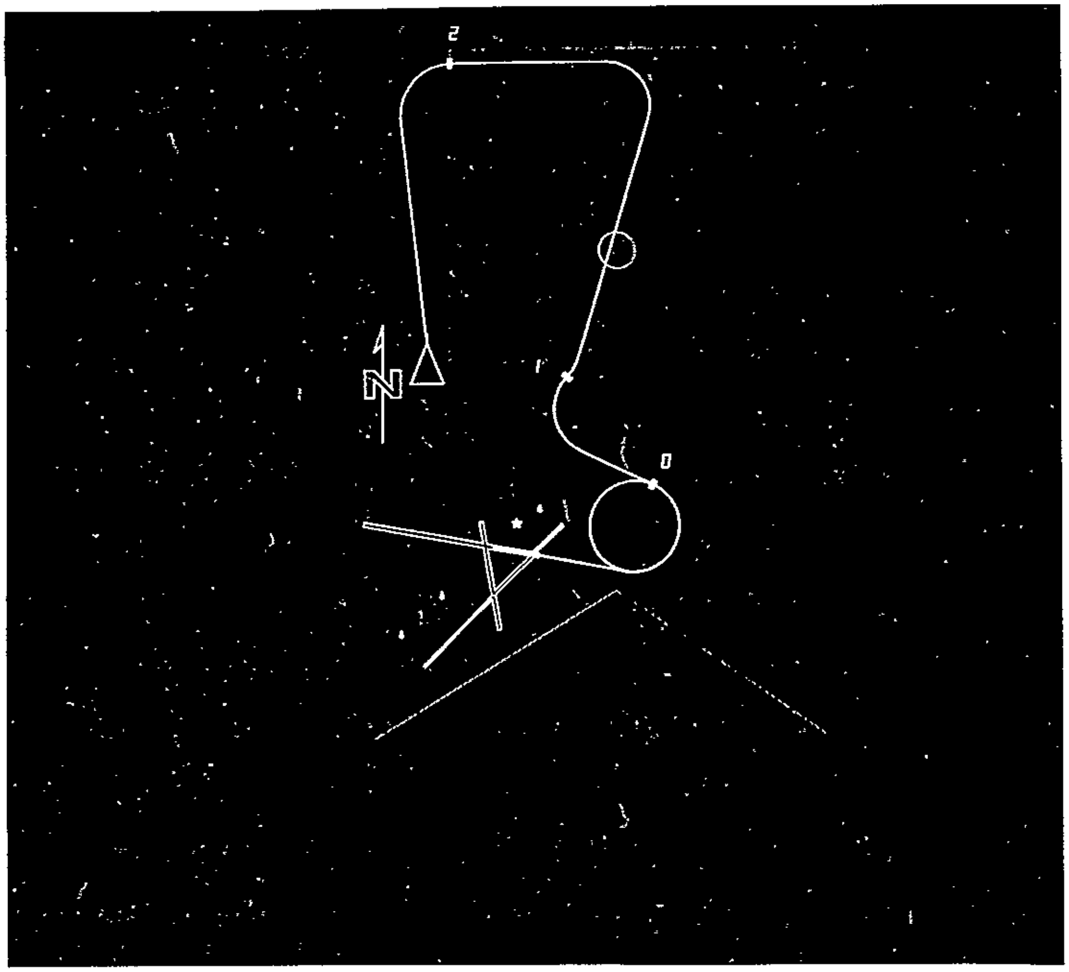

Figure 46
Path Stretching Delay Fan through Avoidance Area

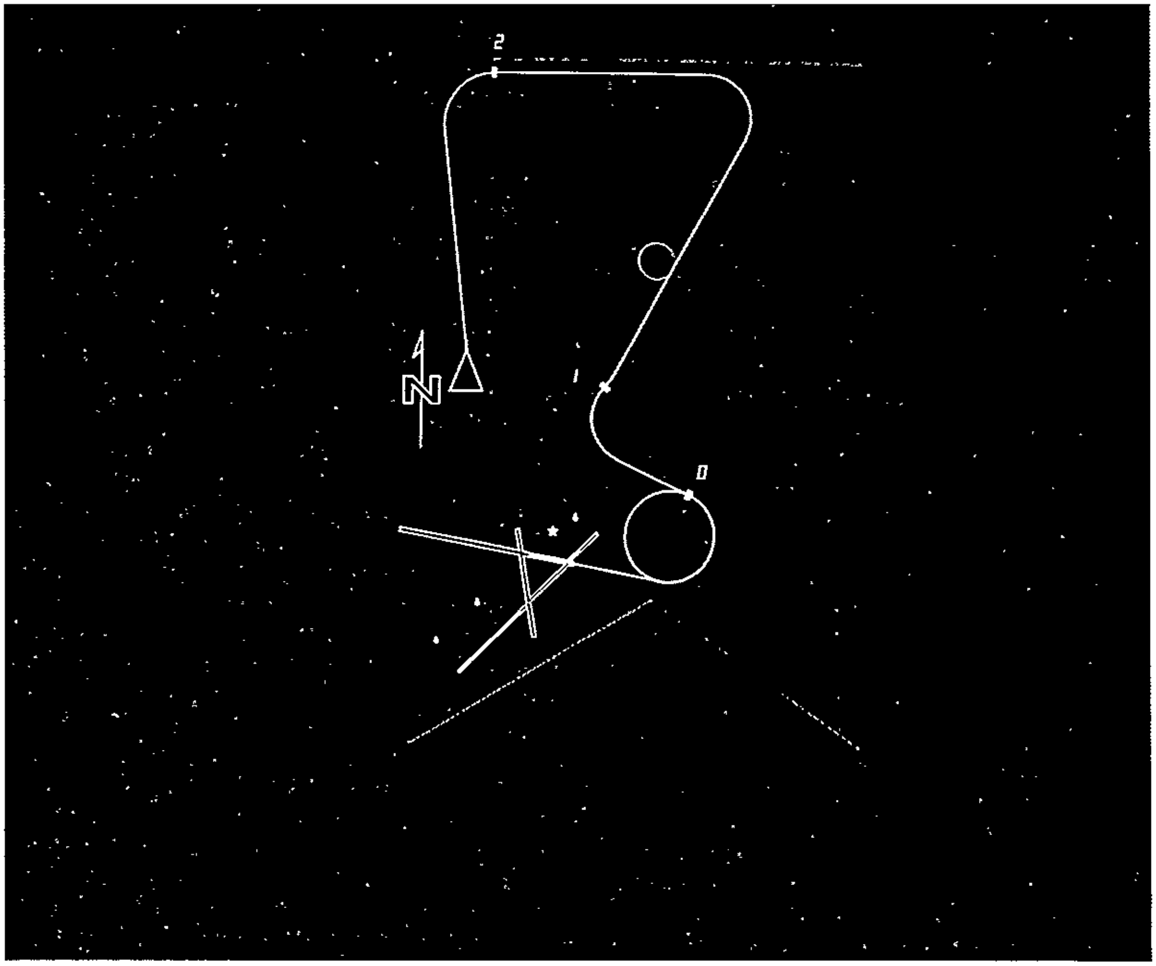

Figure 47
Altered Lateral Path Around Avoidance Area

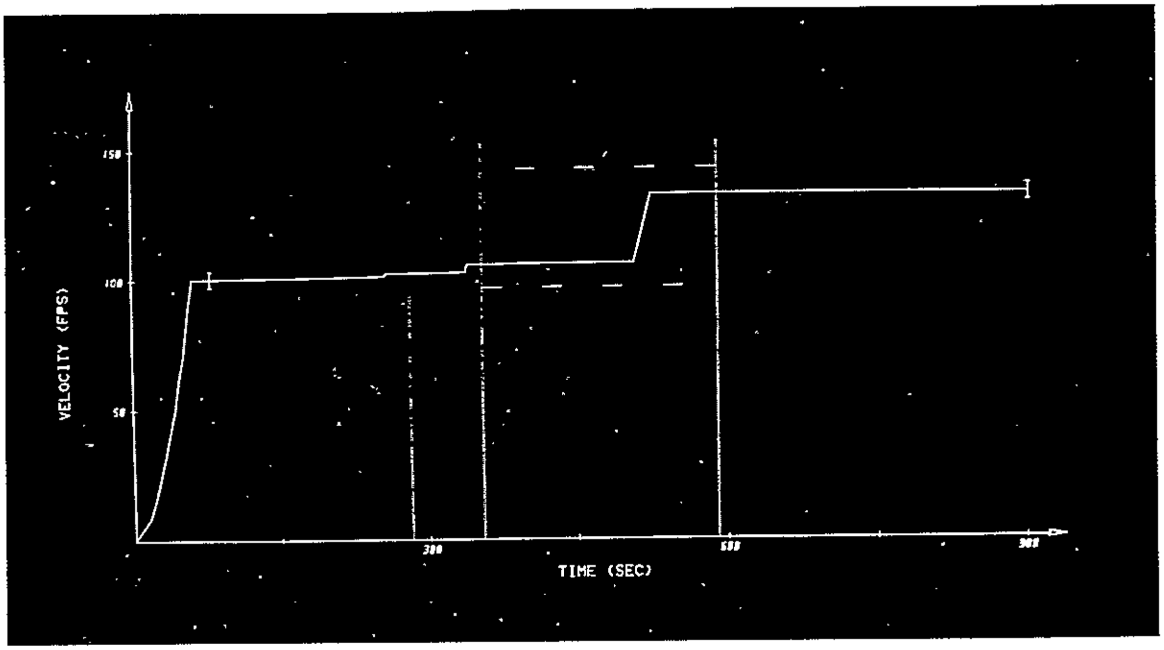

Figure 48
Altered Velocity Profile

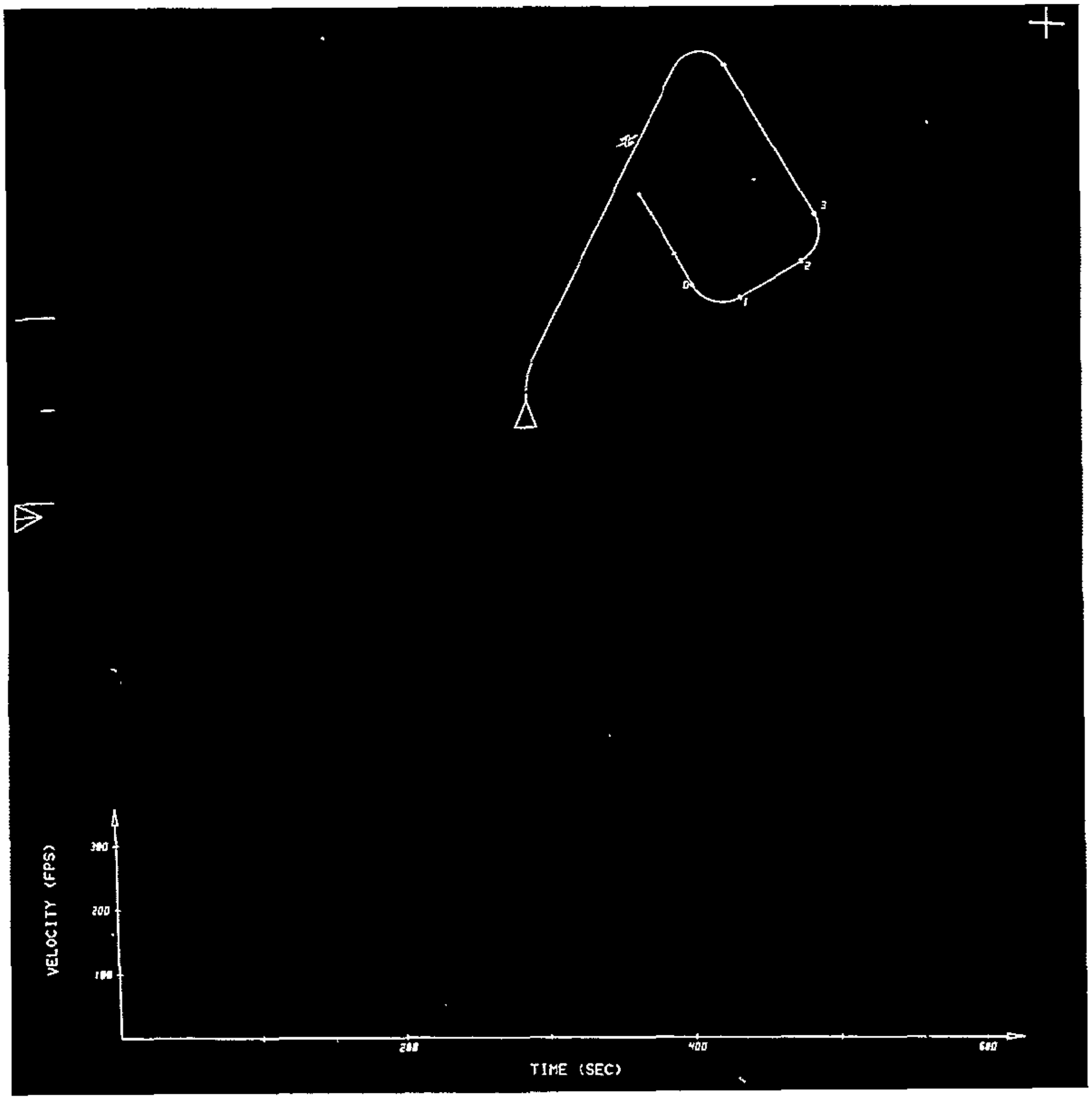

Figure 49
Time Acceptance Display

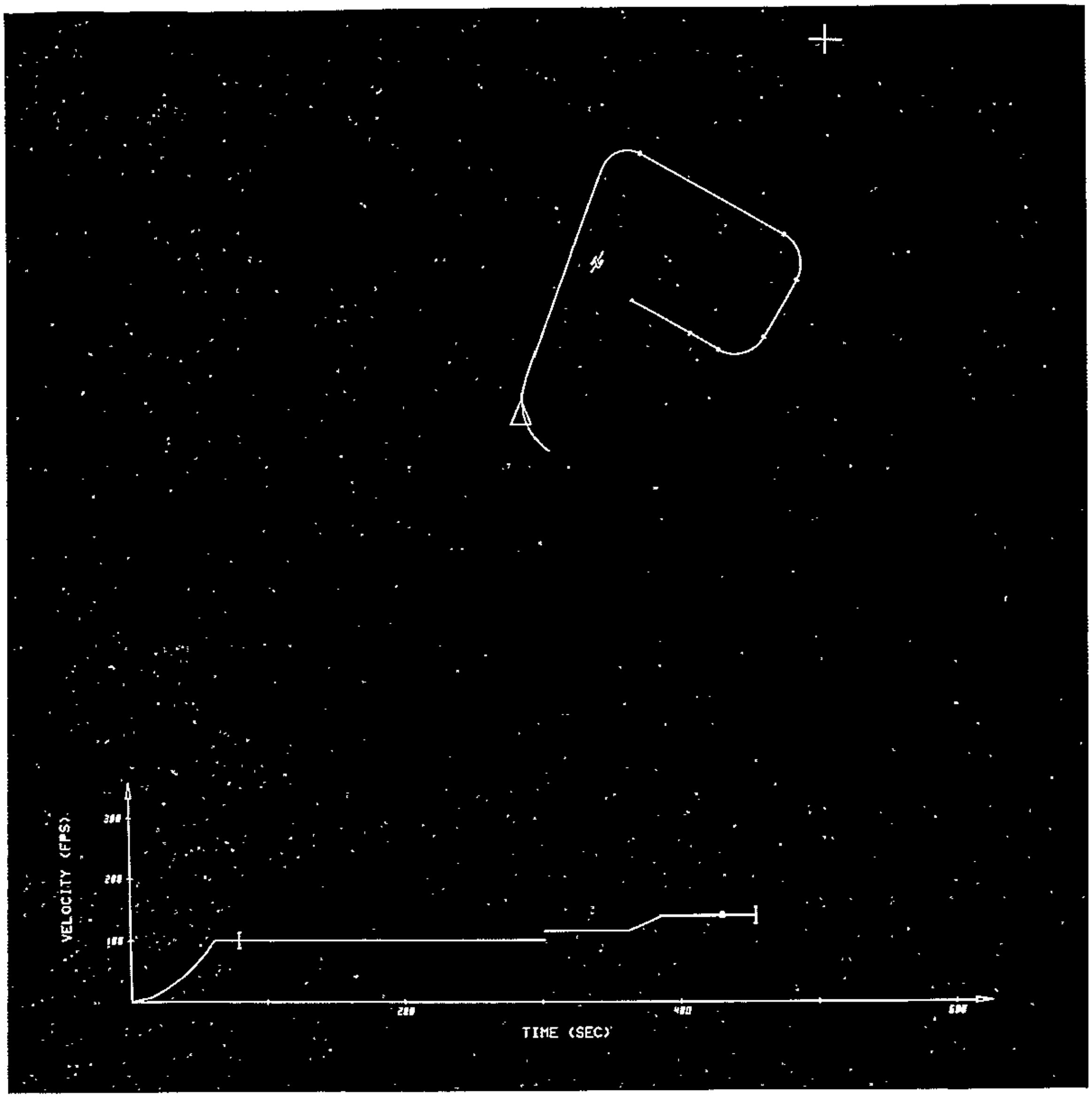

Figure 50
Captured Lateral Path and Airspeed Profile

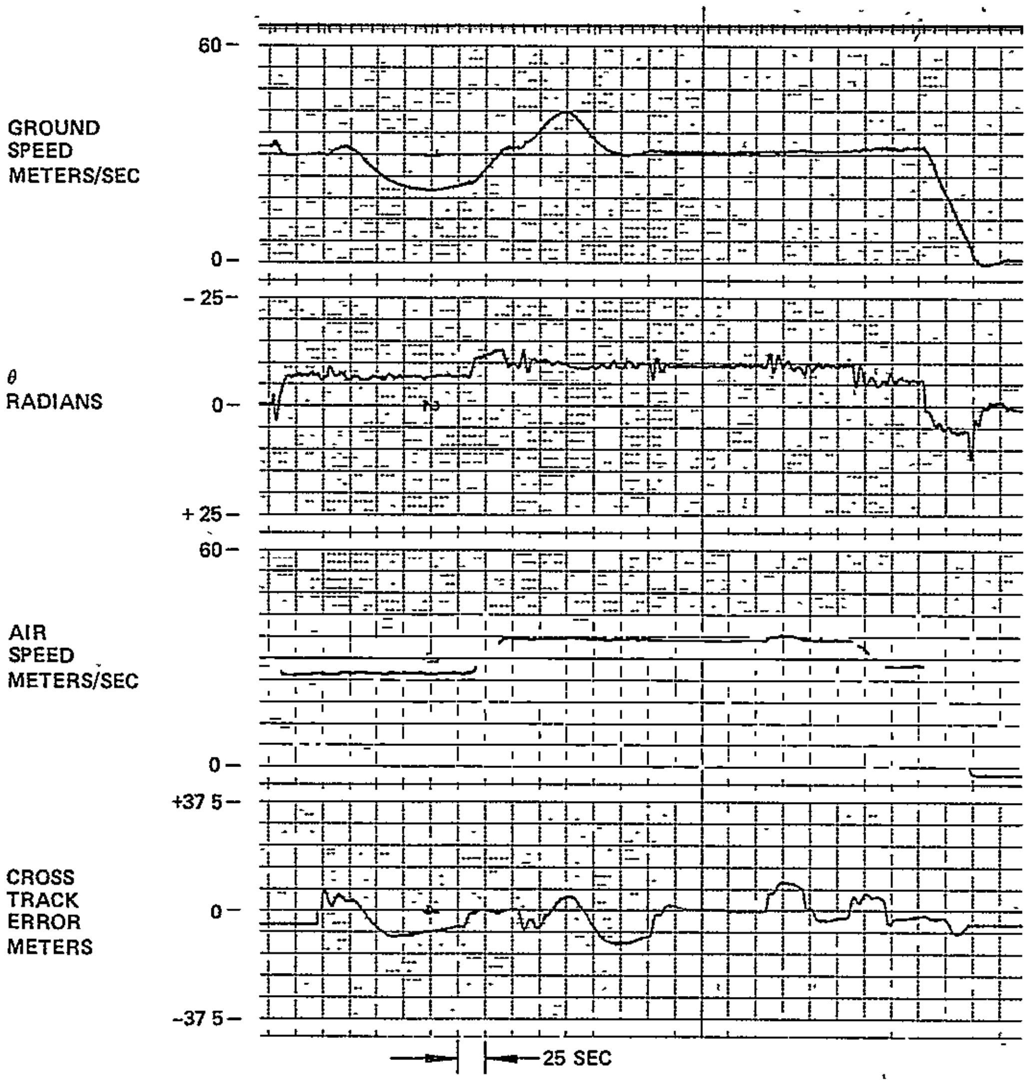

Figure 51
Airspeed Control Time History Plot
(Sheet 1 of 2)

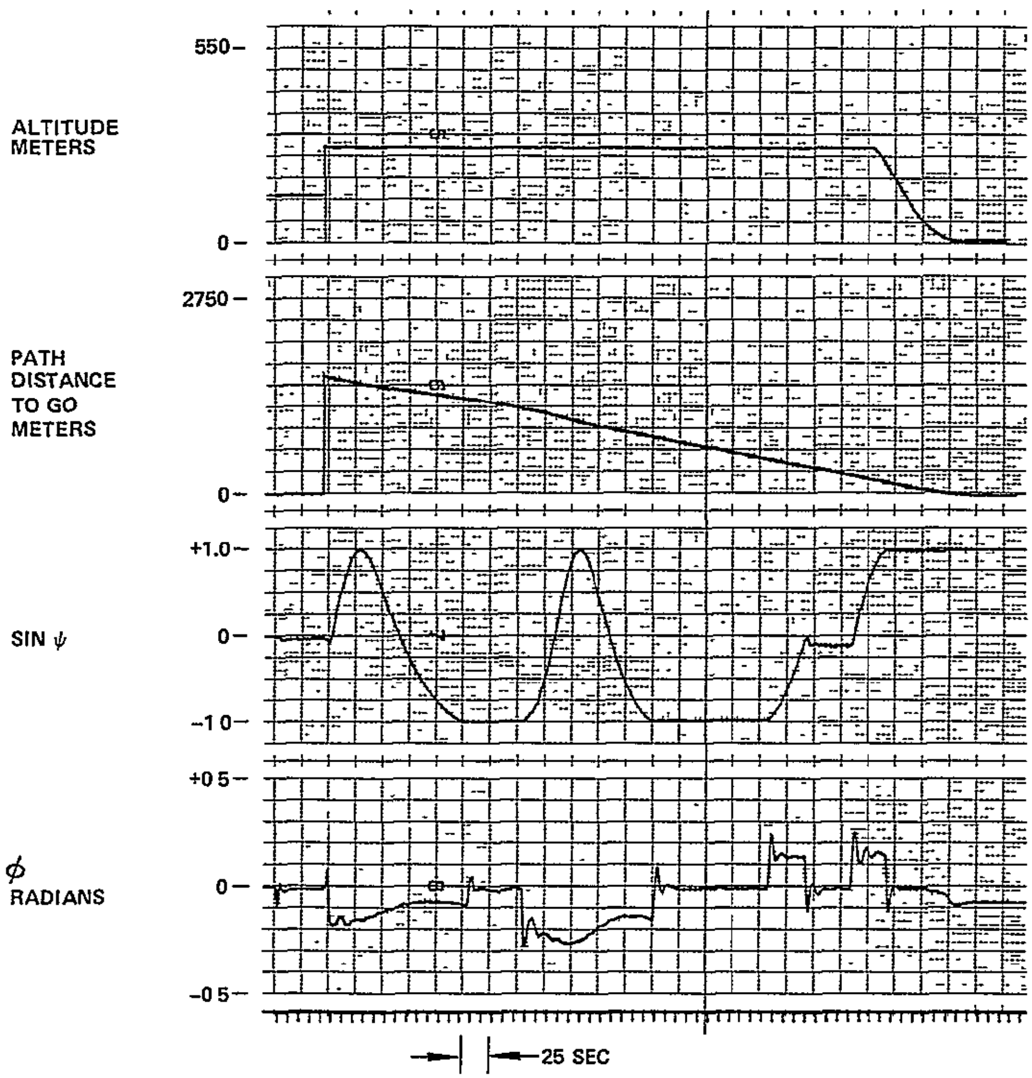

Figure 51
Airspeed Control Time History Plot
(Sheet 2 of 2)

4D Path Performance

A number of nominal paths were chosen to demonstrate the different capabilities of the VALT 4D system. The approach paths were created by the lateral path software to provide baselines for the simulated approaches. To demonstrate the Direct To delay fan prediction capability, the nominal path contained both straight and curved sections with an approach gate and a time of arrival control waypoint located 1219 meters from the hover point. A 2 degree constant attitude deceleration profile was used from the approach gate to the hover point. This type of deceleration profile was used for all simulated approaches. Four additional time control waypoints were located at various points on the approach path. The nominal flight path and a Direct To path capture maneuver are shown in Figure 52. The desired time of arrival at the approach gate and at each of the other time control waypoints was used to create a nominal velocity profile. Arrival times at the various time control waypoints were changed to obtain a variety of velocity profiles and, thereby, a variety of path lengths in order to verify the correct operation of the velocity profile generation and the delay fan switching software. A 6 degree glideslope to a 15 meter hover point was used as the altitude profile for these simulated approaches. A constant altitude of 610 meters was used prior to the glideslope intercept.

Data taken during a simulated 4D approach using the nominal approach path is shown in Figure 53. This data includes time error, pitch attitude, ground speed, crosstrack error, radar altitude, distance to go along the path, the sine of heading, and roll attitude. The data was obtained under zero wind conditions.

A maximum time error of .5 second was observed. A maximum crosstrack error of 18 meters was obtained at the point where a circular arc joins a straight line segment. The crosstrack performance is consistent with that obtained in previous VALT lateral path data runs. In a 4D approach, however, crosstrack error has increased significance since lateral path deviations tend to reduce along track velocity slightly. This in turn results in a pitching motion to restore the small time error that is introduced. These pitching motions and velocity changes are readily apparent on the data traces. This condition is particularly noticeable in flight director aided manual approaches since larger crosstrack errors are generally present and errors are not closed out as rapidly as they are in the automatic mode. The effect that the pilot observes is an apparent roll to pitch coupling.

In addition to the data taken on the nominal flight path, data was taken for each of the various delay fan paths shown in Figure 44. The data in Figures 54 through 61 illustrates the changes in the velocity profile for each of the eight delay fans. The velocity profiles were modified by varying the values of delay fan time and minimum and maximum velocity limits. As can be seen on the traces, the time error was held to within 1 second and the main contributor to time error was crosstrack error.

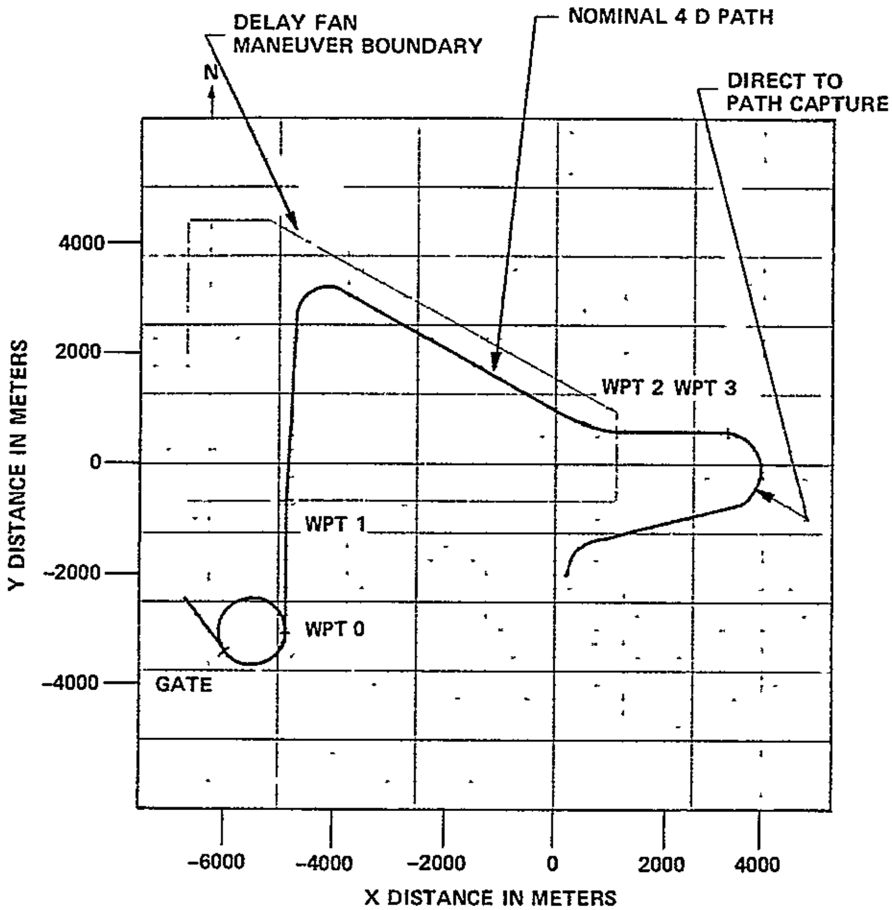

Figure 52
Nominal 4D Flight Path

C-2

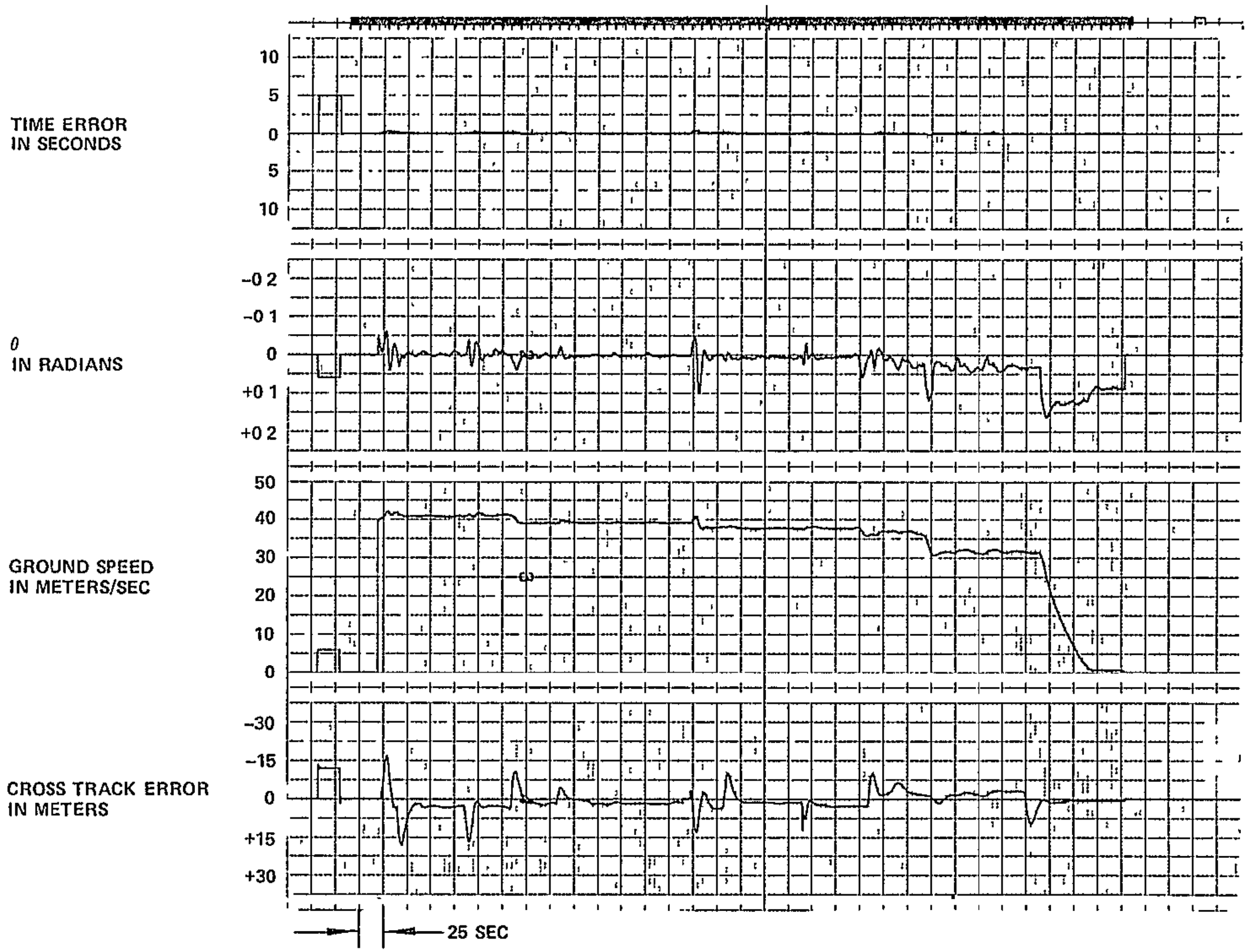

Figure 53
4D Flight Performance Data
(Nominal Path)
(Sheet 1 of 2)

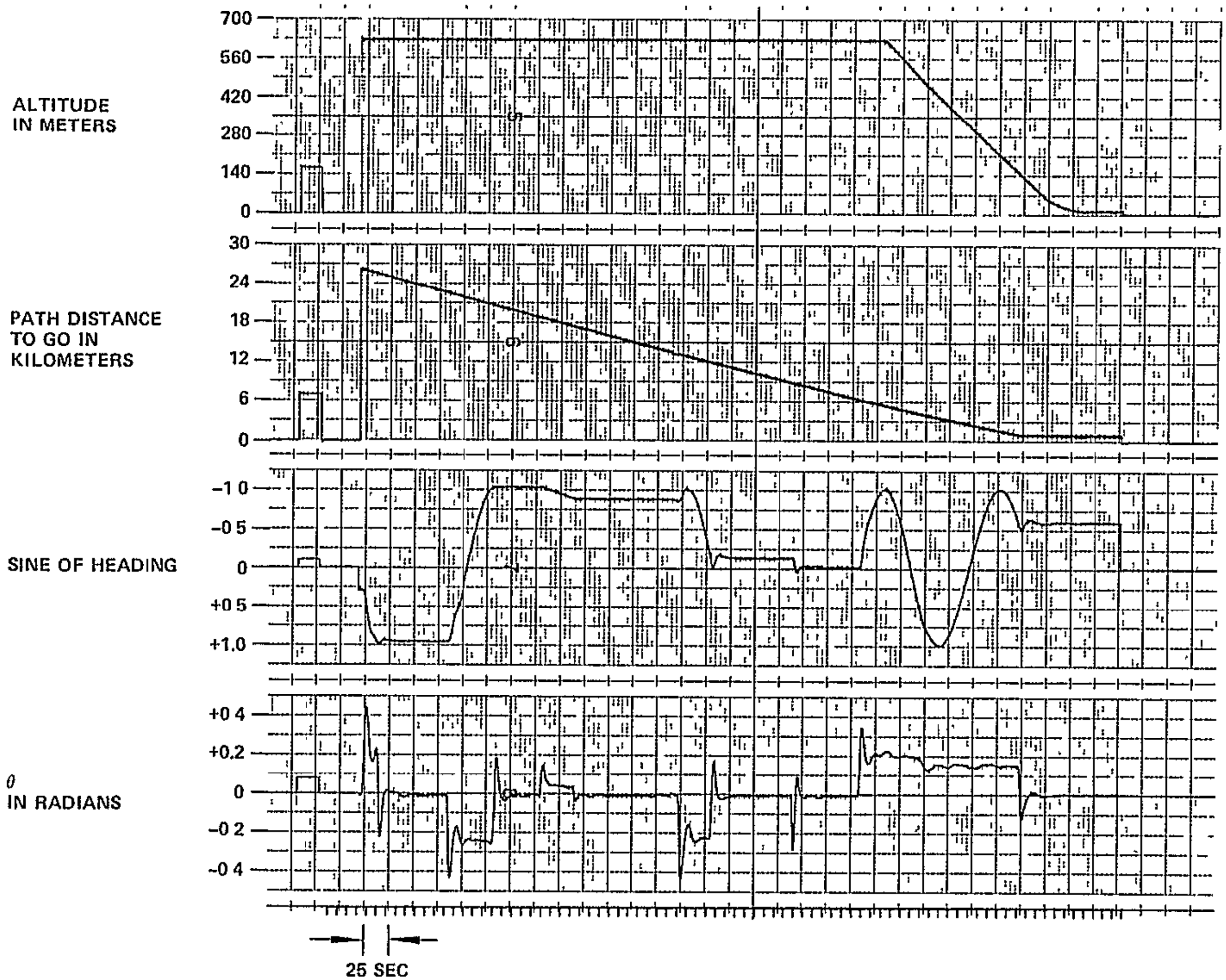

Figure 53
4D Flight Performance Data
(Nominal Path)
(Sheet 2 of 2)

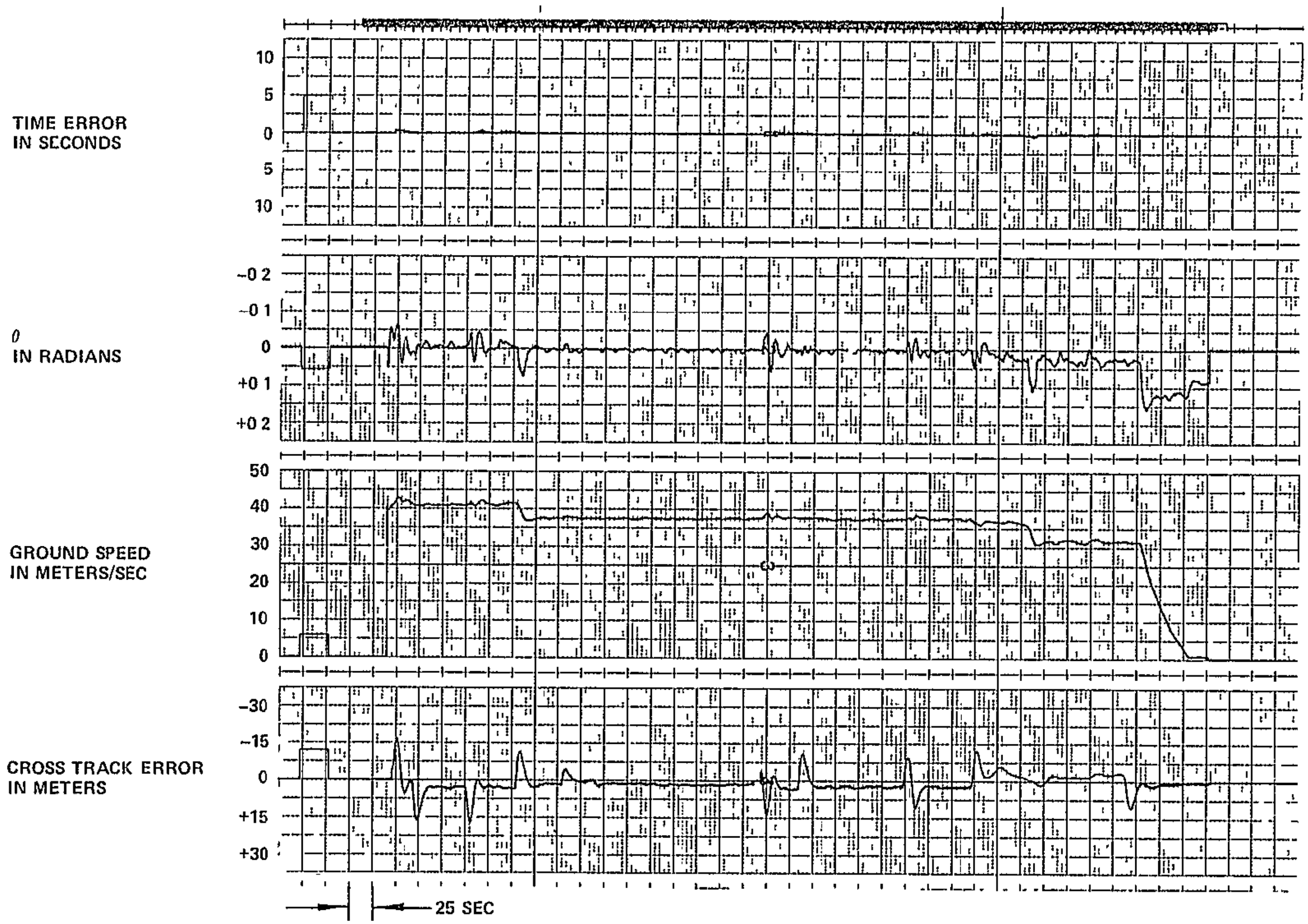

Figure 54
4D Flight Performance Data
Delay Fan Pattern 1

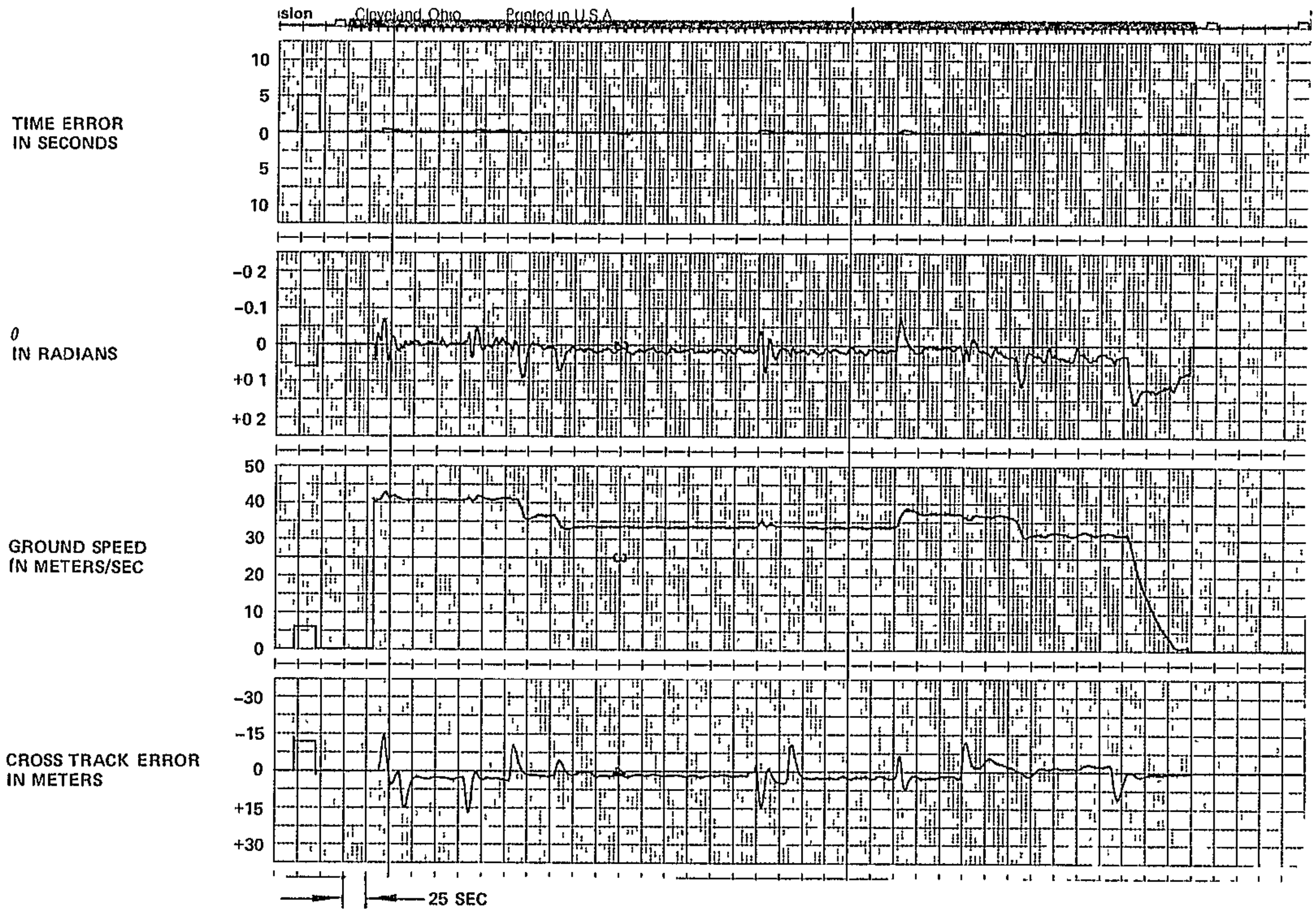

Figure 55
4D Flight Performance Data
Delay Fan Pattern 2

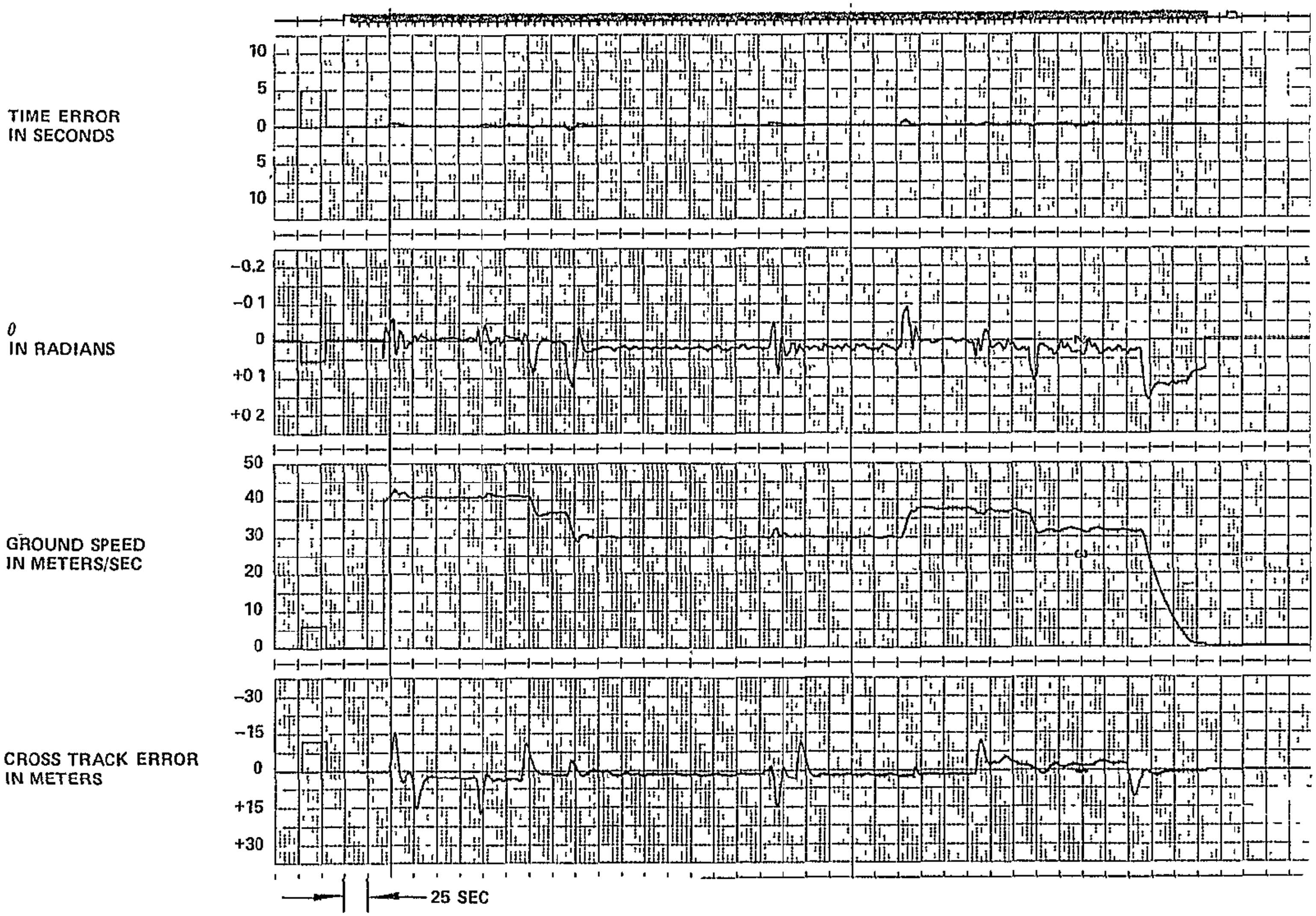

Figure 56
4D Flight Performance Data
Delay Fan Pattern 3

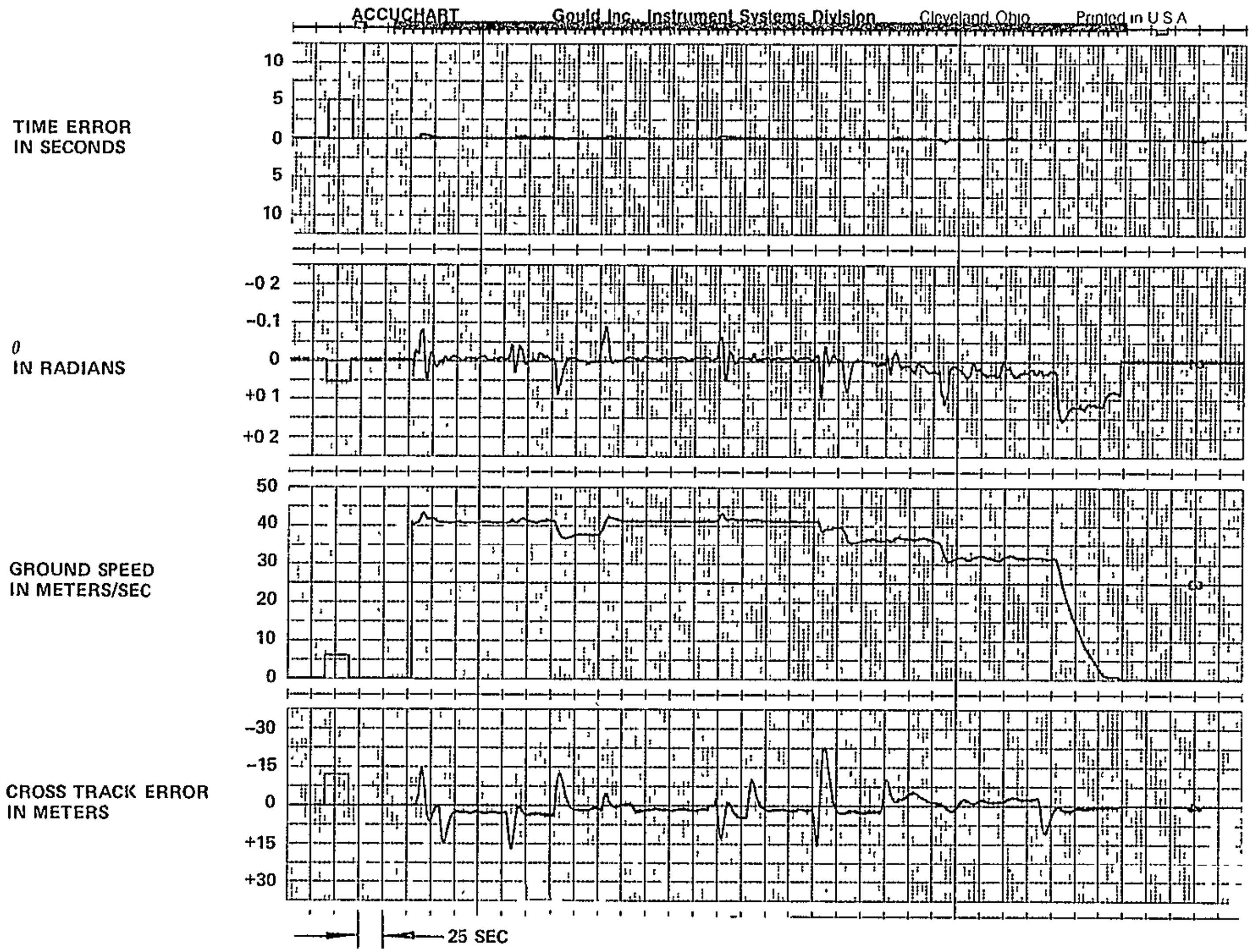

Figure 57
4D Flight Performance Data
Delay Fan Pattern 4

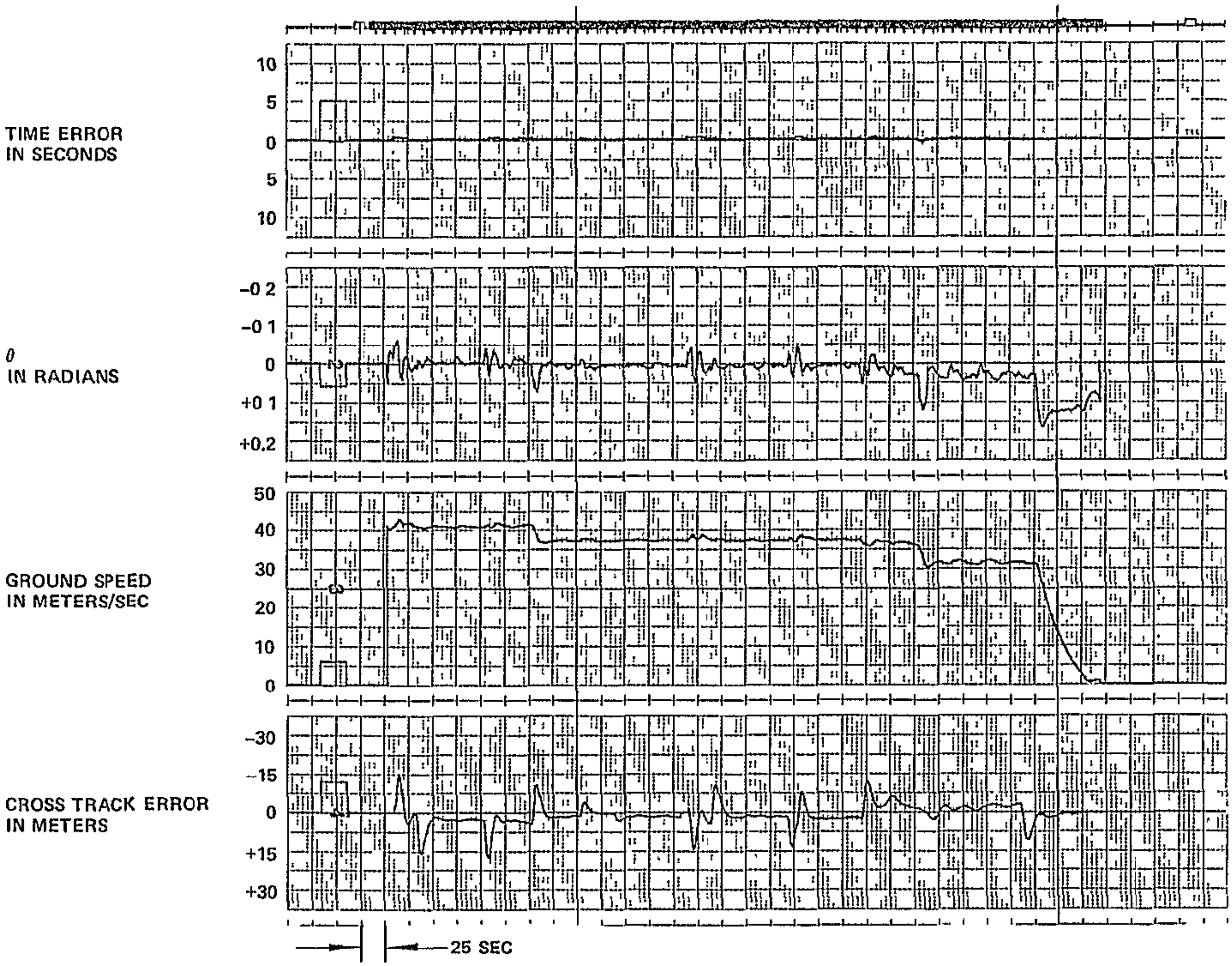

Figure 58
4D Flight Performance Data
Delay Fan Pattern 5

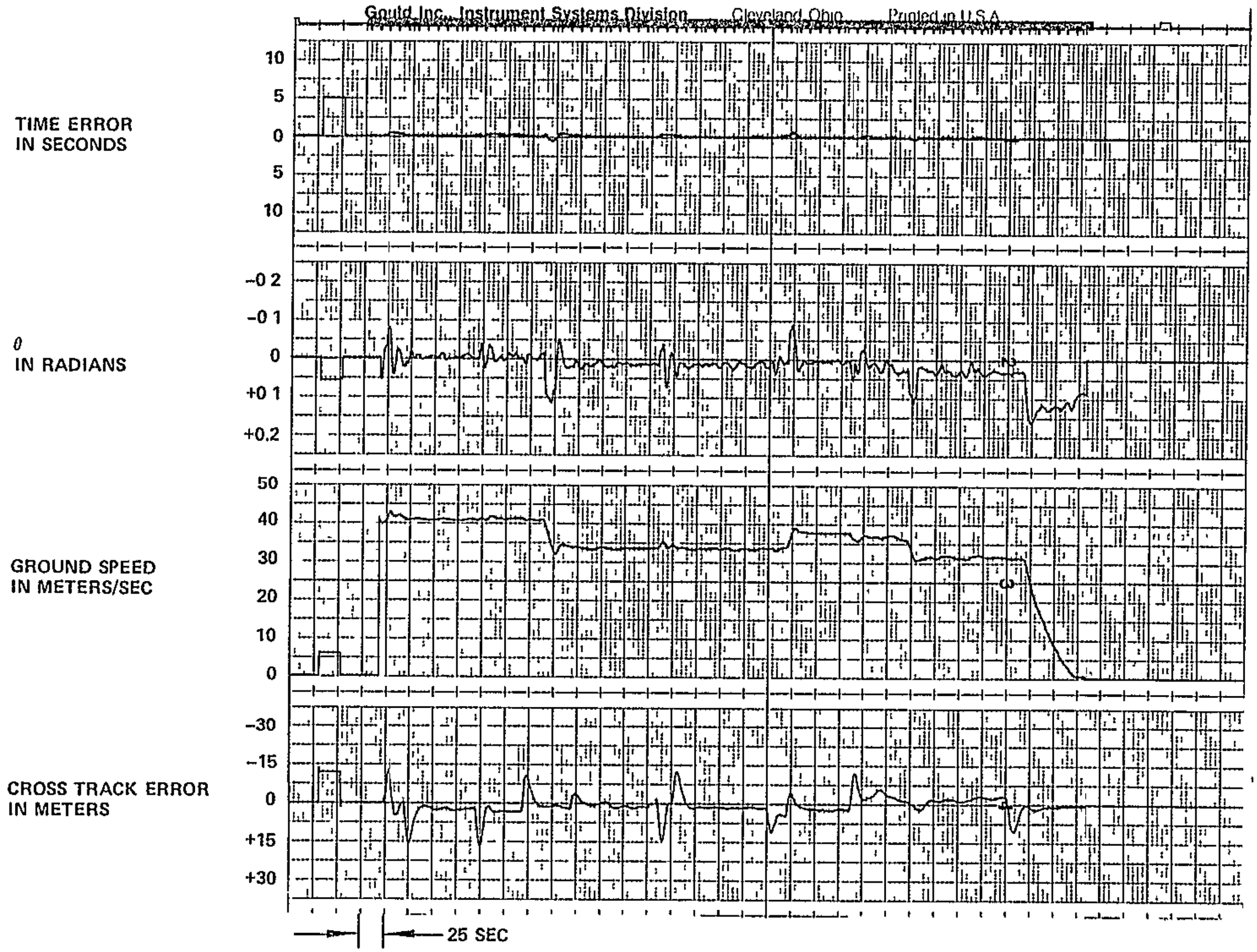

Figure 59
4D Flight Performance Data
Delay Fan Pattern 6

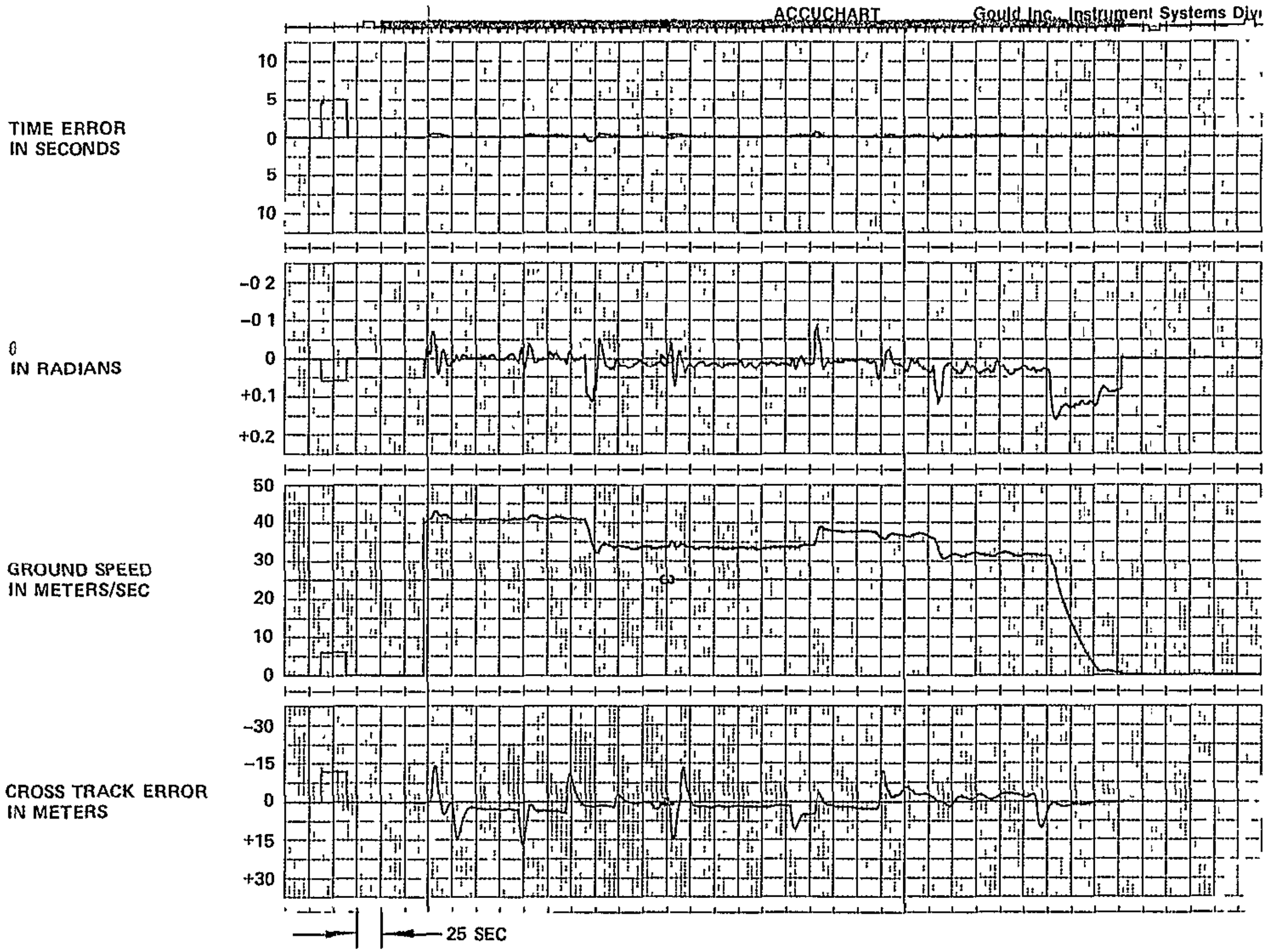

Figure 60
4D Flight Performance Data
Delay Fan Pattern 7

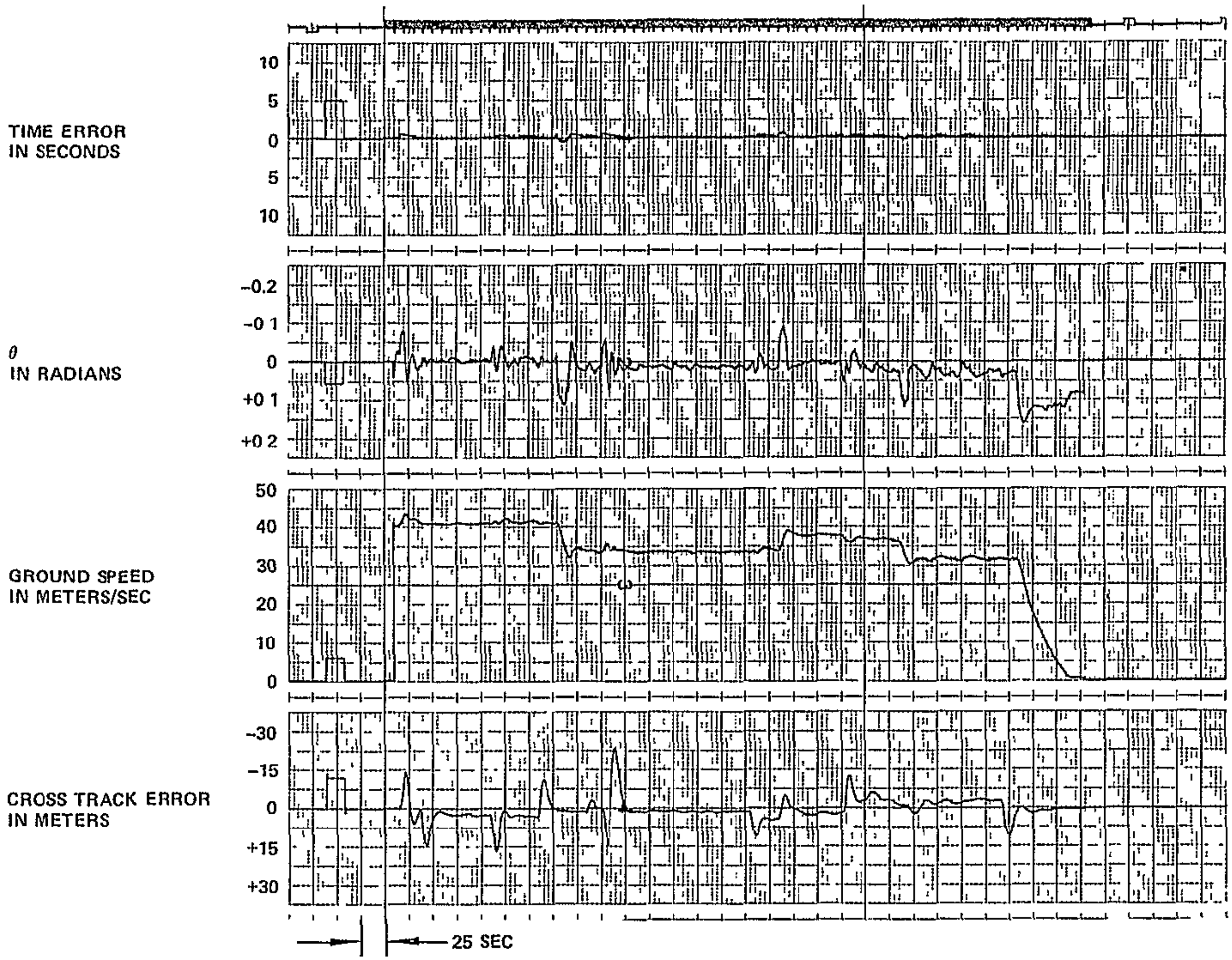

Figure 61
4D Flight Performance Data
Delay Fan Pattern 8

In order to investigate the capability of the direct computation delay fan technique, a nominal path was generated using the VALT lateral path software which consisted of straight lines and curved arc segments with a delay fan area which would require two turns in the same direction. Three time waypoints, in addition to the approach gate, were placed on the flight path. The deceleration profile and glideslope were the same as those used in the previous example, however, a constant altitude of 305 meters prior to the glideslope intercept was used. The nominal path and a Direct To path capture maneuver are shown in Figure 62. By varying the required time at waypoint 2, the various paths shown in Figure 63 were flown and data traces taken. The traces are shown as Figures 64 through 66 and contain the same kind of data shown in the previous examples. Since this is a ground speed control technique, the conclusions drawn from these traces are the same as those from the previous examples. They do, however, illustrate the direct path and path length computation technique which would be more suitable for actual 4D flights.

Another nominal path was generated in order to demonstrate the airspeed control capability. The lateral path consists of five time waypoints and the approach gate on a simple lateral path consisting of two turns and three straight segments. Times at the waypoints were selected so as to generate a velocity profile close to a constant velocity of 30.5 meters per second. The deceleration profile was the same as before and a 6 degree glideslope from an altitude of 305 meters to 15 meters was used for the altitude profile. The simulated approaches were made in the presence of a 6.1 meters per second wind at a heading of 315 degrees. The traces of the simulated aircraft responses are the same as before, except that airspeed was recorded rather than time error. The nominal path including all waypoints and a Direct To capture maneuver are shown in Figure 67. Traces of the simulated approaches to various waypoints are shown in Figures 68 through 70.

As before, a maximum time error of .5 second was observed. The crosstrack error was somewhat larger due to the effects of winds in the simulation. Large crosstrack excursions were seen upon entering the approach because of the technique used for placing the initial point of the Direct To maneuver. The technique used places the initial path point on a straight line extension from the aircraft based on aircraft heading. In the presence of winds, the heading and course are not necessarily the same, therefore producing an initial crosstrack error. The differences in the airspeed and ground speed controls were readily apparent from the traces. The constant airspeeds were seen on the Direct To maneuver turns and the constant ground speed was seen on the fixed path turns. A smooth transition from airspeed control to ground speed control can also be noted.

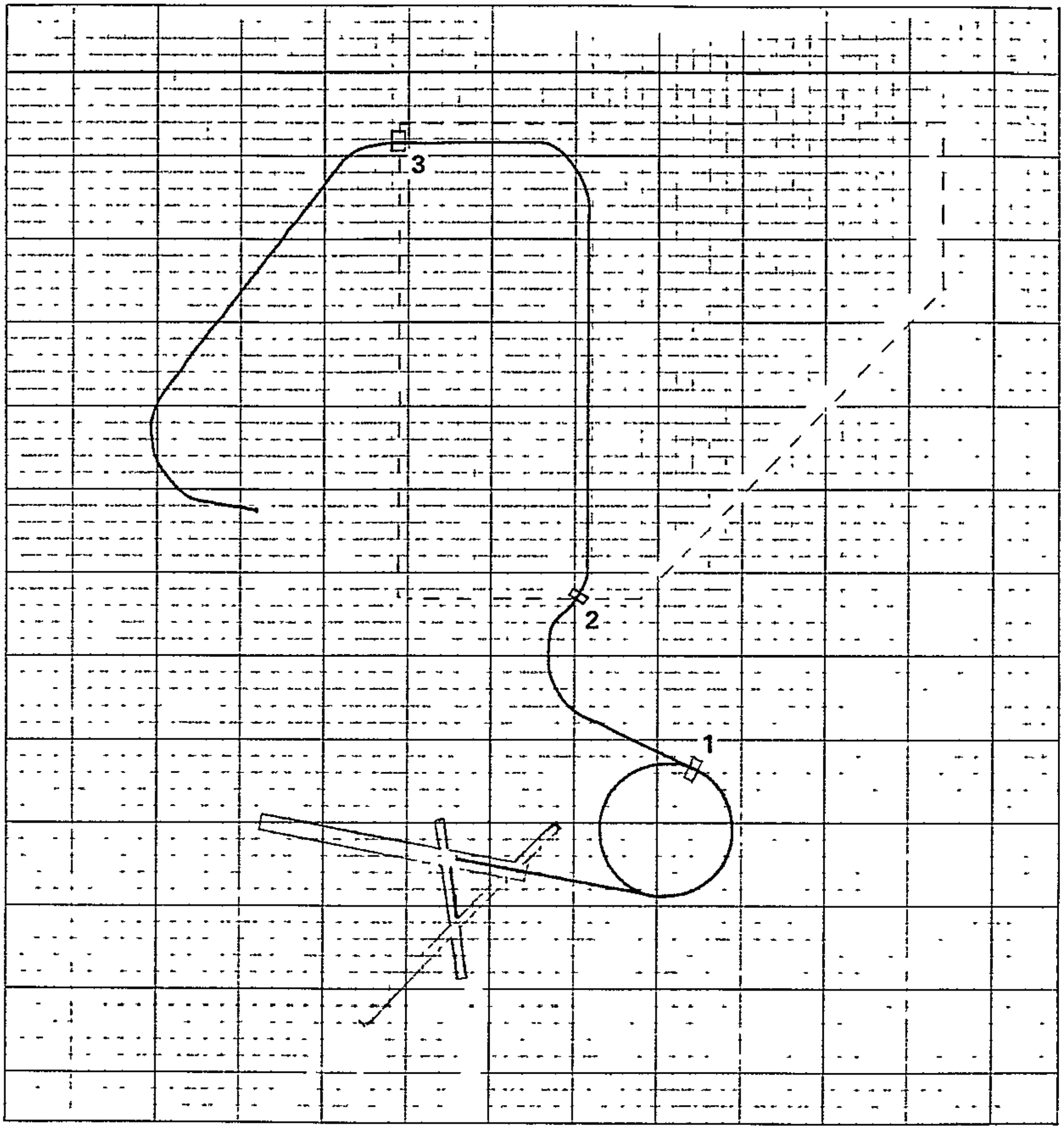

Figure 62
Nominal Delay Fan Path to Wallops

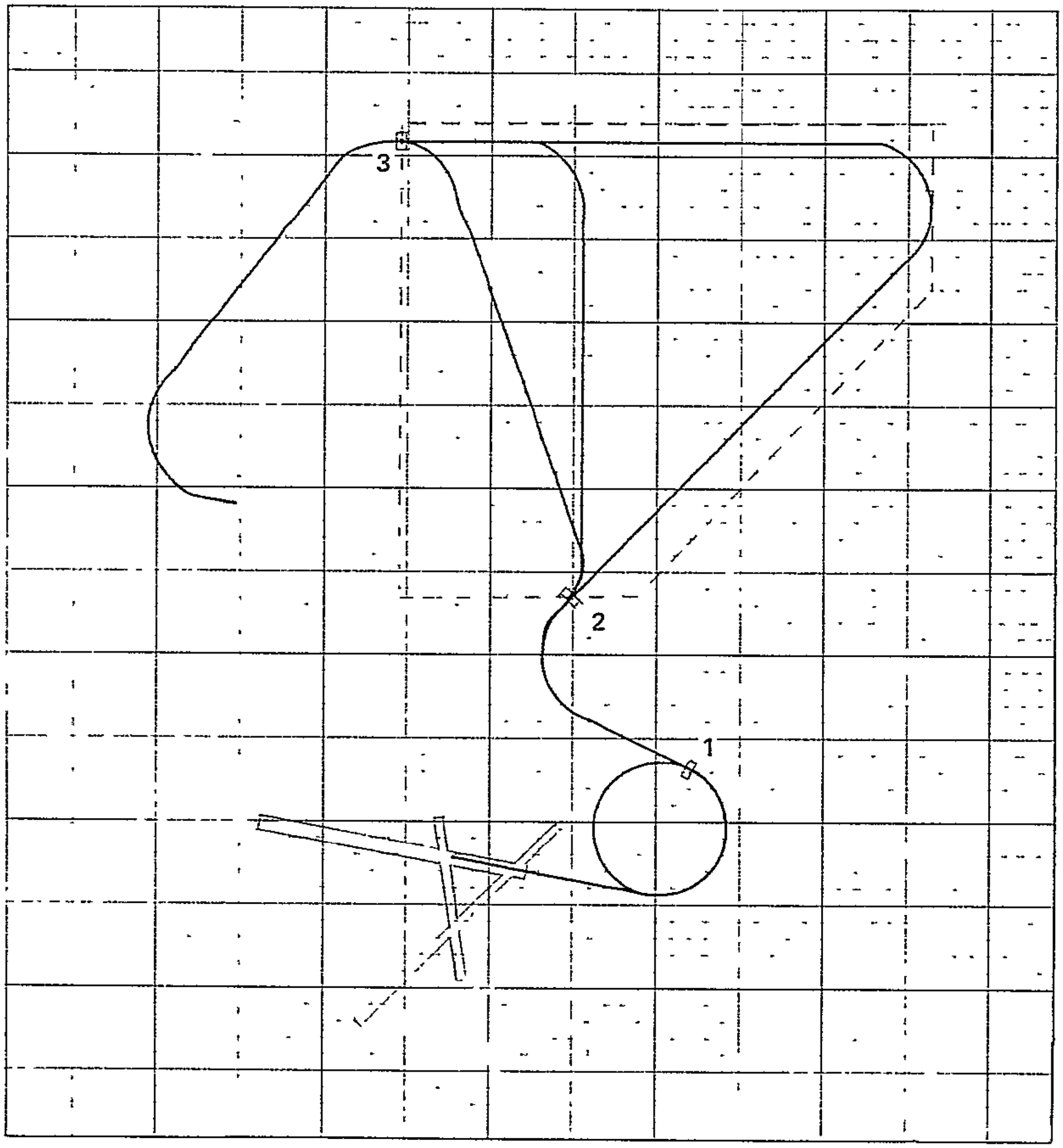

Figure 63
Delay Fans to Wallops

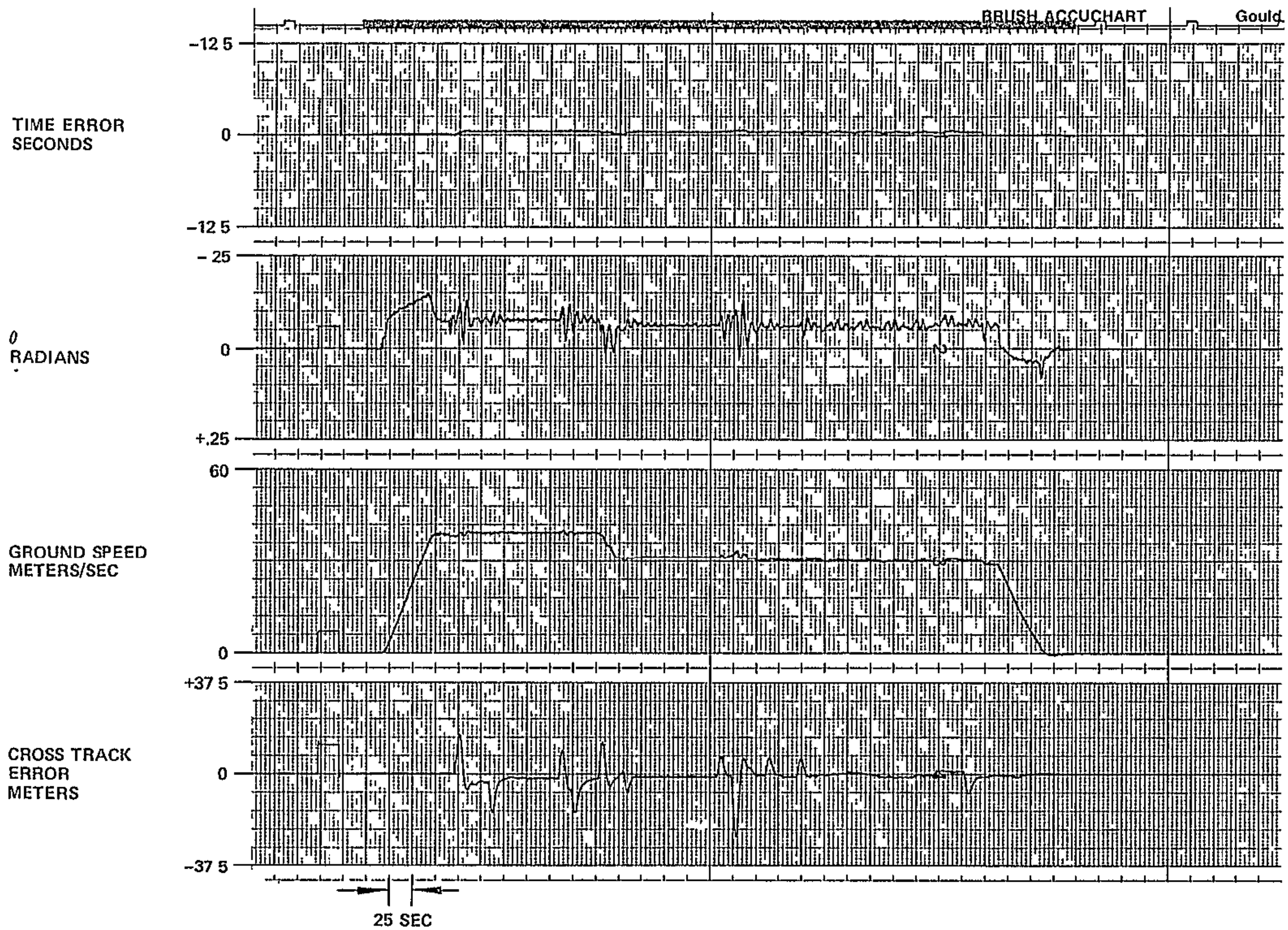

Figure 64
4D Flight Performance Data
Nominal Delay Fan Path Wallops Station
(Sheet 1 of 2)

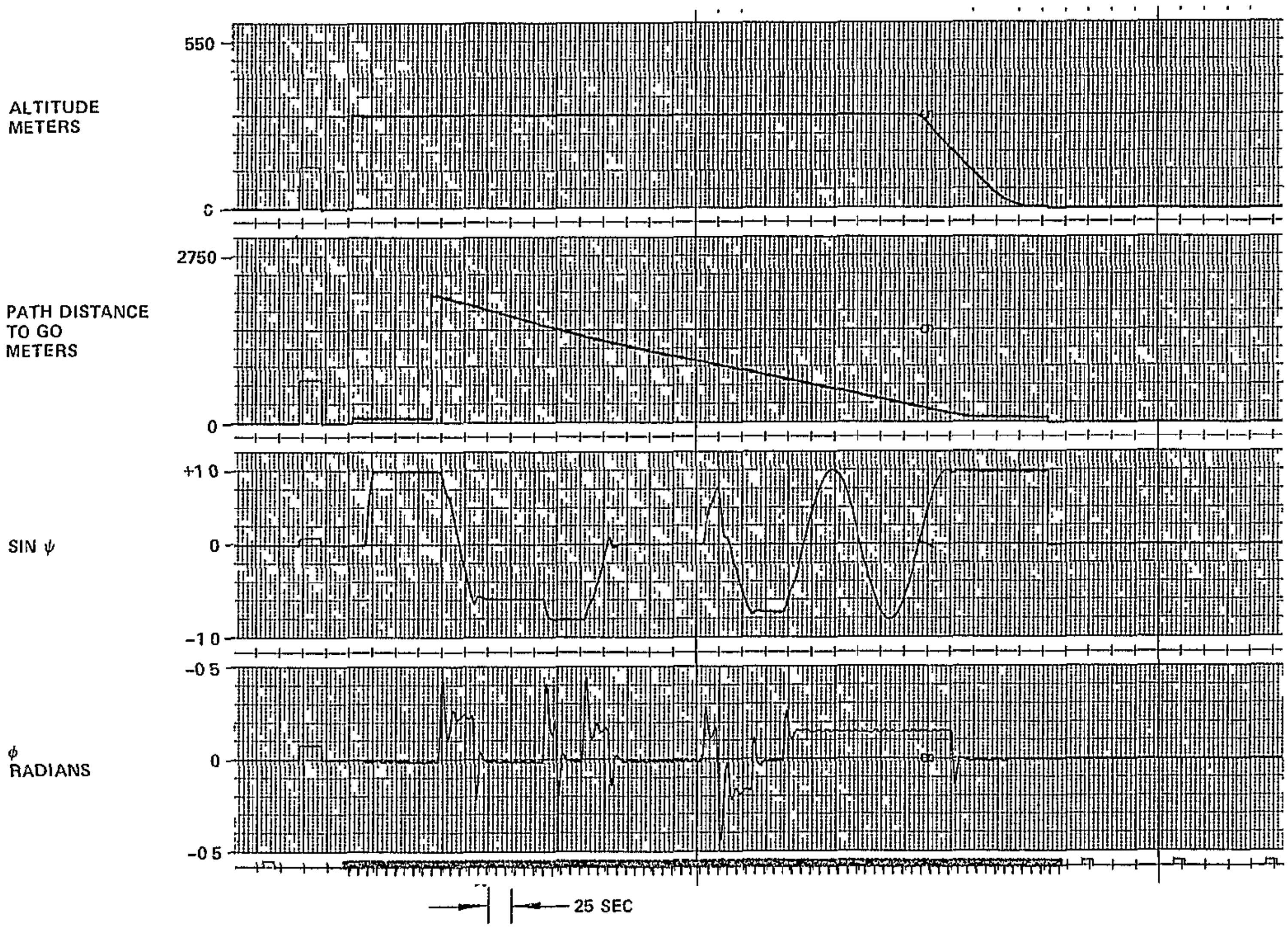

Figure 64
4D Flight Performance Data
Nominal Delay Fan Path Wallops Station
(Sheet 2 of 2)

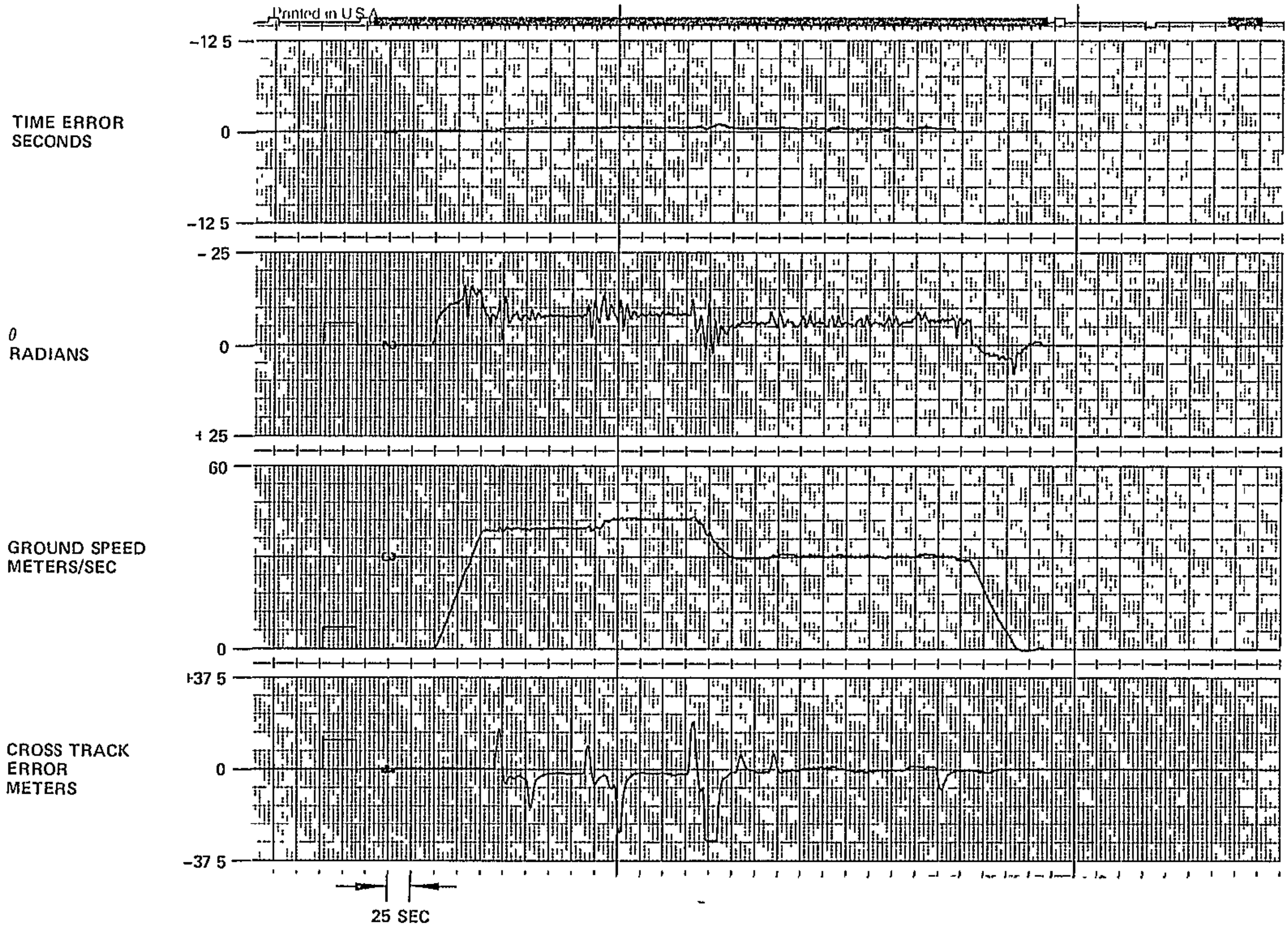

Figure 65
4D Flight Performance Data
Minimum Distance Delay Fan Path Wallops Station
(Sheet 1 of 2)

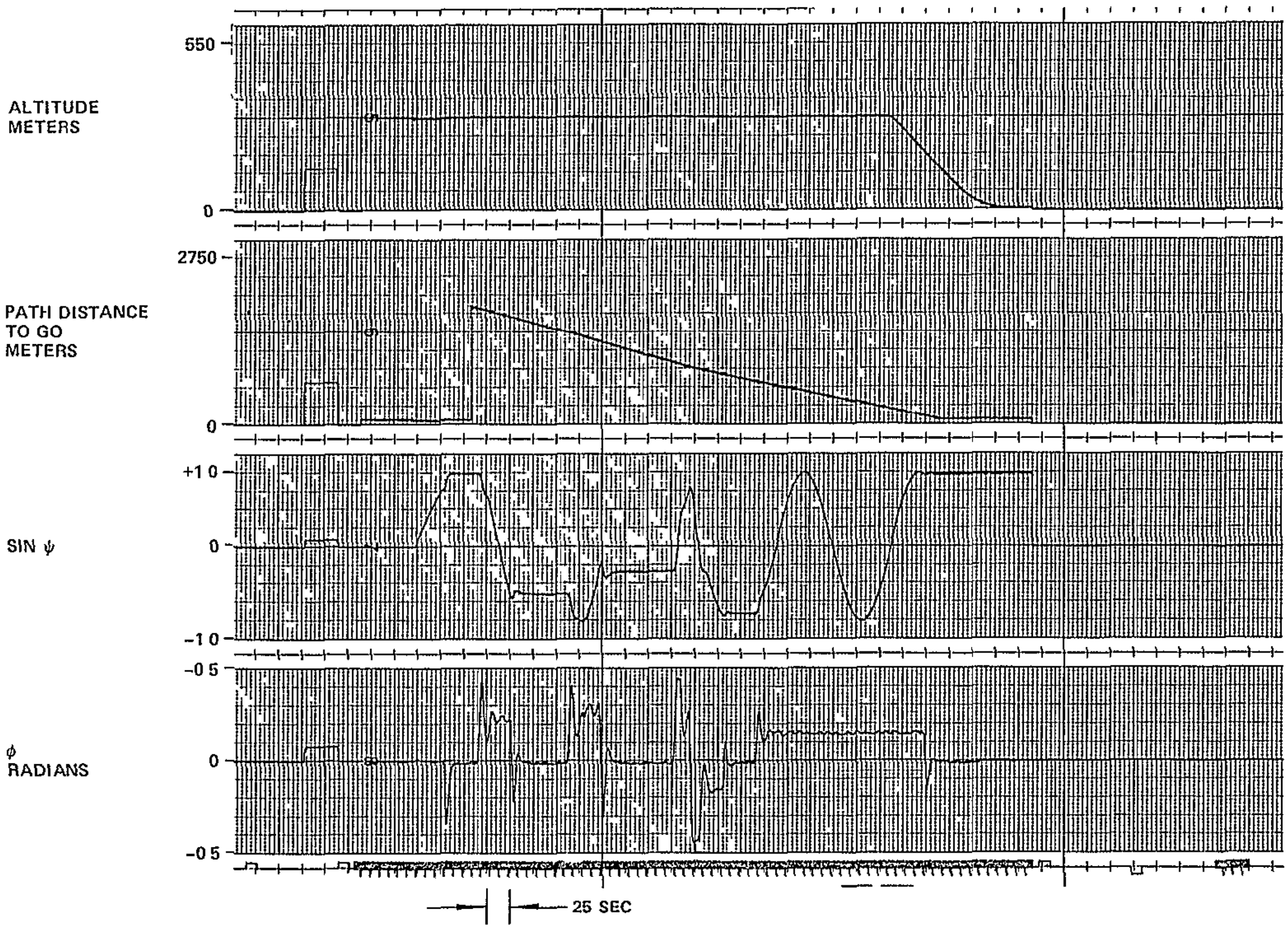

Figure 65
4D Flight Performance Data
Minimum Distance Delay Fan Path Wallops Station
(Sheet 2 of 2)

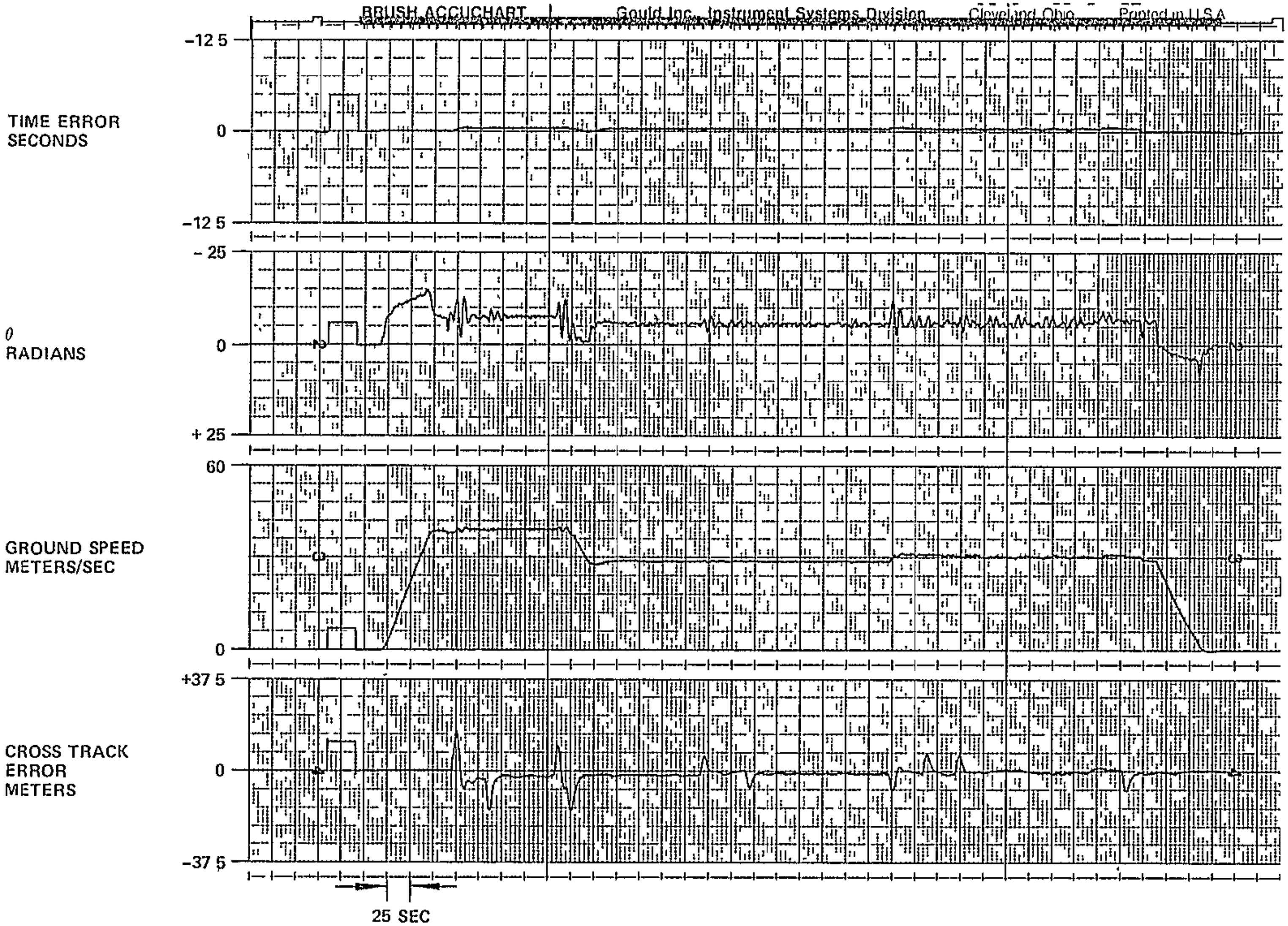

Figure 66
4D Flight Performance Data
Maximum Distance Delay Fan Path Wallops Station
(Sheet 1 of 2)

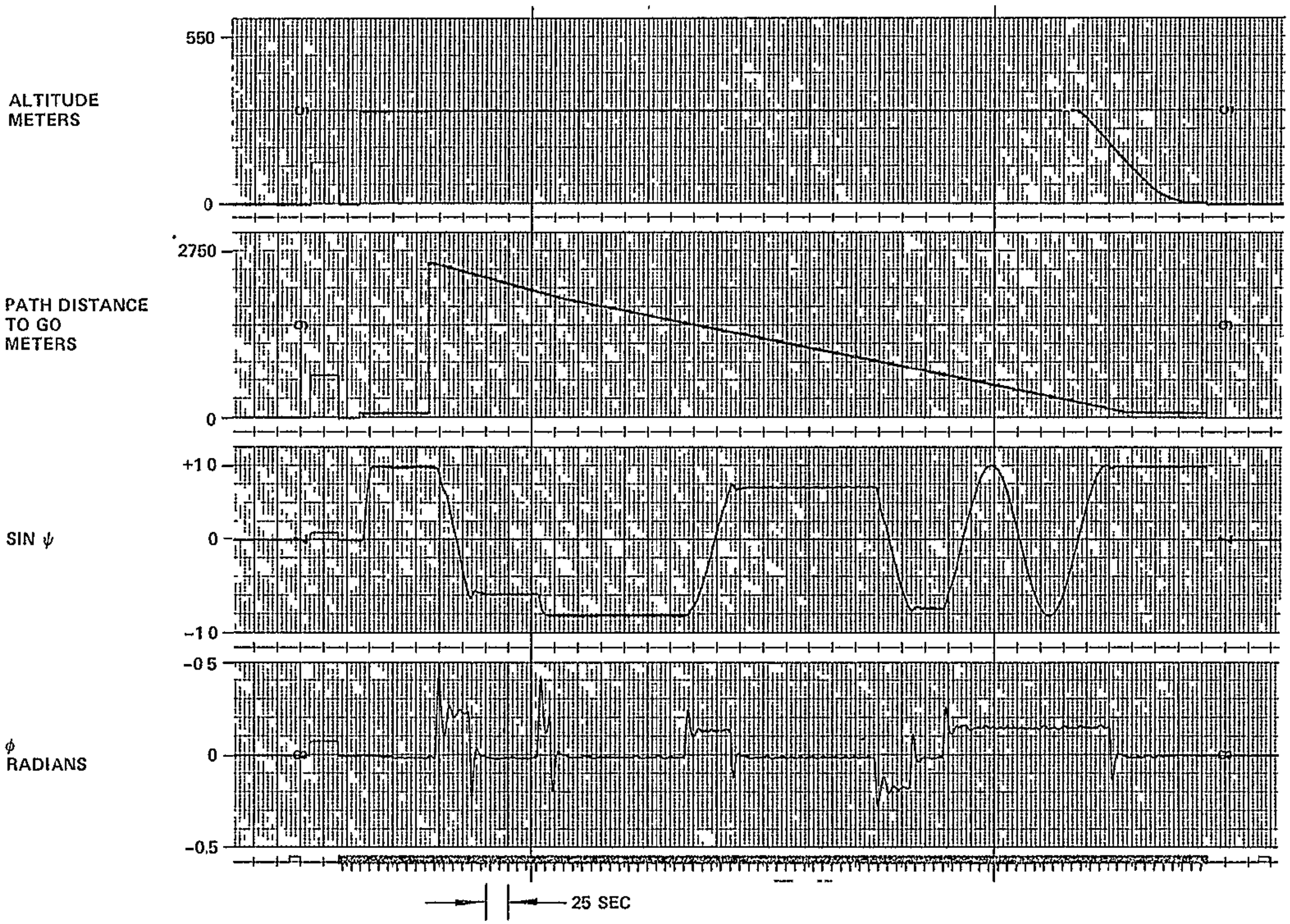

Figure 66
4D Flight Performance Data
Maximum Distance Delay Fan Path Wallops Station
(Sheet 2 of 2)

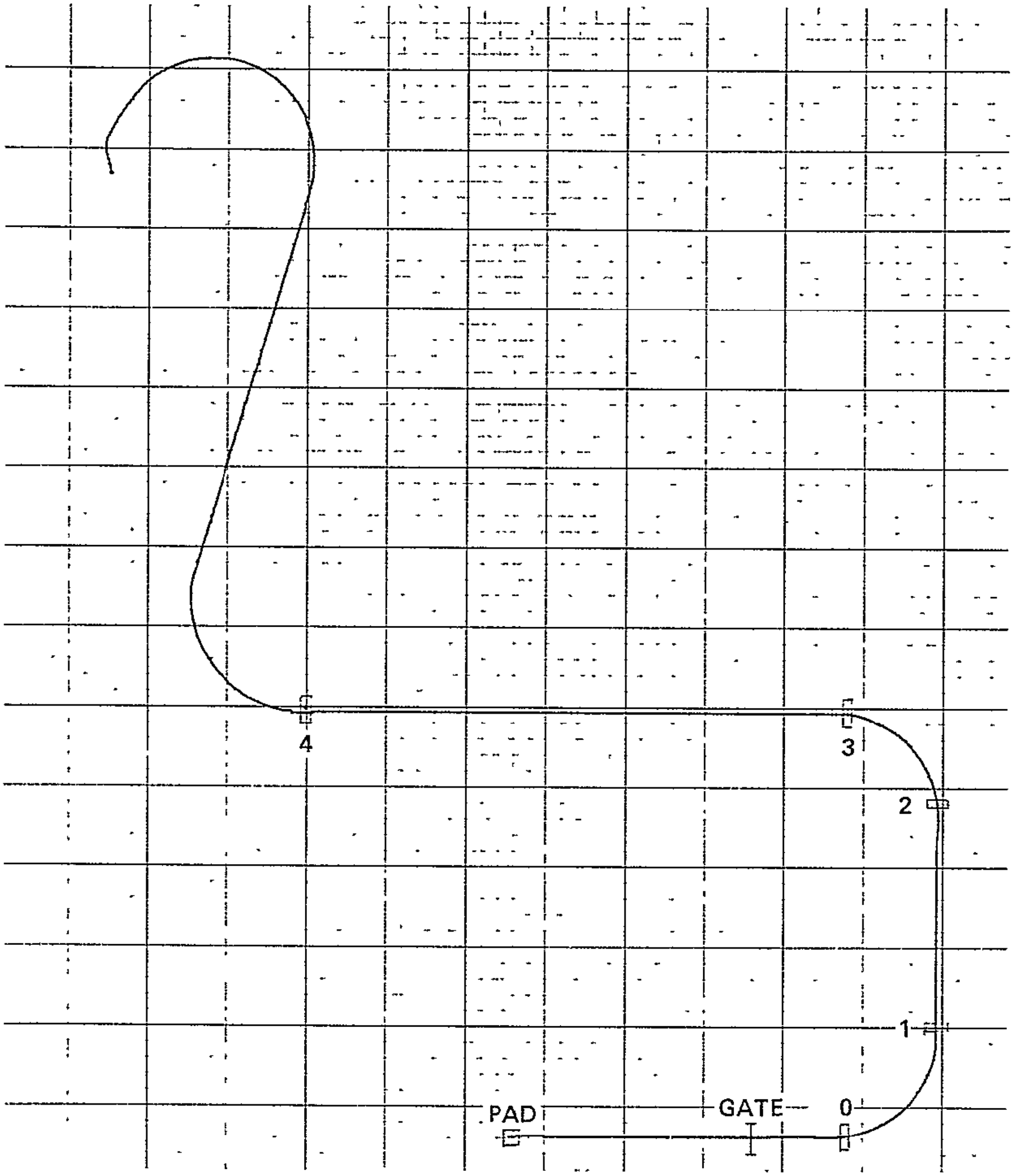

Figure 67
Airspeed Control Nominal Path

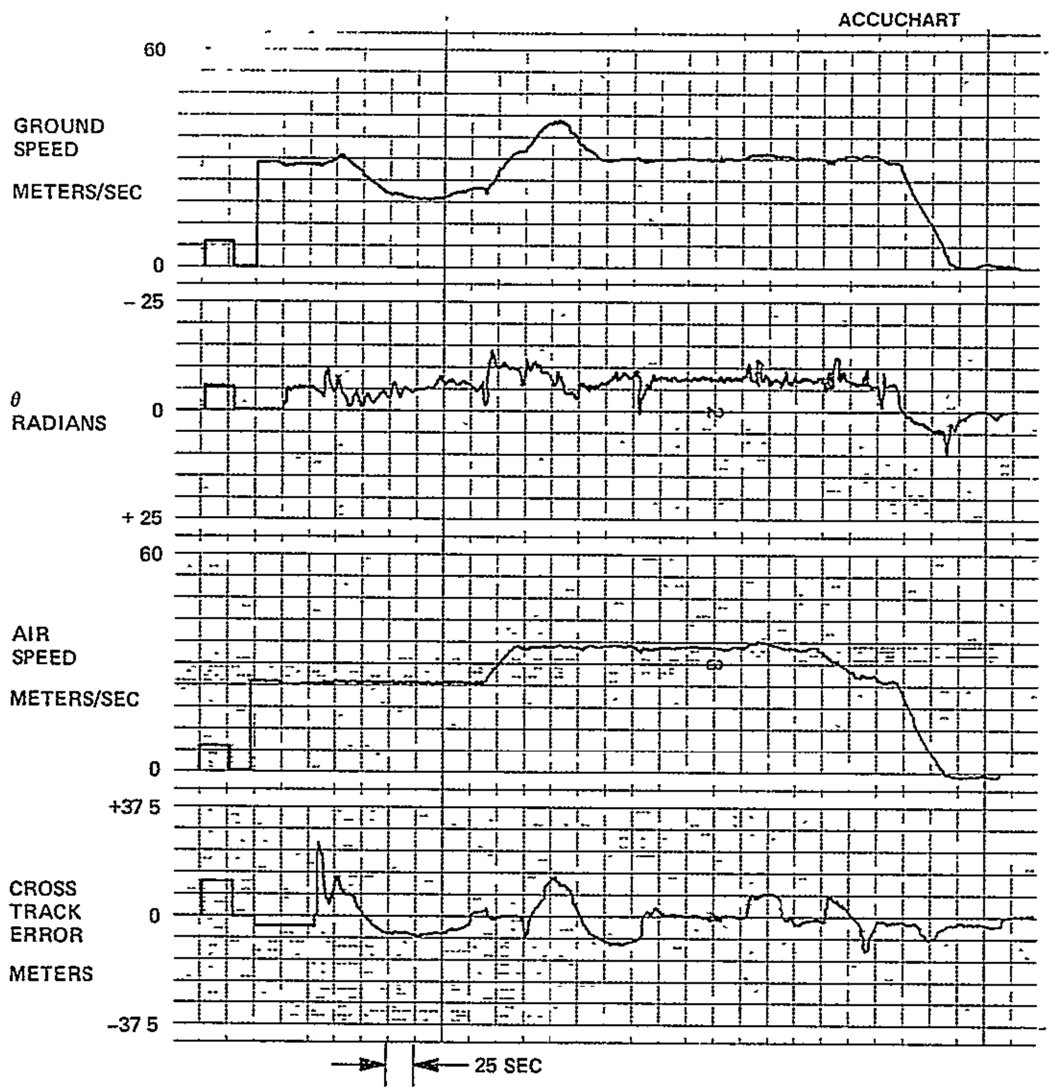

Figure 68
Airspeed Control Run 1

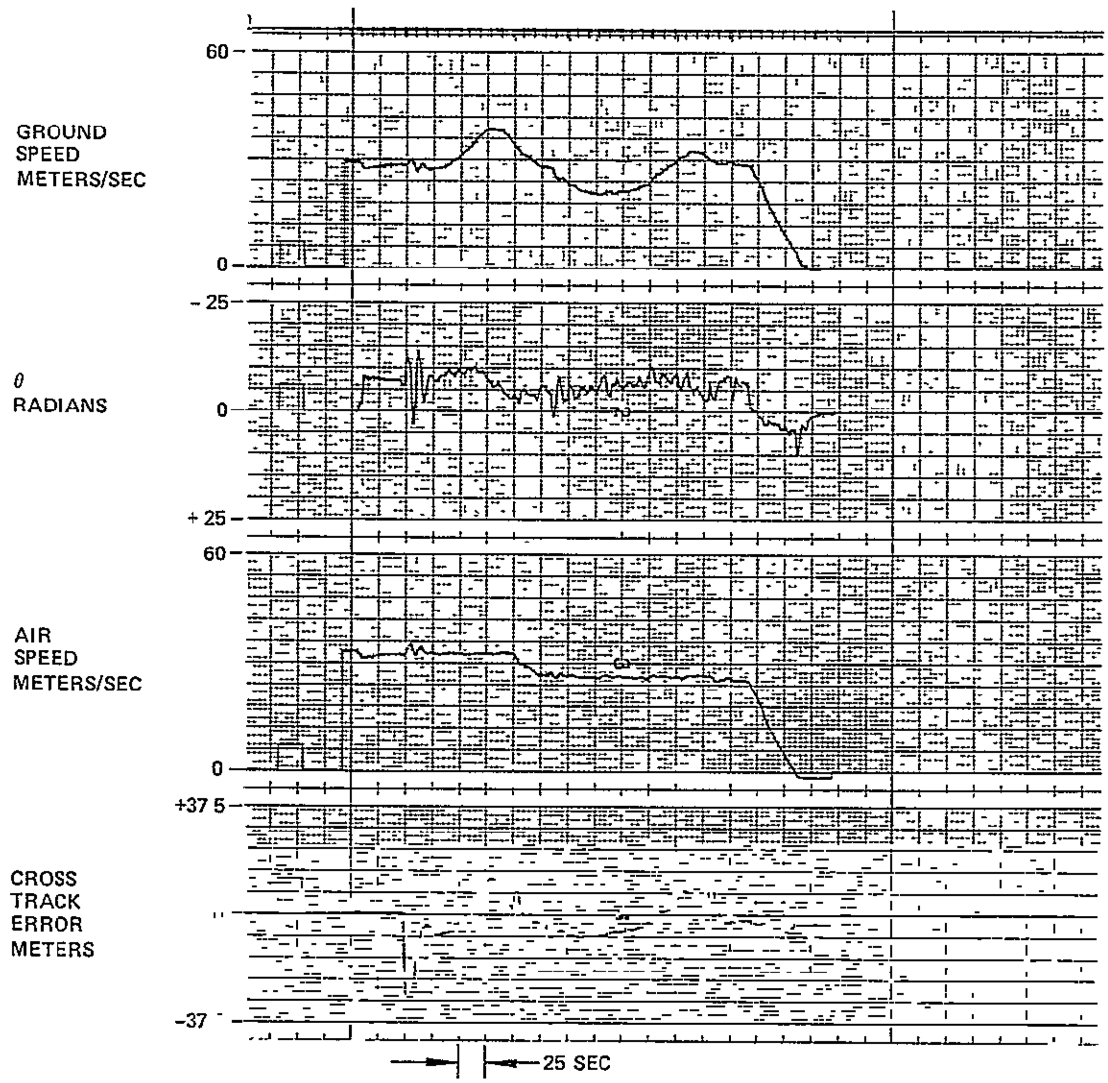

Figure 69
Airspeed Control Run 2

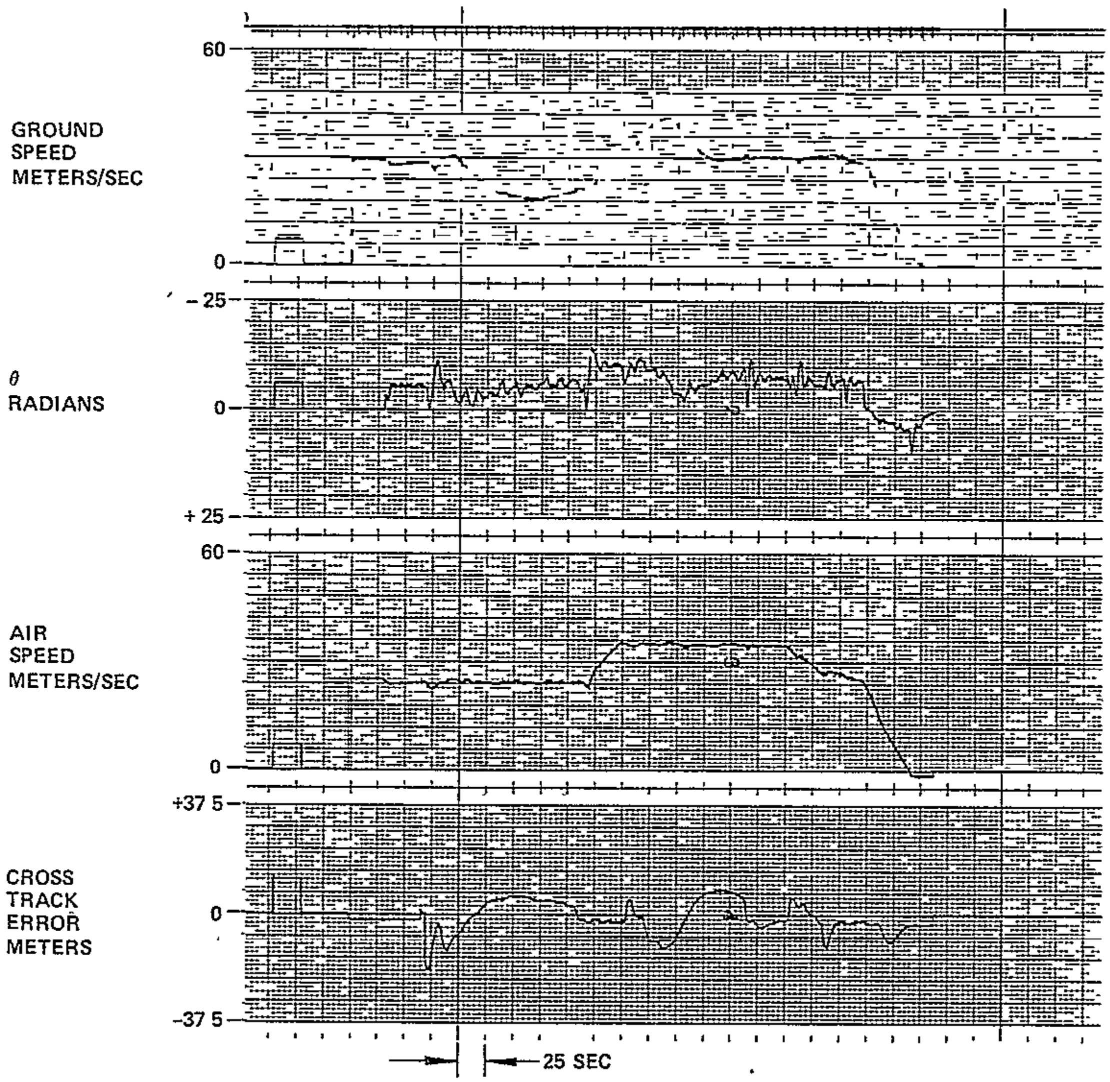

Figure 70
Airspeed Control Run 3

Display Validation

The graphics display software developed in conjunction with 4D control concepts were checked using the SVSVF in a real-time flight simulation configuration. Six display programs were written utilizing various lateral paths and flight conditions to check the following display functions:

- Direct To Capture Paths
- Direct To Delay Fan Paths
- Variable Direct To Radii
- Avoidance Area Limits
- Variable Delay Fan Boundaries
- Joystick and Keyboard Waypoint Selection
- Scale Changes
- North-up and Heading-up Modes
- Moving Map and Fixed Map Displays
- Velocity and Altitude Profiles
- Airspeed Control Display
- Real-time Path Prediction
- Performance Monitors
- Approach Plate Information

Of primary interest in developing displays for this study was the lateral path moving map display. For this display, the two operating modes considered were north-up and heading-up. The heading-up mode, shown in Figure 71 has the aircraft symbol centered on the display and the lateral path map translated and rotated about it as a function of ground position and aircraft heading. The north-up mode, shown in Figure 72 also has the aircraft at the center of the display, however, it is rotated as a function of heading. The lateral path map is maintained in a fixed north-up configuration and translated as a function of aircraft position. Both techniques ensure that the aircraft symbol is always displayed on the CRT screen.

Fixed map displays were developed as part of a performance monitoring scheme so that the pilot could evaluate progress in a given area. The fixed map display has the map oriented north-up with the aircraft symbol translated as a function of position and rotated as a function of heading. The most significant problem noted in this type of display was that the aircraft symbol could be translated off the map and display wrap around could occur. The update rate of the display, however, was much higher than that of the moving map display since the host processor was redrawing fewer vectors for the display. For the moving map displays, the update rate ranged from .2 to .5 Hertz, where the update rate

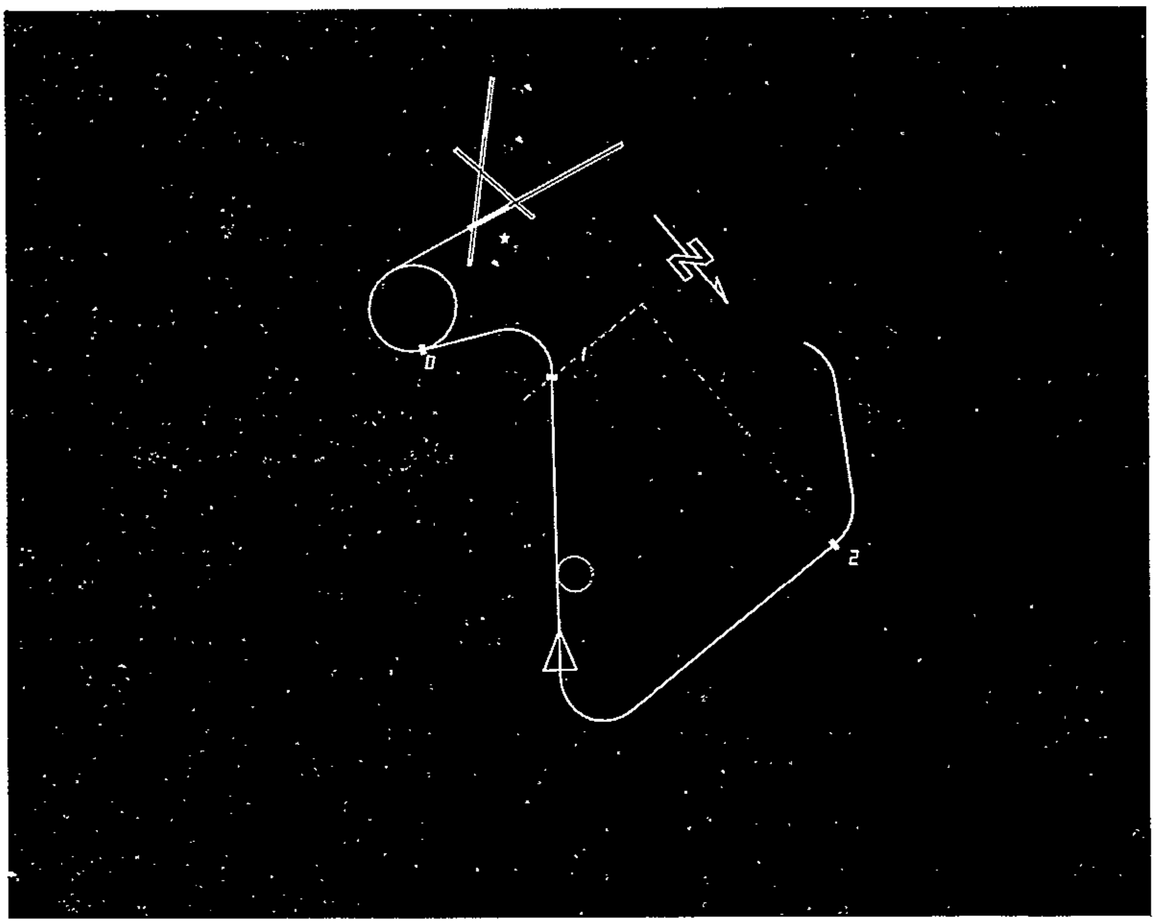

Figure 71
Heading-up Mode - Wallops Runway

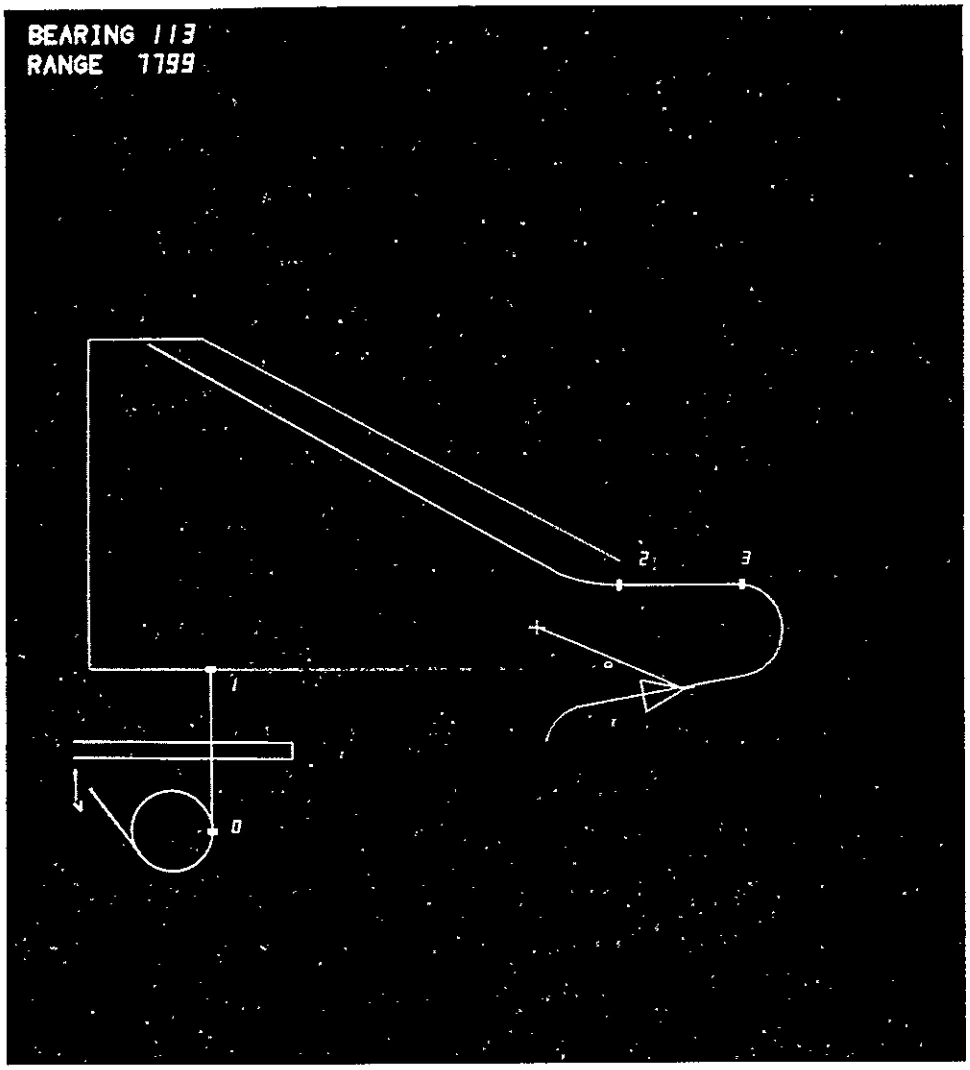

Figure 72
North-up Mode

for the fixed map was approximately 5 Hertz. The slow update rate for the moving map displays is not representative of real aircraft display systems since the rate was due to the slow speed of the graphics host computer.

Real-time lateral path alteration was one of the foremost subjects of this study. Displays were developed to demonstrate the control system's ability to generate Direct To paths with unequal radii for both the path capture and delay fan maneuvers.

Figure 73 shows how the predicted Direct To capture path to a selected waypoint on the lateral path was displayed. As the capture maneuver was being predicted, the displayed capture maneuver was constantly being changed. When an approach was selected, the capture maneuver became a fixed part of the lateral path display and the aircraft would "fly" along the capture maneuver. Figure 74 shows the aircraft on a selected approach with the Direct To capture maneuver as part of the map.

To demonstrate the variable radii capability of the Direct To path generation routine, a number of paths were predicted to a simple straight-in approach path where the path entrance velocity was varied such that the radius of the second turn of the Direct To varied proportionately. The path entrance velocity was varied from 18 m/s to 58 m/s and the changes in the radius of the final turn are shown in Figures 75 through 77. It was found that with the addition of unequal radii capability there were some restrictions on where a capture maneuver could be initiated. When such restrictions occurred, the Direct To path was unflyable and this condition was transmitted to the pilot by deleting the predicted Direct To path from the display. Such a display is shown in Figure 78.

The Direct To path generation capability was also used for path alteration in the delay fan area. Two different types of delay fan generation programs were developed; one being an iterative prediction process and the other being a one pass generation process. Using the iterative process, a fixed out-bound heading in the delay fan area was flown and a Direct To path to the next waypoint continuously calculated as shown in Figure 79. When the time, distance, and velocity profile relationships were satisfied, the system automatically switched to the Direct To capture maneuver for the next waypoint. At that time the Direct To portion of the delay fan became a fixed part of the lateral path display and the extension of the outbound line beyond the Direct To maneuver was deleted from the display. This condition is shown in Figure 80. The one pass delay fan path routine was designed to generate the delay fan path at the same time the velocity profile is generated. Only when the delay fan boundary times or velocity limits were changed did a change in velocity profile occur. The change in the velocity profile could then produce a change in the lateral path as shown in Figures 81 and 82. This display gives the pilot an immediate representation of the path he would be required to fly.

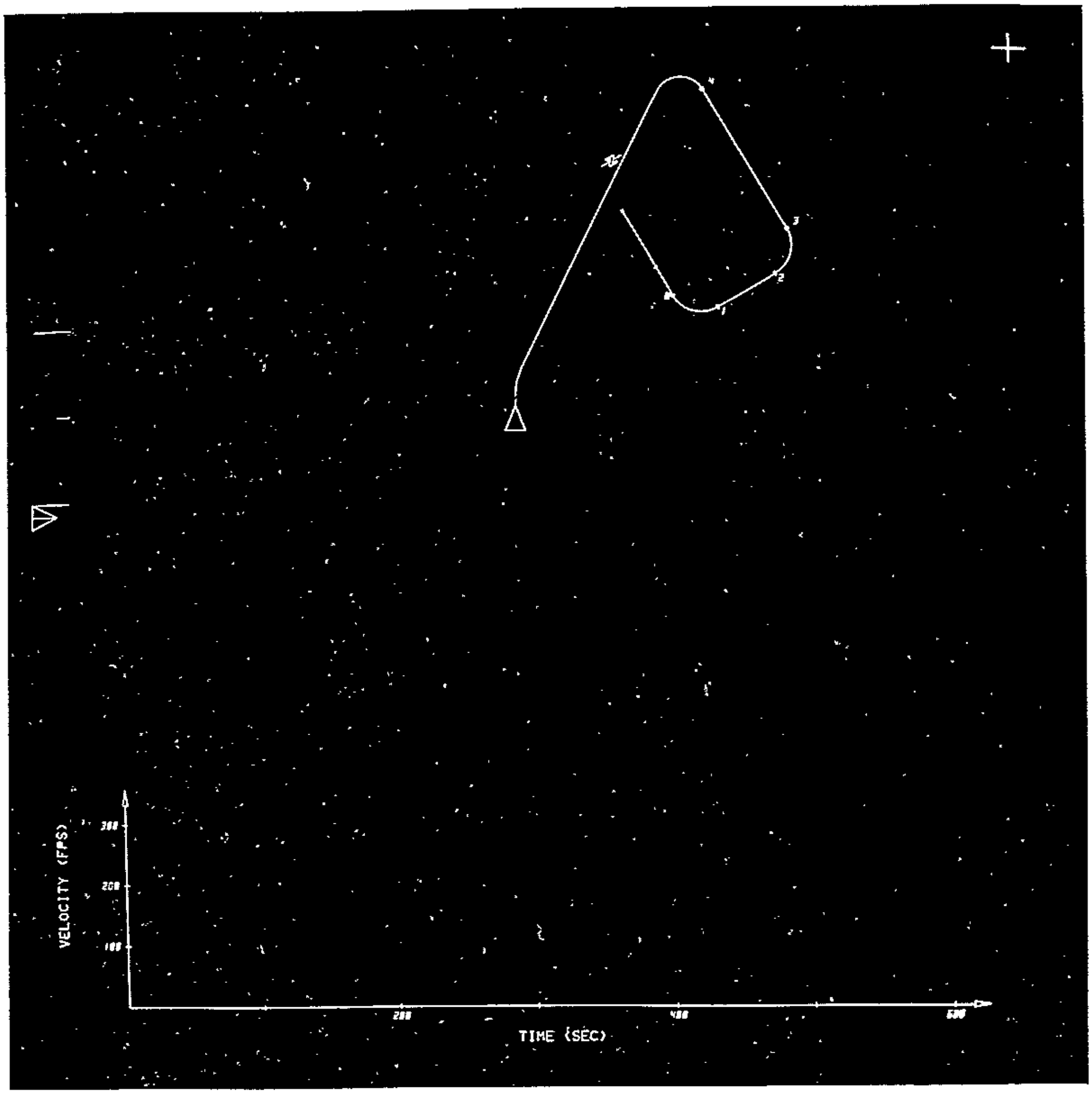

Figure 73
Predicted Direct To Capture Path Waypoint 4

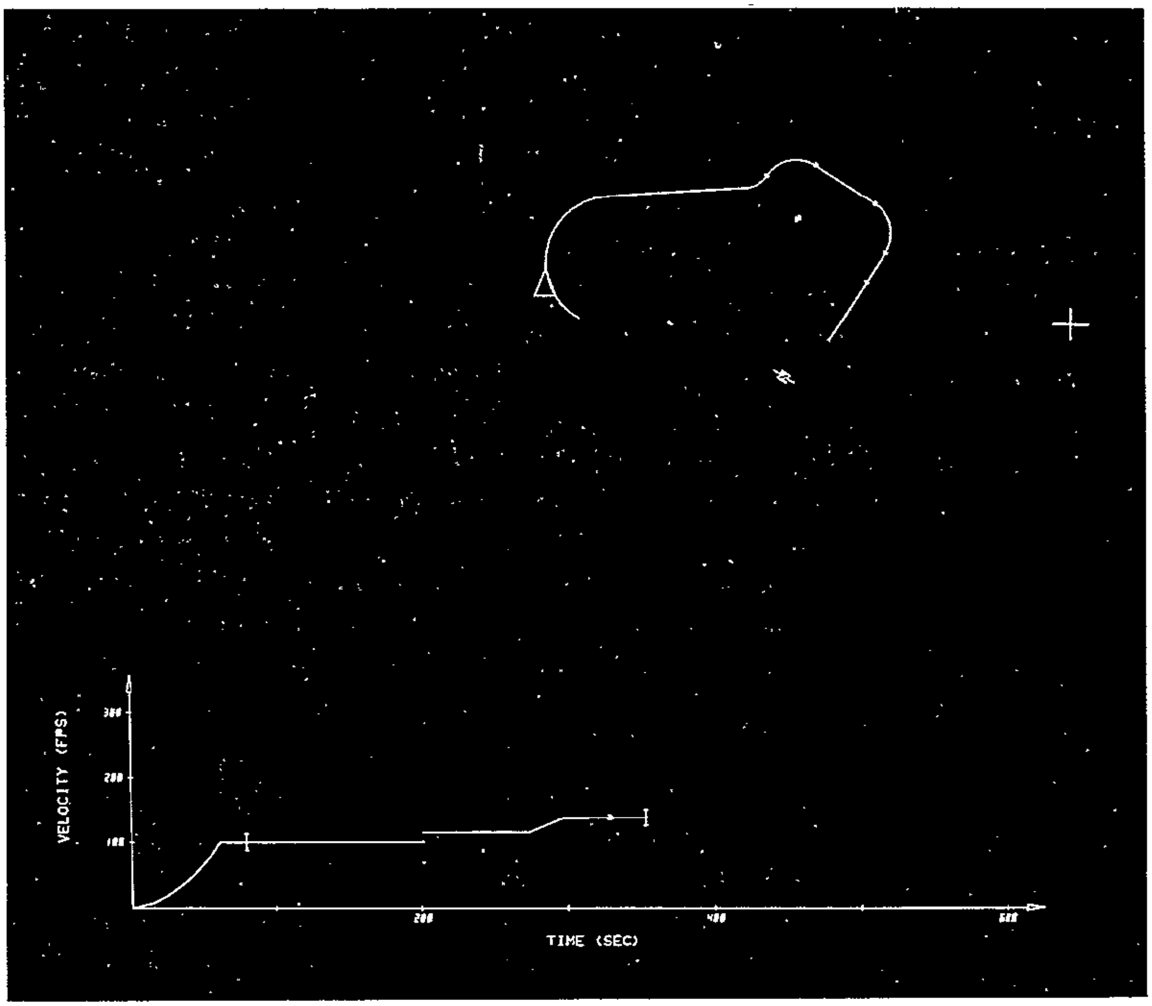

Figure 74
Selected Direct To Capture Path Waypoint 3

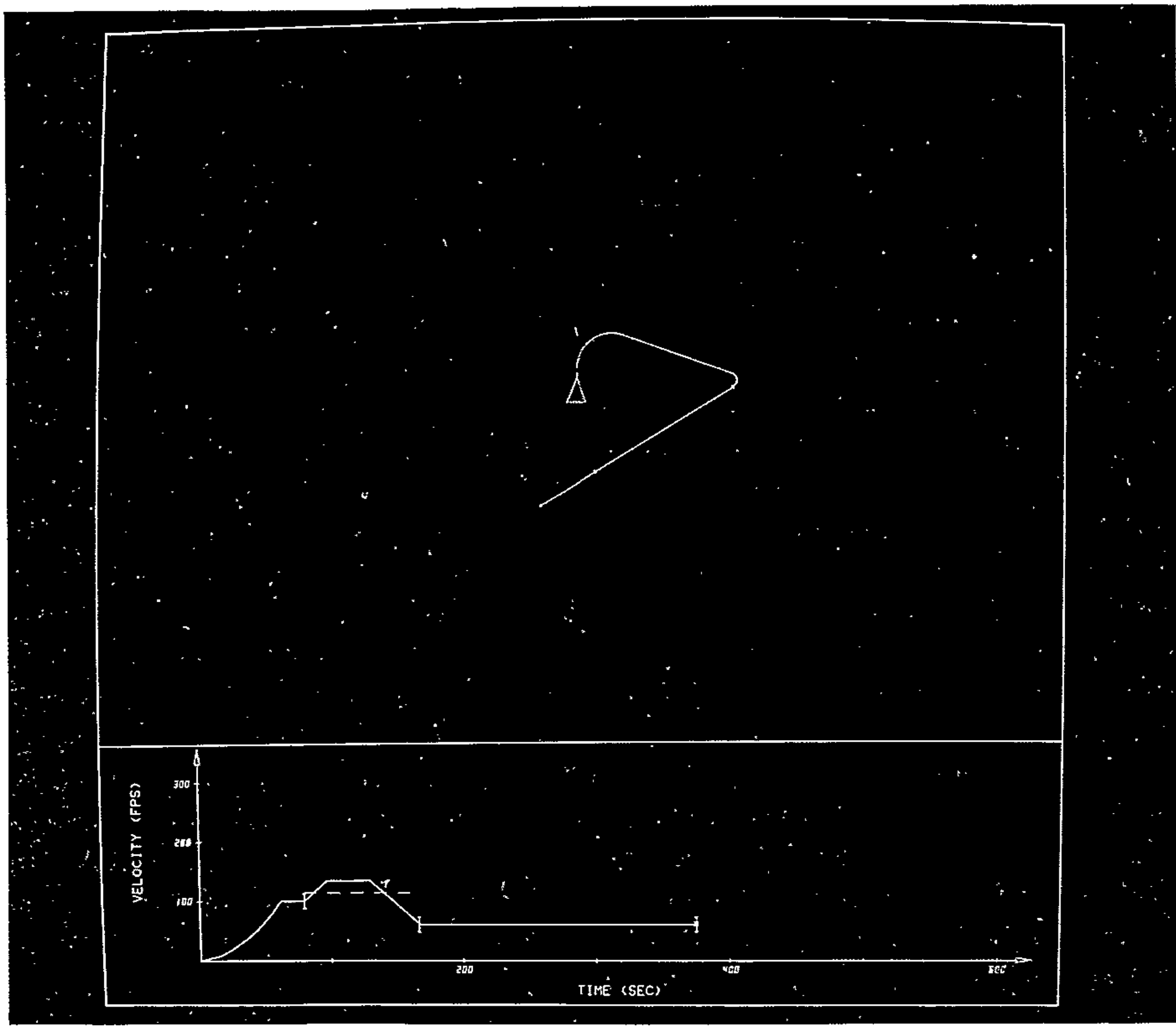

Figure 75
Approach To Single Waypoint Section Capture Velocity: 18 m/s

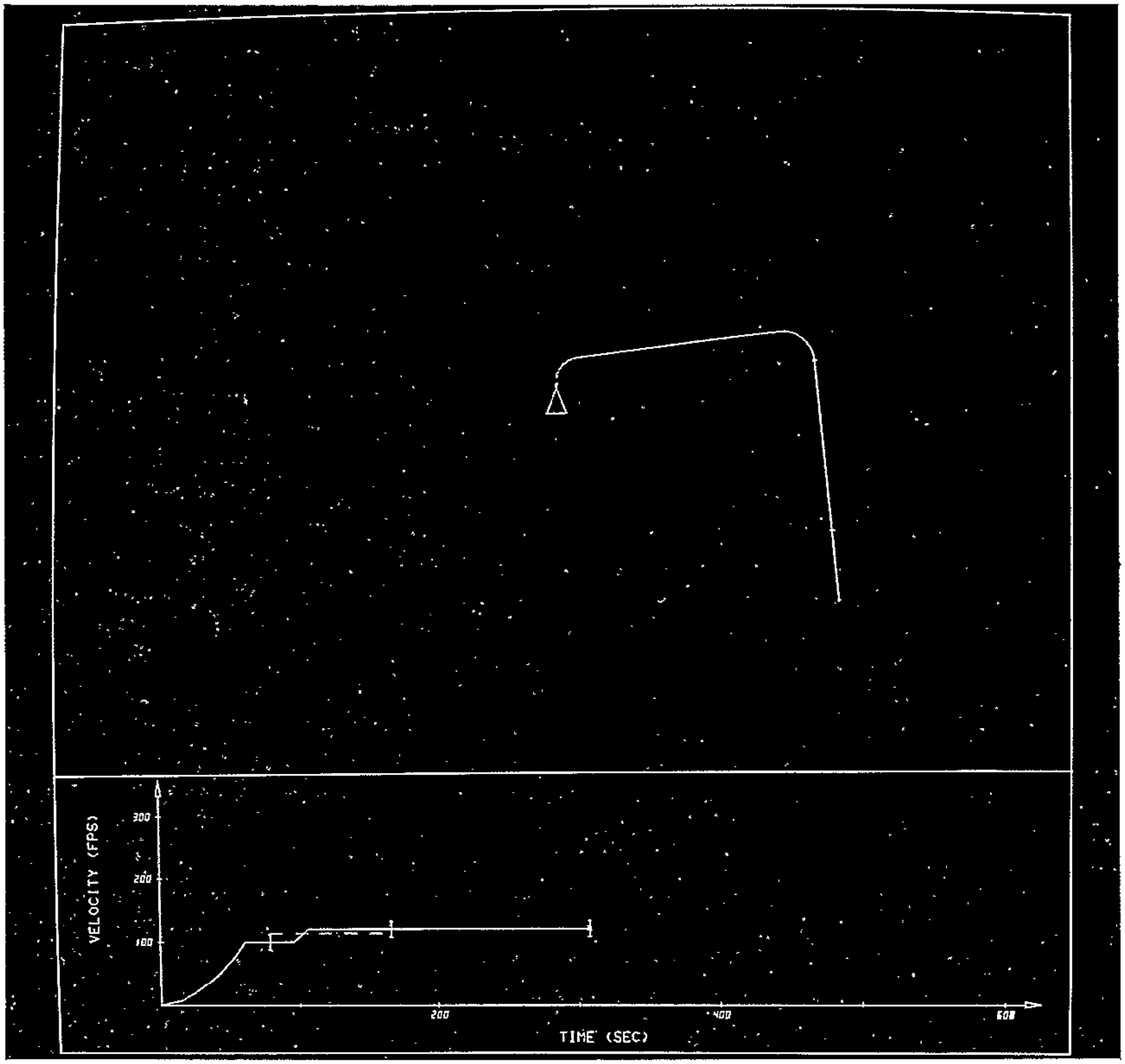

Figure 76
Approach To Single Waypoint Section Capture Velocity: 36 m/s

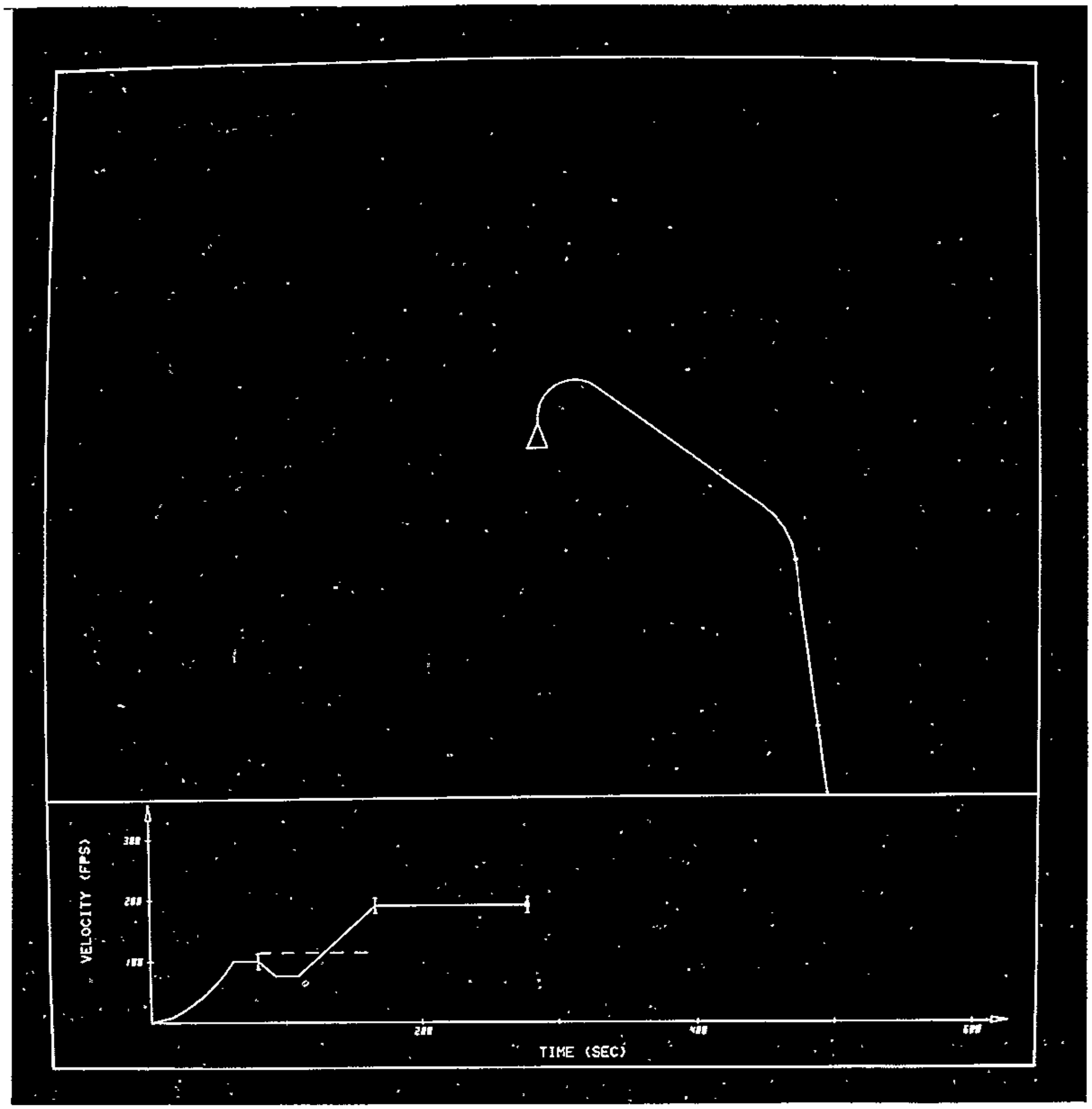

Figure 77
Approach to Single Waypoint Section Capture Velocity: 58 m/s

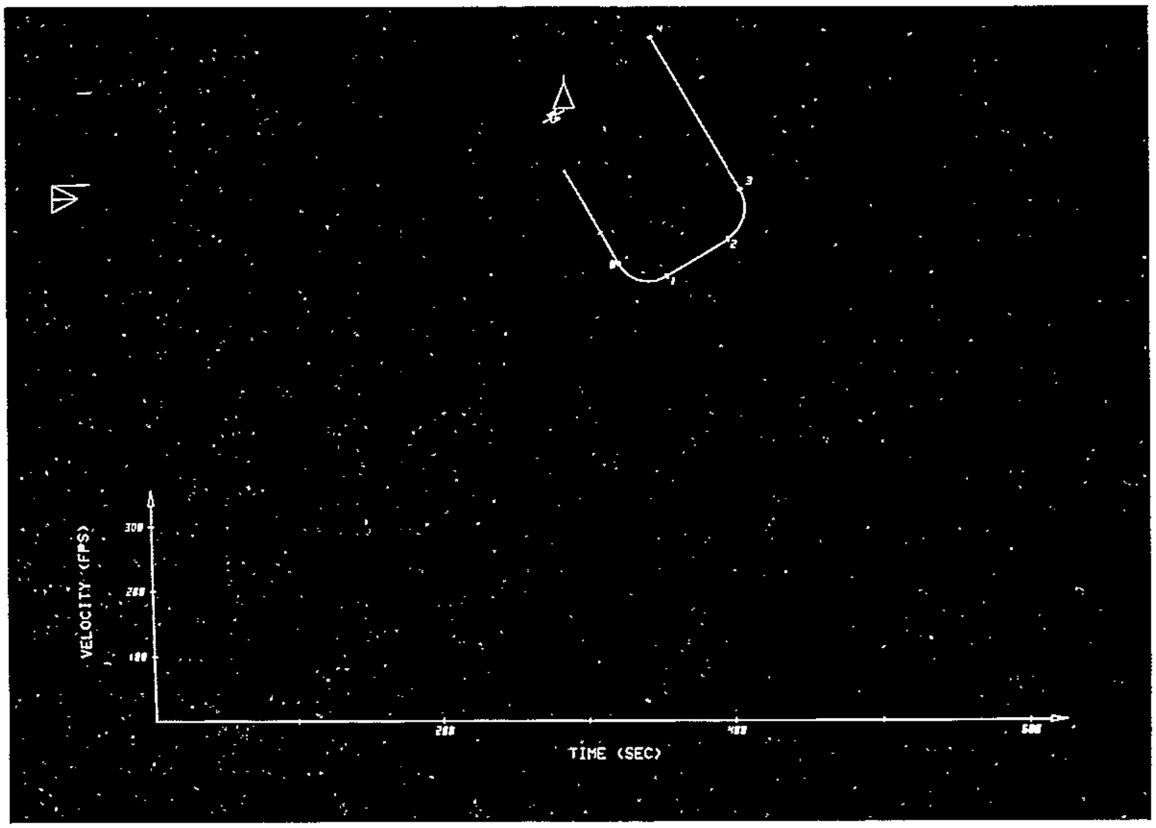

Figure 78
Invalid Direct To

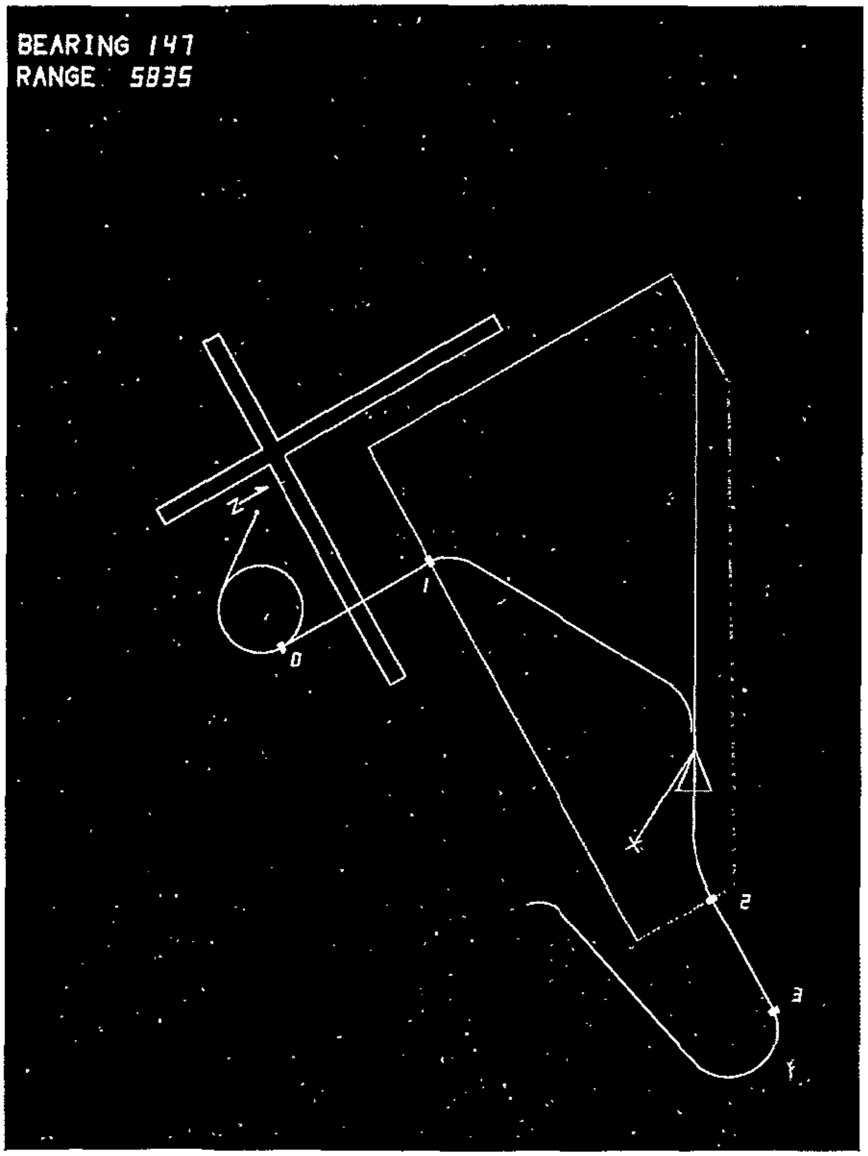

Figure 79
Delay Fan Generation - Iterative Process Predicted Path

Figure 80
Delay Fan Generation - Iterative Process Accepted Path

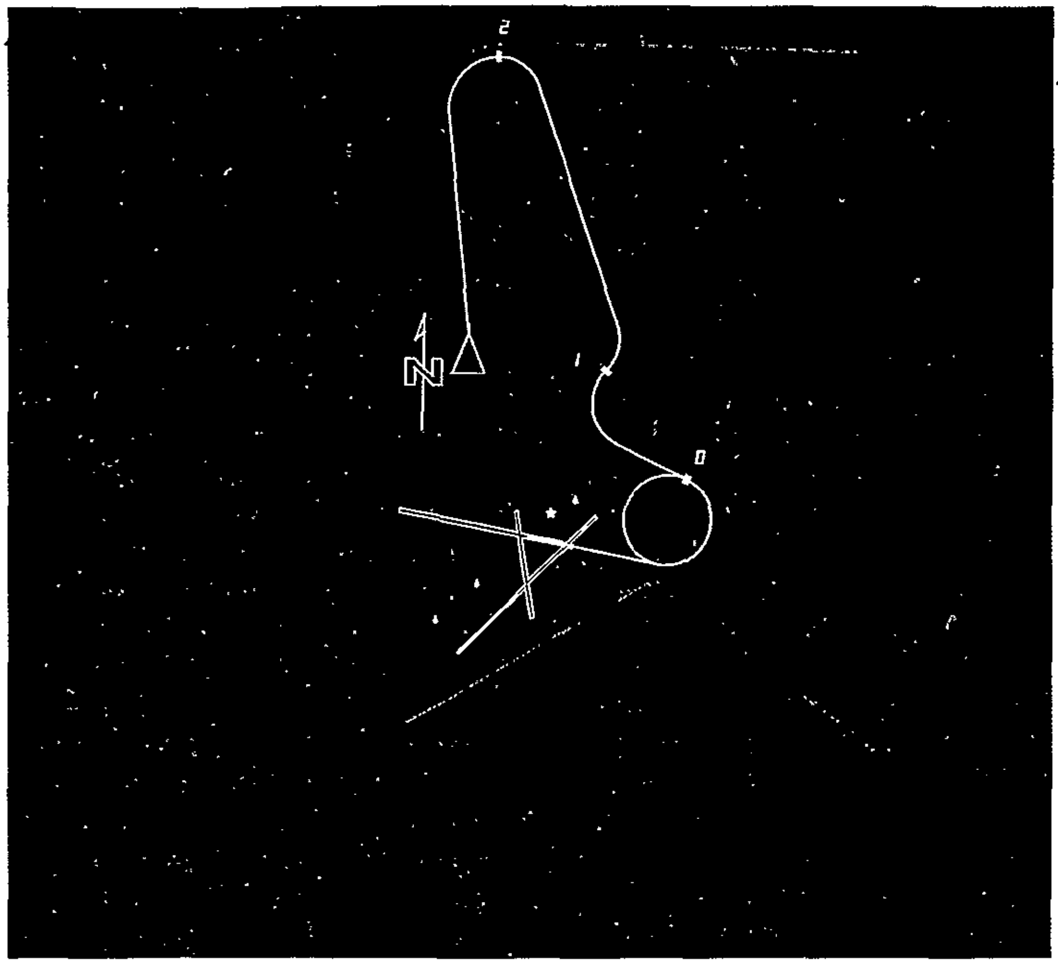

Figure 81
Delay Fan Generation - One Pass Process Minimum Length Path

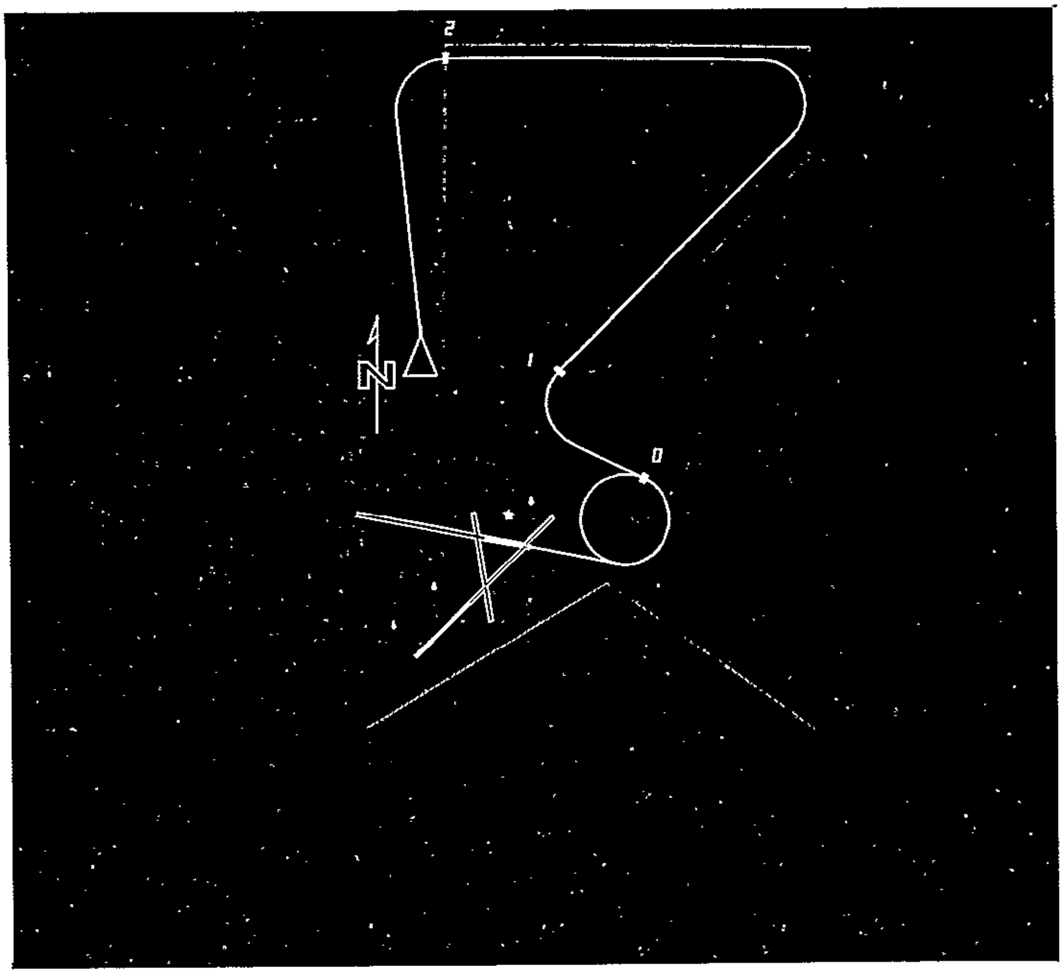

Figure 82
Delay Fan Generation - One Pass Process Maximum Length Path

The ability to see the specified lateral path prior to flying an approach is important when considering avoidance areas around which the path must be constructed. Avoidance areas are defined points around which the flight path must maintain minimum separation distance. Placement of an avoidance area in the delay fan area is shown in Figure 83. A typical delay fan path construction without consideration of the avoidance area is shown in Figure 84. By continuing to move the delay fan maneuver in the same direction as it was being moved from the nominal path, it was found that the avoidance distance could be maintained and the velocity profile could be held within the specified velocity limits. Reconstruction of the lateral path around the avoidance area is shown in Figure 85. The delay fan boundaries also play a part in determining the available delay fan maneuvers. Delay fan boundaries were varied to limit the path alteration capability of the delay fan maneuver. Changes in the delay fan boundary are shown in Figures 86 and 87. Whenever the delay fan boundaries were violated in the generation of a delay fan maneuver, a message was displayed indicating the limits being exceeded.

Selection of time control waypoints for entry points onto the prescribed lateral path was handled in two ways, graphics joystick and keyboard entry. In the joystick selection method the graphics cursor, represented by a small cross shown in Figure 73, was positioned over the desired waypoint using the joystick and the joystick button depressed. The appropriate waypoint number was then sent to the 1819A computer and the lateral path upstream of that waypoint deleted from the display screen. Using the keyboard entry technique, the desired waypoint number was entered into the Nav/Guidance control panel and the path upstream of the waypoint was again deleted from the display. If the delay fan maneuver area was upstream of the selected waypoint, the delay fan boundaries were also deleted from the displays. Once the appropriate portion of the fixed path was displayed, the Direct To path capture maneuver was generated and drawn from the selected waypoint to the aircraft symbol. The effects of selecting various waypoints are shown in Figures 73 and 74.

As progress is made along a selected approach path, less of the total path becomes important to the pilot for successful completion of the approach. When nearing the landing pad, scale changes were made in the display to present a greater displacement for lateral and longitudinal excursions. For the displays which incorporate the Wallops runway system, the scale changes were made in five discrete steps, starting at a distance of 1830 meters from the landing pad. When the distance from the pad is less than 30 meters, the display switches to the hover mode shown in Figure 88. This mode displays only the area immediately surrounding the landing pad and provides altitude information through both scale changes and a changing digital readout. Figures 89 and 90 show the changes in the display for different altitudes and headings.

A secondary function of the displays in this study was to allow the pilot to examine and change the velocity profiles required to fly the approach paths. For the airspeed control study, two types of information were added to the moving map. The first was an indicator showing the relationship between actual flight time and minimum and maximum required flight time, the indicator is shown in Figure 73. When the triangular pointer was above the upper or below the lower time requirement limit, the path was unacceptable from the standpoint of time and velocity. When the pointer was between the two limits, the time and velocity requirements were satisfied and the pilot could select the approach mode. This condition is shown in Figure 91.

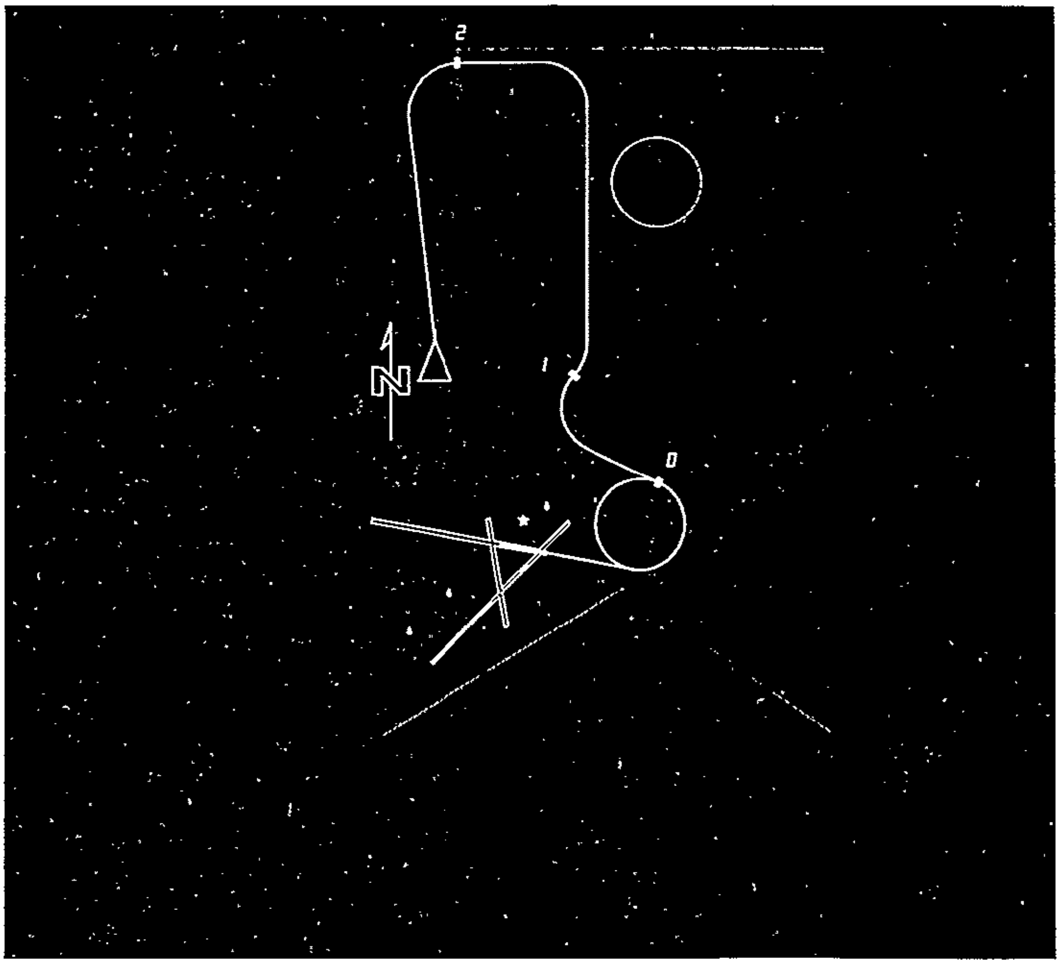

Figure 83
Avoidance Area Placement

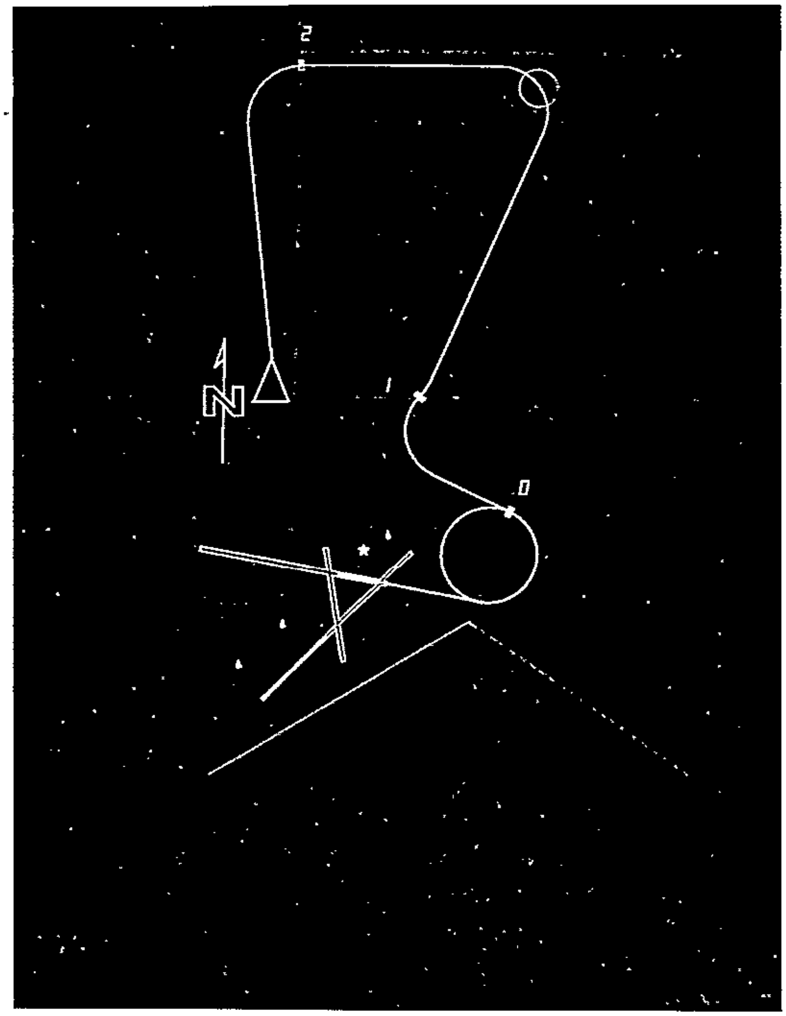

Figure 84
Violation of Avoidance Area

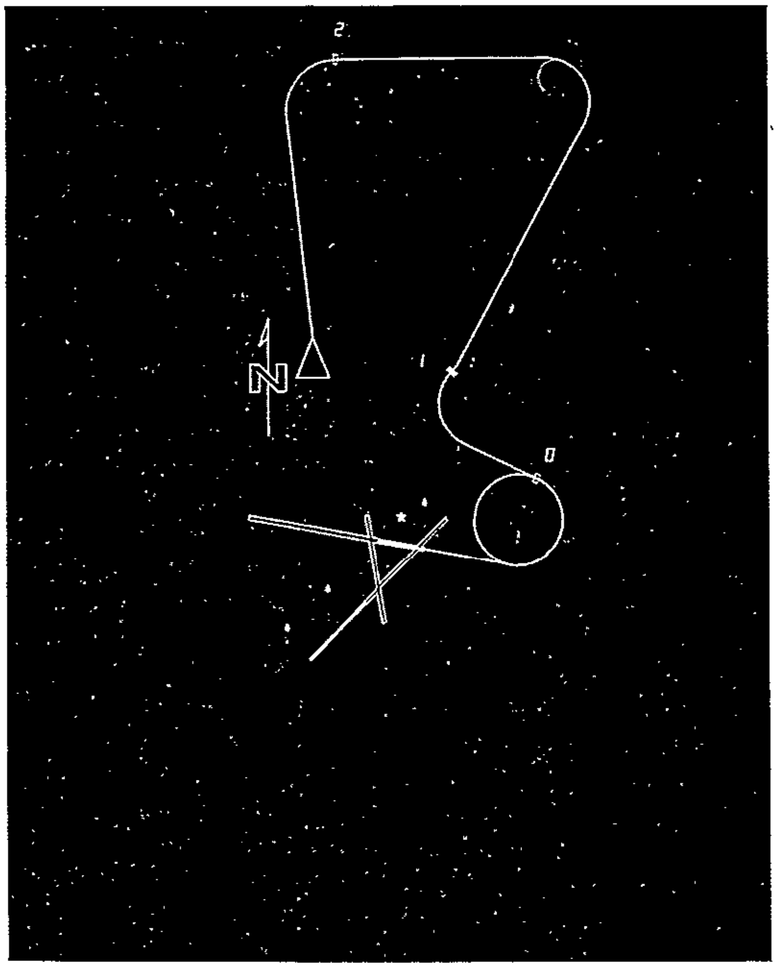

Figure 85
Alteration of Path to Maintain Avoidance Distance

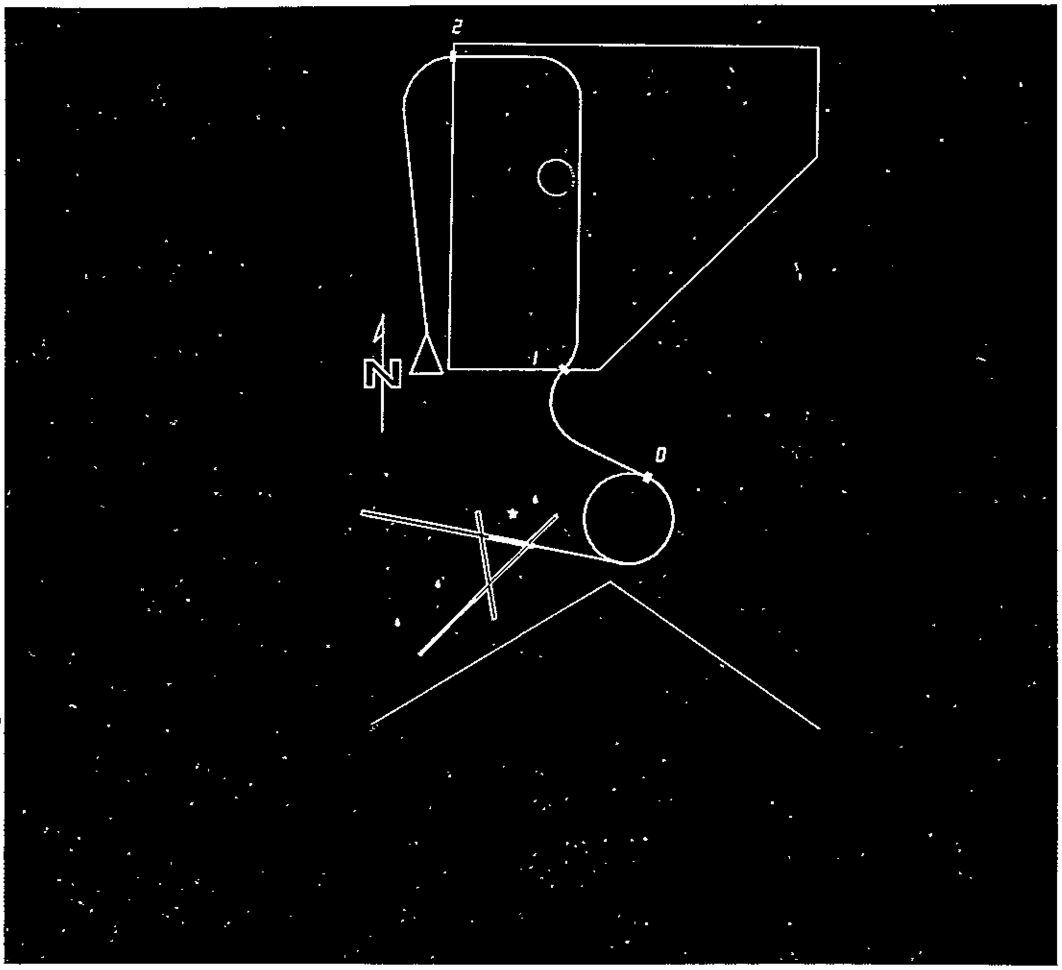

Figure 86
Variable Delay Fan Boundaries

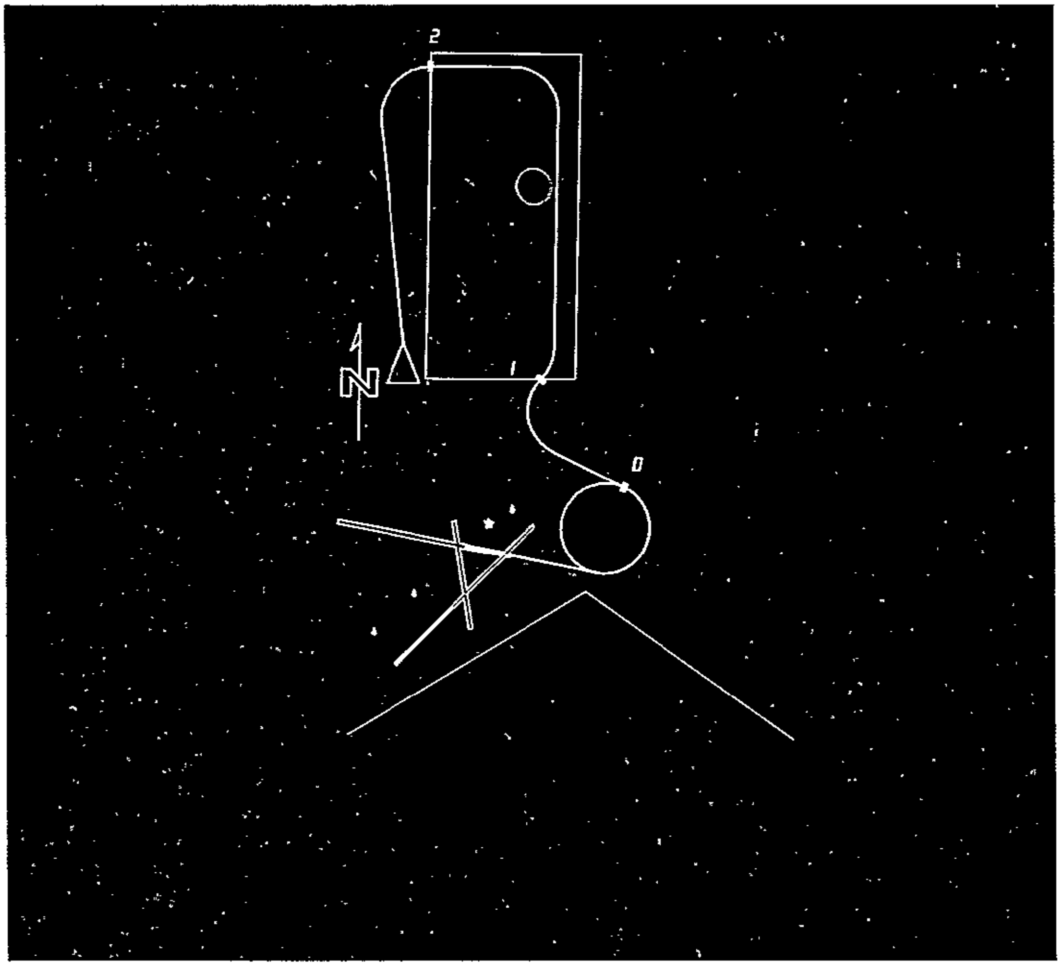

Figure 87
Variable Delay Fan Boundaries

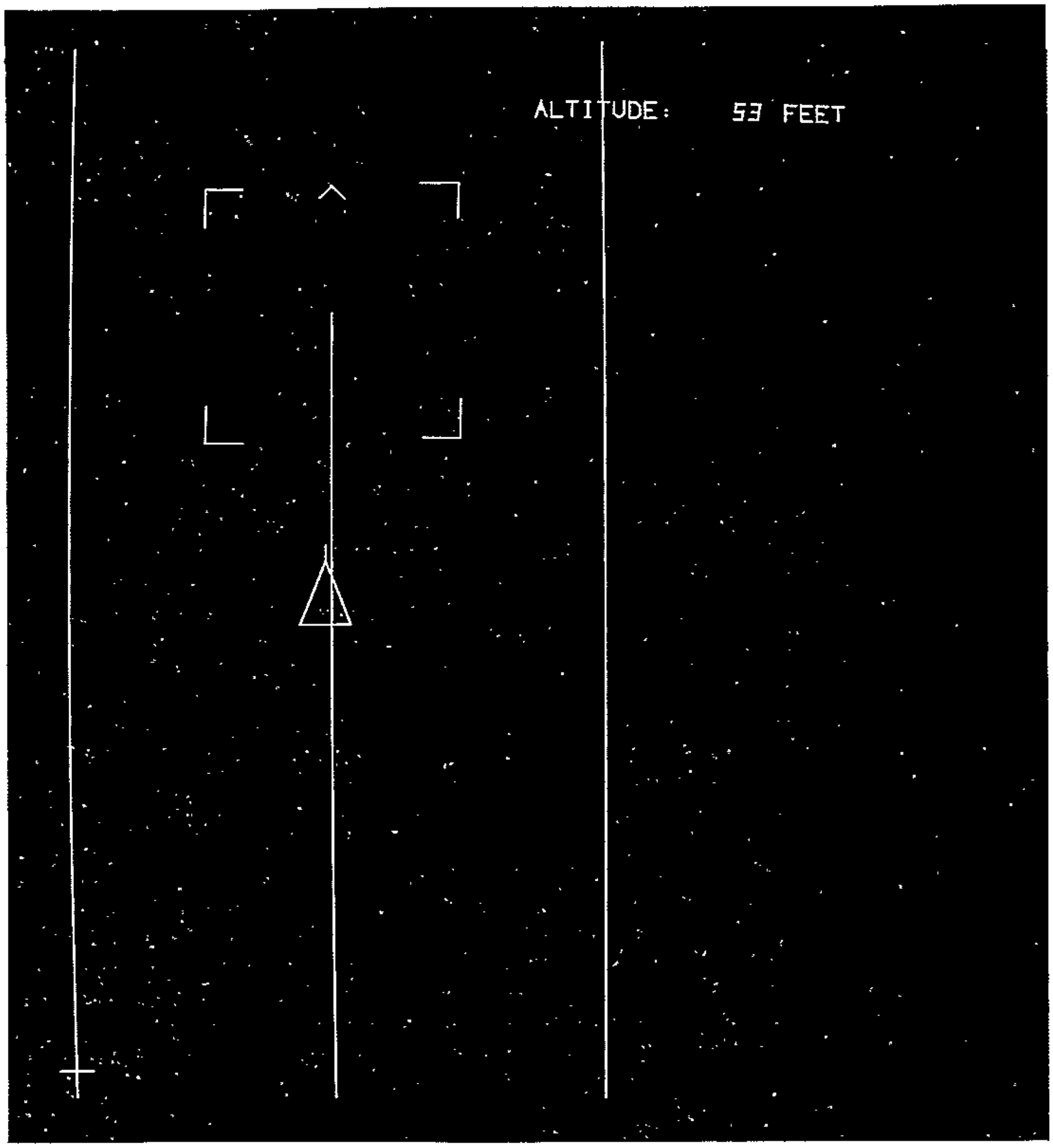

Figure 38
Hover Mode
(Sheet 1 of 3)

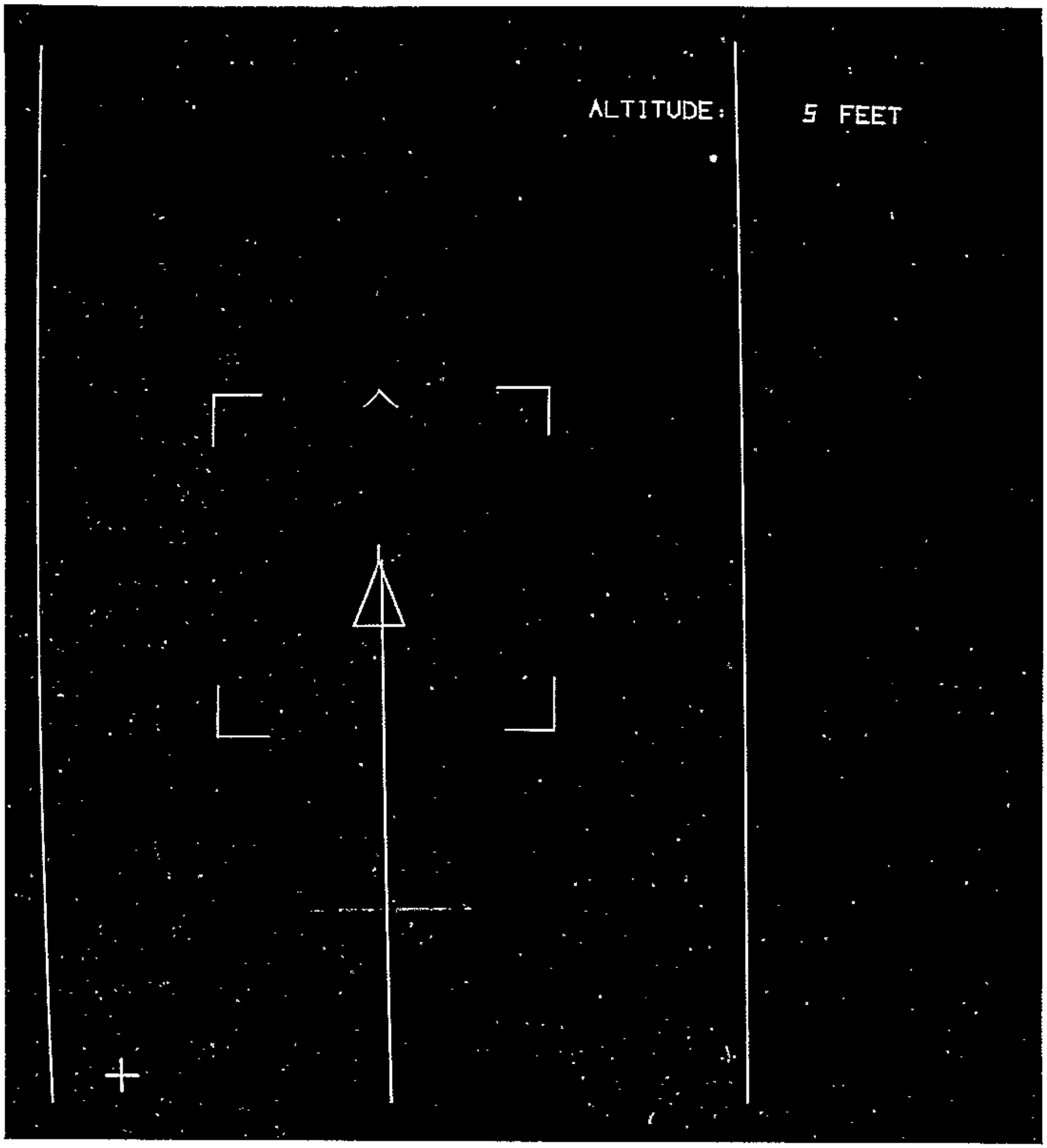

Figure 89
Hover Mode
(Sheet 2 of 3)

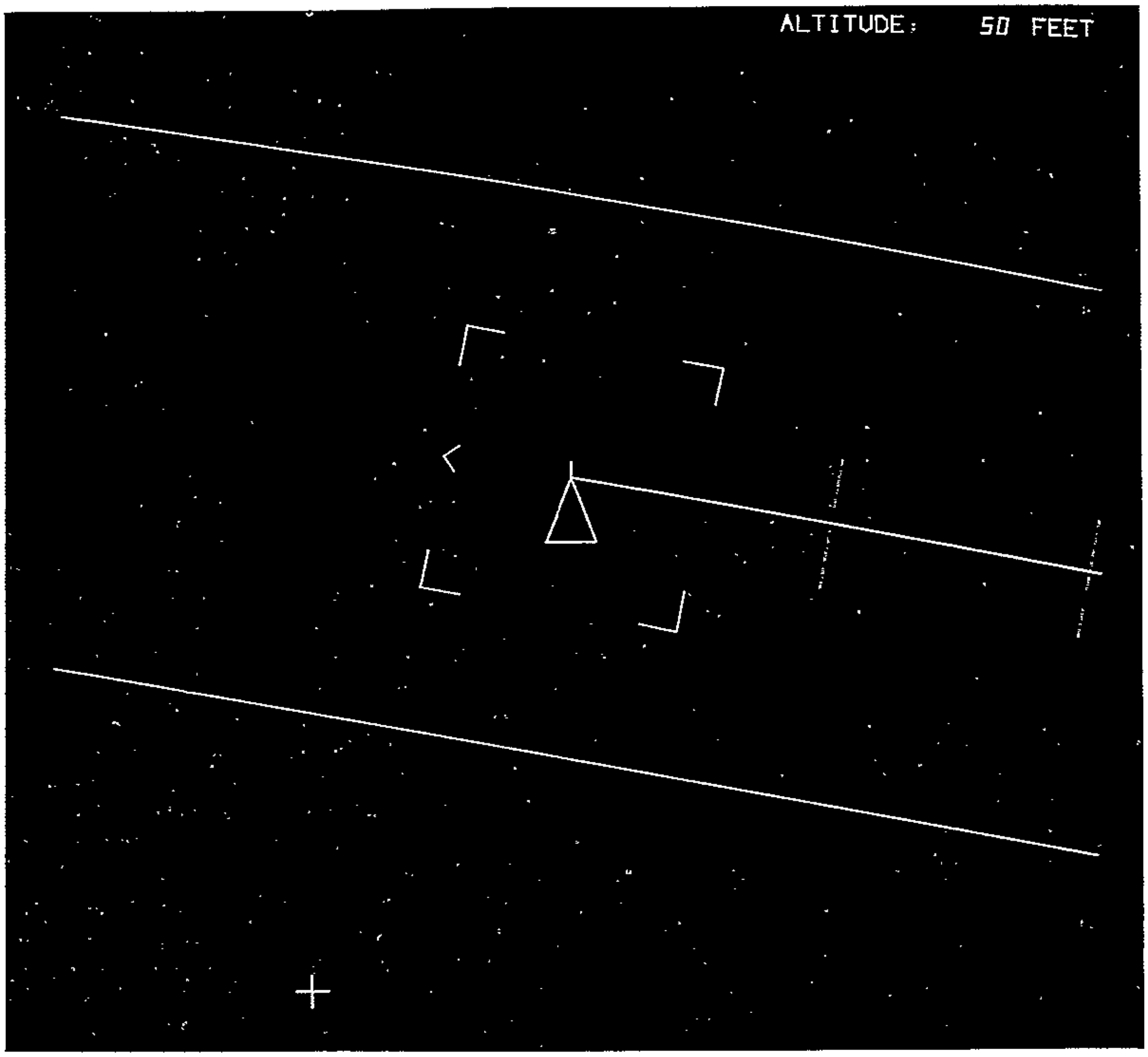

Figure 90
Hover Mode
(Sheet 3 of 3)

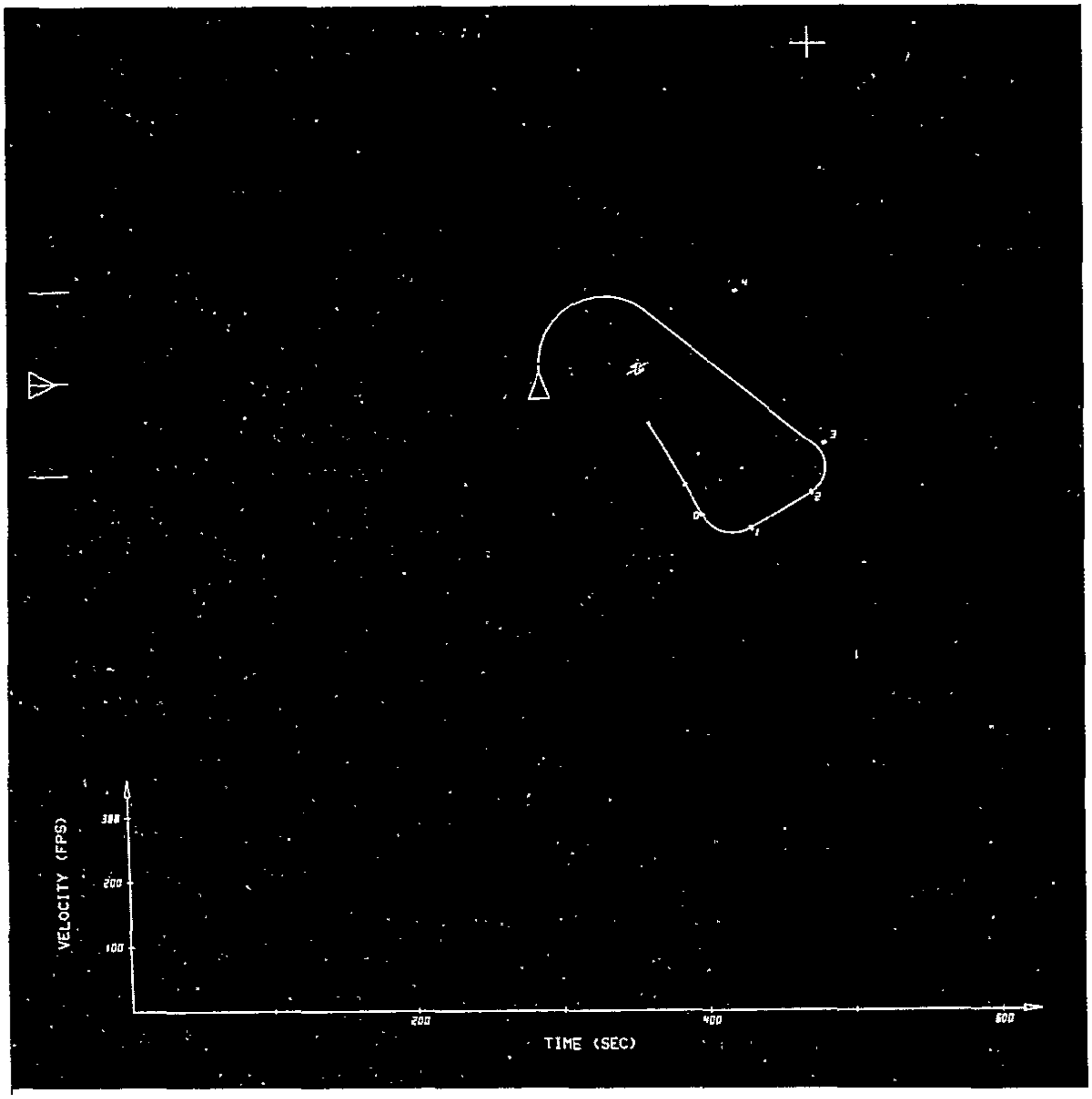

Figure 91
Predicted Direct To Capture Path (Waypoint 2)

Once the approach mode was selected, the time required indicator was eliminated from the display and the velocity profile corresponding to the selected approach was constructed and displayed. The velocity profile shown in Figure 74 is a combination of airspeed and ground speed profiles. The airspeed profile displayed was generated using the Straight Line Acceleration Method (SLAM) routine and shows the airspeed profile from the capture point to the selected waypoint. The rest of the profile is a constant ground speed to the approach gate followed by a constant attitude deceleration. When the approach mode was deselected and the predict mode was reselected, the velocity profile was deleted from the display and the time requirement indicator restored.

Figures 75 and 76 show the capability of the system to generate a three segment velocity profile with both a single speed change and with two speed changes. This was done by changing the waypoint capture velocity and by holding the time and distance for the waypoint section constant. The average velocity was displayed as a dashed line between the section boundary times. The velocity profile was constructed using the technique discussed in Appendix C.

The primary means of time control in the VALT 4D system is velocity manipulation. Within the boundaries of the delay fan area, a nominal lateral path and a nominal velocity profile are defined. These are shown in Figures 92 and 93, respectively. The velocity limits on the velocity profile in the delay fan area are shown as dashed lines. When the time constraints are changed such that the velocity profile reaches one of the limits, the lateral path must be changed to satisfy the velocity and time constraints. Figures 94 and 95 show the minimum and maximum velocity profiles and Figures 81 and 82 show their respective lateral paths.

Conversely, the generation of the delay fan lateral path can have an effect on the velocity profile. For example, if the avoidance area was violated using the basic delay fan generation technique as shown in Figures 96 and 97, the delay fan path length must be changed accordingly to maintain avoidance point separation. By changing the path length, as shown in Figure 98, the velocity profile was required to change in order to satisfy time and distance requirements. The changed velocity profile is shown in Figure 99. It should be noted that this type of profile generation tended to bring the velocity profile off the limits set for the area.

Various performance monitoring displays were checked out on the SVSVF. Two different types of altitude monitors were programmed and evaluated. In Figure 100 a display of the actual altitude profile is shown at the bottom of the CRT screen. The display also includes other information such as:

- Glideslope capture altitude
- Path distance at glideslope capture
- Glideslope angle
- Pictorial description of the altitude profile
- "Star" indicator to signify aircraft position relative to the specified altitude profile.

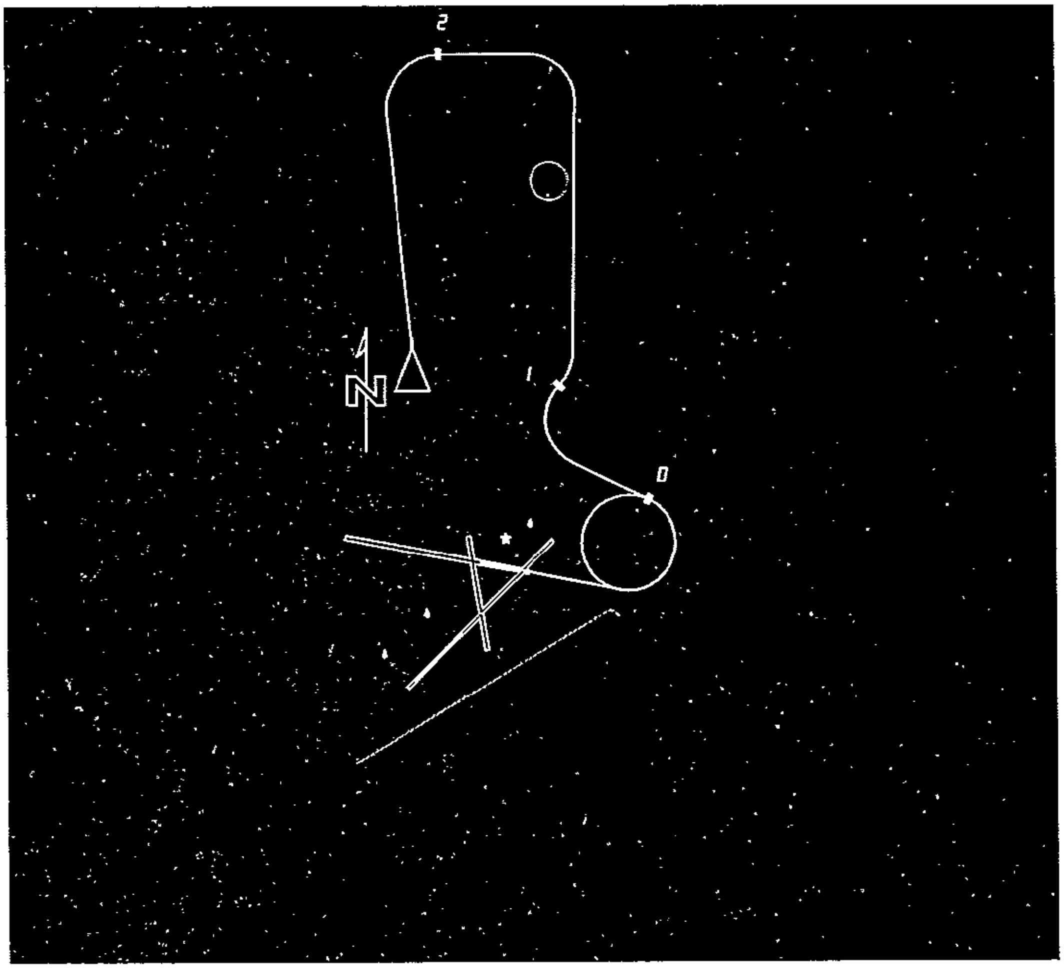

Figure 92
Nominal Delay Fan Path

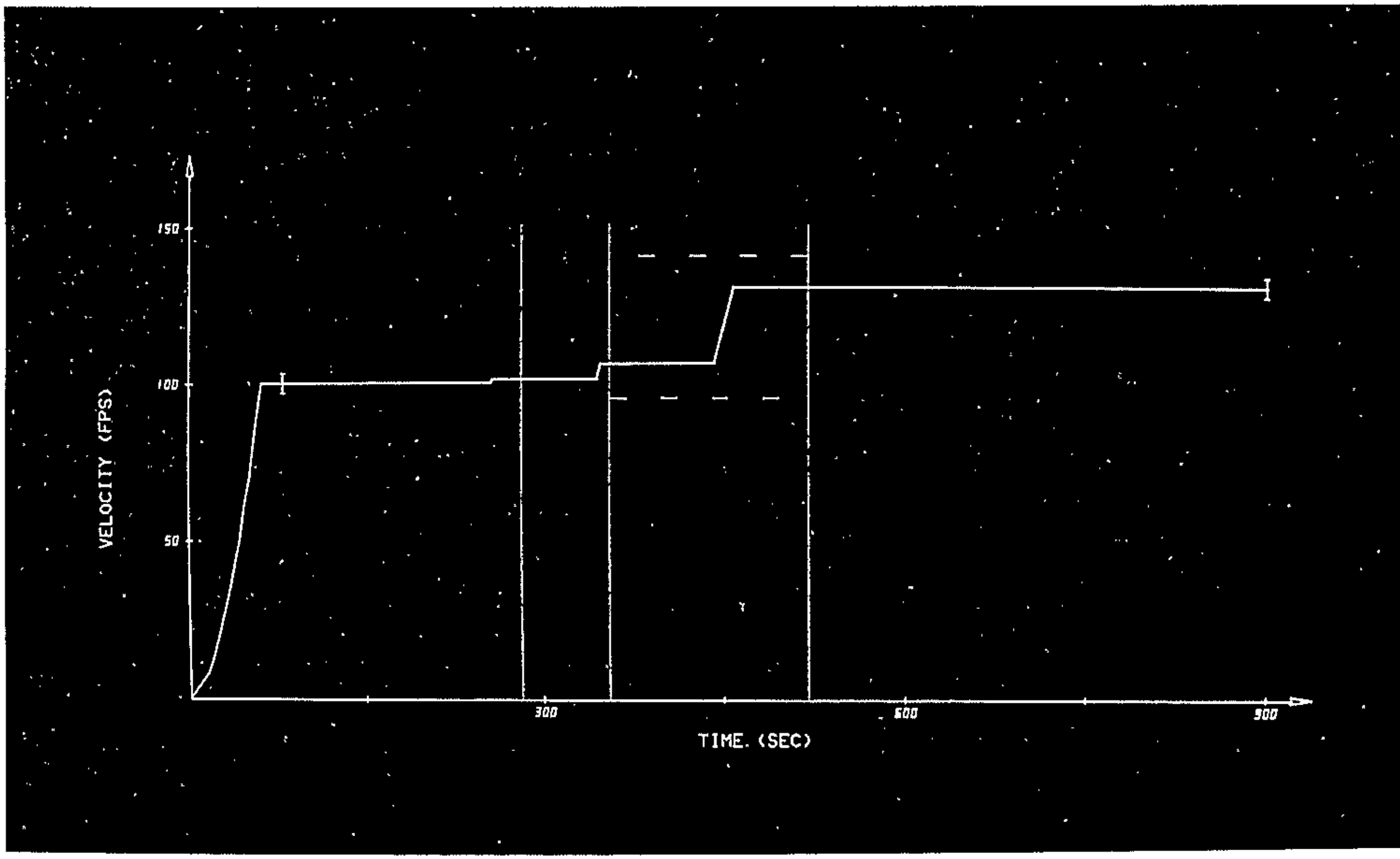

Figure 93
Nominal Velocity Profile

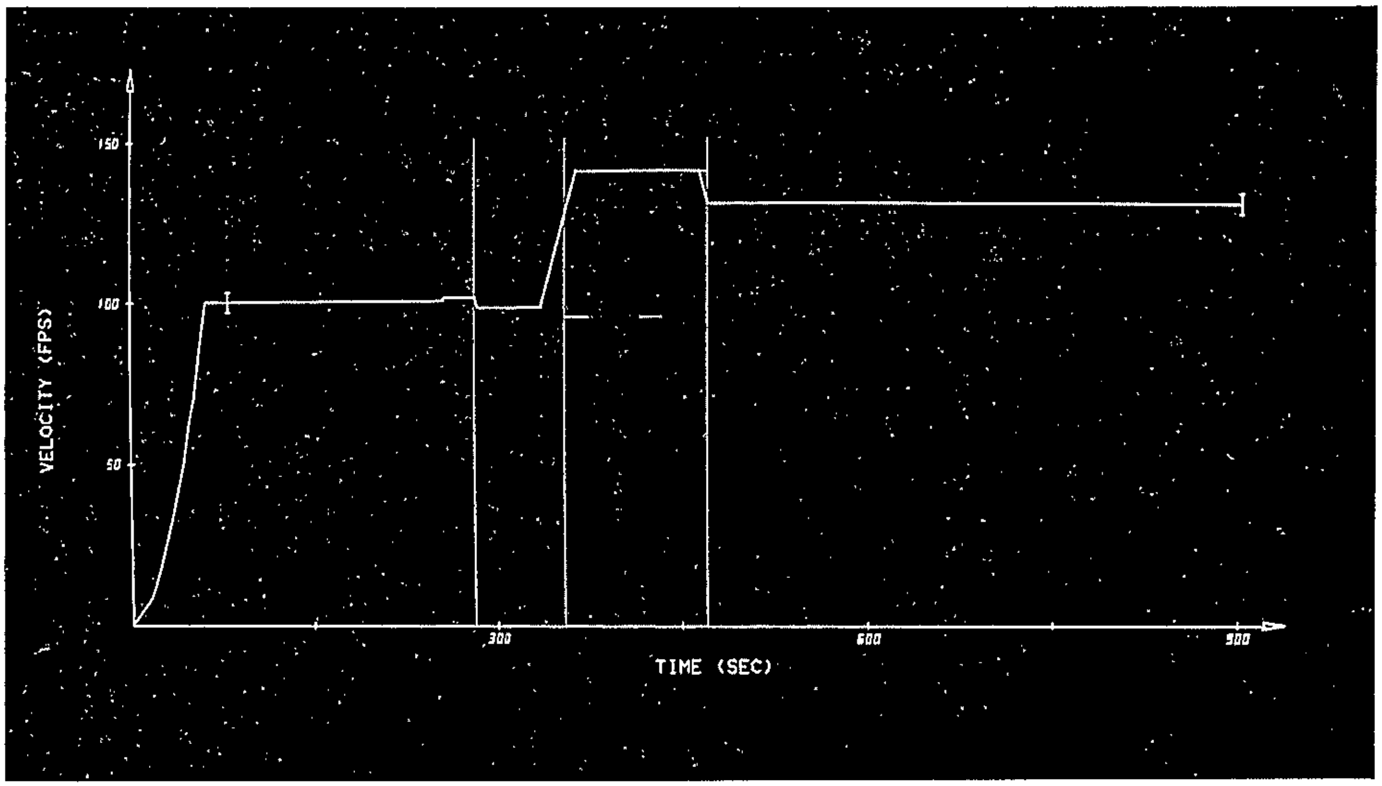

Figure 94
Minimum Time Velocity Profile

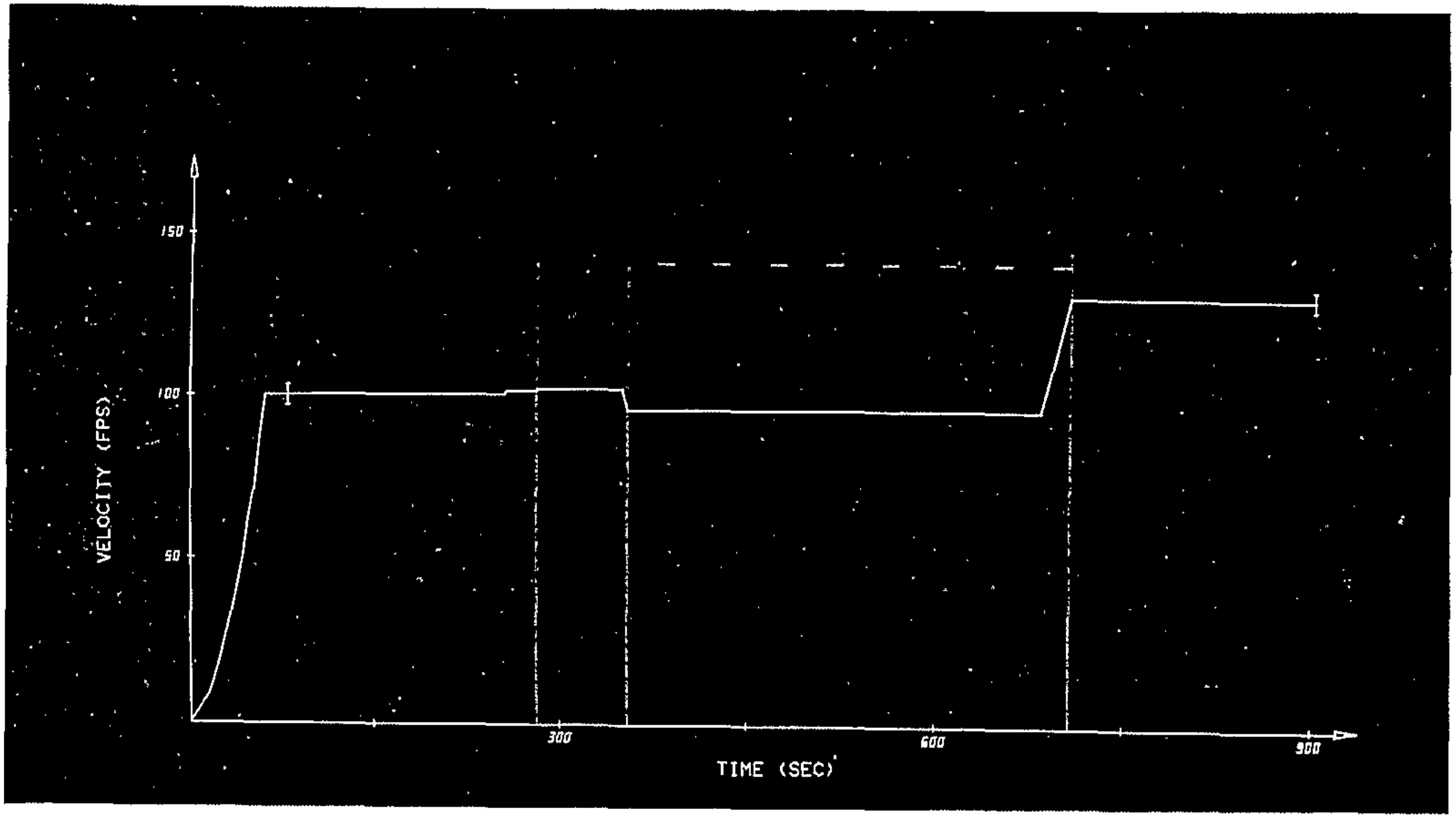

Figure 95
Maximum Time Velocity Profile

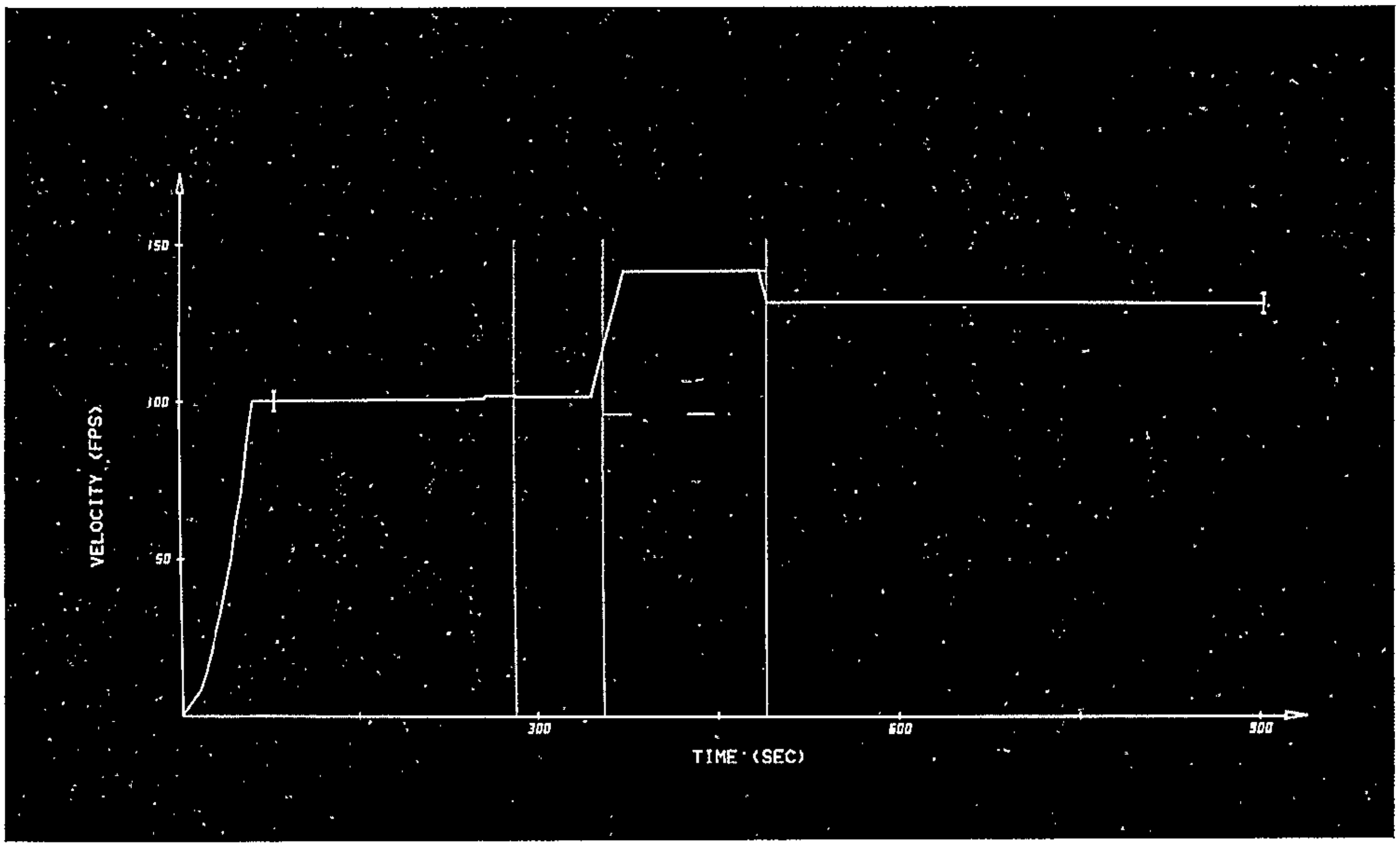

Figure 96
Velocity Profile for Path in Violation of Avoidance Area

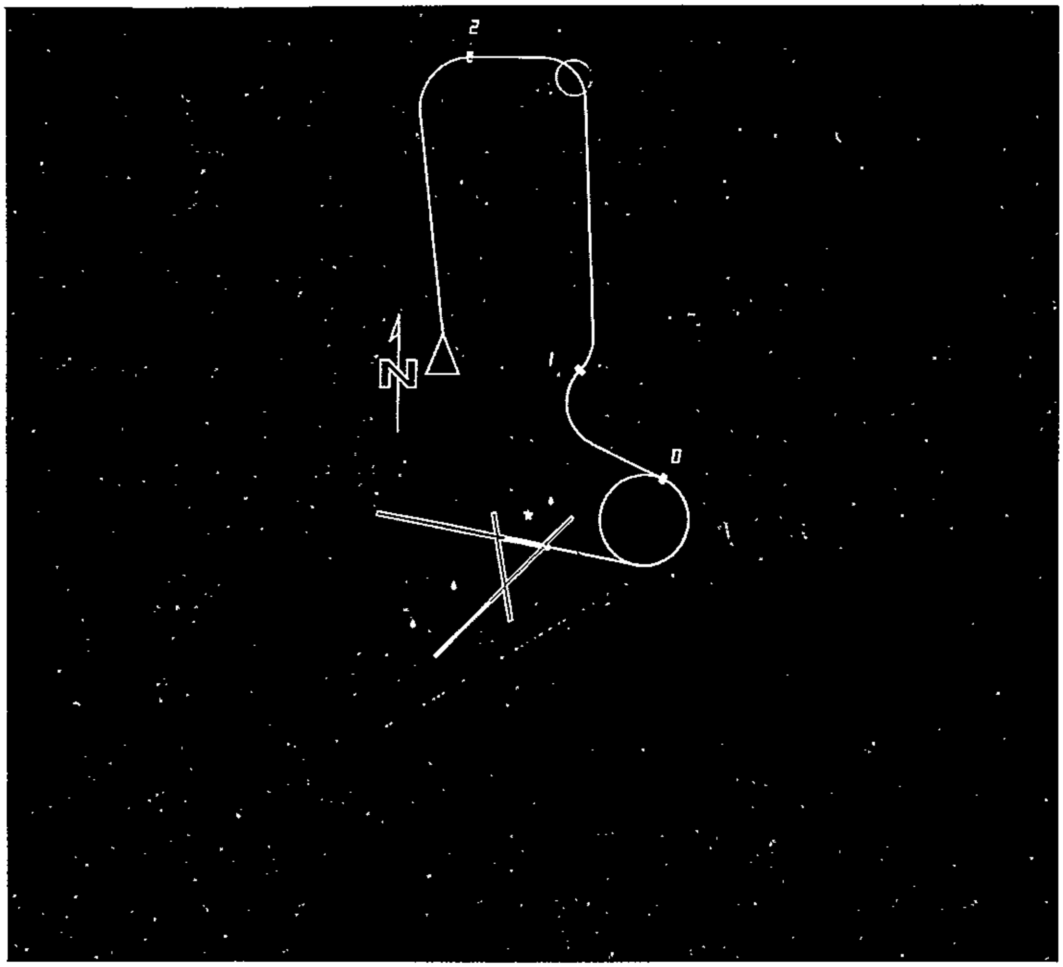

Figure 97
Violation of Avoidance Area

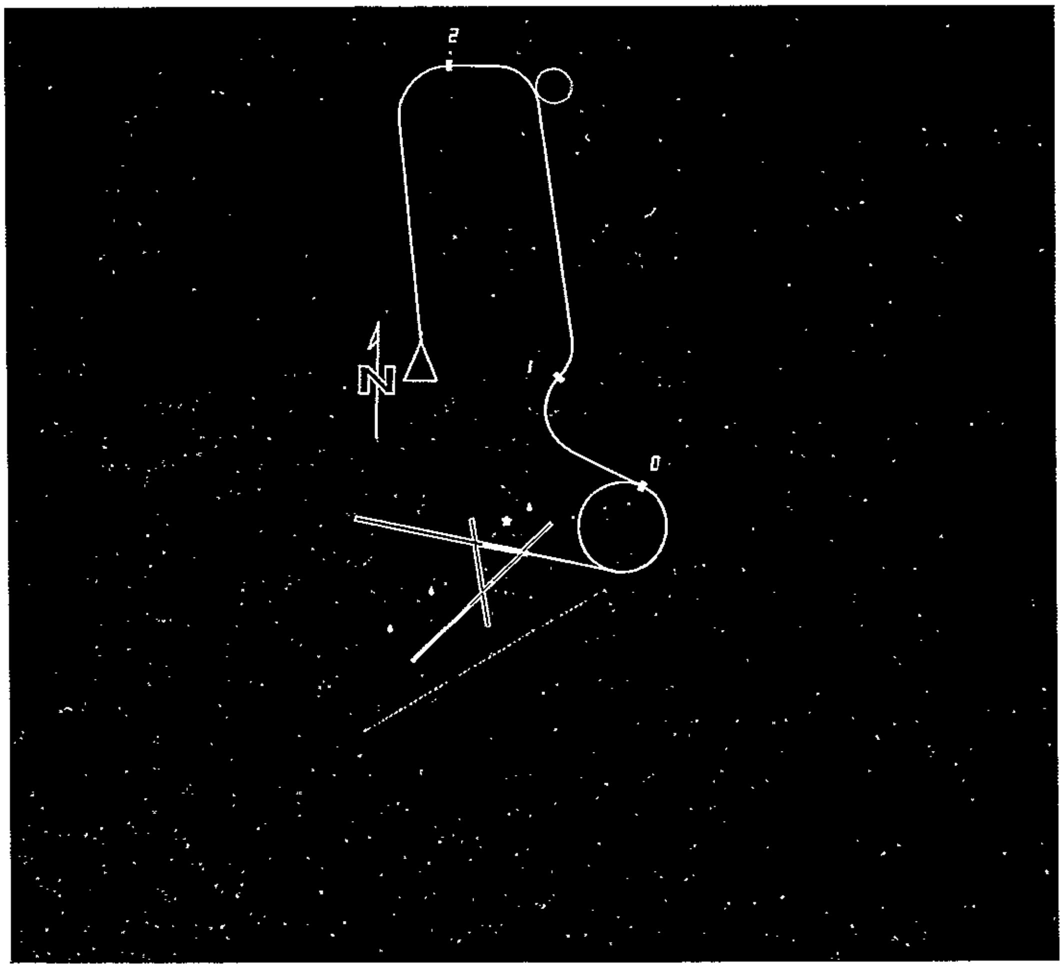

Figure 98
Delay Fan Path Altered to Maintain Avoidance Distance

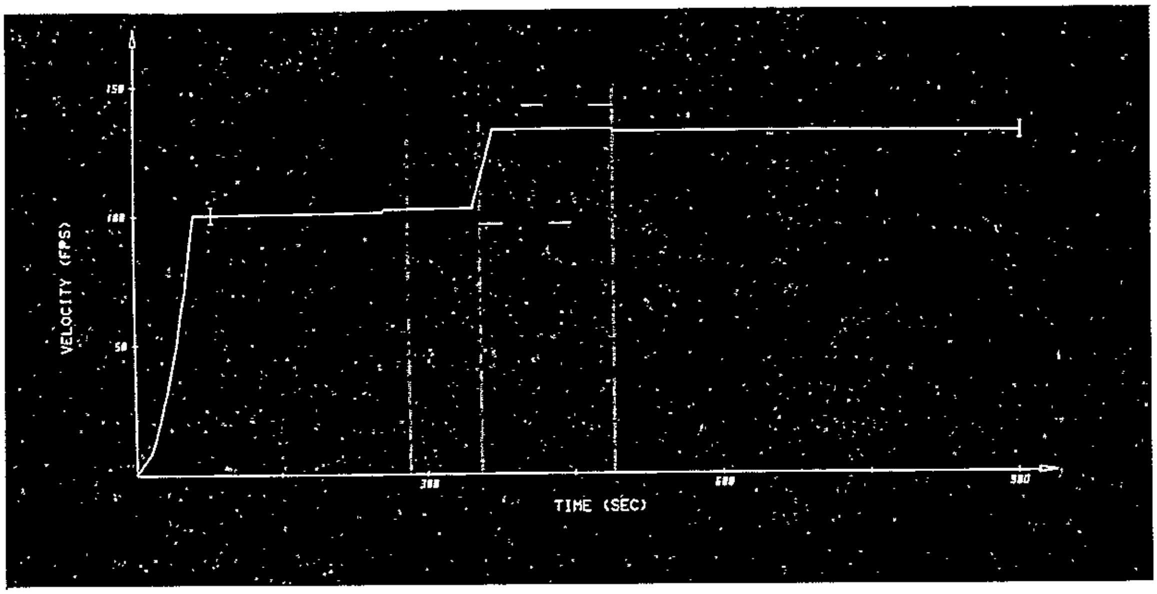

Figure 99
Resultant Velocity Profile for Altered Delay Fan Path

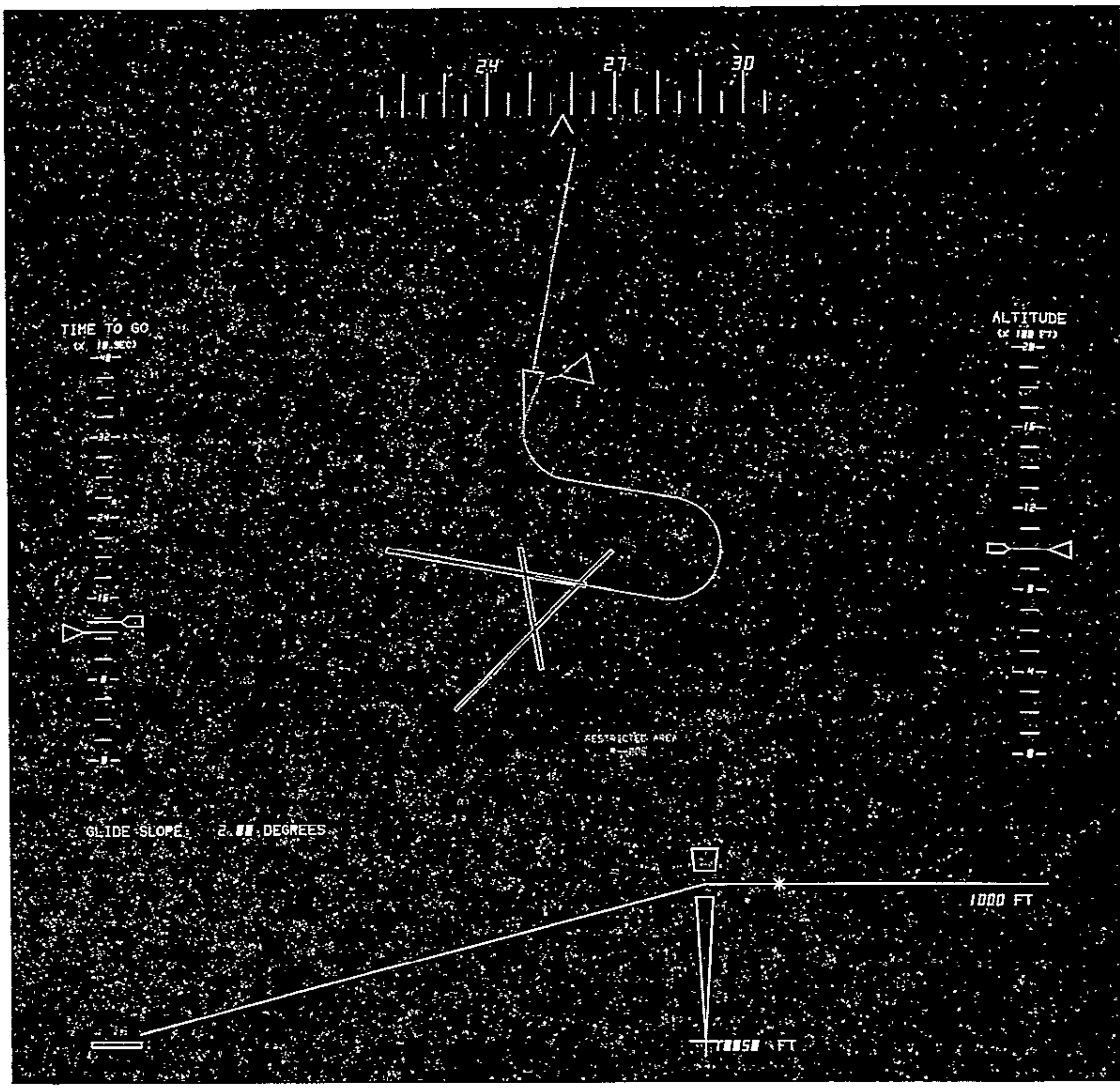

Figure 100
Performance Monitoring Display

The capability to change the profile using the graphics joystick was incorporated into the system. This was done by translating the cursor left or right to select the path distance breakpoint at which the glideslope would begin. Changes in the profile display using this technique are shown in Figures 100 through 102. Altitude performance could also be monitored using the indicator at the right side of the same display. The indicator consists of two pointers moving on a fixed scale. One pointer indicates actual aircraft altitude and the other indicates commanded altitude. Altitude errors were indicated by a mismatch in the two pointers as shown in Figure 101. Proper altitude profile tracking was indicated by alignment of the two pointers as shown in Figure 100.

Another fixed scale indicator was used to check progress in time. The indicator at the left side of Figure 100 shows a time to go monitor with pointers signifying actual and desired time remaining to the approach gate. Again time errors were shown as mismatches between the two pointers.

The last performance indicator incorporated into the display study was a fixed pointer-moving scale display of aircraft heading shown at the top of Figure 100. The scale was graduated at 5 degrees per division and extended plus and minus 45 degrees from the actual aircraft heading. Every third major mark on the scale had a corresponding numeric equivalent of heading in tens of degrees. As the aircraft heading changed the scale would translate left or right to display the appropriate heading. Changes in the displayed heading are shown in FIgures 100 through 102.

The final display incorporated into the study was an approach plate for the Snow Hill VOR approach to the NASA Wallops runway system. This display was generated to demonstrate the capability of the system to possibly call up near terminal area information prior to final approach clearance from ATC. The progress of the aircraft in the terminal area can be seen near the threshold of runway 28 and on the go-around maneuver in Figures 103 and 104.

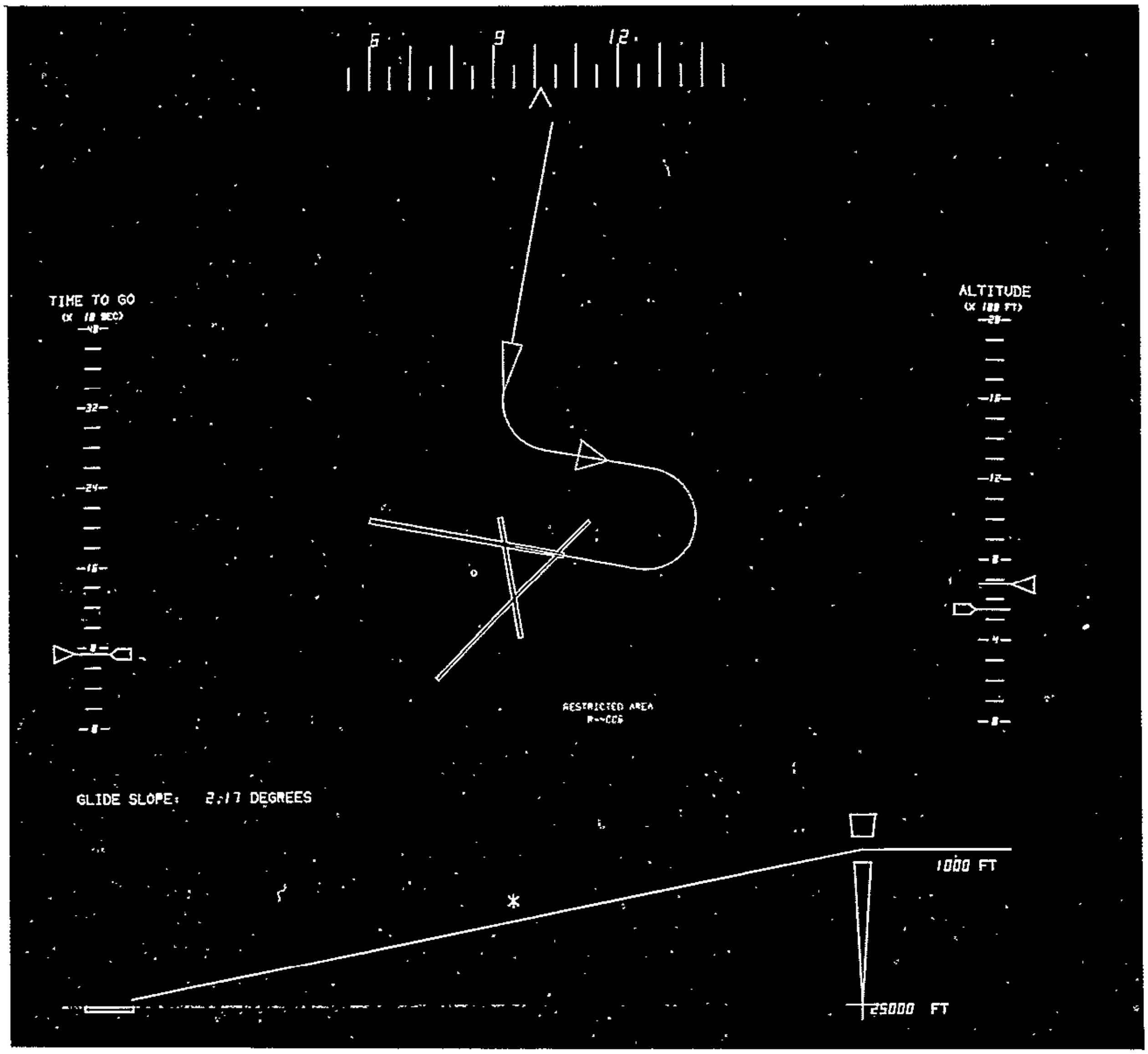

Figure 101
Performance Monitoring Display

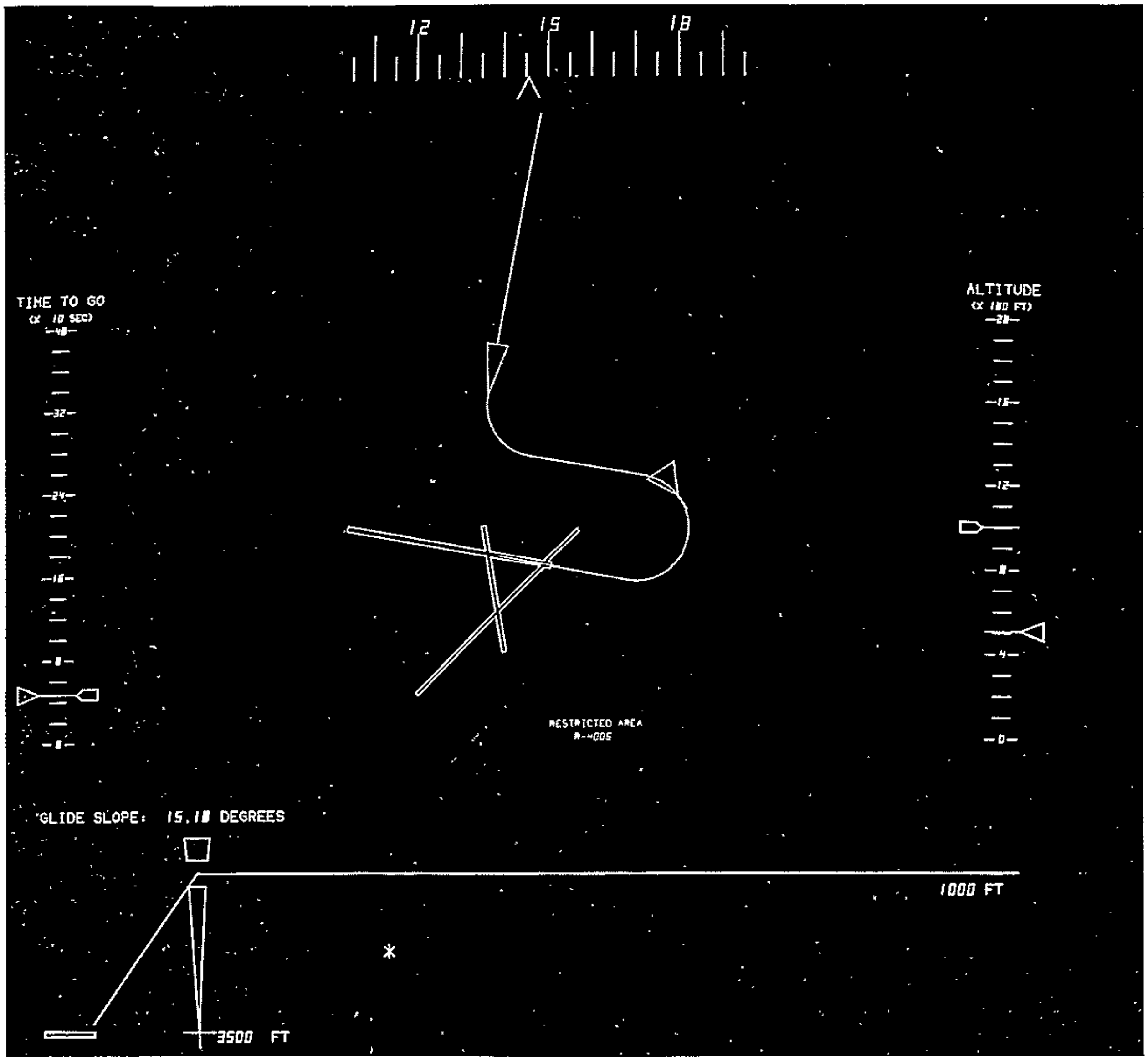

Figure 102
Performance Monitoring Display

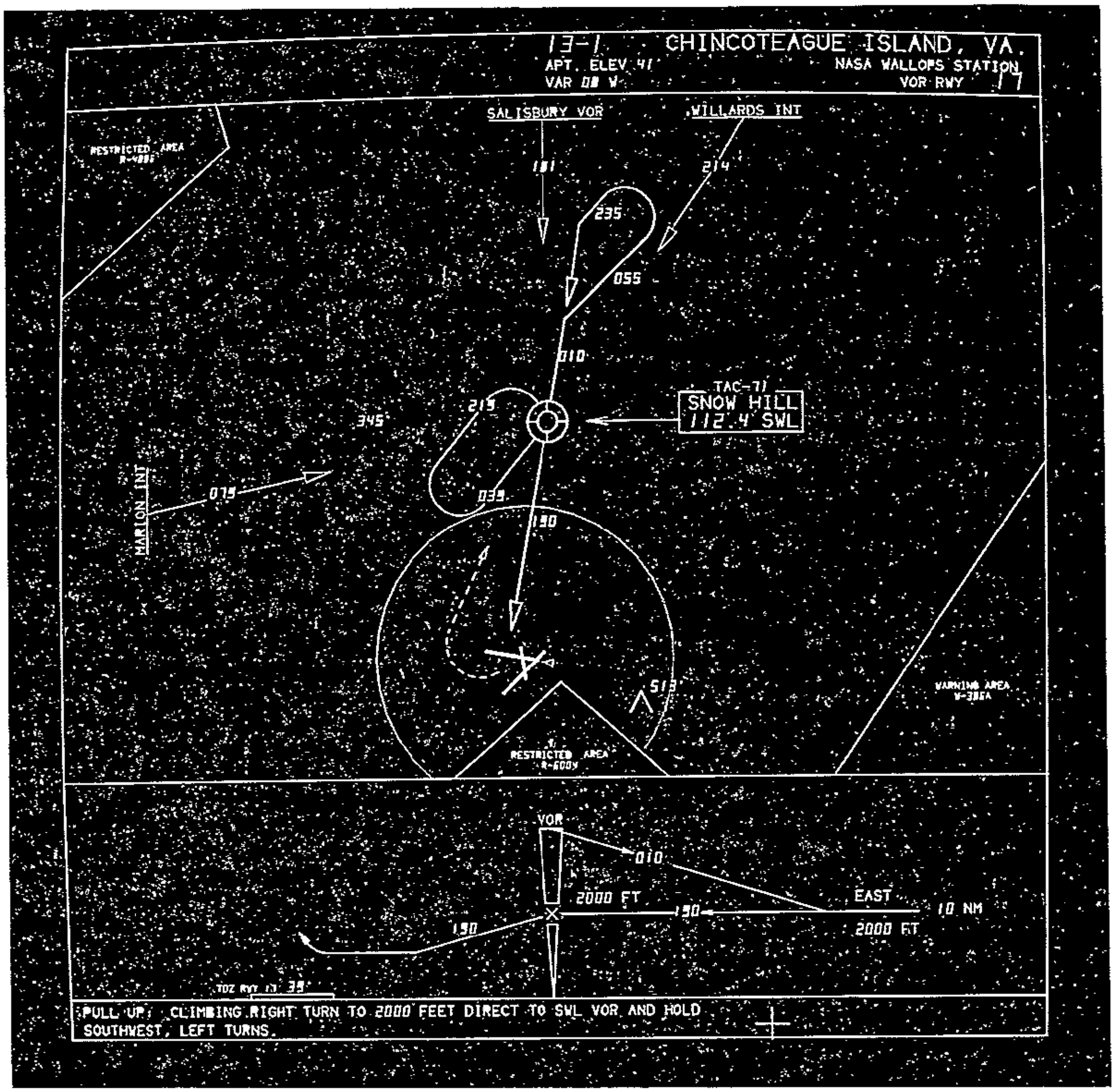

Figure 103
Approach Plate Display

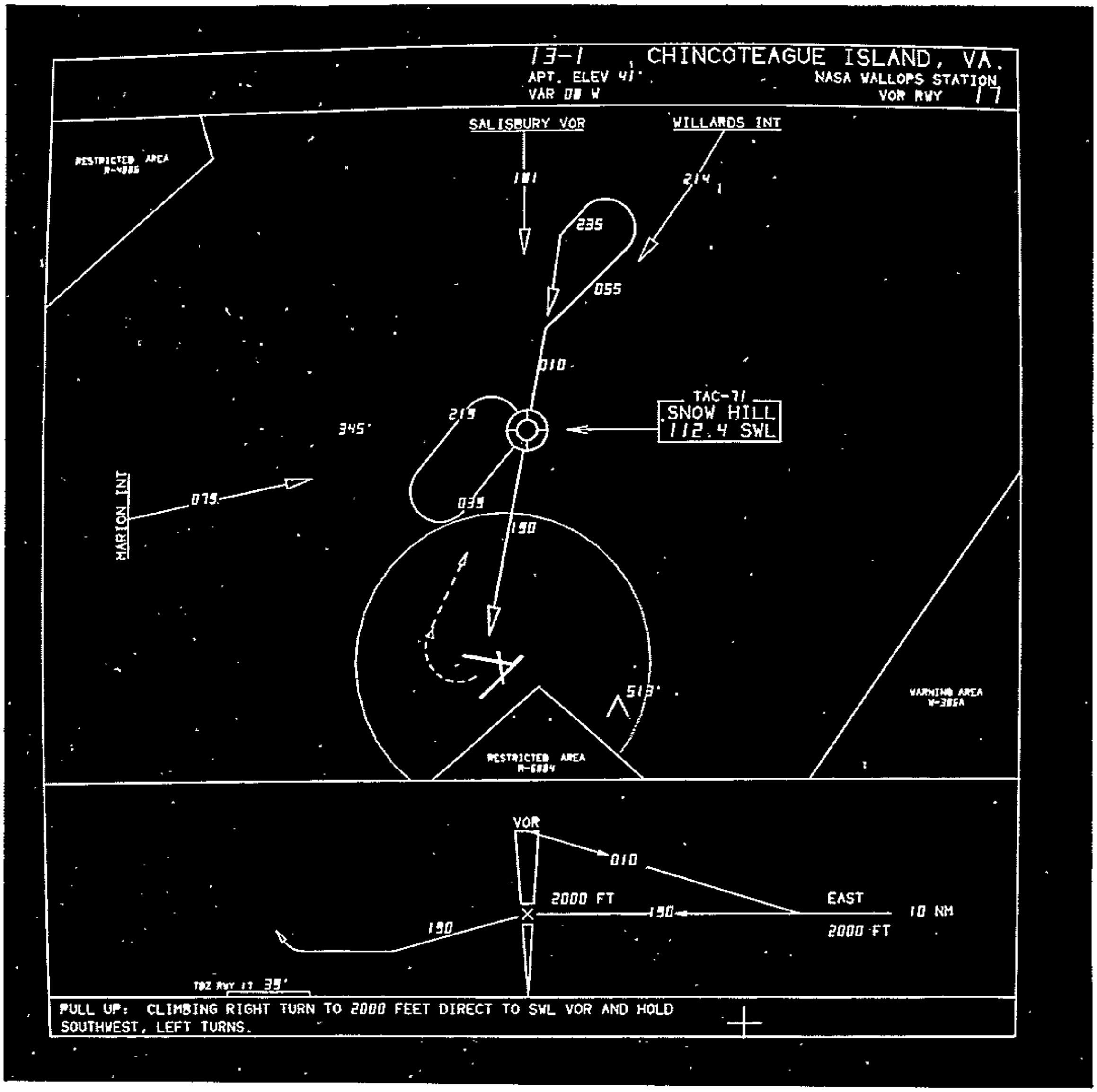

Figure 104
Approach Plate Display

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CONCLUDING REMARKS

This section presents a brief summary of the major findings of the study effort and a recommendation for incorporating a complete 4D capability into the VALT system.

Conclusions

Time Control Techniques - A study of various techniques that have been proposed for aircraft 4D approach systems was undertaken. In general the control techniques fell into two major categories:

- Velocity Control
- Path Alteration

Velocity control can be accomplished through control of either ground speed or airspeed. Path alteration can be accomplished with fixed ground tracks and systematic alteration of these tracks or through the use of more free-form techniques such as maneuver corridors. The use of fixed ground tracks is more suitable for the VALT 4D system.

VALT 4D Path Control - The Direct To path generation technique has proven to be a powerful tool for both the path capture maneuver and the path alteration maneuver. Modification of the basic Direct To concept to include turns of different radii does restrict its use. In the cases where the turn radii are equal, there is always a solution for a path from one point to another. However by allowing different turn radii, conditions can exist where one turn circle is entirely contained within the other turn circle and no tangent line exists between the two circles. Another restriction came about by allowing speed changes only on the straight line segment. Because of this restriction, a minimum separation distance is required between the two turns to perform necessary speed changes. Despite the restrictions involved, the variable radii capability was found to be valuable and takes advantage of the speed range available in the helicopter.

Examination of the various delay fan techniques reveals that most of the paths can be generated using one or more Direct To maneuvers. The symmetrical delay fan is by definition a special case of the Direct To delay fan. It was found, however, to be restrictive in its application to certain maneuver areas. The parallel offset delay fan was also found to be rather restrictive. Both types of delay fans also added unnecessary complexity to the VALT 4D software. Using the Direct To software already developed for the path capture maneuver for the delay fan, the application required only a few minor modifications. The Direct To delay fan is also applicable to more maneuver situations than the other types studied.

VALT 4D Velocity Control - The existing VALT velocity control system is based on ground speed control techniques, thus lending itself to 4D applications based on similar techniques. The use of airspeed based velocity control techniques may, however, result in reduced pilot workload and should be included in the system. The 4D system for VALT, therefore, uses airspeed control techniques during the initial Direct To path capture maneuver and ground speed control techniques once on the nominal approach path. Velocity control was determined to be the primary time control method to be applied in the VALT 4D system due to the speed range of the VALT aircraft. Modifications to speed are also much easier in a real time flight environment than lateral path modifications. Only in cases where velocity limits were exceeded or maneuver obstacles were encountered was path modification utilized.

Velocity Profile Generation - For ground speed control, two different velocity versus time profile techniques were investigated. Neither technique is suitable by itself for a multiple time waypoint system and each technique contains a desirable feature. The single speed change technique allows for constant speed transitions from one time control section to another, but there are distance limitations on a single speed change profile for given entrance and exit velocities and section time. The two-speed change technique has maximum flexibility in that it can produce a profile outside the single-speed change profile limits, but the situation can exist where an immediate change from acceleration to deceleration can exist at the time waypoints. The two-speed change profile nearly always requires a speed change at the waypoint.

Based on these inherent problems, the two techniques have been combined and are used in conjunction with a priority system to generate the complete velocity control profile. The priority system is defined so that the simplest form of control is used first and then the more complex forms are used. In this priority system, the single-speed change is sampled first, and if deemed unacceptable, the two-speed change profile is used. If the two-speed change profile is found unacceptable because of speed limitations, the path is modified if in a allowable maneuver area. In this way, it was found that maximum use of the speed change capability of the aircraft could be realized. A weighted averaging technique was also developed to allow continuous stringing of multiple time control waypoints on the approach path. This technique generates waypoint crossing velocities which lend themselves to generating the simplest case velocity profiles.

Time Error Control - A simple time error control law is sufficient for the VALT 4D system. The control law compares actual remaining clock time to go on the approach with the calculated time to go, based on present position and the nominal velocity profile. An incremental velocity term based on any time difference is generated and added to the nominal velocity reference to create a velocity command. The existing velocity control software is used in conjunction with the 4D velocity command to control the aircraft.

Airspeed Control Study - The airspeed control techniques presented in References 6 and 7 can be readily incorporated into the VALD 4D system. The use of airspeed control may prove to be valuable for low-speed helicopter operations in the presence of winds due to the reduction in trim attitude changes required while flying curved paths. Although this concept was not fully explored, the simulation did illustrate the desired function. Changes in ground speed around the turn on the Direct To capture were readily evident and the system produced the varying bank angle required to hold a circular ground track.

Information Display - The pilot orientation problem that was first evident during the original VALT curved path development work is more significant in the 4D system. Graphical representation of the curved flight paths on a cockpit display provides a simple and efficient means to relay system information and decisions to the pilot. The graphics system also serves as a means for the pilot to participate in decision making pertaining to path selection, profile generation or path acceptance or rejection. By using the graphics joystick, a technique of pilot data entry more efficient than keyboard entry has been developed. The generation of the parameters necessary for information displays and pilot control inputs can be accomplished within the time and memory constraints of the present VALT computer.

Recommendations

The 4D concepts and techniques investigated as part of this study have led to the development of a basic framework for a 4D system suitable for the VALT program. Elements of this framework have been filled out through the generation and verification of digital computer software packages. These packages should be integrated into the VALT flight system software to provide a complete 4D approach capability for the VALT aircraft.

A complete 4D approach capability would include:

- Full predict capability for the Direct To path capture maneuver which compares time, distance and velocity constraints and determines acceptability based on those parameters. If the path is considered unflyable, some indications would be given to the pilot as to possible courses of action to take to satisfy the necessary parameters such as speed up, slow down, turn left, turn right, etc.

- Real time computation of airspeed or ground speed profiles to achieve waypoints at the times specified by ATC.

- Real time path generation or alteration based on ATC inputs of waypoint coordinates and times, avoidance area or delay fan boundary limits.

- Performance monitors for checking actual aircraft progress relative to prescribed 4D profiles.

- Pilot entry techniques for selection of time waypoints, lateral path parameters, velocity and altitude profiles, and path alteration boundaries.

- Displays of approach plates of pertinent terminal area information for pilot orientation prior to approach path selection and generation.

Simulation verification and flight test should then follow to check out the integrated system.

REFERENCES

1. Computer Systems Engineering: Computer-Aided Metering & Spacing with ARTS III. FAA Report RD-70-82, Systems R&D Service, Washington, D.C., December 1970.

2. ERZBERGER, H., BARMAN, J., McLEAN, J.: Optimum Flight Profiles for Short Haul Missions. AIAA Guidance & Control Conference, Paper No. 75-1124, August, 1975.

3. ERZBERGER, H. and LEE, H.: Optimum Horizontal Guidance Techniques for Aircraft. J. Aircraft, Volume 8, No. 2, February 1971.

4. ERZBERGER, H. and LEE, H.: Terminal - Area Guidance Algorithms for Automatic Air-Traffic Control. NASA Technical Note TN D-6773, April 1972.

5. ERZBERGER, H. and PECSVARADI, T.: 4D Guidance System Design with Application to STOL Air-Traffic Control. Joint Automatic Control Conference, August 1972.

6. FOUDRIAT, E.C.: Aircraft 4D Constant Velocity Control System. J. Aircraft Volume 11, No. 6, June 1974.

7. FOUDRIAT, E.C.: A General Algorithm for Relating Ground Trajectory Distance, Elapsed Flight Time, and Aircraft Airspeed and its Application to 4D Guidance. NASA TN D-7876, February 1975.

8. HEMESATH, N.B.: Three and Four Dimensional Area Navigation Study. N75-20283, June 1974.

9. HOFFMAN, W. and HOLLISTER, W.: A Spiral Guidance Approach Concept for Commercial VTOL Operations. NASA-CR-132651, May 1975.

10. HYNES, R.J., STEVENSEN, L.E., CAPEN, E.B.: 4D Guidance of STOL Aircraft AIAA Paper 71-770, July 1971.

11. KELLY, James R.; NIESSEN, Frank R., THIBODEAUX, Jerry J., YENNI, Kenneth R., and GARREN, John F., Jr.: Flight Investigation of Manual and Automatic VTOL Decelerating Instrument Approaches and Landings. NASA TN D-7524, 1974.

12. LEE, H.Q., McLEAN, J.D., ERZBERGER, H.: Control and Guidance Techniques for Automated Air Traffic Control. J. Aircraft Volume 9, No. 7, July 1972.

13. LEE, H.Q., NEUMAN, F., HARDY, G.H.: Four-Dimensional Area Navigation System Description and Flight-Test Results TN D-7874, May 1975.

14. McCONNELL, Walter J. Jr., SKUTECKI, Edmund R., and CALZADO, Alfonso J.: Development of the NASA VALT Digital Navigation System. NASA CR 144894, September 1975.

15. McCONNELL, Walter J. Jr.: A Technique for Generating Arbitrarily Shaped Curved Approach Paths. NASA CR-2734, August 1976.

16. NEUMAN, F., LEE, H.Q.: Flight Experience with Time of Arrival Control for STOL Aircraft in the Terminal Area. AIAA Paper 75-1126, August 1975.

17. NIESSEN, Frank R.: A Low-Cost Inertial Smoothing System for Landing Approach Guidance. NASA TM D-7271, June 1973.

18. PECSVARADI, T.: Four Dimensional Guidance Algorithms for Aircraft in an Air Traffic Control Environment. TN-D-7829, March 1975.

19. TOBIAS, L.: Automated Aircraft Scheduling Methods in the Near Terminal Area. J. Aircraft, Volume 9, No. 8, August 1972.

20. WEIRENGA, R.D.: 4D Navigation Using Integrated Strapdown Inertial/ Differential Loran. A75-37701, 1975.

APPENDIX A

PATH ALTERATION METHODS

Symmetrical Delay Fan

The symmetrical delay fan is one in which the lateral path between consecutive waypoints has symmetry about some bisector. The requirements for the symmetry are:

a) The initial and final turns in the maneuver are in the same direction

b) The straight segments of the maneuver are equal in length

c) All turn circles are of equal radius

These conditions must be satisfied for all combinations of waypoint positions and headings whether the headings are equal or not. Figure 105 shows the symmetry of the delay fan maneuver and the areas of waypoint heading variance. Note that the areas of allowable heading variance can be increased considerably if the middle turn in the maneuver is not restricted to be in the same direction as indicated by the alternate path on Figure 105.

The axis of symmetry is defined as the perpendicular bisector of the line joining the two turn-circle centers. The turn circles must be defined for both the right and left turn cases. Since there are two different lines joining the two pairs of circles, there may be two different bisectors.

In order to produce a symmetrical delay fan, maneuvers where opposite direction initial and final turns may occur must be eliminated. This includes those cases where an inflection point occurs on the nominal path between the initial and final waypoints. In addition, certain areas are excluded since they fall in a "dead zone" which is created when a switch is made from the bisector defined by one pair of circles to the bisector defined by the other pair of circles. This condition only exists when the delay fan is used with different initial and final headings. An example of the dead zone is shown in Figure 106. The inner boundary of the dead zone is determined by the heading line through the first waypoint and the outer boundary by the heading line through the second waypoint.

The dead zone can eliminate a great number of possible paths. A technique is necessary, therefore, that eliminates the dead zone. A technique investigated is that shown in Figure 107. In this method the initial and final turn directions are never changed; therefore, the dead zone need not be negotiated. However, in using this method the delay fan is opposite in direction to the nominal path. This makes the allowable maneuver area very large as well as drastically altering the shape of the nominal path configuration.

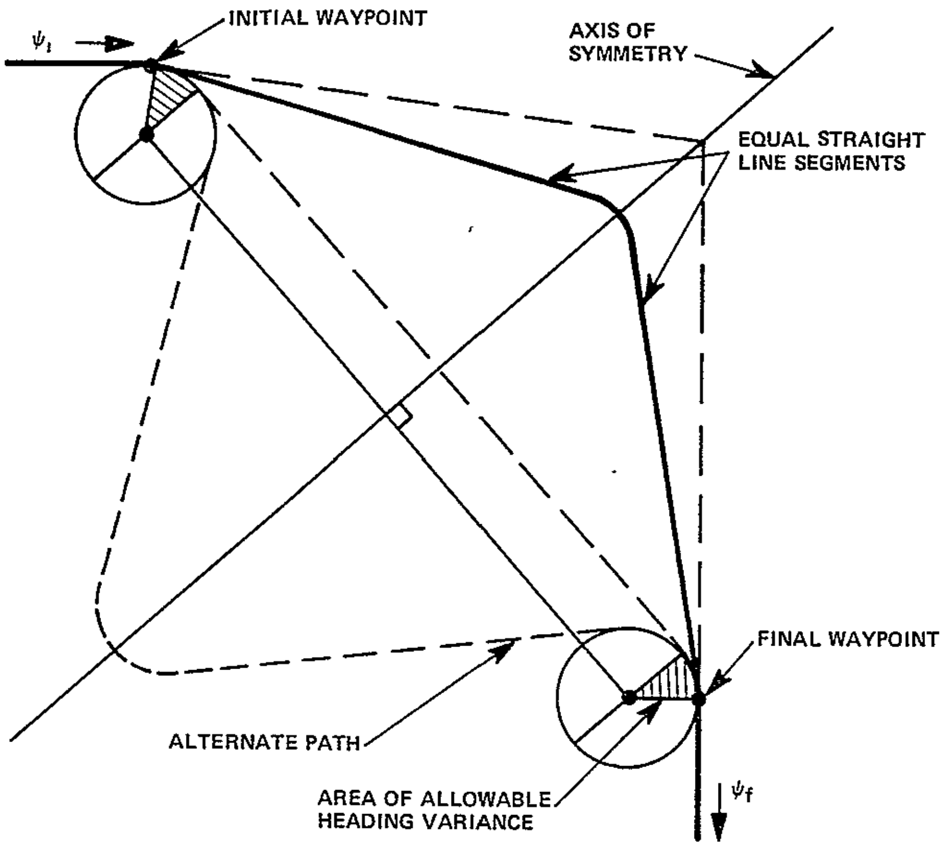

Figure 105
Symmetrical Delay Fan Model

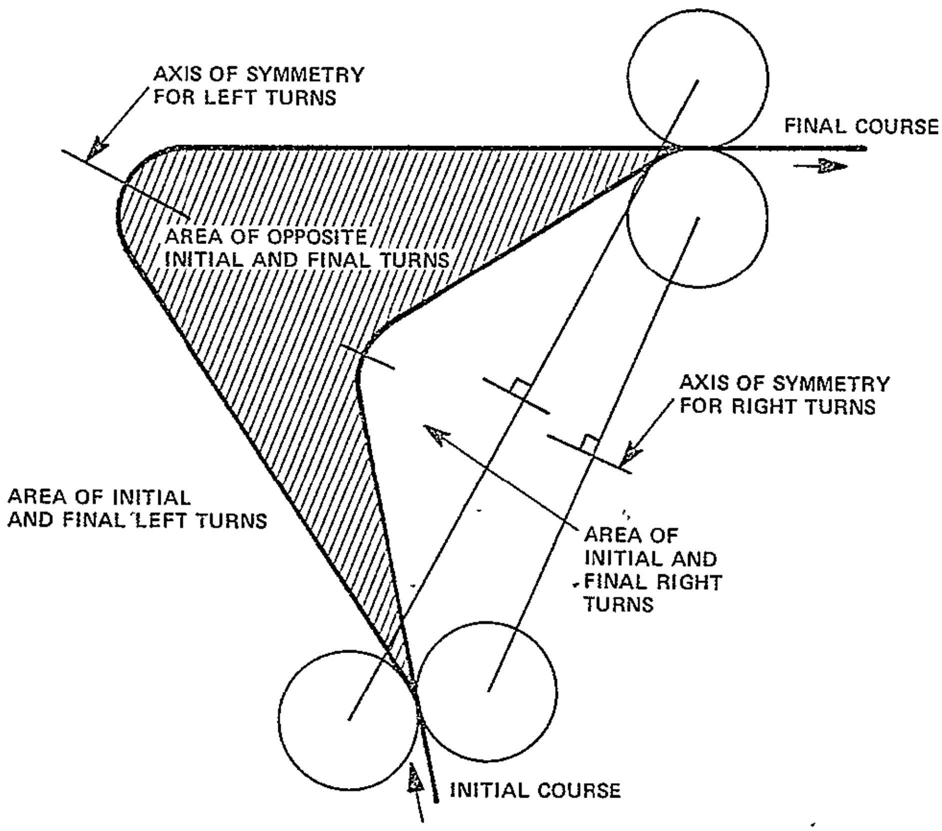

Figure 106
Dead Zone Example

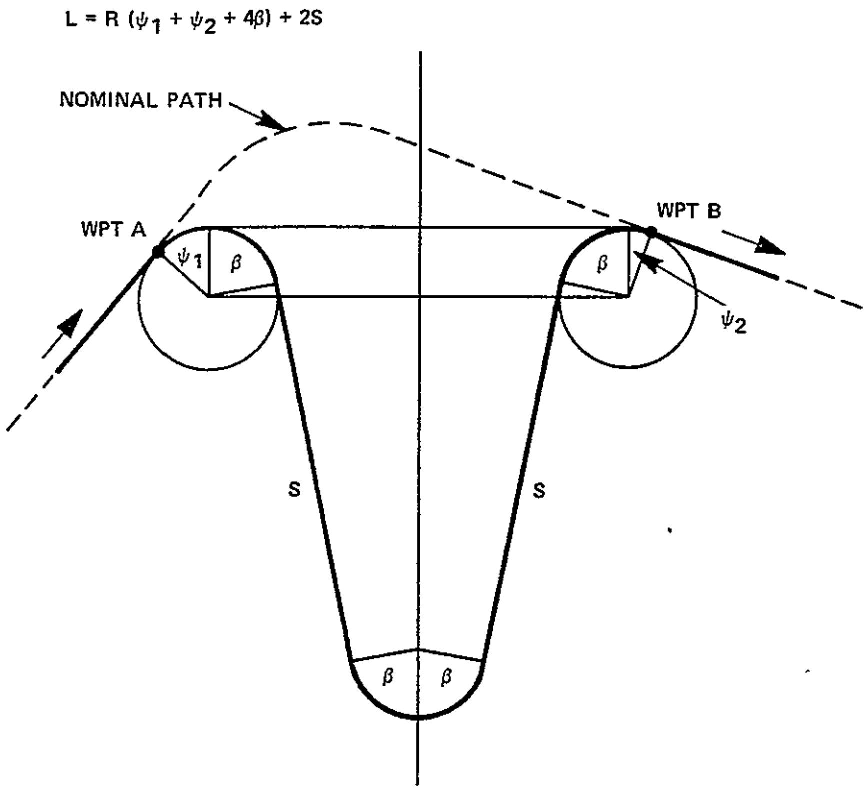

Figure 107
Dead Zone Elimination

To solve for the necessary values of the delay fan, the equations become a function of the symmetry turn angle and the sine of the symmetry turn angle. Depending on the direction of the initial and final turns relative to the direction of the intermediate turn, the equation for solution of this delay fan is of the form:

$$L = 4R\beta + 2\left(\frac{X/2 - 2R \sin \beta}{\cos \beta}\right)$$

Since there is no direct solution for an equation of this type, an iterative solution technique has been developed. The only unknown in this equation is the angle β and by use of a solution for differential equations involving the function of β and the derivative of the function of β, the angle can be determined in a few iterations. The other parameters of the delay fan are then solved directly by use of the angle β. A flow chart depicting the steps required to define a symmetrical delay fan is shown as Figure 108.

Due to the restrictions caused by the dead zone and the rather arbitrary manner in which the symmetrical delay fan maneuver is defined, coding of the flow chart was not attempted. In addition, the Direct To delay fan technique to be discussed next can be used to generate the same maneuvers.

Direct To Delay Fan

The Direct To delay fan maneuver is the most flexible path alteration technique investigated. It does not restrict the shape of the flight path to be altered or the shape of the alteration itself.

The basic geometry of the Direct To delay fan maneuver is shown as Figure 109. Since the general purpose Direct To maneuver is not limited to turns of equal radii, the delay fan maneuver may also utilize this capability. The area of allowable maneuver can be defined and constrained by the direction and magnitude of the initial turn angle (α_L or α_R) and by the length of the path allowed prior to executing the Direct To maneuver. The proper selection of these parameters can result in the generation of delay fan paths that are identical to those generated by other techniques such as the symmetrical delay fan. Like the other delay fan techniques investigated, no direct method of determining the various parameters for a desired path length has been found that will work for all combinations of initial and final headings. The lack of a predetermined solution is not bothersome, however, since the maneuver can be started without prior parameter identification by extending the first straight segment until the predicted Direct To path distance equals the desired path distance. The minimum and maximum path distances can be readily determined from the maximum allowable turn angle and the allowable length of the initial straight segment. A flow chart defining the steps required to develop the Direct To delay fan is shown as Figure 110.

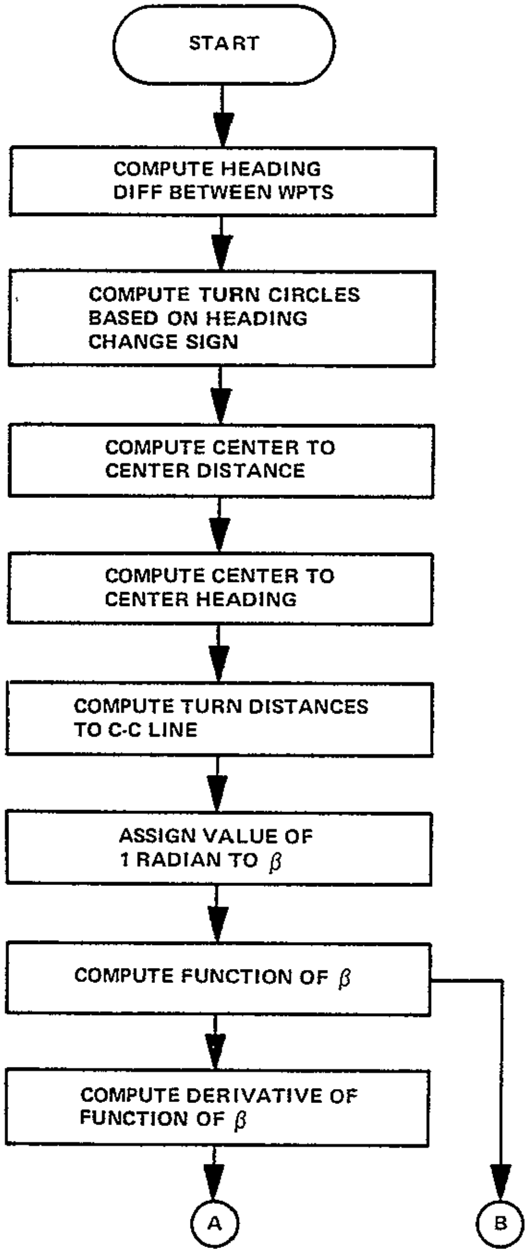

Figure 108
Symmetrical Delay Fan Flow Chart
(Sheet 1 of 2)

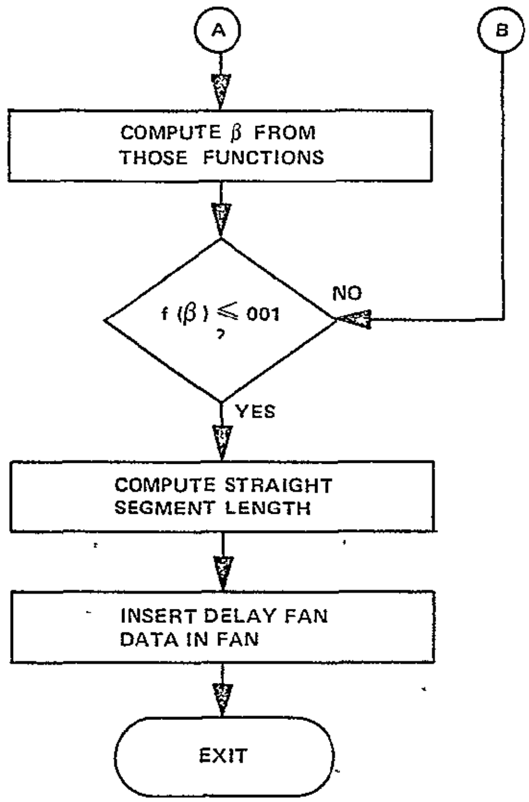

Figure 108
Symmetrical Delay Fan Flow Chart
(Sheet 2 of 2)

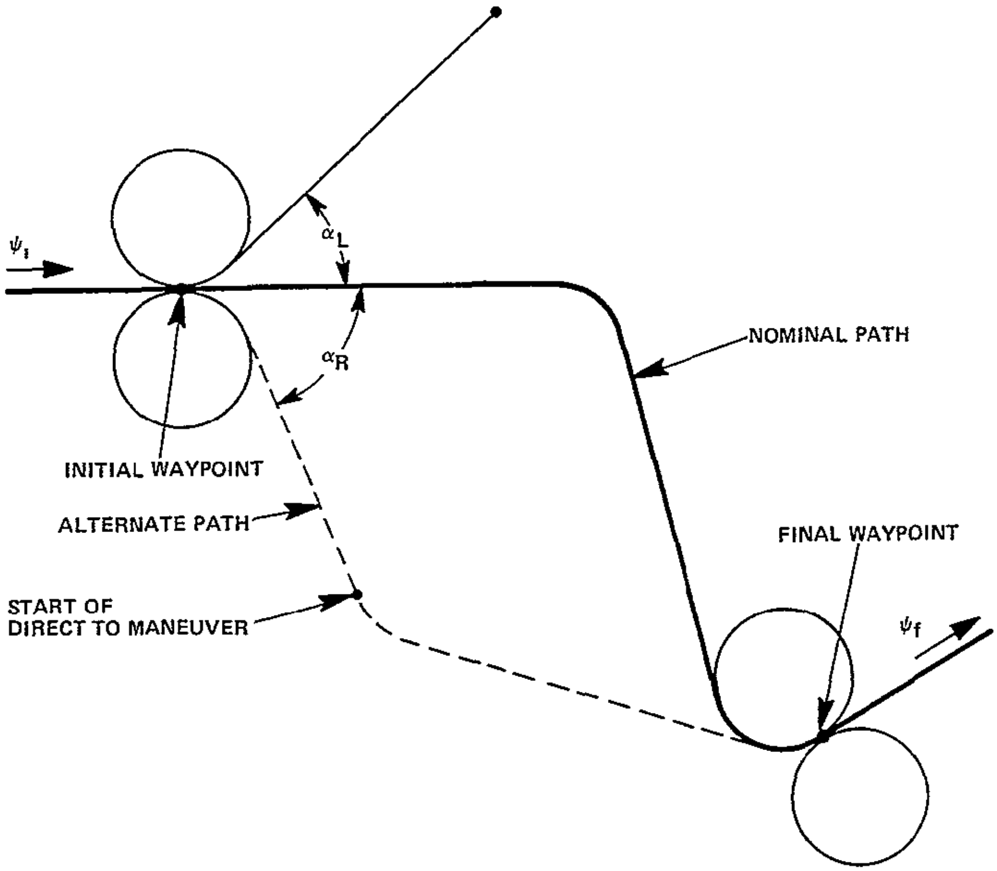

Figure 109
Direct To Delay Fan Model

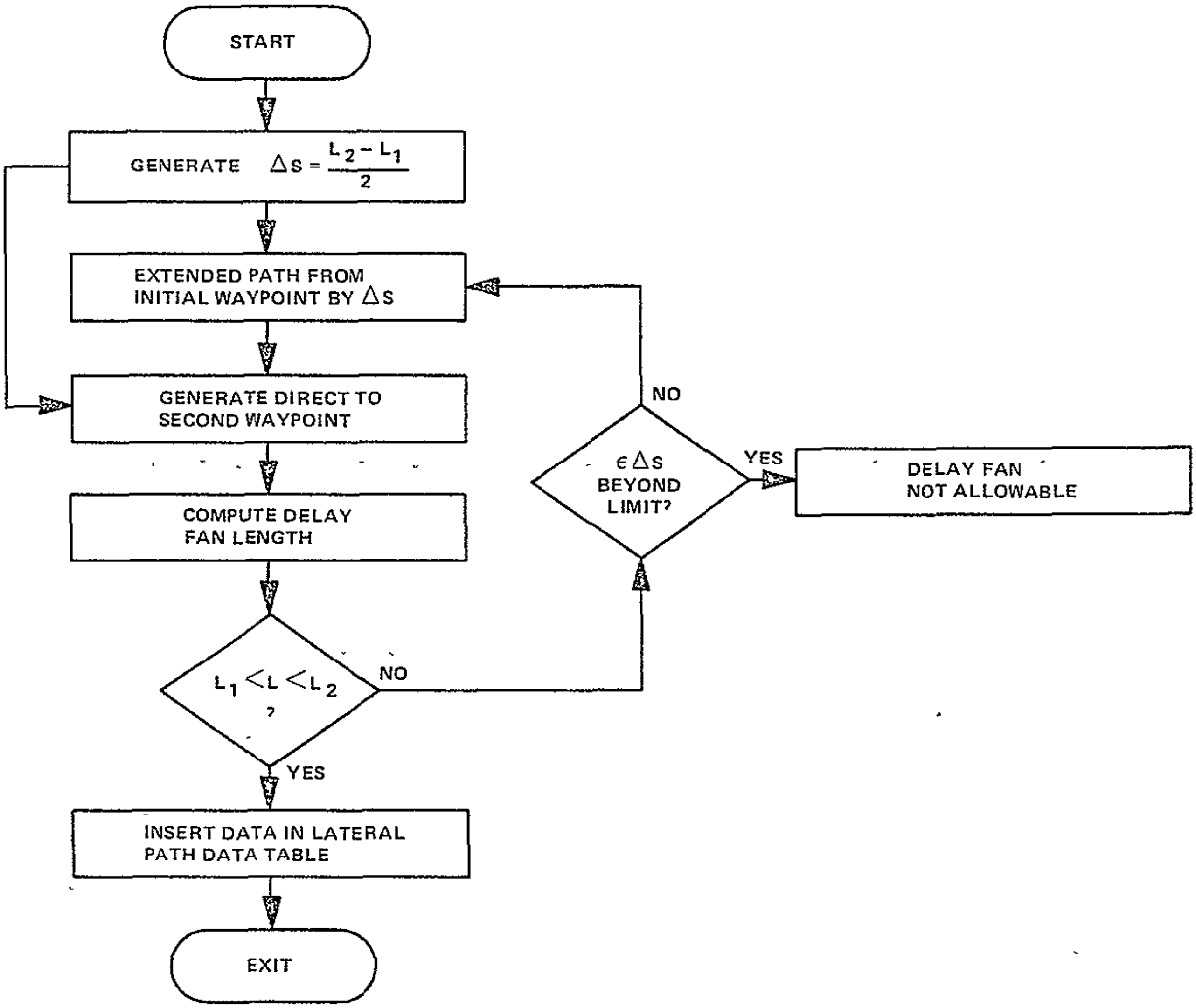

Figure 110
Direct To Delay Fan Flow Chart

Avoidance Areas and Maneuver Boundaries

Restricted areas play a major role in determining path alteration capabilities. By making maneuver area boundaries variable, the path length variations can be severely limited. Changes in the boundaries can be simple shifts of a single boundary or shifts of multiple boundaries so that the maneuver area takes on many different forms. A simple boundary shift capability was incorporated into the VALT 4D system so that delay fan path lengths could be moderately limited. Figure 111 shows how the variable boundary condition was incorporated into the system. When used in conjunction with the Direct To delay fan technique the first turn path can be checked for intersection with the boundary limit in order to determine delay fan acceptability. If found to be unacceptable, the approach can be aborted or the time boundaries of the delay fan area changed to accommodate a flyable delay fan.

Just as important for placing limitations on the delay fan maneuver are avoidance areas. Avoidance areas are defined as avoidance points around which minimum path separation must be maintained. The avoidance point, then, is the center of the avoidance area and the separation distance is the radius. When a delay fan path is generated and passes through the avoidance area, three decisions must be made to generate a new path:

1) Does the new path need to be lengthened or shortened ?

2) How much does the new path need to be lengthened or shortened ?

3) Will the new path interfere with other limits or boundaries placed on the delay fan maneuver ?

An example of how the path can be modified to prevent an avoidance area violation is shown in Figure 112.

Placement of the avoidance area in the delay fan maneuver area is restricted in a way that it cannot be on the nominal path nor on the extension of the inbound heading. This adds practicality to the avoidance area technique as well as simplifying some of the decision process which must take place to generate the delay fan. For the most part, the change in the delay fan path can be made by modifying the straight line segment heading by computing the tangent line from the avoidance area circle to the second turn circle. However, if the first turn radius is larger than the avoidance area radius and the violation of the avoidance area is along the curve of that turn, the decision sequence to determine the amount of modification to the delay fan path is much more complex. A flow chart of the decision process necessary to produce a modified delay fan path around an avoidance area is shown in Figure 113.

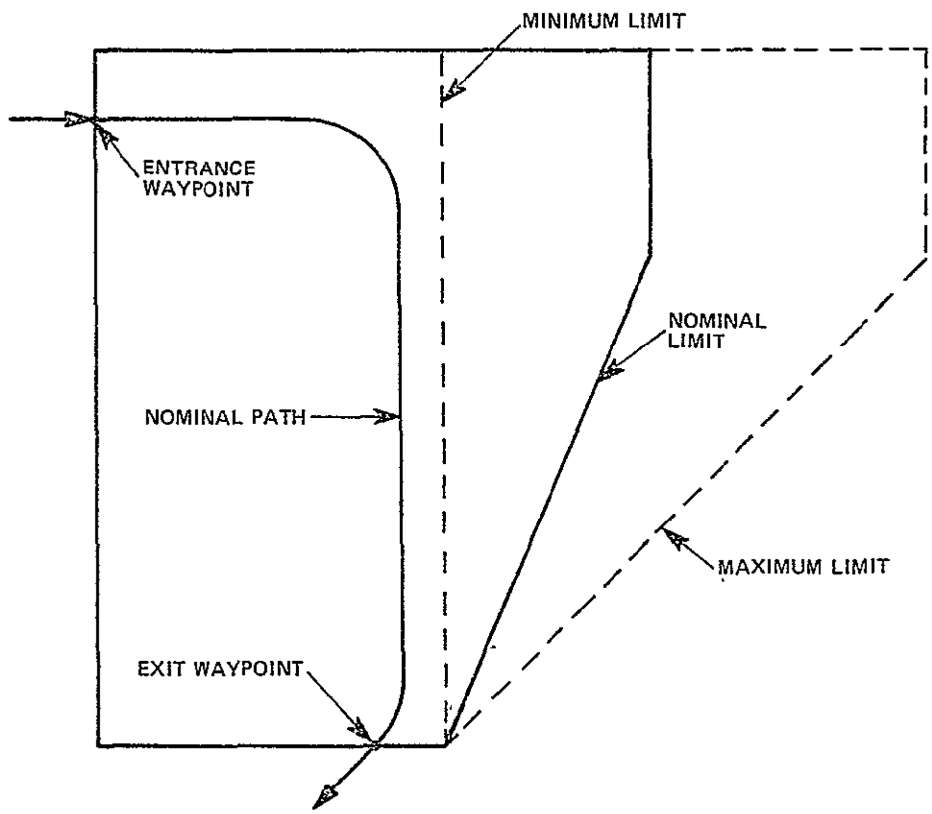

Figure 111
Variable Delay Fan Boundaries

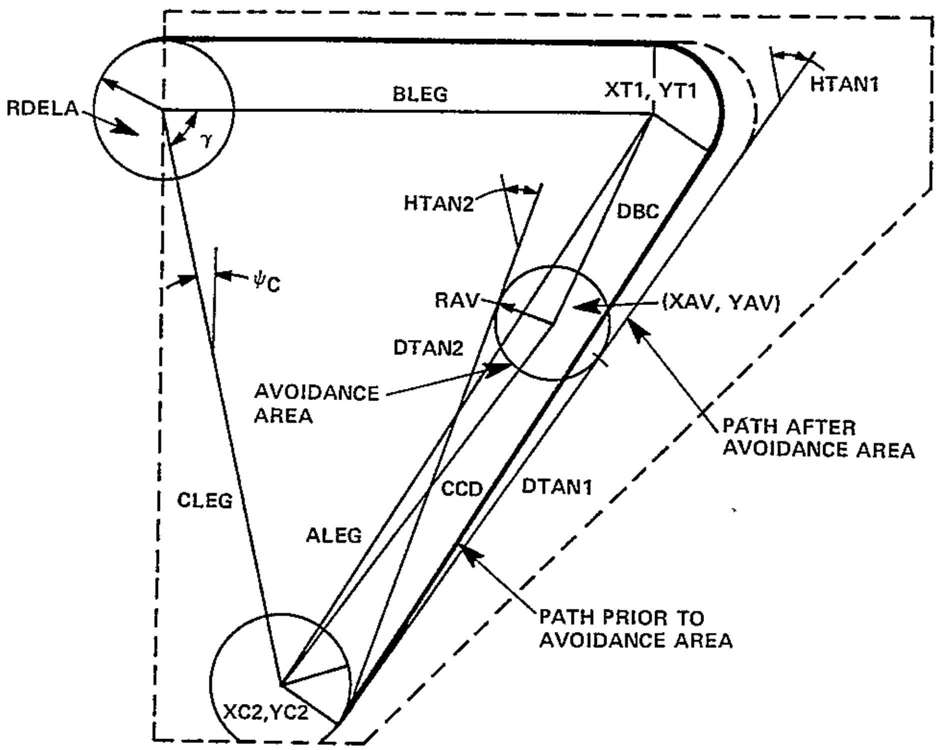

Figure 112
Avoidance Area Variables

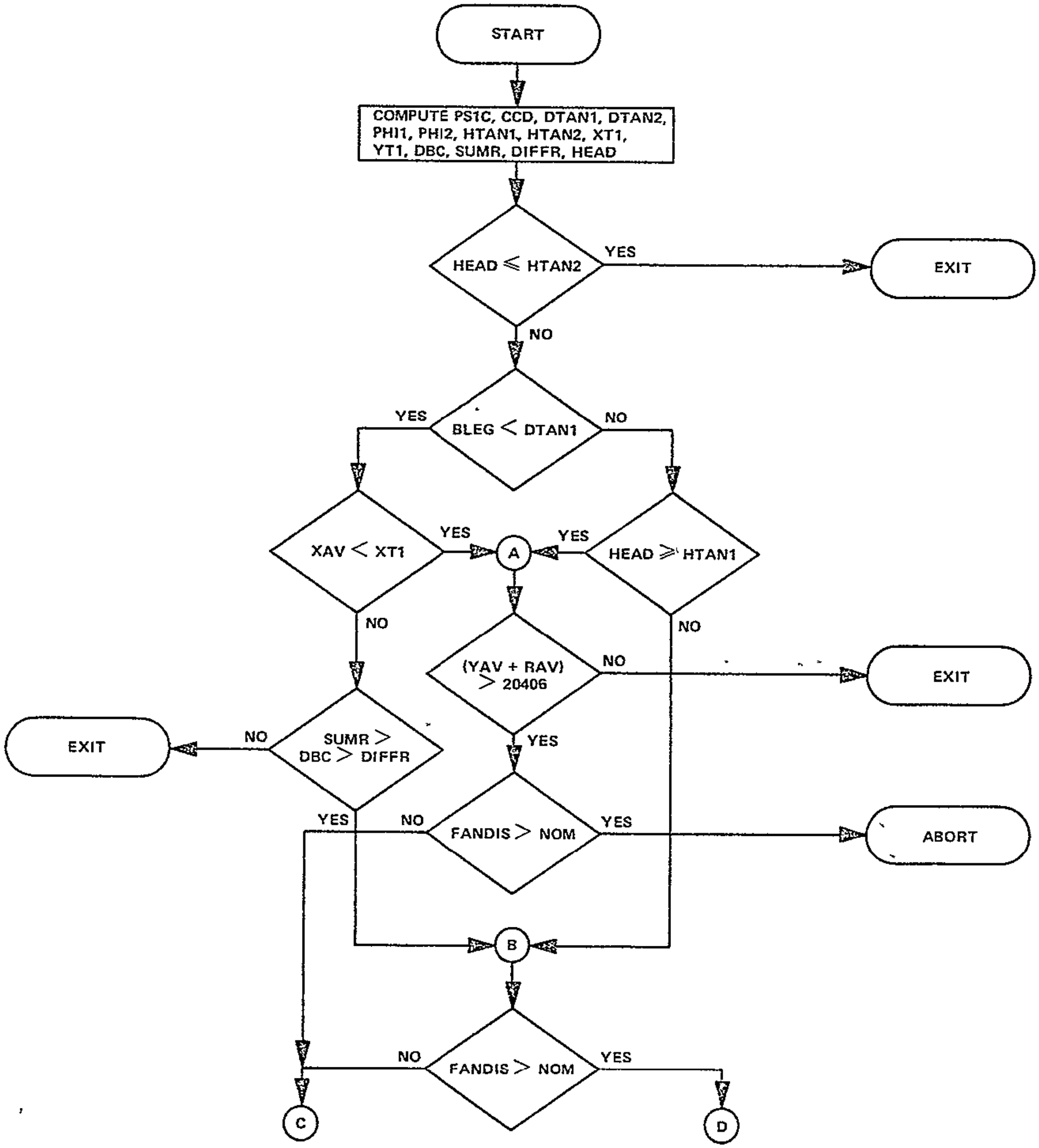

Figure 113
One-Pass Delay Fan Flow Chart
(Sheet 1 of 3)

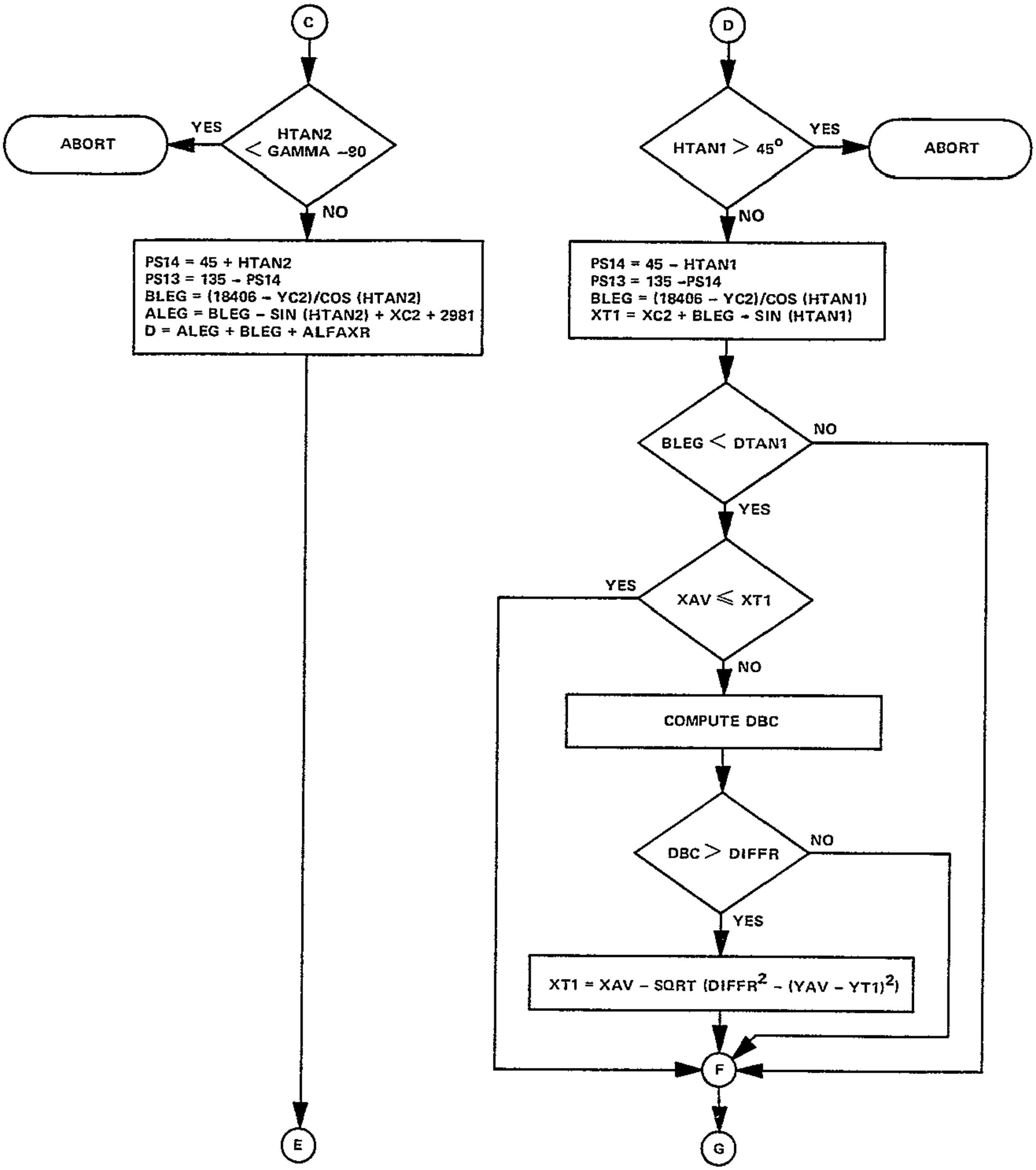

Figure 113
One-Pass Delay Fan Flow Chart
(Sheet 2 of 3)

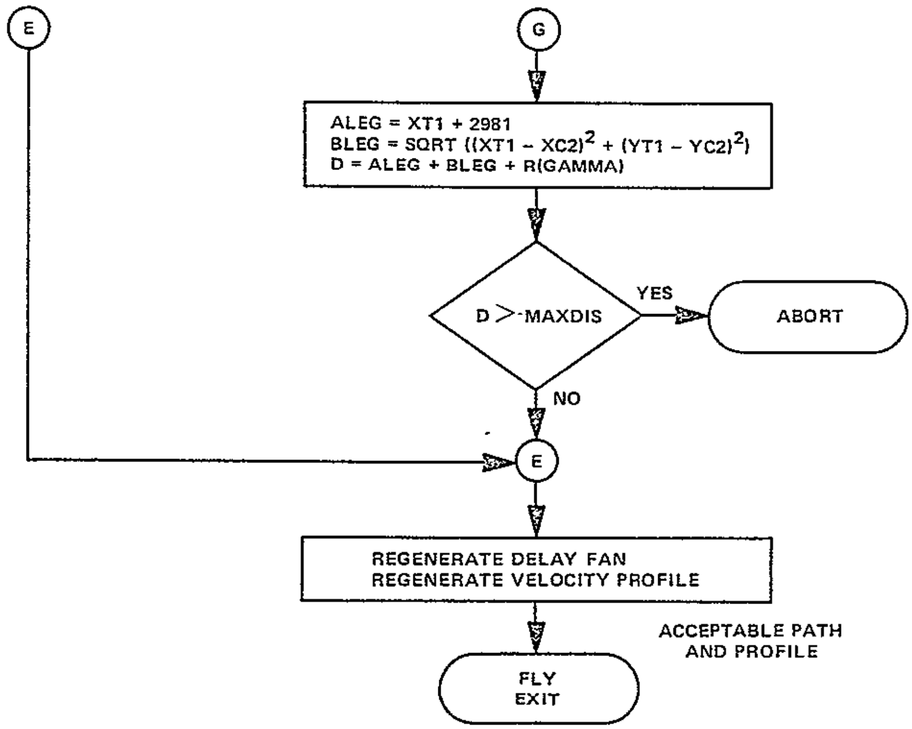

Figure 113
One-Pass Delay Fan Flow Chart
(Sheet 3 of 3)

APPENDIX B

DIRECT TO PATH GENERATION

In the 4D system it is necessary to have a predetermined maneuver to capture the nominal approach path. It is also desirable to have the shortest possible maneuver from one point to another point with any combination of initial and final headings. With these criteria in mind, the Direct To maneuver described in Reference 4 was investigated. This maneuver consists of two circular arc turns of some predetermined radius or radii separated by a single straight line segment. The second circle of the path capture maneuver is tangent to the nominal approach path at the desired capture point. The first circle allows an immediate heading change, when necessary, for tangential capture of the second circle.

VALT Direct To Implementation

It is desirable to have as much flexibility as possible in the Direct To capture maneuver. In Reference 4, the authors propose that the technique be implemented with equal turn radii. This simplifies the computation necessary for generating the capture path, but is directed primarily at the use of fixed wing aircraft which operate over a relatively small speed range during an approach. Because the helicopter is capable of a wide speed range and to incorporate the maximum of flexibility in the capture maneuver, the implementation of the Direct To maneuver with two different radii was undertaken. The two radii are determined by the nominal aircraft velocity at the initial and final points of the maneuver based on the equation

$$R = \frac{V^2}{g \ \mathrm{TAN}\ \phi}$$

Direct To Switching Diagrams

In order to implement a Direct To capture at the 4D path, switching diagrams must be generated. Switching diagrams determine the configuration of the maneuver. The switching diagrams produce an imaginary set of boundaries based on the relative position and heading of the two end points. The configurations of the Direct To capture (turn-straight-turn) are left-straight-right, left-straight-left, right-straight-left, and right-straight-right, or any degenerate case thereof. Reference 4 discusses equations and comparisons necessary to produce switching diagrams for the two turns of equal radii. Changes and restrictions were made in order to implement the Direct To approach with turns of unequal radii.

For simplification of the equations used in the switching diagrams, the positions and headings of the two points are translated and rotated so that the final point coordinates are at the origin of a new coordinate system with the final heading aligned with zero degrees. This rotation makes the position and heading information of the first point absolute relative to the position and heading of the final point. The Direct To path geometry is shown in Figure 114. The turn radii of both turns R_0 and R_f are then normalized to the final turn radius R_f thus producing the normalization factor. The main comparison variables d_0 and d_f are calculated from the equations in Table 3. The format discussed in Reference 4 can then be followed closely with a few modifications for unequal radii.

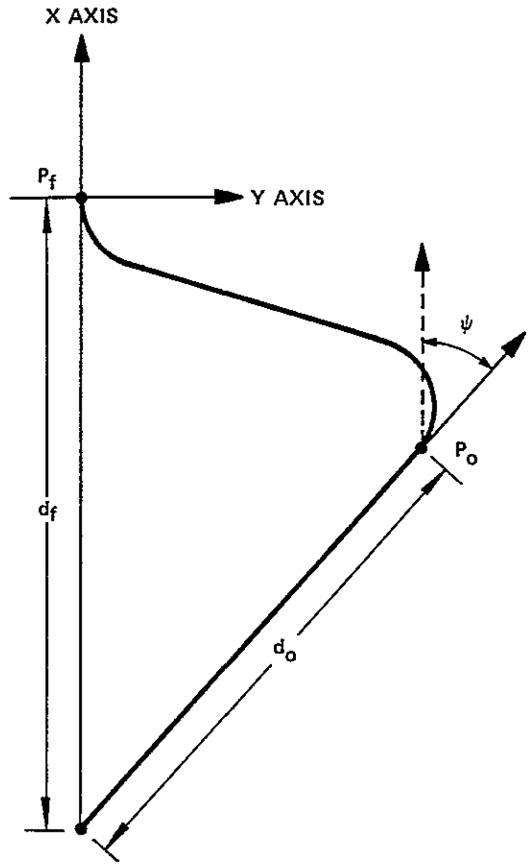

Figure 114
Direct To Path Geometry

TABLE 3

DIRECT TO PATH EQUATIONS

$$d_o = Y/\ (R_f \sin\psi)$$

$$d_f = Y/\ (R_f \tan\psi) - X/R_f$$

$$d_{o\alpha}^{+} = -d_{o\alpha}^{-} = (3 + \cos\psi)/\sin\psi$$

$$d_{o\sigma}^{+} = -d_{o\sigma}^{-} = \tan\ (\psi/2)$$

$$d_{o\beta} = -1/\tan\ (\psi/2)$$

$$d_{o\delta} = d_{o\sigma}^{-} \cos\ \psi - \sin\ \psi - \sqrt{4 - (1 + \cos\psi + d_{o\sigma}^{-}\ \sin\psi)^2}$$

$$d_{f\sigma}^{+} = -d_{f\sigma}^{-} = \tan\ (\psi/2)$$

$$d_{f\gamma}^{+} = \begin{cases} (3\cos\psi + 1)/\sin\psi \\ d_o \cos\psi + \sin\psi + \sqrt{4 - (-d_o \sin\psi + \cos\psi + 1)^2} \\ \qquad\qquad \text{for } d_{o\sigma}^{-} \le d_o \le d_{o\alpha}^{+} \end{cases}$$

$$d_{f\gamma}^{-} = d_o \cos\psi - \sin\psi - \sqrt{4 - (d_o \sin\psi + \cos\psi + 1)^2}$$

$$d_{f\delta}^{+} = d_o \cos\psi - \sin\psi + \sqrt{4 - (d_o \sin\psi + \cos\psi + 1)^2}$$

$$d_{f\delta}^{-} = d_o \cos\psi + \sin\psi - \sqrt{4 - (-d_o \sin\psi + \cos\psi + 1)^2}$$

$$R_{01} = (d_o - \frac{2}{\sin\psi}) \cdot \tan\psi/2$$

$$R_{02} = \frac{d_o}{\tan\psi/2}$$

$$R_{03} = (\frac{d_f - 1}{\cos\ \psi} - d_o) \cdot \tan\ (\frac{90 - \psi}{2})$$

$$R_{04} = (\frac{-d_f - 1}{\cos\psi} + d_o) \cdot \tan\ (\frac{\psi - 90}{2})$$

$$R_{034} = \frac{d_f - 1}{2}$$

$$d_{fmin} = |d_{o\sigma}^{-}| + 2$$

$$-d_{f3} = 2 - d_{o\beta}$$

The switching diagrams for $R_o = R_f = \alpha = 1$ are used for the development of a flow chart of inequality tests. These tests are used to determine a lateral flight configuration for the given initial point P_o, final point P_f and heading angle ψ. Equations of the borders and switching points for equal radii are given in Reference 4 and are also shown in Table 3. Variables necessary to perform the inequality comparisons are calculated and stored for later use. It should be noted here that when doing the inequality comparisons with equal radii it is always possible to perform a Direct To maneuver. All distances and heading angles are covered by the four possible maneuvering configurations. However, this does not hold true for unequal radii, as will be shown later. Figure 115 shows one switching diagram for equal radii generated by this method and the maneuvers which are possible in each area for a heading difference of 45 degrees.

Conditions Where $\alpha > 1$ - For lateral patterns with $R_o > R_f$ or $\alpha > 1$, changes are necessary in the inequality comparisons so that some areas of the switching diagram will be restricted from any possible maneuvers. These areas exist where one turning circle is entirely contained in the other turning circle, thus eliminating mutually tangent lines to both circles. Others exist where the length of the separating straight segment is insufficient to make the required speed change.

Restrictions are handled by setting maximum limits on the initial turn radius. For instance, if the value $d_{o\alpha}^{+} < d_o < d_{o\alpha}^{-}$ the maximum initial radius allowed is a function of d_o and the heading angle ψ. The equation for that limit is then:

$$R_{o1} = (d_o - 2/\sin \psi) \cdot \tan \psi/2$$

This condition is satisfactory for $|d_f| >> d_{o\alpha}^{+}$ since the straight segment length is adequate for necessary speed changes.

In the region of $d_f < d_{f\delta}^{+}$ and $d_o > d_{o\sigma}^{+}$ the maximum allowable initial radius R_{o2} is again a function of only d_o and ψ. This is the case when $\frac{3\pi}{4} < \psi < \pi$. For $\psi < \frac{3\pi}{4}$ the equation for R_{o2} gives very large radius values. In the region of $d_o < d_{o\sigma}^{-}$ and $d_f > d_{f\sigma}^{+}$ the equation for R_{o2} is also applicable. The equation used for R_{o2} is:

$$R_{o2} = d_o \,/\, (\tan \psi/2)$$

It can further be shown that when $R_{o2} = \alpha$, then $R_{o2} = d_o/d_{o\sigma}^{+}$ from the equation of $d_{o\sigma}^{+}$.

The situation changes when $d_{o\sigma}^{-} < d_o < d_{o\alpha}^{+}$ and $d_f > d_{f\gamma}^{+}$. In this area the possibility of the turn circle overlapping is much higher, and because of their orientation, the maximum limit for the initial radius must be a function of both d_o and d_f as well as the heading angle ψ.

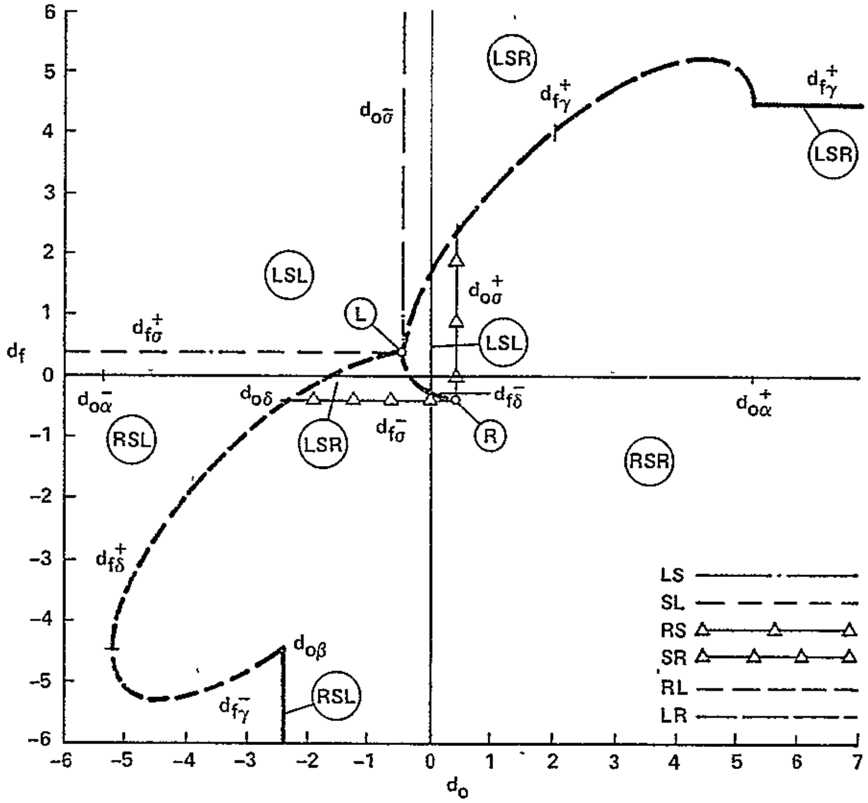

Figure 115
A Direct To Switching Diagram

The equation for this limiting radius is:

$$R_{03} = \left(\frac{d_f - 1}{\cos \psi} - d_o\right) \cdot \tan \left(\frac{90 - \psi}{2}\right)$$

This region also requires a limit be put on the value $d_{f\gamma}^{+}$. This is due primarily to the containment of one turn circle in another. In the case of $\psi = \pi/2$, the value of $d_{fmin} = 3$, and for $\psi > \pi/2$ the value of minimum value for d_f is:

$$d_{fmin} = |d_{o\bar{\sigma}}| + 2$$

It can be shown that $d_{fmin} > d_{f\gamma}^{+}$ in all cases for $\psi \geq \pi/2$ and that this assumption is valid for all cases.

The derivation of the limit R_{04} on the initial turn radius is based primarily on the case of $d_{o\bar{\alpha}} < d_o < d_{o\sigma}^{+}$ and $d_f < d_{f\bar{\gamma}}$ and $d_f < d_{f\bar{\sigma}}$. The equation for R_{04} is again a function of d_o and d_f along with the heading angle ψ. The equation for R_{04} is:

$$R_{04} = \left(\frac{d_f + 1}{\cos \psi} - d_o\right) \cdot \tan \left(\frac{90 - \psi}{2}\right)$$

The value of $d_{f\bar{\gamma}}$ and $d_{f\bar{\sigma}}$ are subject to the restriction that if $d_{f\bar{\gamma}} > d_{f3} < d_{f\bar{\sigma}}$, then $d_f < d_{f3}$. The equation for computing d_{f3} is:

$$d_{f3} = d_{o\beta} - 2$$

If these requirements are not satisfied, then the decision is made that the Direct To cannot be computed from that point.

The final restriction on the initial radius is unique to heading differences of 90 degrees between initial and final points. This value replaces R_{03} and R_{04} whenever that heading difference exists. The equation for R_{034} is:

$$R_{034} = (d_f - 1)/2$$

The heading is not used in this equation since the $\tan \pi/2 = \infty$. The value of the initial radius limiter is then strictly a function of d_f. In this special case, the values $d_{fmin} = -d_{f3} = 3$. This holds true for both areas $3 < d_f < -3$ with the previously discussed boundaries on d_o.

<u>Conditions Where $\alpha < 1$</u> - The case of $R_o < R_f$ or $\alpha < 1$ is yet simpler than that for $R_o > R_f$. In any position where $d_{o\bar{\alpha}} > d_o > d_{o\alpha}^{+}$ and d_f is any value, it is possible to achieve one of the four basic configurations if $\psi < \pi/2$. With slight modifications to some boundaries the same result can be achieved for

$o < \psi < \pi$. If d_o is positive, its magnitude must be greater than d_{01} in the range $d_{f\bar{\sigma}} < d_f < d_{f\bar{\gamma}}^{+}$. The border d_{01} thus replaces the border $d_{o\bar{\sigma}}^{+}$ and is a product of the equation:

$$d_{01} = \frac{2}{\sin \psi} - \frac{\alpha}{\tan \pi/2}$$

The area bounded by $0 < d_o < d_{01}$ and $d_{f\bar{\sigma}} < d_f < d_{f\gamma}^{+}$ is made an exclusion area because speed changes necessary to fly the second turn circle cannot be accomplished in the small distance available on the straight segment.

For d_o less than zero, the flyable regions are all but that bounded by $d_{o\bar{\sigma}} < d_o < o$ and $d_{f\bar{\delta}} < d_f < d_{f\bar{\gamma}}^{+}$. No other restrictions are necessary.

Flow Charts - Five equations are sufficient to regulate the size of R_o when $\alpha > 1$. Flow-charting of the decision table for $R_o > R_f$ is simpler than that for $R_o = R_f$ since the restrictions reduce the area where flyable paths can be generated, thus eliminating some of the switching boundaries. The flow-charting of the cases of $R_o < R_f$ is simpler yet since there are fewer restrictions on those cases. The Direct To path capture maneuver flow chart is shown as Figure 116.

Path Generation

Once the Direct To configuration has been determined, the computation of the turn angles and the straight segment length and direction is relatively simple. Table 4 gives the equations used to compute the following Direct To parameters:

- Straight segment distance based on the center-to-center distance of the two circles and their relation to the straight segment (both on one side of the line or one on each side of the line).
- Straight segment heading based on the tangent line of two circles always being perpendicular to their radii.
- The initial and final turn angles based on the heading change between the straight segment heading and the headings at the two end points.

With the basic values computed it is then a simple matter to rotate the results back into the original coordinate system in order to generate the proper heading and positions. The resulting parameters are inserted into the existing VALT lateral path data table for use with the lateral path program.

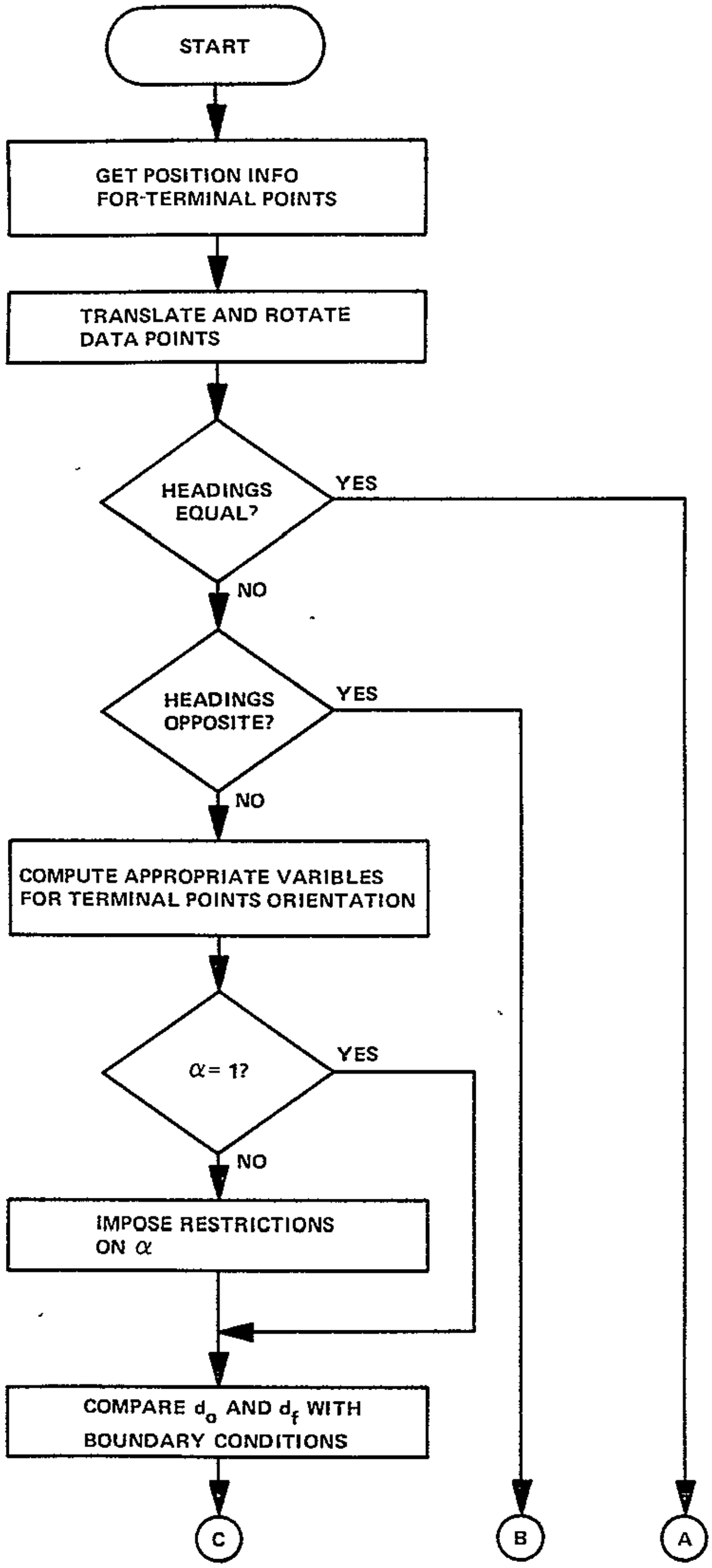

Figure 116
Direct To Capture Flow Chart
(Sheet 1 of 4)

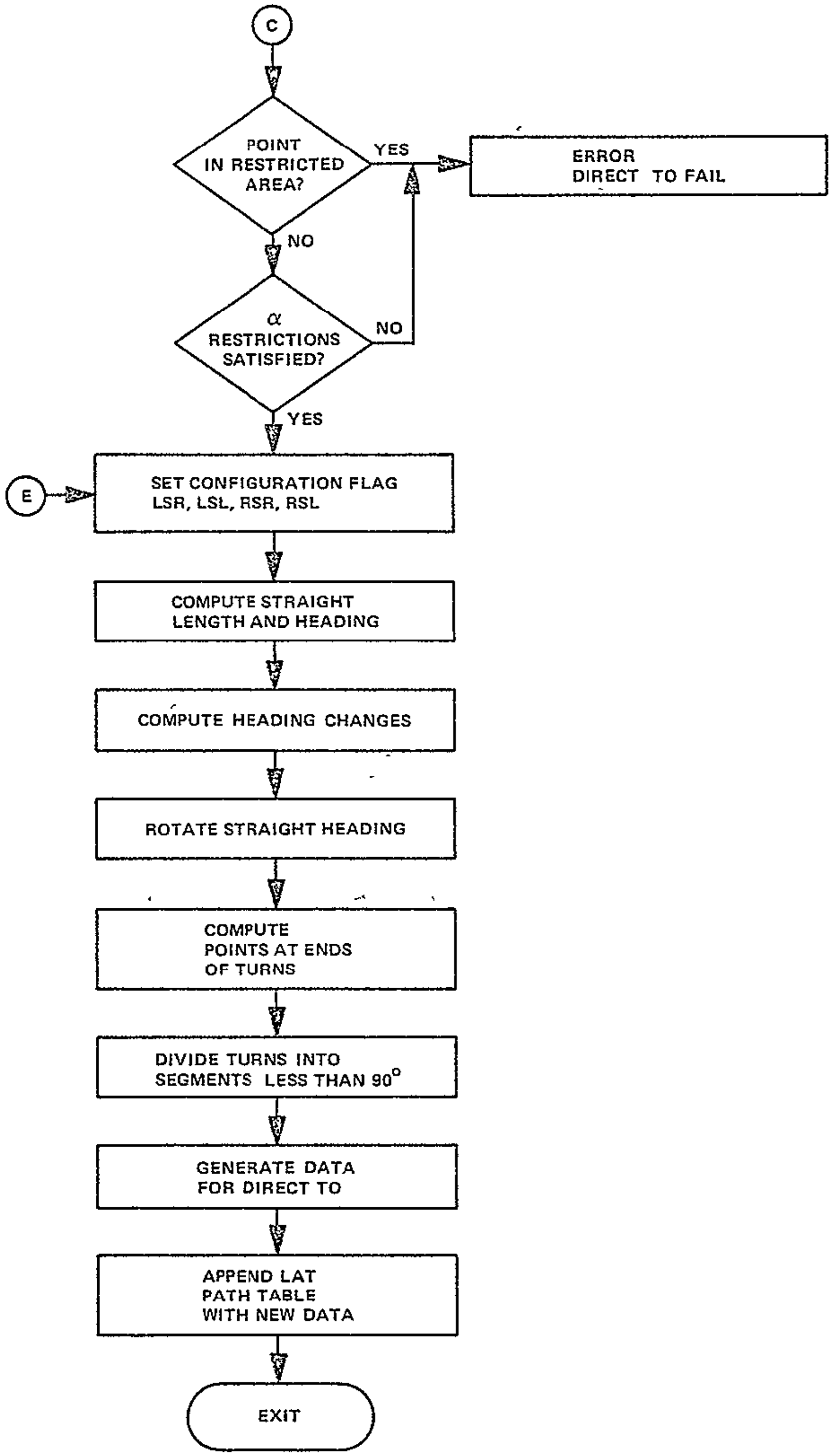

Figure 116
Direct To Capture Flow Chart
(Sheet 2 of 4)

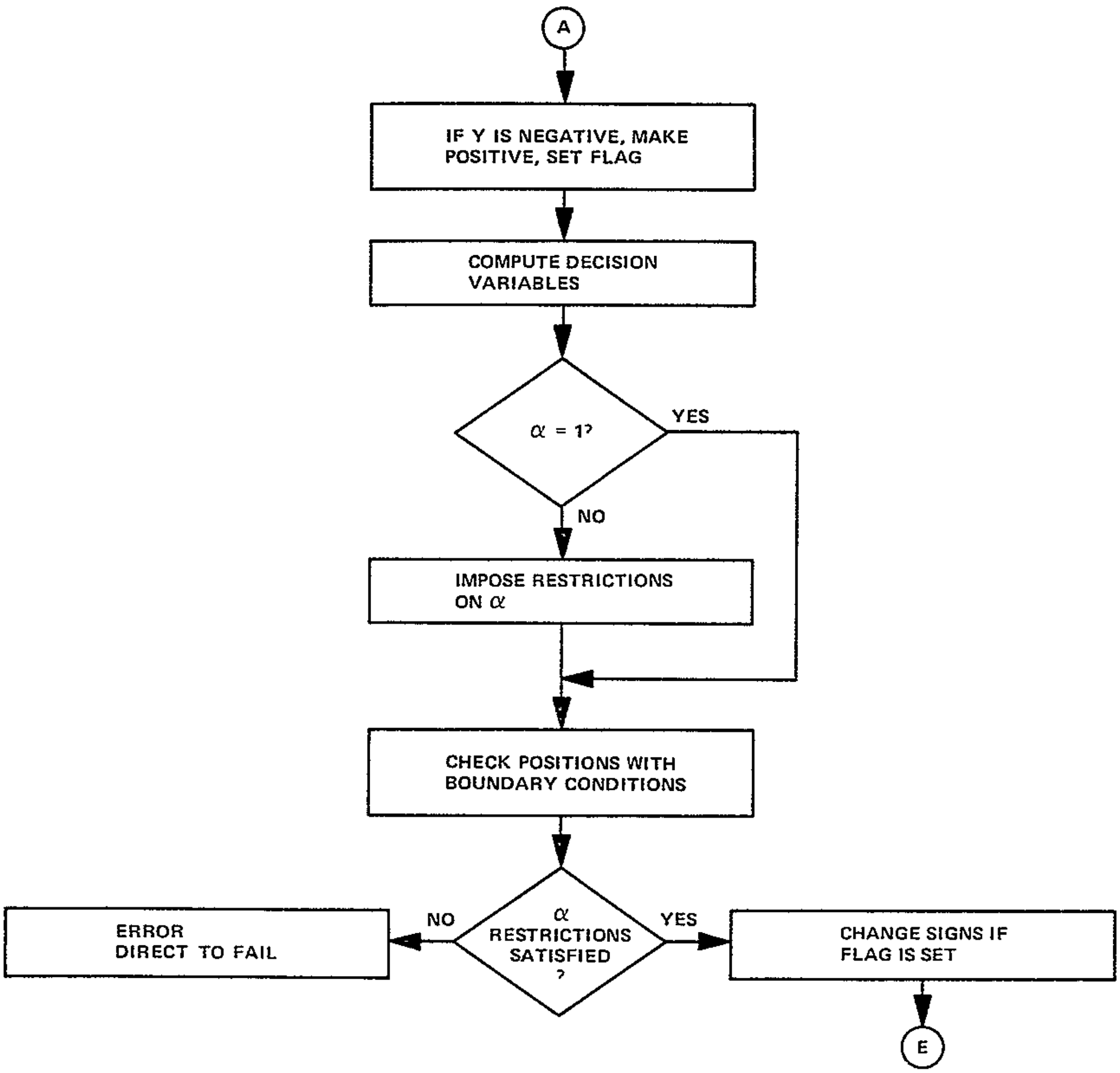

Figure 116
Direct To Capture Flow Chart
(Sheet 3 of 4)

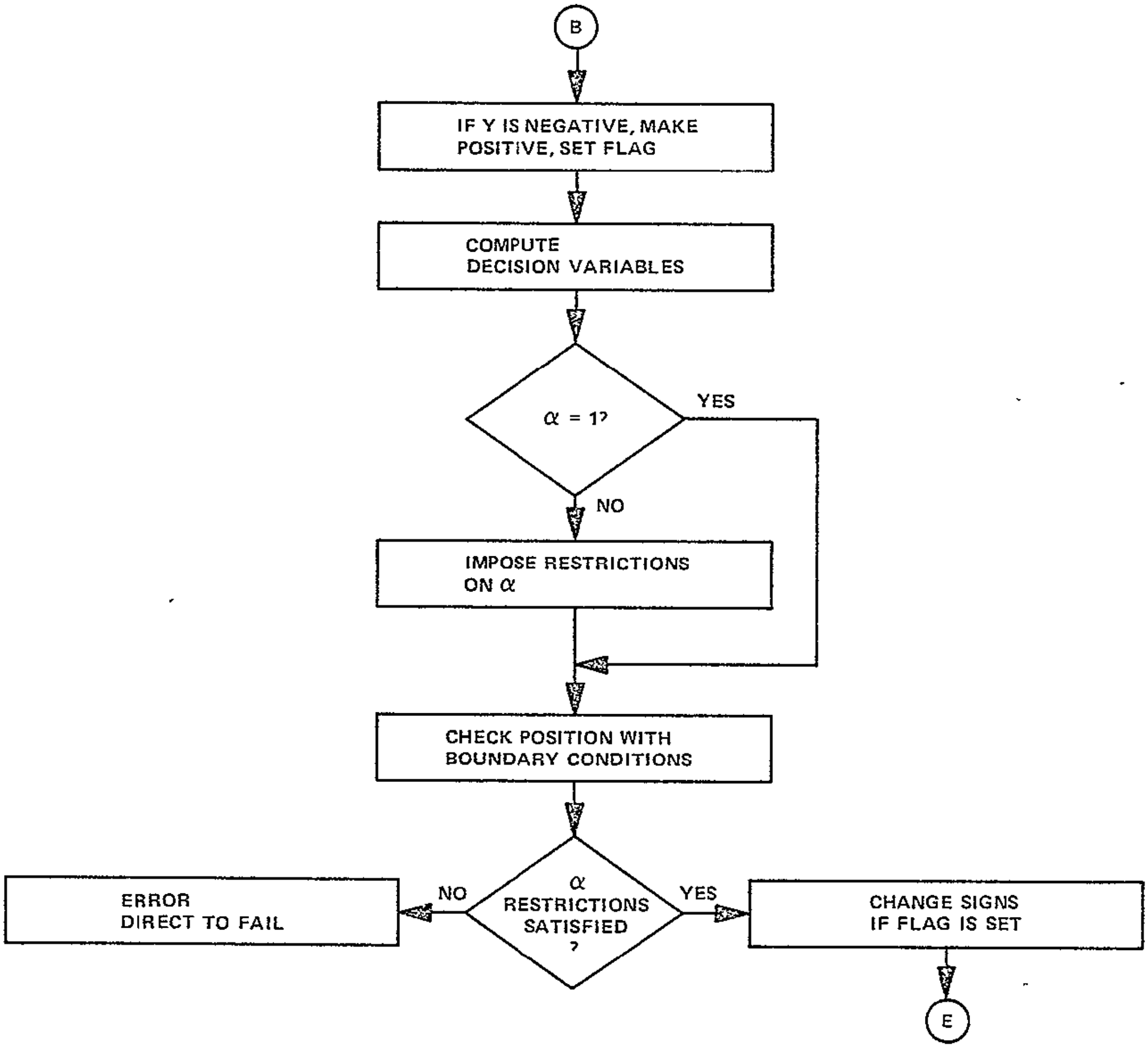

Figure 116
Direct To Capture Flow Chart
(Sheet 4 of 4)

TABLE 4
DIRECT TO PARAMETER EQUATIONS

Pattern Type	$\overline{P_1P_2}$ Straight Segment Length	ψ_s Straight Segment Heading	ψ_1 Initial Turn	ψ_f Final Turn
RSR	$\left[(x-R_1 \sin \psi)^2 + (R_f-R_1 \cos \psi-Y)^2 - (R_1-R_f)^2\right]^{1/2}$	$\tan^{-1} \frac{R_f - R_1 \cos \psi - Y}{-x + R_1 \sin \psi}$ $+ \tan^{-1} \frac{R_1 - R_f}{\overline{P_1P_2}}$	$\psi_s - \psi$: $\psi_s > \psi$ $\psi_s + 2\pi - \psi$: $\psi_s < \psi$	$2\pi - \psi_s$ $\psi_s > 0$ 0 $\psi_s = 0$
RSL	$\frac{R_1 + R_f}{\tan \psi'}$, where $\psi' = \sin^{-1}\left[\frac{R_1 + R_f}{\sqrt{(-x+R_1 \sin \psi)^2 + (R_f+R_1 \cos \psi+Y)^2}}\right]$	$\psi_s = \begin{cases} \psi_1 + \psi'. & \psi_1 + \psi' < 2\pi \\ \psi_1 + \psi' - 2\pi: & \psi_1 + \psi' > 2\pi \end{cases}$ where $\psi_1 = \tan^{-1} \frac{-R_f - R_1 \cos \psi - Y}{-x + R_1 \sin \psi}$	$\psi_s - \psi$: $\psi_s \geq \psi$ $\psi_s + 2\pi - \psi$: $\psi_s < \psi$	ψ_s
LSL	$\left[(x+R_1 \sin \psi)^2 + (-R_f+R_1 \cos \psi-Y)^2 - (R_1-R_f)^2\right]^{1/2}$	$\tan^{-1} \frac{-R_f + R_1 \cos \psi - Y}{-x - R_1 \sin \psi}$ $-\tan^{-1} \frac{R_1 - R_f}{\overline{P_1P_2}}$	$\psi - \psi_s$. $\psi \geq \psi_s$ $\psi + 2\pi - \psi_s$: $\psi < \psi_s$	ψ_s
LSR	$\frac{R_1 + R_f}{\tan \psi'}$, where $\psi' = \sin^{-1} \frac{R_1 + R_f}{\sqrt{(x+R_1 \sin \psi)^2 + (R_f+R_1 \cos \psi-Y)^2}}$	$\psi_s = \begin{cases} \psi_1 - \psi' & \psi_1 - \psi' \geq 0 \\ \psi_1 - \psi' + 2\pi: & \psi_1 - \psi' < 0 \end{cases}$ where $\psi_1 = \tan^{-1} \frac{R_f + R_1 \cos \psi - Y}{-x - R_1 \sin \psi}$	$\psi - \psi_s$: $\psi \geq \psi_s$ $\psi - \psi_s + 2\pi \cdot$ $\psi < \psi_s$	$2\pi - \psi_s$: $\psi_s > 0$ 0: $\psi_s = 0$

APPENDIX C

VELOCITY PROFILE AND TIME CONTROL

One of the major tasks contained in the development of a 4D capability for the VALT System is the generation of a suitable velocity profile. The general approach that has been taken in this study involves the use of the existing software to the maximum extent possible. The major difference occurs in the generation of the data to define the profile. The manual creation and insertion of velocity profile data is not acceptable for 4D approaches since the velocity profile is no longer independent from the lateral path due to the time waypoint restrictions. A technique has therefore been developed to automatically generate the required velocity profile data and to insert that data into a table for use in a time reference velocity control routine.

In order to develop the most flexible 4D system for VALT, a decision was made to allow the use of multiple time control waypoints along the approach path. Since none of the systems investigated addressed the problem of velocity profile generation for multiple time control waypoints, a technique had to be generated to handle this situation.

Waypoint Crossing Velocity Selection

A study of published velocity profile generation schemes indicated that all the suggested techniques assume a single approach segment defined by two position waypoints and a single time increment. The time increment and the path distance are then combined with a desired entry and exit velocity to define a suitable velocity profile. When multiple time control waypoints are involved, however, the generation of waypoint crossing velocities must be handled by the software to preclude velocity, distance and time incompatibilities. The waypoint crossing velocity then becomes the entry velocity for one time control zone and the exit velocity for the preceding time control zone. Once these velocities are determined, the existing profile generation techniques can be used to generate the overall velocity profile.

The generation of the total velocity profile is based on the following assumptions:

- The 4D approach consists of a Direct To maneuver to a selected starting point on a nominal approach path, the nominal approach path itself and a final fixed path for the terminal deceleration maneuver. The desired velocities for entering the nominal approach path and the terminal deceleration maneuver are specified by the user.

- Time control waypoints are specified by the user only along the nominal approach path. The time to traverse the terminal deceleration zone is fixed by the type of deceleration profile used. The time to traverse the Direct To zone is calculated based on the present time of day and the desired time to arrive at the nominal path starting point.

- The nominal approach path contains areas where path alterations are allowed. Each of these areas is bounded by some form of limit variable that is manually entered into the software. The end points of any approach path section that may be altered must be defined as time control waypoints. Any approach path sections that do not contain areas of allowable maneuver are considered as fixed path sections that must be traversed by velocity control only.

- Waypoint crossing velocities are computed by the software using a weighted average technique. For any time control zone, an average velocity can be computed based on the path distance and the allowable traverse time. The crossing velocity between two adjacent time control zones should fall between the two average velocities in order to minimize the number of accelerations and decelerations in the profile. This condition can be overridden, however, by the manual insertion of minimum and maximum velocity limits placed on a particular waypoint section. That is, if a velocity limit is placed on a waypoint section, then its entrance and exit velocities cannot exceed that limit. This then forces the waypoint crossing velocities for a given waypoint section to be within the velocity limits. The crossing velocity is computed as follows:

$$V_x = \frac{V_1 t_1 + V_2 t_2}{t_1 + t_2} \leq V_{max} \text{ and } \geq V_{min}$$

where

V_x = crossing velocity

V_1 = average velocity for zone 1

V_2 = average velocity for zone 2

t_1 = desired time to traverse zone 1

t_2 = desired time to traverse zone 2

The crossing velocity is therefore biased toward the average velocity of the shorter time zone within the minimum and maximum velocity constraints. This bias is necessary since the shorter time zone will be less able to handle any accelerations or decelerations that may be required. For each sector defined by two waypoints, an average velocity can be calculated based on the nominal path length and the time difference between the waypoints. The waypoint crossing velocities are then computed using the equation shown above.

Three-Segment Velocity Profile Techniques

Two types of single time zone profile generation techniques were investigated. The first technique involves two speed changes separated by a constant speed segment while the second technique uses two constant speed segments separated by a single speed change. In both cases, constant, but not necessarily equal, accelerations and decelerations were assumed.

<u>Dual Speed Change Technique</u> - The first method studied is discussed in Reference 3. The basic three-segment pattern for this technique consists of a speed change, a constant speed, and a speed change. The boundaries of each three-segment velocity profile are two adjacent time waypoints, thus making the entire flight path a series of three-segment profiles.

This method is implemented by the use of all known data: time, distance, and velocity for each waypoint and acceleration (preloaded for positive and negative speed changes). The first order of business is to determine the sign of the acceleration segments. This is done by computing the distances L_1 and L_2, as shown in Figure 117, and comparing them with the path section length L to determine the profile configuration. The values for the accelerations, a_1 and a_3, are then used along with the waypoint information and the section velocity limits in the general equation:

$$V_e^2\left(\frac{1}{2a_3}-\frac{1}{2a_1}\right)+V_e\left(T+\frac{Vi}{a_1}-\frac{Vf}{a_3}\right)+\left(\frac{Vf^2}{2a_3}-\frac{Vi^2}{2a_1}-L\right)=0$$

in order to find the intermediate velocity V_e. With V_e known, it is a simple algebraic operation to find times at which speed changes begin and finish. The velocity profile data are then stored in a velocity data table.

Note that, except for a few special cases, every waypoint is preceded and followed by an acceleration or a deceleration. This turns out to be the chief objection to using this technique in a multiple waypoint application, since there is a high probability that a transition from an acceleration to a deceleration, or vice versa, will take place at every waypoint. Since the time to arrive at a waypoint is the critical parameter in the 4D system, the approach to the waypoint should be as simple as possible to reduce pilot workload and increase overall system accuracy. Better overall performance would probably be attained if a constant speed were held through the waypoint. For this reason, a single speed change technique was investigated.

Single Speed Change Technique - In order to combat adjacent speed changes and speed changes at waypoints, a different three-segment profile is defined by two constant speed segments separated by a single speed change segment. The same boundary conditions hold true for this method as for the previous method. The computation of the three-segment profile is simpler since it can be done independent of the acceleration limits. A constant speed change assumption allows a midpoint in the acceleration segment to be chosen as a reference time. In solving for T_1 in Figure 118, the areas A and B can be neglected since they are equal. The equation for solution of this profile then becomes:

$$T_1\,(V_2 - V_1) + (V_1T - L) = 0$$

The times T_a and T_b are then dependent on the acceleration limit for either positive or negative speed changes. The time T_1 is, however, still independent of the acceleration limit.

When used exclusively, this technique has some inherent disadvantages. Since the method of selecting the waypoint crossing velocities sets these velocities between the two adjacent average velocities, it is conceivable that both crossing velocities could be higher than the average velocity for that section. This condition precludes the use of the single speed change profile since the profile requires that the two boundary velocities be above and below the average velocity, thus forcing the speed change segment to cross the average velocity value. If this condition does not exist, the distance covered by the closest velocity profile will be either too long or too short compared with the desired

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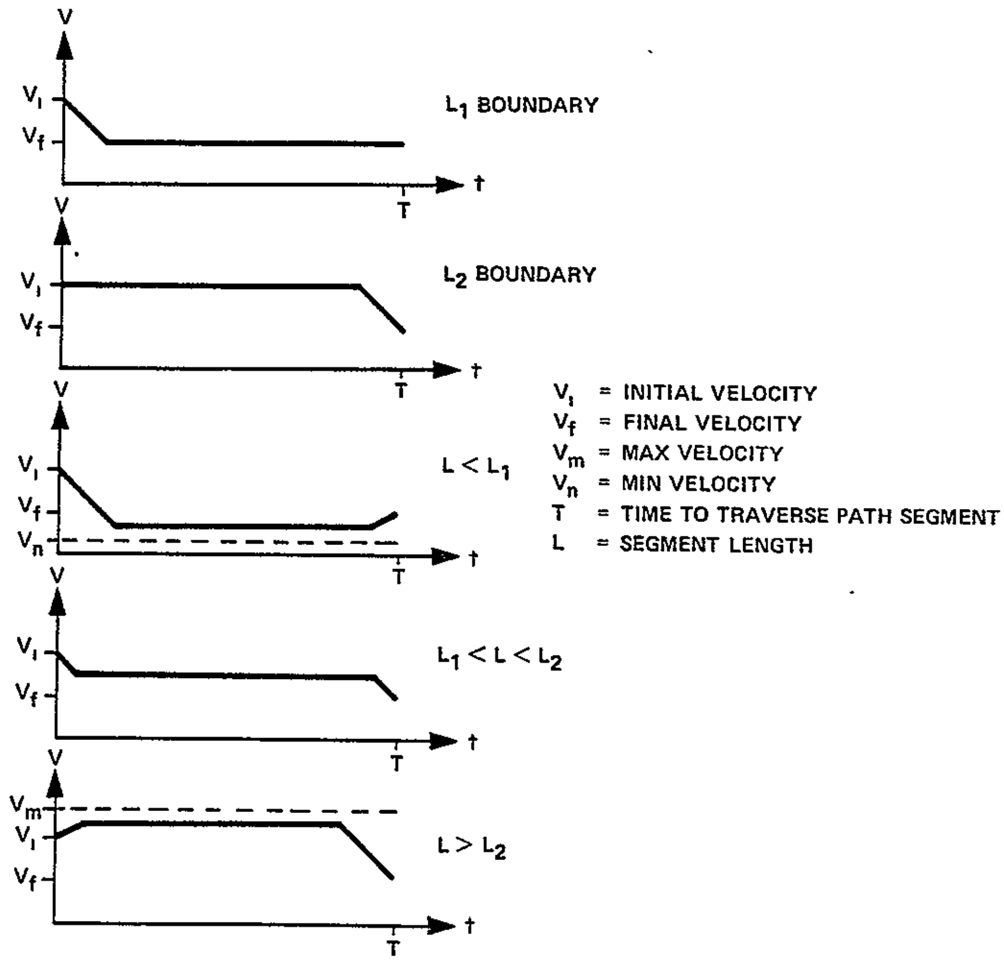

Figure 117
Three Segment Velocity Profile Limits

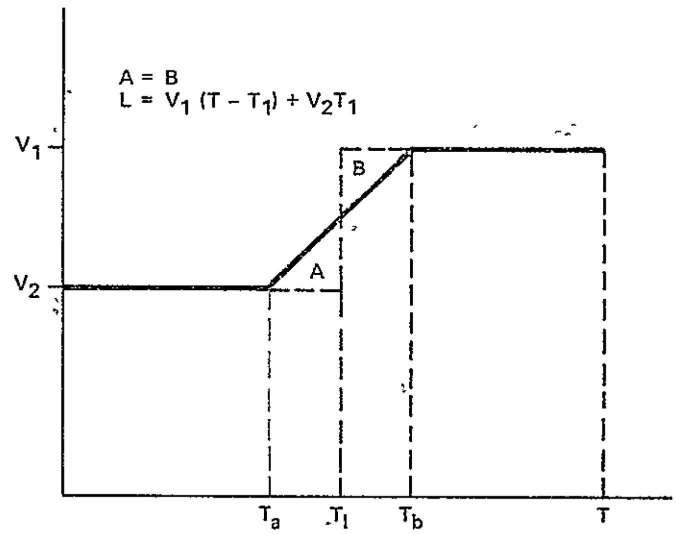

Figure 118
Single Speed Change Technique

distance. The condition goes one step further and shows that the section length L must lie between the boundary lengths L_1 and L_2 for this technique to work. Thus, this technique is not able to completely define all profiles when used with the crossing velocity computation technique previously discussed.

<u>Combination Technique</u> - In order to obtain a solution for all possible velocity profiles, a combination of the dual speed change technique and single speed change technique along with path alteration was considered. The combination of techniques would be based on the following ground rules:

1) Compute, where possible, the single speed change technique for each segment.

2) If not possible, use the dual speed change technique for that particular section.

3) If speed or distance limits are still exceeded, check to see that path alteration is allowed in that section and alter the path as required. If path alteration is not allowed, or if the degree of alteration is not sufficient, then an approach abort situation exists. This technique minimizes the number of accelerations at waypoints and allows path lengths outside the bounds of L_1 and L_2. If none of the conditions can be satisfied, then the path is considered to be unflyable and a message would be displayed to alert the pilot. A flow chart for the velocity profile generation technique is shown as Figure 119.

Time Error Control

The aircraft must be controlled along the flight path subject to the velocity profile just defined. A simple control law has been formulated to generate the velocity commands required to close out time errors. The technique selected uses a real time clock and an estimate of the time required to fly the remaining path distance. The clock is used to compare present time of day with the desired time of arrival in order to generate actual time to go. The velocity profile data table provides velocity information as a function of time; therefore, the velocity profile can be integrated until the value equals the remaining distance to go along the nominal path. The time interval over which this integration is evaluated is the time required to complete the nominal approach. A time error term, Δt, is computed as the difference between the time required to complete the approach and the actual time remaining. The control law used to maintain time control on the approach is of the form:

$$V_{CMD} = V_{REF} + K\ \Delta t$$

Where V_{CMD} is the commanded velocity while V_{REF} is the reference velocity which is extracted from the velocity data table. It should be noted that the $K\ \Delta t$ term is limited so that large time errors do not produce excessive velocity commands.

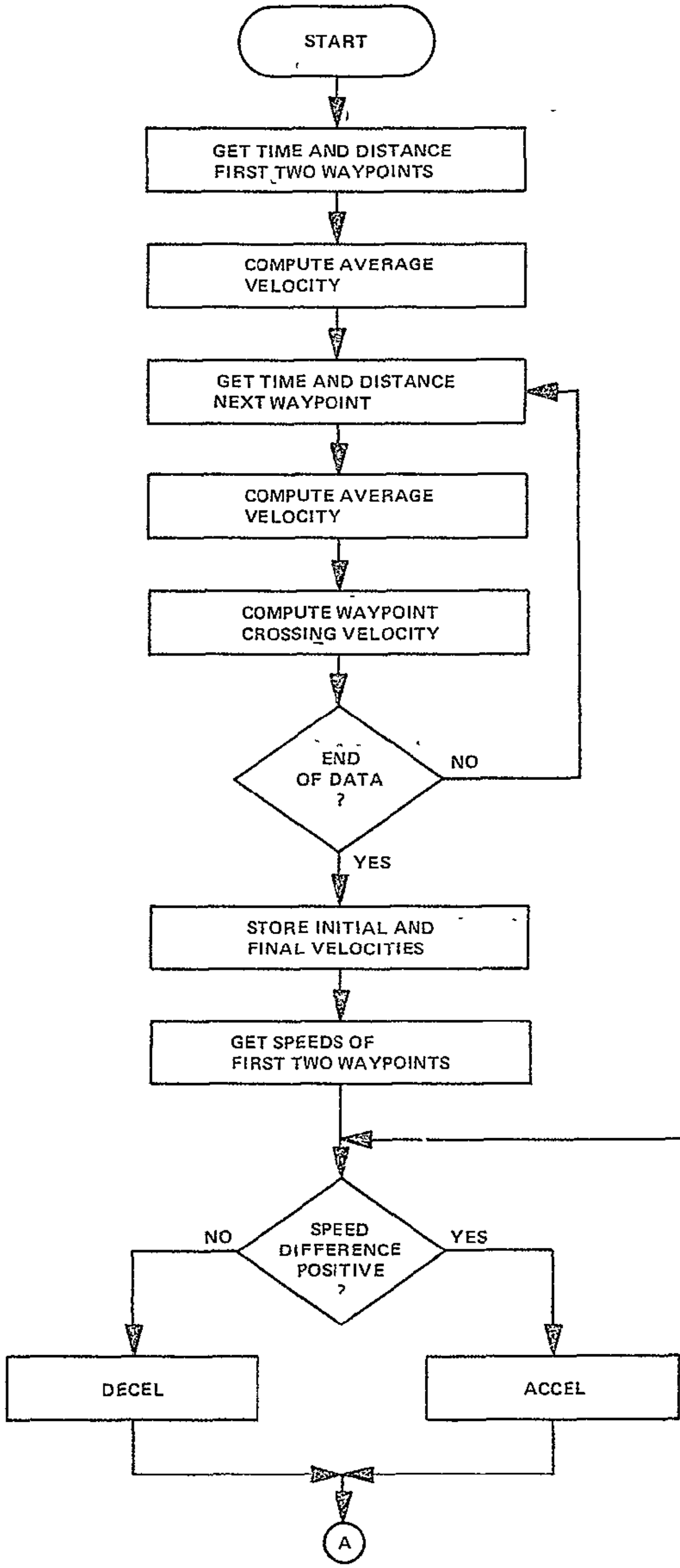

Figure 119
Velocity Profile Flow Chart
(Sheet 1 of 2)

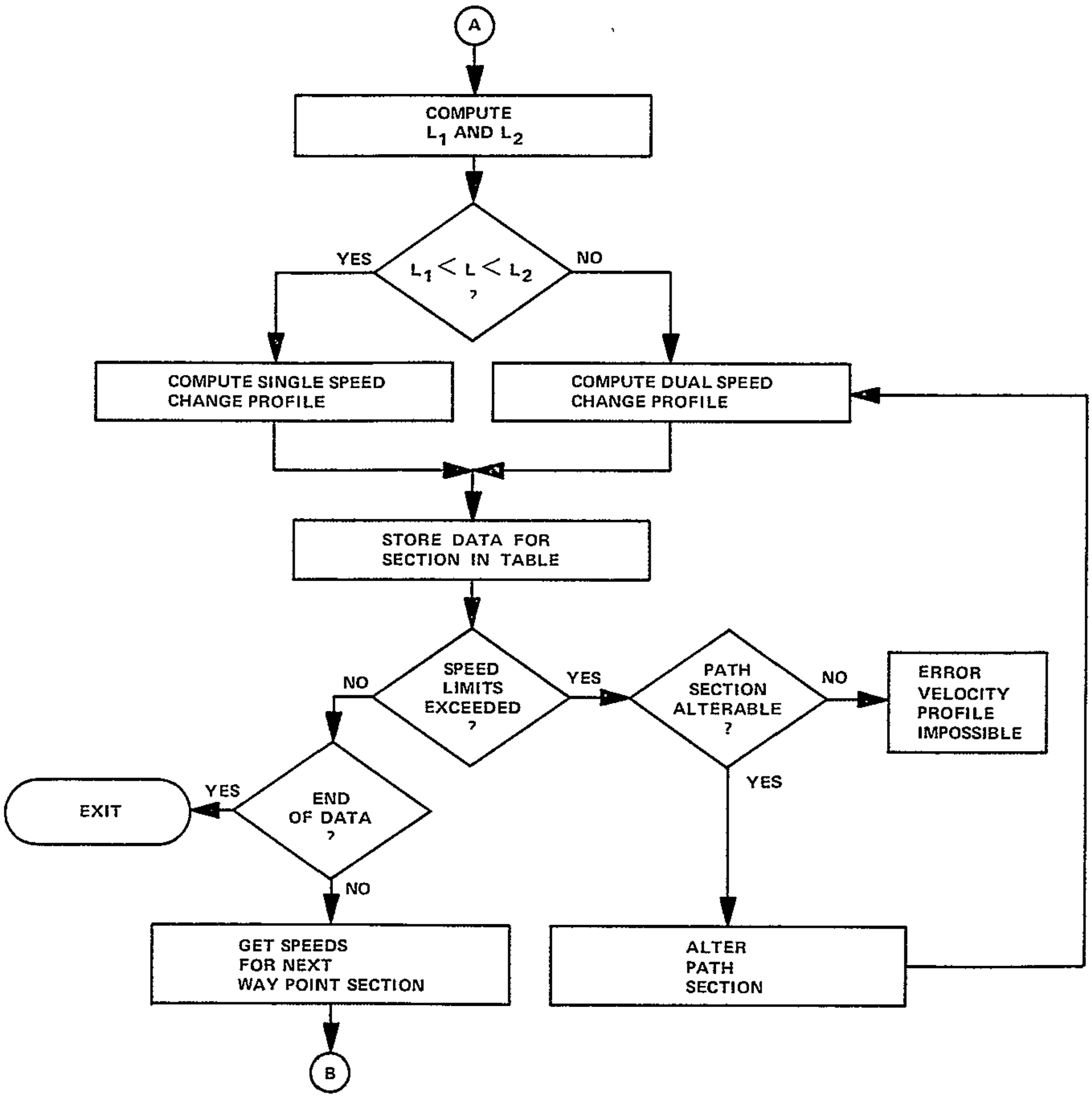

Figure 119
Velocity Profile Flow Chart
(Sheet 2 of 2)

APPENDIX D

TIME CONTROL USING AIRSPEED REFERENCE

The 4D constant velocity control system described in Reference 7 provides a technique for relating ground trajectory distance, elapsed flight time, and aircraft airspeed in the presence of winds. This technique provides a closed form approximation for determining the constant airspeed necessary to fly a fixed ground path consisting of straight line and circular arc segments. Since the Direct To path uses these same elements, this technique allows the use of airspeed referenced commands for 4D velocity control. This concept was incorporated into the VALT 4D study because it may reduce pitch activity in both the automatic and flight director aided approaches.

Basic Time and Distance Relationships

The basic time and distance relationships for aircraft flight in the presence of winds are presented in Reference 7 for ground trajectories consisting of straight line segments and circular arc segments of constant radii. Equations for both constant airspeed conditions and flight with constant values of acceleration and deceleration are derived. The key to the derivation of these equations lies in the use of a series expansion approximation solution to evaluate the incomplete elliptical integral of the second kind. The resulting equations are listed in Table 5 for reference.

4D Algorithm

The basic equations for time to traverse a given path distance and the airspeed required to traverse a given path distance in a specified time were used to develop a 4D velocity control algorithm. A general velocity profile was defined consisting of a constant airspeed section, a speed change section with a constant value of acceleration or deceleration, and a second constant airspeed section. For 4D control it is necessary to accept predetermined values for the initial and final values of airspeed as well as predetermined time to traverse the Direct To flight path. The algorithm is required to determine the distance to be covered by each of the three segments using the airspeed reference equations. There are three possible methods for arriving at a solution to this problem:

1) Varying the position at which a fixed value of acceleration or deceleration is carried out,

2) Varying the magnitude of the acceleration or deceleration, or

3) A combination of the first two methods.

Method 1 was selected for the VALT 4D implementation. The profile can be further classified into one of two types defined by restricting the speed changes to the straight line portion of the path or by allowing the speed change to occur on both the straight and curved portions of the path. Forcing speed changes to occur on the straight line segments is the more restrictive of the two classifications, but is much easier to implement. Both methods were investivated and coded as part of this study; however, only the straight line acceleration technique has been checked out.

TABLE 5

AIRSPEED VELOCITY REFERENCE EQUATIONS

---

1. $$f_2\ (k,\ z) = \frac{V_u}{V_g} = \frac{1}{[(1-k^2\ \sin^2 z)^{1/2} + k\ \cos\ z]}$$

2. $$f_1\ (k,\ z_{i+1},\ z_i) = \frac{1}{1 - k^2}\left[\left(1 - \frac{k^2}{4} - \frac{3k^4}{64}\right)z - k\ \sin\ z + \frac{k^2}{8}\ \sin\ 2z\right]\Bigg|_{z_i}^{z_{i+1}}$$

where $k = \frac{V_w}{V_u}$ and $z = \Psi_g - \Psi_w$

3. $$t_i = \frac{d_i}{V_u} \cdot f_2\ (k,\ z)$$

4. $$t_i' = \frac{R}{V_u} \cdot f_1\ (k,\ z_{i+1},\ z_i)$$

5. $$d_{as}\ (q) = \left(\frac{V_w}{a}\ \cos\ z\right) q + \frac{1}{2a}\left\{q\ (q^2-b^2)^{1/2} - b^2\ \ln\left[q + (q^2-b^2)^{1/2}\right]\right\}\Bigg|_{V_1}^{V_2}$$

where $b = V_w \sin z$ and $q = V_1 + at$

6. $$f_1'\ (k',\ z_{ix},\ z_{ix}+d_z) = \frac{a}{2R}\ (t_n')^2 + \frac{V_1}{R}\ t_n'$$

where $k' = \dfrac{V_w}{V_1 + \frac{a\tau}{2}}$ and $\tau = \dfrac{|d_z| \cdot R}{V_g}$

Straight Line Acceleration Method

The Straight Line Acceleration Method (SLAM) limits the acceleration portion to the straight line segment only. The stabilization time covers the entire final circular arc segment and may extend onto the straight line segment. The time to fly this segment is computed using the equations listed in Table 5. The initial circular arc segment is flown at the initial airspeed with the required traverse time again computed using the Table 5 equations. The straight line segment is divided into three portions:

- Constant initial airspeed section
- Speed change section
- Constant final airspeed section

The airspeeds on the initial and final sections are, of course, the same as those on the initial and final circular arc sections.

For a given wind direction and magnitude, the time and distance to traverse the speed change portion are fixed and the problem becomes one of simply positioning the speed change as required to satisfy the given time constraint. This is achieved by an iterative process in the computer program.

Circular Arc and Straight Line Acceleration Method

The Circular Arc and Straight Line Acceleration Method (CASLAM) is accomplished in essentially the same manner as the SLAM method described above except that the speed change portion of the path is allowed to occur on the circular arc path segments as well as on the straight line segments. Allowing the speed change portion of the profile to occur on the curved section of the path means that the speed change distance and time will vary with path position even though the wind magnitude and direction are constant. This variation will, in turn, alter the distance and time required to traverse the two constant velocity segments and requires a complete recalculation of all the time and distance equations each time the speed change location is changed. Since the position of the speed change segment is determined through an iterative process, the complete determination of a solution requires a significant amount of essentially trial and error calculation.

The CASLAM technique, when completely checked out and debugged, would allow nearly unrestricted use of airspeed referenced velocity control to achieve desired traverse time on the Direct To path capture maneuver. The effort required to achieve this capability cannot be justified as part of this study, since the basic SLAM technique will allow evaluation of the airspeed control concept with significantly less effort at the cost of some path restriction. Since this restriction amounts to nothing more than selecting trajectories with reasonable straight line segments, this limitation has been accepted for the VALT 4D system.

Lateral Control in Presence of Winds

Two forms of lateral control were developed for use in conjunction with the airspeed reference velocity control system. For control on the straight section of the Direct To path, a crab angle lead term was implemented. On the curved segments of the maneuver, a bank angle lead term is utilized.

In the VALT system described in Reference 14, the crosstrack control laws will attempt to maintain minimum lateral errors along the straight segments in the presence of winds by turning into the wind or crabbing to the ground course. In order to maintain this crab angle, the system must maintain a certain amount of lateral error since there is a direct relationship between crosstrack error and heading correction. To minimize the errors developed in a constant wind condition, a crab angle lead term technique was developed which directly relates ground course, airspeed, wind speed, and wind direction. Considering all these factors, a heading command is produced which will direct the aircraft heading into the wind. The equations for the crab angle lead term, similar to those found in Reference 6, are:

$$\cos(\psi_i - \psi_w) = [(1 - k^2 \sin^2 Z_i)^{1/2} + k \cos z_i] \cos z_i - k$$

and

$$\psi_i = \tan^{-1} [(1 - \cos^2 (\psi_i - \psi_w))^{1/2} / \cos(\psi_i - \psi_w)] + \psi_w$$

where k is the ratio of airspeed to windspeed, z_i is the difference between ground course and wind direction, ψ_w is the wind heading and ψ_i is the heading command. Using these equations with the existing VALT math routines gives a heading in all four quadrants.

As on the circular segments of the Direct To, the existing crosstrack controls require a certain lateral error to change the bank angle from the nominal. In the presence of winds, however, flying a constant airspeed around a fixed circular arc requires a changing bank angle to maintain a circular ground track. In order to minimize the lateral errors found in the existing system in windy conditions, a bank angle lead term was developed. Investigation into the equations in Reference 6 for producing the lead term show a basic relationship between ground speed and bank angle. The equations there convert airspeed to ground speed with a small error term. For the most part, the error term was less than 5 percent of the basic ground speed number produced. Therefore, it was felt that, since ground speed is a known variable in the VALT system, the conversion from airspeed to ground speed was not necessary. The simpler equation

$$\phi = \tan^{-1} (V_g^2 / Rg)$$

was used for the bank angle lead term, thus eliminating the computational complexity of the larger equations. Using this equation, the varying bank angle was clearly evident around the turns.

APPENDIX E

FLIGHT PATH DISPLAY TECHNIQUES

The graphics system software consists of FORTRAN callable subroutines, a majority of which were supplied by MEGATEK Corporation and several of which were developed by Sperry Flight Systems. The flight program is made up of six major programs, each of which performs specific functions to demonstrate various display capabilities. The routines and their structures are discussed in this section.

Vendor Supplied Software

The FORTRAN subroutines supplied by MEGATEK enable the programmer to manipulate and display graphical images on the MEGATEK 7000 Graphics Display System. The routines supplied by MEGATEK are organized into the following categories:

1. Initialization
2. Vector moves and draws
3. Rotation, translation, scaling and clipping
4. Text and character string manipulation
5. Picture Control
6. Graphics joystick control

The initialization routines allocate user space and specify the picture configuration in the 7000 memory. Some modification was made to the initialization routine to meet specific requirements in the VALT system.

Vector move and draw routines utilize either absolute or relative vectors. Absolute vector routines cause movement of the display beam to a specified absolute position in the user or screen coordinate system. Relative vector routines cause movement of the display beam relative to the current beam position in either user or screen coordinates. The absolute vector routines use X and Y position data for positioning the beam where the relative vector routines use ΔX and ΔY data for positioning. The move and draw routines operate in an identical fashion with the exception that the vector move routines cause beam movement with the beam "off" and hence are called hidden vectors.

A single FORTRAN subroutine allows the programmer to perform translation, rotation, scaling, and clipping operations in the user coordinate system. Parameters allow the user to specify a rotation angle, window boundaries in user coordinates, and screen boundaries outside of which all data will be blanked. The picture is rotated about the user origin through the indicated angle. Translation, scaling, and clipping are accomplished by matching the user window data to the screen window boundaries.

Text and character string manipulation routines are used to provide the alphanumeric displays. A subroutine converts a floating point number to a character for use by a text display routine. The text string display routine can also be used for alphabetic character display. The picture control routines determine which pictures are to be displayed on the CRT screen.

Four routines are provided for controlling joysticks and retrieving data. One routine starts the joystick digitizing hardware and allows for six different tracking modes. Another routine retrieves the joystick data: X and Y position in screen units, pen status, and X and Y rate. The third joystick routine sets the tracking limits of the joystick cursor by specifying the left, lower, right, and upper screen coordinates for cursor movement. A final routine is called to turn off the joystick digitizing hardware.

Sperry Developed Software

In addition to the routines supplied by MEGATEK, several specialty routines were developed by Sperry Flight Systems to perform operations that are inherent to the objectives of 4D control concepts. These routines were needed to construct Direct To paths, data profiles, and avoidance areas and to enable the joystick to be used as an interface between the pilot and the control system.

The Direct To predict routines were developed in both absolute and relative vector modes. The advantage of employing relative vector strings to describe a character, figure, or point-plot series is that it is very memory efficient since common data for each vector string is stored in memory only once. The absolute vector method was devised and ultimately used because the display manipulation routine supplied with the graphics system required data to be stored in a single array. This made it possible to incorporate the entire lateral path, the nominal path, the Direct To capture path, and the delay fan path into a single array and picture.

The Direct To capture path is to be drawn from a prescribed waypoint to the current aircraft position. The path, as shown in Figure 120, is comprised of two arcs connected by a straight line segment. The required data - the radii and turn angles of the two arcs, the length of the straight line segment, the end point of the path, and the aircraft heading - is supplied by the 1819A. The predict routine uses this information, in conjunction with a circle drawing routine, to construct the path and to load the position and intensity data in the total path array. A flow chart for the predict routine is shown in Figure 121.

A circle drawing routine is required to construct the two arcs in the Direct To path. The curve is drawn using eight short vectors per 90 degrees of arc. The heading of each vector is changed an incremental amount to produce a smooth curve. As in the predict routine, the position and intensity data are loaded into the total path array. The flow chart in Figure 122 defines the circle drawing process.

Since time and memory limitations restricted development of a single display program to perform all the desired functions for this display study, a number of major special function routines were generated to demonstrate the basic capabilities required. The display capabilities addressed as part of this display included curved path displays, velocity and altitude profiles, path

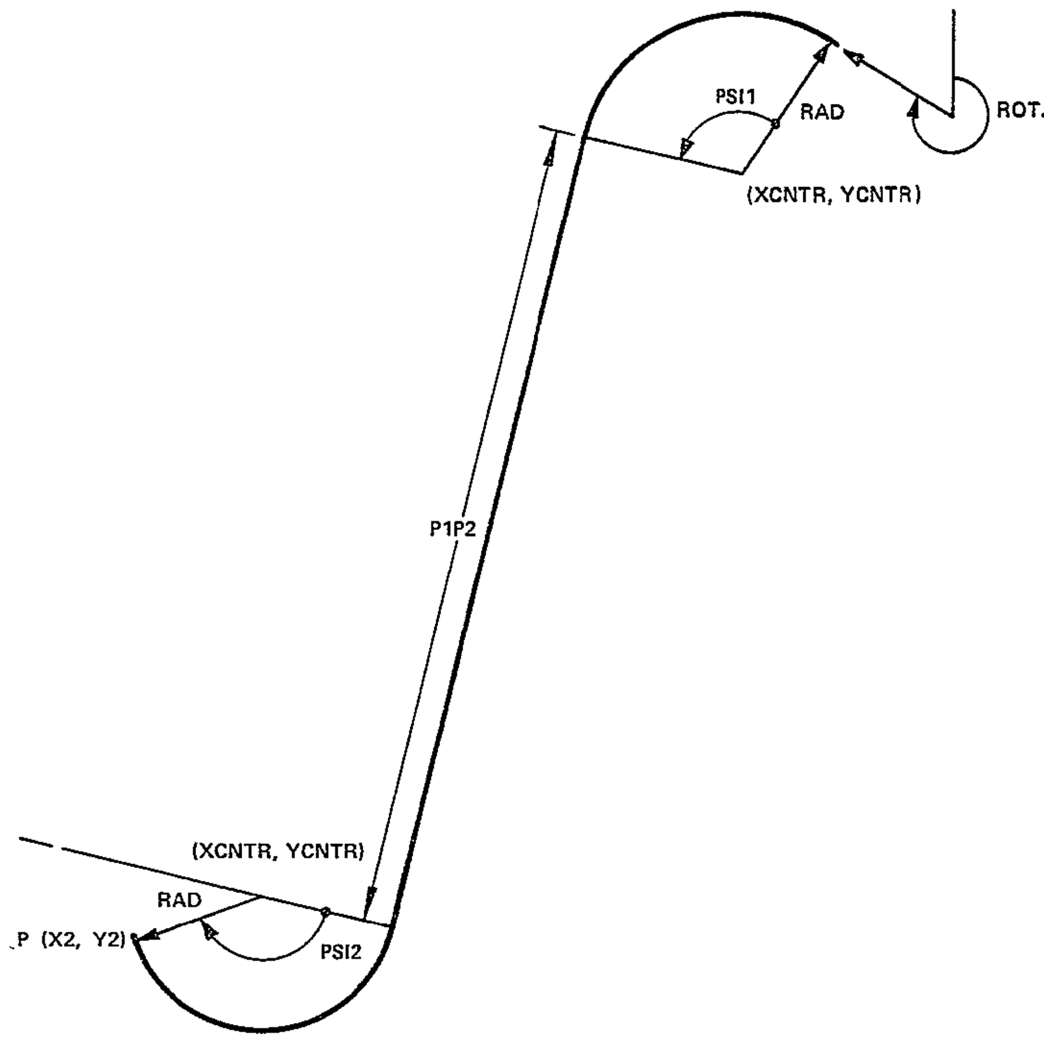

Figure 120
Direct To Path

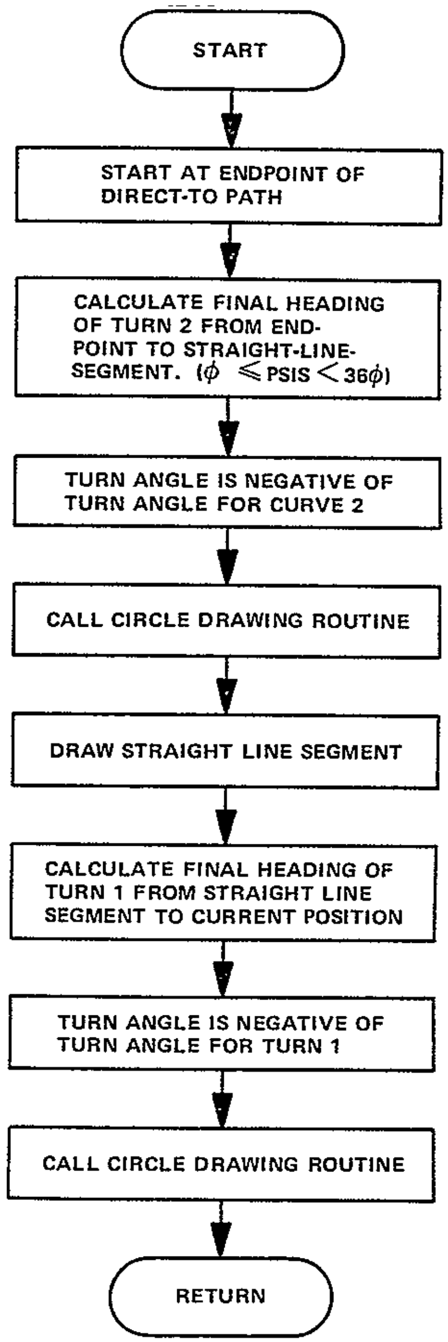

Figure 121
Direct To Path Routine Flow Chart

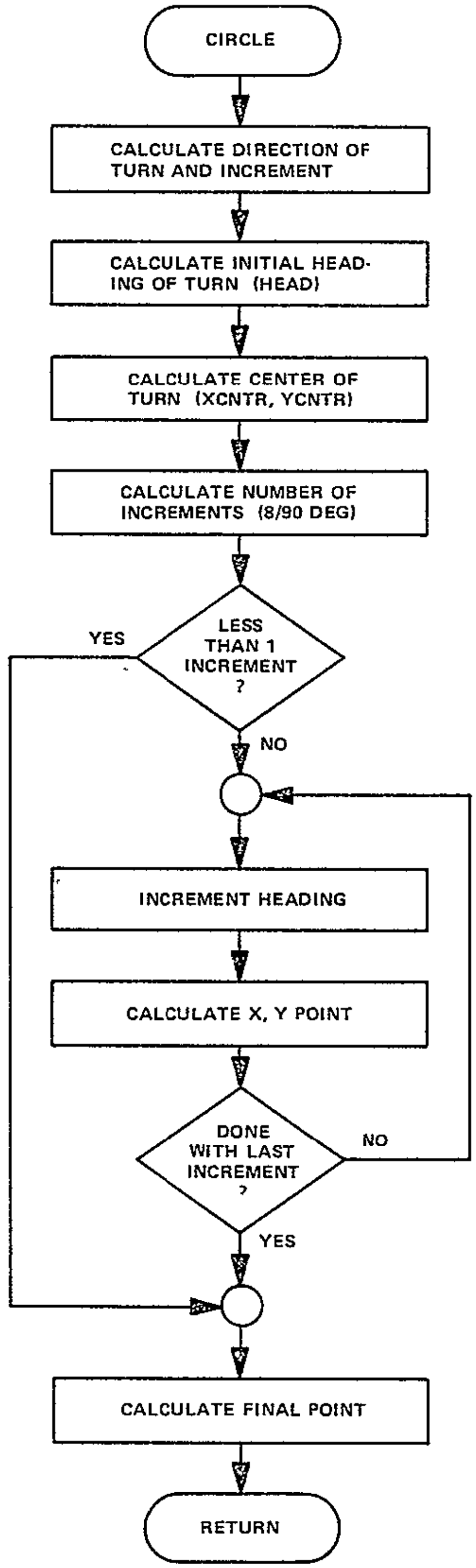

Figure 122
Circle Drawing Routine Flow Chart

alteration maneuver boundaries, avoidance area limits, landing pad presentations, approach plate information, and performance monitors. A nondisplay function of the graphics system which was addressed was pilot control of path parameters by use of the graphics joystick. Several special function programs were developed to transfer data from the graphics joystick to the 1819A computer.

To demonstrate the capabilities of the graphics display system that is incorporated with the 4D control system, five separate display programs were written. Each program consists basically of the main program, a data I/O subroutine, and any required specialty subroutines.

The main program, which is flow charted in Figure 123, contains the data lists for the lateral path, the aircraft symbol, and any charts or graphs. It performs the memory and picture initialization and makes picture assignments. Static displays, pictures that will require no changes and thus do not need to be updated, are constructed in the main program.

A subroutine is called by the main program which performs the data I/O process with the 1819A. The data is stored in an array and will be used in the computations for picture manipulation, determination of the display modes, and in the construction of Direct To paths and data profiles. The flight routine also calls any necessary specialty routines. A flow chart for the flight routine is shown in Figure 124.

The specialty routines perform specific opertions such as the construction of Direct To paths, delay fan paths, avoidance areas, and joystick manipulation of lateral paths and altitude profiles. In each case, the data points calculated by the specialty routines are simply appended to the total path array in the I/O routine. Other operations of the specialty routines are the manipulation of a hover display and the graphical selection of the waypoints.

The data transfer from the 1819A to the NOVA host computer is a handshaking process. The 1819A informs the NOVA by use of a code word that new data is ready to be transmitted. The NOVA must respond with a code that it is ready to receive the data, at which point the 1819A sends a code word with the data informing the NOVA that data is being transferred. Upon receiving the data, the NOVA must respond with another code, this time indicating that the data has been received. After the completion of this process, the cycle may repeat itself for block data transferral. The I/O process occurs as a function of the update rate of the slower of the two computers, with the optimum rate being determined by the cycle time of the 1819A. The 1819A update rate is 40 milliseconds while the update rate of the NOVA 1200 ranges from .1 second to 6.0 seconds, depending upon the complexity of the picture and the method used to manipulate it.

Although the majority of the data is transferred from the 1819A to the graphics host computer, it is also possible to send data to the 1819A. Since a minimal amount of data is required by the 1819A from the NOVA, it was possible to send the data along with the code word indicating that the NOVA is ready to receive data. A flow chart of the I/O activity between the 1819A and the NOVA is shown in Figure 125.

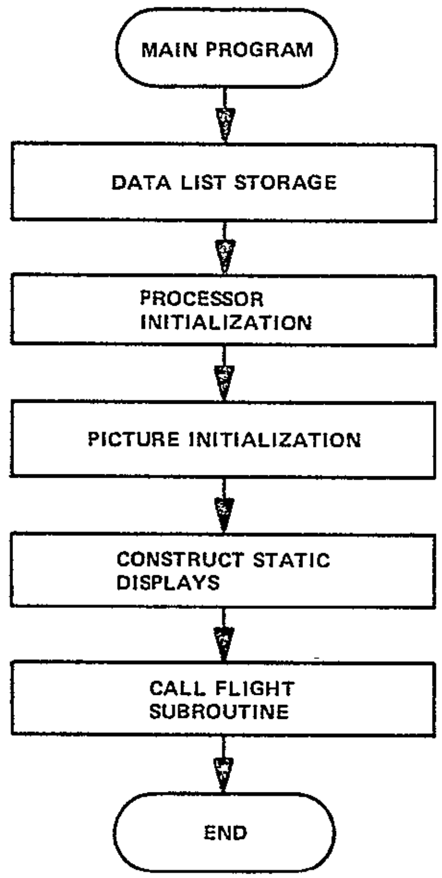

Figure 123
Main Program Flow Chart

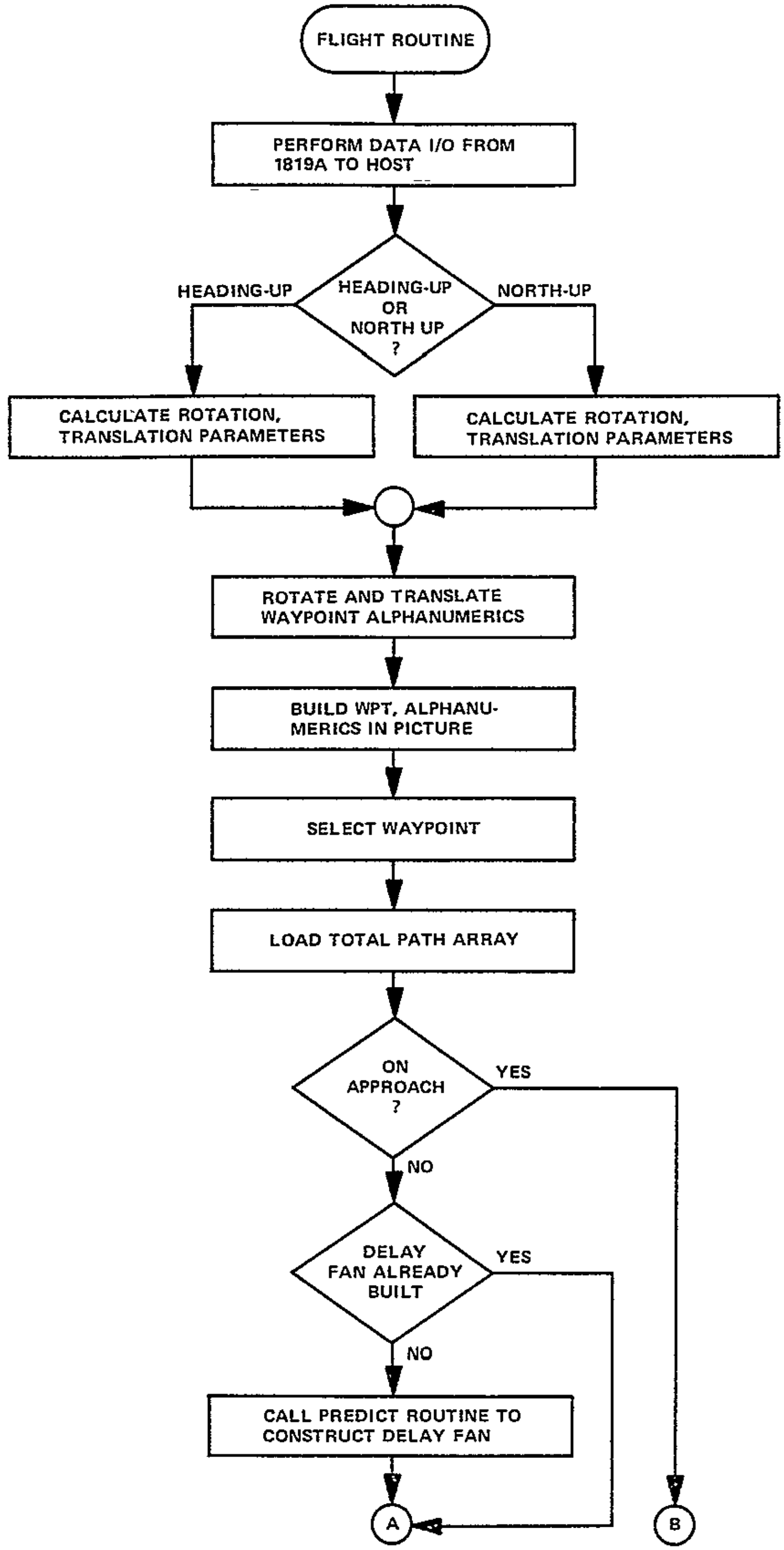

Figure 124
Flight Routine Flow Chart
(Sheet 1 of 2)

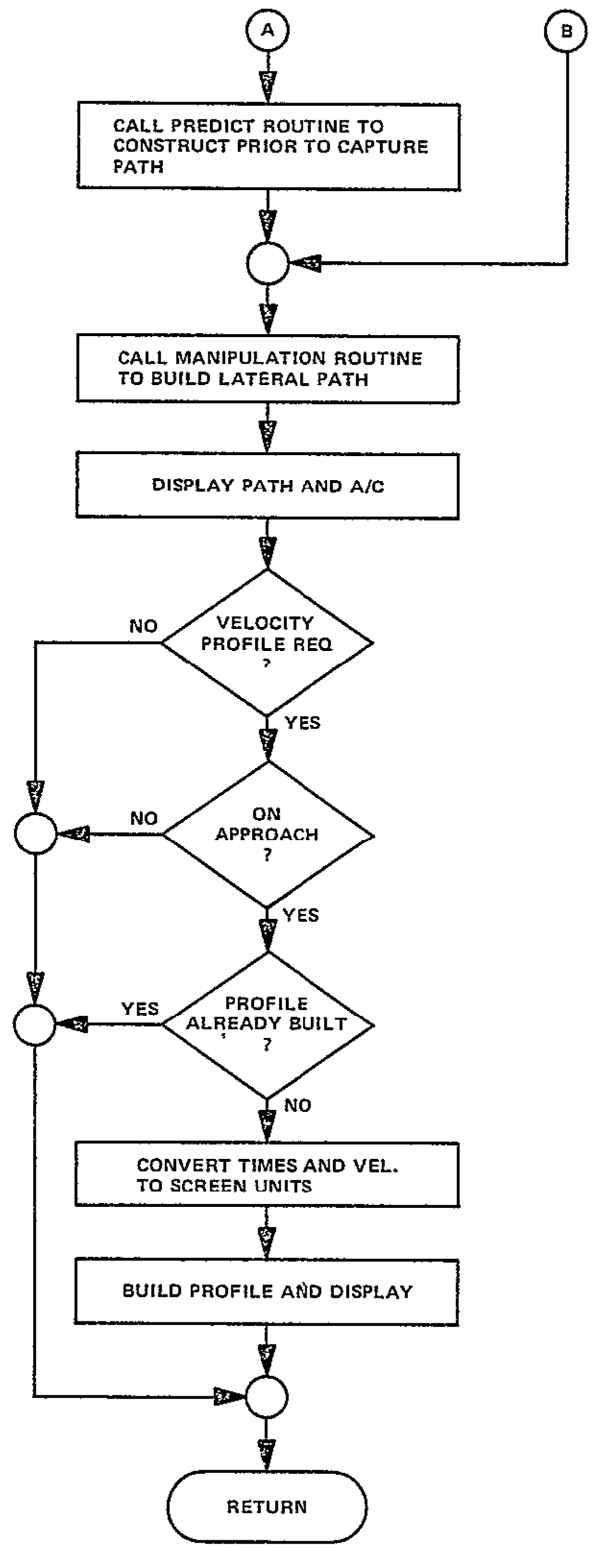

Figure 124
Flight Routine Flow Chart
(Sheet 2 of 2)

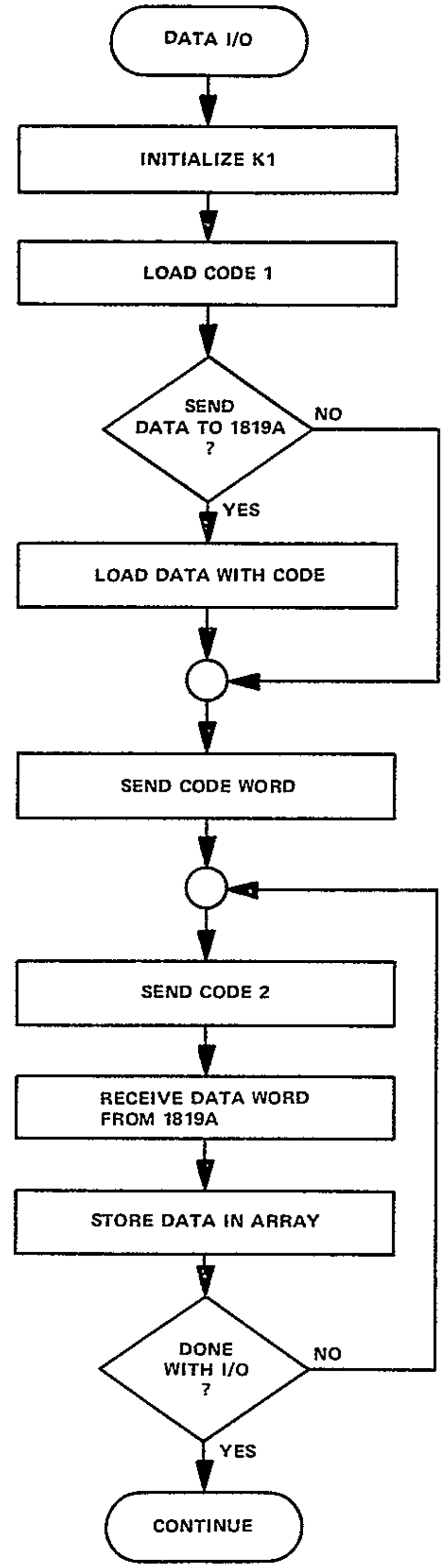

Figure 125
Data I/O 1819A/NOVA Flow Chart

The update rate of the simulation system could be improved by the addition of rotation, translation, scaling, and clipping hardware to the graphics system. This would permit the user to move a complete picture or a series of vectors on the display screen with a minimum amount of software manipulation of the vector lists in the host computer. The host would provide the translation, rotation, scaling, and clipping parameters. The 7000 Display Processor would apply these parameters to each vector before it is displayed. Other methods that could be employed to improve the update rate of the graphics system include the addition of floating point hardware to the NOVA computer or the use of a faster host computer. In either case, the host computer speed is increased to provide a faster update rate on the graphics display.

The first demonstration program is the alteration and examination of an airspeed based velocity profile on the Direct To portion of the path. The speed profile along the fixed portion of the path, from the point of capture to the touchdown point, is fixed and, therefore, the time along this portion of the path is also fixed. The fixed portion of the lateral path has five time waypoints, which may be graphically selected by the pilot. Selection of a waypoint is made by positioning the joystick cursor over a waypoint and depressing the button on the joystick. The position of the joystick cursor will be read during each cycle. However, its position is only compared to the position of the five waypoints with the button depressed. If the position of the cursor coincides with one of the five waypoints, the waypoint number is set equal to the newly selected waypoint. If the cursor position does not coincide with a waypoint, the cursor position will be read again and the comparisons will be made until a waypoint is selected or until the button is released. A flow chart for the waypoint selection is shown in Figure 126.

The lateral path is built in the following manner. The data points for the entire fixed portion of the path are stored in a preloaded data list. The data points for the path, up to the selected waypoint, are transferred to a total path array. A routine is then called to calculate the data points for the Direct To path, which will be drawn from the capture point on the path to the current position of the aircraft. The data points of the Direct To path are appended to the total path array, thus giving a single, continuous array and path. The fixed portion of the path is drawn only to the selected waypoint. However, each waypoint, designated by a small rectangle, is always displayed to make selection of a new waypoint possible.

After the Direct To path has been built and the entire lateral path has been loaded into the total path array, the path is constructed using a manipulation routine that performs the rotation, translation, scaling, and clipping operations. In addition to the path array, the manipulation routine also requires a control matrix that contains the corners of the screen and user windows and a rotation angle. The translation and scaling operations are performed by matching the user window corners to the corners of the screen window. All data outside the screen window is blanked. Two pictures are assigned to the lateral path so that while one picture is being displayed, the next picture may be built by the manipulation routine.

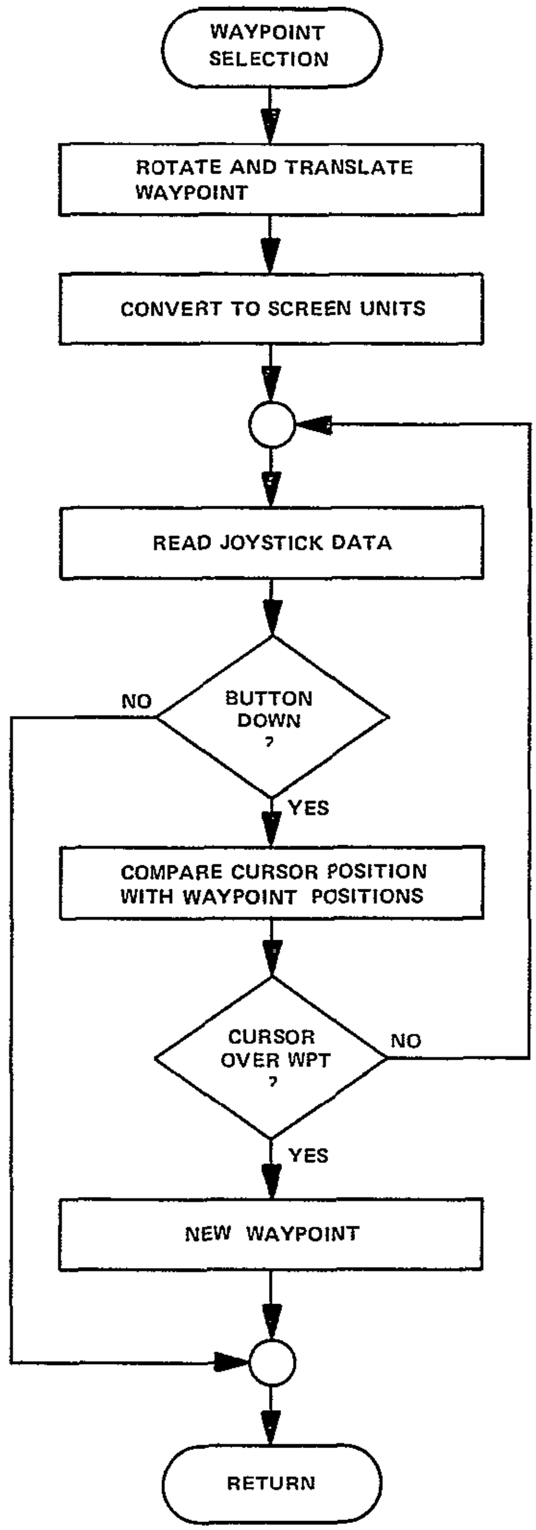

Figure 126
Graphical Selection of Waypoints

The prior-to-capture Direct To path is updated and built each cycle unless an approach has been selected or the Direct To path is invalid. If an approach has been selected, the Direct To path becomes a permanent part of the lateral path display. A flag is set indicating that the call to the routine to compute the Direct To data points for the path is to be omitted. If the Direct To path is invalid, the Direct To portion of the path is removed from the display and the Direct To computations are, again, omitted.

A feature of this demonstration is the capability of a real time prediction. This is shown graphically by the indicator at the left of the display. The actual time to go, represented by the triangular pointer, is shown relative to the time to go if the Direct To path was flown entirely at the capture velocity and the time to go if the Direct To path was flown at the exit velocity. The time scale and pointer are built in separate pictures as static displays. The pointer is translated relative to the maximum and minimum times. If actual time to go is greater than the maximum time or less than the minimum time, the actual time to go pointer is placed above or below the time scale which indicates that the time limits have been exceeded, but not to what degree.

Once a valid profile can be built and an approach is selected, the time prediction scale is removed from the display and the velocity profile is drawn. The velocity profile may be divided into three sections; the decel portion, the profile on the fixed lateral path and the profile on the Direct To path.

The decel portion of the speed profile is a deceleration that provides a constant 2 degrees pitch attitude above trim. This decel portion is not subject to change and the data points for the display are stored in an array.

The ground speed along the fixed portion of the path from the selected waypoint to the approach gate is held at a constant speed of 58 knots. Since the distance and velocity along the fixed path is known, the time from each waypoint to the approach gate is also known. To construct this portion of the profile, the Y-coordinate is held at a constant value equivalent to 58 knots and drawn from the approach gate to the time corresponding to the selected waypoint.

The final section of the speed profile is on the Direct To portion of the lateral path. It is to be a three-segment profile consisting of a constant velocity segment, an acceleration segment, and another constant velocity segment. The time of the acceleration, the times of the constant velocity segments, and the capture velocity are provided to the graphics host computer by the 1819A. The host computer converts the times and velocity to screen coordinates to be drawn in the display.

The velocity profile axes and alphanumerics are always displayed. The velocity profile is displayed only when the aircraft is on an approach.

A velocity profile marker is translated in the X and Y axes to track the velocity profile. The marker is removed from the display when the aircraft reaches the approach gate as the time and velocity points for the decel are not available to the graphics host computer.

The path display is a moving map display in a heading up mode. In this configuration, the aircraft symbol remains fixed in the center of the CRT and the path is translated and rotated about it, giving an inside looking out appearance. This configuration requires that the data array for the path, which is much more complex than the data list for the aircraft symbol, must be translated, rotated, scaled, and clipped by the manipulation routine. This drastically affects the update rate of the graphics host computer. For this particular display the cycle time is approximately 3 seconds.

The slow update rate adversely affects the waypoint selection and the continuity of the motion of the displays. When a waypoint is selected, it is actually not changed in the flight program for one cycle and it is not changed in the display for two complete cycles. Therefore, once the waypoint is changed, it will not be seen for approximately 6 seconds. Also, with such a slow update, the motion of the displays appears very discontinuous, since the changes in this rotation and translation parameters may be quite large. The effect of the real time prediction indicator is diminished since the indicator may change from one extreme to the other in one or two cycles.

The examination and alteration of the velocity profile along the approach path using three segment profiles with both one and two speed changes was the next demonstration. The approach path consists of a single waypoint section of fixed time and distance, a landing pad, an approach gate, and a capture gate. The position and intensity data are stored in a data list in the main program.

A Direct To path is predicted and built from the capture point to the present aircraft position. The path data is computed by the predict routine and appended to the path array. If on an approach, a flag is set, indicating that the prior to capture path is to be a permanent part of the display and the call to the predict routine is omitted.

The method of altering the velocity profile is by changing the capture velocity, which is done through a keyboard entry on the Navigation/Guidance Control Panel.

The velocity profile for the path from the approach gate to the touchdown point is the decel profile which is stored in a data list in the main program. The data for the velocity profile along the waypoint section is transferred from the 1819A to the graphics host computer which converts the data to screen units and places it in the profile array. The profile is drawn in Picture 6 using an absolute vector drawing routine in screen coordinates. The average velocity along the waypoint section is indicated by the dashed, horizontal line.

The update rate for this display was still quite slow since the manipulation routine was used. The update rate is about 2.5 seconds per cycle which is an improvement over the first demonstration. This was due to the fact that the path was made up of a maximum of 84 vectors as opposed to a maximum of 141 vectors in the previous demonstration.

The third demonstration involved performance monitoring displays, approach plate information, altitude profile examination and alteration, and a hover display. Since the main objective was to demonstrate the system's capability to manipulate various performance monitoring displays, the maps for the approach plate and the monitor display are in a fixed, north-up configuration. This method provides the maximum update rate and makes it possible to build the pictures as static displays.

By using the north-up, fixed map configuration for the approach plate display and monitor display, only the aircraft symbols had to be rotated. Since rotation of a picture requires either the use of the manipulation routine or to compute the position of each vector each cycle, the fewer vectors in the picture, the faster the update rate will be. Since the aircraft symbol would also be translated and the clipping operation would not be necessary, a more efficient translation routine could be used that operates on an entire picture instead of each individual vector, as does the manipulation routine.

The program was organized into the main program and a data I/O routine, which determines the display mode and calls the appropriate display routine; the approach plate display, the performance monitor display or the hover display.

The main program organizes the data lists, initializes the processor memory and each picture, builds the static displays, and initializes the joystick digitizing hardware. The method of storing the data lists for the displays was changed due to the large size of some of the arrays and the number of different arrays. To conserve memory space in the graphics host computer, the data lists are stored in files on the disk, eliminating the use of much of the common blocks and data arrays in the program. To access the data lists on the disk, the program opens the particular file and assigns it a channel number. A data set, X and Y position and intensity, is read and drawn. This is repeated for the entire list, eliminating the need to store the data in an array. The file must then be closed before proceeding onto the next data list and display. This method of data retrieval is flow charted in Figure 127.

The data I/O routine, called by the main program, receives the data from the 1819A flight computer and stores it in an array. The breakpoint for the altitude profile is sent to the 1819A along with the code word that acknowledges that the NOVA is ready to receive data. Based on a display flag, an approach flag, and the distance remaining on the path, a call to the appropriate display routine is made. If the distance to go is less than 30 meters and approach 28 is selected, the hover display routine is called. If the above conditions are not satisfied, the aircraft symbol is rotated to the correct heading and the data is stored in an array. A call is then made to the approach plate display or the monitor display, based on the display flag.

The approach plate is a reproduction of the NASA Wallops Station, Chincoteague Island, Virginia approach chart. If the display routine that was called prior to the call to the approach plate display was the monitor or hover display, the 16 pictures that are used for those displays must be turned off and the pictures containing the aircraft symbol and approach chart turned on. However, if successive calls are made to the approach plate routine, the correct pictures are already on or off and the calls to the picture control routine are omitted. The aircraft symbol, in either case, is rebuilt and then translated, using the more efficient translation routine. The update rate for the approach plate display is about 10 cycles per second.

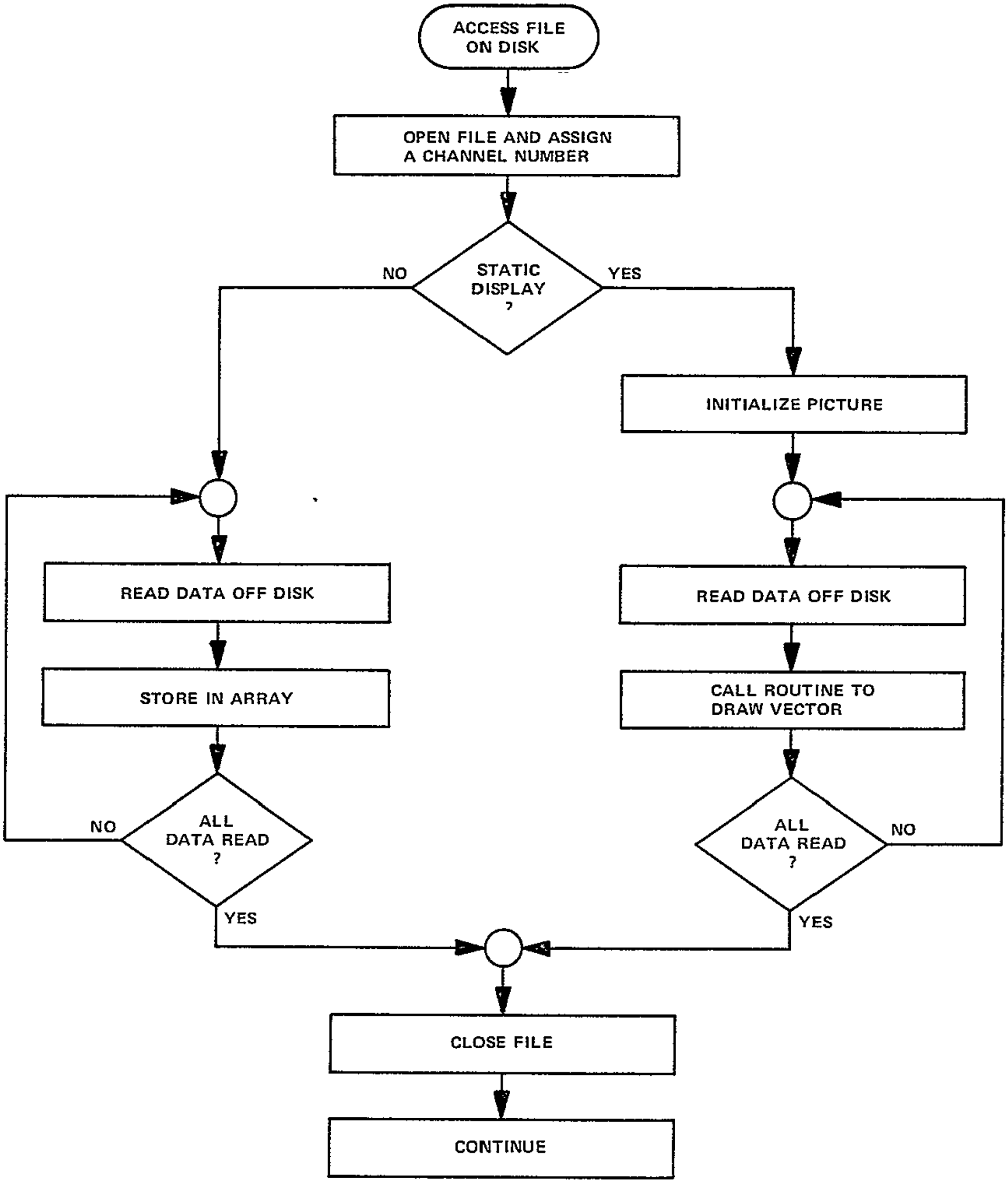

Figure 127
Access File on Disk Flow Chart

The performance monitoring displays include a heading indicator, a time to go indicator, an altitude indicator, and an altitude profile. Three approach paths are provided to the NASA Wallops Station runway system. All the pictures are static displays and are built in the main program except for the aircraft symbol and alphanumerics for the heading indicator.

A default altitude profile, with a breakpoint of 3000 meters and a glide-slope of 5.4 degrees is drawn in the main program. The profile may be changed by the pilot through the use of the joystick. The breakpoint is computed based on the X position of the joystick cursor. The limits on the cursor movement in the X axis determines the minimum and maximum altitude profiles. The cursor position is read each cycle, but the profile is changed and rebuilt only if the button on the joystick is depressed.

An altitude profile marker is used to track the actual altitude and distance to go on the path. If the profile is changed so as to cause a difference in the commanded altitude and actual altitude the movement of the marker demonstrates the ability of the control system to close out errors.

The heading indicator, located at the top of the CRT screen, is a fixed pointer-moving scale indicator with a range of ±45 degrees about the actual heading. The pointer is fixed at the horizontal center of the CRT and the alphanumerics and graduated scale pictures are translated relative to it. The numbers for the heading indicator are placed every 30 degrees and are stored in an array. The alphanumeric picture must be rebuilt for a heading change of ±15 degrees.

The time to go indicator and the altitude indicator are identical in their function. Both display actual and commanded parameters to reveal any errors and the system's attempt to correct an error if it occurs. The command pointers for each indicator are positioned towards the center of the CRT and the actual pointers are triangular and are on the outside of the scales. As in the case with the altitude profile and marker, when the profile changes so as to cause a difference in the commanded and actual parameters the altitude graph will also show the error and the attempt to correct it.

Path selection is made by setting a flag using the Navigation/Guidance Control Panel. Each of the three paths is contained in a separate picture. Displaying the selected path is simply a matter of turning on the correct picture and turning off the other two.

The hover display is called when the aircraft is on approach path 28-10 and the path distance remaining to the landing site is less than 30 meters. The display consists of the lateral path, landing pad, runway, and aircraft symbol. The display is in a heading-up, moving map configuration, requiring the use of the manipulation routine to perform the rotation, translation, scaling, and clipping operations.

The objective of the hover display is to provide a greater resolution of the horizontal situation and also to provide altitude information. Achievement of these objectives is done by manipulating scaling. When in the hover mode, the scale factor not only is at its smallest value to display the largest map, but it also becomes a function of altitude, decreasing as altitude decreases and increasing as altitude increases. The map is scaled by placing the scale factors in the control matrix and then matching the corners of the user window to the screen window. To further describe the vertical position of the aircraft, an alphanumeric display was added that gives digital readout of the actual altitude.

The cycle time of the program, while in the hover display, increased to .6 second per cycle. This was due directly to the fact that the manipulation routine was required for construction of the map. However, since the map was relatively simple, the update rate was considerably better than in the previous demonstrations. The use of the manipulation routine also made it necessary to reserve two pictures for the map, one to be displayed while the other is being built.

Of the 18 display elements, only three are used in the hover display. This requires that the remaining 15 must be turned off to eliminate the other maps, symbols, and graphs. However, as with the approach plate display, if successive calls are made to the hover display routine the correct elements have been turned off in a previous call and the calls to the picture control routine to turn off the remaining elements may be omitted.

The update rate for the monitor and approach plate displays were improved greatly by using a fixed map display. However, in using this method, a problem may occur if the position of the aircraft lies beyond the boundaries of the user window. If this happens, the aircraft symbol will wrap around on the CRT screen, giving an incorrect description of the horizontal situation.

It was also observed that the intensity of the approach plate display was significantly less as compared to the other displays. This is a result of the large number of vectors and alphanumeric character strings needed to reproduce the approach plate.

The final two demonstrations involved the examination and alteration of the velocity profile in the delay fan region. In previous programs, the velocity profile and the lateral path were both displayed simultaneously. To better illustrate the alterations in the velocity profile and since the lateral path covers a larger area and is more intricate, the velocity profile display is separate from the lateral path display. A display flag, set by a keyboard entry, indicates which display is to be shown. Since only one display is shown at a given time, and each display requires different data, the display flag also determines which set of data is to be transferred from the 1819A to the graphics host computer. Therefore, instead of sending over 40 data words each cycle, the process determines which set of data to transmit, the velocity profile data or the lateral path data, and then needs only to send 20 data words each cycle.

The lateral path is composed of the NASA Wallops Station Runway System, a spiral descent, the delay fan area, three capture waypoints and alphanumerics, a delay fan path and a prior-to-capture path. The data list, due to its complexity (202 vectors), is stored in a file on the disk and is accessed by the main program. The display is in the heading-up, moving map configuration and incorporates five discrete scale changes based on the path distance remaining on the approach to the touchdown point. The first scale change occurs with 1800 meters remaining to the landing pad. The display is scaled by matching the corners of the screen window to the corners of the user window that are contained in the control matrix for the manipulation routine.

The lateral path is constructed by loading the data points into a total path array, which is used by the manipulation routine. The points of the prescribed path are first loaded into the total path array. The number of points that are stored is determined by the selected waypoint. Waypoint selection is made through a keyboard entry on the Nav/Guidance Panel. The selection of the waypoint also affects the construction of the delay fan path. If waypoints 0 or 1 are selected, the delay fan area is omitted from the display and there is no need to construct a delay fan path. The construction of the delay fan path uses the same predict routine as do all Direct To paths. However, the delay fan path always has the same endpoint and initial heading, so these values may be entered as constants. The delay fan path should only be rebuilt if it changes. The turn angle of the first turn of the delay fan path is used as the check. If the turn angle is changed, the delay fan path is rebuilt. The data points for the delay fan path, computed in the predict routine, are appended to the total path array. The prior-to-capture path is built next. It is a Direct To path built from the capture waypoint to the present aircraft position. The prior-to-capture path is rebuilt each cycle unless an approach has been selected, at which point it becomes a permanent part of the lateral path. The data points for the prior-to-capture path are also appended to the total path array. The lateral path is built and placed in a picture by the manipulation routine. In addition to the total path arrays, the manipulation routine requires a control matrix, the number of points in the path array, the picture number and a control word for the clipping operations.

The waypoint alphanumerics are contained in two pictures separate from the lateral path pictures. They are scaled by inserting the computed scale factor, ratio of screen units to user units, in the call to the picture initialization routine. The numbers are converted to a character by the text and character string manipulation routines.

The velocity profile may be divided into four sections; one for each of the three waypoint sections and one for the prior to capture path. The velocity profile from the landing pad to waypoint 0 is fixed and, therefore, the data points for this section of the profile are contained in a data list along with the data points for the velocity profile axes. The profile axes and the first section of the profile are built as a static display by the main program in Picture 6.

The velocity profile for waypoint Section 1 and the delay fan area is variable and made up of three segment profiles, which may include both one or two speed changes. Six sets of data, a velocity and a time, are necessary to define the profile in this region. Each velocity and time parameter is converted to screen units and the profile is constructed by making consecutive draws to each data point. In the delay fan region, the maximum and minimum velocity limits are indicated by drawing a dashed line from the upper to lower time boundary of the delay fan region.

For the prior to capture path, the velocity profile is a constant velocity profile. It is constructed by extending a line from the time corresponding to waypoint 2 at the value equivalent to the entrance velocity to the delay fan region.

In Demonstration 4, the alteration of the velocity profile occurs as a result of a change in the time boundaries in the delay fan region. The velocity profile and Direct To paths are determined in the flight control program and the data is sent to the graphics host computer to build the displays. If the velocity profile is changed from the previous profile, it must be rebuilt. To determine a change in the velocity profile, the time boundary at waypoint 2 is checked. If this parameter changes, the profile has been altered and it must be rebuilt.

It was desired to observe how the location of an avoidance area or a maneuver boundary affects the velocity profile. The avoidance area was defined as a circle of radius RAV. The center and radius of the avoidance area are sent to the graphics host computer by the 1819A. The circle is constructed in a manner similar to the routine that constructs the circular arcs for the predict routine. The data points for the avoidance area are appended to the total path array. The vertical east boundary of the delay fan area is varied in the X-axis by replacing the X coordinates in the data list for that boundary with the desired position. The location and size of the avoidance area and the X position of the variable boundary are input to the flight computer as keyboard entries.

A time, other than the time boundary for the delay fan region, had to be selected as the check for a change in the velocity profile since the profile will change, depending on the location of the avoidance area, even though the time boundaries remain the same.

The effect of the complexity of the displays is very apparent in these last two demonstrations. The manipulation routine, required because of the heading-up, moving map configuration, is required to perform rotation, translation, scaling, and clipping operations on up to 370 vectors. The cycle time for these two demonstrations was 6 seconds when displaying the lateral path.

APPENDIX F

In addition to the articles and papers listed in the References, the following articles and papers were reviewed as part of this study.

1. ATHANS, M.: Application of Modern Control Theory to Scheduling and Path-Stretching Maneuvers of Aircraft in the Near Terminal Area. NASA CR-142058 Oct 74

2. ATHANS, M. and PORTER, L. W.: An Approach to Semiautomatic Scheduling and Holding Strategies for Air Traffic Control. Proceeding 1971 Joint Automatic Control Conference, Aug 71, AD-721474

3. BRYSON, A. E. and HO, Y. C.: Applied Optimal Control. Braisdell, 69

4. DUNING, K. E., HEMESATH, N. B., HICKOK, C. W., LAMMERS, D. G., GOEMAAT, M. L.: Curved Approach Path Study. FAA-RD-72-143.

5. FOSTER, J. L.: Microwave Landing System Effect on the Flight Guidance and Control System. AIAA Paper No. 72-755 Aug, 72

6. HINDSON, W. S. and GOULD, D. G.: Modification of V/STOL Instrument Approach Geometry as a Means of Compensating for Along-Track Wind Effects. AD-775-927 Jan, 74

7. HOFFMAN, W. C., HOLLISTER, W. M., and HOWELL, J. D.: Navigation and Guidance Requirements for Commercial VTOL Operations. NASA CR-132423 Jan, 74

8. HOFFMAN, W. C., ZVARA, J., BRYSON, A. E., HAM, N. D.: Automatic Guidance Concept for VTOL Aircraft. J. Aircraft Vol 8, No. 8, Aug, 71

9. HUNTLEY: Landing Transition Paths Which Optimize Fuel, Time or Distance for Jet-Lift VTOL Transport Aircraft in Steep Approaches. N74-28527

10. JACOBSON, I., KUHLTHAU, A. R.: Determining STOL Ride Quality Criteria - Passenger Acceptance. J. Aircraft 73

11. KISHI, F. H., PFEFFER, I.: Approach Guidance to Circular Flight Paths. J Aircraft Vol 8, No. 2 Feb, 71

12. MADDEN, P., DESAI, M.: Non-Linear Trajectory Following in the Terminal Area: Guidance Control and Flight Mechanics Concept Using the Microwave Landing System. AIAA Paper No. 73-903 Aug, 73

13. McELREATH, K. W., KLEIN, J. A., THOMAS, R.C.: Pilot-in-the-Loop Control Systems (A Different Approach). AIAA A73-35063, May, 73

14. McGEE, L. A., CHRISTENSEN, J. V.: Enroute Position and Time Control for Aircraft Using Kalman Filtering of Radio Aid Data. NASA TN D 7509, Dec, 7

15. MENGA, G., ERZBERGER, H.: Time Controlled Descent Guidance in Uncertain Winds AIAA Paper 75-1078 Aug, 75

16. MERCER, J. C.: Application of Automation in Terminal Area Air Traffic Control. AIAA Paper 68-1100 Oct, 68

17. MIELE, A.: Flight Mechanics, Vol 1, Theory of Flight Paths. ADDISON-WESLEY, 1962

18. NAGARAJAN, N.: Discrete Optimal Control Approach to a Four-Dimensional Guidance Problem Near Terminal Areas. Int Journal of Control, Vol 20, No. 2, 1974

19. NEUMAN, F., WARNER, D. N.: A STOL Terminal Area Navigation System. TM X-62,348, May, 74

20. ROSSITER, S. B., MAURER, J., O'BRIEN, P. J.: ATC Concepts for V/STOL Vehicles. Rept No. FAA RD-73-47 Apr, 73

21. SCHMIDT, D. K., SWAIM, R. L.: An Optimal Control Approach to Terminal Area Air Traffic Control. J Aircraft Vol 10, No. 3, March, 73

22. SMITH, D. W., NEUMAN, F., WATSON, D. M., HARDY, G. H.: A Flight Investigation of a Terminal Area Navigation and Guidance Concept for STOL Aircraft. TMX-62,375 July, 74

23. TOBIAS, L., ERZBERGER, H.: Simulation of 4D RNAV in the Terminal Area. Proceedings, 1974 IEEE, Oct, 74

24. ERZBERGER, H., BARMAN, J., McLEAN, J.: Fixed Range Optimum Trajectories for Short Haul Aircraft. TND-8115, Dec, 75