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# A Simulation Study of Crew Performance in Operating an Advanced Transport Aircraft in an Automated Terminal Area Environment

Jacob A. Houck
*Langley Research Center*
*Hampton, Virginia*

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# INTRODUCTION

The Advanced Transport Operating Systems (ATOPS) Program (formerly called the Terminal Configured Vehicle (TCV) Program, refs. 1 and 2) has been established by NASA to perform flight-management and operating-systems research broadly aimed at improving the safety and efficiency of transport-aircraft all-weather operations in the evolving National Airspace System. (A glossary of acronyms used in this paper is presented after the references.) The goal of the ATOPS Program is to blend recent and emerging technology advancements in airborne avionics systems and information displays with human factors into effective system concepts that can be uniformly applied to transport aircraft operating in a 1990's air traffic environment. Specific objectives of the ATOPS Program are to propose and investigate concepts offering improvements to aircraft systems, flight deck design, and crew procedures providing more efficient operations; to develop and investigate ways to improve the exchange of information between aircraft and air traffic control (ATC) throughout the flight profile; and to identify and promote consideration of aircraft capabilities and limitations in the design of ATC-system improvements to facilitate more efficient operations. These are accomplished by conducting analysis, simulation, and flight tests and by sponsoring similar research by the aircraft industry.

Two of the research facilities available for the ATOPS Program are the Langley ATOPS Aft Flight Deck (ATOPS AFD) Simulator and the Terminal Area Air Traffic Model (TAATM) Simulation. Previous ATOPS AFD simulation studies (e.g., refs. 3 and 4) have been concerned with new concepts in control and/or display systems or with modifications to the existing systems. These studies have required the use of single-pilot operation to evaluate the concepts over limited flight regimes with no interaction with air traffic controllers or with other aircraft. The TAATM simulation, a computer model designed to represent the terminal area ATC environment using software controllers and aircraft, has been used in a batch (stand-alone) mode to conduct analytical studies, such as those described in references 5 to 7, with no interaction with actual air traffic controllers or with actual aircraft and crews. A proposal was made whereby the two simulations would be linked together to allow terminal area system studies to be performed. This would have the effect of providing the ATOPS AFD simulator with a realistic ATC environment so that the crew would be confronted with realistic procedure and workload scenarios including controller instructions. It would also exercise the capability of inserting a "live" aircraft into the TAATM simulation. This total system simulation would provide an environment to evaluate problems caused by linking the two separate simulations together. At the same time, two research studies were conducted as a single joint-system simulation effort. The study documented here was the evaluation of the performance of a group of ATOPS flight crews using an advanced display system and two types of control systems (automatic and manual) in an automated ATC environment. The second study was the real-time simulation portion of the evaluation of the microwave landing system (MLS) effect on the delivery performance of the automated ATC system described in reference 7. This report describes the two simulations which were linked together, presents the evaluation of the flight crew performance using the two separate control systems, discusses some problems encountered during the study, and presents a set of recommendations for future consideration.

## EXPERIMENTAL SIMULATION DESCRIPTION

The experimental simulation setup for this study was comprised of two major components, the ATOPS AFD simulation and the TAATM ATC simulation. Figure 1 presents a block diagram indicating how these two components are linked together. Each of the two simulations resides in its own CDC CYBER 175 computer. Communication between the two simulations for data transfer (positions, velocities, etc.) is carried out through the use of two digital-analog subsystems. Air traffic controller instructions issued to the flight crew and their responses are transmitted over an audio channel. This linking together of the two simulations provides a realistic ATC environment for the ATOPS flight crew and inserts a "live" aircraft into the TAATM simulation.

### ATOPS AFD Simulation

The ATOPS Program operates a Boeing 737-100 aircraft (fig. 2) to conduct flight research aspects of the program. The aircraft is equipped with a special research flight deck, located approximately 6 m aft of the standard flight deck. An extensive array of electronic equipment and data recording systems is installed throughout the former passenger cabin (fig. 3). The aircraft can be flown from the aft flight deck using advanced flight-control and electronic-display systems that can be programmed for research purposes. Two safety pilots located in the standard flight deck are responsible for all phases of flight safety and for most traffic clearances. Two research pilots usually fly the aircraft from the aft cockpit during test periods, which can last from take-off through landing.

Figure 4 presents a picture of the interior of the ATOPS AFD simulator, which is a near replicate of the AFD located onboard the ATOPS research aircraft. The simulation (ref. 2) includes a nonlinear mathematical model of the aircraft with the addition of landing gear dynamics, gust and wind models, nonlinear actuator models, and instrument and microwave landing system (ILS and MLS) sensor models. In addition, automatic-flight-control and navigation-control functions have also been simulated. The simulator cockpit is outfitted with advanced flight-control and electronic-display systems. These include an advanced guidance and control system (AGCS), an electronic attitude director indicator (EADI), an electronic horizontal situation indicator (EHSI), and a navigation control and display unit (NCDU).

The various AGCS modes are engaged using the control panel pictured in figure 5. These control modes provide the pilot with desired levels of automation and are designed to relieve the pilot's workload. The AGCS modes include two levels of control-wheel steering (attitude and velocity vector), four levels of outer-loop guidance and control (track angle and flight-path angle select, horizontal path guidance, vertical path guidance, and time path guidance), an autoland system, an altitude hold system, and an autothrottle system.

The EADI, pictured in figure 6 and described in reference 8, is the pilot's primary display of pitch and roll attitude for instrument flight. Optional symbology for display of the aircraft velocity vector, flight-path acceleration, vertical and horizontal guidance errors, speed error, perspective runway and centerline, and radar altitude are integrated into the EADI display format.

The EHSI, pictured in figure 7 and described in reference 9, is the pilot's primary navigation display for instrument flight. It is configured to represent a map and provides the pilot with an accurate display of aircraft position relative to the horizontal guidance path, flight-plan waypoints, and geographic points of interest. The desired horizontal flight path is displayed by a solid line connecting the waypoints. The operating modes of the pilot's and copilot's EHSI's are independent and may be operated in either track-up (normal) or north-up modes and with different scales and different information options.

The primary input device to the navigation and guidance system is the NCDU pictured in figure 8. The unit consists of a keyboard and a small cathode-ray tube (CRT) display on which pages of navigation and guidance information may be displayed. Guidance paths may be built using the NCDU as an input-output device. During the flight, variables of interest, such as path guidance errors, may be displayed on the CRT.

## TAATM ATC Simulation

The TAATM, described in reference 7, is a flexible computer simulation of the airborne, ground control, and communication aspects of the terminal area environment. The airborne aspects modeled include simplified aircraft dynamics, performance capabilities for 20 different classes of aircraft, traffic samples (including mix and route loadings), intended flight plans, flight-path errors, and wind effects. The ground control aspects include a metering and spacing control technique (described below), control options (speed control, alternative paths, etc.), instrument flight rules (IFR) separation standards, navigational aids, terminal area geometrics, airroute structuring, runway handling constraints, and surveillance errors. The communication aspects of TAATM reflect only communication from controller to pilot and include message content, delays associated with the actual delivery of a message, delays associated with controller workload, and priority delivery of messages.

After first regulating the terminal area arrival rate, the fixed-path metering and spacing control logic depicted in figure 9 is comprised of two major levels of control capability. These are delay spacing and precise final spacing. Delay spacing (schedule maintenance) has three types of control. First, each route contains a holding pattern to absorb large delays that cannot be accommodated by speed control. Second, speed control is accomplished by regulating indicated airspeed at predefined points on the flight path. Third, if conditions arise such that speed control can no longer resolve the problem, then each route has an area where the aircraft can be vectored to generate needed delay. These vectoring areas are used only as backup modes. Precise final spacing on all nonstraight-in paths consists of two path adjustment commands in the downwind-base-final area to account for system or aircraft performance errors. The first path adjustment (through a direct-engage capability) is used to attempt to negate existing system errors at the entrance to the downwind leg, and the second adjustment is used for correcting system time errors still remaining on the base leg. These control maneuvers also allow schedule adjustment by forward or backward arrival-time "slippage." The delay-vectoring and the direct-engage maneuvers are determined through a technique called direct-course-error (DICE) readout which determines the time error at the exit point of the vector space or at the outer marker, if the aircraft turned to the desired point at that instant. When the value of this error approaches zero, the controller instructs the aircraft to turn toward the point in question. This ATC system operates under the assumption that all aircraft have area navigation (RNAV) capability. For a more detailed discussion of this control logic, the reader is directed to reference 7.

The TAATM simulation can be run in either a real-time or a fast-time mode, and it outputs the following overall performance measures for trade-off evaluations of various navigational or control techniques as they relate to the terminal area environment:

1. Delivery accuracy at the outer marker

2. Interarrival errors at the outer marker

3. Separation errors over the runway threshold

4. Time between arrivals at the runway threshold

5. Imposed en route delays

6. Imposed holding delays

7. Average flight time in the terminal area

8. Landing rate

9. Histograms of range to closest aircraft

10. Individual aircraft ground track

11. Position and time exposure traffic flow plot

In addition, the real-time mode offers a visual display, depicted in figure 10, of the terminal area environment for exercising and testing the actual interfaces with a manned aircraft cockpit.

## DESCRIPTION OF EXPERIMENT

This experiment had two major purposes. The major purpose, from the standpoint of ATC systems, was to study the effects on delivery accuracy of aircraft using the precision of MLS operating with a ground-derived, fixed-path metering and spacing ATC system. The reader is directed to reference 7 for a discussion of this portion of the experiment. This report discusses the results related to the airborne systems. The major purpose, from this standpoint, was to study the interaction of the flight deck systems (crew, controls, and displays) with an ATC environment having automated features. The following were some specific objectives of the study: evaluate crew performance using two types of aircraft control systems; evaluate, from a terminal area mission standpoint, the realism of the simulation provided to the crew; and, to a lesser extent, provide aircraft simulation data to evaluate the realism of aircraft dynamics programmed in the TAATM Simulation Program.

### Scenario

The terminal area geometry of Stapleton International Airport, Denver, Colorado, was chosen as the ATC environment for this experiment. This was the route structure for which the fixed-path metering and spacing system used in the experiment was designed. The terminal area had an experimental route and sector structure which was broken down into the North and South Approach Control Sectors, the Local Approach Control Sector, the Final Approach Control Sector, and the Tower Control Sector. Figure 11 shows the seven standard terminal arrival routes (STAR's) used for this study. Two routes merge at the BYERS waypoint to form a straight-in arrival from the east, two routes merge at the MEEKER waypoint to form a corner-post arrival from the northwest, one route through the SHAWNEE waypoint forms a corner-post arrival from the southwest, and two routes merge at the ELIZABETH waypoint to form a corner-post arrival from the south. Each STAR has specified fixes (BYERS, LONGMONT, SHAWNEE, and ELIZABETH) for holding, and delay-vectoring regions are represented by the dashed areas in the figure. In addition to the route structure and navigational aids, a representative arrival traffic distribution and aircraft mix were simulated. After some experimentation, a peak traffic density of 30 aircraft arrivals per hour was chosen for the single runway (runway 26L) which was simulated.

To provide further realism in the simulation, a wind model for the Denver area was included in both the TAATM and ATOPS AFD simulations. This model is presented as follows:

$$W_S = [\omega + \rho(h - h_o)](1 + B_s)$$

$$W_D = [\psi + \gamma(h - h_o)](1 + B_d)$$

where

| | |
|---|---|
| $W_S$ | wind speed, knots |
| $W_D$ | wind direction measured from true north, deg |
| $\omega$ | wind speed at ground level, knots |
| $\rho$ | change in speed with change in altitude, knots/m |
| $h$ | aircraft altitude above mean sea level, m |
| $h_o$ | airport altitude above mean sea level, m |
| $B_s$ | wind speed bias, percent |
| $\psi$ | wind direction at ground level measured from true north, deg |
| $\gamma$ | change in wind direction (measured from true north) with change in altitude, deg/m |
| $B_d$ | wind direction bias, percent |

The nominal values for the Denver Stapleton terminal area are

$\omega = 7.918$ knots

$\rho = 0.007769$ knots/m

$B_s = 10$ percent

$\psi = 277°$

$\gamma = 0°$ per meter

$B_d = 5$ percent

$h_o = 1624.6$ m

## Experimental Areas of Interest

The factors examined in this experiment were split into two categories, flight deck systems and ATC system scenarios. The flight deck system variables were represented by a manual mode and an automatic mode. The manual mode was defined as consisting of the velocity control-wheel steering (VCWS) system, the autothrottle system, and the advanced electronic display systems. The control-wheel steering mode is a computer-augmented, manual control mode which allows the pilot to input rate commands through the column and/or wheel and to maintain attitude when a zero rate is commanded. The VCWS system (ref. 10), in particular, allows the pilot to control the orientation of the aircraft velocity vector as defined in an inertial axis system. Vertical flight-path angle and track angle are the principal orientations controlled with the addition of a bank-angle hold mode for bank angles exceeding 2.5°. The status of the flight-path angle is available to the pilot on the EADI display, and the track angle is available on the EHSI display. In addition, a curved trend vector which predicts where the aircraft will be 30, 60, and 90 sec ahead based on present ground speed and bank angle is available on the EHSI display. This is a very useful symbol when flying curved ground tracks and when trying to arrive at a point at a specified time. Finally, an altitude-range arc symbol is available on the EHSI display, which indicates where along the ground track the aircraft will arrive at a specified altitude if a given vertical flight-path angle is maintained. References 8 and 9 describe the EADI and EHSI displays in more detail. In this mode, the crew was required to fly and land the aircraft manually and to make speed adjustments using the autothrottle system.

The automatic mode was defined as consisting of the automatic horizontal path guidance system, the flight-path angle select system, the autoland system, the autothrottle system, and the advanced electronic display systems. The horizontal path guidance system couples the flight-control system to the programmed ground track and enables the aircraft to follow the track automatically. The flight-path angle select system is a semiautomatic control system which allows the pilot to select, capture, and then hold a specified vertical flight-path angle. The autoland system allows for capture and tracking of either an ILS or an MLS signal. The maneuver includes localizer and glide-slope capture and tracking, automatic decrab, automatic flare, and roll-out. In a holding-pattern, a vector, or a direct-engage maneuver, the pilot uses the velocity control-wheel steering system to accomplish the maneuver. This is done because the desired maneuver would require the aircraft to leave the programmed horizontal path, and thus the horizontal path guidance would have to be disengaged. Another semiautomatic control system, track angle select, was available to the pilots but was ruled out for most maneuvers because of control system restrictions on maximum commanded bank angle (maximum of 25°). This system is similar to the flight-path angle select system in that it allows the pilot to select, capture, and hold a specified magnetic track angle. As with the manual control system, the pilot used the same advanced electronic display systems while flying the aircraft.

The ATC system variables were represented by the following three different close-in approach navigation systems: (1) a ±60° coverage MLS, (2) a ±40° coverage MLS, and (3) very high frequency omnidirectional range/distance measuring equipment (VOR/DME) coupled with a standard ILS. (Hereinafter, the systems will be referred to as 60° MLS, 40° MLS, and ILS.) When the aircraft was outside the coverage of the MLS or ILS, the aircraft was navigated along the routes using standard VOR/DME radio navigational aids.

The experiment consisted of three two-man crews made up from three NASA research pilots who alternated as the captain of the crew. The first officer position was filled from the same three research pilots with the research engineer substituting when a research pilot was not available. Each of the three crews made six flights for each of the three ATC navigation systems given above for both control system modes. (See table 1.) Three of the six flights were classified as straight-in arrivals and the other three were classified as corner-post arrivals. A given crew completed all automatic control runs before starting any manual control runs. In addition, all runs for a given ATC system (e.g., 60° MLS) were completed before the runs for the next system were started. A given flight took anywhere from 20 to 30 minutes to complete depending on the type of arrival and the maneuvers (such as holding patterns) required during the flight to meet metering and spacing requirements.

## Crew Task

The task presented to each crew was to fly an RNAV route into the simulated Denver terminal area either by manual or by automatic control coupled with the autothrottle system and to perform all other normal flight deck tasks associated with flying through a terminal area. The crew was required to respond to air traffic controller instructions for speed and altitude changes, delay vectors, holding patterns, and direct-engage maneuvers. The nominal flight-path procedure in flying an approach was to adhere to the STAR specifications except in response to controller instructions. Figure 12 presents the pilot's navigation chart for the two LONGMONT STAR's. Minimum altitudes are given in feet for the various waypoints on the STAR along with nominal airspeeds in knots (represented by K in the figure) for the segments between the waypoints. The published holding pattern at the LONGMONT arrival fix, the gate, the outer marker (OM), and the arrival runway positions are indicated for the pilot's reference. Finally, the various radio frequencies for use in communicating with the air traffic controllers are noted near the top of the figure. Figure 12 can be compared with figure 9 to see the relationship between the crew's task and the fixed-path metering and spacing control logic. Figures 13 to 15 present the navigation charts for the other five STAR's used in this experiment. In addition to the navigation charts, the same information was presented on the EHSI for use in navigating the aircraft.

## Typical Flight

Figure 16 presents the radar-derived ground track of a typical flight for the SHAWNEE STAR. (This figure can be compared to fig. 14 for waypoint names, etc.) The aircraft followed the route to the SHAWNEE arrival fix, where it was required to make one holding-pattern maneuver before it was cleared for inbound flight on the STAR. Once past the SOUTH1 waypoint, the aircraft was given a direct-engage instruction to turn immediately to the ALTURA waypoint. This was followed by a second direct-engage instruction to turn to the GATE waypoint, where the final approach path was intercepted. Both maneuvers were used to reduce the effects of either aircraft or ATC system error or both, which may have occurred. Notice the aircraft's ground track is offset from the STAR during the early portion of the flight. This is due to the navigation errors associated with the onboard equipment, the VOR system, and the ground-based radar system (ref. 7). Also notice that the ground-track errors decrease once the aircraft crosses into the MLS region due to the higher accuracy of the MLS.

Figures 17 to 19 present typical flights for the BYERS, LONGMONT, and ELIZABETH STAR's. These three specific flights are presented to illustrate particular aspects of a flight. Figure 17 presents a straight-in approach and illustrates the path correction which takes place when the aircraft enters MLS or ILS coverage (at a maximum range of 30 n.mi.). In addition, this flight illustrates the use of the vector maneuver to delay the arrival of the aircraft. Figure 18 presents a LONGMONT arrival which was not required to hold or vector; however, an elongated downwind maneuver was required to delay the aircraft somewhat during the final portion of the flight. Figure 19 presents an ELIZABETH arrival which was required to hold and then followed the nominal path to the runway. Here again, one can see the path errors associated with navigating by VOR/DME outside of the MLS or ILS coverage.

## RESULTS

This section presents terminal area arrival performance (all parts of the flight except final approach), final approach performance, time errors, and communications workload, followed by results from the pilot questionnaires and pilot comments concerning their overall evaluation of the experiment.

The data are divided according to the automatic and manual control systems and are further categorized according to straight-in arrivals and corner-post arrivals. This is done for the following two reasons: (1) more turning and navigating were required in the corner-post arrivals, and (2) the straight-in arrivals were under the more accurate guidance of MLS or ILS coverage most of the flight whereas the corner-post arrivals contained more time navigating using less accurate VOR/DME signals until they crossed into the MLS or ILS coverage. Finally, the data are subdivided according to the type of final approach navigation, that is, 60° MLS, 40° MLS, or ILS guidance. Thus, each data set is based on nine flights. For all discussions concerning the comparison of the individual ATC systems, the reader is directed to reference 7, as this paper deals only with the performance of the aircraft and its crew.

### Terminal Area Arrival Performance

Terminal area arrival performance is characterized by cross-track error, altitude error, and airspeed error at specific waypoints during a flight through the terminal area. The data are presented for four waypoints on the STAR's and are divided between straight-in and corner-post arrivals. The waypoints for each type of arrival were chosen so that the aircraft operational characteristics (airspeed, altitude, holding fix, etc.) would be similar to those of the other type of arrival. The waypoints chosen for the straight-in arrival were as follows (see fig. 11): waypoint I - BYERS; waypoint II - WATKINS; waypoint III - ALTURA; and waypoint IV - GATE. For the corner-post arrivals, the following waypoints were chosen (see fig. 11): waypoint I - LONGMONT, SHAWNEE, and ELIZABETH; waypoint II - BRIGHTON, CONIFER, and FRANKTON; waypoint III - NORTH1 and SOUTH1; and waypoint IV - GATE. Finally, speed brake and landing gear movements during the terminal area arrival portion of the flight are discussed with regard to workload and procedures.

Cross-track error.- Figure 20 presents mean and standard deviation data for terminal area cross-track error. The cross-track error is defined as the lateral distance error from the programmed path at the waypoint in question. Holding, turning, and vectoring maneuvers at waypoints I and III had a tendency to cause the aircraft to fly off the programmed path and away from the waypoint in question. For these reasons, only waypoints II and IV can be used for control systems comparisons. In all cases, the aircraft was required to fly directly over these waypoints.

For waypoint II, the mean cross-track errors for all cases except the manual ILS case for the corner-post arrival are less than 100 m. For this case, there was a tendency to track to the left of the path by all the pilots. Since the standard deviation for this case is comparable to that of the other manual cases, the only explanation offered is that an undetected path bias may have been present during this set of flights. When the data are subjected to analysis of variance (ANOVA) studies (ref. 11), there are significant differences at the 1-percent confidence level for all major factors (with the exception of the crew factor) and for several of the two-factor interactions. (See table 2 for ANOVA factors and table 3 for ANOVA results.) These results stem from the fact that the tracking performance is more accurate with the automatic control system, as would be expected, and from the fact that the aircraft, for the straight-in approach, is under more accurate guidance (MLS or ILS, see fig. 11) at this waypoint.

For waypoint IV, the obvious difference is the increased standard deviations for the corner-post approaches, which are caused by maneuvering the aircraft to gain a smooth intercept of the final approach path in the vicinity of this waypoint. The mean errors are small, however, and the ANOVA results indicate no significant difference at the 1-percent or 5-percent levels.

In summary, the cross-track errors as a whole were acceptable. With the pilot using the EHSI display, the accuracy of the flight plan flown with the manual control system was lower than but operationally insignificant from that flown with the automatic control system.

Altitude error.- Figure 21 presents mean and standard deviation data for terminal area altitude error. Waypoint I will not be discussed because the altitudes varied between flights because of air traffic controller instructions and assigned altitudes in the holding-pattern stack. The data are presented for the same conditions as for the cross-track error.

For waypoint II, there is relatively little difference in the mean errors, and the errors themselves are almost negligible. In addition, the standard deviations are reasonably small. The ANOVA results (table 3) indicate a difference in the crew factor at the 1-percent level and an interaction between the approach factor and the crew factor at the 5-percent level.

For waypoint III, one can see a slightly larger difference between the straight-in approach and the corner-post approach compared with waypoint II. The ANOVA results show a significant difference at the 1-percent level for the approach factor. The tendency was to fly high at this waypoint on the corner-post approach, and this was caused by the fact that a turn was also required at this waypoint. The ANOVA results also show a significant difference at the 1-percent level for the crew factor, indicating that altitude control varied between the crews. In addition to the single-factor results, the control-crew and the approach-crew interactions show significance at the 1-percent level, indicating that the differences in controls and approaches varied between the crews.

For waypoint IV, although the ANOVA results indicate a significant difference at the 1-percent level in the control factor, there is relatively little difference in the magnitude of the mean errors, and the errors themselves are small and insignificant. The ANOVA results appear to be caused by the pilots maintaining a more consistent level of performance when flying with the manual control system. Their workload was probably increased somewhat when using automatic controls at this waypoint since they were required to change from horizontal path guidance to either velocity control-wheel steering or to track angle select for the direct-engage maneuver and to then arm the autoland system, thus causing their attention to be diverted from the altitude control for short periods of time.

In summary, the altitude errors were small and were mostly caused by the accuracy of the placement of the altitude-range arc depicted on the EHSI display. This arc indicated where along the path the aircraft would reach a selected altitude based on a commanded vertical flight-path angle. So long as the aircraft was slightly high at the waypoint, the pilots were satisfied. Adding to the difficulty of placing this arc was the fact that the arc was driven by actual vertical flight-path angle instead of commanded vertical flight-path angle, which caused the arc to bounce and required the pilot to fine tune the arc placement. This was true no matter which control system was used. It can be concluded that the pilots were able to perform as well using the manual control system as they did when using the automatic control system and that the altitude-range arc symbology on the EHSI display played a significant part in this result.

Airspeed error.- Figure 22 presents mean and standard deviation data for terminal area airspeed error which is measured from controller assigned airspeeds. For waypoint I, the aircraft have a larger mean error for the corner-post approach than for the straight-in approach. The ANOVA results (table 3) show a 1-percent level of significance for the approach-crew interaction, thus indicating that the airspeed error for the approaches varied between the crews. This can be seen in the raw data. This larger error is mainly due to the following three factors: (1) in some flights the pilot had shorter distances (from the initial-condition point to waypoint I) in which to slow down while at the same time flying with a tail wind; (2) the pilot was required to make 900- to 1200-m descents in addition to the airspeed reduction; and (3) if a hold was required, as was the case for most of the corner-post approaches, then an additional 40 knots of airspeed had to be lost in the same distance. During this descent-deceleration path into the waypoint, the pilot used everything at his disposal to slow down (i.e., idle throttles and speed brake deflection).

For waypoint II, there is little difference in the mean airspeed errors and the values are insignificant. The spread in standard deviation is caused in most data sets by the airspeed error in only one flight. The ANOVA results, as with waypoint I, show a significant difference in the approach-crew interaction, though at the 5-percent level this time.

For waypoint III, there is essentially no mean airspeed error for the straight-in approach. The mean errors are slightly larger for the corner-post approach, and there is an obvious increase in standard deviation. However, as was the case with waypoint II, this is caused by errors in one or two flights in each data set. The ANOVA results show a 5-percent level of significant difference in the approach-crew interaction, once again indicating that the airspeed error for the approaches varied between the crews. These errors could easily have resulted due to the pilots slowing somewhat before the waypoint on the corner-post approach because they were expecting to level off, make a turn, and get an airspeed reduction at the waypoint; in some cases a direct-engage maneuver would also be required just past the waypoint, thus calling for a second turn in the opposite direction. Thus, their mental and physical workloads would be higher on the corner-post approach than on the straight-in approach and would be an additional cause for the occurrence of the errors on specific flights.

For waypoint IV, there is almost no error for the straight-in approach. The pilots had plenty of time to reduce and stabilize the aircraft's airspeed. For the corner-post approach, however, the mean errors and the standard deviations are higher, and the ANOVA results (table 3) indicate a significant difference between approach types at the 1-percent level. The airspeed errors are due to the shorter distances over which airspeed could be reduced when the aircraft performed a direct-engage maneuver and due to a lag in reducing airspeed because the pilots had more tasks to accomplish during this portion of the flight. In addition, the ANOVA results show significance for the control-crew and control-approach interactions at the 1-percent and 5-percent levels, respectively, indicating that the differences in the controls varied between the crews and the approaches.

In summary, the airspeed errors varied according to type of approach and particular waypoint. The majority of the errors were caused by short paths in which to reduce airspeed, high pilot workload at particular waypoints, and anticipation of air traffic controller instructions (reductions below current airspeeds).

Terminal area speed brake movement and landing gear extension.- In order to get a feel for some of the procedure and workload problems associated with the airspeed reduction maneuvers, data were taken on terminal area speed brake movement and landing gear extension. It was necessary to use the speed brake when moving the throttles to idle would not accomplish a commanded airspeed reduction in the specified distance and when moving the throttles to idle during a descent was not enough to maintain a selected airspeed. Examples of these conditions were the large airspeed reductions from cruise required for approaching and entering holding patterns and the maintenance of an airspeed during a short segment with a large decrease in altitude. The B-737-100 simulated in the flight deck portion of this study was a very "clean" aircraft and did not have as much deceleration capability as the B-737-200 computer-generated aircraft simulated in TAATM. Thus, the aircraft was more difficult to slow and more difficult to maintain at a given airspeed in a descent. Approximately 90 percent of the flights required some amount of speed brake use to reduce airspeed. Figure 23 shows the means and standard deviations for speed brake movement. A speed brake movement is defined to have occurred when there was an obvious start and stop in motion of the speed brake handle. For example, if the pilot moved the handle, made an obvious discrete stop, and then moved the handle again, no matter how long the stop, this was counted as two movements. There appears to be little difference in speed brake movement when comparing the overall control system configurations; however, there are approximately two more speed brake movements for the corner-post approach compared with the straight-in approach. The ANOVA results (table 3) indicate that the difference in approach types is significant at the 1-percent level. This result is consistent with the fact that the corner-post approaches contain an additional altitude reduction where the use of the speed brake might be required to maintain airspeed. In addition, significant ANOVA results at the 1-percent level for the crew factor indicate that the pilots used the speed brakes differing amounts, and this can be seen in the raw data. (One pilot used more speed brake movement than the other two.) Finally, the control-crew interaction is significant at the 1-percent level, indicating that the differences for the controls varied between the crews.

Another indication of the difficulty in slowing the aircraft is shown in the number of flights requiring an early landing gear extension to help reduce airspeed (table 4). An early landing gear extension is defined as an extension anywhere other than on final approach to the runway. The table shows that in addition to using idle thrust and the speed brakes, the extension of the landing gear was sometimes required to produce more drag to help reduce the airspeed to that called for by the air traffic controller. In some cases, the pilot decided not to extend the landing gear for fuel conservation and passenger-comfort reasons, and thus the aircraft was fast at the waypoint in question. The landing gear extension was always used as a last resort after the throttles were at idle and the speed brakes were fully deployed. Once the landing gear was extended it remained extended, except for two straight-in approaches and one corner-post approach during which the landing gear was extended upon reducing airspeed to enter a holding pattern and retracted upon leaving the holding pattern. All other landing gear extensions for the corner-post approaches occurred on the path segments into waypoint III (NORTH1 or SOUTH1), and the one additional landing gear extension for the straight-in approach occurred inside of waypoint III (ALTURA).

In summary, airspeed reductions for the given terminal area route structure required the use of the speed brakes most of the time and required the extension of the landing gear a third of the time on corner-post approaches, thus increasing the workload of the pilots in the areas of additional airspeed monitoring and control movement. The main problem was that the aircraft (B-737-100) did not have enough airspeed reduction capability when necessary. In addition, it was not capable of maintaining a given airspeed in a descent as well as the aircraft (B-737-200) simulated in the TAATM program. It is possible that the B-737-100, a smaller aircraft than the B-737-200, should be classified with small DC-9 aircraft as far as TAATM studies are concerned, thus resulting in more realistic airspeed commands.

## Final Approach and Touchdown Performance

Final approach and touchdown performance is characterized by discussions of glide-slope and localizer errors at the 30.5-m (100.0-ft) altitude window and by discussions of touchdown footprint and sink rate at touchdown.

Glide-slope and localizer errors.- Figure 24 presents the glide-slope and localizer errors for the 30.5-m (100.0-ft) altitude window. Plotted are the means and standard deviations for the control system used during the approach (automatic or manual). The data are further divided between straight-in approach and corner-post approach. Since the characteristics of the three final approach navigation systems were equivalent during this segment of the flights, the data are not divided according to the ATC system used. For glide-slope error, there is essentially no difference in the mean errors for three of the data sets. The mean error for the data set for manual control with straight-in approach is approximately twice the values of the other three data sets, although operationally this is an insignificant difference. The standard deviations for the manual control system are 3.0 times as great as those for the automatic control system for the straight-in approach and 3.4 times as great for the corner-post approach. The ANOVA results (table 5) indicate a significant difference at the 5-percent level in the approach factor for glide-slope error.

For localizer error, the same three data sets tend to group together again, though with a slightly larger mean error and a slightly larger spread in mean error between the three data sets. The mean error for the data set for manual control with straight-in approach is approximately one-half the error for the other data sets; again, these are insignificant differences. The large standard deviation for the data set for automatic control with corner-post approach is a reflection of one flight. When this flight is removed from the data set, the standard deviation reduces from 4.61 m to 0.86 m and is essentially the same as the other automatic control data set. In addition, the mean error also reduces to essentially the same value as the other data set. The large error for this flight is a reflection of a piloting error which occurred in arming the autoland system when the pilot pushed the wrong switch on the AGCS panel. This flight would have resulted in a go-around in actual operations. For the data set for manual control with corner-post approach, two flights cause the standard deviation to be somewhat larger than the data set for manual control with straight-in approach. When data from these two flights are removed, the standard deviation reduces to essentially the same value as the other manual data set. Both of these flights resulted in landings, although they were approximately 12 m off the centerline of the runway. With data from these three flights removed, the localizer error standard deviation for the data set for manual control with straight-in approach is 6.2 times as great as the automatic data set, and the data set for manual control with corner-post approach is 6.6 times as great as the automatic data set. The ANOVA results (table 5) indicate a significant difference at the 5-percent level in localizer error for the control factor.

Runway touchdown performance.- Figures 25 and 26 present the runway touchdown footprint and the sink rate at touchdown. Plotted are the means and standard deviations of the longitudinal and lateral touchdown points and of the sink rate at touchdown for the control system in use and the type of approach. The aircraft was landed by using the perspective runway symbology on the EADI display (see fig. 6), and no out-of-the-window visual scene was provided. For the automatic control landings, the mean longitudinal touchdown point is the same for both types of approaches. The standard deviations vary between 39.5 m and 70.5 m for straight-in and corner-post approaches. One pilot procedure which caused the longitudinal touchdown point to vary for the automatic landings was that during the latter stage of the flare maneuver, the pilots almost always disengaged the autothrottles and manually controlled the throttles to reduce engine thrust to idle instead of allowing the autoland-autothrottle systems to perform the maneuver automatically. This caused the touchdown point to vary more than would have occurred if the automatic systems had remained engaged. For manual landings, the mean longitudinal touchdown points for straight-in and corner-post approaches are 50 m and 18 m shorter than for automatic landings, and the respective standard deviations are 150 m and 180 m. The ANOVA results (table 5) indicate a significant difference at the 1-percent level in the crew factor and in the control-crew interaction, showing that the pilots performed differently (seen in the raw data) and that they varied between the control systems in use. Although the control factor does not show a significant difference at the 5-percent level, it is just below registering.

The mean lateral touchdown points, for all practical purposes, are the same for both control systems and both approach types. Between the two extreme cases, the difference is approximately 1.2 m, and this reduces to 0.6 m when the one flight which would have resulted in a go-around is removed from the data set. The standard deviations for the automatic landings are 0.8 m and 1.0 m for straight-in and corner-post approaches with the one flight removed. (Fig. 25 contains data from all flights.) The standard deviations for the manual landings are 4.2 m and 6.4 m for straight-in and corner-post approaches. The ANOVA results indicate no significant differences in any of the factors or interactions.

The mean sink rate at touchdown (fig. 26) for the manual control system is two to three times as great as that for the automatic control system. This is also true for the standard deviations. There is relatively little difference between the approach types for a particular control system. The values for the automatic control system might have been somewhat lower and less spread if the pilots had not disengaged the autothrottle system just before touchdown. As stated previously, the aircraft was landed using a perspective runway symbol on the EADI. Using this display, the pilot had no depth perception cue and relied on the copilot calling out the altitudes to make the touchdown. They did not have a good visual sensation as to how fast they were approaching the ground, and therefore they tended to hit hard sometimes. In other cases, they floated down the runway "feeling" for the ground and thus landed long, affecting longitudinal touchdown performance. In addition, the increase in workload when landing manually tends to aggravate this situation. The ANOVA results indicate a significant difference at the 1-percent level for both control and crew factors. The significant crew factor indicates that the sink rate landing performance differed between the pilots.

To summarize the final approach performance, the pilots, though not able to perform as accurately with the manual control system as with the automatic control system, were still able to perform within acceptable limits. This is important because the pilots preferred to use the manual control system. They commented that they were more alert and aware of their environment when flying in the manual control mode. The major causes of differences in the data appear to be pilot procedure in using throttles on the automatic approaches and pilot workload and lack of depth perception with the perspective runway symbology during the manual approaches.

## Time Performance

Time performance is characterized by discussions of arrival-time error at the initial arrival fix, holding-pattern exit-time error, and outer-marker arrival-time error. In addition, a discussion of bank-angle excursions as related to time performance is presented.

Arrival-time error at the initial arrival fix.- Figure 27 presents the means and standard deviations of arrival-time error at the initial arrival fix (BYERS, LONGMONT, SHAWNEE, or ELIZABETH). The straight-in approach shows a mean error of approximately 20 sec late whereas the corner-post approach mean error is approximately 10 sec late. The ANOVA results indicate a significant difference in arrival-time errors at the 1-percent level for the approach factor. There are several possible reasons for the difference in arrival-time error. For the corner-post approaches, the pilots, in some cases, had shorter distances in which to slow the aircraft and perform a descent. Having difficulty slowing the aircraft actually caused the aircraft to arrive more nearly on time. Second, the straight-in approaches had head-wind conditions, whereas most of the corner-post approaches had tail-wind conditions. Thus, the straight-in approaches tended to slow quickly, but in relation to ground track, the corner-post approaches tended not to slow quickly, especially when a slower airspeed (40 knots slower) was required for a hold. Third, the pilots tended to start to reduce airspeed as soon as they entered the terminal area instead of waiting for an ATC airspeed reduction instruction, because they had learned that they would have problems slowing as they descended. The fact that the aircraft were still too fast at the fix for the corner-post approaches (due to the above reasons) probably helped reduce the effect of the early airspeed reduction, and thus the aircraft came closer to arriving on time. For the straight-in approaches, the aircraft had slowed too soon and were late. It should be pointed out that the pilots were not given a time objective to reach the initial arrival fix; instead, they were issued airspeed instructions, so they had no way of knowing whether they were late or early.

Holding-pattern exit-time error.- Table 6 presents the holding-pattern exit-time error data for the first holding pattern that occurred on each flight. When a hold was required to delay the aircraft, the air traffic controller issued an instruction to the aircraft telling the pilot to hold at the initial arrival fix and to exit the fix at a specific time. It was left up to the pilot to determine what type and size of holding pattern was required to complete the task. The pattern could be as simple as a 360° turn taking 3 minutes to complete, or as complex as a series of racetrack paths taking more time to complete. In order to help perform the holding-pattern maneuver, the pilot had available two special symbols on the EHSI display. These were the holding-pattern symbol and the curved-trend-vector symbol, which are presented in figure 28 and are described in detail in reference 9. The holding-pattern symbol in figure 28 has been rotated somewhat to be seen more easily by the reader. The holding-pattern symbol consists of two fixed-length parallel lines oriented in the direction of the exiting heading from the holding fix, and the curved-trend-vector symbol consists of a dashed line showing where the aircraft will be 30 sec, 60 sec, and 90 sec ahead of the present position based on current flight conditions. In addition, the pilot had a time readout available on the NCDU display. Although the data are split between automatic and manual control systems for record keeping, the majority of all holding patterns were flown using the manual control system because of pilot request. Early holding patterns with automatic control were flown using the track angle select mode, but the pilots had trouble meeting instructed holding exit times and felt that part of the problem was caused by the limitation on the automatic control system of a 25° maximum bank angle. Thus, they could not turn the aircraft as sharply as they desired. Even with the help of the advanced displays, there was a wide variation in the data. The pilots were from 58 sec late to 78 sec early in leaving the holding pattern. In some cases, these time errors contributed to forcing the aircraft into another holding pattern. The overall holding-pattern mean time error for all cases was 3.0 sec late with a standard deviation of ±27.7 sec. There were several items which contributed to these time errors. The pilots had to contend with the changing wind conditions as they flew the holding pattern (as much as an 80-knot change in ground speed from the upwind portion to the downwind portion of the pattern). In some cases, the aircraft was too fast entering the holding pattern, especially on the corner-post approaches. In addition to the aircraft's excess airspeed entering the pattern, the aircraft, at times, was accelerating when exiting the pattern because the pilots expected an instruction to increase airspeed which they did not always receive. The pilots felt at times that if they had received the holding instruction sooner, they could have controlled their entering airspeed somewhat better. A final factor contributing to the time errors was altitude changes during some of the holding patterns.

A few approaches required more than one holding pattern. Only two straight-in approaches required two holding patterns, whereas a total of nine corner-post approaches required two or more holding patterns. (Three approaches required three holding patterns.) This was caused partially by the ATC fixed-path metering and spacing algorithms putting greater priority on the straight-in approaches. The additional holding patterns affected the total flight time and also contributed to increased workload on the pilots.

Outer-marker arrival-time error.- Figure 29 presents the means and standard deviations of the outer-marker arrival-time error. The straight-in approaches tended to arrive early and the corner-post approaches tended to arrive late. The ANOVA results indicate a significant difference in outer-marker arrival-time error for the approach factor at the 1-percent level and for the crew factor at the 5-percent level. There are several possible reasons for these errors. On the straight-in approach, there is only one vectoring area which the air traffic controller can use to help delay the aircraft, and this is normally used to correct large errors and only as a last resort. On the corner-post approach, the controller has the downwind and base legs coupled with the direct-engage maneuver where path stretching can be used to help make adjustments to the arrival time. Finally, it is felt that some of the late corner-post arrivals were caused by pilot-induced factors. These factors are as follows:

1. The pilot did not respond quickly enough to the direct-engage-maneuver instruction.

2. The pilot was reluctant, from a passenger-comfort consideration, to put the aircraft into bank angles greater than 30°. This was sometimes required in order to respond to the direct-engage-maneuver instruction on time.

3. The pilot was reluctant to move off the nominal path to make very small adjustments called for by a direct-engage maneuver, especially if the aircraft was flying on automatic controls and would be required to reconfigure to manual control to respond to the direct-engage-maneuver instruction.

4. The pilot tended to give himself a small outside lead at the end of the direct-engage maneuver instead of heading directly at the waypoint, thus affecting the accuracy of the aircraft aim point. This was done so that he could complete a smooth turn into the path at the waypoint, especially at the GATE waypoint.

Bank-angle excursions.- In the preceding section, comments are made about the pilot being reluctant to exceed 30° in a bank angle because of passenger-comfort considerations. Table 7 presents a summary of bank-angle excursions of 30° or greater. In some of the automatic control system cases, the control system was reconfigured to manual in order to perform the required maneuver since the automatic control system was restricted to maximum bank angles of 25°. For the straight-in approach, about 26 percent of the flights required a large bank angle, with most occurrences happening in holding patterns. Two flights required large bank angles in vectors, and one flight required a large bank angle in a path turn. (One of these flights also had a large bank angle in the holding pattern.) For the corner-post approach, over 57 percent of the flights required a large bank angle at least once in the flight. These occurrences took place during holding patterns, direct-engage maneuvers, and path turns. Again, most of the occurrences happened in the holding patterns. Nine flights had an occurrence during a direct-engage maneuver, and one flight had an occurrence during a path turn. (Some flights had large bank angles in more than one type of maneuver.) This indicates that the aircraft using automatic controls would have trouble performing required time-critical maneuvers so long as the bank angle was limited to 25°.

## Communications

Figure 30 presents the following three sets of communication data which were collected during all flights: (1) the total number of communication messages from the ATOPS aircraft; (2) the total number of communication messages from the air traffic controller to the ATOPS aircraft; and (3) the total number of communication messages, all of which were heard in the ATOPS aircraft, from the air traffic controller to all aircraft (including ATOPS aircraft). The only real differences in the total number of ATOPS aircraft communications showed up for the approach factor (as would be expected) because the corner-post approaches were longer than the straight-in approaches and there were more communications taking place. This also held true for the total number of air traffic controller communications with the ATOPS aircraft. In both cases, the ANOVA results confirm this by indicating a significant difference for the approach factor at the 1-percent level. Comparison of the two sets of data shows that the ATOPS aircraft accounted for slightly more communications than the air traffic controller. In the third set of data (total number of air traffic controller communications to all aircraft), the variation also occurs for the approach factor. In this case, the larger number of voice communications occurred for the straight-in approaches, which had a larger number of aircraft per route. (See ref. 7.) The straight-in approach accounted for 40 percent of the traffic, whereas the three corner-post approaches accounted for 60 percent of the traffic, but not spread evenly between them. The ANOVA results indicate a significant difference for approach factor at the 5-percent level. In addition, the ANOVA results indicate a significant difference for the approach-crew interaction at the 1-percent level; thus, the difference in number of ATC voice communications for the approaches varied between crews. This is not surprising since the traffic density varies from route to route, as mentioned above, and also varies during different times of the day on a given route.

## Pilot Questionnaires

The two subjective questionnaires presented in the appendix were completed by the pilots, the first at the conclusion of each flight and the second at the conclusion of each simulator session. Both questionnaires were adapted from air traffic controller questionnaires found in reference 12.

Flight-evaluation questionnaire.- The first questionnaire answered by the pilots was the flight-evaluation questionnaire shown in the appendix. Both crew members were asked to answer this questionnaire at the conclusion of each flight from the point of view of their individual activities during the flight. Table 8 presents the results of the questionnaires answered by the captain of each crew. Since a qualified pilot acting as first officer was not available during some of the flights and the first officer's duties were therefore performed by the research engineer, data for the first officer will not be presented here. The captains' data, with all ATC navigation systems combined as one, are divided into automatic and manual control systems and straight-in and corner-post approaches.

Question 1(a) asks the pilot to evaluate the ride quality of the flight from a passenger's point of view. The mean value results (table 8) lie between a rating of 5 and 6 (halfway between an "average" and "best" rating) for three of the four cases. The case for the automatic control system corner-post approach was given a mean value of 4.1 which is the middle, or average, rating. Some of the factors which contributed to the ratings, according to pilot comments, were as follows:

1. Airspeed changes - the pilots felt that the passengers might be bothered by the engine sounds during some of the airspeed control maneuvers which were required.

2. Speed brake deployment - the pilots felt that the vibration caused by speed brake use in the extreme cases might be annoying.

3. Landing gear extension and retraction - for the few cases in which the pilots were required to extend and then retract the landing gear to achieve a required airspeed reduction, the pilots again felt that the noise and bumps would be annoying.

4. Banking maneuvers - the pilots felt that some of the bank angles (up to 45° in several cases) required for holding patterns and for direct-engage maneuvers would cause some concern with the passengers.

5. Control system changes - switching between automatic and manual control systems in a few cases caused some operational problems, such as pushing wrong switches.

6. Automatic-control-system changes - switching from track angle select mode to autoland during sharp intercepts of the localizer caused some oscillations which, again, might disturb the passengers.

Factors 4, 5, and 6 were definitely causes in the rating of 4.1 for the case of the automatic control system with corner-post approach. In general, however, the pilots rated the ride quality as very good.

Question 1(b) deals with the pilot's perception of his total workload. As would be expected, the results show the workload to be lower for the straight-in approach (very few deviations from the programmed path) and lower for the automatic control system (table 8). Workload, in general, was rated as being low to average, and the differences between the different combinations of approaches and control systems were fairly small. This reinforces the pilots' preference for flying the manual control system, that is, the workload was approximately the same, but they felt that they were more aware of the situation when using the manual controls.

Question 1(c) deals with the pilot's frustration in performing the flights. The frustration level was rated as being fairly low and was essentially the same for all combinations of control systems and approaches with the exception of the case of the automatic control system with straight-in approach, which was slightly lower. (See table 8.)

In question 2, the pilot is asked to further evaluate his workload in the following four areas: manual, visual, mental, and verbal. In all but three comparisons, the workload ratings were lower for the automatic control system and for the straight-in approach (table 8). For the three exceptions, the rating values were the same. The visual factor received the highest workload rating, and the verbal factor received the lowest rating. All the ratings fell between a very low workload value and an average workload value. Again, the ratings comparisons between the two control systems indicate that the pilots' desires to use the manual control system are reasonable.

Finally, in question 3, the pilot is asked to make further comments about the flight. In general, this section was used to indicate piloting problems which occurred during the flight.

Metering and spacing ATC questionnaire.- The second of the two questionnaires answered by the pilots was used to evaluate their reaction to a more automated ATC system working toward a delivery-time objective. This questionnaire, also presented in the appendix, was answered at the end of each simulation session. The results of the questionnaire, presented in table 9, indicate a high degree of acceptance by the pilots of an ATC system attempting to meet time objectives. They felt that it would be easy to learn to live with, would improve ATC procedures, would result in a more orderly and precise ATC system, and thus would decrease delays in the terminal area. The only area in which a neutral answer was given pertains to whether or not the pilot's job would be more difficult. Finally, they felt this type of system would work in the real world and ought to be implemented. The reader is reminded that the pilots were speaking from the standpoint of using an advanced flight deck with advanced controls and displays (the study assumed all aircraft were RNAV equipped) and that the pilots used in this study were research pilots and not commercial line pilots.

## Pilot Comments

At the end of the study, the pilots involved were asked to comment on the study and the simulation facility. The comments presented here are those that tended to appear across the group. As far as the simulation (aircraft and ATC environment) was concerned, the pilots felt that it was very realistic. They were required to use a full crew (two-man crew in the case of ATOPS) and to perform their appropriate tasks with realistic workloads. The ATC environment was realistic in that there was an air traffic controller instructing the aircraft to make maneuvers (airspeed reductions, vectors, altitude changes, holds, etc.) through the VHF communication system. One pilot went so far as to comment, "This is the first time in my career that the simulation was totally realistic."

Comments having to do specifically with the research task revolve around the pilot's ability to respond to air traffic controller's instructions. This ability depends on several factors, such as aircraft performance limitations, passenger comfort limitations, and accurate display of aircraft position and approach information. Examples of the above were the problems encountered in decelerating and descending and the high-bank-angle turns as mentioned in earlier sections of this report. The pilots felt that two of the most useful pieces of information available to them for navigation were the altitude-range arc and the curved-trend-vector symbols displayed on the EHSI. It was suggested that a symbol similar to the altitude-range arc for use in airspeed-range maneuvers might have helped solve the deceleration problems. In addition, the pilots felt that the holding-pattern symbol, as defined, was inadequate for performing maneuvers in which they were instructed to be at the exit fix at a specified time.

A major comment made by all participants was the preference for using the manual control system with autothrottles. The pilots felt that they were more aware of their environment and more on top of the situation when using the manual control system than they were when using the automatic control system, which required more monitoring than flying. They were able to keep their eyes on the primary displays and did not have to look at the AGCS mode control panel to make control inputs as was the case with the automatic control system. (Except for a small number of flights, the captain retained control of all control system inputs and did not ask the first officer for help.) Finally, they felt that they could provide a smoother flight using the manual control system. The objective data from the study tend to reinforce their comments that they could perform within acceptable operational tolerances using the manual control system.

## RECOMMENDATIONS

Based on the results of this study and comments made by the participating pilots, recommendations are made in the following areas:

1. Display additions and modifications.

   a. Develop and implement on the electronic horizontal situation indicator (EHSI) display an airspeed-range arc similar in concept to the existing altitude-range arc which would indicate to the pilot where along a displayed ground track the aircraft would reach a selected airspeed. This should help reduce some of the airspeed control problems which occurred in this study.

   b. Modify the altitude-range arc logic so that it is driven by commanded vertical flight-path angle instead of actual vertical flight-path angle. This would make the symbol easier to position and would eliminate the present unsteady behavior of the symbol.

   c. Develop and implement on the EHSI display a new holding-pattern symbol the size of which takes into consideration prevailing wind conditions (speed and direction), aircraft airspeed, and time and distance to go to meet specified holding-pattern exit time (similar to direct-course-error (DICE) countdown in the Terminal Area Air Traffic Model (TAATM)).

   d. Determine a method by which the depth perception problem with the perspective runway on the electronic attitude director indicator (EADI) display can be overcome to help improve touchdown performance for the manual control system.

2. Automatic control system modification. Increase the bank-angle limit from 25° to 30° for the automatic control system. If the limit had been set at 30°, the pilots might not have had to reconfigure to the manual control system as much in order to fly holding-pattern and direct-engage maneuvers, and instead they could have flown the maneuver using the track angle select mode.

3. Areas for possible future study.

   a. A formal study looking at the effects on delivery-time errors of aim-point accuracy during the direct-engage maneuvers. The related MLS metering and spacing study presents a limited amount of data concerning this area.

   b. An evaluation of crew procedures to determine if some of the physical setting of control functions (such as autothrottle airspeed selection and altitude reference selection) when called for by the captain can be turned over to the first officer.

   c. Determine, for TAATM considerations, whether a separate B-737-100 class of aircraft or inclusion of the Advanced Transport Operating Systems (ATOPS) aircraft with the smaller DC-9 class of aircraft is more realistic than including the ATOPS aircraft with the B-737-200 class of aircraft.

d. Consideration should be given to using a total system facility such as the one described herein as a final test for new control systems, displays, procedures, and so forth, so that a realistic environment and workload are present for the pilots. This would help establish whether or not the same results would occur when the pilots are presented with the requirement to perform all the tasks associated with flying an aircraft in the real world and not just the isolated environment of a part-task experiment.

## CONCLUDING REMARKS

This report has described the linking together of two simulations, the Langley Advanced Transport Operating Systems (ATOPS) Aft Flight Deck (AFD) Simulator and the Terminal Area Air Traffic Model (TAATM) Simulation, to allow terminal area systems studies to be conducted. This provided the realism of an air traffic control (ATC) environment with live air traffic controller communication to the flight crews and the capability of inserting a "live" aircraft into the TAATM simulation to interact with the computer-generated aircraft that it models. A joint study was conducted to evaluate the performance of flight crews using advanced display systems and two different control systems (automatic and manual) in an automated ATC system and to evaluate the effect of the microwave landing system (MLS) on the delivery performance of a fixed-path metering and spacing system.

The pilots considered the total simulation to be highly realistic and very effective in both the flight deck and ATC terminal area environments. The pilots overwhelmingly favored using the manual control system because they felt that they were more alert and aware of what was happening in the cockpit and in the terminal area environment. The automatic control system cases were more a matter of monitoring and then reacting when something off the nominal was required, such as a direct-engage command. The pilots commented that if the bank angle had not been limited to a maximum of 25° in the automatic control system, they would not have had to reconfigure to the manual system as often for turning maneuvers such as holding patterns and direct engage. Although the pilots did not perform as well using the manual control system as they did with the automatic control system, their performances were within acceptable operational limits, and their workload did not increase noticeably. The pilots were fairly comfortable with the automated terminal area environment simulated and with the types of ATC instructions which were issued. The pilots made several recommendations for improvements to some of the display symbology, including modifications to the altitude-range arc, holding pattern, and a new airspeed-range arc. In addition, a depth perception problem encountered with the perspective runway should be looked at in future display work.

This study also indicated some areas for future consideration, such as a study on the effect of aim-point accuracy during the direct-engage maneuvers, an evaluation of the assignment of particular crew duties, and an evaluation of whether a new class of aircraft for the TAATM simulation is needed to more accurately represent the B-737-100 aircraft modeled in the ATOPS AFD simulator. Finally, some consideration should be given to using this type of system simulation as a final evaluation tool for new aircraft control and display system designs in order to realistically simulate the total environment in which the system will be used.

Langley Research Center
National Aeronautics and Space Administration
Hampton, VA 23665
March 16, 1983

## FLIGHT EVALUATION SHEET

Name and
Crew Position ______________________ A/C # ______________________
Run # ______________________

Date ______________ ATC Density ______________________

ATC Route ______________ Control Configuration ______________________

Please answer questionnaire from the point of view of the crew position you performed.

1. Circle the numbers which best describe how you feel in reference to this run. Comment if you wish in the space provided.

   (a) RIDE QUALITY (Passenger Comfort)

   (low) 1 2 3 4 5 6 7 (high)

   Comment: ______________________

   ______________________

   (b) TOTAL WORKLOAD

   (low) 1 2 3 4 5 6 7 (high)

   Comment: ______________________

   ______________________

   (c) FRUSTRATION

   (low) 1 2 3 4 5 6 7 (high)

   Comment: ______________________

   ______________________

2. Estimate your manual, visual, mental, and verbal workloads separately for this run.

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| (a) MANUAL: | (low) | 1 | 2 | 3 | 4 | 5 | 6 | 7 | (high) |
| (b) VISUAL: | (low) | 1 | 2 | 3 | 4 | 5 | 6 | 7 | (high) |
| (c) MENTAL: | (low) | 1 | 2 | 3 | 4 | 5 | 6 | 7 | (high) |
| (d) VERBAL | (low) | 1 | 2 | 3 | 4 | 5 | 6 | 7 | (high) |

3. Please make any other comments on the run below. Use back of sheet if necessary.

APPENDIX

## QUESTIONNAIRE - METERING AND SPACING STUDY

Name ______________________________

Date ______________ Control Configuration ______________

On the basis of your present knowledge of Metering and Spacing (M&S) in the terminal area, indicate the strength of your agreement or disagreement with each of the following statements. When a comparison is called for, make it with respect to current terminal area ATC systems.

| | | AGREE | | NEUTRAL | | DISAGREE |
|---|---|---|---|---|---|---|
| 1. | M&S is easy to learn to live with. | 1 | 2 | 3 | 4 | 5 |
| 2. | M&S will make the pilot's job more difficult. | 1 | 2 | 3 | 4 | 5 |
| 3. | M&S will never work in the real-world ATC system. | 1 | 2 | 3 | 4 | 5 |
| 4. | M&S will help improve ATC procedures. | 1 | 2 | 3 | 4 | 5 |
| 5. | M&S will decrease delays in the terminal area at busy airports. | 1 | 2 | 3 | 4 | 5 |
| 6. | M&S will result in a more orderly and precise ATC system. | 1 | 2 | 3 | 4 | 5 |
| 7. | M&S should be put into operational usage at dense terminal areas. | 1 | 2 | 3 | 4 | 5 |

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## GLOSSARY

| | |
|---|---|
| ADC | analog-to-digital converter |
| AFD | aft flight deck |
| AGCS | advanced guidance and control system |
| ANOVA | analysis of variance |
| ATC | air traffic control |
| ATOPS | Advanced Transport Operating Systems |
| CRT | cathode-ray tube |
| DAC | digital-to-analog converter |
| DICE | direct-course-error |
| DME | distance measuring equipment |
| EADI | electronic attitude director indicator |
| EHSI | electronic horizontal situation indicator |
| IFR | instrument flight rules |
| ILS | instrument landing system |
| MLS | microwave landing system |
| NCDU | navigation control and display unit |
| OM | outer marker |
| RNAV | area navigation |
| SMT | scheduled outer marker arrival time |
| STAR | standard terminal arrival route |
| TAATM | Terminal Area Air Traffic Model |
| TCV | Terminal Configured Vehicle |
| VCWS | velocity control-wheel steering |
| VHF | very high frequency |
| VOR | very high frequency omnidirectional range |

TABLE 1.- EXPERIMENTAL RUN MATRIX

| Crew | Number of straight-in arrivals using - | | | Number of corner-post arrivals using - | | |
| --- | --- | --- | --- | --- | --- | --- |
| | 60° MLS | 40° MLS | ILS | 60° MLS | 40° MLS | ILS |
| Automatic-mode control system | | | | | | |
| 1 | 3 | 3 | 3 | 3 | 3 | 3 |
| 2 | 3 | 3 | 3 | 3 | 3 | 3 |
| 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| Manual-mode control system | | | | | | |
| 1 | 3 | 3 | 3 | 3 | 3 | 3 |
| 2 | 3 | 3 | 3 | 3 | 3 | 3 |
| 3 | 3 | 3 | 3 | 3 | 3 | 3 |

TABLE 2.- MAJOR FACTORS AND INTERACTIONS FOR ANALYSIS OF VARIANCE STUDIES

| Factors and interactions[a] | Degrees of freedom |
| --- | --- |
| A | 1 |
| B | 1 |
| C | 2 |
| D | 2 |
| E | 2 |
| AB | 1 |
| AC | 2 |
| AD | 2 |
| BC | 2 |
| BD | 2 |
| CD | 4 |
| ABC | 2 |
| ABD | 2 |
| ACD | 4 |
| BCD | 4 |
| ABCD | 4 |
| Error | 70 |
| Total | 107 |

[a]Factors considered:
A - Control system (automatic and manual)
B - Approach (straight-in and corner-post)
C - ATC system (60° MLS, 40° MLS, and ILS)
D - Crews
E - Replicates

TABLE 3.- ANOVA RESULTS FOR TERMINAL AREA ARRIVAL PERFORMANCE

| Performance characteristic | ANOVA[a] results for[b] - | | | | | |
|---|---|---|---|---|---|---|
| | A | B | D | AB | AD | BD |
| Cross-track error: | | | | | | |
| Waypoint II | ** | ** | | ** | | ** |
| Waypoint IV | | | | | | |
| Altitude error: | | | | | | |
| Waypoint II | | | ** | | | * |
| Waypoint III | | ** | ** | | ** | ** |
| Waypoint IV | ** | | | | | |
| Airspeed error: | | | | | | |
| Waypoint I | | | | | | ** |
| Waypoint II | | | | | | * |
| Waypoint III | | | | | | * |
| Waypoint IV | | ** | | * | ** | |
| Speed brake movement | | ** | ** | | ** | |

[a]Confidence levels as follows: * - 5 percent; ** - 1 percent.
[b]Factors considered as follows: A - control system; B - approach; D - crew.

TABLE 4. - FLIGHTS REQUIRING AN EARLY LANDING GEAR EXTENSION TO HELP REDUCE AIRSPEED

| ATC system | Number of flights using - | |
|---|---|---|
| | Automatic control system | Manual control system |
| Straight-in approach | | |
| $60^{\circ}$ MLS | 0 | 0 |
| $40^{\circ}$ MLS | 0 | 1 |
| ILS | 0 | 2 |
| Corner-post approach | | |
| $60^{\circ}$ MLS | 4 | 3 |
| $40^{\circ}$ MLS | 4 | 1 |
| ILS | 2 | 4 |

TABLE 5.- ANOVA RESULTS FOR FINAL APPROACH AND TOUCHDOWN PERFORMANCE

| Performance characteristic | ANOVA[a] results for[b] - | | | | | |
|---|---|---|---|---|---|---|
| | A | B | D | AB | AD | BD |
| Glide-slope error | | * | | | | |
| Localizer error | * | | | | | |
| Longitudinal touchdown position | | | ** | | ** | |
| Lateral touchdown position | | | | | | |
| Sink rate at touchdown | ** | | ** | | | |

[a]Confidence levels as follows: * - 5 percent; ** - 1 percent.
[b]Factors considered as follows: A - control system; B - approach; D - crew.

TABLE 6.- HOLDING-PATTERN EXIT-TIME ERRORS

| Control system | ATC system | No. of flights with holds | Average time error, sec (a) | Time-error spread, sec (a) |
|---|---|---|---|---|
| Straight-in approach | | | | |
| Automatic | 60° MLS | 3 | 5.7 E | 3 L to 12 E |
| | 40° MLS | 3 | 8.7 L | 29 L to 7 E |
| | ILS | 3 | 24.3 L | 58 L to 7 L |
| Manual | 60° MLS | 3 | 16.7 L | 45 L to 15 E |
| | 40° MLS | 3 | 3.0 L | 7 L to 4 E |
| | ILS | 3 | 2.7 E | 16 L to 23 E |
| Corner-post approach | | | | |
| Automatic | 60° MLS | 9 | 6.1 L | 45 L to 65 E |
| | 40° MLS | 9 | 9.8 E | 22 L to 78 E |
| | ILS | 4 | 8.8 L | 46 L to 38 E |
| Manual | 60° MLS | 9 | 8.3 E | 21 L to 74 E |
| | 40° MLS | 9 | 7.8 L | 50 L to 15 E |
| | ILS | 4 | 13.8 L | 38 L to 1 E |

[a]Symbols used are as follows: E - early; L - late.

TABLE 7.- BANK-ANGLE EXCURSIONS

| ATC navigation system | Number of flights with bank angles $\geqslant 30°$ for - | |
|---|---|---|
| | Automatic control system | Manual control system |
| Straight-in approach | | |
| 60° MLS | 1 | 4 |
| 40° MLS | 1 | 3 |
| ILS | 2 | 3 |
| Corner-post approach | | |
| 60° MLS | 4 | 8 |
| 40° MLS | 5 | 9 |
| ILS | 2 | 3 |

Table 8.- RESULTS FOR FLIGHT EVALUATION QUESTIONNAIRE

| Question | Control System | Mean ± standard deviation for - | |
|---|---|---|---|
| | | Straight-in approach (a) | Corner-post approach (a) |
| Ride quality | Automatic<br>Manual | 5.2 ± 1.5<br>5.5 ± 1.0 | 4.1 ± 1.5<br>5.5 ± 1.2 |
| Total workload | Automatic<br>Manual | 2.4 ± 0.7<br>3.4 ± 0.9 | 3.0 ± 0.7<br>3.7 ± 1.0 |
| Frustration | Automatic<br>Manual | 2.1 ± 0.7<br>2.9 ± 1.3 | 2.8 ± 1.1<br>2.8 ± 1.4 |
| Manual workload | Automatic<br>Manual | 2.2 ± 0.6<br>3.5 ± 0.6 | 2.7 ± 0.7<br>3.5 ± 0.9 |
| Visual workload | Automatic<br>Manual | 2.9 ± 0.7<br>3.6 ± 0.6 | 3.2 ± 0.8<br>3.8 ± 0.7 |
| Mental workload | Automatic<br>Manual | 2.6 ± 0.8<br>3.2 ± 0.7 | 3.2 ± 0.8<br>3.3 ± 1.0 |
| Verbal workload | Automatic<br>Manual | 1.7 ± 0.7<br>1.7 ± 0.5 | 1.7 ± 0.8<br>1.8 ± 0.6 |

[a]Values correspond to the following: 1 - low; 4 - average; 7 - high.

Table 9.- RESULTS FOR METERING AND SPACING ATC QUESTIONNAIRE

| Question | Control system | Mean ± standard deviation (a) |
|---|---|---|
| 1 | Automatic<br>Manual | 1.8 ± 0.6<br>2.1 ± 0.5 |
| 2 | Automatic<br>Manual | 2.8 ± 1.4<br>3.0 ± 1.4 |
| 3 | Automatic<br>Manual | 4.2 ± 0.7<br>4.6 ± 0.5 |
| 4 | Automatic<br>Manual | 1.9 ± 0.6<br>1.9 ± 0.9 |
| 5 | Automatic<br>Manual | 2.0 ± 0.5<br>1.8 ± 0.6 |
| 6 | Automatic<br>Manual | 1.9 ± 0.7<br>1.7 ± 0.6 |
| 7 | Automatic<br>Manual | 1.7 ± 0.6<br>1.7 ± 0.6 |

[a]Values correspond to the following: 1 - agree; 3 - neutral; 5- disagree.

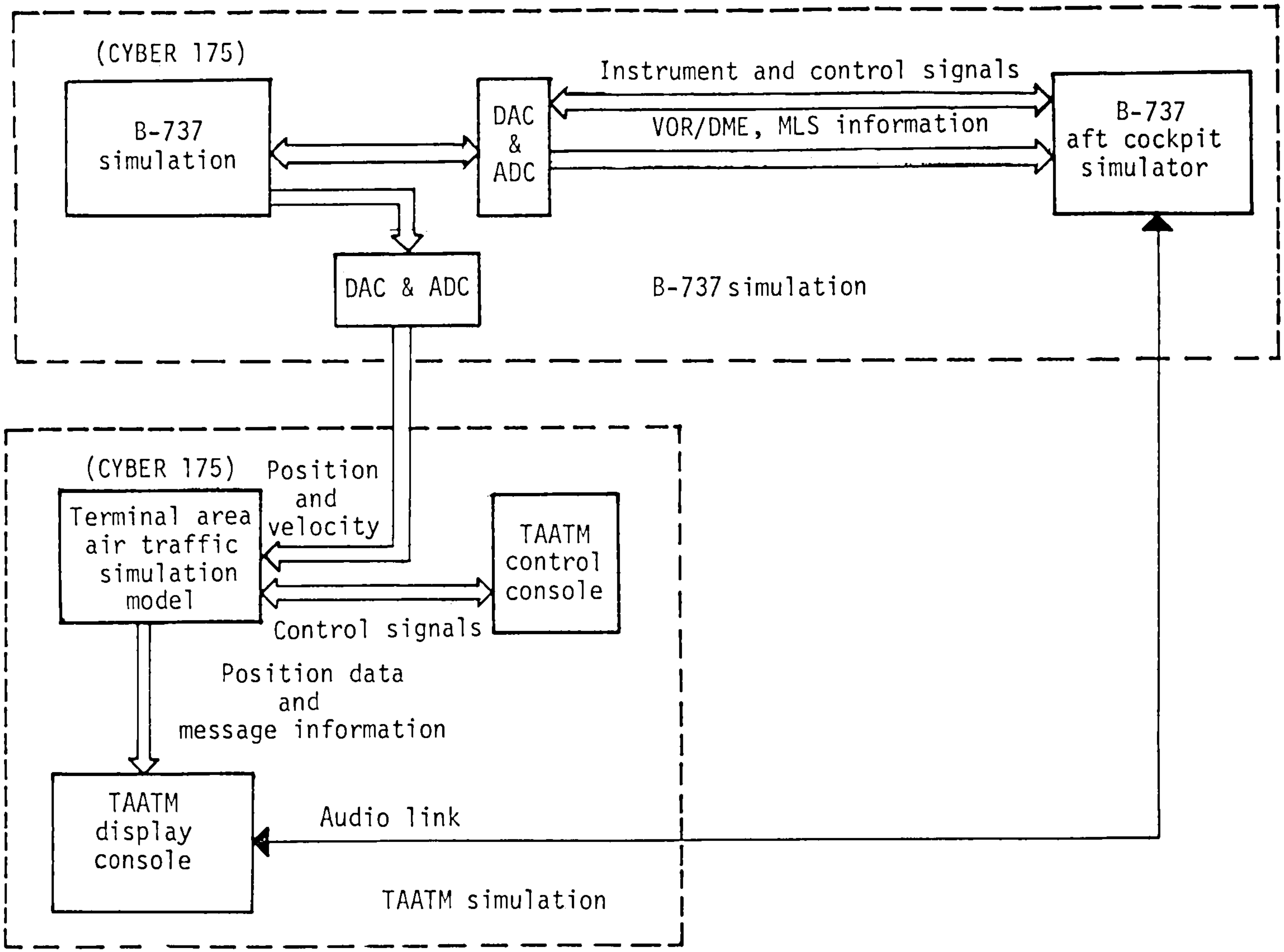
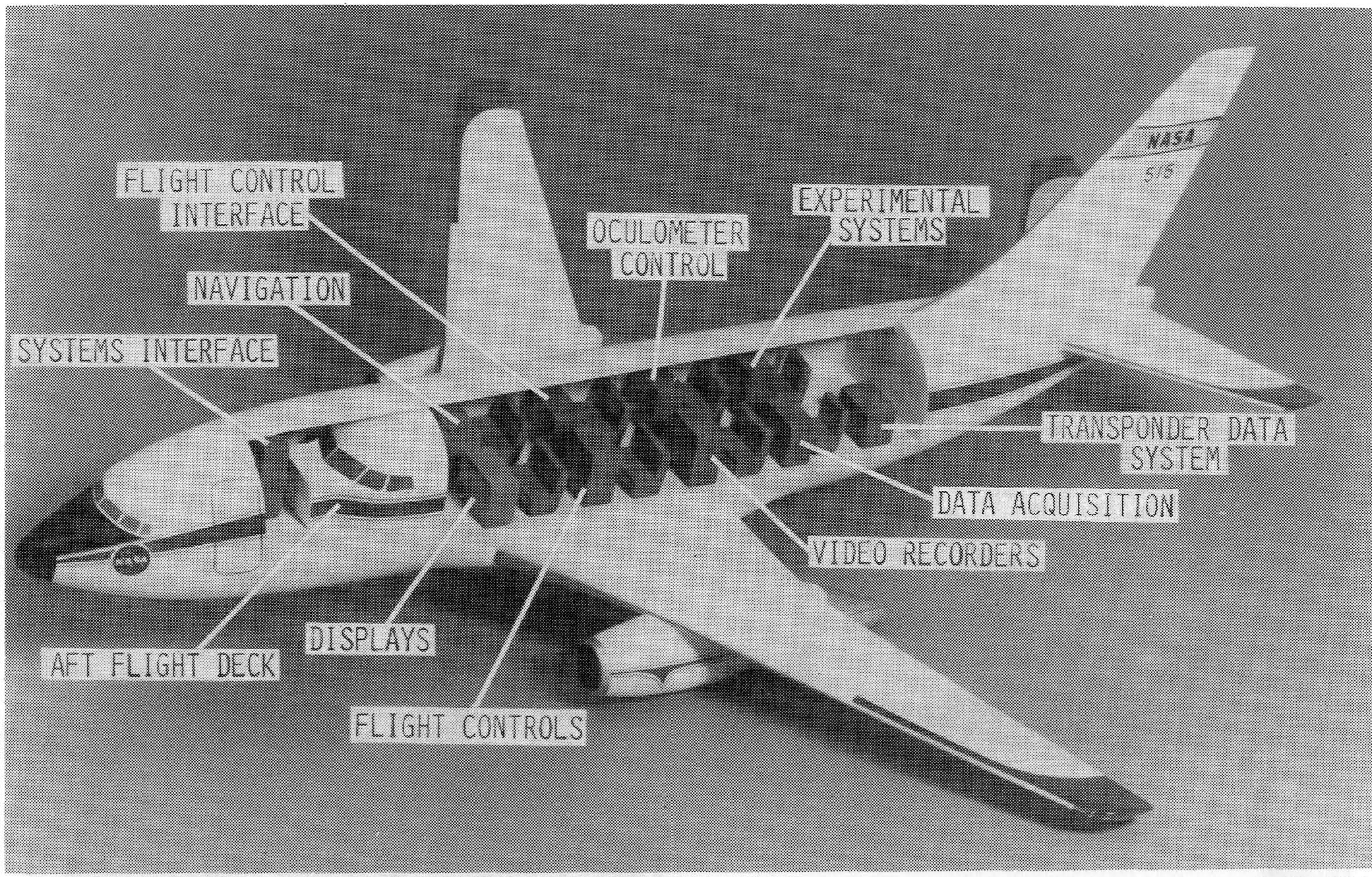



Figure 1.- Block diagram of experimental simulation setup.

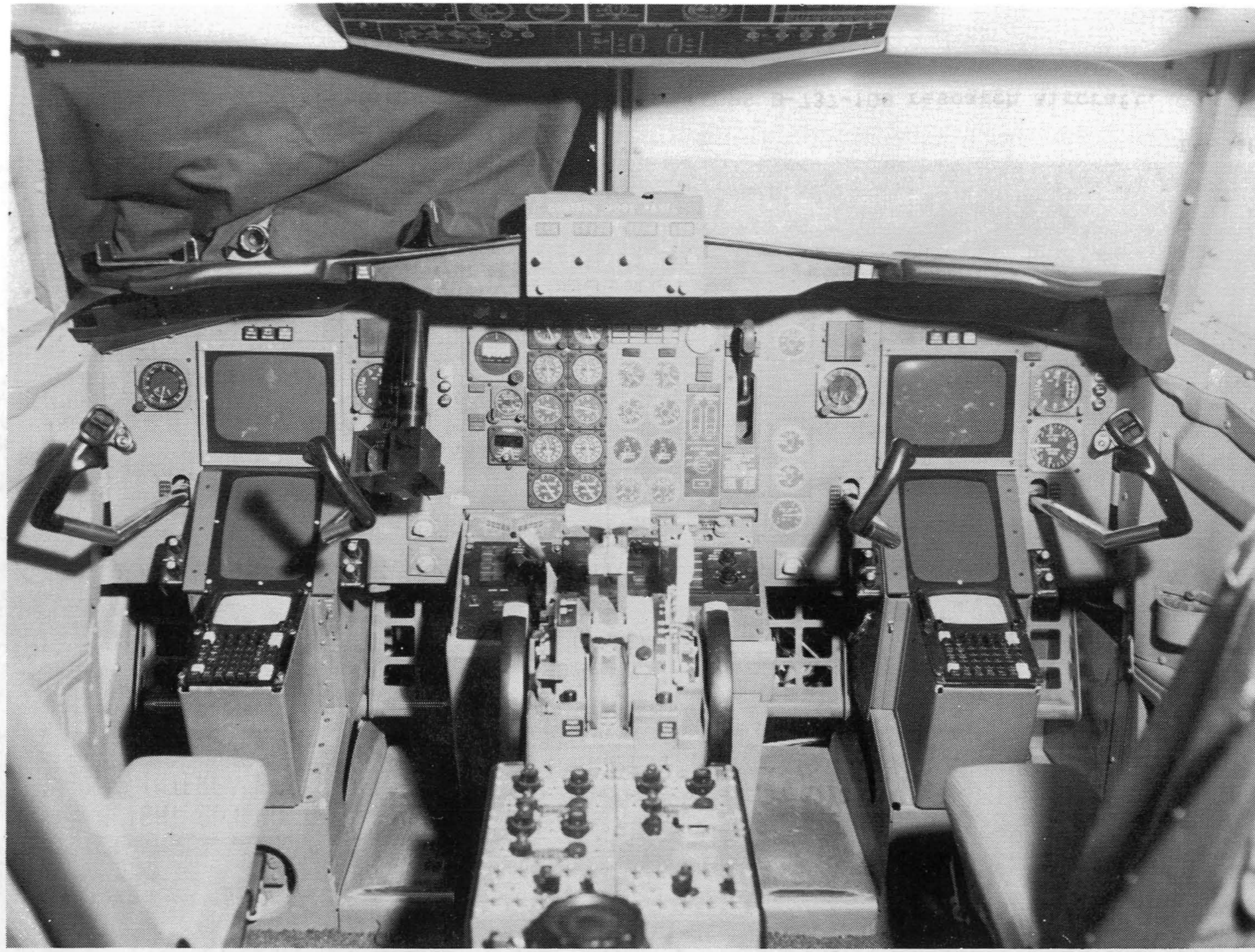

L-73-6283

Figure 2.- ATOPS B-737-100 research aircraft.




L-80-8015

Figure 3.- Internal arrangement of ATOPS B-737-100 research aircraft.

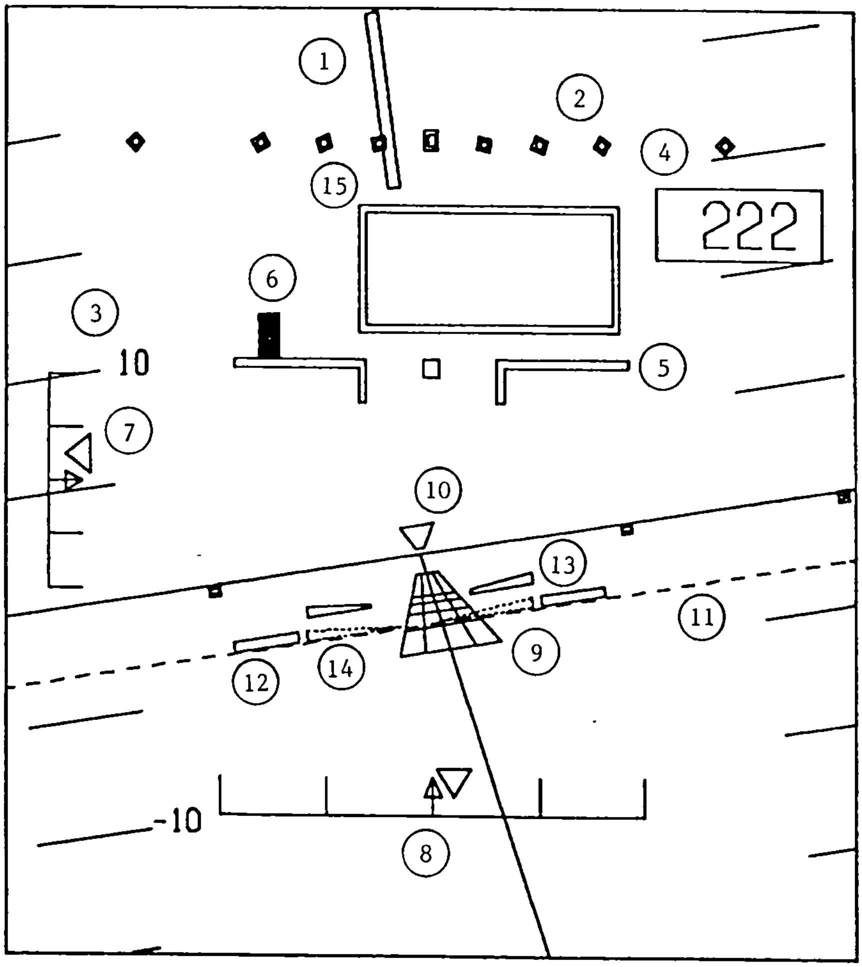


L-79-640

Figure 4.- ATOPS AFD simulator cockpit.


L-76-4228

Figure 5.- Advanced guidance and control system control panel.




(1) Roll pointer

(2) Roll scale

(3) Pitch grid

(4) Radar altitude

(5) Aircraft reference symbol

(6) Speed error indicator

(7) Glide-slope error indicator

(8) Localizer error indicator

(9) Runway symbol

(10) Track pointer

(11) Pitch reference line

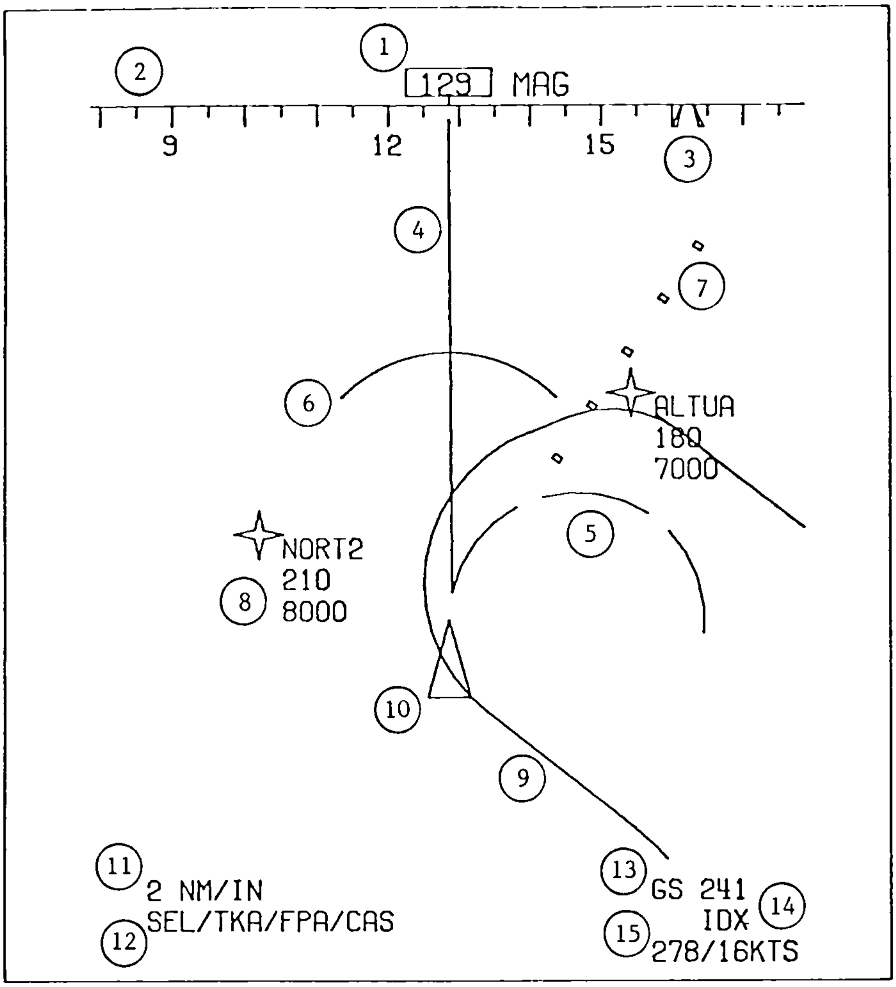
(12) Flight-path acceleration

(13) Flight-path angle

(14) Reference flight-path angle

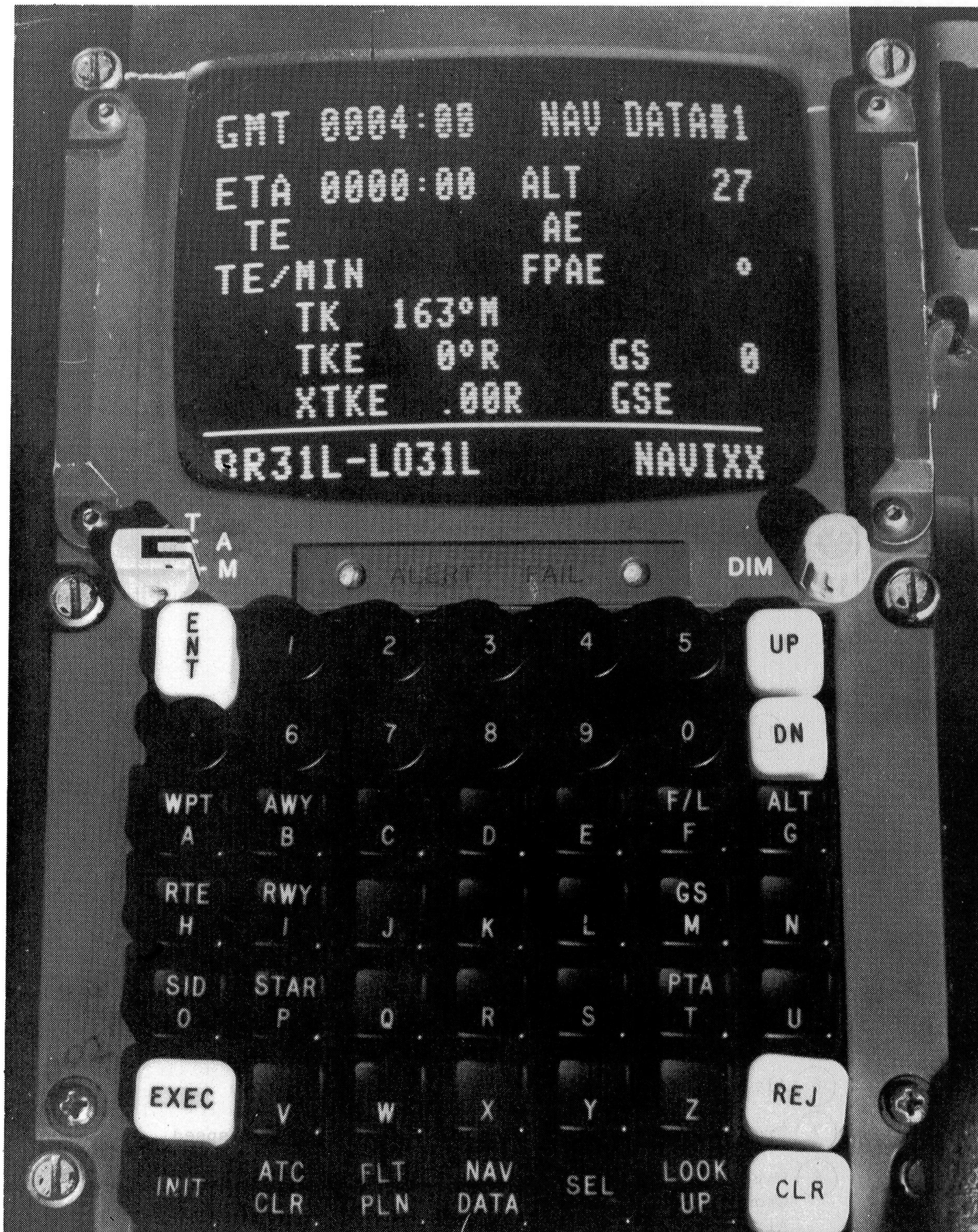
(15) ILS box

Figure 6.- Electronic attitude director indicator.




1 Magnetic track angle
2 Magnetic track angle scale
3 Track bug
4 Straight trend vector
5 Curved trend vector
6 Altitude-range arc
7 Track select dots
8 Waypoint name
Ground speed
Altitude
9 Flight plan
10 Aircraft symbol
11 Map scale
12 Control mode
13 Ground speed
14 Navigation mode
15 Wind direction/speed

Figure 7.- Electronic horizontal situation indicator.




L-83-51

Figure 8.- Navigation control and display unit.

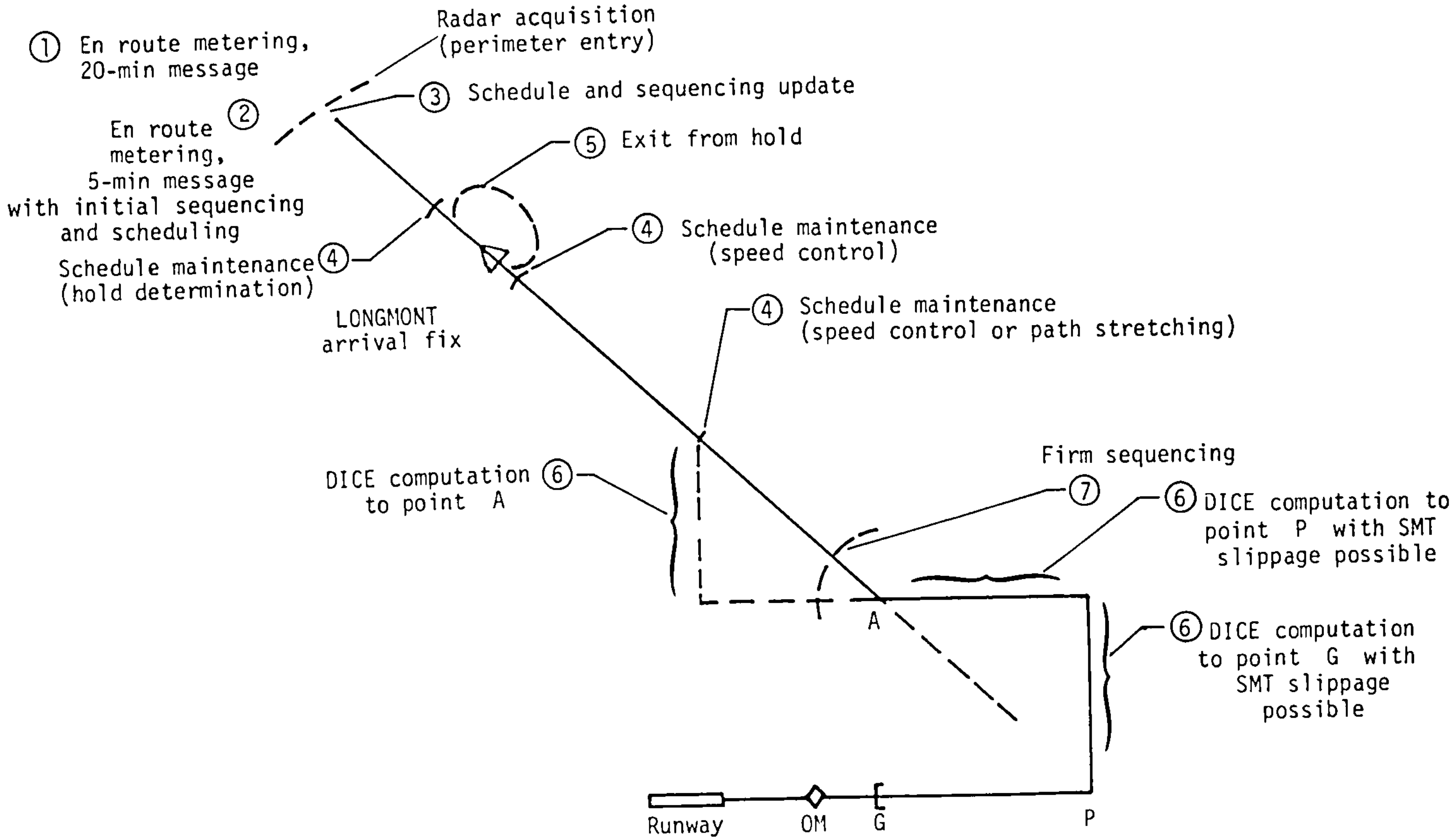



Figure 9.- Metering and spacing control logic.

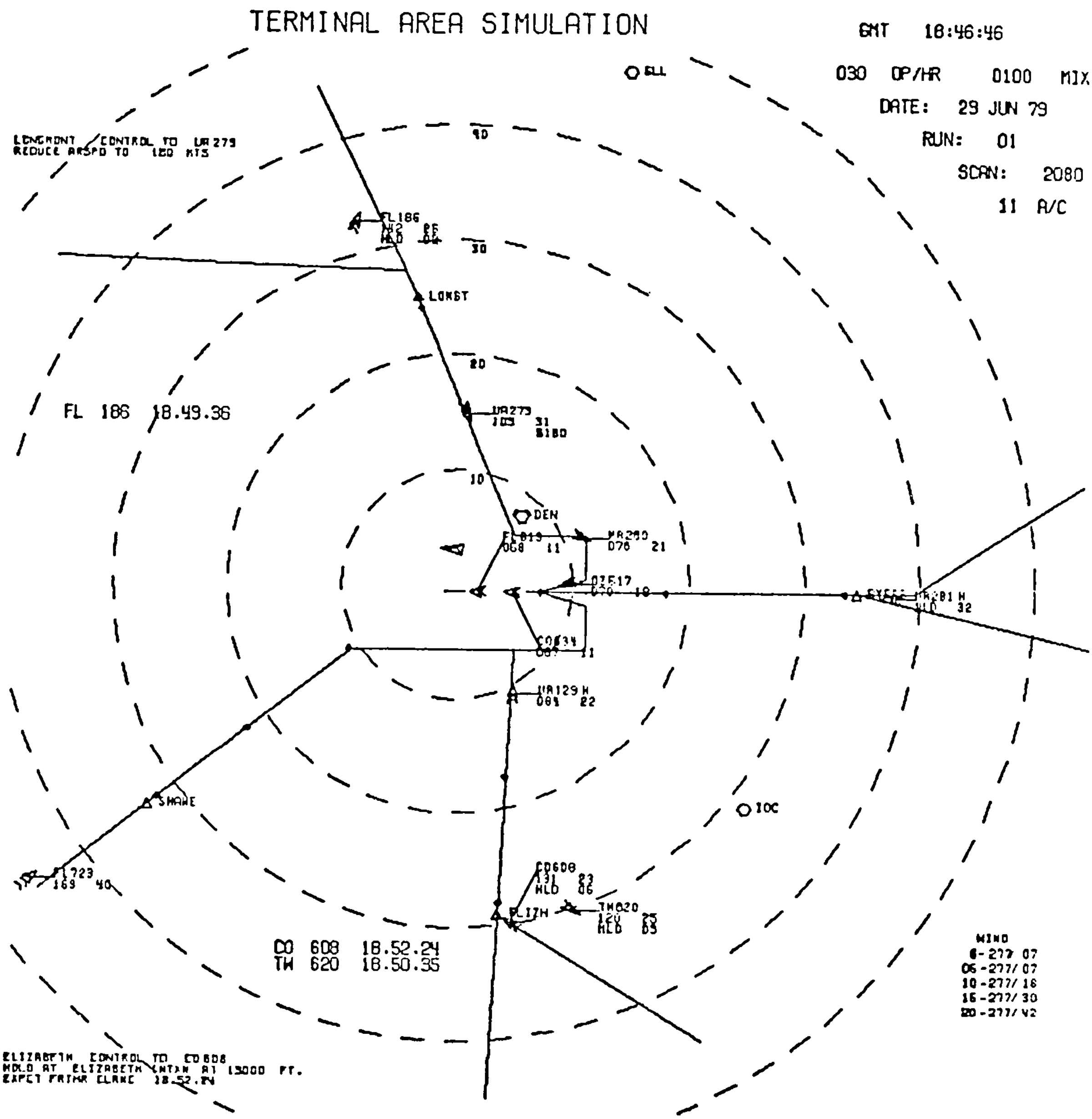



Figure 10.- Example of TAATM simulated controller display.

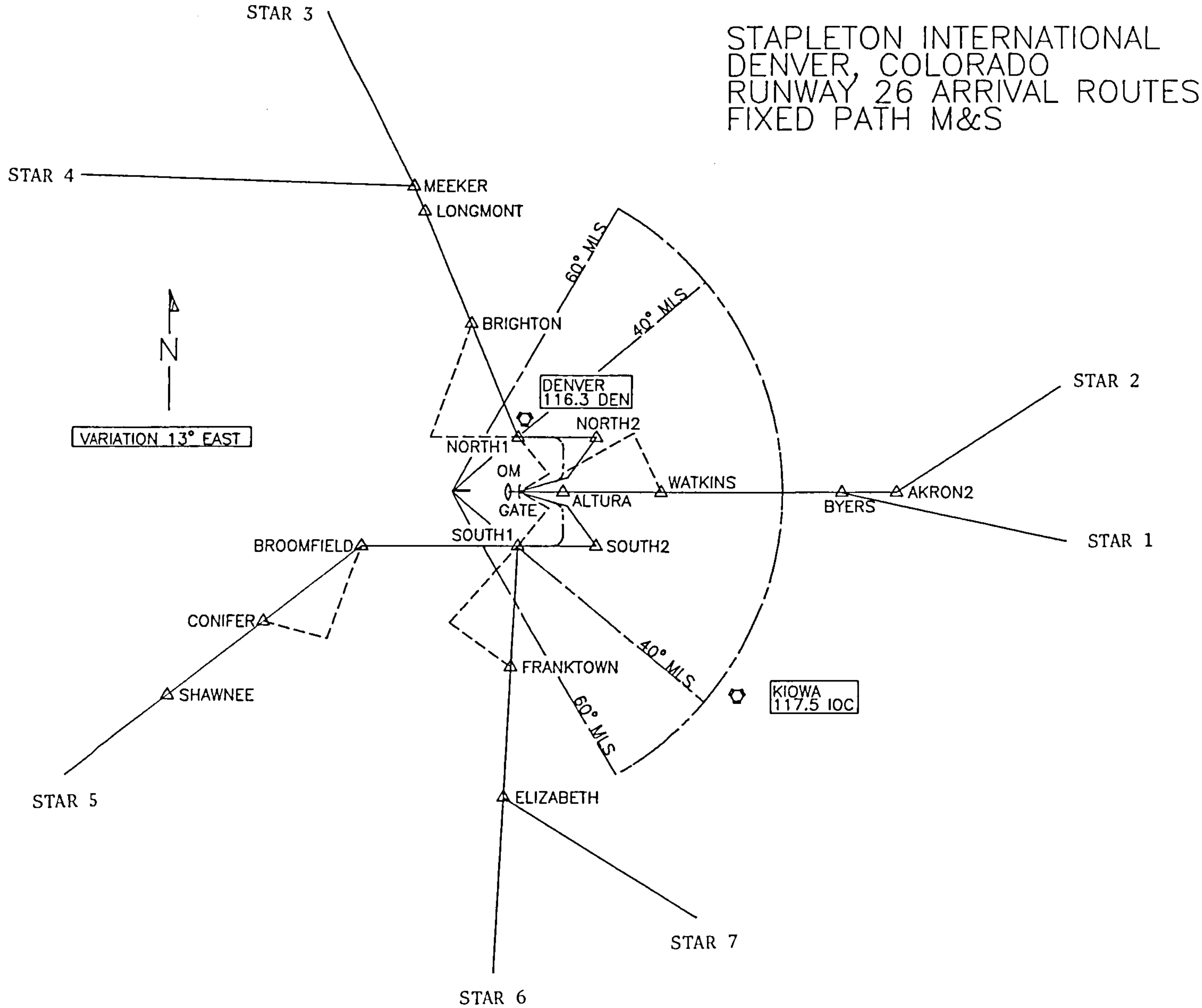



Figure 11.- Simulated terminal area for Stapleton International Airport, Denver, Colorado.

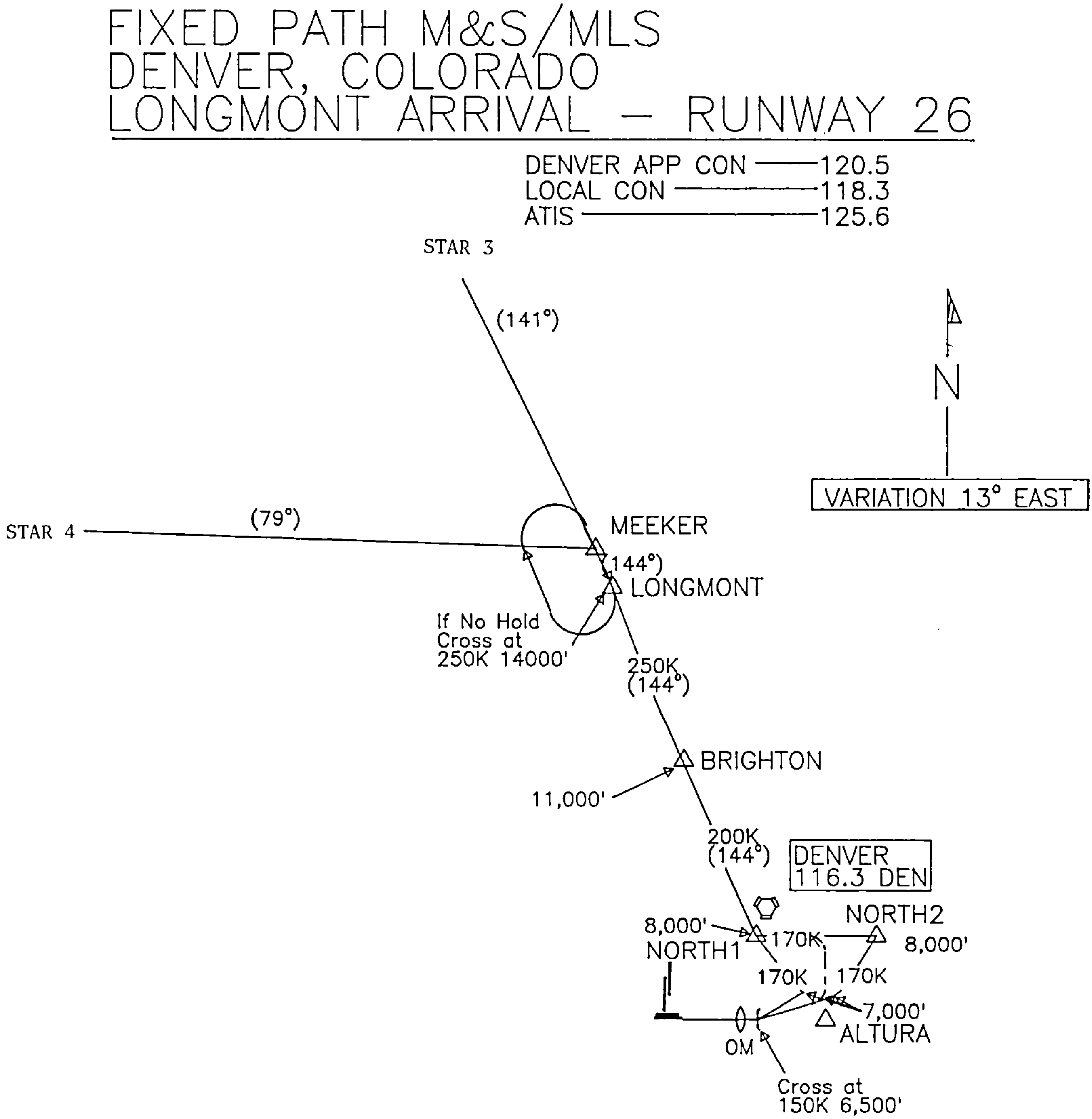



Figure 12.- Pilot's navigation chart for LONGMONT STAR's.

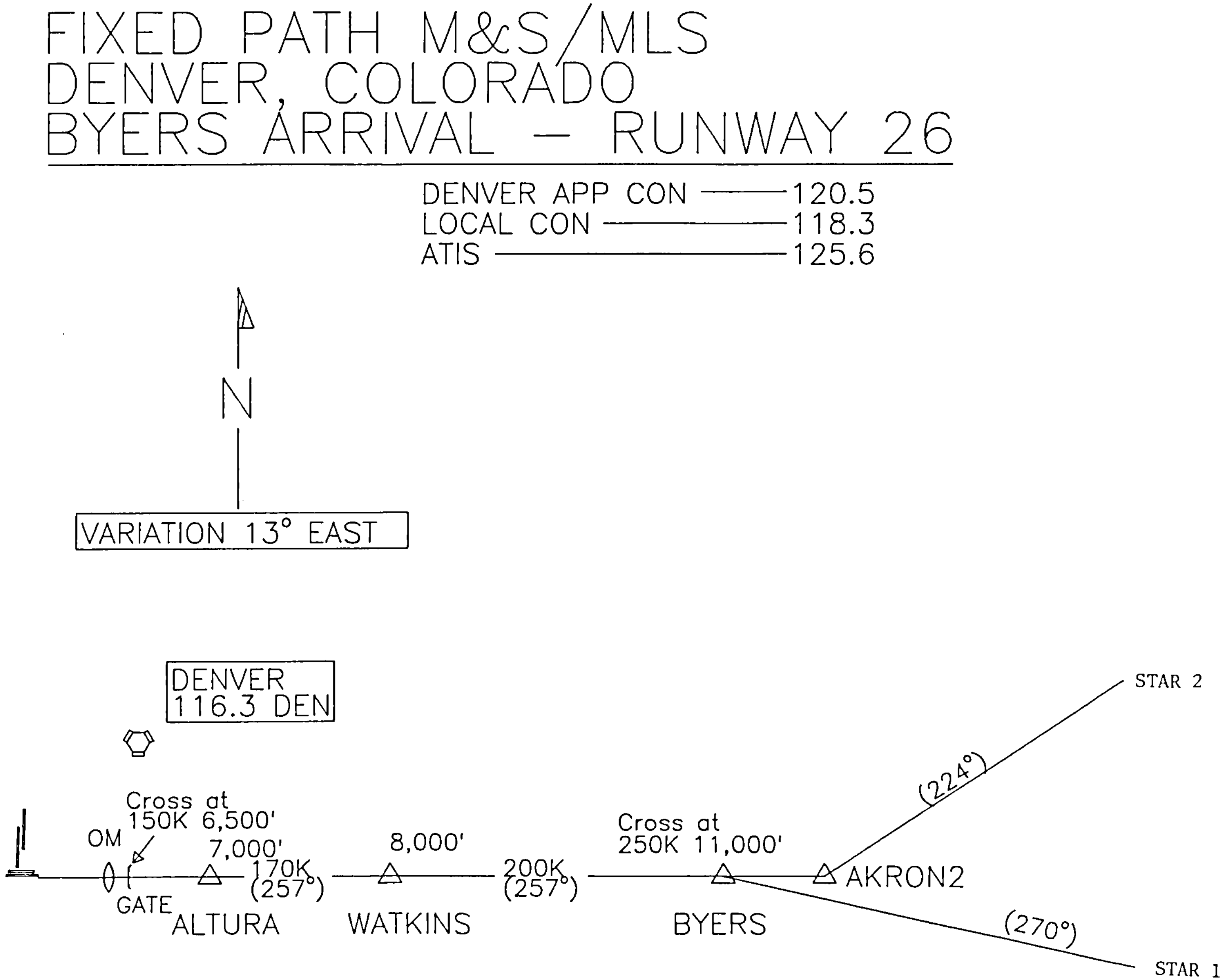



Figure 13.- Pilot's navigation chart for BYERS STAR's.

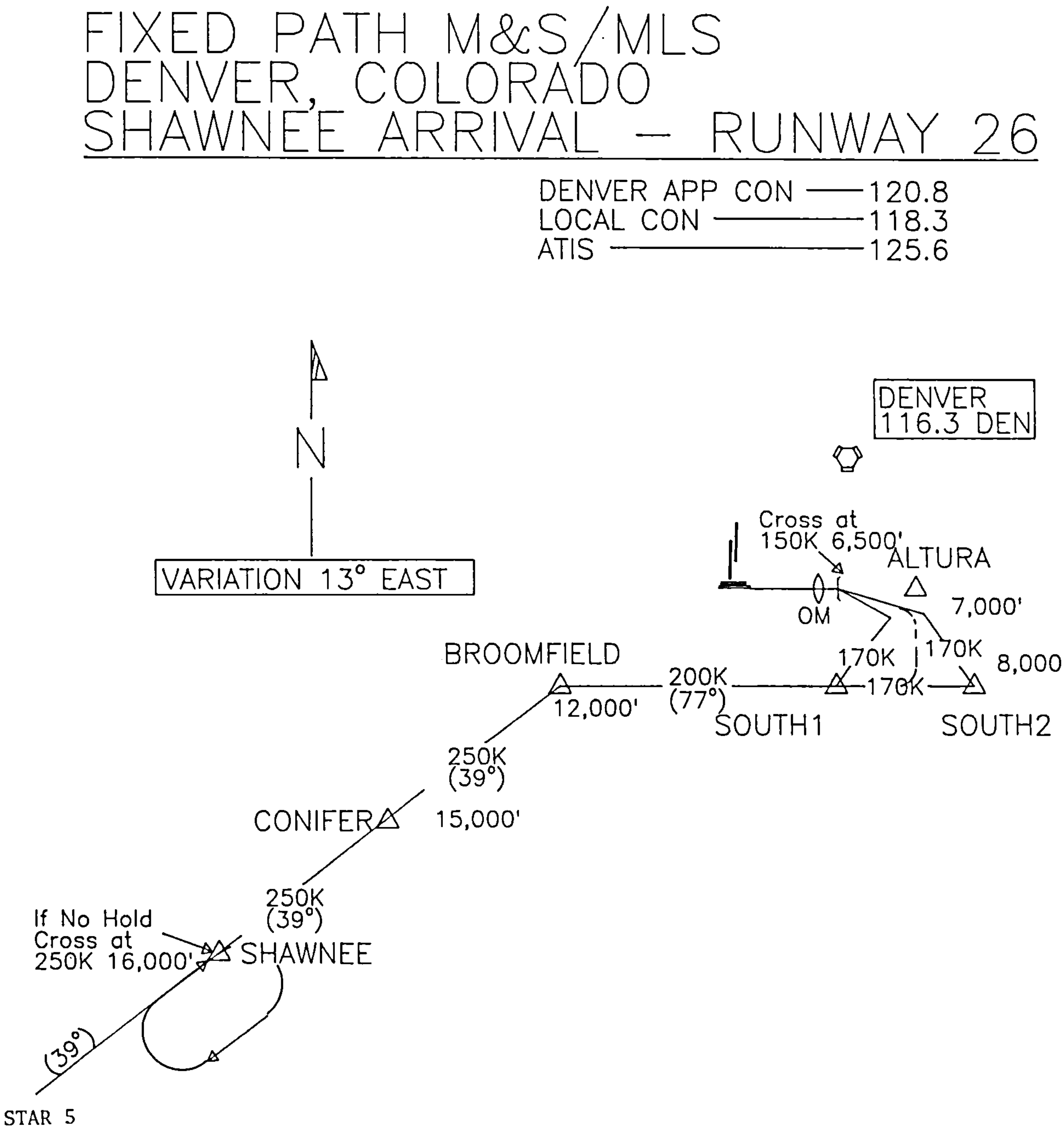



Figure 14.- Pilot's navigation chart for SHAWNEE STAR.

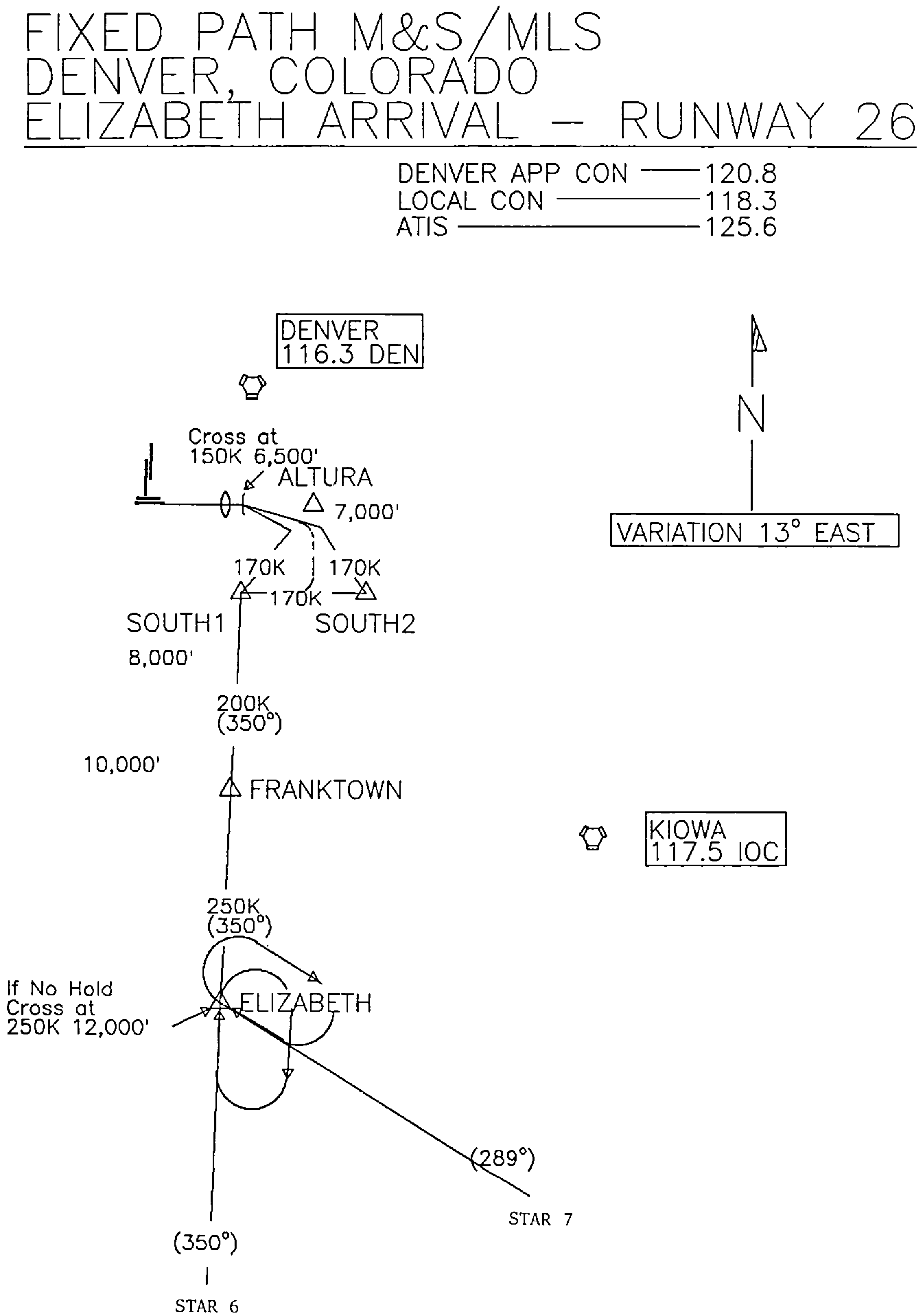



Figure 15.- Pilot's navigation chart for ELIZABETH STAR's.

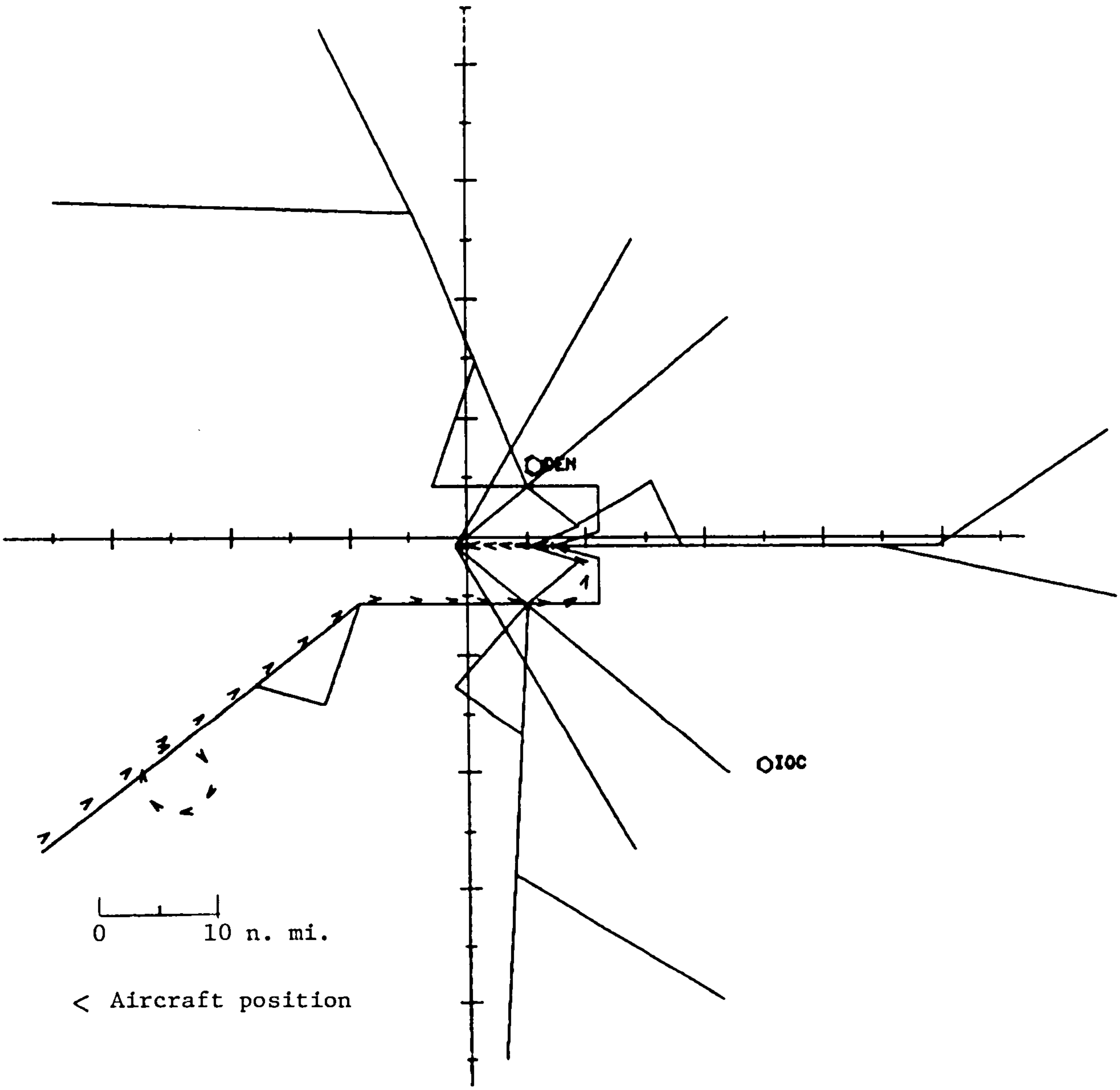



Figure 16.- Typical flight ground track for SHAWNEE STAR.

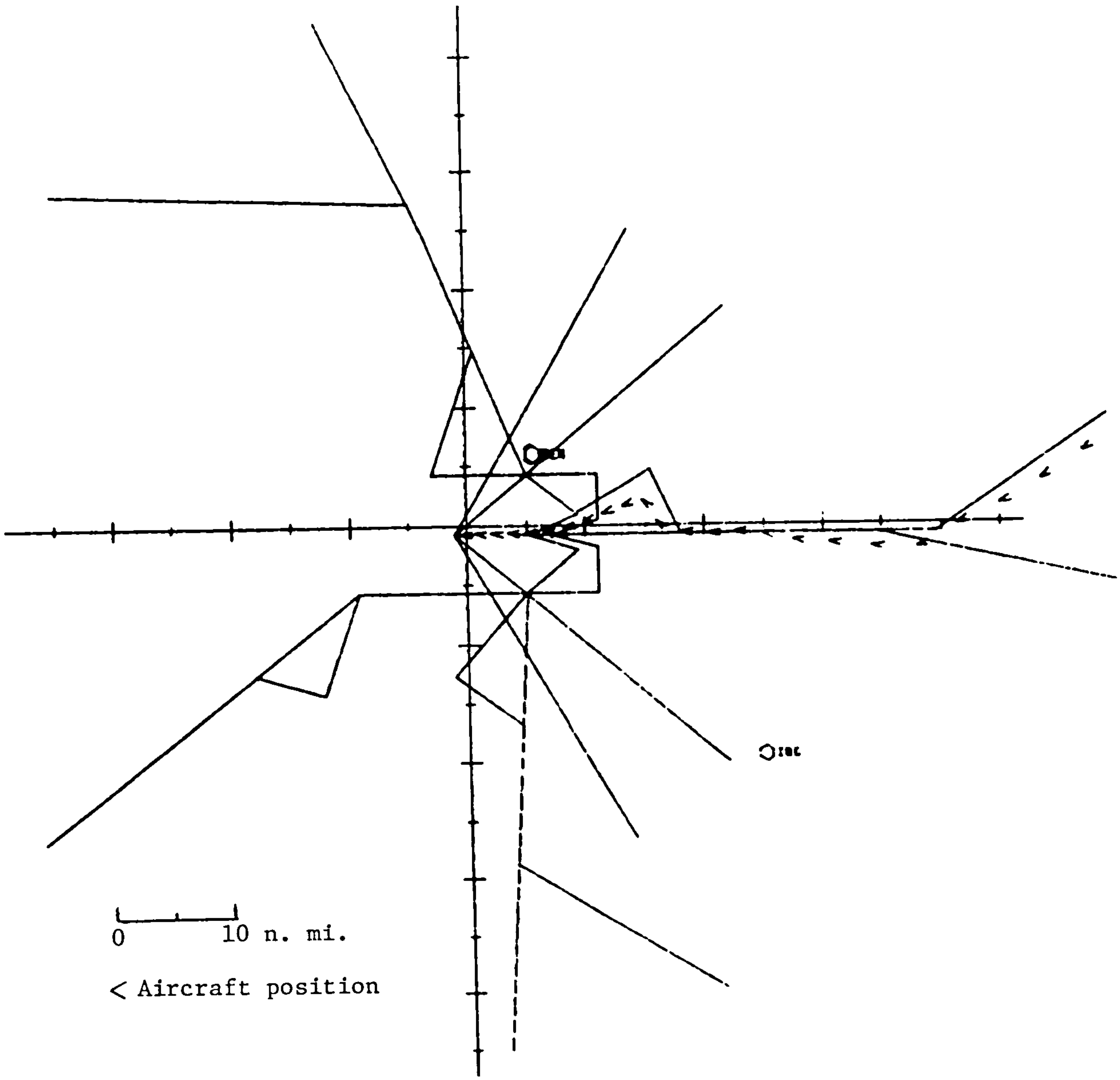



Figure 17.- Typical flight ground track for BYERS STAR.

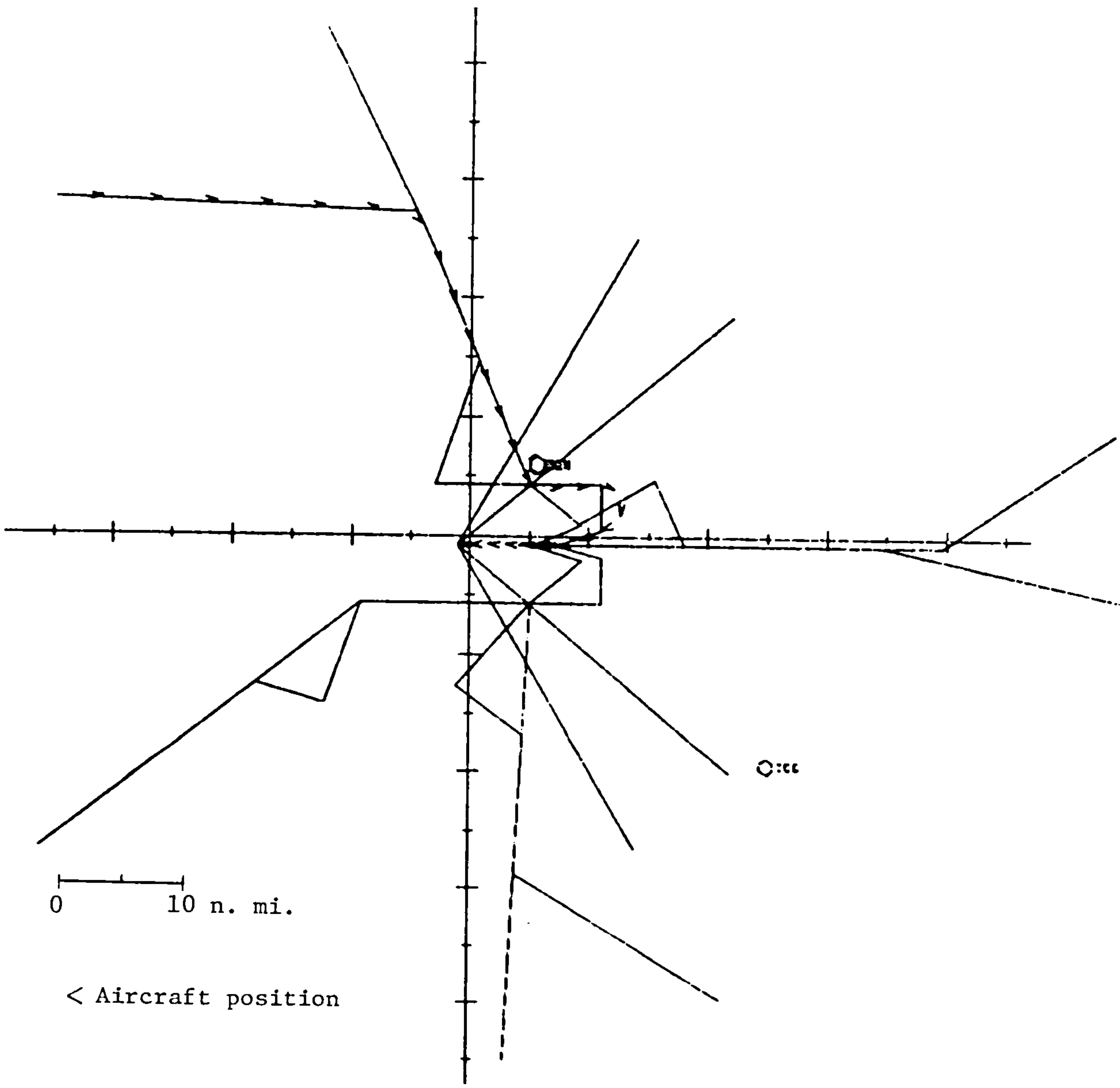



Figure 18.- Typical flight ground track for LONGMONT STAR.

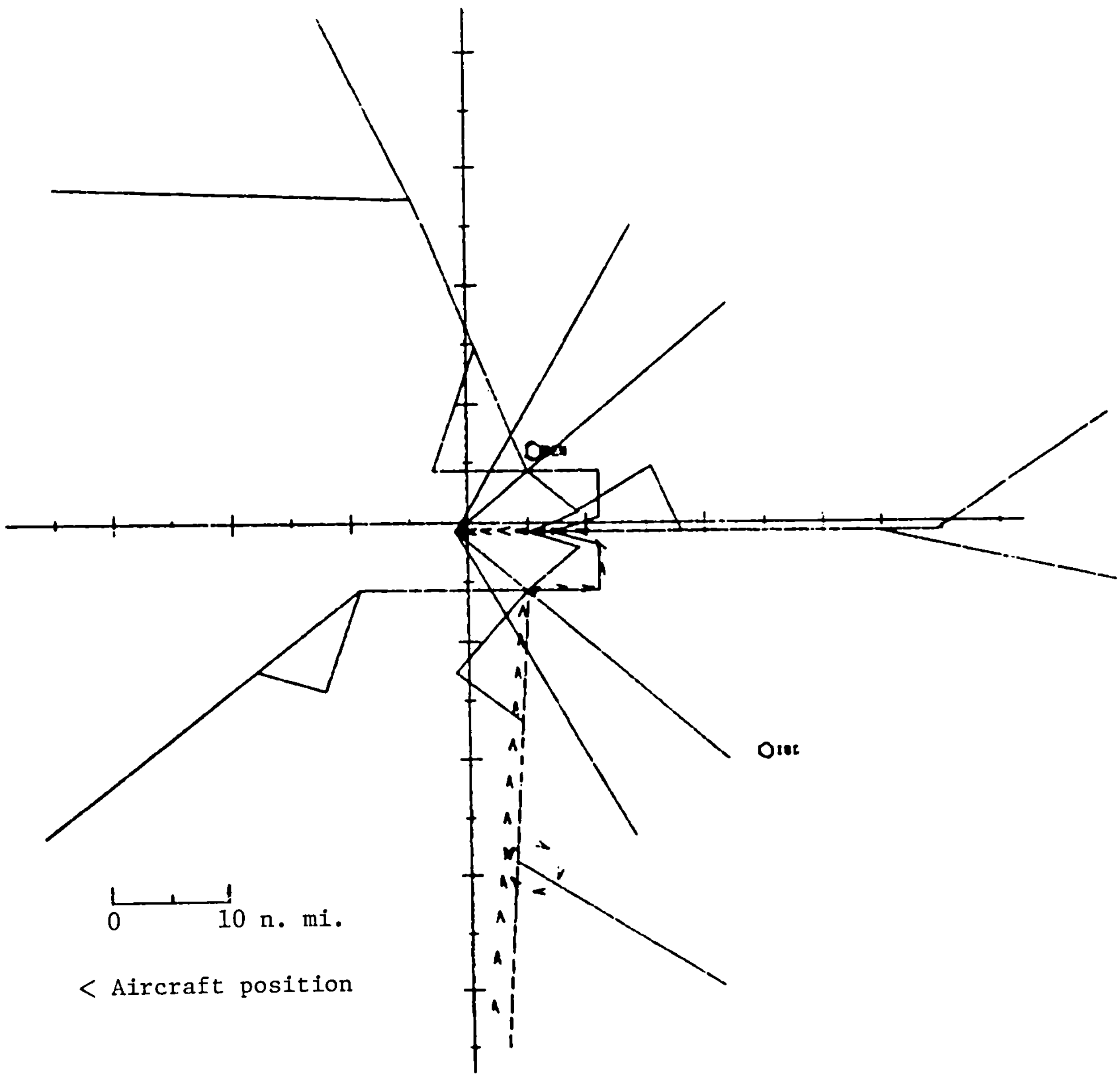
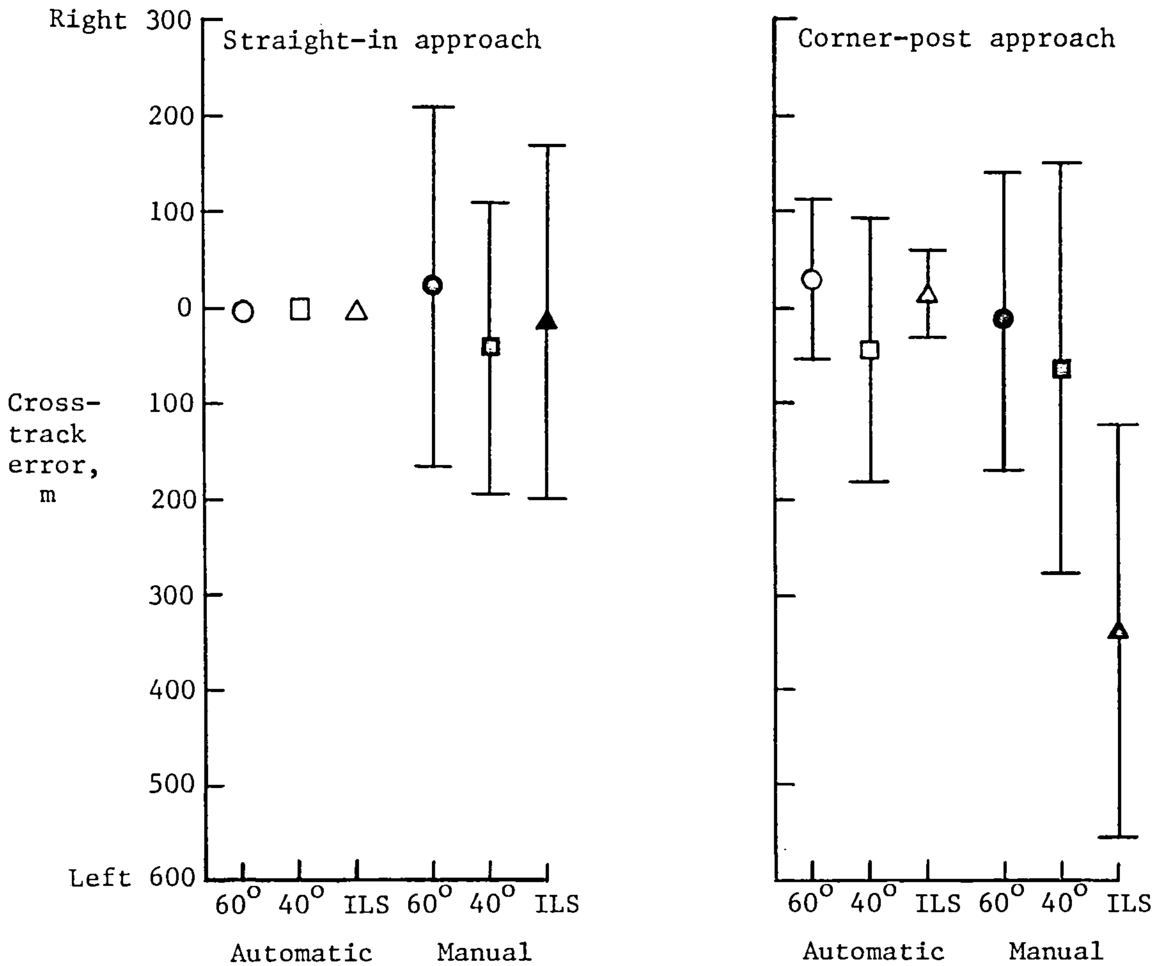
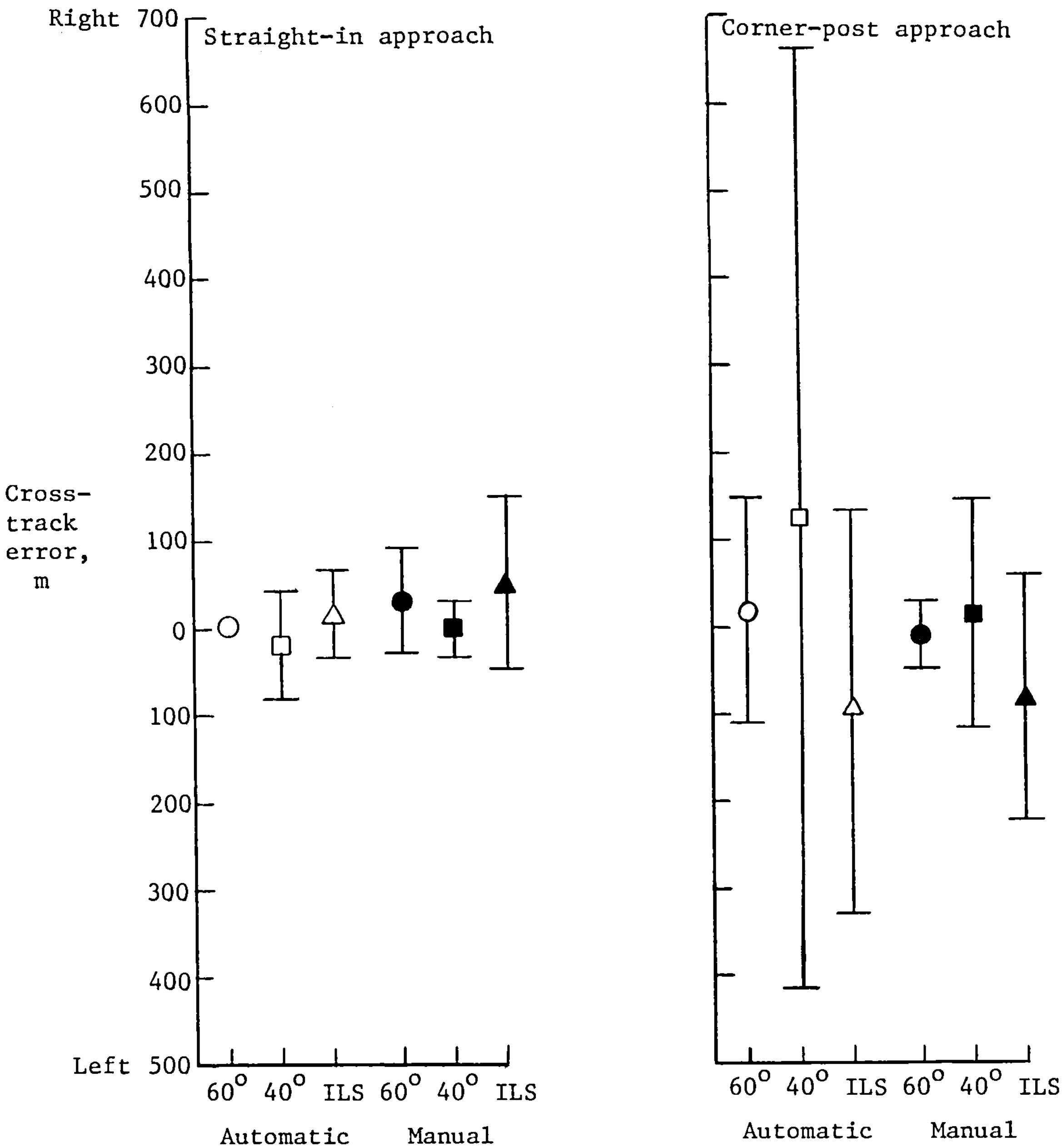



Figure 19.- Typical flight ground track for ELIZABETH STAR.



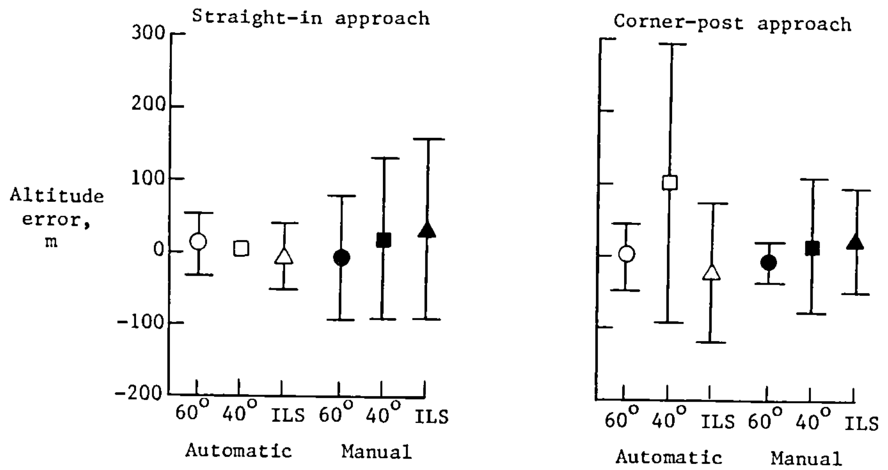

(a) Waypoint II.

Figure 20.- Means and standard deviations for terminal area cross-track error.

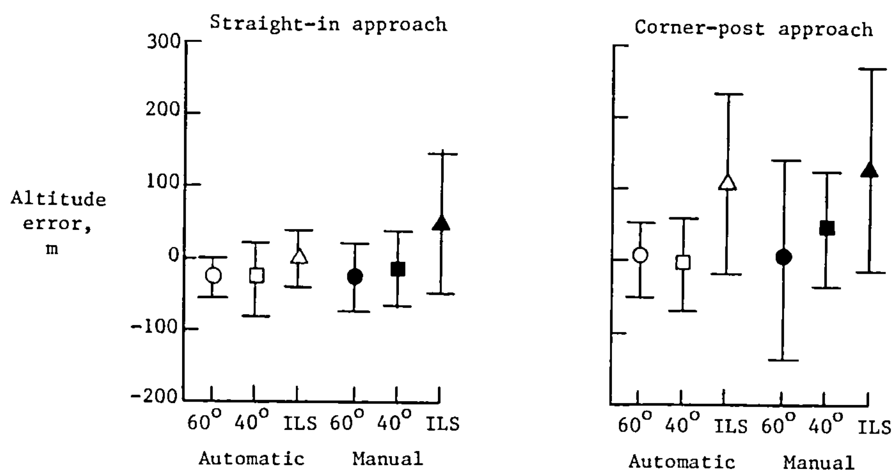



(b) Waypoint IV.

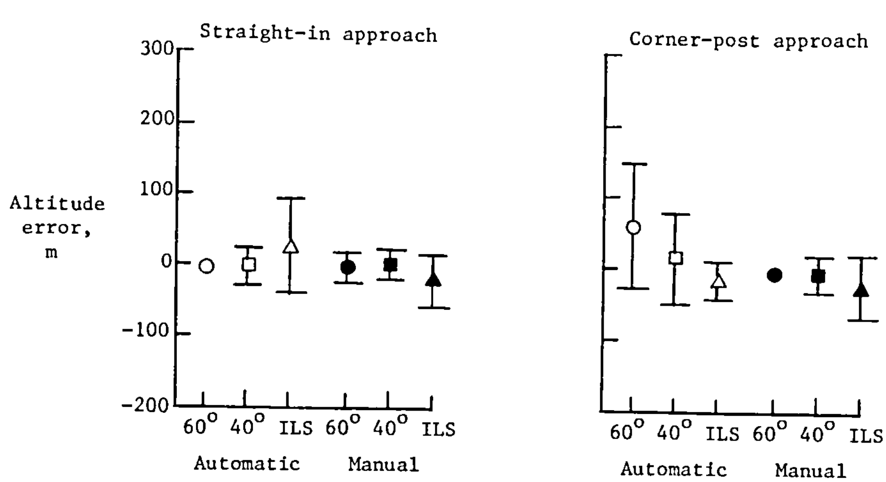
Figure 20.- Concluded.




(a) Waypoint II.

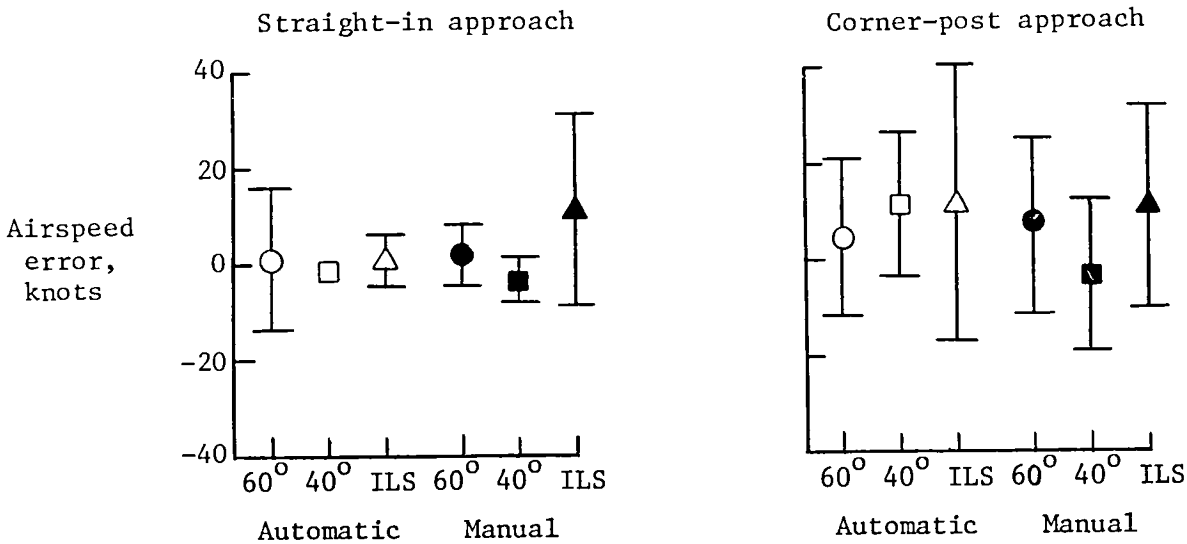



(b) Waypoint III.

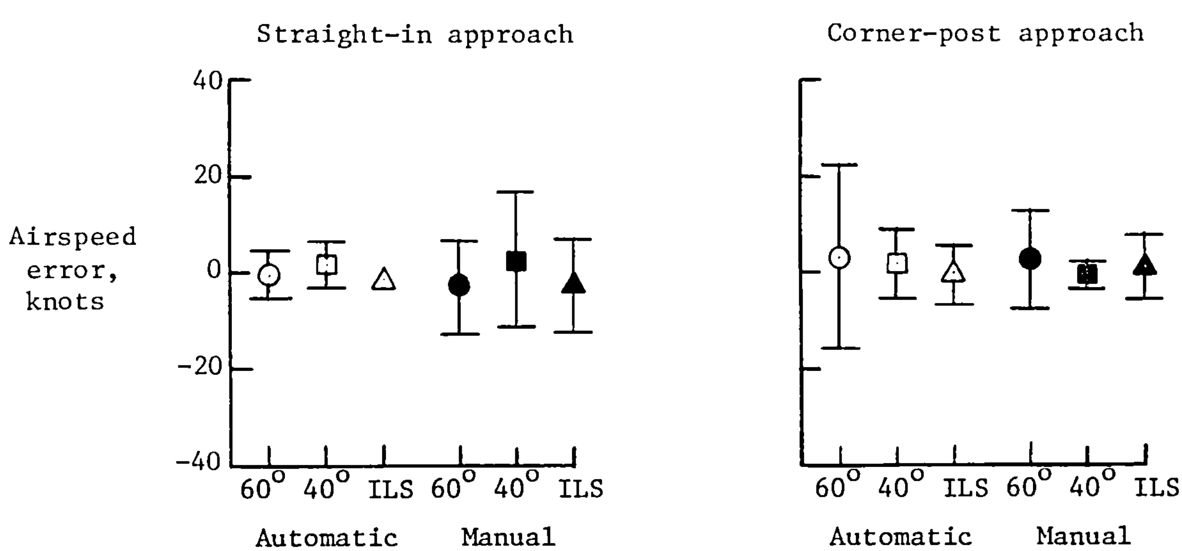



(c) Waypoint IV.

Figure 21.- Means and standard deviations for terminal area altitude error.

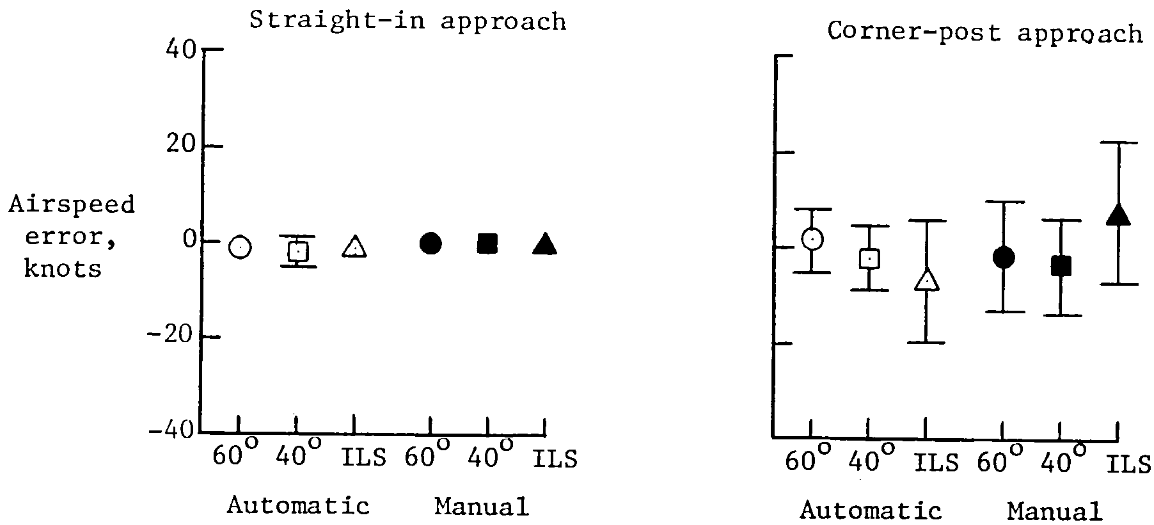



(a) Waypoint I.

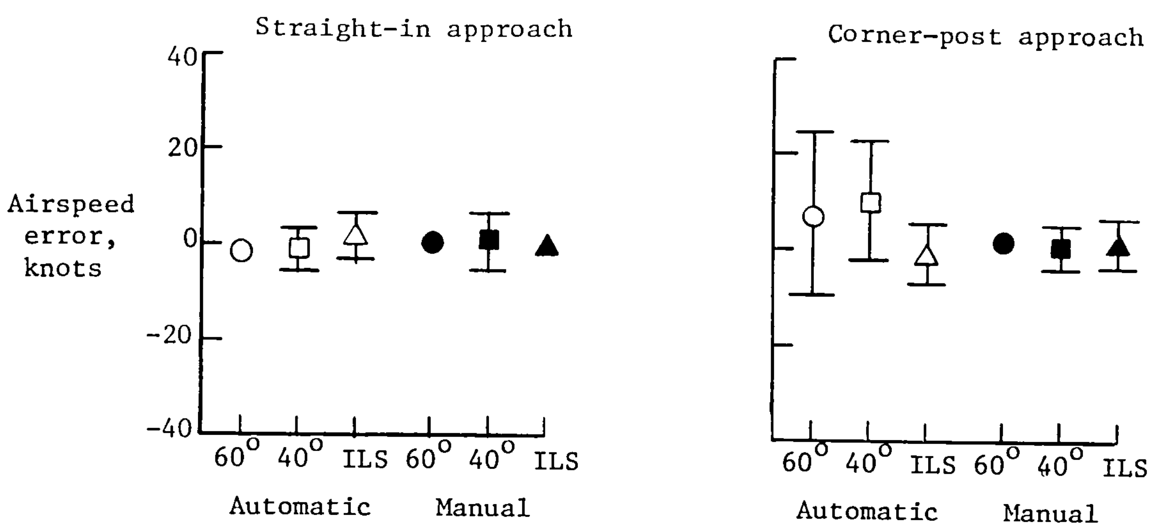



(b) Waypoint II.

Figure 22.- Means and standard deviations for terminal area airspeed error.




(c) Waypoint III.




(d) Waypoint IV.

Figure 22.- Concluded.

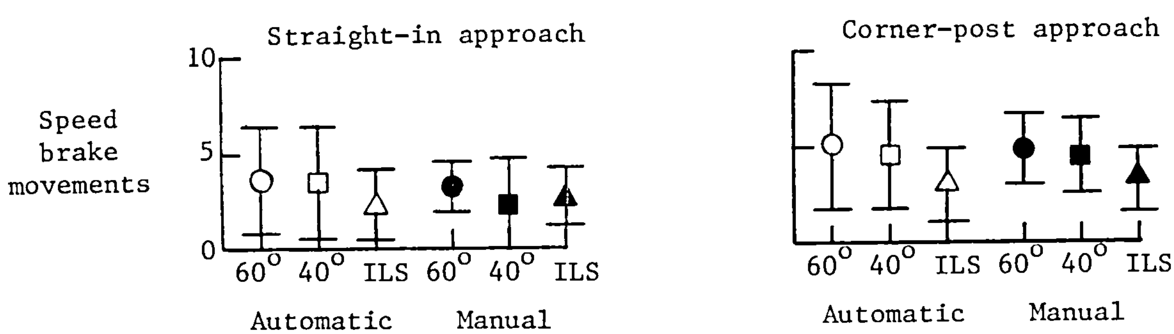



Figure 23.- Means and standard deviations for terminal area speed brake movement.

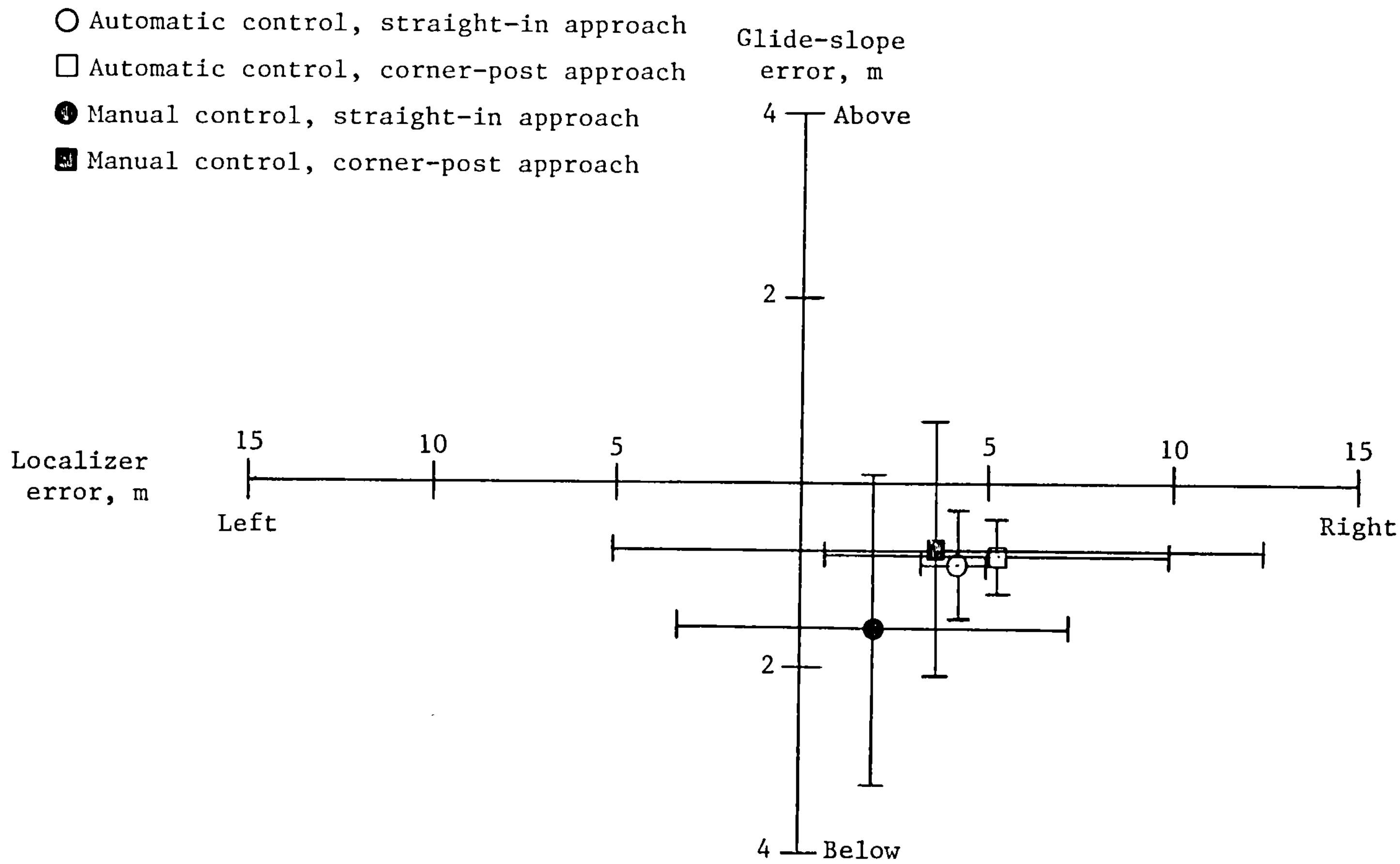



Figure 24.- Means and standard deviations for glide-slope and localizer errors at the 30.5-m (100.0-ft) altitude window.

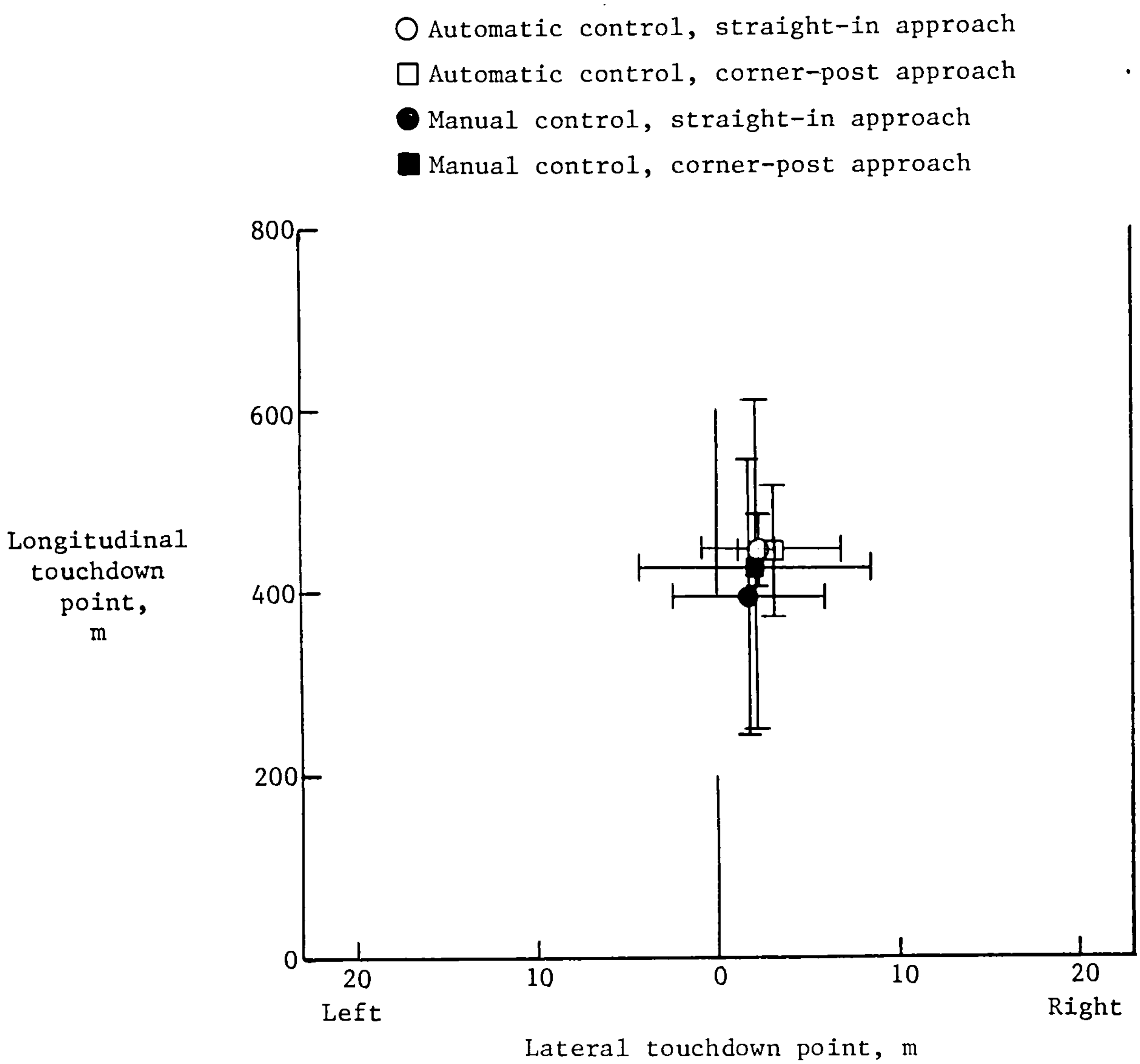



Figure 25.- Means and standard deviations for runway touchdown footprint.

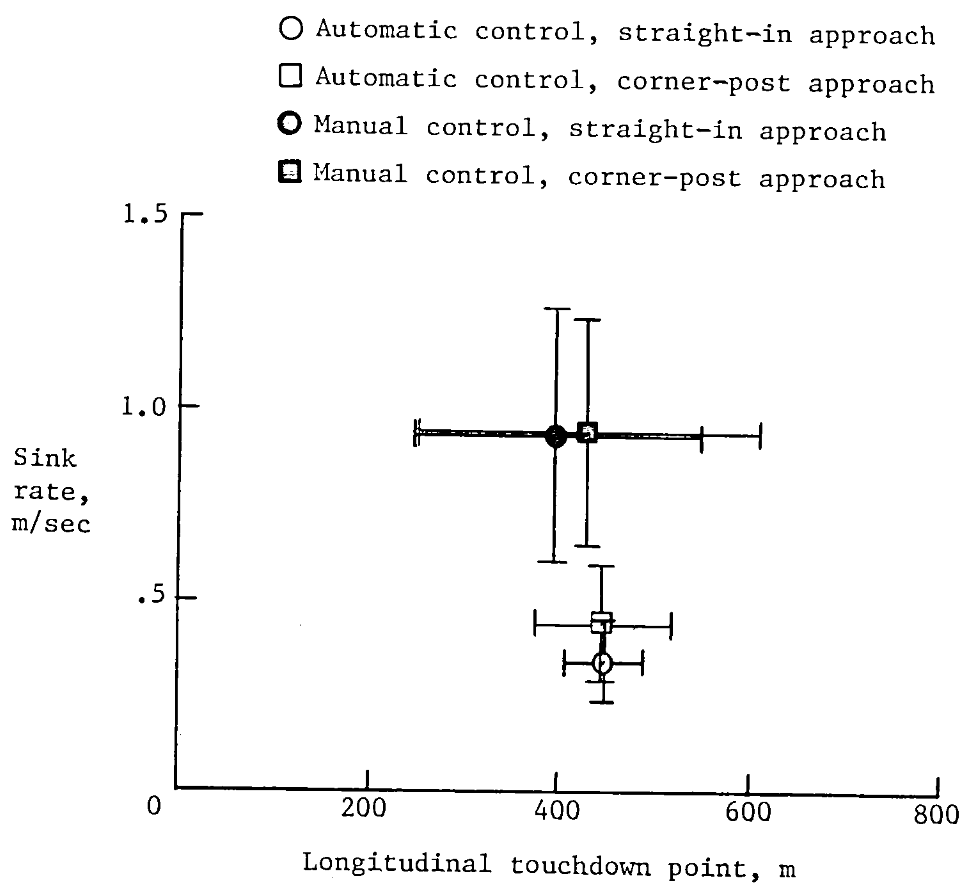



Figure 26.- Means and standard deviations for sink rate at touchdown.

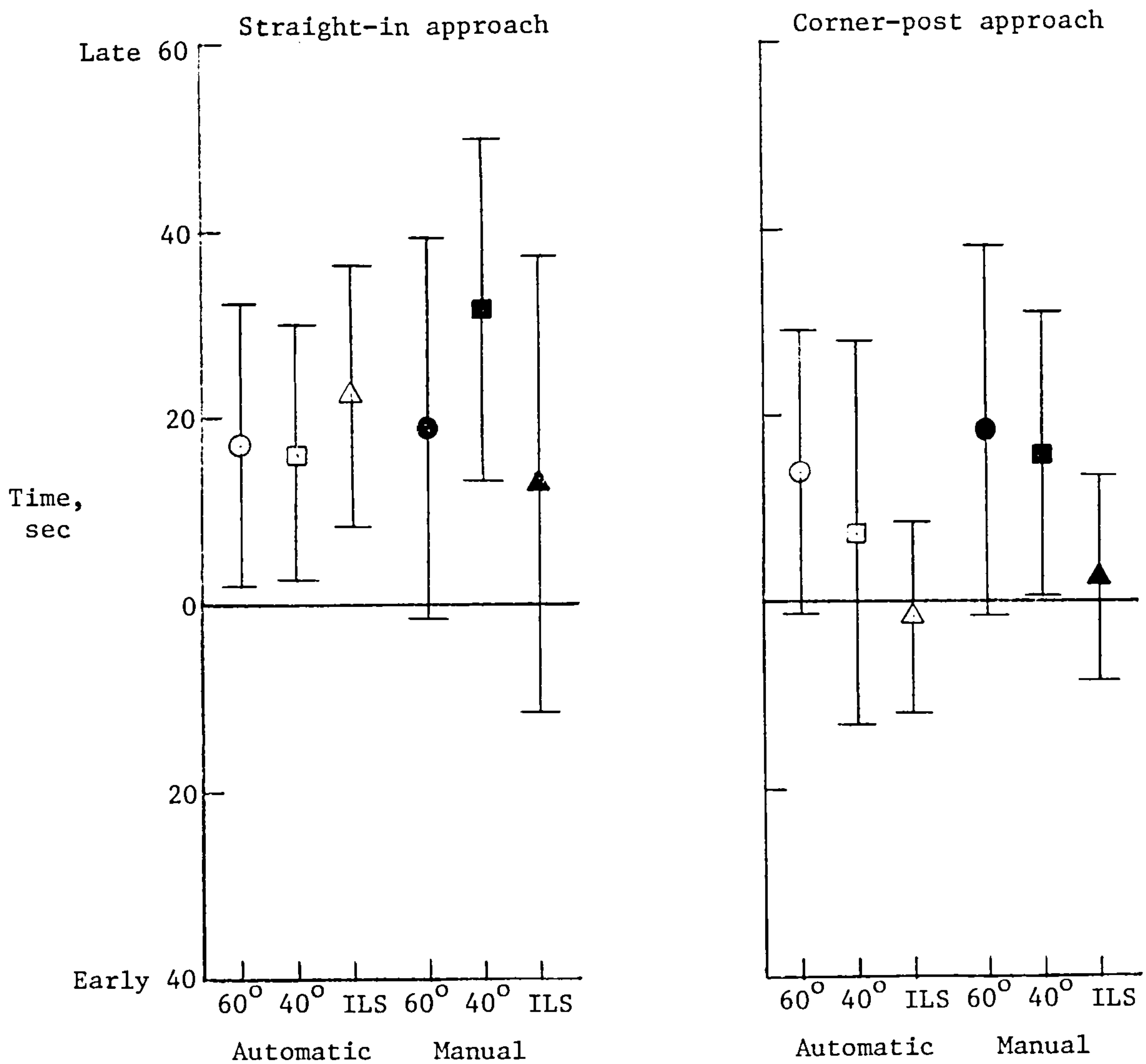
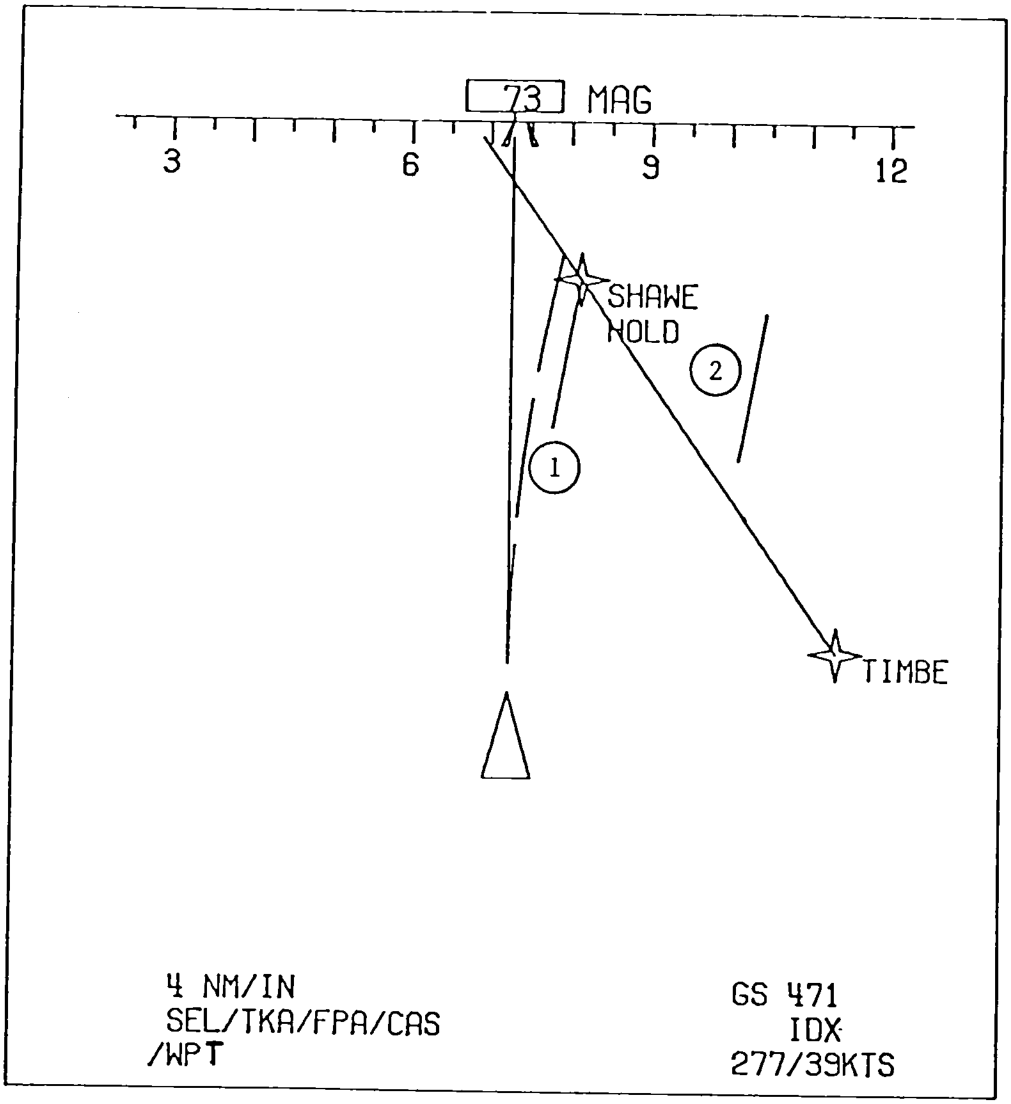



Figure 27.- Means and standard deviations for arrival-time error at the initial arrival fix.




(1) Curved trend vector

(2) Holding pattern

Figure 28.- Holding-pattern and curved-trend-vector symbols for the electronic horizontal situation indicator.

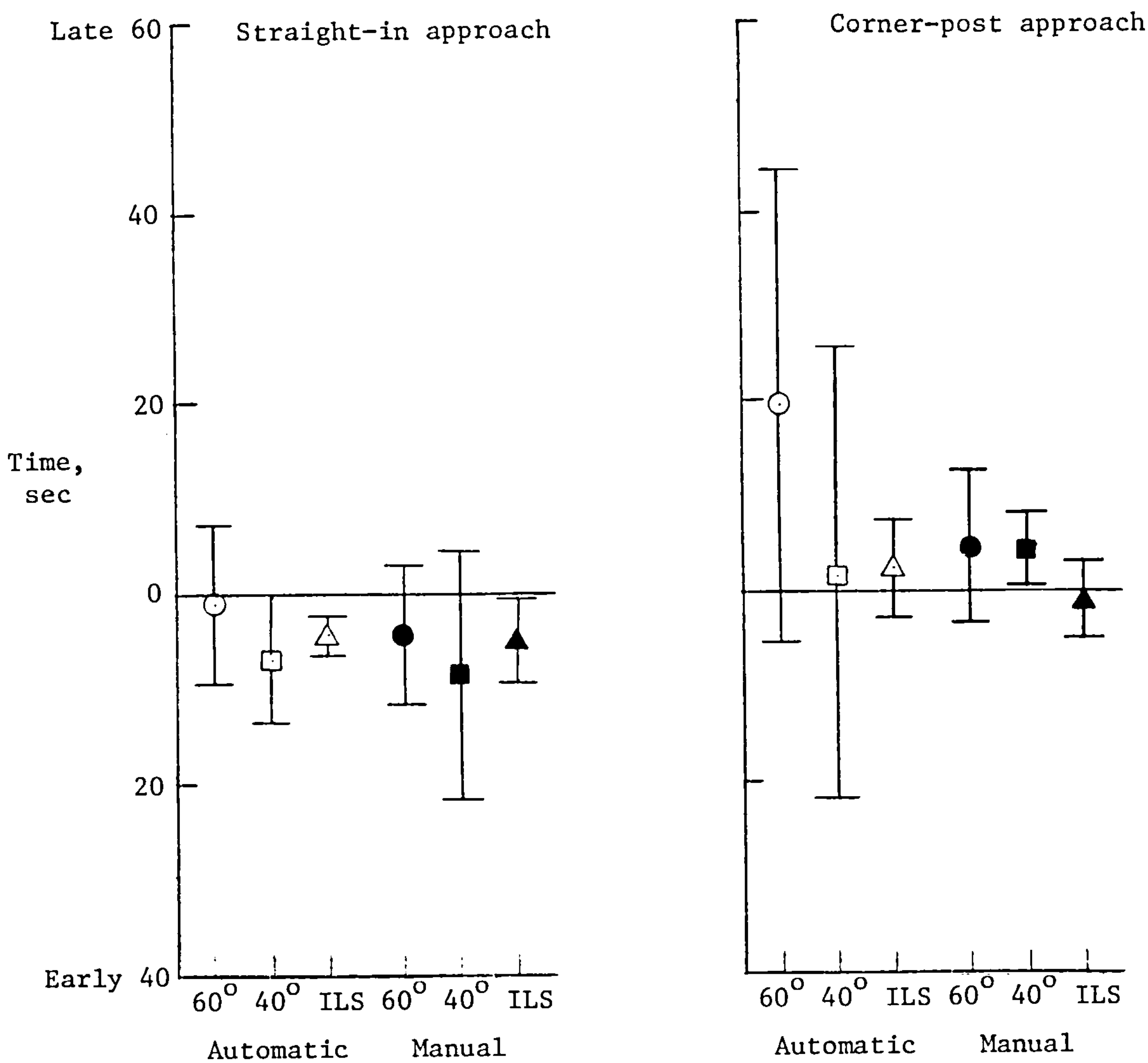



Figure 29.- Means and standard deviations for outer-marker arrival-time error.

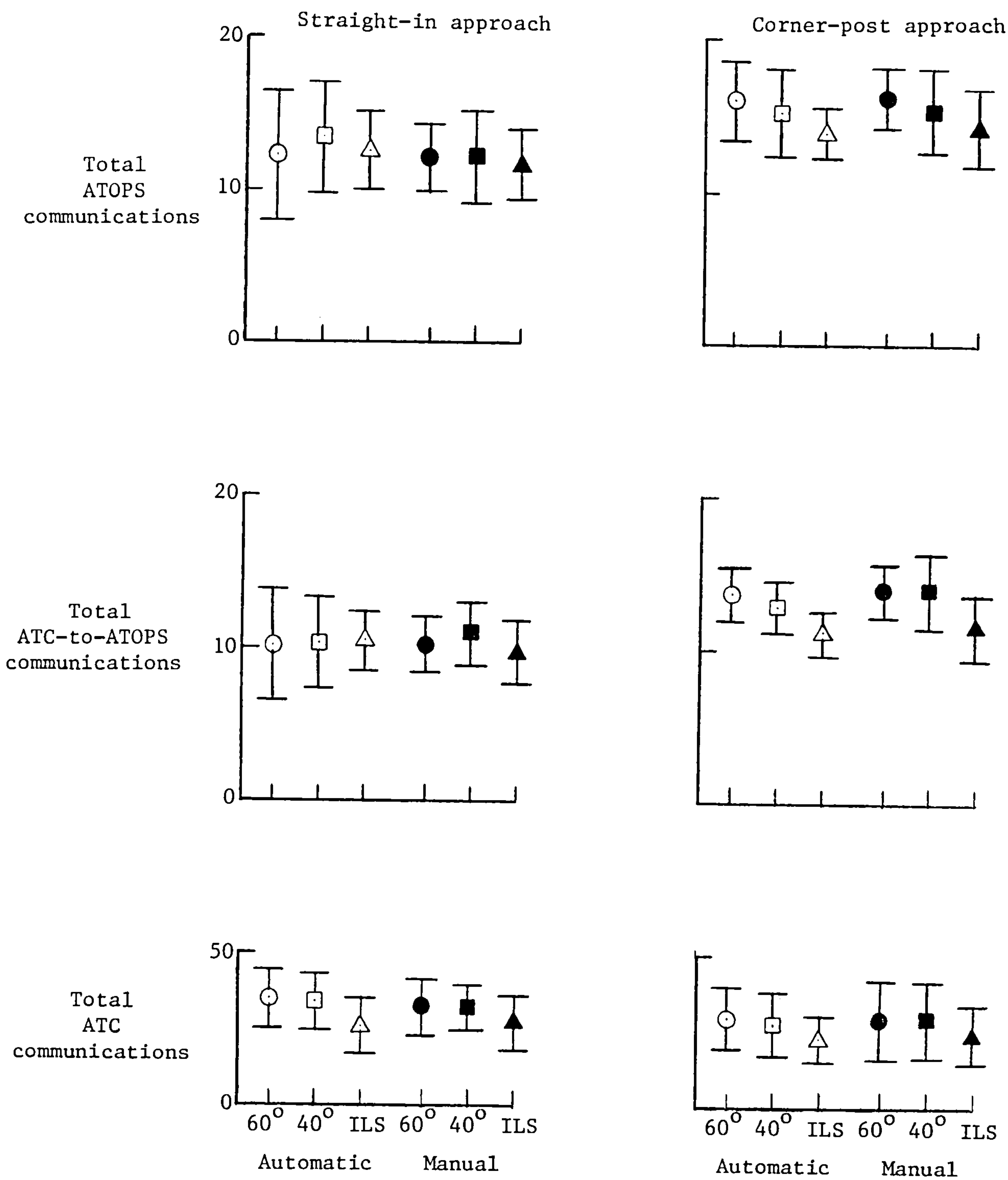



Figure 30.- Means and standard deviations for voice communication results.

| 1. Report No. | 2. Government Accession No. | 3. Recipient's Catalog No. |
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| NASA TM-84610 | | |

| 4. Title and Subtitle | 5. Report Date |
|---|---|
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16. Abstract

This report describes a simulation study assessing crew performance operating an advanced transport aircraft in an automated terminal area environment. The study required the linking together of the Langley Advanced Transport Operating Systems Aft Flight Deck Simulator with the Terminal Area Air Traffic Model Simulation. This provided the realism of an air traffic control (ATC) environment with audio controller instructions for the flight crews and also provided the capability of inserting a "live" aircraft into the terminal area model to interact with computer-generated aircraft. The study assessed crew performance using the advanced displays and two separate control systems (automatic and manual) in flying area navigation routes in the automated ATC environment. Although the crews did not perform as well using the manual control system, their performances were within acceptable operational limits with little increase in workload. This is important because the crews favored using the manual control system and felt they were more alert and aware of their environment when using it.

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