A FLIGHT INVESTIGATION OF A TERMINAL AREA NAVIGATION AND GUIDANCE CONCEPT FOR STOL AIRCRAFT

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INTRODUCTION

Studies have shown (e.g., refs. 1 and 2) that short-haul aircraft may provide an effective transportation system that can operate into city centers and suburban facilities. To provide the detailed data base required for the design and development of such a short-haul system, a joint DOT/NASA STOL Operating Systems Experiment Program has been initiated. As a part of this joint program, NASA/Ames has developed an experiments program with the overall objective of providing information that will aid in the choice of terminal area guidance, navigation, and control system concepts for short-haul aircraft, and investigating operational procedures.

In a short-haul transportation system, various levels of avionics systems capability may be needed. Simple, low-cost systems may be adequate for navigation, guidance, and control of aircraft operating in low-density traffic conditions and relatively good weather. More complex and costly automated systems may be economically justifiable for operations in high-density traffic conditions and poor weather. The test data obtained in this program will provide a basis for the selection of system capability to meet operational requirements (e.g., runway requirements, weather minimums, etc.) and will also provide means for estimating the system acceptability and system cost.

A digital avionics system referred to as STOLAND has been purchased and installed (without servos) in the NASA CV-340 twin-engine transport aircraft. Nineteen test flights have been made since October 1973 to obtain preliminary STOLAND performance data in the manual flight director mode using time-controlled guidance.

STOLAND is also installed (with servos) in the powered-lift Augmentor Wing Jet STOL research aircraft (fig. 1) described in reference 3 and a DeHavilland DHC-6 Twin Otter STOL aircraft. Investigations will soon be conducted in these aircraft to obtain performance data on both simple and sophisticated avionics system concepts and the corresponding STOL operational procedures. This report briefly describes the system concept and presents the more significant flight test results obtained in the CV-340 aircraft.

SYSTEM CONCEPT AND OPERATION

STOLAND is an integrated digital avionics system having a computer of sufficient size, speed, and capability to perform all terminal area navigation, guidance, and control functions, and to automatically control and guide a STOL test vehicle along a curved reference approach flight path. Included in the system are the autopilot modes considered standard for commercial transport aircraft and an autothrottle. This system was built by Sperry Flight Systems to meet stringent performance and environmental requirements. The major components of the system are a Sperry 1819A general-purpose digital computer and a data adapter that interfaces all the navigation aids, displays, controls, and servo actuators (fig. 2). The navigation aids include VHF omnirange (VOR), distance measuring equipment (DME), tactical air navigation (TACAN) receiver, instrument landing system (ILS), microwave modular instrument landing system described in reference 4 (MODILS), inertial navigation system (INS), and radio altimeter.

The system components installed in the cockpit of the aircraft (fig. 3) include the Sperry RD202A horizontal situation indicator (HSI), control wheel, electronic attitude director indicator (EADI), multifunction display (MFD), MFD control panel, mode select panel (MSP), status panel, and data entry panel. During automatic operation, the pilot monitors the system operation through the various cockpit displays. During flight director operation, the pilot uses the same set of displays for guidance information along the reference flight path and to monitor the system. An illustration of the approach flight path flown in the CV-340 is shown in figure 4. It consists of a long inbound leg (waypoints 1-10), a 180° turn to final approach with a 5° glide slope occuring half way around the turn (waypoints 10-12), and a final straight-in approach (waypoints 12-14).

The navigation system used for the approach provides estimates of position and velocity with respect to a runway coordinate system, which has its origin at the glide-slope intercept point (fig. 4). The position and velocity estimate are generated using ground navigation aid information blended in a complementary filter with inertial information obtained from body-mounted accelerometers and attitude sensors, and air data obtained from a barometric altimeter and an airspeed sensor. The ground navigation data are obtained from TACAN except when the aircraft is in MODILS coverage after passing point A (fig. 4). The navigation system also estimates wind velocity utilizing air data. In the event of a momentary loss of ground radio navigation aid information, navigation is accomplished by dead reckoning using air data. Upon regaining radio information, the system automatically switches back to the use of radio data. A detailed description of the navigation system is presented in reference 5.

The guidance system used for the approach is based on a flight path, stored in the airborne computer, which is specified by waypoints (X,Y,Z coordinates) and associated information such as the radius of turn between waypoints and the maximum, minimum, and nominal airspeed between waypoints. The approach guidance is initiated when the aircraft captures the rear extension of the straight line between waypoints 8 and 9 (see dotted line, fig. 4). At waypoint 8, controlled time of arrival (4D) guidance is initiated. Slightly before waypoint 10, a predictive bank angle command is given, and just before waypoint 11, a constant vertical acceleration maneuver is performed to acquire the 5° flight-path angle. The short straight-in section (waypoints 12-13) is the last segment using the 4D guidance laws given below. The remaining flight path to flare is flown with similar lateral and longitudinal guidance laws except for the system gains, which are relatively low from waypoints 1 to 13, and are high from waypoint 13 to flare to assure precise path tracking.

For lateral tracking the guidance law is:

$$\phi_c = K_1 Y_{err} + K_2 \dot{Y} + \phi_p$$

where

Y_{err}	cross track error
$\dot{Y}$	cross track velocity
ϕ_p	equals zero, for a straight line track

and

$$\phi_p = \tan^{-1} \frac{V_g^{\ 2}}{Rg}$$

for a circular track where

V_g	ground speed
R	radius of turn
g	acceleration due to gravity

For vertical tracking the guidance law is:

$$\theta_c = \frac{K_3}{V_g} h_{err} + K_4 \gamma_{err} + \frac{K_5}{V_g} \int h_{err}\, dt$$

where

$\gamma_{err} = \gamma_{nom} - \gamma_I$ (γ = flight-path angle)

h_{err}	altitude error
γ_I	equals $\frac{h_I}{V_g}$, inertial flight-path angle derived from the navigation system

As previously stated, 4D guidance is initiated at waypoint 8 (fig. 4). From this point, the system attempts to arrive at waypoint 13 at a given time.

Control of arrival time at waypoint 13 is based only on speed control, which is provided by controlling the throttle as a function of an airspeed error. In the flight director mode, the airspeed command is displayed on the EADI. The airspeed command V_c is defined as the algebraic sum of a prescribed nominal airspeed (V_{nom}) and an error that is proportional to an aircraft position error (ΔS):

$$V_c = V_{nom} - 0.04\ \Delta S\ \text{(m/sec)}$$

where ΔS is the distance along the track from the estimated aircraft position to a moving target, which represents the desired aircraft position. As the aircraft arrives at waypoint 8, the target and aircraft positions are made to coincide. The computed nominal arrival time at waypoint 13 is based on the time it would take to fly from waypoint 8 provided the aircraft flew the path exactly at the nominal airspeed and there was no wind. To account for winds, the position of the moving target is recomputed every 10 sec based on the latest estimate of wind velocity and direction. This new computed target position assures that the target will arrive at waypoint 13 at the nominal arrival time while moving at the nominal airspeed. If the wind were changing during the approach, the computed positions of the target would have step changes every 10 sec which would result in excessive throttle activity. To limit the throttle activity, the time rate of change in the value of ΔS in the above equation is limited to 6.1 m/sec.

RESULTS AND DISCUSSION

As previously noted, the primary purpose of flight tests in the CV-340 was to validate the operation of the STOLAND system and to obtain a preliminary insight into the navigation and guidance system performance. The data presented are from a set of 20 simulated IFR (hooded) approaches conducted during the latter stages of the tests.

For the CV-340 flights, aircraft position data were provided by a modified NIKE-HERCULES tracking radar. These tracking data were smoothed with a minimum mean-square filter to obtain a best estimate of the actual aircraft position.

The data presented in this report are referenced to a coordinate system whose origin is at the MODILS glide-slope intercept point (GSIP) on runway 35 at Crows Landing NALF (see fig. 4). The XY plane is tangent to the earth at the origin; the X axis is positive in the direction of landing, the Y axis is positive to the right, and the H (altitude) axis is positive up. Representative performance of the guidance and navigation systems along a typical approach is discussed, as well as summary data for all approaches.

Performance for a Typical Approach

The reference flight path and an example of a typical approach are shown in figure 5. The top half of the figure shows the reference path and the downrange-crossrange (X vs Y) plot of aircraft position, and the lower part shows the corresponding altitude-downrange (H vs X) plot. The waypoints are shown for reference. The sum of the system errors is represented by the lateral and vertical deviations from the reference path.

As shown in figure 5 the approach was initiated at about 520 m altitude, about 280 m to the right, and 30 m above the reference path. During the turn to final approach, the aircraft remained to the right of the path and then acquired the runway centerline, maintaining that course for the remainder of the approach. The aircraft remained about 10 to 30 m above the reference path during the whole approach. The major error prior to MODILS acquisition can be attributed to the effect of a TACAN DME bias. The errors attributable to the navigation and the guidance systems are discussed below.

Navigation- Figure 6 presents the lateral (cross track) and vertical navigation errors for the approach shown in figure 5, and the envelope of errors experienced in the 20 simulated IFR approaches. The error presented is the difference between the onboard estimate of the aircraft position and the tracking radar measured position. The error shown in these traces is the combined effect of errors due to ground navaid and airborne receiver signal errors, off-nominal atmosphere effects, small errors in the ground radar tracking data, and the basic navigation system errors resulting from software/hardware mechanization. The waypoints are labeled for cross reference with figure 5.

The envelope of lateral navigation errors at initiation of the approach at waypoint 8 are as large as 200 m. These errors converge to a maximum less than 70 m at the initiation of the turn at waypoint 10, where they start to increase again to values as large as 150 m. Examination of the data indicate that these navigation errors result from TACAN errors in both range and azimuth. A short time after passing waypoint 10, a transition from TACAN to MODILS navigation is initiated. Navigation errors then converge smoothly to less than 15 m after transition to MODILS is completed.

The envelope of the time history of the vertical navigation error shows errors as large as 24 m at initiation of the approach at waypoint 8. The vertical navigation errors are always positive and are probably a result of a bias in the baro-altimeter. It should be noted that the baro-altimeter reference was set prior to each approach based on information radioed from the control tower, which gives a correct barometric altitude at the runway level only. After transition to MODILS and the start of the descent at waypoint 11, the baro-altimeter measurement is slowly blended with and replaced by the more accurate MODILS data to prevent a step change in estimated altitude at the initiation of glide-slope tracking. The vertical navigation error converges to a constant value of approximately 5 m. This bias is unexplained at this time, although it is speculated that several error sources could be the cause. For example, a MODILS DME error of about 60 m could result in the 5-m error. It is clear that more accurate navigation is required for final flare - e.g., a radio altimeter or a second, more accurate elevation scanner.

Guidance- Figure 7 presents the lateral and vertical guidance errors for the approach shown in figure 5 and the envelope of errors experienced in the

20 simulated IFR approaches. The error shown is the difference between the onboard estimate of position and the reference flight path. The waypoints are labeled for cross reference with figure 5. The envelope of time histories of the lateral guidance error shows errors as large as 400 m at the initiation of the approach at waypoint 8; prior to switching to MODILS, these errors converge to smaller values. On switching to MODILS from TACAN, the lateral navigation error decreases while the lateral guidance error increases, reaching a maximum at about waypoint 11. This increase in the lateral guidance error results from a TACAN range bias error that causes the aircraft to fly on the right of the reference path from waypoint 8 to point A (see fig. 5). Upon switching to MODILS, which is a more accurate navigation aid, the navigation estimate indicates that the aircraft is flying to the right of the reference path, thereby generating a lateral guidance error while the navigation error converges to a small value. As a result of the low gain of the guidance system, the aircraft is guided slowly to the reference path. After passing waypoint 11, the lateral navigation and guidance errors converge to small values. As shown in figure 7, the envelope of the lateral guidance error converges to about ±20 m between waypoints 13 and 14 (i.e., 1600 m from touchdown). The envelope of vertical guidance error shows errors as large as 15 m at the initiation of the approach at waypoint 8 and is generally above the desired path. The magnitude of the error represented by the envelope remains approximately constant between waypoints 8 and 10. As shown by the solid line in figure 7, transients occur in the vertical guidance error when the navigation switches from TACAN to MODILS and at approximately waypoint 11 when the descent is initiated. The switching transient decays and the vertical guidance error envelope converges to about ±3 m between waypoints 13 and 14 as a result of the high-gain guidance law and high-gain navigation filters used during the final straight-in approach.

Summary Performance Data;

Errors Prior to Flare ($h \simeq 30.5$ m)

Navigation- Figure 8 shows the difference between the aircraft position as measured by ground radar and the onboard position estimate as the aircraft passed through a window positioned at a nominal altitude of 30.5 m on a 5° glide slope. (The symbols represent data obtained from flights on two different days.) The data show that the aircraft was to the left of the runway centerline and above the glide slope for the majority of the approaches. For these data, the vertical mean error is 2.4 m above the reference glide slope with a lateral mean error of 1.9 m to the left of centerline. The 2σ errors about the mean are ±2.6 m in altitude and ±4.2 m in the lateral direction.

Guidance- Guidance errors measured at an altitude of 30.5 m are presented in figure 9. The reference in this case is the MODILS 5° glide slope as computed by the navigation equations. If the guidance errors were zero, the data points would be clustered on the estimated glide-slope centerline which is the origin of the graph. For these data, the vertical mean error is 0.8 m below the glide slope with a lateral mean error of 0.8 m to the left of centerline. The 2σ vertical and lateral errors about the mean are ±2.2 m and ±6.8 m, respectively.

Comparison of Flight Data with CTOL Requirements

The test flight data were compared with FAA Category II flight director certification criteria for CTOL aircraft to determine whether the navigation system under investigation might be feasible for a flight director landing on a STOL runway in marginal weather. The FAA criteria are included in figure 9. The FAA criteria from AC 120-29 state that on the localizer,

> "From an altitude 300 feet above runway elevation on the approach path to the decision altitude (100 feet), the flight director should cause the airplane to track to within ±25 microamperes (95-percent probability) of the indicated course. The performance should be free of sustained oscillations."

and on the glide slope,

> "From 700 feet altitude to the decision altitude (100 feet), the flight director should cause the airplane to track the center of the indicated glide slope to within ±75 microamperes or ±12 feet, whichever is the larger, without sustained oscillations."

Based on a conventional CTOL runway arrangement, these criteria would translate into allowable deviations of about ±3.7 m (12 ft) vertical and ±21 m (69 ft) laterally for a CTOL aircraft at a longitudinal location defined by the 30.5-m (100-ft) altitude point on a 2.7° glide slope.

Figure 9 indicates that the 2σ errors measured in the test flights are within those prescribed for CTOL Category II system landing minima (shaded in fig. 9). Additional testing is needed to define the performance criteria for STOL aircraft certification for Category II weather minima. This comparison of the test flight data with the FAA criteria is not entirely valid, because the landing system, the wind environment, the glide slope, and other parameters were different from those outlined in the FAA advisory circular. Nevertheless, it gives some measure of the system performance.

Speed Control and Longitudinal Guidance

Figure 10 presents the longitudinal guidance error (ΔS), the commanded airspeed, the true airspeed, and the ground speed for the approach shown in figure 5. Also shown are the nominal airspeed specified for the reference path (fig. 5) and the boundaries of the allowable airspeed commands, designated by the unshaded area, which are based on the aircraft performance capabilities. A comparison of the ground speed and true airspeed in figure 10 indicates the strong headwind conditions experienced by the aircraft on the flight path between waypoints 8 and 10. Under such conditions, the aircraft should fly at an airspeed above the nominal to meet the specified arrival time. As shown, the longitudinal error, ΔS, increased linearly and the airspeed command increased above the nominal airspeed for the first 3000 m of track distance. From waypoints 10 to 11, ΔS decreased linearly at its rate limit, as the aircraft caught up with the target and the commanded airspeed approached the nominal. In this approach a longitudinal error, ΔS, of 76 m, which is equivalent to a 1.3-sec time error, remained to be corrected at waypoint 13.

Time-of-Arrival Errors at Waypoint 13

Figure 11 is a histogram of the time of arrival errors at waypoint 13 for the simulated instrument (hooded) approaches. For these tests, the mean time-of-arrival error is 3.7 sec (late) with 2σ deviation of ±3.4 sec. The mean time-of-arrival error obtained during these tests may result from the TACAN range error which caused the actual longitudinal distance flown to be longer than the reference path. Additional data are required to establish the system performance for all TACAN errors.

It is interesting to note that current manual guidance techniques enable air traffic controllers to deliver CTOL aircraft to the runway within about ±15 sec of the predicted arrival time (ref. 6). This capability corresponds to a single runway acceptance rate of about 40 IFR arrivals per hour using current separation standards. Using the improved capability of the automatic time of arrival guidance system described here it would be possible to increase the runway acceptance rate by about 40 percent (see ref. 6).

CONCLUSIONS

Results are presented for 20 flight director approaches made during an investigation of a STOL approach and landing concept using the NASA CV-340 aircraft. Results of these limited tests led to the following conclusions:

1. Blended radio/inertial navigation using TACAN and a microwave scanning beam landing guidance system (MODILS) permitted a smooth transition from area navigation (TACAN) to precision terminal navigation (MODILS).

2. Guidance system (flight director) performance measured at an altitude of 30.5 m was within that prescribed in FAA AC 120-29 for Category II CTOL operations on a standard runway.

3. Time of arrival at a point about 2 mi from touchdown was about 4 sec ±3 sec (2σ) later than the computed nominal arrival time.

REFERENCES

1. Anon.: Civil Aviation Research and Development Policy Study - Report. NASA SP-265, 1971. (Also available as DOT TST-10-4.)

2. Anon.: Civil Aviation Research and Development Policy Study - Supporting Papers. NASA SP-266, 1971. (Also available as DOT TST-10-5.)

3. H. G. Quigley; R. C. Innis; and S. Grossmith: A Flight Investigation of the STOL Characteristics of an Augmented Jet Flap STOL Research Aircraft. NASA TM X-62,334, May 1974.

4. Glen D. Adams: Evaluation of STOL Modular Instrument Landing System (MODILS). National Aviation Facilities Experimental Center, Atlantic City, N. J. 08405. FAA, Dept. of Transportation, Report FAARD-72-4, May 1972.

5. Frank Neuman and David N. Warner, Jr.: A STOL Terminal Area Navigation System. NASA TM X-62,348, May 1974.

6. Anon.: Report of Department of Transportation Air Traffic Control Advisory Committee, Dept. of Transportation, Washington, D. C., Dec. 1969.

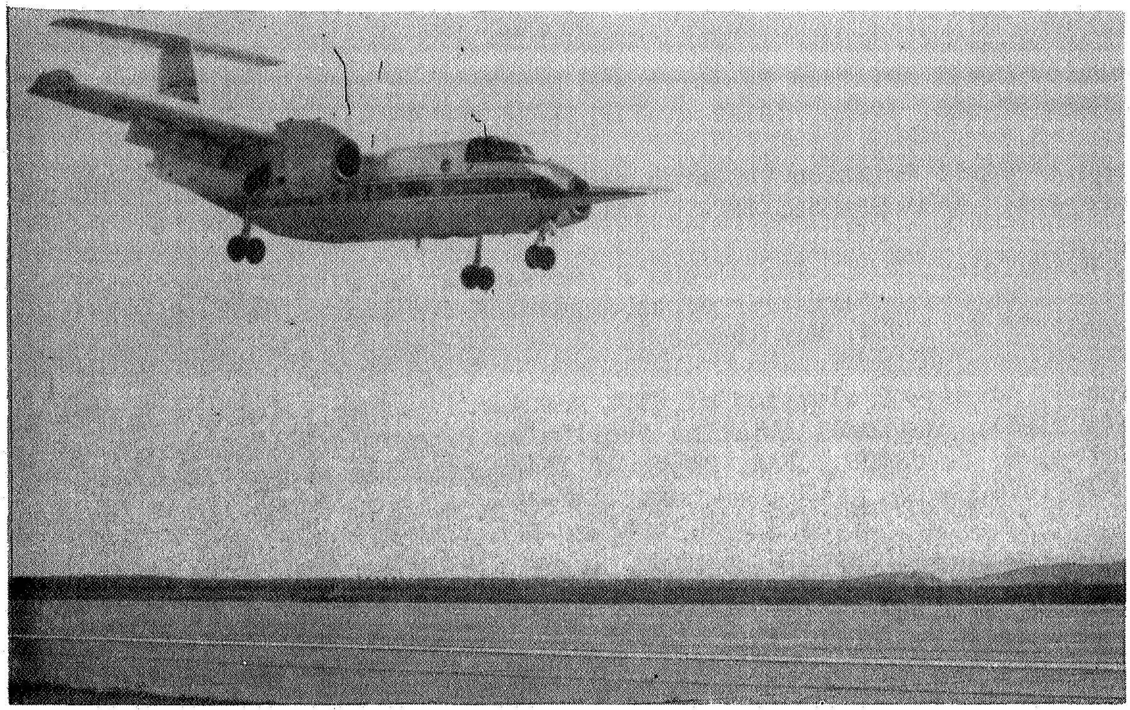

Figure 1.- Augmentor wing jet STOL research aircraft.

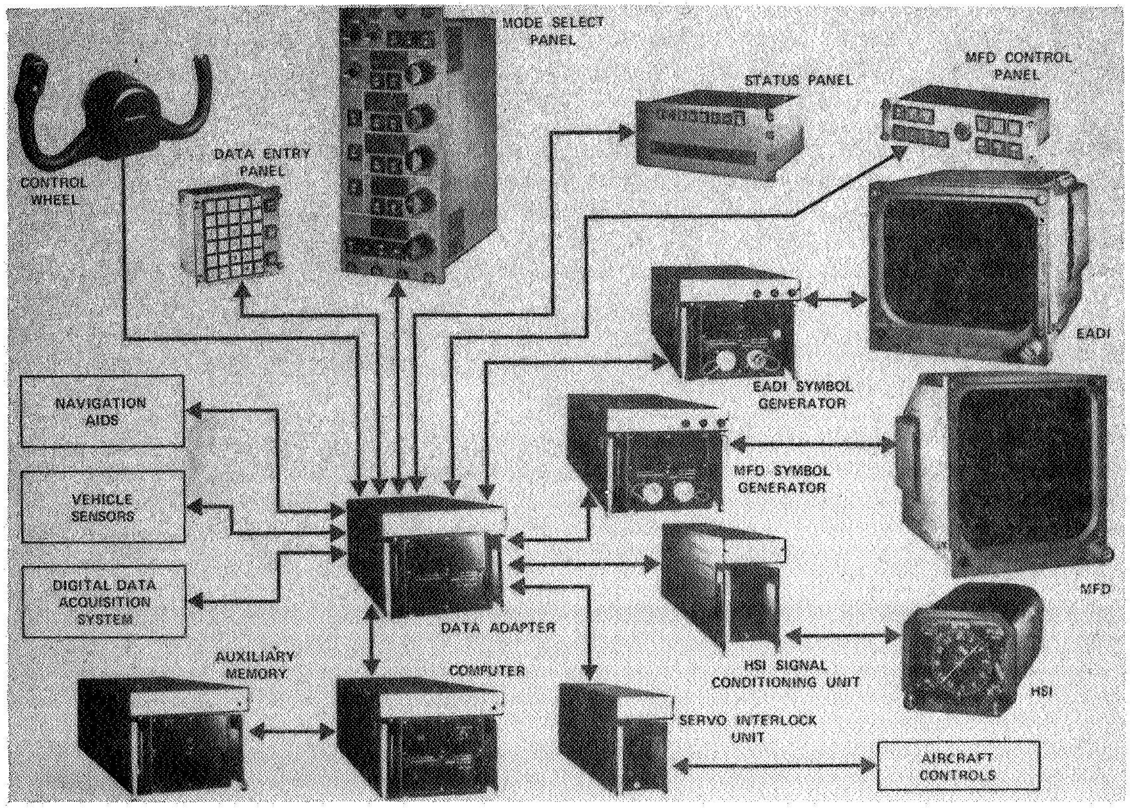

Figure 2.- STOLAND flight-test system.

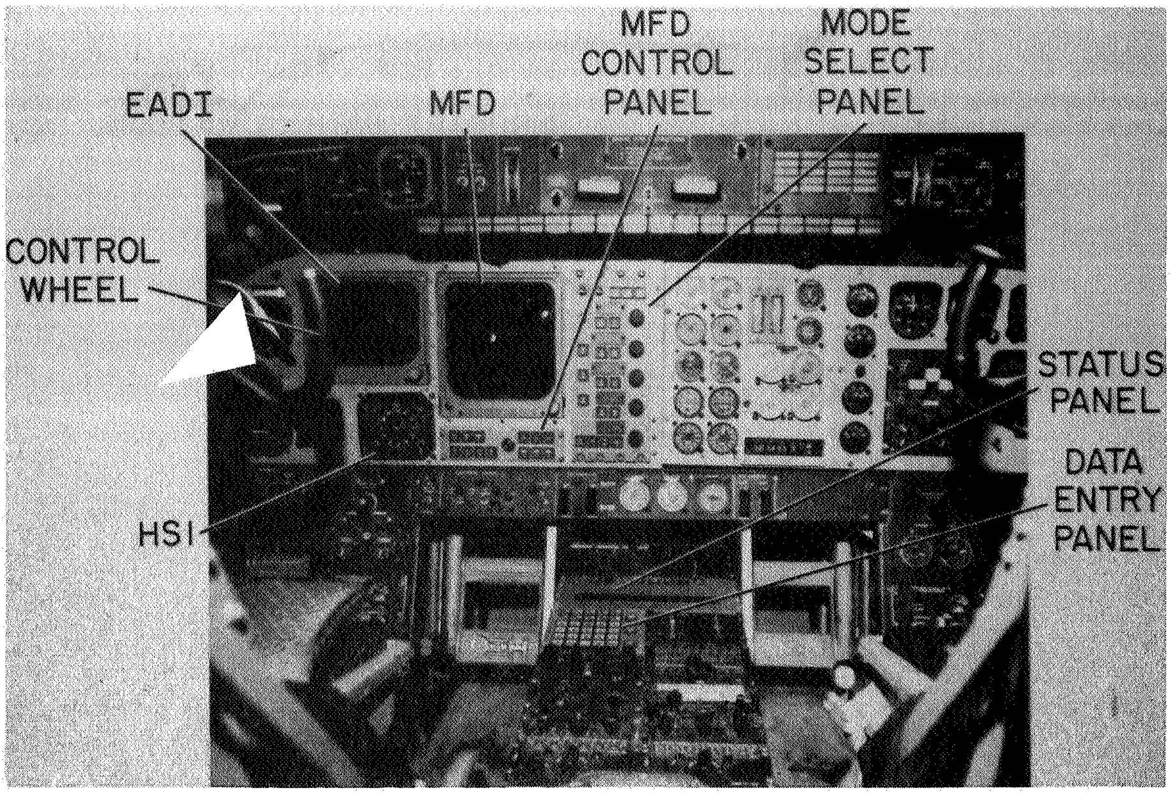

Figure 3.- STOLAND cockpit installation.

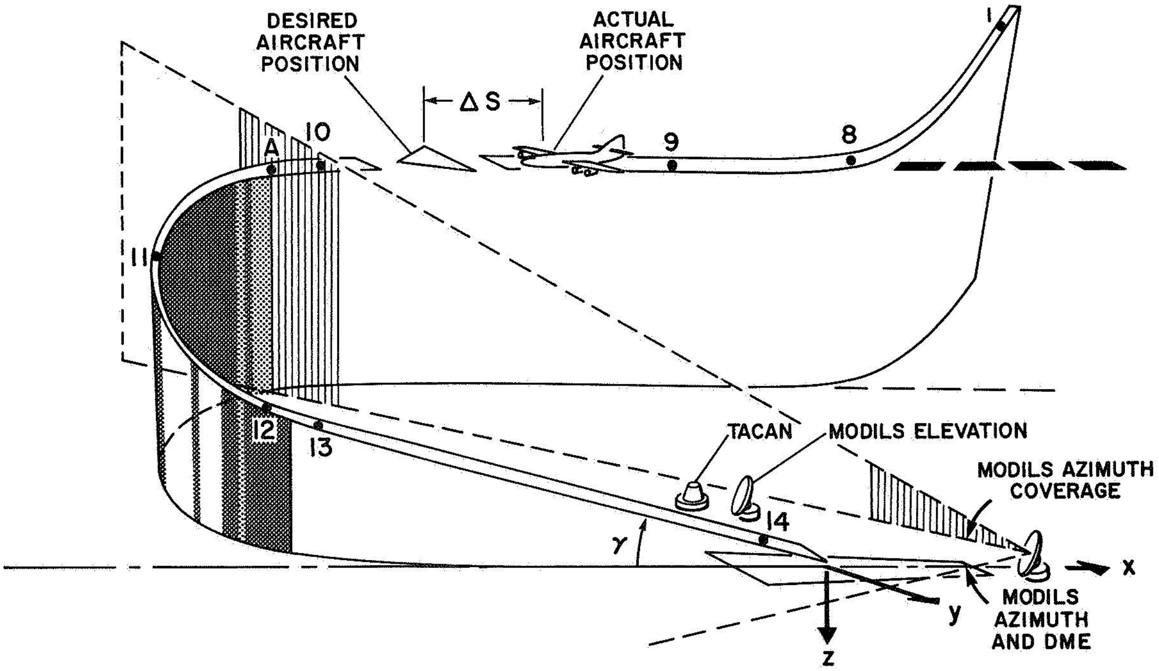

Figure 4.- Approach flight path.

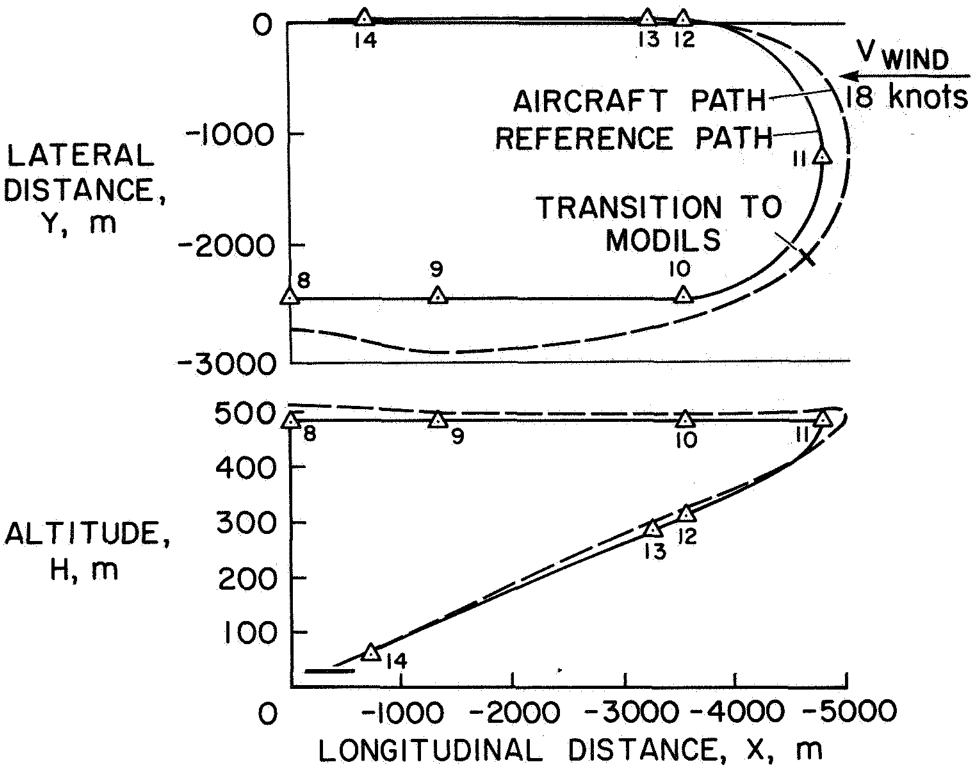

Figure 5.- Typical flight path.

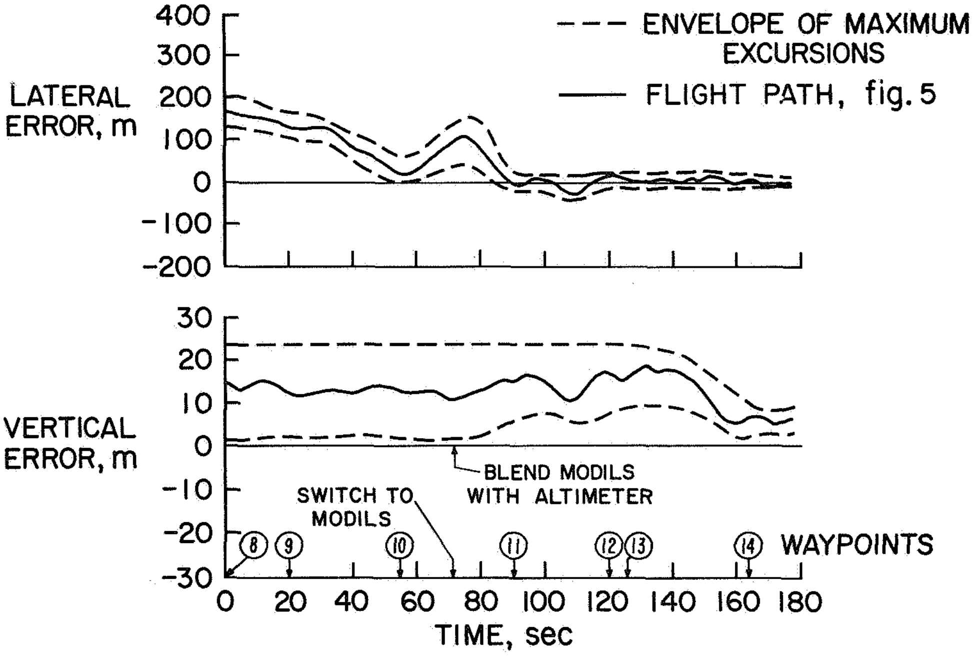

Figure 6.- Navigation errors.

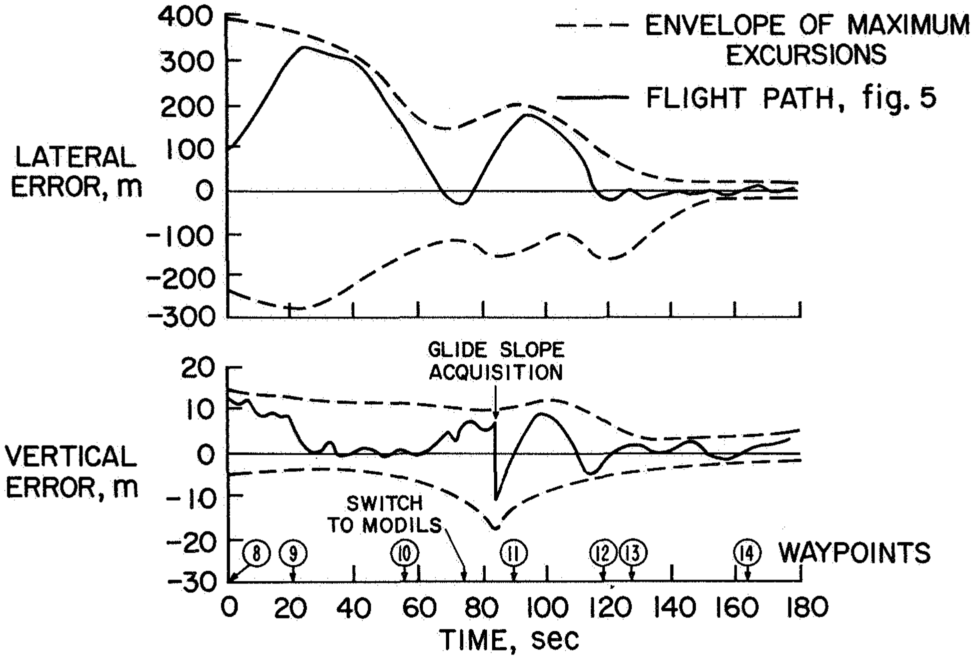

Figure 7.- Guidance errors.

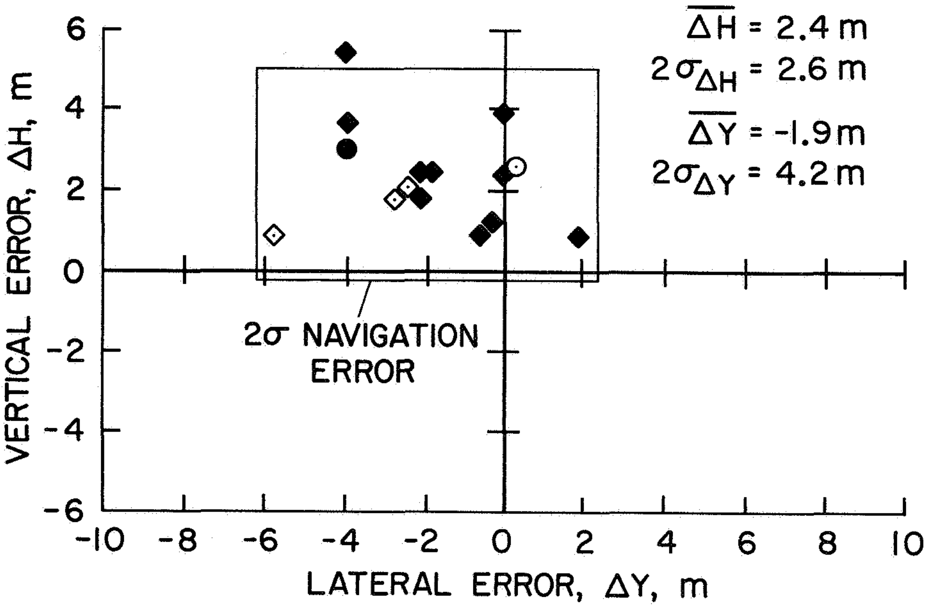

Figure 8.- Navigation errors at 30.5 m.

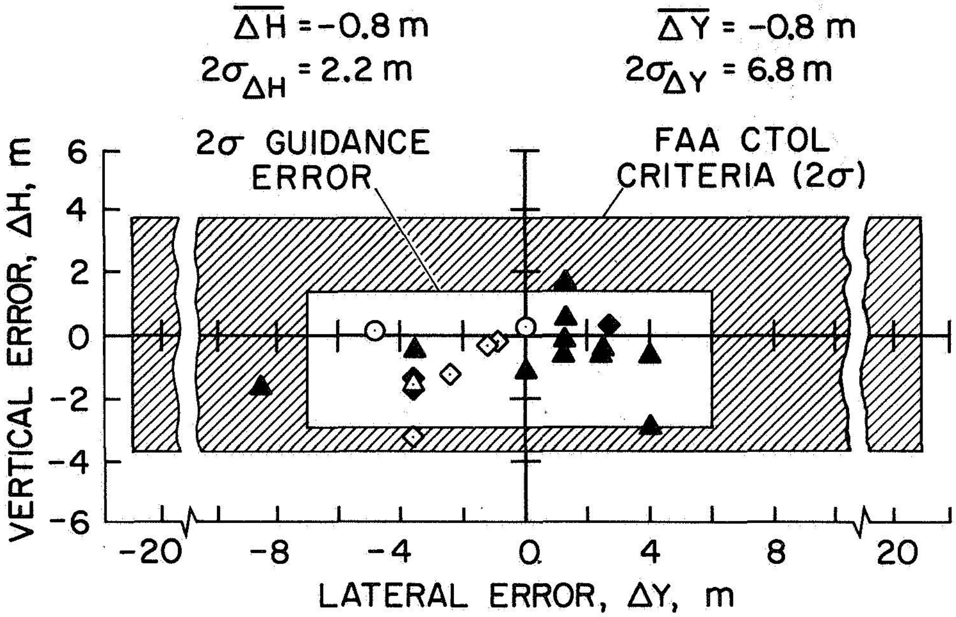

Figure 9.- Guidance errors at 30.5 m.

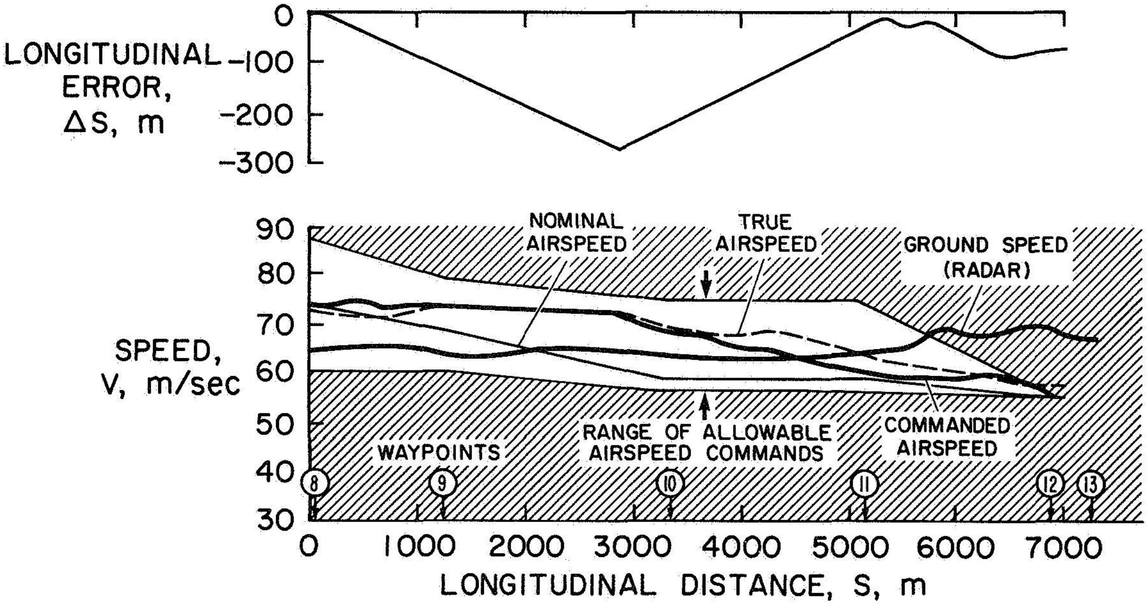

Figure 10.- Longitudinal guidance.

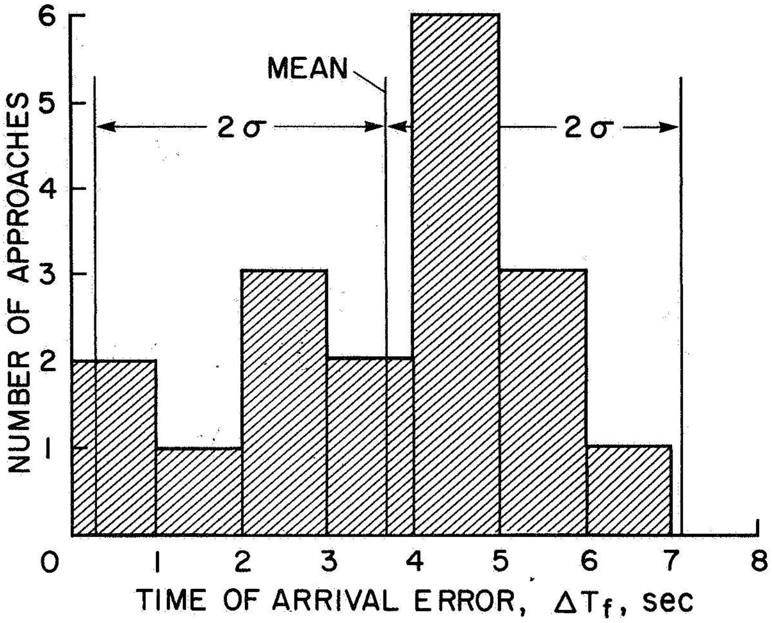

Figure 11.- Time-of-arrival error at waypoint 13.