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PILOT'S MANUAL FOR AUTOMATED 4D GUIDANCE SYSTEM

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SUMMARY

Operational procedures and modes of an experimental 4D guidance system are described from the pilot's point of view. The system consists of the experimental avionics equipment referred to as STOLAND and a specially developed software package for the STOLAND digital computer. A unique capture mode of the system provides arrival time control and automatic tracking of the 4D flight path from any feasible initial aircraft state to any waypoint. Precise arrival time at a waypoint is achieved by means of speed control or, if large delays are required, by path stretching. Continuous recomputation and display of the capture flight path prior to engaging the system permits the pilot to determine the exact moment for terminating a holding or path stretching maneuver in order to achieve a specified arrival time. The STOLAND multifunction display displays curved flight path and arrival time information to the pilot. The system will be used for flight research in terminal area operating procedures of STOL aircraft.

INTRODUCTION

This report is intended to serve as a user's guide to the Automated Guidance System developed at Ames Research Center and implemented for flight research on the experimental avionics equipment referred to as STOLAND. Operational features of the system and its use in an advanced terminal area environment

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are described from the point of view of the pilot. The guidance and control logic programmed into the system is explained in non-mathematical terms to the degree needed to show the response of the system to various operational situations. A reader interested in design details of this guidance concept should consult references 1-3.

The STOLAND avionics equipment on which the concept has been implemented consists of a general purpose digital computer, various cockpit displays, a control panel, a keyboard and interfaces with the aircraft actuators and sensors. This avionics package is being used by NASA Ames Research Center to investigate various types of guidance and navigation concepts for STOL aircraft. The basic STOLAND equipment also provides a spectrum of guidance functions ranging from basic autopilot modes to automatic landing. An overview of the STOLAND equipment and its software is given in reference 4. The software for the Ames Automated Guidance System augments the basic STOLAND software and is coresident with it on the STOLAND digital computer. Thus, the pilot has access to the Ames 4D guidance modes and the basic STOLAND autopilot modes on the same flight.

The Ames Automated Guidance System is designed to provide time-controlled (4D) guidance along a curved flight path. In addition, this capability is enhanced with the following features to increase the versatility of the system in the terminal area.

The pilot can initiate 4D guidance from virtually any initial aircraft position, altitude, heading and airspeed. This is achieved by means of a capturing mode which performs 4D guidance from the current aircraft state to the first waypoint of the stored reference trajectory. The pilot also has the option of using either speed control alone or path stretching and/or holding to control arrival time. Path stretching or holding maneuvers are either flown manually, or using the STOLAND autopilot modes. The time to terminate the maneuver in order to achieve a specified delay is indicated on the Multi-function Display (MFD).

The 4D trajectory is compensated for wind conditions in two ways; first for predicted winds before the start of 4D tracking and then for currently measured winds while 4D tracking is in progress.

Arrival times, compensated for wind conditions, are presented on the MFD in Standard Time.

Finally, a greatly simplified method of trajectory specification is used that permits the pilot to enter a complex trajectory via the keyboard with the absolute minimum number of input data.

ACKNOWLEDGEMENTS

Both the development of the guidance concept and its implementation on STOLAND was an in-house effort involving a number of contributors. Thomas Pecsvaradi developed most of the trajectory synthesis procedures and also wrote the necessary assembly language programs. Homer Lee developed

the control law and wrote the assembly language programs for tracking of the reference trajectory. Neil Warner wrote the MFD and Keyboard programs. Jayant Karmarkar performed the difficult job of integrating the various software packages and interfacing these packages with the STOLAND system.

GENERAL DISCUSSION OF SYSTEM MODES

Trajectory Selection and Wind Input

As the first step in using the system, the pilot selects the desired trajectory by depressing one of the four trajectory buttons on the STOLAND control panel. The system responds by drawing the horizontal plane projection of the chosen trajectory on the MFD. Alternately, he can replace any of the four prestored trajectories with a new trajectory entered manually via the keyboard. The method used to specify a trajectory and to enter it using the keyboard is described in a later section.

At this time the wind vector should be entered via the keyboard using the mnemonic EWM = DD, KK where DD is given in decadegrees and KK in knots. This wind vector is used by the system before the start of automatic tracking to calculate the reference speed profile required for 4D guidance. In the automatic tracking mode, described in a later section, the estimate of the wind vector provided by the STOLAND navigation system replaces this pilot entered vector.

Since it is often true that the wind is a strong function of the altitude, it is necessary to compromise in the selection of the wind vector. If the pilot knows the wind at various altitudes, it is recommended that he enter the wind vector for the altitude at which the aircraft will experience the greatest sensitivity to winds. This usually occurs near the end of the trajectory when the aircraft is flying at low airspeed.

Predictive Mode

Next, the pilot enters the predictive mode by typing the mnemonic FOD = 1 on the keyboard. The function of this mode is to compute the capturing maneuver required to fly from the current position and heading to the starting waypoint of the trajectory and to display it on the Multifunction Display (MFD) for the pilot's approval. If the system finds a feasible capturing maneuver, it is displayed with dashed lines starting at the current aircraft position and ending at the starting waypoint of the reference trajectory. In the lower left corner of the display three additional types of information required for 4D trajectory control are displayed. The first of these is the predicted time of arrival at the end of the reference trajectory. The time of this arrival, identified by the mnemonic TOA = hh:mm:ss and calculated in hours, minutes and seconds of standard time, includes the time to fly along the capturing maneuver as well as the time to fly the reference trajectory. The second type of information displayed is the maximum advance and delay in the time of arrival to the final waypoint that can be obtained by airspeed control. This information is displayed as TDA =- mm:ss; mm:ss where the negative time indicates advance and the positive time delay in arrival time in minute and seconds. The third type of information shown is the number of the next waypoint and the time enroute, which are displayed as follows, TWPnnmm:ss where nn indicates the waypoint number.

An important feature of the predictive mode is that all MFD quantities described in the preceding paragraph are recomputed continuously using the current aircraft position, altitude, heading and airspeed. In a later section we describe how this continuously computed information can be used to fly precisely timed path stretching or holding maneuvers. Another feature of this mode is that it is strictly passive, used only to display information. In it, the pilot can fly the aircraft manually or he can engage any other STOLAND flight control mode such as heading hold, altitude hold or autothrottle.

Figure 1 shows a photograph of the MFD displaying the reference trajectory (solid), the capture maneuver (dashed) and, in the lower left hand corner, the waypoint and arrival time information. Current position of the aircraft is indicated by the small isoceles triangle, whose long base line points along the current heading. Dots trailing behind the aircraft symbol show the recent flight path of the aircraft. In the upper left hand corner, the barometric altitude is given in feet and in the upper right corner current time is displayed.

If at any time the system fails to compute a capturing maneuver, the waypoint and arrival time data will disappear and instead a blinking message on the MFD will explain the reason for the failure. The failure to capture, which generally can occur only when the aircraft is relatively close to the starting waypoint, is caused by one or more of the following conditions. At the aircraft's current position, speed, altitude and heading, the system cannot find a horizontal maneuver to capture the first waypoint, or the aircraft has insufficient time to decelerate to the first waypoint or the altitude difference is too large. The corresponding messages displayed for each of these three conditions are "NO CAP HOR:nn", "NO CAP ALT:nn", or "NO CAP VEL:nn", where nn indicates the number of the waypoint that is to be captured. If the NO CAP HOR:nn message appears on the MFD, the dashed lines for the horizontal capturing maneuver will, of course, be absent.

Instead of capturing the first waypoint a command is available to specify any point used in the definition of the reference trajectory as the point to capture the trajectory. This feature adds considerable flexibility to the four prestored trajectories. To specify waypoint j as the capture point, the pilot types WPT=j.

After the command FOD=1 has been entered the trajectory selection buttons are locked out, that is to say the trajectory shown on the MFD will not be affected by pressing these buttons. To select a different trajectory, the pilot must first exit from the predictive mode by entering FOD=0, make the selection and then reenter FOD=1.

The Tracking Mode

As long as the MFD indicates a valid capture maneuver, the pilot can command automatic tracking of the trajectory by setting the FULL AUTO switch to the on position. This causes the system to generate the appropriate SAS and airspeed commands to capture and then track the reference trajectory. After the tracking command has been entered, the dotted portion of the trajectory shown on the MFD changes to a solid line and the time of arrival (TOA) freezes at the current value. The predicted capturing maneuver, previously shown dotted, changes to a solid line and is flown as an extension of the main trajectory.

Also shown on the MFD in the tracking mode is a second aircraft symbol referred to as the phantom aircraft. The phantom starts its motion at the time the track command is entered. From its initial position which coincides with the actual aircraft position, it follows the reference trajectory as long as the track mode is engaged. The speed profile of the phantom aircraft is such that it will reach the final waypoint of the reference trajectory at the time indicated on the MFD. Comparison of the position error between the phantom and the actual aircraft gives the pilot an indication of the tracking fidelity of the control law. The photograph of the MFD reproduced in figure 2 shows the situation a short time after the tracking command was entered. Since the phantom was being tracked automatically, the symbols for the phantom and the aircraft position very nearly coincide.

While the system is capturing or tracking the reference trajectory, the maximum values of the time delay and time advance (TDA) by which the time of arrival at the final waypoint can be shifted are constantly being updated. Also the next waypoint and the time to this point continue to be updated. By typing the mnenomic TDC followed by time in minutes and seconds, the pilot can cause the predicted time of arrival to be shifted to a new value without interrupting the tracking of the reference trajectory. An error message will appear on the keyboard status panel if he should type a number not within the allowable range displayed on the MFD.

Disengaging the Tracking Mode

While the aircraft is tracking the reference trajectory, the pilot may wish to temporarily disengage the tracking mode, fly the aircraft manually or use other autopilot modes and then return to tracking of the same reference trajectory. Reasons for a temporary disengage may be the need to perform collision avoidance, holding or path stretching maneuvers. But to what point on the reference trajectory should the system guide the aircraft after the track mode is engaged again? Although the answer to this question cannot be anticipated correctly in all cases, we have chosen the beginning of the straight line segment at the current next waypoint as the point to recapture the reference trajectory.

The procedure for disengaging the tracking mode is simply to set the FULL AUTO switch to the off position, which has the effect of returning the system to the predictive mode described earlier. As soon as the command has been entered, the pilot can resume manual control or engage other autopilot modes. Since the system is in the predictive mode, the MFD will show the capturing maneuver from the current position to the next point where the aircraft will return to the trajectory. Time to the return waypoint and time to the final waypoint are updated and displayed as before. Also, the display will indicate when the new starting point cannot be captured. Furthermore, the pilot can use the WPT command to change the starting point if the one selected by the system at the time of the disengage command is not suitable.

In addition to setting the FULL AUTO switch off, the pilot has two other methods for overriding the tracking mode. If he shakes or forces the control column or the throttle lever, the effect is the same as turning the FULL AUTO switch off, namely the system is taken out of the tracking mode and placed in the predictive mode, where the pilot has manual control of the aircraft. He can also exit from the automated guidance system entirely and purge the current trajectory by entering the command FOD=0. Following execution of this command, the system is left in the manual control mode.

Effect of Large Tracking Error

During fully automatic tracking of the reference trajectory the control law is constantly nulling spatial and temporal tracking errors caused by wind disturbances and navigation system errors. However, the control law has limited authority, and sufficiently strong disturbances or navigation errors can result in large errors between the aircraft and reference trajectory. The system will call the pilot's attention to this condition by a blinking message on the MFD announcing "Guidance Errors Exceeded" if the X, Y, Z, heading errors or speed errors exceed specified limits. These limits, which quantitatively define large errors, are entered during preflight. Further actions to be taken when this condition occurs are left to the pilot. The system presents only the message but does not disconnect.

One possible action the pilot could take in response to this condition is to disengage the tracking mode temporarily. As already explained, this results in a new capturing maneuver to be computed to the next current waypoint starting at the current aircraft position and state. Reentering the tracking command will cause the phantom aircraft to be in coincidence with the current aircraft position, thus eliminating the large error condition. The pilot has to judge whether this action is acceptable.

After the guidance system has flow the aircraft to the end of the 4D reference trajectory, the system will automatically switch to Flare and Decrab. Although this is considered the normal termination point of 4D guidance, the system could, of course, be reprogrammed to terminate at any other point.

System Flow Chart and List of Commands and Messages

The general description of the system given in the preceding discussion can be summarized in the simplified flow chart form as shown in figure 3. Each of the functions previously described establishes a computation loop. There are four such loops corresponding to trajectory selection (loop 1), trajectory prediction (loop 2), trajectory tracking (loop 3) and no capture (loop 4). All loops except 4 are chosen by pilot entered commands represented by decision elements in the chart.

Tables 1 and 2 give complete lists of the keyboard commands and MFD messages available in the Automated Guidance System modes. Each command or message is followed by a brief description of its use or meaning.

WAYPOINT DEFINITIONS AND 3D PATH CALCULATIONS

The problem of calculating the 3D path is divided into two problems. First the projection of the trajectory in a horizontal plane is computed from an analysis of waypoint coordinates and desired turning radii. Then the known arc length of the horizontal trajectory together with the altitude difference between adjacent waypoints is used to determine the flight path angle and, therefore, the altitude profile between adjacent waypoints. The exact procedure for converting waypoint coordinates and turning radii into a curved 3D trajectory depends crucially on the interpretation of waypoints. Analysis of the type of curved trajectories that occur in the terminal area shows the need for two types of waypoints which we refer to as ordinary and final heading waypoints.

Ordinary Waypoints

In area navigation systems, navigation routes are specified by waypoints located at the intersection of straight line segments. We retain this concept and add only the specification of the radius of the circular arc to fill in the corner formed by the intersecting straight lines. However, the specification of the turning radius is optional. If the pilot does not include it in the specification data, the system chooses a turning radius corresponding to a nominal bank angle of 20 degrees. We call waypoints of this type ordinary waypoints.

Figure 4a illustrates the construction of a trajectory between four ordinary waypoints. Note that except at the first and last waypoints the trajectory does not pass through the waypoints themselves. Also, the rule used to construct a trajectory between ordinary waypoints can only be applied if the circular arcs at adjacent waypoints do not overlap. The system will inform the pilot with an MFD error message indicating which pair of adjacent waypoints are too close.

Final Heading Waypoints

This type is illustrated in figure 4b. Instead of rounding the corner at the intersection of two lines, the trajectory for this type passes through the waypoint at the end of a turn. The construction of the trajectory must begin at the last waypoint where a final heading, Ψ_4, must be specified by the pilot. The heading of the preceding waypoint is then implicitly defined by the straight line segment starting at WP3 and ending at the tangent point to the circular arc at WP4.

There are two reasons for introducing this type of waypoint. First, it simplifies the specification of some trajectory segments, such as the turn at WP2 which contains more than 180°. A single ordinary waypoint cannot be used to specify such segments. Second, this type is required if the arrival time is to be specified at the waypoint. To calculate the arrival time at a waypoint accurately, the trajectory must pass through that waypoint. Thus, the last waypoint of a 4D trajectory must always be a final heading waypoint.

As was the case for the ordinary waypoints, it is possible that turns at adjacent waypoints overlap. If the system detects this condition in the waypoint data, the pilot is informed by an appropriate message on the MFD.

Also, for both types of waypoints, the first trajectory segment is always a straight line beginning at the first waypoint. In the next section we will describe the technique used to capture the first waypoint from the current aircraft position.

Altitude Profile

The simplest possible altitude profile is chosen between two adjacent waypoints. It is determined by calculating the flight path angle required to fly from the altitude specified at one waypoint to that of the next one. For both ordinary or final heading waypoints the convention is adopted that the altitude specified at a waypoint shall be achieved at the end of the turn required at a waypoint. Figure 5 shows the altitude profile along an assumed horizontal trajectory using this convention.

The flight path angle computed for each waypoint is tested if it falls within the permissible range. The maximum and minimum flight path angles defining the permissible range are specified in a preflight program. If the required angle falls outside the range, a message on the MFD informs the pilot of this condition.

Airspeed Profile and Flap Schedule

In order to compute the time required to traverse a 3D trajectory, it is necessary to specify in advance how the aircraft is to change speed as a function of the position along the trajectory. In the interests of fuel economy, minimum aircraft noise, and passenger acceptance, speed changes should occur at as few points as possible and with acceptable rates. If the aircraft is entering the terminal area to make a landing approach, speed reductions must be accompanied by appropriate flap extensions.

The speed profile along the reference 3D trajectory is determined from the airspeed the pilot has specified at each waypoint. The rule used to change the airspeed from a speed specified at one waypoint to that of the next one is as follows: The speed change is made at constant deceleration/acceleration, and is started at a point such that the new airspeed will be achieved exactly at the end of the turn of the next waypoint. The acceleration/deceleration to be used must be included as part of the trajectory specification. By placing the flaps control switch in the automatic position, flaps will be lowered automatically when the aircraft first reaches the flaps down airspeed. The existing STOLAND automatic flap extension logic is used to command the flaps. An example speed profile is illustrated in figure 6, which shows the variation of airspeed as a function of distance along the ground track of the reference trajectory. Note that a constant rate of airspeed change yields a non-linear airspeed change as a function of distance.

After converting the airspeed profile to ground speed along the trajectory by adding in the wind vector, the 4D guidance system computes the time interval to traverse the trajectory. This time interval, together with the time enroute from current position to the start of the trajectory is added to current time to yield the arrival time (TOA) at the end of the trajectory.

The next step is to specify the procedure for modifying the speed profile in order to change the arrival time. Consultation with pilots and examination of existing ATC procedures suggested the technique illustrated in figure 7. When the pilot first enters the predictive mode the base line speed profile described in the preceding paragraph is used to compute TOA. This profile which yields the minimum arrival time is then flown by default unless the pilot modifies the TOA. Delay in arrival time is achieved by starting the deceleration to each waypoint speed earlier than for the base line profile, as illustrated by the intermediate delay profile. The profile giving maximum time delay is obtained by starting the deceleration to the next waypoint speed at the end of the turn of the current waypoint. The two values of time which follow TDA on the MFD are computed for the base line and the max. delay profiles.

When the pilot enters a time delay specification, the system computes the new starting points of the deceleration segments so as to achieve the value of delay specified and then updates the TOA shown on the MFD. After retarding the arrival time, the pilot can also advance it again by the same or a smaller amount. If the arrival time has been retarded, the MFD displays both the additional time delay still available as well as the advance in arrival time that can be achieved by returning to the base line speed profile.

As the aircraft flies along the reference trajectory, the system continues to compute the remaining advance and delay of arrival time available relative to the predicted time of arrival. Of course, the available range contracts to zero as the aircraft approaches the final waypoint.

Trajectory Specification via Keyboard

The specification of complex trajectories by means of a sequence of waypoints, though simple in concept, is probably still too tedius and distracting to be of much use to pilots in flight. Moreover, the availability of prestored trajectories, together with the ability to change the capture waypoint should provide the pilot with sufficient flexibility in trajectory selection during any particular flight. Nevertheless, an in-flight procedure for defining a new trajectory is available to the pilot.

The procedure consists of entering sequentially via the keyboard the waypoint coordinates of a trajectory and other quantities associated with each waypoint. Specifically, each waypoint of a trajectory is identified by a sequence integer, a type integer, three coordinate numbers, an airspeed and a turning radius. The format for entering these quantities is illustrated in Table 3 for an example trajectory. Origin of the coordinate system is assumed to be the desired touchdown point and the reference direction is the landing direction. After the data for the final waypoint has been entered the system computes the 3D reference trajectory and stores it in one of the locations set aside for flight path storage. If any adjacent waypoint pairs are too close, the keyboard status panel indicates an error message and invites the pilot to change the coordinates causing the message. After the corrections have been entered, the system again attempts to compute the 3D trajectory. This process continues until a valid trajectory is obtained.

THE CAPTURING MANEUVER

In the preceding section we described the technique used to specify a trajectory from first to last waypoint. Since initially the aircraft will generally not be at the first waypoint with the required initial conditions, we have to develop procedures for guiding the aircraft from its current position and state to the conditions specified at the first waypoint. This is referred to as the capturing maneuver.

The requirement for the capturing maneuver is that it must deliver the aircraft to the first waypoint with the specified altitude, airspeed and heading. The system must also inform the pilot when operational and passenger constraints do not permit a capturing maneuver from the current aircraft state.

The capturing maneuver is synthesized in three steps. First, the horizontal maneuver is computed so as to deliver the aircraft over the first waypoint with the heading of the first straight line segment. This part of the maneuver generally consists of a turn, followed by a straight line segment, followed by a turn. Second, the altitude profile is computed. It consists of a constant flight path angle chosen such that the aircraft will achieve the altitude specified for the first waypoint at the end of the horizontal capturing maneuver. Finally the airspeed profile along this 3D path is chosen as a constant airspeed segment followed by a constant deceleration or acceleration segment. The beginning of the deceleration or acceleration is computed such that the desired airspeed at the first waypoint is reached in coincidence with the end of the 3D capturing maneuver. As long as the tracking mode is not engaged, the capturing maneuver is recomputed about once a second. In this way, the optimum capturing maneuver is available at whatever time the pilot enters the tracking command.

The examples shown in figures 8-10 illustrate various aspects in the calculation of the capturing maneuver. In each of the examples a capturing maneuver is calculated from some initial condition designated by IP1, IP2, or IP3 to a final condition at waypoint 1 (WP1). The trajectory from waypoint 1 is assumed to be the final approach to landing although in general it is the current next waypoint of a trajectory. In figure 8 the aircraft is approaching with the altitude and speed specified for the capture point, WP1, but it is flying along a line perpendicular to the final heading. The horizontal capturing maneuvers that the system generates at three different points along the aircraft's line of flight, are drawn in the figure. They are Left Turn, Straight, Right Turn at IP1, no capture possible at IP2, and Right Turn, Straight, Right Turn at IP3. These three situations would appear on the MFD in succession if the aircraft is permitted to fly along its initial line of flight. The set of points along the line of flight where a no capture message would be displayed on the MFD is also indicated in the figure.

In figure 9, the aircraft is approaching at 6000 ft. altitude along a different line, which is also perpendicular to the desired final heading. The approach speed is again 140 knots. Although a horizontal capture maneuver exists for all points along the line of flight, the flight path angle required to capture the 2000 ft. waypoint altitude is less than the minimum permissible value of - 10° degrees along some of the points. At these points a no capture message would appear on the MFD.

A third approach condition is shown in figure 10. Here the aircraft is at the desired waypoint altitude of 2000 ft. but its approach speed is 200 knots, and the initial line of flight is at 74° with respect to the desired final heading. Horizontal capture maneuvers exist at points IP1, IP2, IP4, but at IP2 airspeed capture fails because there is insufficient distance along the horizontal trajectory to decelerate from 200 to 100 knots. At IP3, the horizontal capture maneuver also fails to exist. The turning radius used in computing the horizontal capturing maneuver is chosen so that a specified maximum bank angle will not be exceeded during turns. In the examples this limit was set at 20°.

Definition of current First Waypoint

While the system is in the tracking mode, i.e. the reference trajectory is being tracked, the system is continuously updating the position of a pointer in the waypoint table which indicates how far the aircraft has progressed along the reference trajectory. The position of the pointer actually identifies the next waypoint in the sequence. This waypoint is referred to as the next current waypoint, and is the one that the system would try to capture when reentering the tracking mode after a temporary disengage. In order to avoid capturing difficulties, the pointer is advanced to the next waypoint somewhat in advance of the aircraft's arrival at a waypoint. The jump from one waypoint to the next is made approximately 10 seconds prior to starting a turn at a waypoint. However, the pointer does not move past the last waypoint, thus requiring the aircraft to always capture the last waypoint.

PATH STRETCHING OR HOLDING

In the predictive mode, selected by entering FOD=1 on the keyboard, the MFD displays the trajectory, the capturing maneuver, the time to fly (TWP) from the current position to the first waypoint and the time of arrival (TOA) at the last waypoint. The quantity TWP is given relative to the present, whereas TOA is presented in absolute time, for example, in hours, minutes and seconds of Pacific Standard Time. These quantities are continuously recomputed, using the current aircraft position, altitude, heading and speed. This feature of the predictive mode can be used by the pilot to delay his arrival at any waypoint on the trajectory by precisely timed path stretching or holding maneuvers. We will describe the required procedure with reference to two examples.

Figure 11 shows the aircraft currently at P1 flying along a straight line segment toward WP1. Here, WP1 is the final approach gate, but more generally it should be considered as the next current waypoint of a trajectory. In either the predictive or the tracking mode, the MFD will display TOA and TWP for the condition shown in figure 11. Suppose the pilot wants to use a path stretching maneuver to delay his arrival at WP1 by one minute. This translates into a desired TOA of 10:21:00. The procedure is as follows:

1. The pilot takes the system out of the tracking mode. There is no restriction on the time to do this,

but the aircraft should be far enough from WP1 so that recapturing of WP1 is not in doubt.

2. The pilot banks right or left until the aircraft's heading has changed by about 45 to 90°. This maneuver begins at P2. As soon as the heading starts to change, the TOA will begin to increase. The rate of change of TOA depends on the new heading angle. The greater the heading change, the greater will be the rate of change of TOA.
3. While flying along the straight section, the pilot observes the TOA. When it has increased to the desired value of 10:21:00, the pilot enters the tracking command. (Point P4 in figure 5). The TOA freezes at this value and the aircraft begins a capturing maneuver for WP1.

There is, of course, no requirement that the path stretching maneuver be of the form illustrated in figure 11. Any flight path that deviates from the direct path toward WP1, will similarly cause the TOA to increase. As an alternative to path stretching, the pilot could also use an airspeed reduction to increase the TOA. This technique is not as effective as path stretching for increasing the TOA at close range to WP1. However, it is useful for incremental adjustments in arrival time.

To obtain a time delay of several minutes, a holding pattern is normally used instead of path stretching.

Essentially the same procedure as for path stretching determines when to leave the holding pattern in order to arrive at WP1 at a specified time. The technique is illustrated in figure 12. At P1 the aircraft is heading toward WP1 with the indicated TOA, and TWP. At this point, a delay of 5 minutes is required. The pilot begins to fly the holding pattern at P2 with the system in the predictive mode. He continues to fly the pattern manually until the TOA has increased by four minutes. This occurs at P3 after 1¼ times around the pattern. If he now enters the track command, the aircraft will follow the trajectory shown in figure 12 and arrive at WP1 at TOA= 10:25:00. It should be evident from earlier descriptions of the capturing maneuver that the pilot is not constrained to fly any particular holding pattern. It is only necessary that the pattern be flown far enough from WP1 such that WP1 can be captured from every point along the pattern.

CONCLUDING REMARKS

The principal use of the system as currently configured is for investigating new guidance techniques in an advanced terminal area environment. It can be used to conduct experiments requiring either 3D or 4D guidance. The 3D path specified may consist of any combination of curved, straight, descending, and decelerating flight segments. The control law provides wind compensation and automatic tracking along the flight path. Time of arrival at the end of the flight path is displayed to the pilot, but this information can be ignored if it is not of interest in 3D experiments.

A unique feature of the system is its capture mode which computes, on line, a curved, minimum time trajectory from any initial position to the start of the reference flight path. This feature has direct application to current CTOL operations and could be incorporated in any aircraft equipped with area navigation. Pilot evaluation of this feature will receive the highest priority in the first flight tests. Later flight experiments will focus on defining pilot-controller procedures for the 4D guidance mode of the system.

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TABLE 1

KEYBOARD COMMANDS

Command	Use
FOD=1	To enter predictive mode of Ames 4D system. Prepares system for capturing and tracking of reference trajectory. Causes waypoint arrival times and capturing maneuver to be displayed on MFD. System has no control authority in this mode.
FOD=0	Takes system out of Ames 4D mode.
FULL AUTO to "on" position.	Initiates automatic capturing and tracking of reference trajectory. To be accepted by the system, this command must be preceded by FOD=1, and capture of first waypoint must be possible.
FULL AUTO to "off" position.	Returns system to be predictive mode. After entering it, pilot has manual control of a/c.
TDC=±mm:ss	Causes the time of arrival (TOA) to be modified from the current value by ± mm (minutes:) ss (seconds). Positive sign for delay, negative sign for advance. This command can be entered only in the tracking mode. Entered value must fall in the range shown on MFD under TDA.
WPT=j	Specifies waypoint j as the first waypoint of the trajectory to be captured. Not accepted in tracking mode.
EWM=dd, kk	Estimated wind vector, wind direction, dd, in decidegrees and magnitude, kk, in knots

TABLE 2

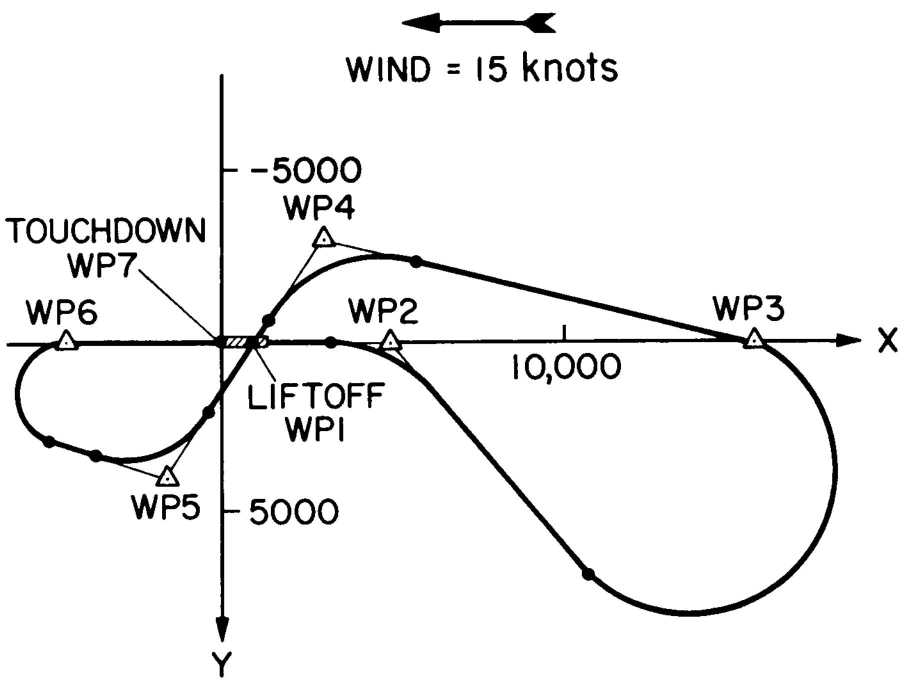
MFD MESSAGES

Message	Explanation
TOA hh:mm:ss	Predicted time of arrival to last waypoint of trajectory in standard time.
TWPnn: mm,ss	Time to current next waypoint,nn.
TDA: _mm:ss, mm:ss	Time delay (+sign) and time advance (neg. sign) available between current position and last waypoint of trajectory, using speed control only.
NO CAP HOR:nn	Horizontal capture maneuver to waypoint nn fails to exist.
NO CAP ALT:n,n	Altitude capture maneuver to waypoint nn fails to exist.
NO CAP VEL:n,n	Speed capture maneuver to waypoint nn fails to exist.
ERRORS	Difference between reference position and state and A/C position and state exceeds values set in preflight.

TABLE 3

PILOT INPUT FOR EXAMPLE TRAJECTORY

Waypoint Number	Waypoint[1] Type	Waypoint Coordinates ft. x	y	h	Airspeed ft/sec.	Turning Radius[4] ft.
1	-[2]	1000	0	0	135	4000
2	0	5000	0	600	250	4000
3	1	15000	0	2000	250	4000
4	0	3000	-3000	1500	200	4000
5	-	1500	4000	1000	135	3000
6	1	-4500	4000	1000	110	1500
7	-[3]	0	0	0	110	1500



1 Waypoint type designation: 0 or default implies ordinary waypoint.
1 implies final heading waypoint.

2,3 First and last waypoints are always assumed to be final heading types. Final heading of last waypoint is assumed to be the heading of the runway.

4 Turning radius specification is optional. If defaulted, turning radius is chosen on the basis of a 20° bank angle limit.

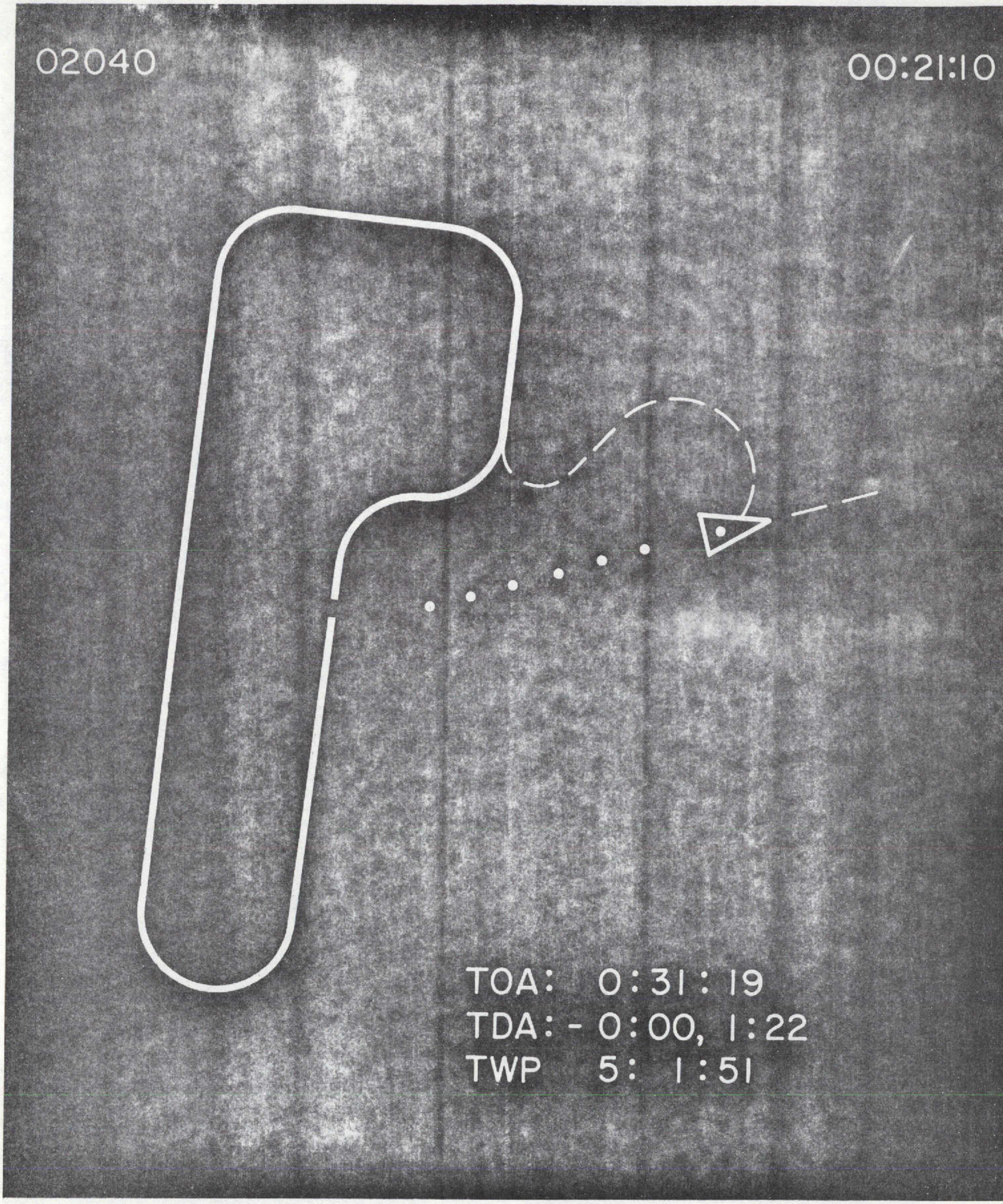


FIGURE 1 Photograph of MFD displaying reference trajectory, capture maneuver and arrival time information.

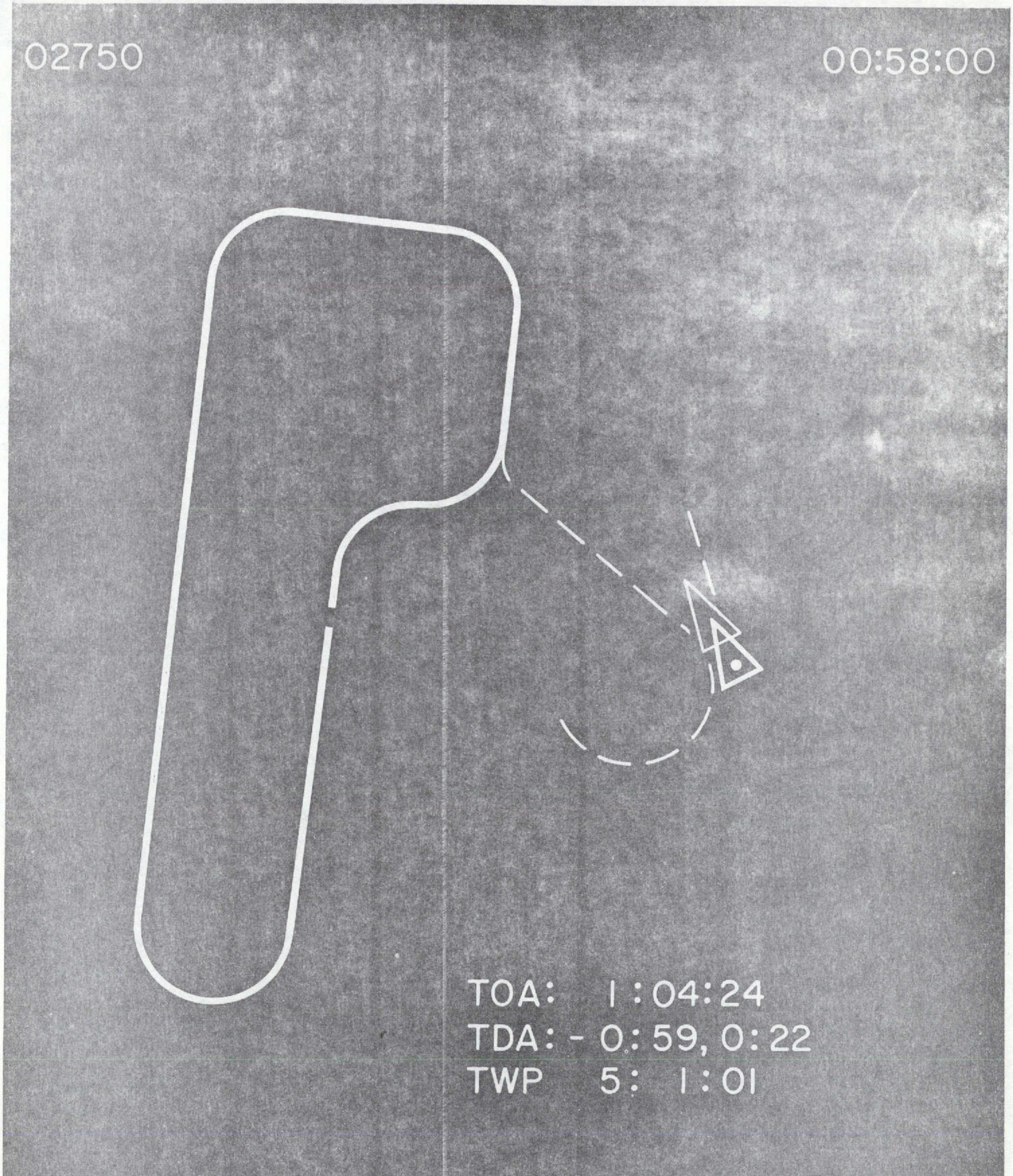


FIGURE 2 Photograph of MFD illustrating tracking error between A/C and phantom.

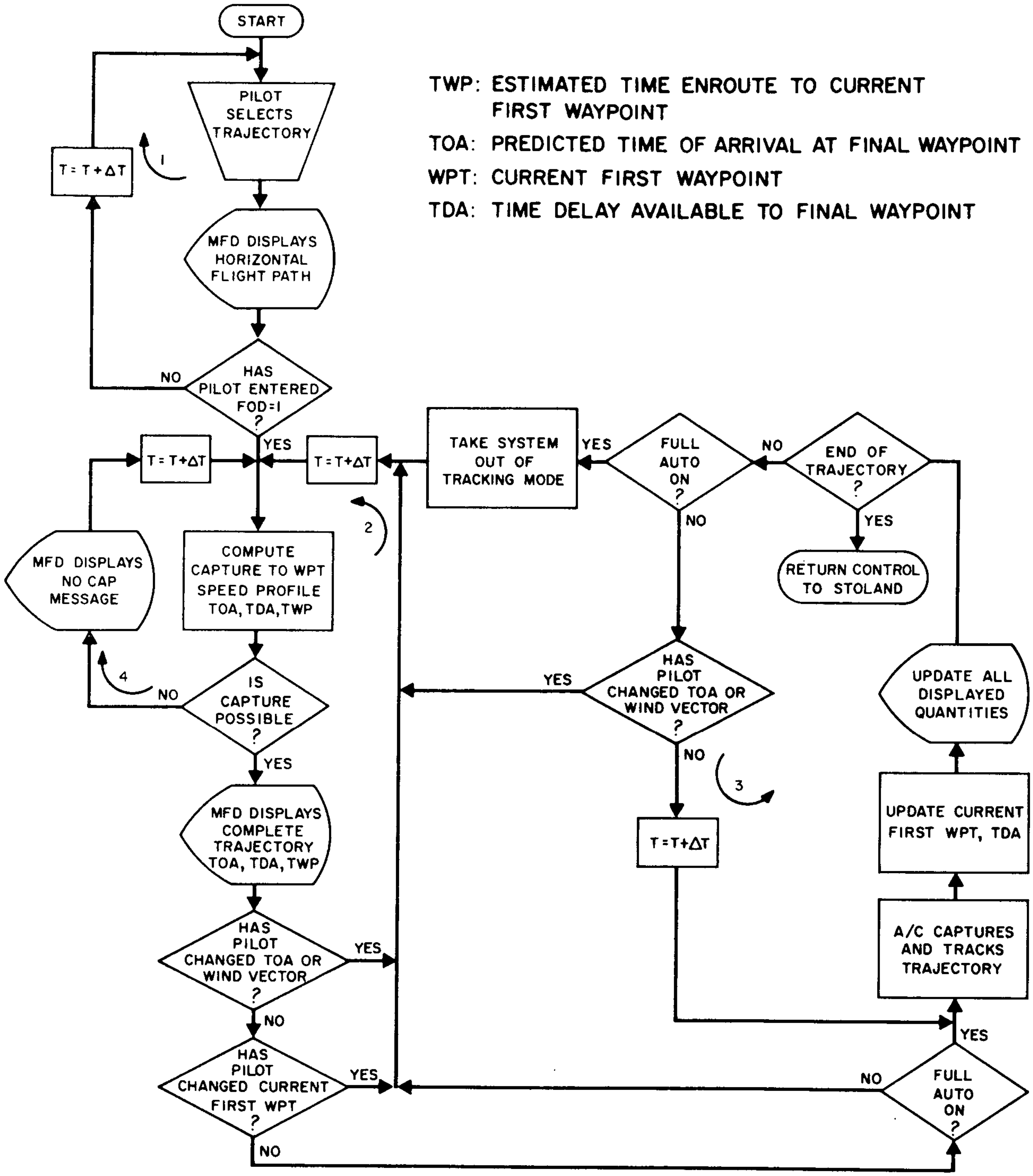


FIGURE 3. Simplified flow chart of 4D guidance system

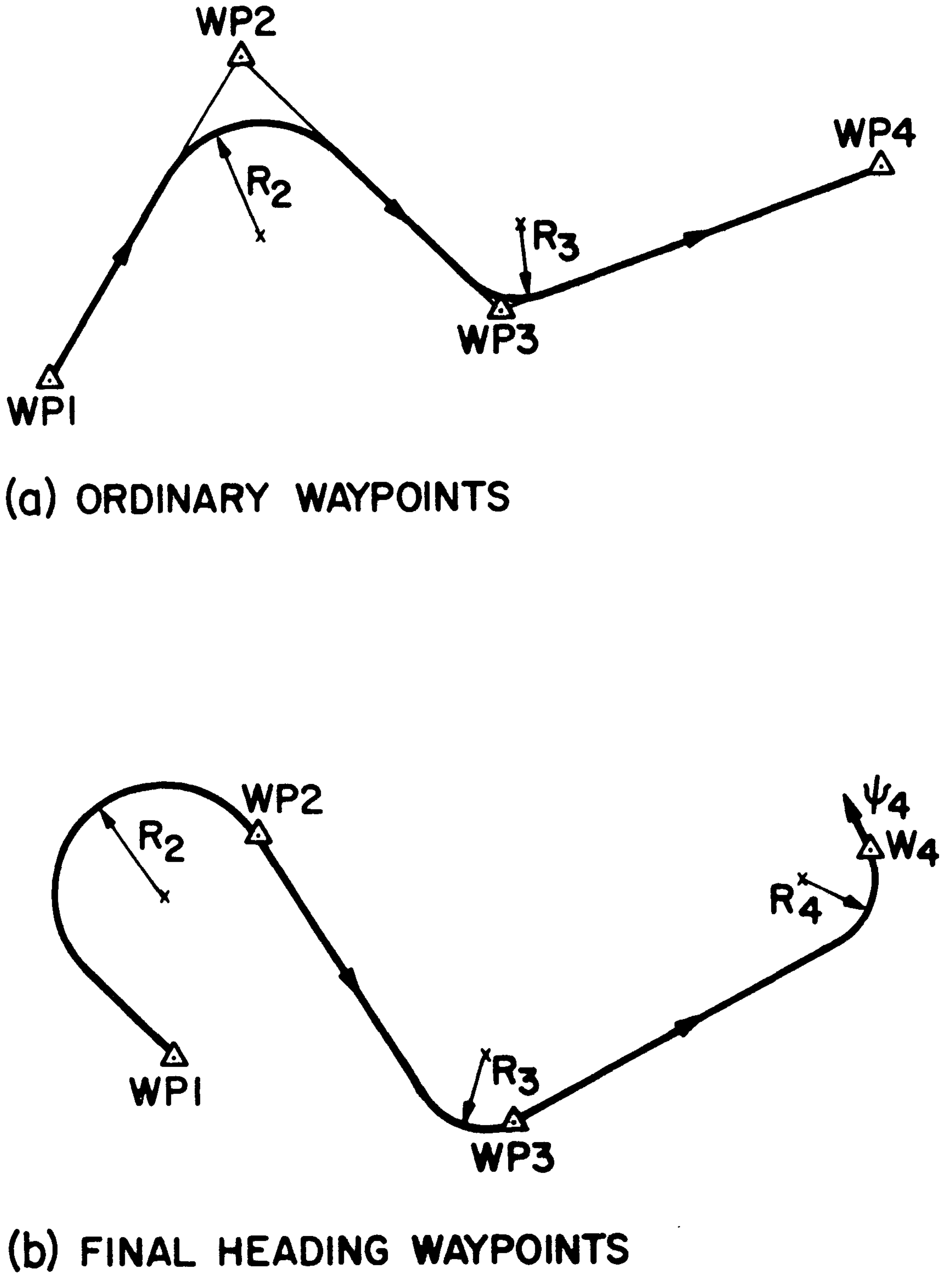


FIGURE 4 Illustration of horizontal waypoint types

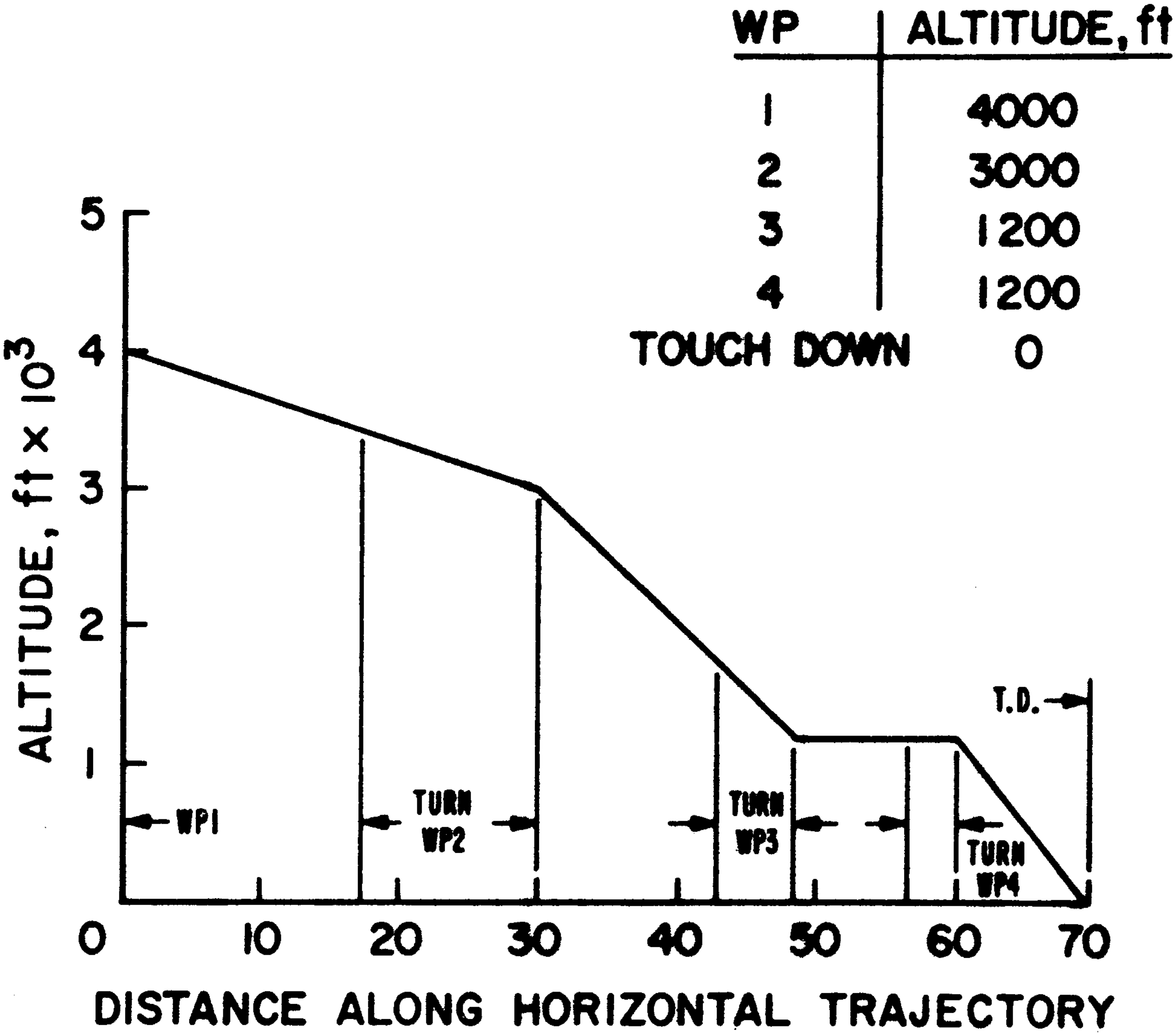


FIGURE 5 Specification of altitude profile.

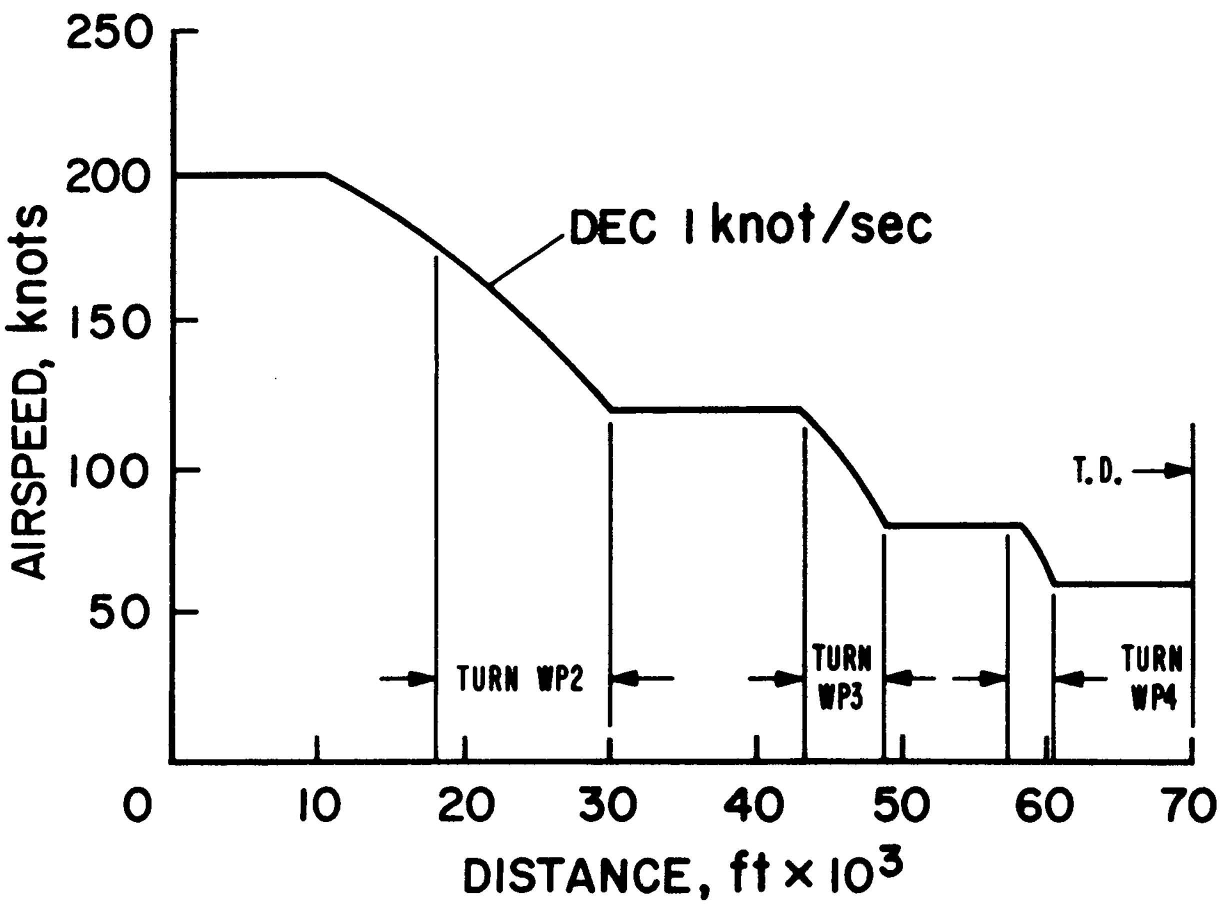


FIGURE 6 Specification of speed profile.

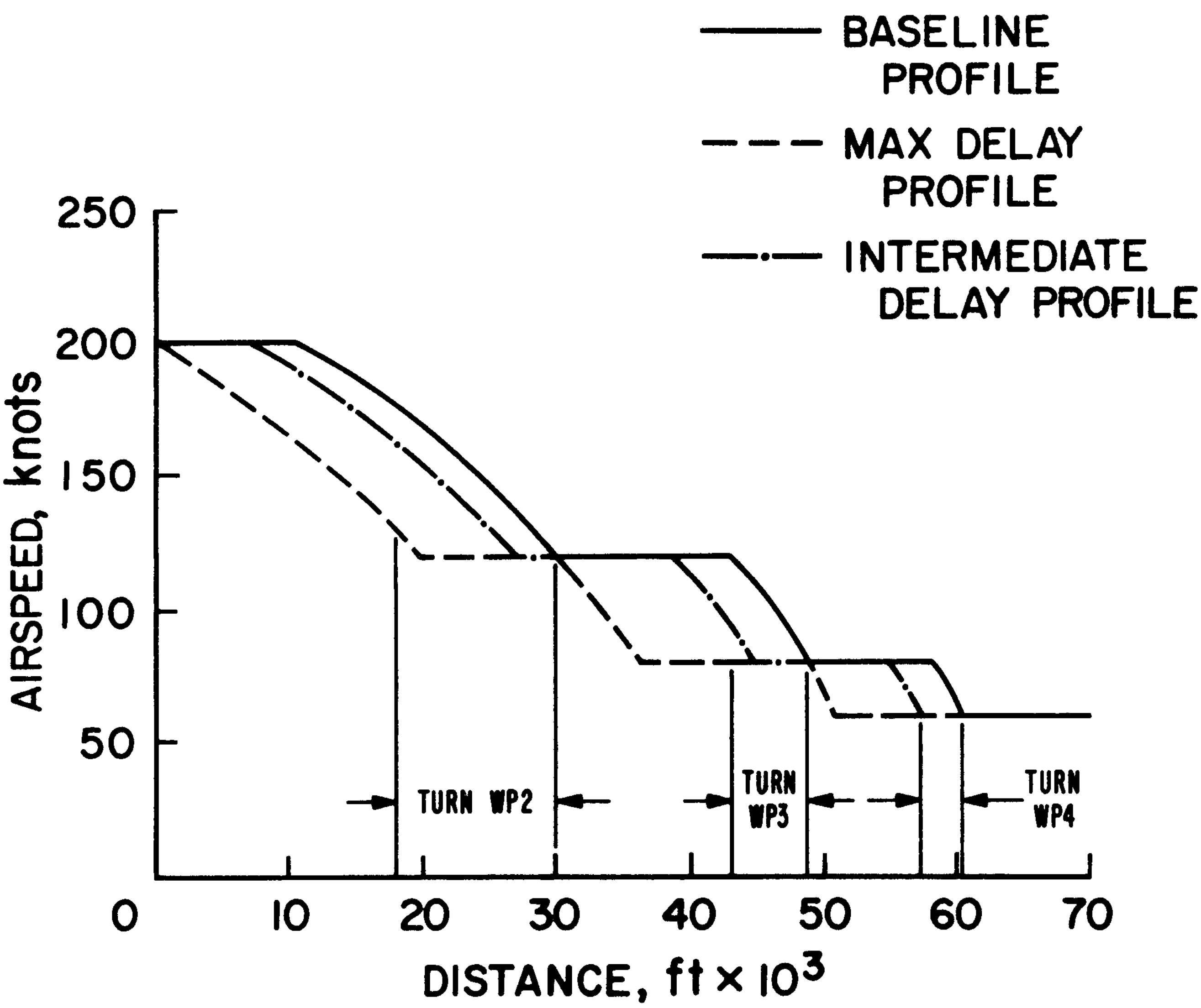
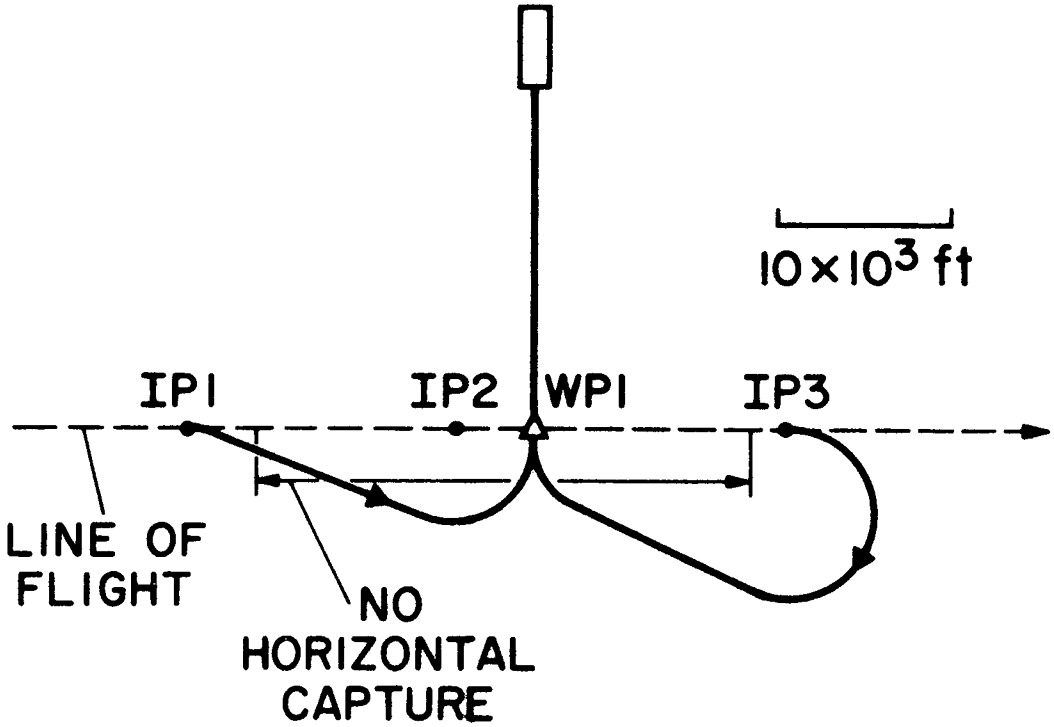


FIGURE 7 Procedure for modifying speed profile.



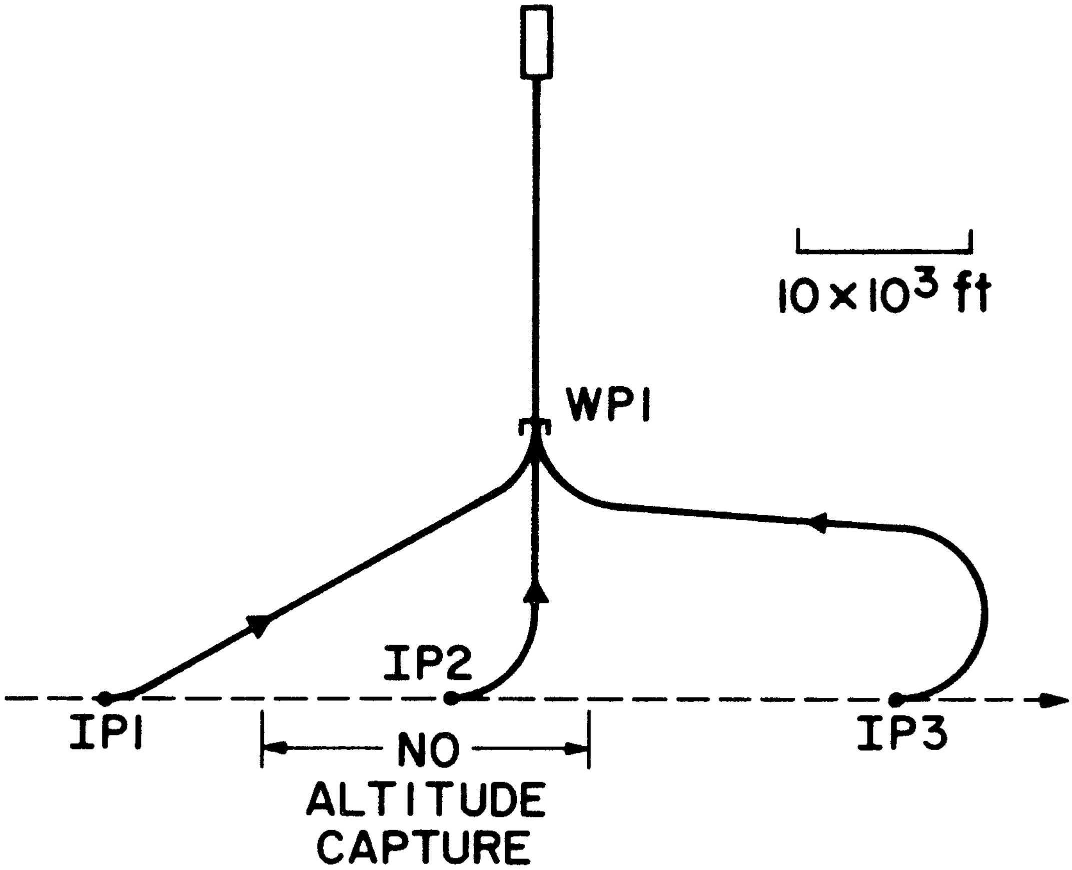
INITIAL CONDITIONS	END CONDITIONS AT WP1	MANEUVER CONSTRAINTS
h = 1500 ft V = 140 knots ψ = 90 deg	1500 ft 140 knots 0 deg	MAX BANK = 20 deg MAX DEC = 1 knot/sec MIN γ = -10 deg

SUMMARY OF CAPTURE MANEUVER

INITIAL POSITION	HORIZONTAL MANEUVER*	γ	TIME TO DEC	TWP	DISPLAY
IP1	RSL	0	0	1:40	HORIZ TRAJEC
IP2	—	—	—	—	NO CAP HORIZ
IP3	RSR	0	0	2:30	HORIZ TRAJEC

*L = LEFT, S = STRAIGHT, R = RIGHT

FIGURE 8 Illustration of horizontal capture.



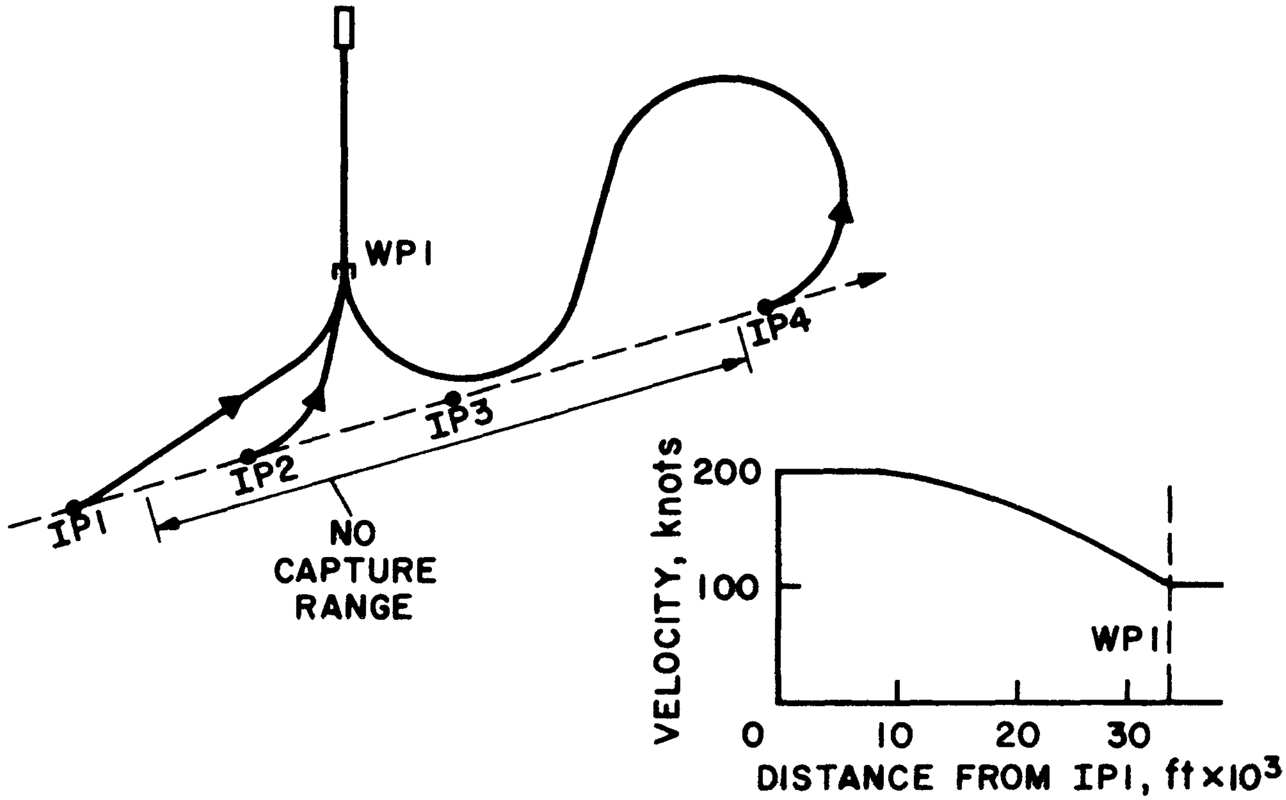
INITIAL CONDITIONS	END CONDITIONS AT WP1	MANEUVER CONSTRAINTS
h = 5500 ft V = 140 knots ψ = 90 deg	1500 ft 140 knots 0 deg	MAX BANK = 20 deg MAX DEC = 1 knot/sec MIN γ = -10 deg

SUMMARY OF CAPTURE MANEUVER

INITIAL POSITION	HORIZONTAL MANEUVER*	γ	TIME TO DEC	TWP	DISPLAY
IP1	LSL	-7.5°	0	2:10	HORIZ TRAJEC
IP2	LS	-14°	0	—	NO CAP ALT
IP3	LSR	-5.6°	0	3:20	HORIZ TRAJEC

*L = LEFT, S = STRAIGHT, R = RIGHT

FIGURE 9 Illustration of horizontal and altitude capture.



INITIAL CONDITIONS	END CONDITIONS AT WP1	MANEUVER CONSTRAINTS
h = 1500 ft V = 200 knots ψ = 74 deg	1500 ft 100 knots 0 deg	MAX BANK = 20 deg MAX DEC = 1 knot/sec MIN γ = −10 deg

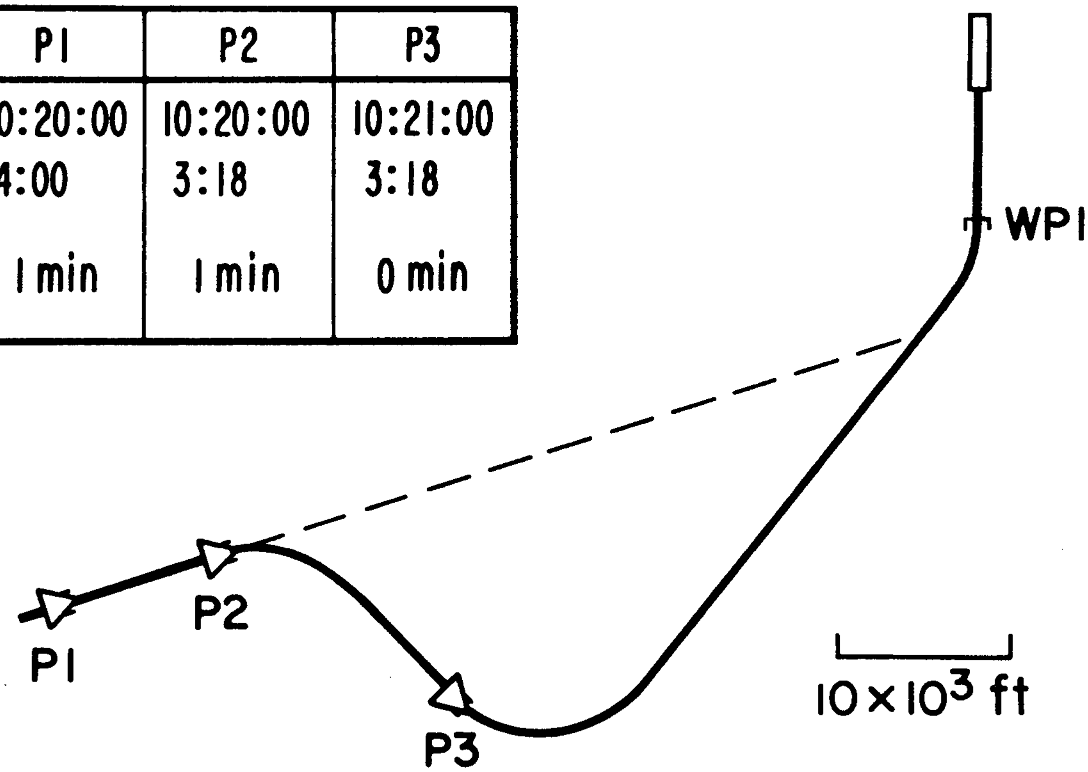
SUMMARY OF CAPTURE MANEUVERS

INITIAL POSITION	HORIZONTAL MANEUVER*	γ	TIME TO DEC	TWP	DISPLAY
IP1	LSL	0	100 sec	2:07	HORIZ TRAJEC
IP2	LSL	0	—	—	NO CAP VEL
IP3	—	—	—	—	NO CAP HOR
IP4	LSR	0	100 sec	4:30	HORIZ TRAJEC

*L = LEFT, S = STRAIGHT, R = RIGHT

FIGURE 10 Illustration of horizontal and speed capture.

	P1	P2	P3
TOA	10:20:00	10:20:00	10:21:00
TWP	4:00	3:18	3:18
DESIRED DELAY	1 min	1 min	0 min



$V = 140$ knots, $h = 3000$ ft

FIGURE 11 Timing of Path stretching maneuvers.

	P1	P2	P3
TOA	10:20:00	10:20:00	10:25:00
TWP	5:20	3:40	4:00
DESIRED DELAY	5 min	5 min	0 min

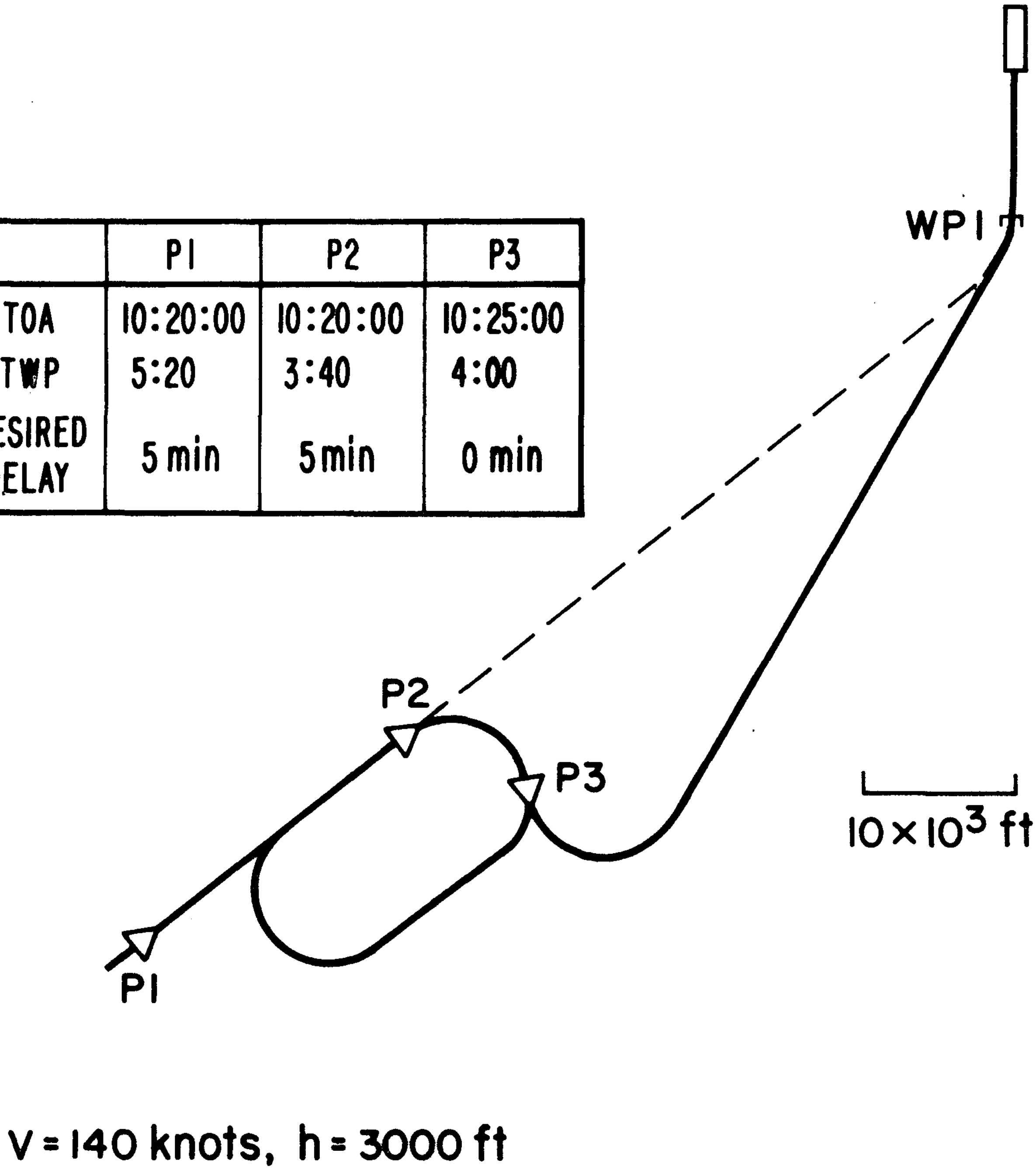


FIGURE 12 Timing of Holding Maneuvers.