NASA Contractor Report 4450

Evaluation of Microwave Landing System Approaches in a Wide-Body Transport Simulator

L. G. Summers and J. B. Feather

CONTRACT NAS1-18028
JUNE 1992

NASA

NASA Contractor Report 4450

Evaluation of Microwave Landing System Approaches in a Wide-Body Transport Simulator

L. G. Summers and J. B. Feather
Douglas Aircraft Company
McDonnell Douglas Corporation
Long Beach, California

Prepared for
Langley Research Center
under Contract NAS1-18028

NASA

National Aeronautics and
Space Administration

Office of Management

Scientific and Technical
Information Program

1992

ACKNOWLEDGMENTS

The successful completion of this study involved a number of persons, and it is impossible to acknowledge all of them individually. Foremost, the authors would like to thank the flight crews from the airlines, the FAA, and Douglas Aircraft for their participation in this program. Without these flight crews, there would not be any results.

The authors would like to thank Barry Billmann and Christopher Wolf of the FAA Technical Center and Dr. Charles Knox of NASA-Langley Research Center for their technical direction and assistance throughout the study. The authors would like to thank Captains Joe Oliver of ALPA and Wally Gilman of American Airlines for their critique and assistance during the checkout phase of the study.

Special thanks go to the many people who assisted during the performance of the study. This includes Pete Hammontre and other personnel of the Crew Station Simulation Laboratory at Douglas for their development of the simulation and support throughout the study, personnel from the FAA Technical Center for their role as observers, and personnel of the Crew Systems Technology Group at Douglas for their participation in the design and conduct of the test program.

SUMMARY

The objective of the study was to determine the suitability of flying complex curved approaches using the microwave landing system with a wide-body transport aircraft. Fifty pilots in crews of two participated in the evaluation using a fixed base simulator that emulated an MD-11 aircraft. Five approaches — a straight-in approach and four curved approaches — were flown by the pilots using a flight director.

The test variables included (1) manual and autothrottles, (2) wind direction, and (3) type of navigation display. The navigation display was either a map or a horizontal situation indicator (HSI). A complex wind that changed direction and speed with altitude and included moderate turbulence was used. Visibility conditions were Category I or better.

Subjective test data included pilot responses to questionnaires and pilot comments. Objective performance data included tracking accuracy, position error at decision height, and control activity. Results of the evaluation indicate that flying curved MLS approaches with a wide-body transport aircraft is operationally acceptable depending upon the length of the final straight segment and the complexity of the approach.

CONTENTS

CONTENTS
(Continued)

FIGURES

FIGURES
(Continued)

TABLES

LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS

AGL	Above Ground Level
ALPA	Airline Pilots Association
ANOVA	Analysis of Variance
ATA	Air Transport Association
ATD	Along Track Distance
CDI	Course Deviation Indicator
DEC	Digital Equipment Corporation
DME/P	Precision Distance Measurement Equipment
EAD	Engine and Alert Display
FAA	Federal Aviation Administration
FAF	Final Approach Fix
FD	Flight Director
FMS	Flight Management System
G/S	Glide Slope
HSI	Horizontal Situation Indicator
LOC	Localizer
LTCP	Last Turn Completion Point
MCDU	Multifunction Control Display Unit
MLS	Microwave Landing System
MOPS	Minimum Operational Performance Standards
NASA	National Aeronautics and Space Administration
ND	Navigation Display
NLR	National Aerospace Laboratory (Netherlands)
PFD	Primary Flight Display
RMS	Root Mean Square
VASI	Vertical Approach Slope Indicator
VFA	Visual Flight Attachment

SECTION 1
INTRODUCTION

1.1 BACKGROUND

The Federal Aviation Administration (FAA) has undertaken a multiproject program to identify and evaluate both economic and technical benefits of the microwave landing system (MLS). An overall objective of this program is to demonstrate that the MLS increases airport capacity, reduces air traffic controller workload, improves noise abatement, and results in more efficient air traffic operations in the terminal area. This multiproject program is to provide the basis for implementating the MLS. The program was initiated in 1989.

As part of this program, a wide-body simulator evaluation was conducted by Douglas Aircraft Company using a fixed-base engineering simulator. This simulator was configured to represent an MD-11 aircraft with CRT displays. This program augments prior (Reference 1) and current simulation studies performed at the National Aerospace Laboratory (NLR) of the Netherlands on a research flight simulator that is programmed to simulate a 747-200 aircraft. Although the objectives of both evaluations were the same, there were some basic differences in the evaluations:

1. The NLR simulator employed a motion base with a general-purpose cockpit, and the Douglas simulator utilized a fixed base with an emulated MD-11 cockpit.
2. Individualized MLS guidance algorithms were developed for each study.
3. There were differences in the course deviation indicator's sensitivity.
4. There were differences in the complexity of the approaches.
5. There were differences in the contingencies that were simulated.

A test plan for the Douglas study was developed with inputs from the FAA Technical Center at Atlantic City, NJ, and the National Aeronautics and Space Administration (NASA) at Langley, VA. Prior to the formal tests, the simulator handling qualities were reviewed by MD-11 engineering test pilots and an FAA MD-11 certification pilot. Representatives of the Air Transport Association (ATA) and the Airlines Pilot's Association (ALPA) reviewed the simulator, test scenarios, briefing procedures, data collection methodology, and the questionnaires. All pertinent issues that these individuals raised were resolved prior to initiation of the formal tests.

This report describes the test methodology, reviews the subjective pilot responses and the objective performance data, and presents conclusions drawn from the results. The findings will be used as a partial fulfillment of the FAA's program objectives.

1.2 OBJECTIVE OF CURRENT STUDY

The objective of the study was to evaluate the suitability of selected approach paths that are designed to take full advantage of the MLS capabilities. This objective includes evaluating guidance concepts for lateral path control and vertical descent profiles. In addition, display formats dedicated to MLS approaches were implemented and evaluated. To meet these objectives, a test plan was formulated in which 25 two-man flight crews flew a total of 600 approaches. Both subjective and objective data were collected and analyzed during the course of the evaluation.

SECTION 2
SIMULATOR DESCRIPTION

2.1 GENERAL

The fixed-base simulator consists of a DC-10 cockpit shell with six-across CRT displays, a hydraulically driven control wheel and column, functional secondary flight controls, back-driven autothrottles, a glareshield flight control panel, and an outside visual scene.

The layout of the cockpit is shown in Figure 2-1. The CRT displays were six-across, 8- by 8-inch Xytron tubes programmed by a Silicon Graphics computer. Three display generators were used for generating the primary flight, navigation, and engine displays. The navigation display had two modes — the map mode and the approach mode (the horizontal situation indicator). The displays on the right side

Figure 2-1. Fixed-Base Research and Development Simulator

were duplicates of those on the left side, which did not allow the alternate navigation display formats to be shown at the same time. Switches were provided on the forward pedestal to change the range of the map mode. A flat panel display was installed in the center of the forward pedestal to emulate the flight management system (FMS) multifunction control display unit (MCDU) display. The flight plan (or legs) page was displayed on this unit. The glareshield's flight control panel was partially operational in that the speed preselect and select control and the speed window were active. This allowed the flight crew to select the speed in the autothrottles mode and the speed bug on the primary flight display.

A McFadden hydraulic force wheel and column system was provided on the left side of the cockpit. This unit allowed programmable forces to be computer controlled in both the pitch and roll axes to simulate the force loading of a wide-body aircraft. Rudder pedals and toe brakes were provided with passive springs. The throttles were servo driven by a dc stepper motor. The dynamic characteristics of the autothrottles back drive were computer controlled. The secondary flight controls, flap/slat, and spoiler handles were components from a DC-10 pedestal.

The out-of-the-window display used a rear projection screen placed 8 feet from the pilot's eyes. The display can be viewed from the left side of the cockpit. The forward visual image is generated by a Redifon Visual Flight Attachment (VFA) consisting of a terrain board, a servo-driven color television camera system and associated electronics and lighting. The terrain board model is a three-dimensional 750-to-1 scale model. The terrain consists of an airport runway and surroundings. The runway is 10,400 feet long and 200 feet wide with approach lights, strobes, marker and threshold bars, touchdown zone, VASI, taxiway, edge lights, and centerline lights. The terrain model board is lighted to provide day, dusk, or night conditions. The VFA is capable of simulated cloud bases of 0 to 750 feet, along with reference visual ranges of 0 to 6 miles. The overall transport lag is 160 milliseconds.

2.2 AIRCRAFT SIMULATION

A standardized modular software system was used for the simulation. The aerodynamics model is based on coefficient-of-lift equations. It was developed from original MD-11 wind tunnel data and refined by aerodynamic engineers. The engine model is based on the General Electric CF6-80C2-D1F engines and is entered three times to simulate each engine separately. The cockpit hardware is interfaced by a flight deck software package to a flight control model. Other software packages that interface with the simulation are atmosphere, winds, turbulence, and terrain models. Special software was developed as part of this study for the MLS sensor and guidance models and the experimental control packages. The computation iteration frequency was 20 hertz.

The aircraft models and the MLS guidance equations are calculated by two DEC VAX 11/785 computers that are coupled via a shared memory system. In addition, an Avalon-20 processor is installed in the Unibus system of one of the computers to provide additional processing power for the engine model. The models are linked to the cockpit via a parallel bus to a LSI-11 computer. A data recording system allows the recording of any aircraft or test parameter in real time. These parameters can be displayed in real time and printed in either graphic or tabular format.

2.3 MLS AREA NAVIGATION AND CURVED APPROACHES

This study evaluates one straight-in approach and four curved approaches. The straight-in approach uses azimuth and elevation angle signals from an airborne MLS receiver. These signals drive the course deviation displays and the flight director. An airborne area navigation computer is not required. This mode of operation has been termed angle-only operations and is equivalent to ILS operations. This approach was the baseline for comparison with the curved approaches.

The remaining four approaches were curved approaches. For this study, it was assumed that the airborne area navigation computer was the FMS of a current-generation wide-body transport. The curved approaches are Level III of the three levels of MLS area navigation approaches defined by the minimum operational performance standards (MOPS) developed by Radio Technical Commission for Aeronautics (Reference 2). Curved approaches consist of straight track and curved track segments. The area navigation computer provides steering commands based on cross-track deviations for both the straight and the curved track segments. The Level III approaches track a fixed path around the turn. Most aircraft guidance functions, including Level II or segmented approaches and the lateral navigation mode of the FMS, provide steering commands and deviations about straight line segments. Steering from one segment to the next is not about a fixed track but is dependent upon the angular difference between two straight intersecting segments and the speed of the aircraft.

The curved approaches were defined so that the control mode would switch from computed guidance to angle-only operations for the final straight segment. At this time, the sensitivity of the course deviation display changes from criteria established in the MOPS (Reference 2) to a sensitivity that is equivalent to ILS. The approach paths were constructed so that a turn waypoint was at the intersection of the two straight segments and the turns were of a fixed radius that intersected the straight segments at a tangent. This path definition produced an abeam waypoint instead of a fly-over waypoint.

2.4 MLS GUIDANCE ALGORITHMS

Guidance commands for both lateral and vertical path control are generated by algorithms that are based on past MLS system studies (Reference 3). These algorithms have been modified from batch simulation computer programs to run in real time. They have also been changed to accommodate a pilot in the loop (e.g., to calculate signals for the displays, provide situational awareness and alerts when path deviations exceed certain criteria, etc.).

Basically, these algorithms generate deviations from desired lateral and vertical paths, based on a waypoint data base, and provide steering commands to return the aircraft to its desired path. Displays (in the form of flight director commands, course deviation indicators, and along-track distance) are driven by signals from the guidance algorithm to allow the pilot to fly the complex MLS curved paths and segmented glide paths. The guidance algorithms are implemented in the area navigation computer by converting the MLS receiver azimuth and elevation angle data and the range from the DME/P transponder to aircraft Cartesian coordinates in space. No MLS signal source errors were modeled for this simulation. Since stored waypoint data define the desired path in space, deviations from this desired path can be computed and used in generating the steering signal.

The desired lateral path is defined as a ground track composed of straight and circular arc segments. An along-track distance (ATD) that is computed along the curved ground track is used in the algorithm to keep track of where the aircraft is relative to the MLS datum at the Cartesian coordinate center. This datum is defined on the runway centerline where the 3-degree glide path intercepts the ground plane.

The desired vertical path is defined in a vertical plane and is composed of level and descent segments relative to the along-track distance. In this way, the vertical profile is defined by a glide path as compared to a straight-in glide slope used in ILS approaches. The MLS vertical profile is defined independently of the lateral path and segmented sections can be placed along any desired portion of the approach. Detailed descriptions of the specific approach paths are presented and discussed in Section 3.

Flight mode switching occurs along the MLS path more than once during an approach. If the aircraft is outside MLS coverage, the lateral mode is in lateral navigation mode of the flight management system and the vertical mode is in altitude hold. Upon entering MLS coverage, both modes are switched to MLS azimuth mode and MLS elevation mode. The azimuth mode guidance is based on the lateral deviations relative to the desired path over the ground. Computed signals are generated in this mode to provide flight director guidance to the pilot. Similarly, the elevation mode is based on vertical deviations from the desired altitude. The pitch flight director commands are driven accordingly to provide the pilot with vertical guidance information. Two curved approaches used in this study were initiated outside coverage, and MLS coverage was captured. The other two curved approaches were initiated inside coverage. In the latter cases, it was assumed that MLS guidance had been established and tracking of the desired path was under way.

The second mode switching occurred when the aircraft had made the turn to final straight segment. At that time, the mode was switched to angle-only guidance. This guidance emulates an ILS approach and has a different course deviation display sensitivity compared to the area navigation guidance defined by the MOPS criteria (Reference 2). Figure 2-2 compares the angle-only and the area navigation sensitivities. For lateral area navigation, the full scale deflection is equal to ±350 feet at runway threshold, splays out at an angle of 3 degrees until a full-scale deflection of ±1,500 feet is reached, and then remains constant. Full-scale deflection on ILS splays out from the localizer transmitter (or azimuth transmitter in the case of MLS) at the far end of the runway to pass through ±350 feet at runway threshold. Therefore, the splay angle is dependent upon the runway length. For vertical area navigation, full-scale deflection is equal to ± 10 feet from the nominal glide path at the runway threshold, splays out at a 0.75-degree angle from the nominal glide path until full-scale deflection is ±250 feet, and then it remains constant. The ILS splays out at a 0.7-degree angle from the nominal glide slope. If the aircraft is at the position shown in the figures, there will be an abrupt change in the course deviation displacement when the switchover to angle-only operations occur.

2.5 FLIGHT DISPLAYS

The flight displays were a primary flight display (PFD), a navigation display (ND), an engine and alert display (EAD), and the display of the multifunction control display unit (MCDU). The PFD and ND emulated an early version of the MD-11 displays. However, modifications were made for the MLS approaches and the formats are 90 percent of the MD-11 size because the active display area of the simulator's CRTs is smaller. The EAD is an early version of the MD-11 tape instruments, and the MCDU display is a flight plan page that was modified to emulate a legs page of a Boeing 767 flight management system (FMS). (The MD-11 flight plan page did not have the distance between waypoints on the same page as the course, speed, and altitude.)

The PFD is shown in Figure 2-3. The PFD combines the function of the flight mode annunciator (FMA) and the basic T. The T contains the airspeed tape, the attitude director indicator, the altitude tape, the vertical speed indicator, and the partial compass rose. The following modifications were made for the MLS approaches:

1. The lateral and vertical windows of the FMA were modified for MLS. Instead of an ILS ARMED mode, there was an MLS ARMED mode. The color of this annunciation was magenta because the MLS guidance is controlled by the FMS. Upon entering MLS coverage the lateral mode of the FMA changes to AZIMUTH in magenta instead of LOC. Upon interception of the glide path, the vertical mode changes to ELEV in magenta instead of G/S. When the control mode switches from computed guidance to angle guidance, the annunciations change to AZ ANGLE and EL ANGLE, and the color changes to white, indicating control has switched from the FMS to the flight control computer.

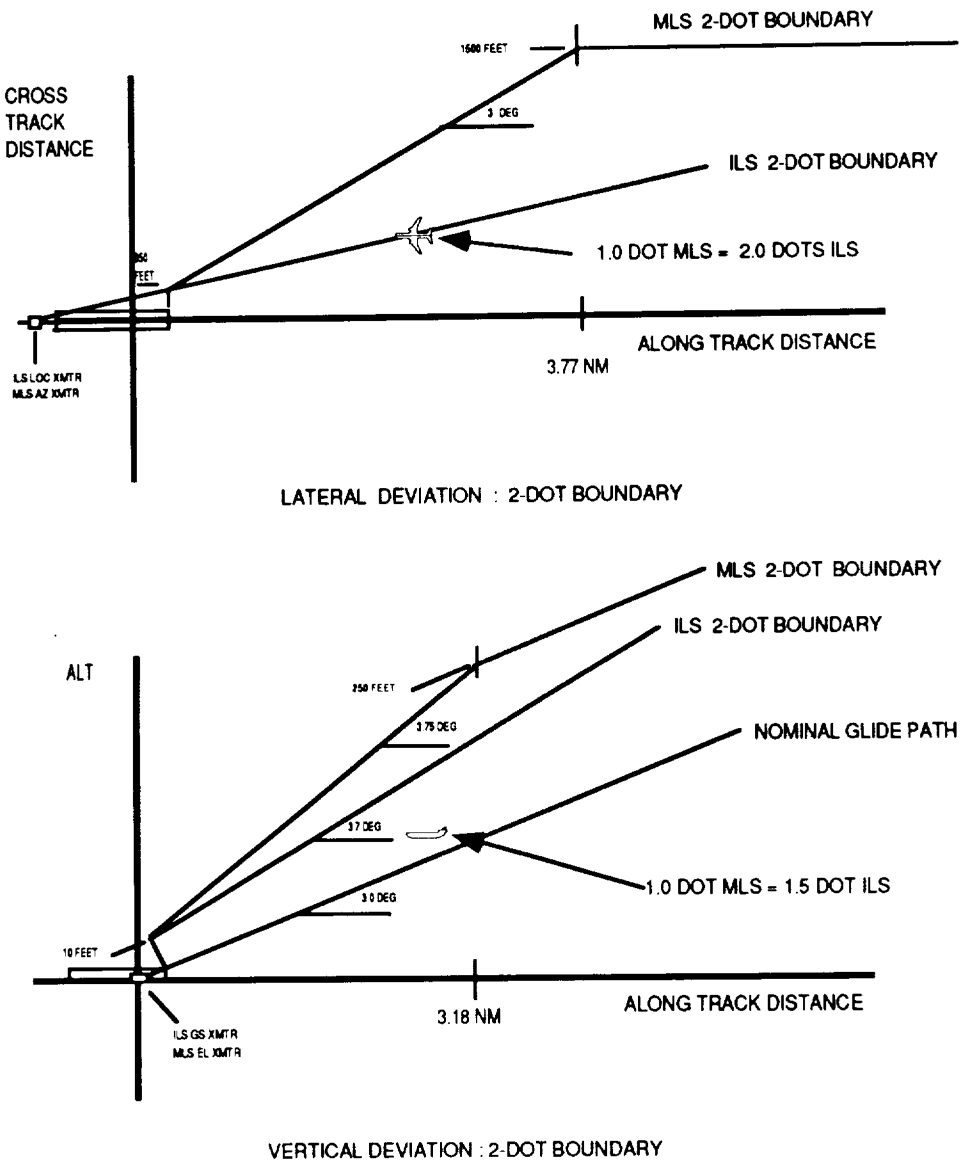


Figure 2-2. Comparison of MLS Area Navigation CDI Sensitivity and ILS CDI Sensitivity

2. The pointers of the course deviation indicators (CDI) are normally unfilled. Five seconds prior to a turn, the lateral CDI flashes filled three times and remains filled throughout the turn. When a straight segment is reached, it flashes three times again and remains unfilled. The vertical CDI will flash three times before glide path intercept and remain filled throughout the descent. If there is a level-off segment, the CDI flashes three times and remains unfilled during the level portion of flight. When the control mode switches from computed guidance to angle guidance, the pointers change color from magenta to white. (This is contrary to the Federal Aviation Administration Advisory Circular 25-11 (Reference 4), which states that the color coding of CDI pointers are to be magenta, representing radio navigation.)

3. The partial compass rose is always heading oriented, and a green diamond shows the drift angle. A solid magenta circle represents the computed course. The magenta circle will continuously change course when the simulated aircraft is turning and will always remain at the drift angle

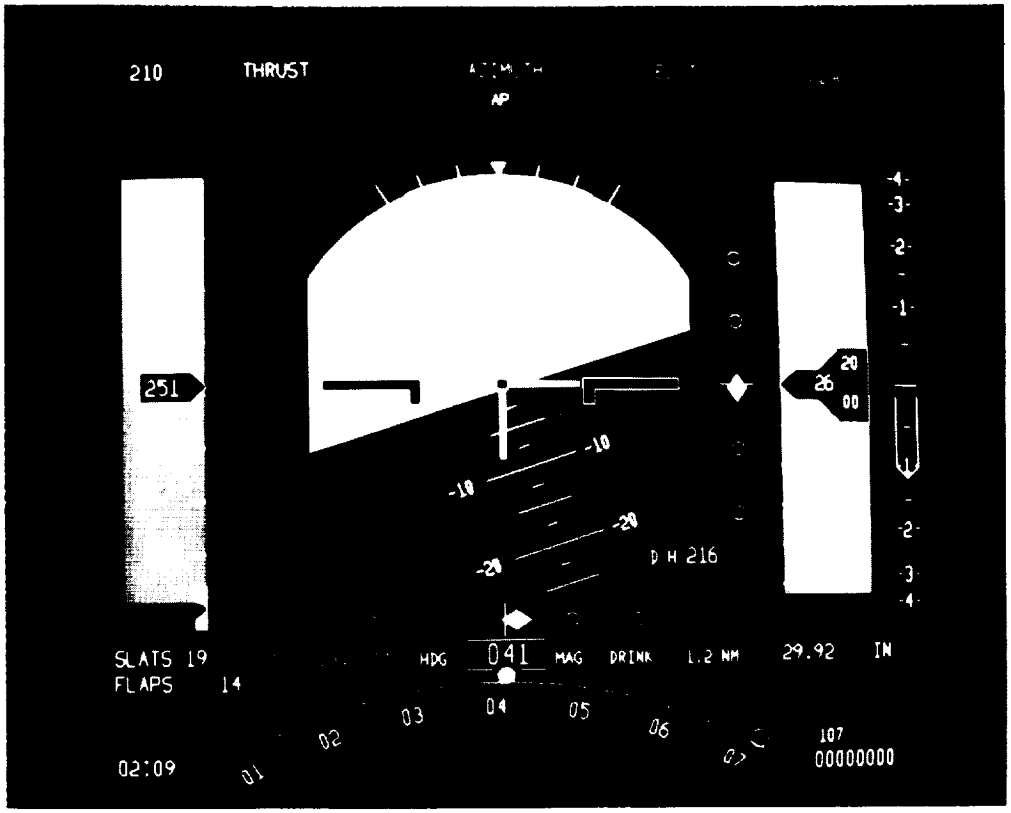


Figure 2-3. Primary Flight Display

position if the aircraft is on track. An unfilled magenta circle will move out 5 seconds prior to a turn and go to the course of the next straight segment. (If it is off scale, it parks at the end of the scale and a digital number appears indicating the course.)

4. The along-track distance appears to the left of the heading readout, and the distance to the next waypoint appears to the right of the heading readout.

The ND has two modes — map and approach (Figures 2-4 and 2-5). The approach mode is equivalent to a horizontal situation indicator (HSI) or compass rose and will be referred to as an HSI. For the simulation, the map mode was track oriented and the approach mode was heading oriented. The modifications to the map mode for MLS operations were as follows:

1. Bearing Pointer 1 was used for the bearing to the azimuth transmitter, and the bearing/range readout in the lower left corner represented raw data to the azimuth and the DME/P transmitter antennas.[1]
2. The ATD was added to the left side of the display, and a vertical deviation indicator was added to the right side of the display.
3. A map mode range of 5 nautical miles was added to provide more accuracy for tracking with the map display. (The MD-11 has a minimum range of 10 miles.)

1. The simulation was set up so that the display shows the bearing and range to the MLS datum. However, this is computed data and dependent upon the MLS data word giving the location of the MLS datum. Instead of modifying the simulation, the waypoint data block was made to match this bearing and range. The pilots were told that these data represent raw data.

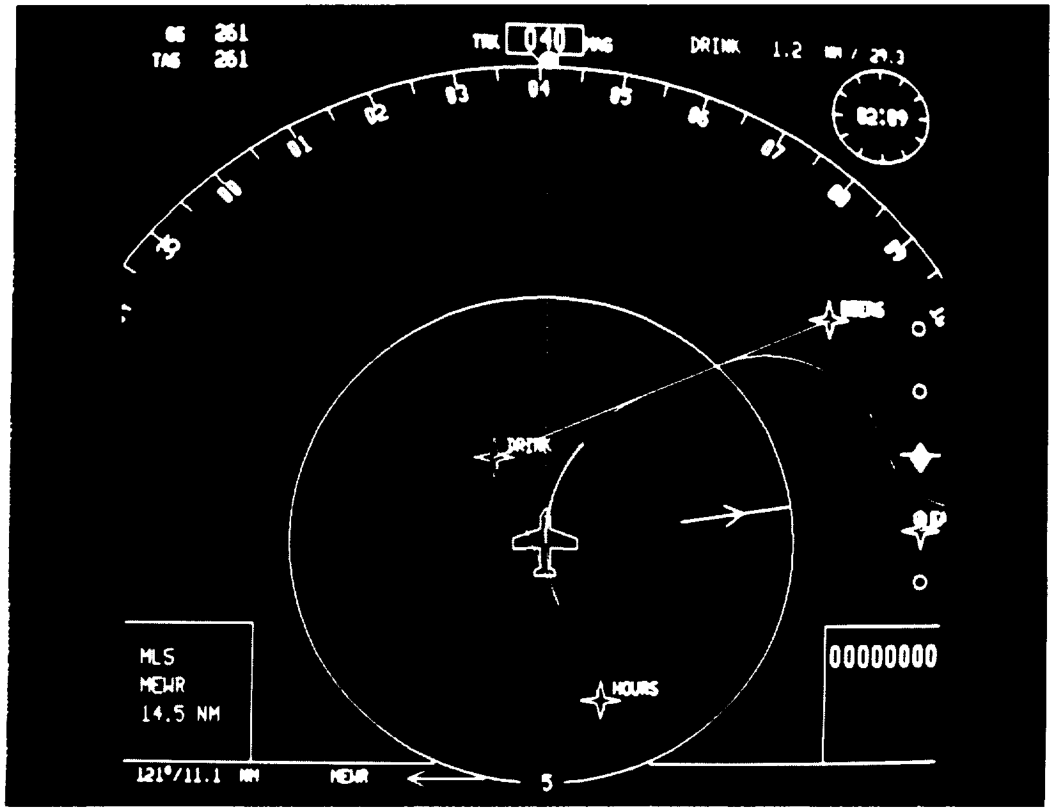


Figure 2-4. Map Mode of the Navigation Display

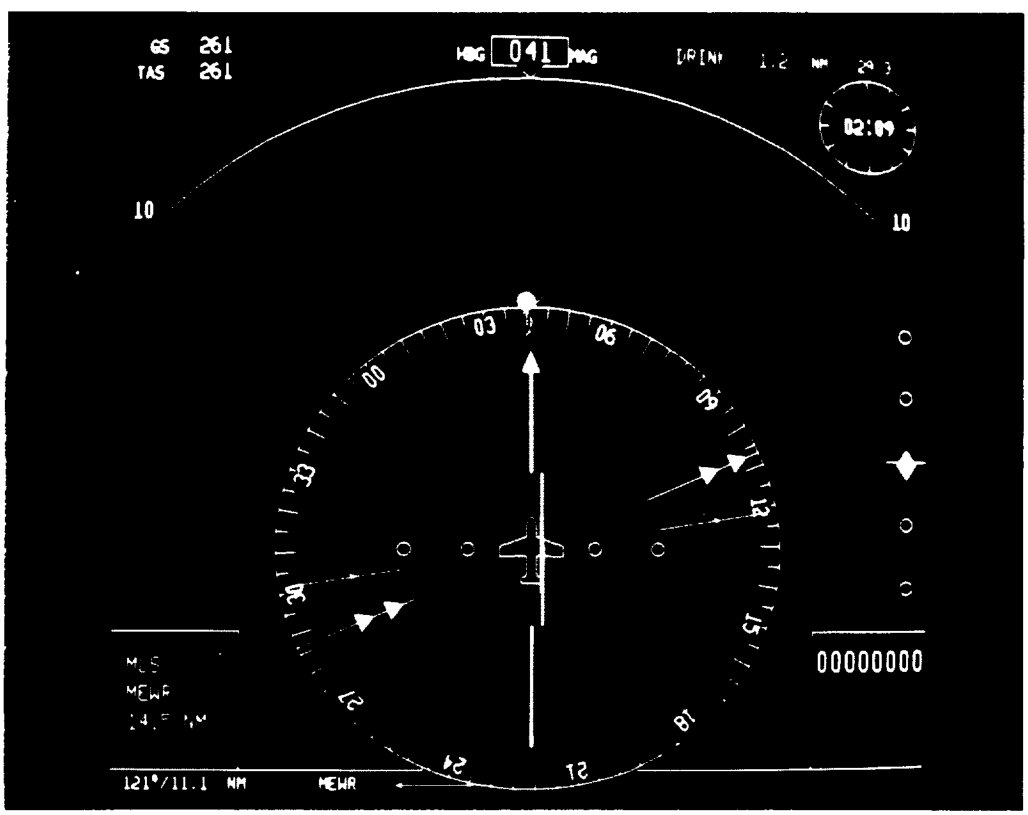


Figure 2-5. Approach or HSI Mode of the Navigation Display

The same modifications listed under Items (1) and (2) were made to the approach mode. In addition, a second course pointer with a double arrow was added. Five seconds prior to a turn, the double arrow pointer would move to the course of the next straight segment. The single arrow pointer was the computed course and would change course depending upon the computed track angle. The course deviation bar showed the cross-track error from the computed course.

SECTION 3
SIMULATED APPROACHES

3.1 GENERAL

Five different approaches were programmed and used during this evaluation. The first was a straight-in approach that used angle-only operations and emulated an ILS approach. It was used as a baseline for comparison with the curved approaches.

The remaining approaches contained lateral curved paths of differing degrees of complexity, including one with a segmented glide path. Each path was designed to test performance limits, and each was more difficult than the procedures permitted by FAA Order 8260.36 (Reference 5). The more difficult procedures were:

1. The approaches contained final straight segments from less than 1 to 2.7 nautical miles. The order requires the final segment to be at least 3.4 nautical miles for Category D (wide-body transport) aircraft.
2. Except for one approach (La Guardia 13), the approaches contained curves with radii shorter than the order allows for Category D aircraft. The minimum radius for Category D aircraft should be 1.75 nautical miles.
3. One approach (Newark 11) contained a segmented glide path, which is not permitted by the order.

The details of each approach and the rationale for its choice are discussed in the following sections. The order of presentation is based on the length of the final straight-in segment, with the straight-in approach being first.

3.2 KENNEDY INTERNATIONAL JFK-31R

This is a straight-in approach using angle-only operations. The Jeppesen approach chart is shown in Figure 3-1.[2] The initial position of the simulated aircraft was on a heading of 344 and about 6.1 nautical miles from intercept. The intercept was between ALLER and WENKE at 11 nautical miles along-track distance (ATD). This approach was set up so that a nominal 30-degree intercept of the 314 final track angle would occur, which is analogous to an ILS capture. The final approach fix (FAF) is at WENKE, which is 6 nautical miles from the touchdown zone or datum. No specific curved segment is defined from transition between the initial bearing and the final approach. An asymptotic segment was flown as in an ILS approach.

The initial altitude was 2,200 feet with capture of the 3-degree glide path at 7.0 nautical miles ATD.

3.3 LA GUARDIA LGA-13

This approach was designed to collect data for the length of the final straight segment required after a large turn and for examining the length of the straight line segment between consecutive turns. Figure 3-2 contains the Jeppesen chart for the La Guardia approach to Runway 13. The simulation starts

---

2. The Jeppesen approach charts were printed specifically for this evaluation. The plates for the curved approaches have two revisions since the original printing: (1) the bearing (in degrees) and the range (in nautical miles) to the MLS datum were added to the waypoint data blocks, and (2) the limits of combined MLS azimuth and elevation coverage were added. These additions were made by mutual agreement between the FAA and Douglas Aircraft. Permission to use the plates has been granted.

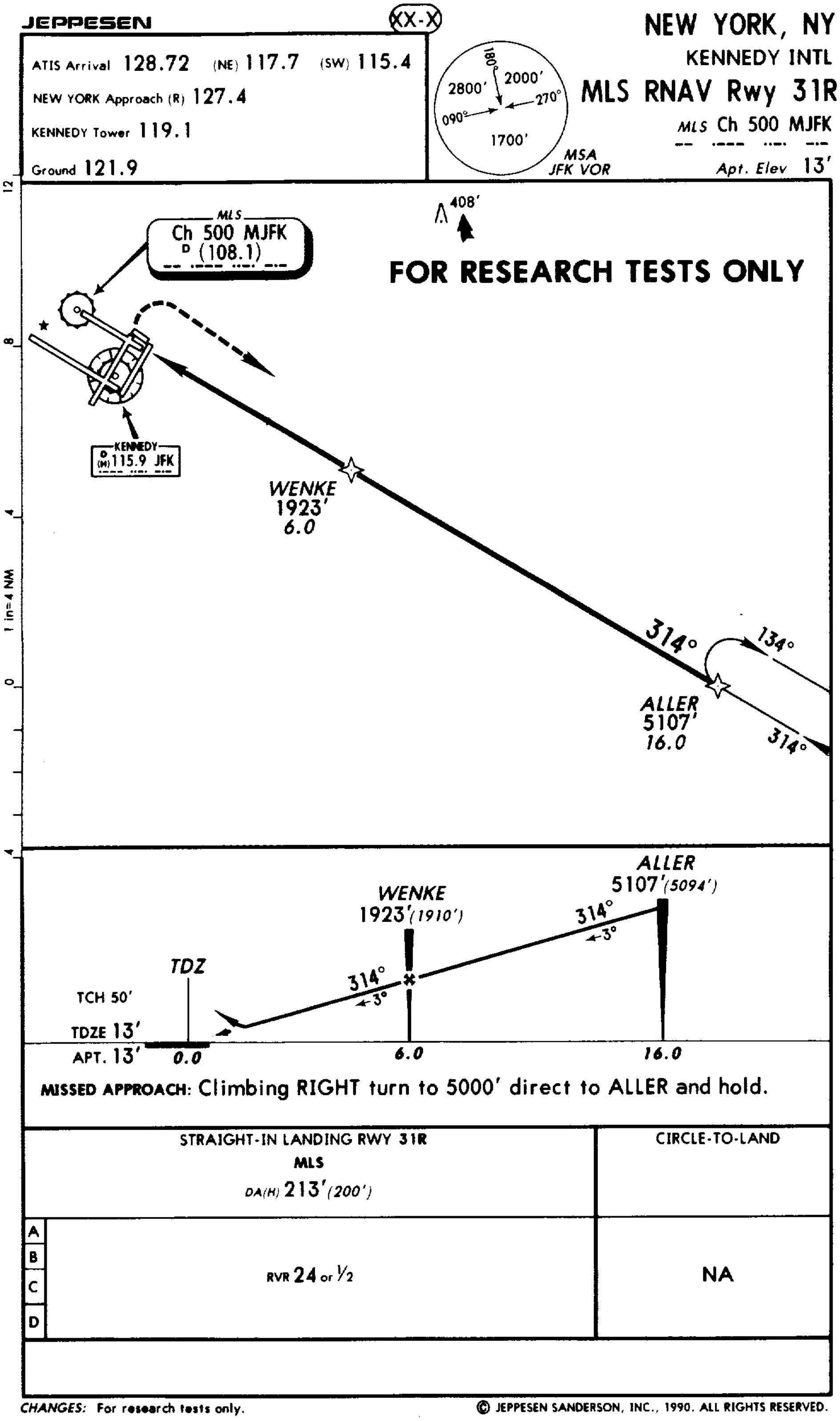
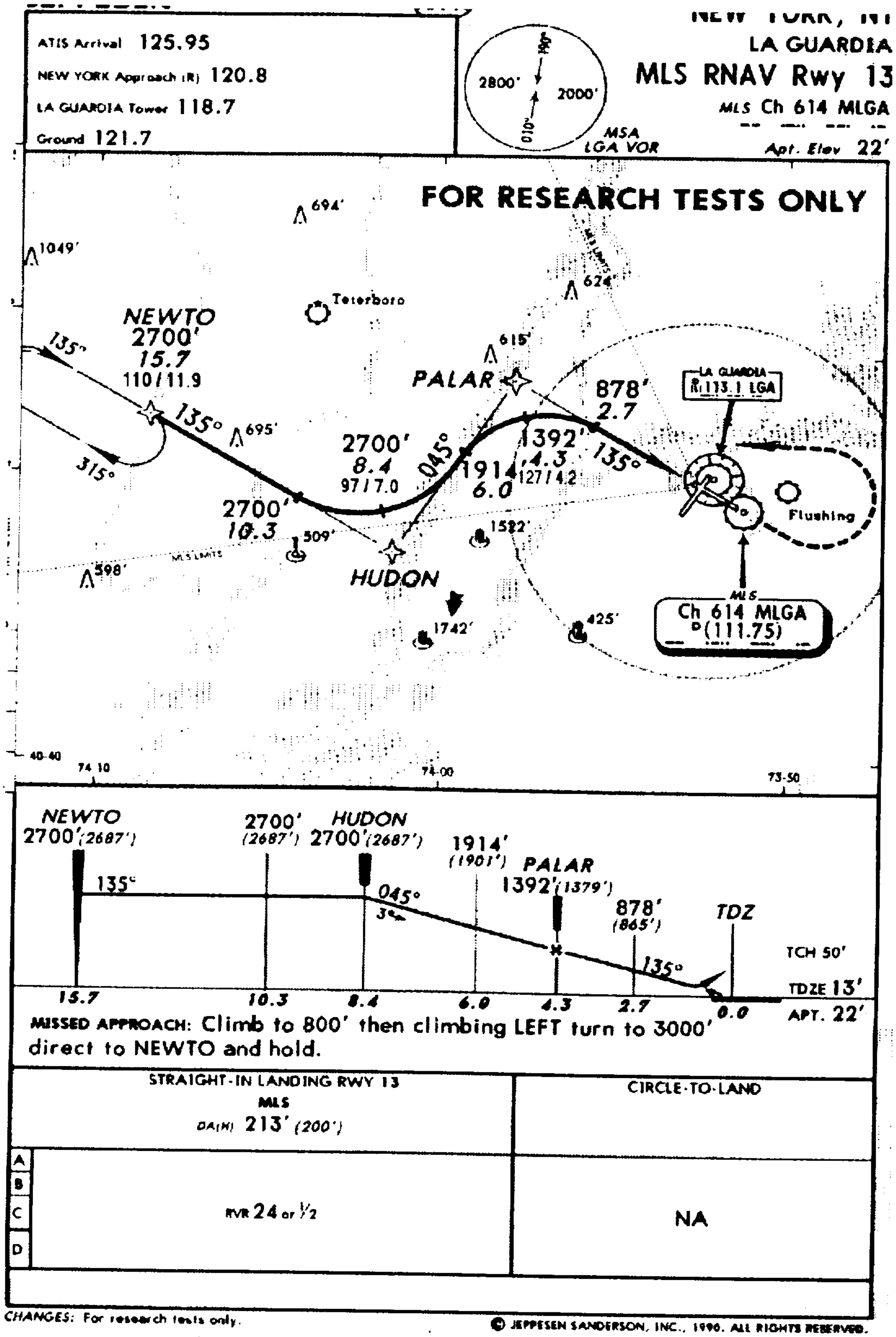


Figure 3-1. Approach Chart for JFK-31R



Reproduced with permission of Jeppesen Sanderson Inc

Figure 3-2. Approach Chart for LGA-13

at NEWTO within MLS coverage and makes two consecutive 90-degree turns to a 2.7-nautical-mile straight-in final. The first turn radius is 15,000 feet and the second is 12,000 feet. LGA-13, as well as the other curved approaches, was designed to contain turn radii that decrease in length as the along-track distance decreases. This design allows for reasonable bank angles for the initial clean airspeed and maintains those angles as aircraft speed decreases. The straight segment between the two turns is 0.5 nautical mile. The 3-degree glide path capture occurs abeam of HUDON, which is halfway through the turn. The final approach fix was at PALAR.

3.4 NEWARK INTERNATIONAL EWR-11

This approach was designed to collect data for (1) vertical transitions (change in the desired flight path angle) during straight line segments and turns, (2) the length of the final straight segment after a large turn, and (3) the length of a straight line segment between consecutive turns.

The EWR-11 approach in Figure 3-3 contains two 90-degree right turns followed by a 90-degree left turn and a 1.9-nautical-mile straight final segment. The turn radii were 20,000, 15,000 and 10,000 feet, respectively. There is a 1.6-nautical-mile straight segment between the first two turns and a 0.7-nautical-mile segment between the second and third turns.

This approach has the only segmented glide path in this evaluation. The first descent is at HOURS on a 3-degree glide path. Abeam of BEERS, halfway in the first turn, there is a level-off segment at 2,280 feet. Abeam of DRINK, halfway in the second turn, final descent on a 3-degree glide path occurs. This vertical profile was specifically designed to evaluate glide path changes during the turns. The final approach fix was at BEERS.

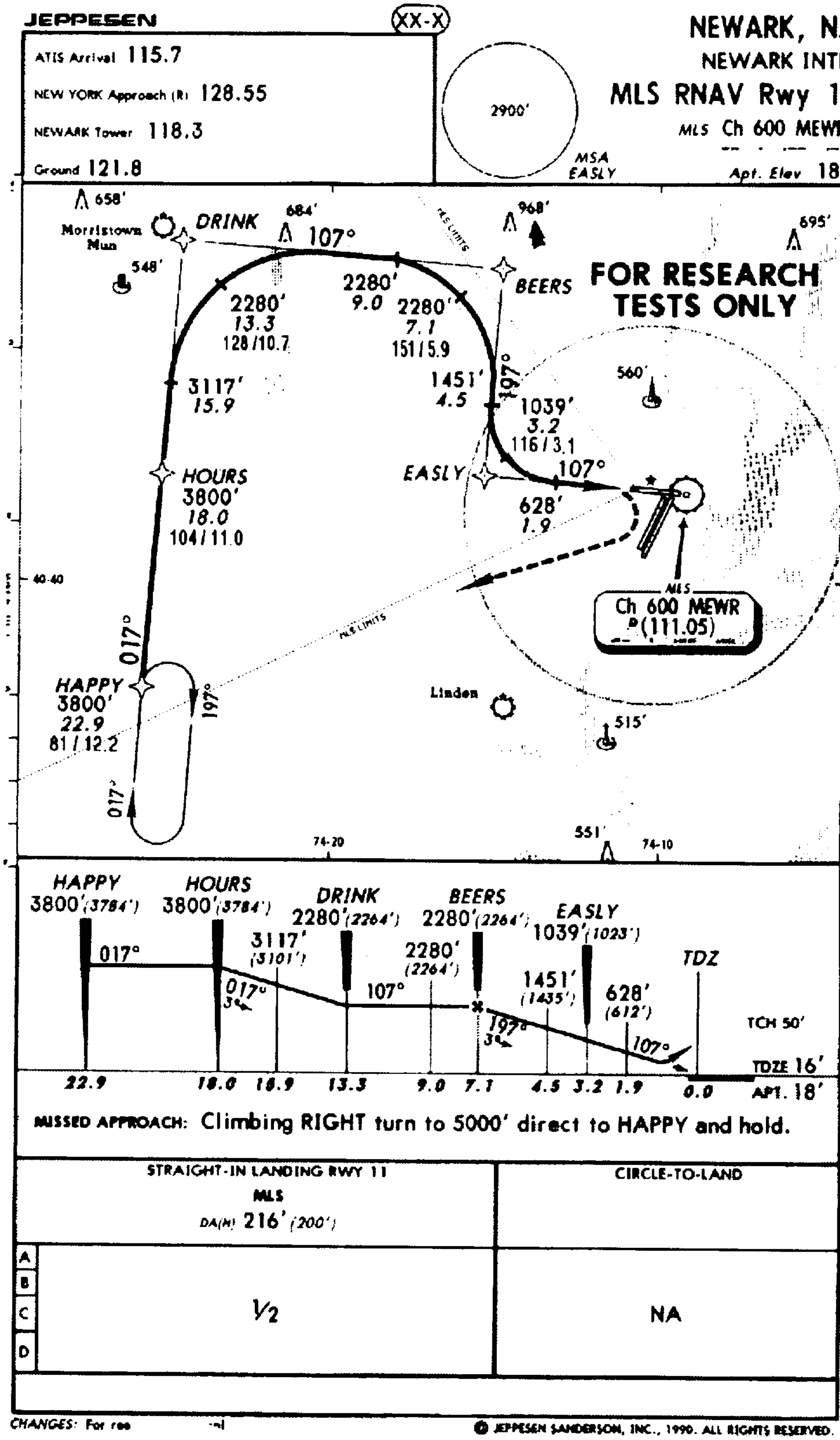
3.5 KENNEDY INTERNATIONAL JFK-13R

This approach is very similar to the Canarsie Visual approach except that precision guidance and navigation information is provided. Also, the turn radius on the MLS approach is shorter at 7,500 feet. This approach is designed to collect data for the length of the final straight segment after a large turn. JFK-13R is one of the two approaches used in the evaluation where the initial position of the simulated aircraft is outside of MLS coverage. The Jeppesen chart is shown in Figure 3-4. The aircraft starts at ASALT, and transition to MLS coverage occurs at 2 nautical miles from ASALT. The aircraft remains on the 043 radial until a 4-degree course change occurs at the CRI VOR to 047. Four miles later, the turn is made to line up with the extended runway centerline. The final straight segment is 1.0 nautical mile, and the last turn completion point is at 300 feet AGL. Consequently, the visual minimum for this approach was 350 feet. The vertical path profile for JFK-13R consists of glide path capture at CRI VOR, which coincides with the 4-degree course change and the final approach fix.

3.6 WASHINGTON NATIONAL DCA-18

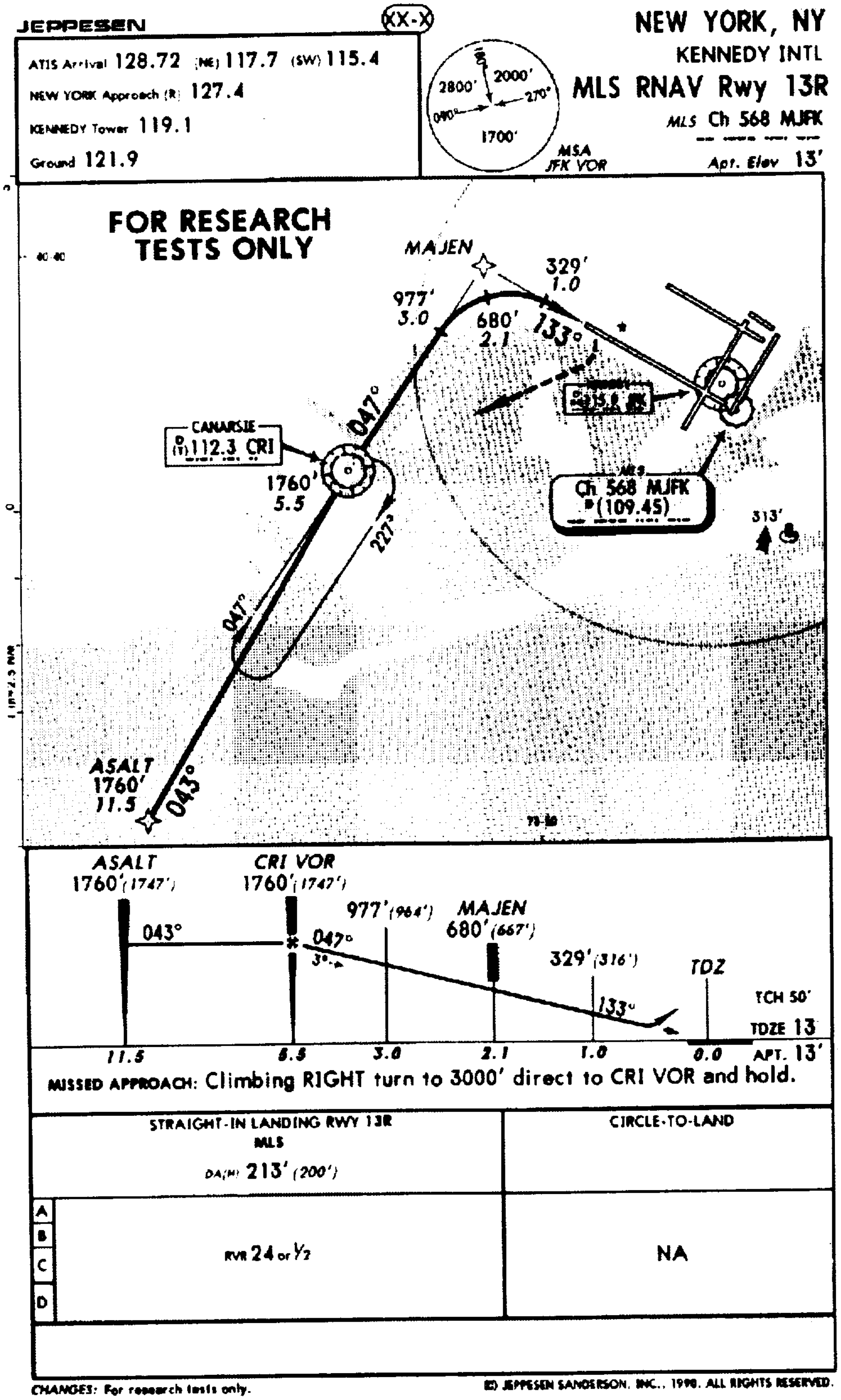
This approach is very similar to the actual River Visual approach at Washington National except that precision navigation and guidance information are provided. It was designed with eight waypoints to approximate the route over the Potomac River. There are several short turn segments with very short straight segments in between at the end of this approach. The turn radii vary from 12,500 feet at the beginning of the approach to 7,500 feet for the three final turns.

DCA-18 Jeppesen chart is shown in Figure 3-5. The initial simulated aircraft position is outside of coverage. The aircraft is positioned on a 095 course 4 nautical miles from NICAL. MLS coverage is entered after a short 0.7-nautical-mile segment. MLS guidance continues the aircraft on the same course until a programmed turn is made to intersect the 146 leg between NICAL and REDUM.



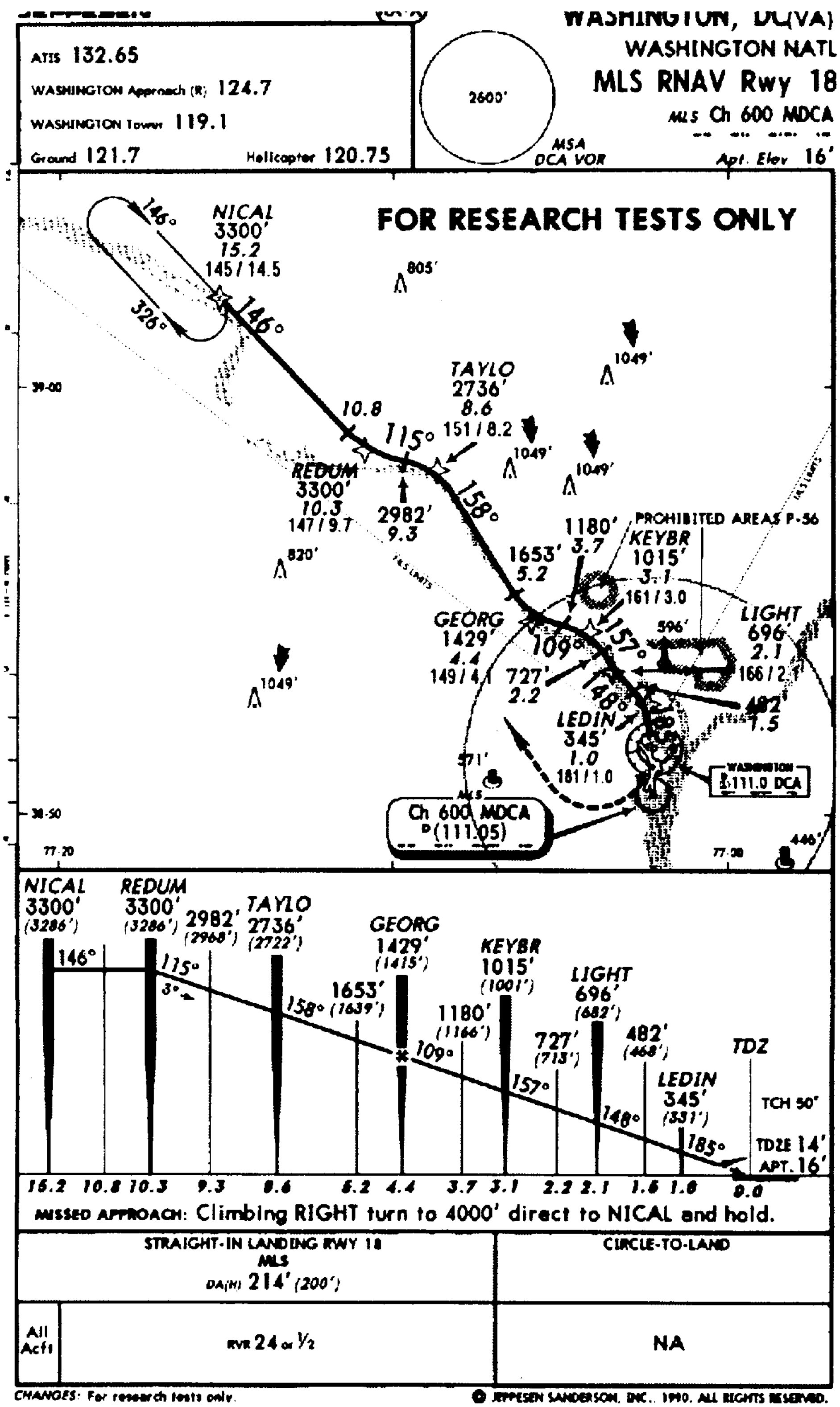
Reproduced with permission of Jeppesen Sanderson Inc

Figure 3-3. Approach Chart for EWR-11



Reproduced with permission of Jeppesen Sanderson Inc

Figure 3-4. Approach Chart for JFK-13R



Reproduced with permission of Jeppesen Sanderson Inc

Figure 3-5. Approach Chart for DCA-18

The approach is rather benign until the beginning of the turn at GEORG. After that, there are three short-segment, small-radii turns with straight segments of 0.5 nautical mile or less. After completing the last turn at LEDIN, the final straight segment is 0.6 nautical miles which occurs at decision height. Consequently, this approach had a higher visual minimum of 350 feet for the study. The 3-degree glide path capture occurred at REDUM and the final approach fix was at GEORG.

SECTION 4
TEST CONDITIONS

4.1 EXPERIMENTAL VARIABLES

Besides the five approaches, the other independent variables were the type of navigation display, the throttle mode, and the wind direction. These variables were selected to determine if there was any differences in pilot acceptance or performance among these conditions. As a subexperiment, two contingencies were evaluated: a flight director failure and an engine fire warning. The two navigation displays were the map mode and the approach mode (HSI). These display formats are described in Section 2.5. There were two throttle modes — manual and autothrottles. The wind direction was either a left or right crosswind at the runway.

4.2 WIND CONDITIONS

Except for wind direction, the same wind and turbulence models were used for all the test trials. This was a changing wind with a Dryden turbulence model added. The wind was programmed as a function of altitude above ground level. Figure 4-1 shows the geometry used in defining the left and right winds. (In the test results, a negative lateral error will be to the left of the flight path and a positive lateral error will be to the right of the flight path.) Both the wind direction and wind speed relative to the runway centerline varied as the aircraft descended. Figure 4-2 shows the wind speed and direction as a function of altitude. The wind profile was defined so that the head wind component would be 25 knots and the crosswind component would be 15 knots. Figure 4-3 shows these components as a function of altitude.

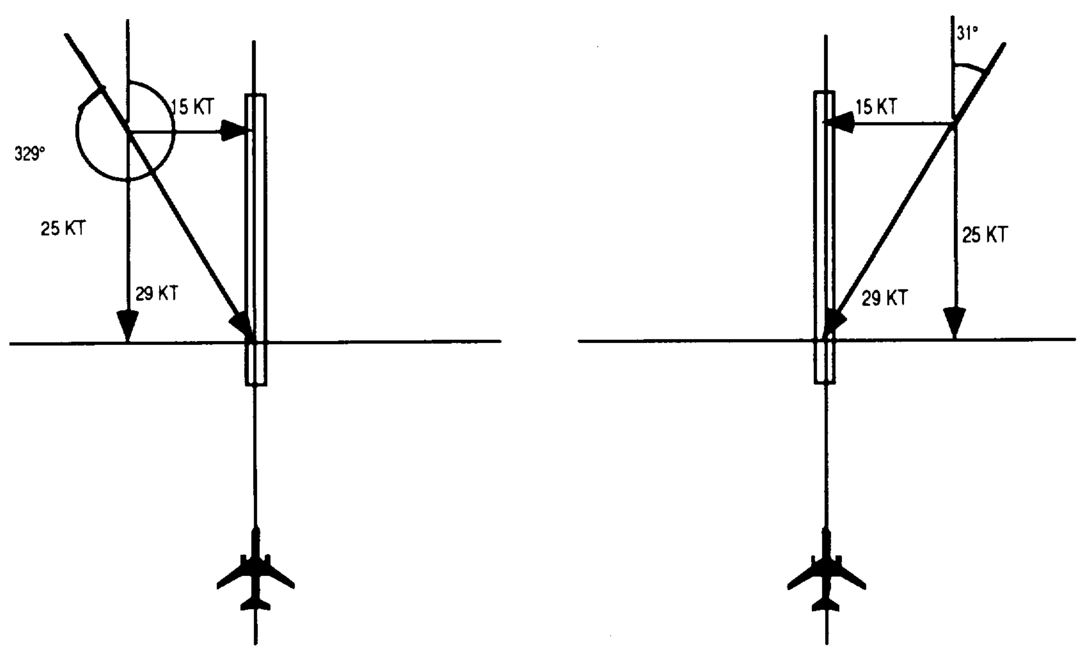


Figure 4-1. Direction of the Left and Right Crosswinds at the Runway

4.3 VISIBILITY CONDITIONS

Two visibility and cloud base conditions were used for the study. One was equivalent to Category I instrument landing conditions with a cloud base of 200 feet and a runway visual range of 3,000 feet.

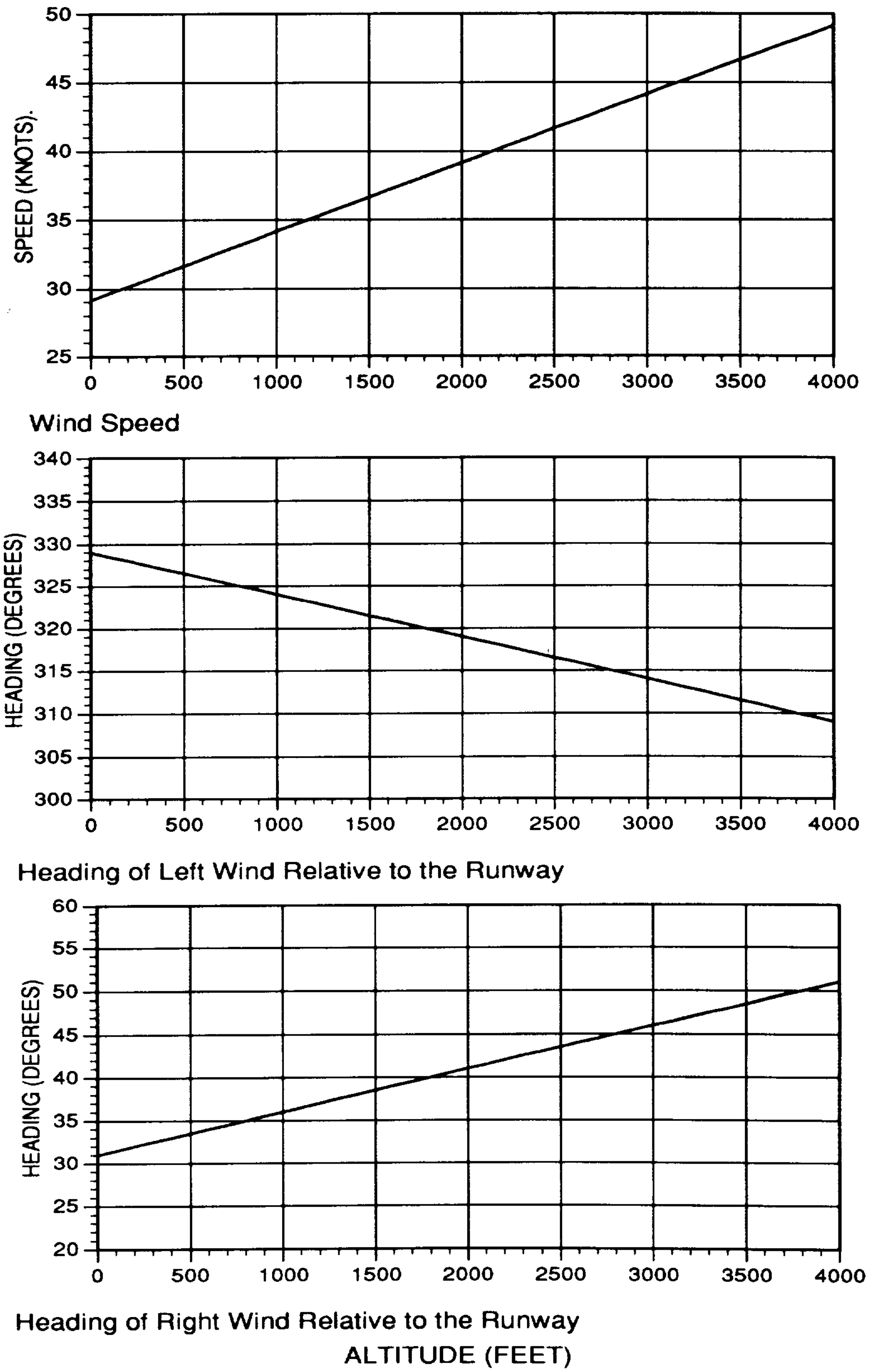


Figure 4-2. Relationship of Wind Speed and Direction as a Function of Altitude

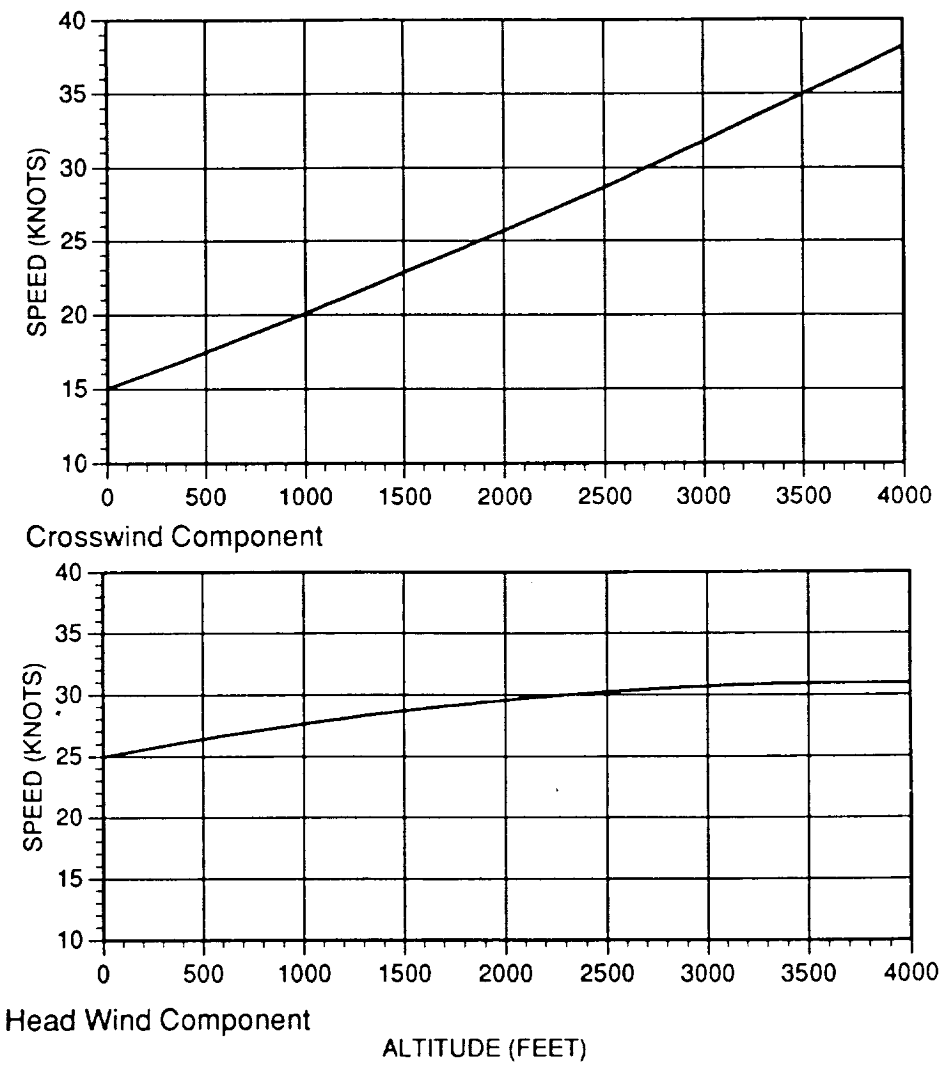


Figure 4-3. Crosswind and Head Wind Speed Components Relative to the Runway

The other was better than Category I, with a cloud base of 350 feet and a runway visual range of 6,000 feet. Visibility varied with the approach. JFK-31R, LGA-13, and EWR-11 had lower visibility, and JFK-13R and DCA-18 had higher visibility. The higher visibility was selected for these approaches to make them more operationally feasible with the altitude of the final turns. Since the last turn completion point occurred below 350 feet for JFK-13R and DCA-18, the pilot flying had the option of being head up or remaining head down prior to decision height. This produced a confounding factor for the comparison of the approaches. With the lower visibility, the pilots are dependent upon the MLS guidance at decision height, but with the higher visibility they have the capability of either staying head down or going head up and using the visual scene for guidance.

4.4 CREW FLIGHT PROCEDURES

The initial conditions for a test trial were as follows: The flight was assumed to be cleared for approach and landing and any other air traffic control communications were not necessary. The approach was previously selected in the flight management computer, inserted into the flight plan, and the MLS capture mode was armed. Barometric pressure at the field and decision height were set. The flight crew was required to perform an initial condition checklist. (The checklist is presented in Appendix A.) This included the approach briefing, checking the landing data, the missed approach briefing, cross-checking the waypoint data on the MCDU flight plan page with the approach chart, and checking the throttle setting.

The simulated aircraft weight and center of gravity were the same for each trial. The weight was a moderate landing weight of 400,000 pounds and the center of gravity was 22 percent. Initially, the aircraft was clean and at a speed of 210 knots. Two configuration and speed changes were recommended. The first was slats extended, a flap setting of 28 degrees, and a speed of 165 knots. The second or final was flaps at 50 degrees and a landing speed of 147 knots. The reference speed was 143 knots.

The initial position and altitude of the aircraft was a function of the approach. For JFK-13R and DCA-18, the aircraft was in the lateral navigation mode and MLS was armed. For the other approaches, the aircraft was within MLS coverage and azimuth was captured. The vertical mode was always altitude hold, but the altitude differed depending upon the approach.

The recommended crew coordination procedures for the approach, missed approach, flight director failure, and engine fire warning are presented in Appendix A. The flight crews were instructed to follow these procedures or their carrier's procedures for these flight conditions. In addition to the carrier's procedures, they were instructed to follow three procedures that were unique to this evaluation:

1. At the time the course or vertical deviation indicator flashes, the pilot not flying checks the approach chart and calls out the next activity. For example, "Turning to a track of 107 around DRINK" or "Glide path capture at HOURS."
2. When crossing over or abeam of a waypoint, the pilot not flying cross-checks the bearing and distance to the azimuth and DME/P transmitters (which appear in the lower left corner of the navigation display) with the waypoint data on the approach chart. If they agree, he calls out, "Waypoint check." This procedure was provided to verify that the computed guidance was correct. (If the waypoint data do not agree, he informs the pilot flying that the data do not check and a missed approach is performed.)
3. When the pilot flying feels like he is stabilized on the approach, he calls out, "Stabilized," and makes a mental note in order to answer the stabilization question after the trial. The interpretation of stabilized on approach was left up to the individual pilot.

If MLS guidance remained valid during a missed approach, the flight crews were instructed to climb to the missed approach altitude and continue to fly the lateral MLS guidance to the runway threshold. If the threshold was reached or the MLS guidance was invalid (an RNAV FAIL message would appear on the PFD), they were instructed to execute the first turn of the missed approach procedure as described on the approach chart.

4.5 FAILURE SCENARIOS

Two failure scenarios were provided: a flight director failure and an engine fire warning. The pilots were instructed to continue with the approach if at all possible after the failures occurred. The time these failures occurred varied with the approach and occurred before the last turn. The along-track distances for their occurrence are listed in Table 4-1. (For the first five flight crews, the failures on JFK-31R, JFK-13R, and DCA-18 occurred after or during the last turn and for JFK-13R and DCA-18, they occurred below visual minimum. The occurrence position was adjusted for the subsequent runs so that the pilots would have to depend upon MLS guidance.)

For the flight director failure, the flight director was biased out of view and an FD FAIL message occurred on the PFD. The course and vertical deviation data on the PFD and the navigation display still provided valid information. For the engine fire warning, the master warning light turned on, an ENG 3 FIRE annunciation appeared on the engine and alert display, and the Number 3 engine lost thrust. The flight crews were instructed to perform the emergency procedures, including engine shutdown.

Table 4-1.
The Along-Track Distance at Which the Contingencies Were Inserted

APPROACH	POINT OF INSERTION
JFK-311R	13.16 NM
LGA-13	7.40 NM
EWR-11	13.13 NM
JFK-13R	3.95 NM
DCA-18	6.90 NM

SECTION 5
EXPERIMENTAL DESIGN

5.1 FLIGHT CREWS

Fifty pilots participated in the formal evaluation — 28 pilots recruited by the Air Transport Association from eight U.S. airlines, 18 FAA pilots, and 4 Douglas pilots. All pilots except for two first officers from the airlines were captains. The pilots from the airlines were a mixture of line, management, and training pilots. The FAA pilots were a mixture of certification and check pilots. The Douglas pilots were one crew from MD-11 engineering test and one from MD-11 training.

Forty-four of the pilots had wide-body aircraft experience on MD-11, DC-10, 747, L-1011, 767, and A300 aircraft. Nine pilots were qualified on the MD-11, including the four Douglas pilots, three FAA certification pilots, one FAA check pilot, and one airline pilot. Six of the FAA pilots had only narrow-body aircraft experience. All pilots except two of the FAA pilots had extensive experience with transport aircraft. Thirty-two of the pilots had flight experience with EFIS displays. Ten pilots — six airline pilots and four FAA pilots — had previous experience with flight or simulator evaluations of curved approaches.

5.2 STATISTICAL DESIGN

A fractional-factorial, repeated-measures statistical design was used for the evaluation. A pilot received two repetitions of each approach, or 10 trials, and both levels of each treatment condition, (i.e., navigation display type, throttle mode, and wind direction) on each approach. However, a pilot received only two out of eight possible combinations on each approach. (Since there were two levels of navigation display, wind direction, and throttle mode, there were $2 \times 2 \times 2 = 8$ combinations.) All combinations of treatment conditions were divided equally among all the pilots. This design allows all main effects and first-order interactions to be tested, but it assumes that the higher order interactions are not significant.

The order of presentation of the navigation display, wind direction, and throttle mode treatment conditions was counterbalanced between pilots, and the order of presentation of the approaches was randomized. This was performed to minimize the effects of the order of presentation.

The pilots participated in the evaluation as flight crews of two. The first pilot would fly in the left seat for three trials, while the second pilot would sit in the right seat as the pilot not flying. Then the crew would switch seats, and the second pilot would fly three trials. Since data obtained from members of a single flight crew are not independent samples, the first and second pilots of a flight crew were treated as members of separate groups for the purpose of statistical analysis.

The contingencies were treated as separate experiments embedded in the above design. Each pilot received one trial using a specific approach on each contingency. Therefore, the treatment conditions were between-group variables. There were five pilots within each group for this evaluation.

5.3 TEST PROCEDURES

Each flight crew participated in the evaluation for 2 days. The first day consisted of the pilot briefing and practice trials. The second day consisted of 24 data trials (12 for each pilot) and the debriefing.

Each pilot was sent a prebriefing package several days prior to participation in the evaluation. The material in this package is presented in Appendix A. The briefing included an introduction to MLS presented by the FAA observer plus videos describing the MLS features. The remainder of the briefing was presented by the test conductor. This was followed by a description of the test conditions, a general description of the simulator, a detailed description of the flight displays, a detailed explanation of the test and crew procedures, and a review of each approach chart.

The level of detail given in the flight display briefing varied with the flight crew. If the pilots had MD-11 experience, only the features that were unique to the MLS evaluation were described. Otherwise, all the features of the display formats were explained. This briefing included a video of the display formats with an explanation of the various display features.

The test conductor reviewed the test and crew procedures with special attention to the procedures that were unique to MLS. He provided the configuration changes and speeds for the approaches. Each approach chart was reviewed. The initial position and altitude, the waypoints, the turns, the glide path changes, and the positions for the speed reductions were identified. The recommended positions for the speed reductions were when the simulated aircraft was straight and level. The initial speed reduction was prior to glide path intercept, and the second was prior to the final approach fix.

The briefing was followed by a familiarization period in the simulator. The first trial was with autopilot and autothrottles on the LGA-13 approach. This allowed the flight crews to become familiar with the test conditions, the checklists, the configuration changes, the speed reductions, and the displays without manually flying the simulator.

The first pilot received three practice trials. The pilots switched seats and the second pilot received three practice trials. Seats were switched again and the order was repeated so that each pilot received six practice trials. The order of the approaches were the same for all practice trials: JFK-31R, EWR-11, DCA-18, LGA-13, JFK-13R, and a flight director failure on LGA-13. Combinations of the other treatment conditions were balanced between the two pilots. During practice, the flight director failure trial was always flown with the HSI display and manual throttles. This allowed each pilot to fly a worst case condition (although not the most difficult approach) during practice. The flight director failure was repeated until the pilot made a successful landing.

The next day was devoted to data trials. The day was divided into four sessions where each pilot performed three trials in a row before switching seats. The test conductor would inform the flight crew of the approach, the type of navigation display, the throttle mode, and the meteorological conditions at the runway. He would wait until the crew had completed the initial condition checklist and informed the test conductor that they were ready to start. The test conductor would place the simulator in compute. Both the test conductor and the FAA observer would write down any significant malfunctions of the simulator, whether the run ended in a successful landing, and obvious comments made by the pilots. After the crew finished a trial, the FAA observer handed the flight crew a questionnaire specific to that trial. (The questionnaires are presented in Appendix B.) If the flight crew asked specific questions, the test conductor would try to answer them. Otherwise, the test conductor or the FAA observer would not volunteer any information.

5.4 PERFORMANCE CRITERIA AND DEPENDENT MEASURES

5.4.1 Performance Criteria

The primary criteria for determination of a successful approach were the simulated aircraft position, attitude, speed, and sink rate at decision height (200 feet AGL). The other criteria were the root mean square (rms) flight technical error throughout the approach.

Performance criteria for a successful MLS Category I approach have not been established. AC 120-29, "Criteria for Approving Category I and Category II Minima for FAR 121 Operations," (Reference 6) establishes performance criteria for a Category II approach but not for a Category I approach. The criteria for a Category II approach are listed in Table 5-1. These criteria require the aircraft to be within the boundaries of the runway. Kelly (Reference 7) discusses an implied decision window for an MLS Category I approach that requires the aircraft to be within a ± 1-dot course deviation window. For the current study, a successful approach was established as being within the ± 1-dot window, trimmed, within ±5 knots of airspeed, and no adverse bank angle or heading changes required to correct to final course.

Table 5-1
Criteria for a Successful Category II Approach (AC 120-29)

1. THE AIRPLANE IS TRIMMED SO AS TO ALLOW FOR COTINUATION OF NORMAL APPROACH AND LANDING
2. THE INDICATED AIRSPEED AND HEADING ARE SATISFACTORY FOR A NORMAL FLARE AND LANDING. IF AN AUTOTHROTTLE CONTROL SYSTEM IS USED, SPEED MUST BE ± 5 KNOTS OF PROGRAMMED AIRSPEED BUT MAY NOT BE LESS THAN COMPUTED THRESHOLD SPEED.
3. THE AIRPLANE IS POSITIONED SO THAT THE COCKPIT IS WITHIN AND TRACKING SO AS TO REMAIN WITHIN THE LATERAL CONFINES OF THE RUNWAY EXTENDED.
4. DEVIATION FROM GLIDE SLOPE DOES NOT EXCEED ±75 MICROAMPS (1 DOT) AS DISPLAYED ON THE ILS INDICATOR.
5. NO UNUSUAL ROUGHNESS OR EXCESSIVE ATTITUDE CHANGES OCCUR AFTER LEAVING THE MIDDLE MARKER.

5.4.2 Dependent Measures

Both subjective and objective measures were used to evaluate the flight crews' performance on the various approaches. The subjective measures were based on the questionnaire to which the pilots responded after each trial and the posttest questionnaire. The objective measures were parameters recorded by the simulator's computer.

The subjective measures were divided into three categories: (1) pilot workload, (2) flyability of the approach, and (3) operational acceptance of the approach. There were four questions that pertained to workload. Two questions were a comparison of workload with two benchmarks: (1) an ILS precision approach and (2) a VOR nonprecision approach. Two questions were workload ratings, one by the pilot flying and one by the pilot not flying. The scale used for the workload ratings was the modified Cooper-Harper rating (Reference 8). The rating scale is presented in Figure 5-1. There were four questions on the flyability of the approach: (1) the point at which the pilot flying felt that he was stabilized on the approach, (2) whether the turns were too steep, (3) whether the pilot was comfortable with glide path changes during the turn, and (4) whether the length of the final straight segment was long enough. There was one question on the operational acceptance of the approach. In addition, there was a posttest question on the operational acceptance of the MLS curved approaches.

The objective data included missed approaches, performance data for a given segment of flight, and performance data at specific locations on the flight path. The performance data per flight segment included lateral and vertical deviation data, amount of control activity as a workload measure, and ride comfort data. The deviation data included root-mean-square flight technical error per unit time, the average flight technical error per unit time, and the maximum flight technical error. Control activity was the total number of control inputs per unit time. A control input was defined as any movement of the controls that was greater than 2.5 percent of full-scale deflection. For manual throttles, it included wheel, column, rudder pedals, pitch trim, and throttle activity. For autothrottles, it included wheel, column, rudder pedals, and pitch trim activity. Ride quality data included maximum bank angle, maximum vertical and lateral acceleration, and the number of acceleration changes per unit time greater than 0.05 g. The data at specific locations included the aircraft position in three axes, attitude in three axes, airspeed, descent rate, and flight director errors.

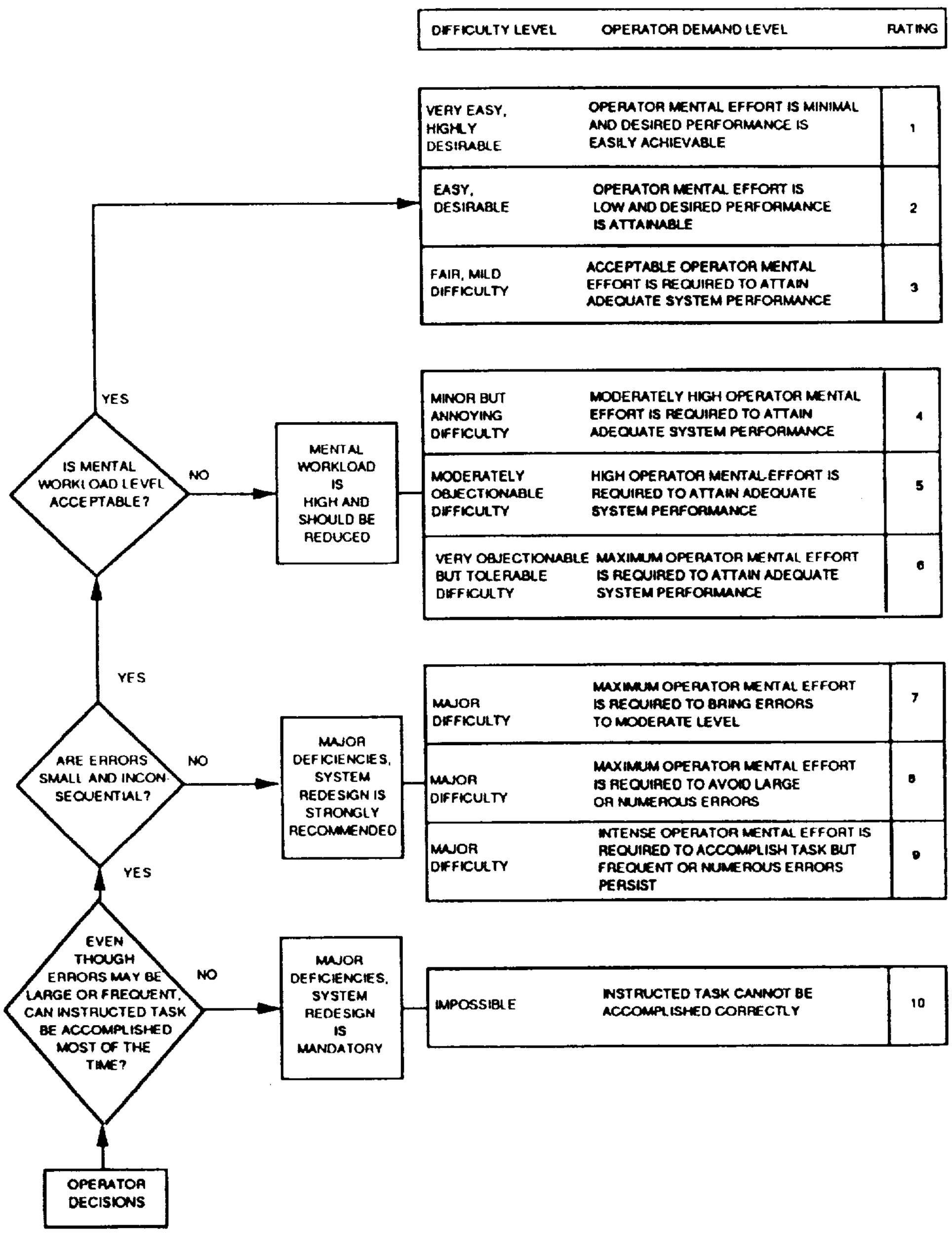


Figure 5-1. Modified Cooper-Harper Workload Rating Scale

SECTION 6
TEST RESULTS

6.1 OVERVIEW

Subjective data were collected from all 600 experimental trials. Objective data were collected from 594 trials. On the EWR-11 trials, there were 57 out of 100 trials with missing touchdown data and 37 trials with missing decision height data. This occurred because the data record was shorter than the trial length. There were 15 additional trials with data missing at decision height and touchdown due to simulator failures.

The results are presented in four parts: (1) a summary of the statistical analyses, (2) the subjective results of the main experiment, (3) the objective results of the main experiment, and (4) the subjective and objective results for the failure scenarios.

6.2 SUMMARY OF THE STATISTICAL ANALYSES

The subjective results were analyzed by contingency analysis using the Chi Square statistical test. The contingency analysis determines if there is a difference in the pilot's response to the questions as a function of the experimental conditions. The statistical results are presented in Appendix C. The only experimental variable that was statistically significant was the approach. The other variables, (type of display, throttle mode, and wind direction) were not significant.

The objective measures were initially analyzed by the analysis of variance (ANOVA) statistical test. Since it was a fractional factorial design, three ANOVAs with one between-group variable and two within-group variables were performed on each dependent measure. The within-group variables were approach by navigation display, approach by throttle mode, and approach by wind direction. The between-group variable was the first and second pilot of a flight crew. The probability level for significance (the probability due to the chance of accepting a difference between the experimental conditions when there is none) was selected at 0.01 because of the large number of dependent variables and the large sample size. Summary tables of the ANOVA tests are provided in Appendix C. If an independent variable or the interaction of two variables was significant, the standard error of the mean was obtained for each level of the variable to determine which levels differed from each other. These results are summarized by data plots showing the average value across pilots and the $\pm$ 1 standard error of the mean. These plots are presented in Appendix C.

There were no significant differences between the two pilot groups, i.e., the first and second pilot of a flight crew. There were no interactions between the two groups and any of the other variables. Generally, the approaches were significantly different for the majority of the performance measures. There were significant differences between the other test conditions, i.e., navigation display, throttle mode, and wind direction with some of the dependent variables. There were some interactions of these conditions with approaches. These significant differences will be discussed in the objective results section.

6.3 SUBJECTIVE RESULTS

The subjective results are divided into pilot workload, subjective opinion on the flyability of an approach, and acceptance of an approach. These are in response to the specific questions in the questionnaires. There were significant differences between the approaches for all of these measures. Responses to these questions are presented by the percentage of pilots making the same response. In addition, the pilots made individual comments pertaining to workload, flyability, operational acceptance, the display, and the approach charts. The comments were tabulated and are presented as the percentage of pilots (the number is presented in parenthesis) making the same or similar comments.

6.3.1 Pilot Workload

Subjective rating of the pilot flying's workload was performed in three ways: (1) comparison with workload for an ILS precision approach as a benchmark, (2) comparison with a VOR nonprecision approach as benchmark, and (3) rating the workload on a 10-point scale using a modified Cooper-Harper scale. The comparison of the five approaches to an ILS approach is shown graphically in Figure 6-1, and the VOR comparison is shown in Figure 6-2. The JFK-31R approach was rated the same as the ILS, while all four curved approaches were rated as more difficult. The degree of difficulty depended upon the complexity of the approach. LGA-13 and JFK-13R have approximately the same difficulty level, and EWR-11 and DCA-18 are increasingly more difficult. In comparison with a nonprecision VOR approach, the majority of pilots thought that LGA-13, JFK-13R, and EWR-11 were the same or easier while DCA-18 was more difficult.

The pilots were asked to perform the same comparisons on the posttest questionnaire for all of the curved approaches. The results are shown in Figure 6-3. These results show that, overall, the pilots thought that MLS curved approaches were more difficult than ILS precision approaches but the same as or easier than VOR nonprecision approaches.

The modified Cooper-Harper workload ratings for the pilot flying are presented in Figure 6-4. The figure shows that most pilots gave the JFK-31R approach a workload rating between 2 and 3. Except for DCA-18, the majority of pilots rated the curved approaches between 3 and 4, and for the DCA-18 approach between 3 to 6. Three pilots gave DCA-18 a 9 rating and two gave it a 10. Twenty-four percent of the pilots (12) made comments about the difficulty of the DCA-18 approach. The general comments were that there were too many turns, and the last turn occurred too close to the ground.

The pilot not flying was asked to rate his workload using the modified Cooper-Harper rating scale since he had additional tasks in comparison to an ILS approach. Figure 6-5 shows the ratings according to approach. The workload was a function of the number of waypoint checks required on the approach. The waypoint checks received a number of comments which are listed in Table 6-1.

6.3.2 Flyability of the Approaches

There were four questions that dealt with the flyability of the approaches. These were (1) the point at which the pilot flying felt he was stabilized, (2) whether he considered any of the turns too steep, (3) whether he was comfortable with the glide path changes during a turn, and (4) whether the final straight segment was long enough.

Since the definition of stabilization was left up to the pilots, they responded by either giving an altitude, an along-track distance, or a waypoint at which they felt they were stabilized. These data points were converted to along-track distances. The data were divided into increments of 0 to 0.5, 0.5 to 1.0, 1.0 to 2.0, 2.0 to 4.0, 4.0 to 8.0, and greater than 8.0 nautical miles. These categories correspond to above ground level altitudes of 160, 320, 640, 1,280, and 2,560 feet, respectively. The results for the different approaches are presented in Figure 6-6. The results show that the approaches with a straight segment longer than 1.0 nautical mile, 89 percent of the trials were stabilized by 1.0 nautical mile. For the JFK-13R approach, 90 percent were stabilized by 0.50 nautical mile, and for the DCA-18 approach only 78 percent were stabilized by 0.5 nautical mile.

The responses to the other questions are presented in Figure 6-7. For steepness of turns, JFK-13R and DCA-18 had a higher number of "yes" responses than the other two curved approaches. Most

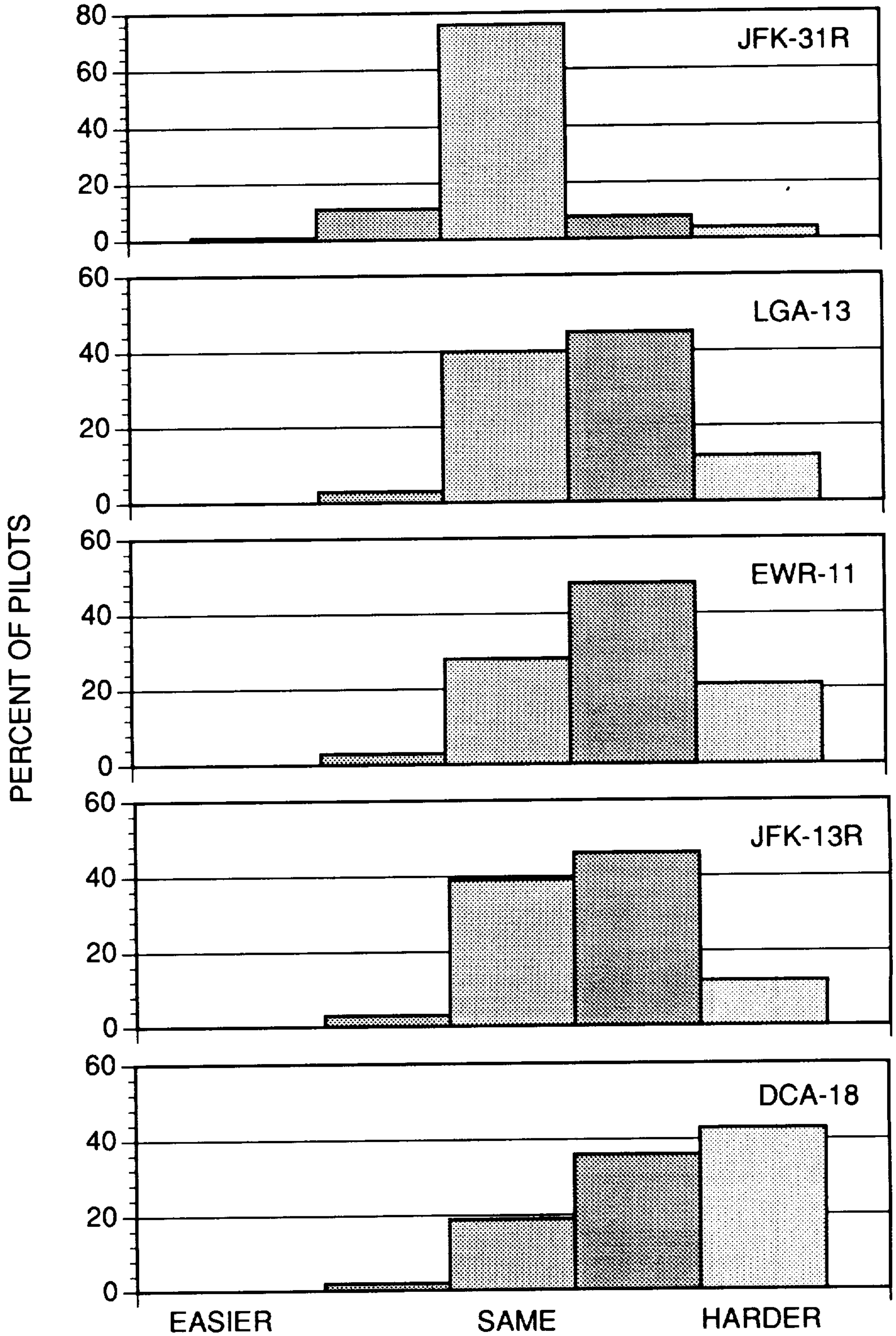


Figure 6-1. Pilots' Response to the Question, "Was the Approach More Difficult Than an ILS Precision Approach?"

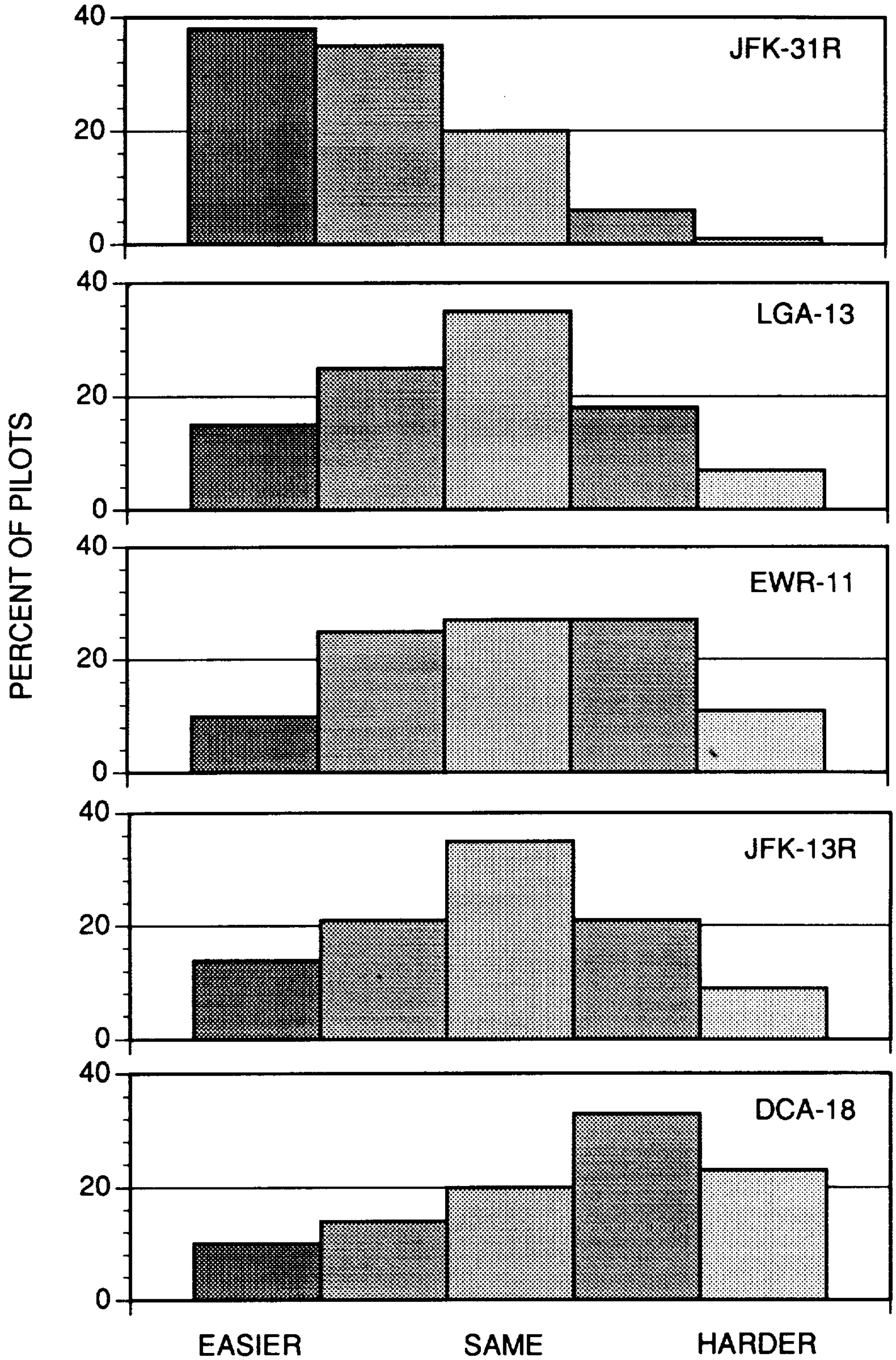


Figure 6-2. Pilots' Response to the Question, "Was the Approach More Difficult Than a Nonprecision VOR?"

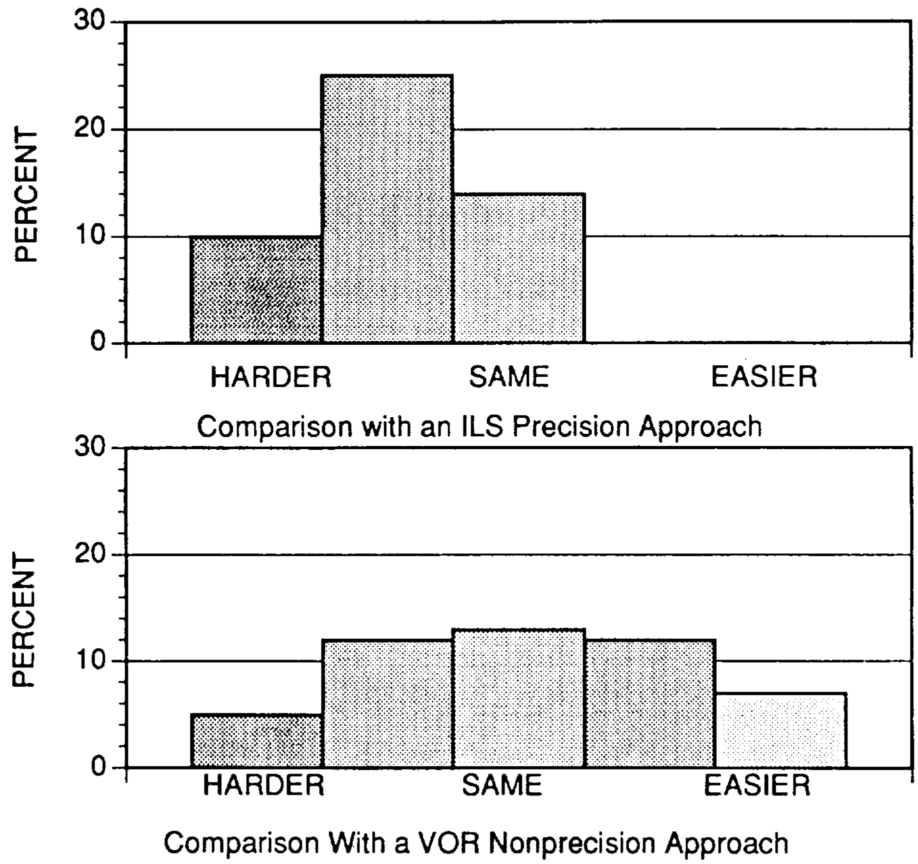


Figure 6-3. Posttest Question on the Workload Comparison of MLS Curved Approaches With Other Approaches

of the pilot comments applied to the final turn at LEDIN on the DCA-18 approach. The general comment was that the turn was too steep for that low of an altitude (320 feet), especially with a right crosswind.

For the comfort rating of the glide path changes during a turn, most of the "no" responses occurred at the level-off at the BEERS turn on EWR-11. The pilot comments on the glide path changes during a turn and the percentage of pilots making them are listed in Table 6-2. Again, the majority of the comments were related to the level-off on EWR-11.

The "no" responses to the question on the adequacy of the final straight segment increased with a decrease in the final straight segment length. The majority of the comments made in relation to the approaches were on DCA-18. Fifty percent of the pilots thought the turn was too low to adequately stabilize the aircraft with the crosswind used in the evaluation.

It should be noted that FAA Order 8260.36 (Reference 5) does not permit the design of procedures for Category D aircraft that generated these comments; i.e., straight-in segments less than 3.7 miles, turn radii less than 1.75 miles, and the level-off procedure in EWR-11.

6.3.3 Operational Acceptance of the MLS Curved Approaches

The pilots were asked after each trial whether or not an approach was operationally acceptable. The "yes" responses are presented in Figure 6-8. These responses are very similar to the acceptability of

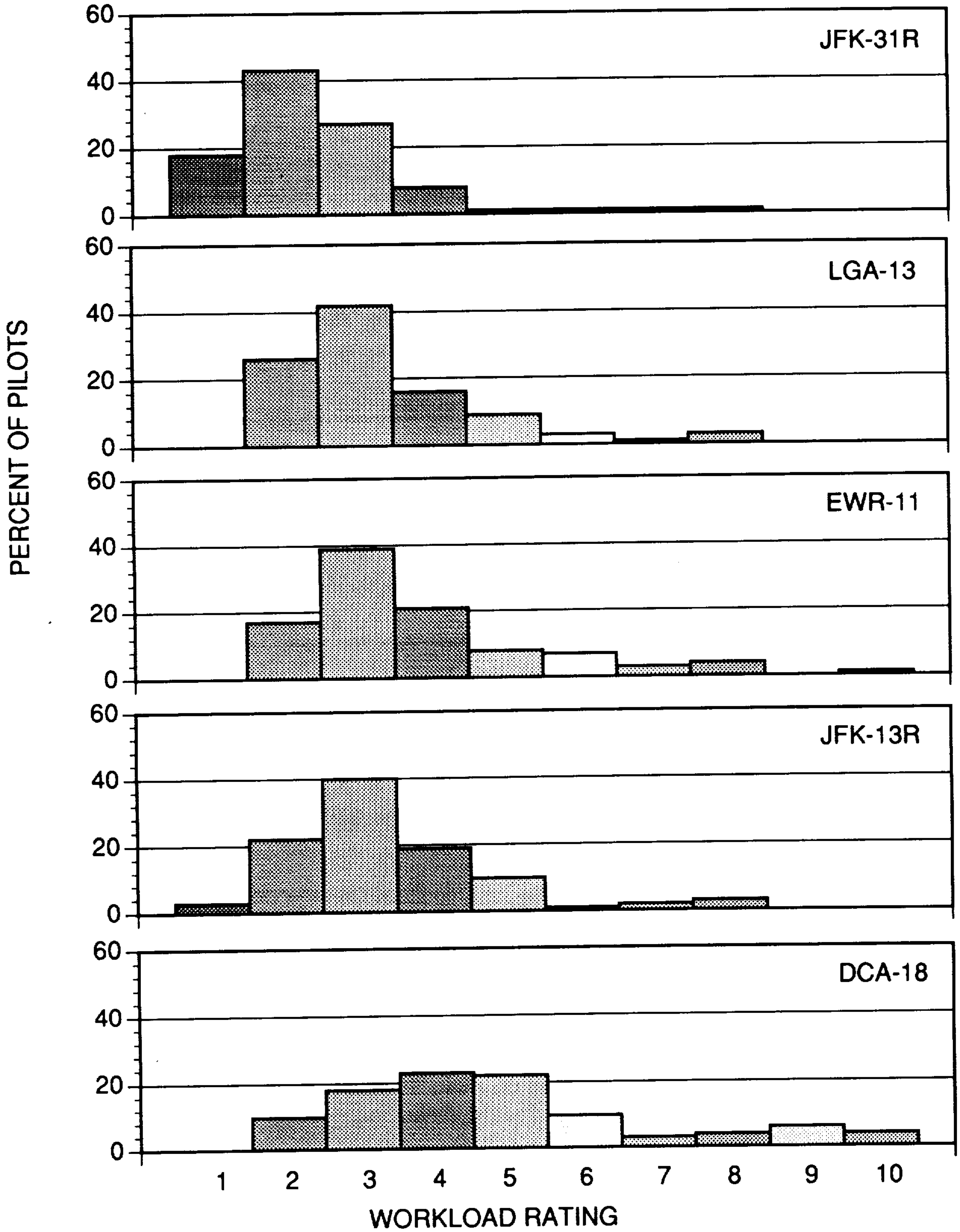


Figure 6-4. Modified Cooper-Harper Workload Ratings for the Pilot Flying

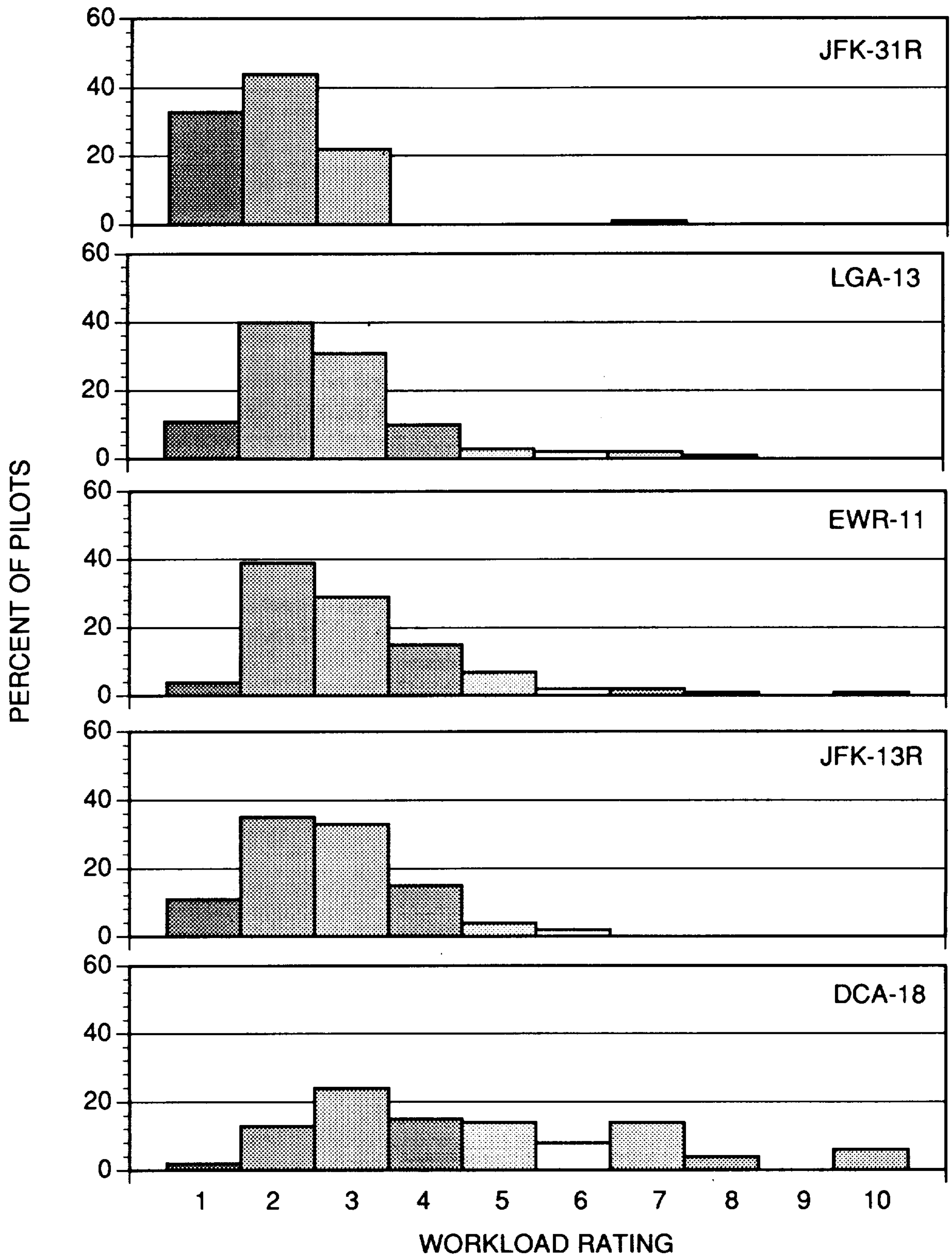


Figure 6-5. Modified Cooper-Harper Workload Ratings for the Pilot Not Flying

Table 6-1.
Pilot Comments on Cross-Checking the Bearing and Range at or Abeam of the Waypoints Against the Data on the Approach Plate

	PILOT COMMENT	PERCENT (NUMBER)
1.	CROSS-CHECKING OF THE WAYPOINT DATA IS UNNECESSARY.	8% (4)
2.	ONLY TWO WAYPOINT CROSS-CHECKS SHOULD BE REQUIRED PER APPROACH.	6% (3)
3.	WAYPOINT CROSS-CHECKS SHOULD NOT OCCUR BELOW THE FINAL APPROACH FIX.	6% (3)
4.	ONLY ONE CROSS-CHECK SHOULD BE REQUIRED PER APPROACH.	4% (2)
5.	CROSS CHECKS OF WAYPOINTS ARE NECESSARY.	4% (2)

the length of the final straight segment. Both the operational acceptance of the approach and the acceptability of the final segment length are plotted against the length of the final straight segment in Figure 6-9. This figure shows the strong correlation between pilot acceptance and the final segment length. In addition, these results are almost identical to the results obtained in the study at the Netherlands Aerospace Laboratory (Reference 1). The fact that both studies obtained the same results on pilot acceptance validates these findings.

Prior to presenting the briefing and the test runs, the pilots were asked their opinion of MLS. These results are presented in Table 6-3 along with the posttest question on operational acceptance of curved approaches. Only two pilots (a flight crew) thought that the curved approaches were unacceptable. The reasons given by that crew were, "The curved approaches were too busy with more than one turn, and the final straight segment was too short and close to the ground." The pilots who responded with conditional acceptance gave a number of reasons, which are listed in Table 6-4. The primary reasons are (1) the final straight segment needs to be long enough to stabilize the aircraft, (2) the map mode of the navigation display is required for situational awareness, (3) a flight director is required, and (4) less complicated approaches are required; i.e., a constant glide path and a limited number of turns. Only one pilot was concerned with missed approaches despite the number of missed approaches experienced by the pilots.

6.3.4 Other Comments

On the posttest questionnaire, the pilots were asked to comment on the displays and the approach charts. These comments are presented in Table 6-5. The most numerous comments on the primary flight display were due to the fact that the display area of the simulator's CRTs are 10 percent smaller than the MD-11 CRTs. This caused the displays to appear more cluttered and reduced the character size. The change in sensitivity of the CDIs from computed guidance to angle-only guidance was noticeable and received a number of written and verbal comments.

Since the pilots were required to cross-check the raw data with the bearing and range data on the approach charts, the location and readability of this information received a number of comments. Bearing Pointer 1 on the navigation display was used to present the raw data from the MLS transmitters. Sixteen pilots thought it should be located in a more obvious location and be easier to read. Twenty-four pilots thought that the waypoint data should be easier to read on the approach charts. In addition, 16 pilots thought that the approach charts were generally too cluttered. If cross-checking of the waypoint data is a standard feature of the MLS curved approach procedures, more attention must be paid to the presentation of the bearing and range data in the design of the display formats and the approach charts.

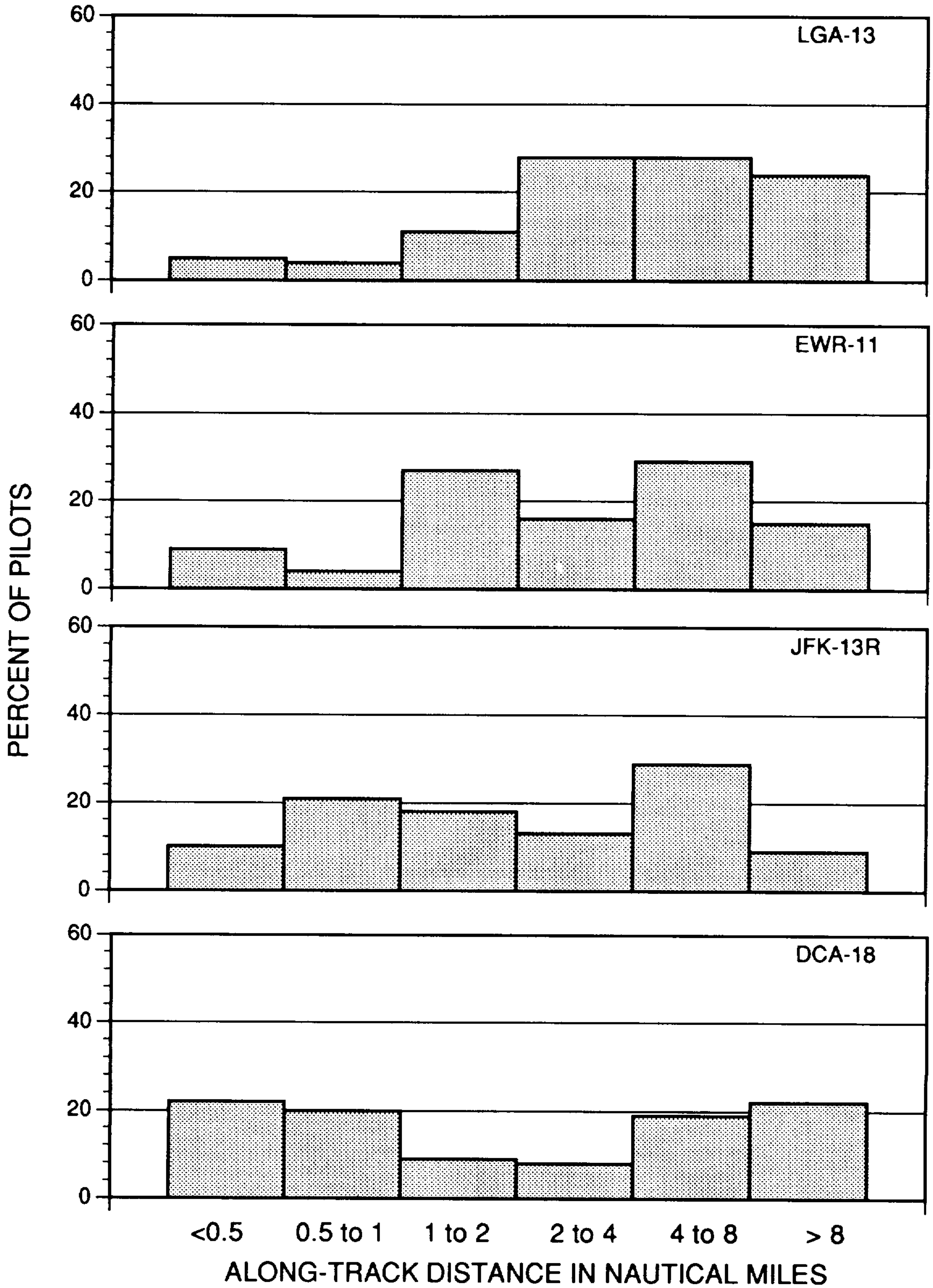
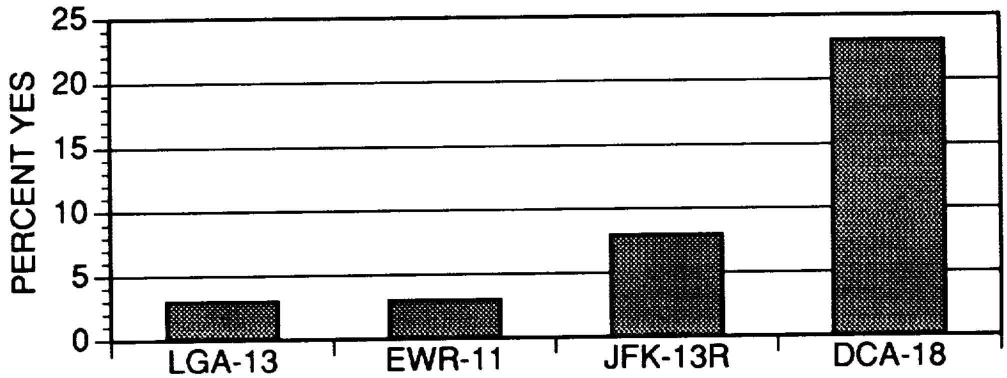
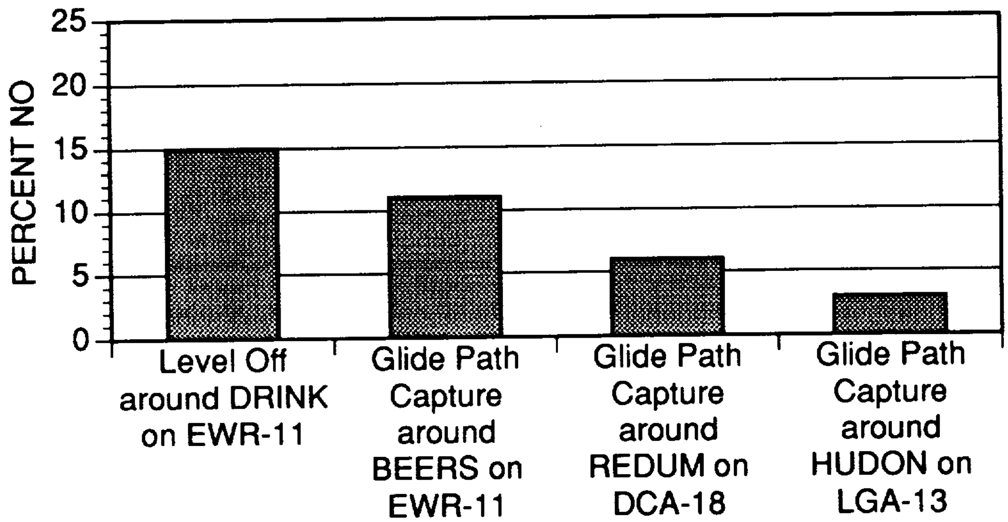


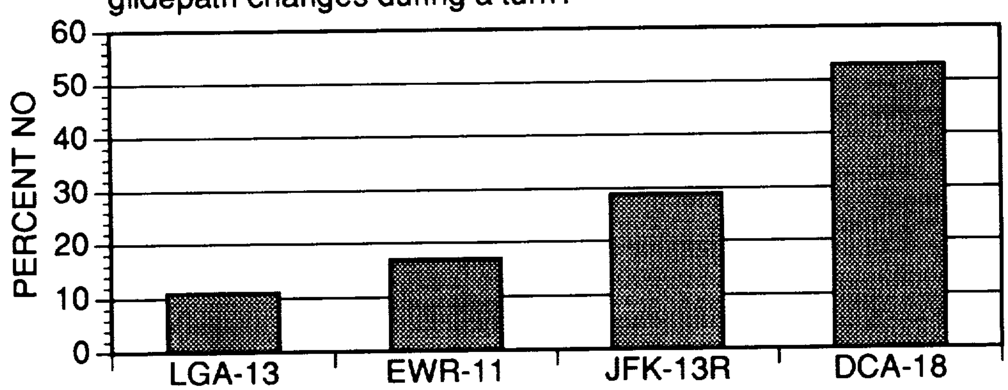
Figure 6-6. The Along-Track Distance at Which the Pilot Indicated That He Was Stabilized



Responses to the question, "Are any turns too steep?"



Responses to the question, "Are you comfortable with the glidepath changes during a turn?"



Responses to the question, "Is the final straight segment adequate for the approach?"

Figure 6-7. Responses to the Questions on the Flyability of the Approaches

Table 6-2
Pilot Comments on Glide Path Changes During the Turns

	COMMENT	PERCENT (NUMBER)
1.	THE GLIDE PATH CHANGES MAKE THE TURNS TOO BUSY.	6% (3)
2.	WITH THAT MANY CHANGES, IT IS TOO EASY TO MAKE A MISTAKE.	2% (1)
3.	ALL GLIDE PATH CHANGES SHOULD OCCUR WHEN WINGS ARE LEVEL.	2% (1)
4.	WOULD PREFER A CONSTANT DESCENT INSTEAD OF THE LEVEL OFF.	2% (1)

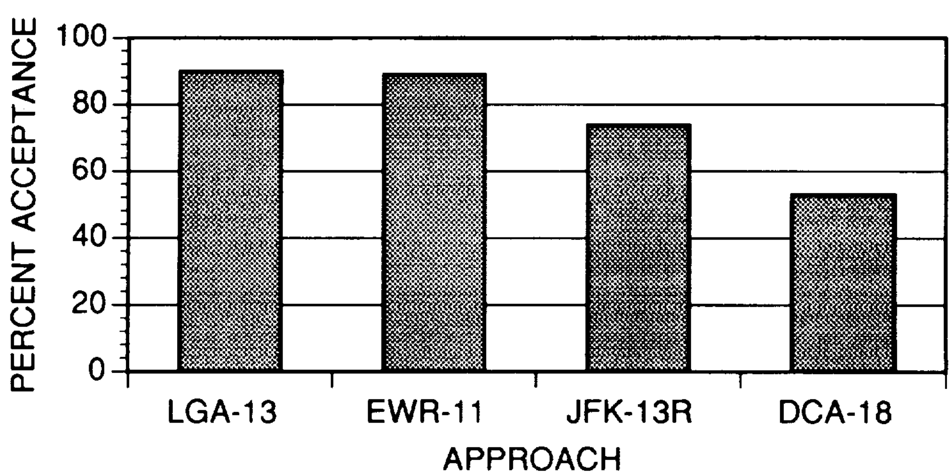


Figure 6-8. Pilots' Response to the Question of Whether the Approach Is Operationally Acceptable

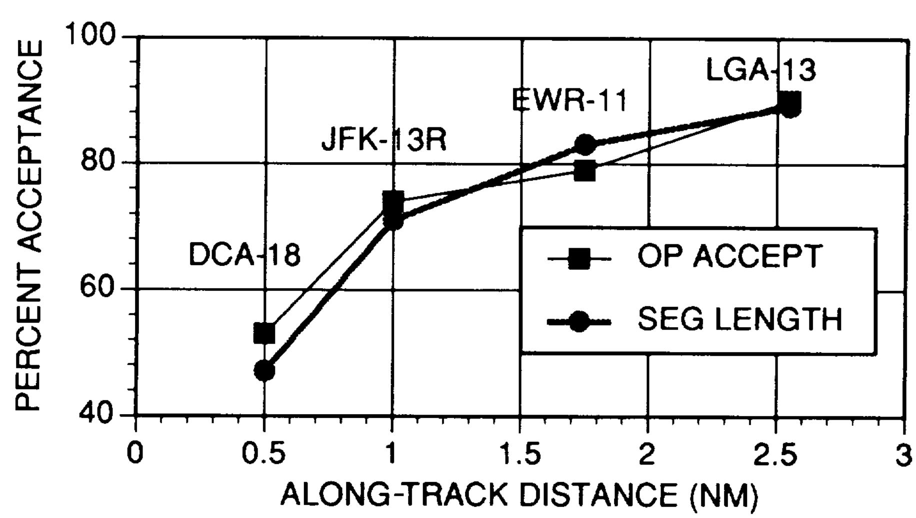


Figure 6-9. Pilot Acceptance of the Approach and the Segment Length Plotted Against the Final Straight Segment Length for the Different Approaches

Table 6-3
Pretest Opinion and Posttest Acceptance of MLS Curved Approaches.

PRETEST OPTION		POSTTEST ACCEPTANCE	
GOOD POTENTIAL	50% (25)	UNCONDITIONAL	44% (22)
OTHER METHODS ARE BETTER	12% (6)	CONDITIONAL	52% (26)
NO OPINION	38% (19)	UNACCEPTABLE	4% (2)

Table 6-4
Pilot Comments on the Conditional Acceptance of the MLS Curved Approaches

	PILOT COMMENT	PERCENT (NUMBER)
1.	FINAL STRAIGHT SEGMENT NEEDS TO BE LONG ENOUGH TO STABILIZE THE AIRCRAFT.	34% (9)
2.	MAP MODE OF THE NAVIGATION DISPLAY IS REQUIRED.	31% (8)
3.	FLIGHT DIRECTOR GUIDANCE IS REQUIRED.	18% (5)
4.	LESS COMPLICATED APPROACHES ARE REQUIRED.	18% (5)
5.	THE SIMULATOR IS INADEQUATE TO EVALUATE THE APPROACHES.	8% (2)
6.	THE GLIDE PATH SHOULD BE INTERCEPTED PRIOR TO THE TURNS.	4% (1)
7.	IT WILL DEPEND UPON THE WIND AND WEATHER CONDITIONS.	4% (1)
8.	IT WILL REQUIRE ADEQUATE TRAINING OF THE PILOTS.	4% (1)
9.	MINIMA SHOULD BE A 1000-FOOT CEILING AND A RVR OF 3 MILES UNTIL FAILURE MODES ARE TESTED.	4% (1)
10.	THE GO-AROUND QUESTION REQUIRES RESOLUTION.	4% (1)

6.4 OBJECTIVE TEST RESULTS

The objective results included (1) the number of missed approaches, (2) the performance data per flight segment, and (3) performance data at decision height and touchdown. The flight segment data included track deviation data, maximum bank angle, control activity, and ride quality data. The performance data at decision height included the error windows and the stabilization data, and at touchdown, it included the dispersion data, flight path errors, and vertical speed.

6.4.1 Missed Approaches

Of 478 trials without a flight director failure or engine fire warning, there were 17 missed approaches or 3.5 percent. These included incidences wherein the pilot flying declared a missed approach and proceeded to go around and cases where the pilot landed but the touchdown position was outside the runway boundary. The latter were considered missed approaches since the pilot should have elected to go around before he landed.

The distribution by approach of the 17 missed approaches is shown in Figure 6-10. There were more missed approaches with DCA-18, which was the most complex approach path. Otherwise, this distribution appears to be random and not correlated with the final segment length. This is due to the small

Table 6-5.
Pilot Comments on the Display Formats

COMMENTS	PERCENT (NUMBER)
PRIMARY FLIGHT DISPLAY	
1. DISPLAY IS TOO CLUTTERED.	14% (7)
2. CHARACTER SIZES ARE TOO SMALL.	10% (5)
3. THE CDI 'S FLASH RATE SHOULD BE HIGHER.	6% (3)
4. THE ALONG-TRACK DISTANCE AND DISTANCE TO NEXT WAYPOINT SHOULD BE IN A MORE OBVIOUS LOCATION.	4% (2)
5. THE COMPUTED COURSE INDICATOR ON PARTIAL COMPASS ROSE IS CONFUSING.	4% (2)
6. THE CDI INDICATORS SHOULD ONLY BE SOLID DURING TURN OR GLIDE PATH INTERCEPT.	2% (1)
7. THE CDI'S ARE CONFUSING.	2% (1)
8. THE CDI SENSITIVITY CHANGE FROM COMPUTED TRACK TO ANGLE-ONLY TRACKING IS UNACCEPTABLE.	8% (4)
9. THE COLOR CHANGE OF THE CDI'S INDICATORS FROM MAGENTA TO WHITE IS AGAINST AC-25-11.	4% (2)
10. THE AIRSPEED TREND VECTOR IS TOO SENSITIVE.	4% (2)
11. THE FLIGHT MODE ANNUNCIATOR SHOULD BE REVISED.	2% (1)
12. THE ALONG-TRACK DISTANCE AND DISTANCE TO NEXT WAYPOINT SHOULD BE REMOVED FROM THE PFD.	2% (1)
13. THE MINIMA WARNING IS NOT ADEQUATE.	2% (1)
14. TOO MUCH EYE SCAN IS REQUIRED.	2% (1)
15. THE PARTIAL COMPASS ROSE SHOULD BE TRACK INSTEAD OF HEADING ORIENTED.	2% (1)

Table 6-5
Pilot Comments on the Display Formats
(Continued)

COMMENT		PERCENT (NUMBER)
NAVIGATION DISPLAY		
1.	BEARING/RANGE READOUT OF RAW DATA IS TOO SMALL.	8% (4)
2.	BEARING/RANGE READOUT OF RAW DATA SHOULD BE IN A MORE OBVIOUS PLACE.	10% (5)
3.	THE APPROACH MODE (HSI) IS UNSATISFACTORY.	4% (2)
4.	ALTITUDE DATA SHOULD BE PLACE ON THE MAP.	2% (1)
5.	GLIDE PATH INTERCEPT POINTS SHOULD BE PLACED ON THE MAP.	2% (1)
6.	THE MAP SHOULD HAVE A FULL COMPASS ROSE.	2% (1)
7.	MAP DOES NOT HAVE ENOUGH RESOLUTION TO FLY BY.	2% (1)
8.	THE MAP AIRCRAFT SYMBOL IS TOO COMPLEX FOR ACCURATE TRACKING.	2% (1)
APPROACH CHARTS		
1.	THE CHARTS, ESPECIALLY DCA-18, ARE TOO CLUTTERED AND DIFFICULT TO READ.	32% (16)
2.	THE WAYPOINT DATA SHOULD BE ARRANGED SEQUENTIALLY FOR EASE IN READING.	8% (4)
3.	THE WAYPOINT DATA SHOULD BE IN BLOCKS OR DIRECTLY BELOW THE WAYPOINT ON THE PLAN VIEW.	4% (2)
4.	THE WAYPOINT DATA SHOULD BE ON THE PROFILE VIEW.	4% (2)
5.	THE WAYPOINTS SHOULD BE ON THE FLIGHT PATH INSTEAD OF ABEAM.	4% (2)
6.	THE FINAL APPROACH FIX SHOULD BE ON THE PLAN VIEW.	2% (1)
7.	THE TURNS SHOULD BE ON THE PROFILE VIEW.	2% (1)
8.	ELIMINATE THE TURN INTERCEPT POINTS.	2% (1)
9.	PLACE THE REQUIRED SPEEDS AND CONFIGURATION ON THE CHARTS.	2% (1)

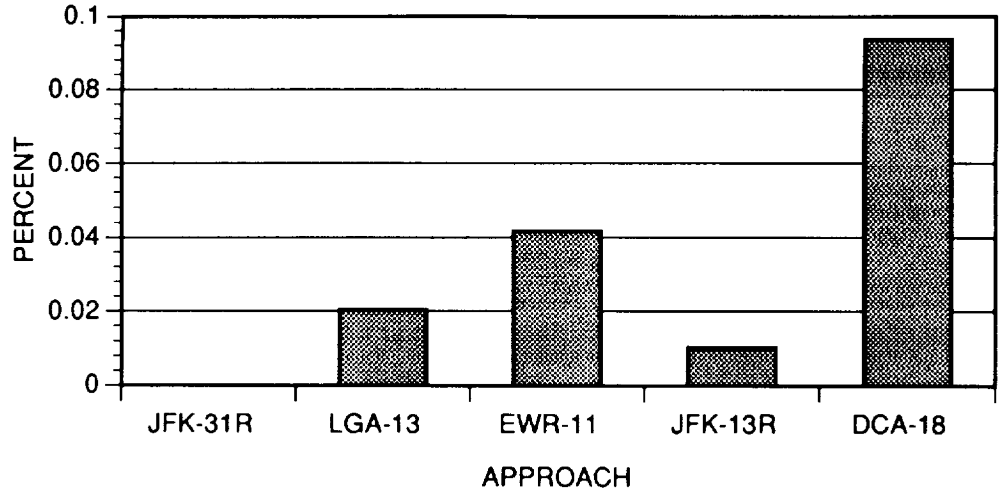


Figure 6-10. The Percent of Missed Approaches for the Different Approaches

sample size and the low probability of occurrence of the missed approaches. Also, the missed approaches were not correlated with any other test condition, i.e., type of navigation display, throttle mode, or wind direction.

6.4.2 Performance Data per Flight Segment

Each approach path was divided into four segments. These are illustrated in Figure 6-11. The first segment was path capture until 3.62 nautical miles along-track distance (ATD). This was based upon this segment's having a constant CDI sensitivity where the full-scale lateral deflection was ± 1,500 feet and the vertical deflection was ± 250 feet. The different approaches have different lengths for this segment, and there are a different number of turns. The second segment was from 3.62 nautical miles ATD to the last turn completion point (LTCP). All the curved approaches had one turn within 3.62 nautical miles; DCA-18 had two turns. The along-track distances of the LTCPs were different, which meant the segment lengths were different. The third segment was from the LTCP to decision height (200 feet above ground level), which also had different segment lengths depending upon the approach. In the third segment, the CDI sensitivity switches from computed deviation to ILS equivalent deviation, as described in Section 2.4. The final segment was from decision height to touchdown, which was identical for all the approaches.

Only three segments were used for JFK-31R because it was a straight-line approach after path capture. These segments were from glide path capture to 3.62 nautical miles, 3.62 to decision height, and decision height to touchdown. The second segment of JFK-31R was considered equivalent to the second and third segments of the curved approaches.

6.4.2.1 Track Deviation Data Versus Approach — The primary measure of tracking performance is the root-mean-square (rms) flight technical error over the flight segment. (The root-mean-square error is the square root of the sum of the squares of the flight technical error for each time increment divided by the total number of time increments.) The flight technical error is the difference between the indicated position and the commanded position of the simulated aircraft. The other measures of performance were the average flight technical error and the maximum flight technical error within a flight segment.

The statistical tests in Appendix C show that the lateral errors for the different approaches were significantly different for every flight segment. The lateral rms flight technical error averaged across

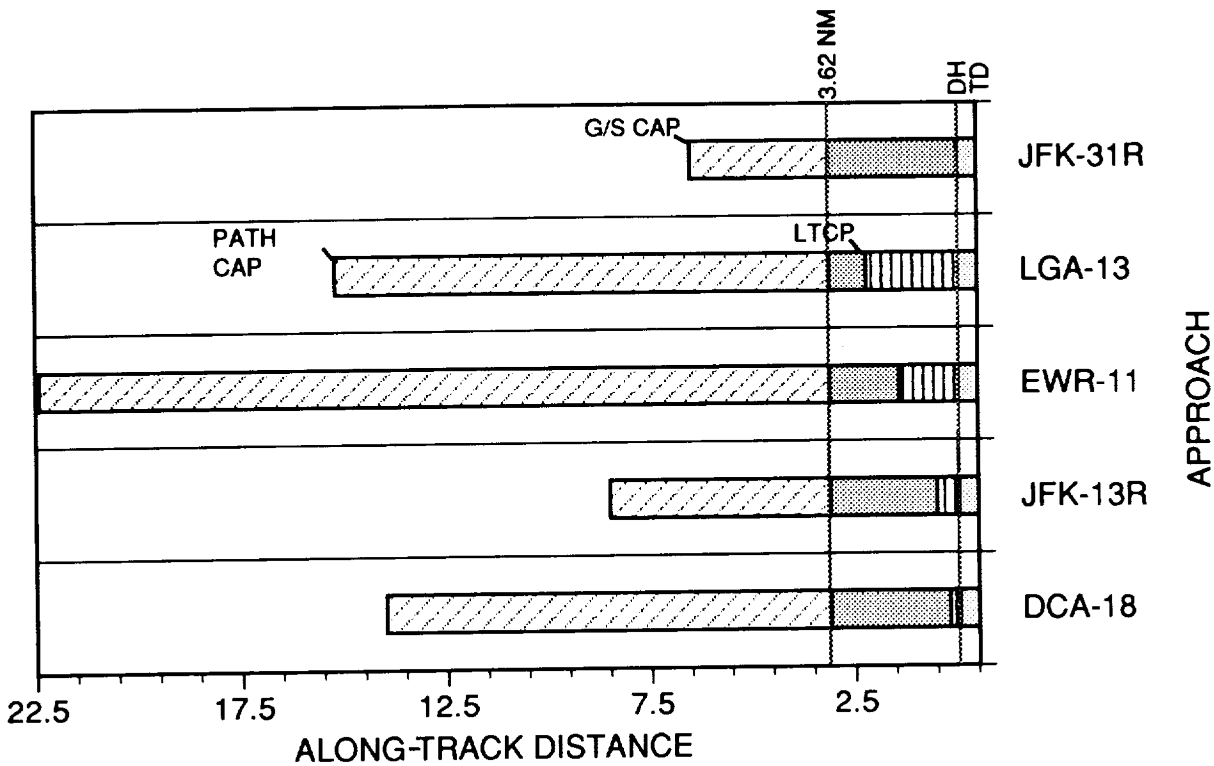
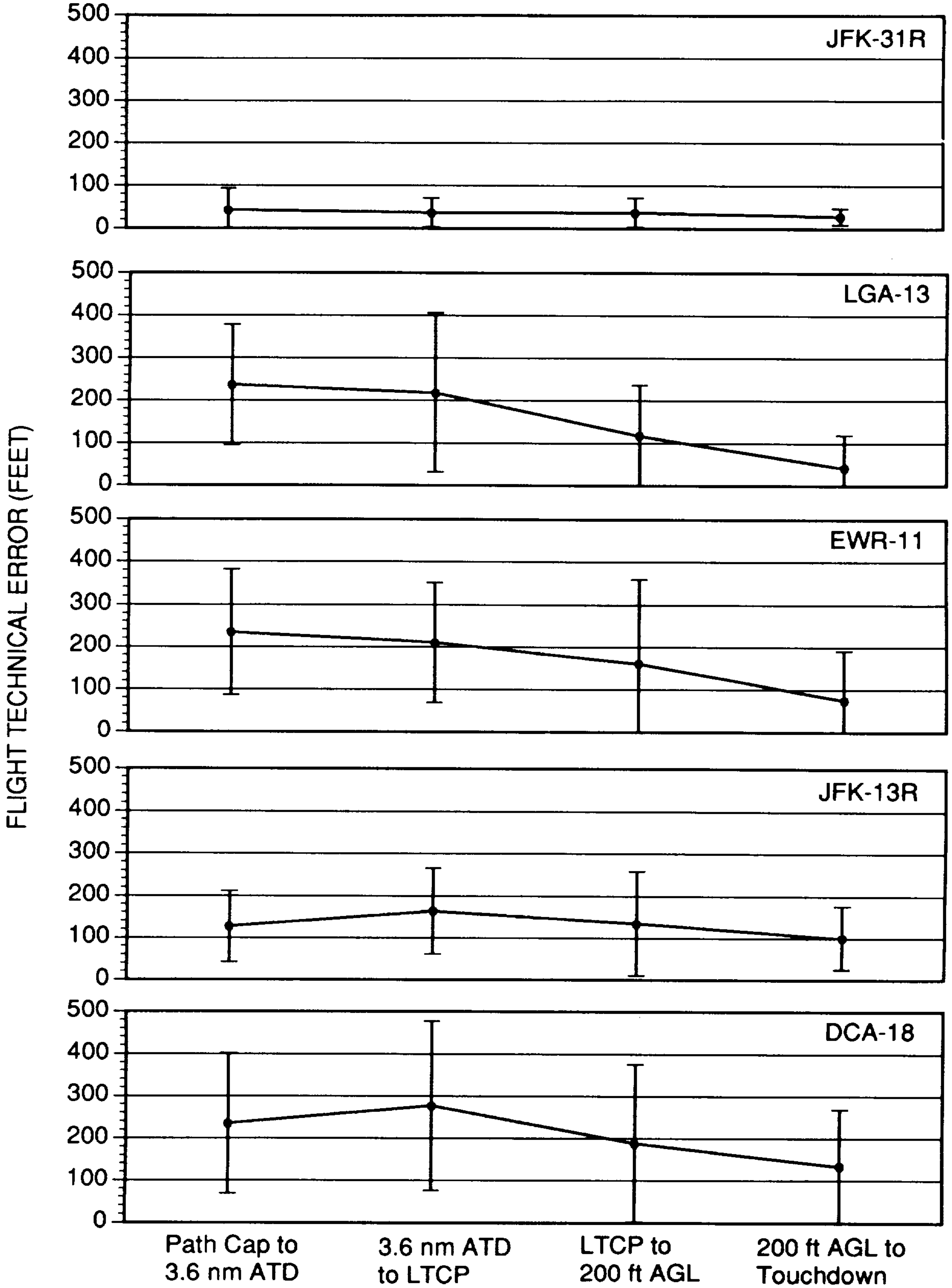


Figure 6-11. Flight Segment Length for the Different Approaches

pilots for the five approaches are presented in Figure 6-12. For the first flight segment, the average rms flight technical errors were (1) 240 feet for the approaches with turns; (2) 130 feet for JFK-13R, which did not have a turn within the first segment; and (3) 50 feet for the straight-in approach at JFK-31R. The second segment showed the lateral errors decreased for all the curved approaches except DCA-18. For the third and fourth segment, the rms errors continued to decrease. These decreases are related to the increase in both the CDI sensitivity and the flight director gain. The maximum absolute flight technical errors for each segment are shown in Figure 6-13. These results show the same trend as the rms tracking errors.

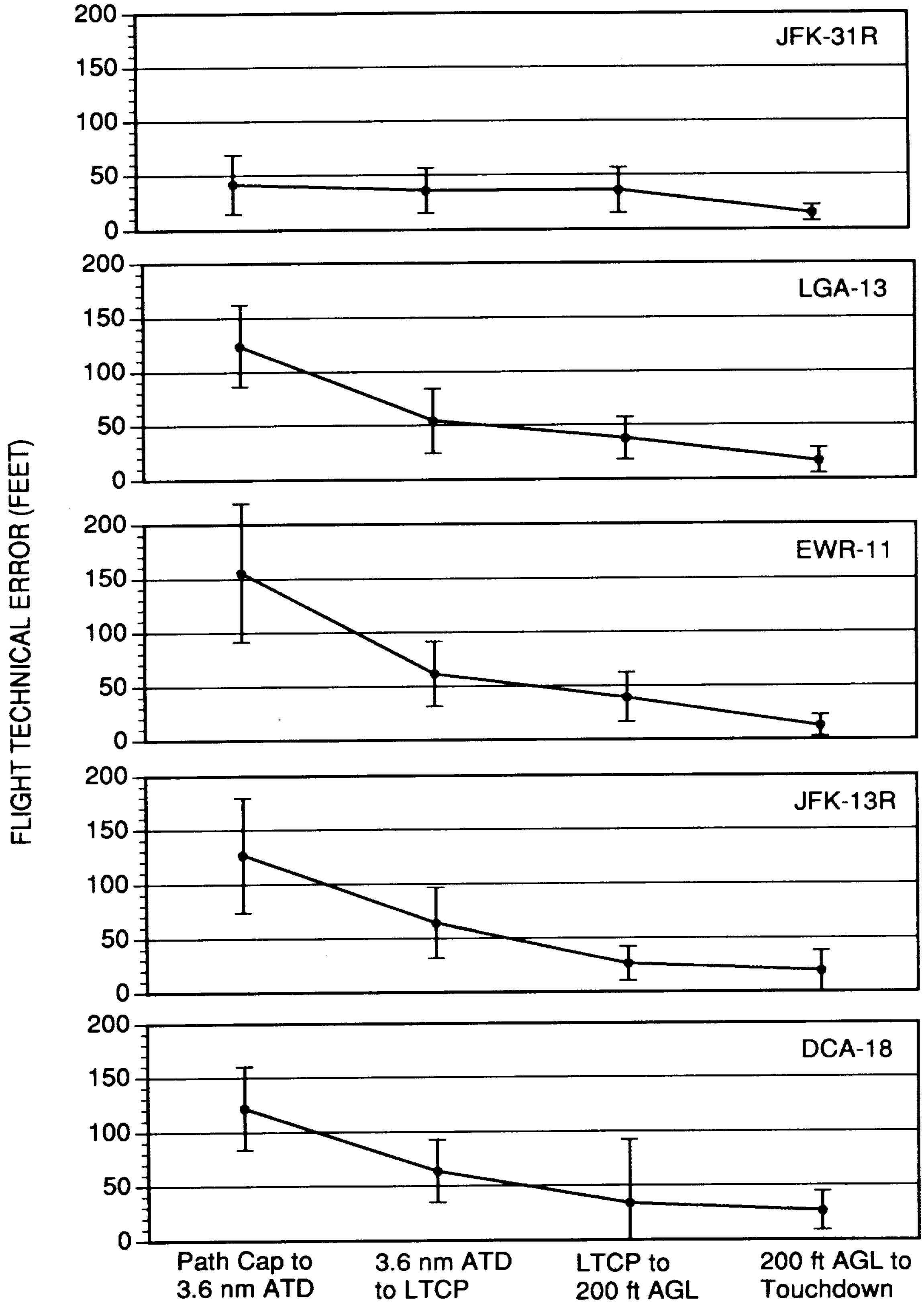
The vertical rms flight technical errors averaged across pilots for the different approaches are presented in Figure 6-14. This shows that all four curved approaches have similar vertical performance, while the straight-in approach (JFK-31R) had less error. It also shows that the rms error decreases steadily with an increase in CDI sensitivity. The maximum absolute vertical flight technical errors averaged across pilots are shown in Figure 6-15. These results show the same trend as the rms tracking errors.

6.4.2.2 Effects of Other Test Conditions on Track Deviations — The effects of the other test conditions depended upon the flight segment. The throttle mode and the wind direction had significant differences, as presented in Appendix C. Autothrottles had less lateral rms errors from path capture to LTCP and less vertical rms errors from 3.62 nautical miles to LTCP. There were no significant interactions of autothrottles with the approaches. Autothrottles allowed the pilots to focus their attention more on flight path performance instead of having to divide it with speed control. The left wind had more lateral rms error than the right wind between path capture and 3.62 nautical miles ATD and from decision height to touchdown. There was a significant interaction between wind direction and approach for the average lateral error from decision height to touchdown. This depended upon the direction of the final turn and the direction of the wind.



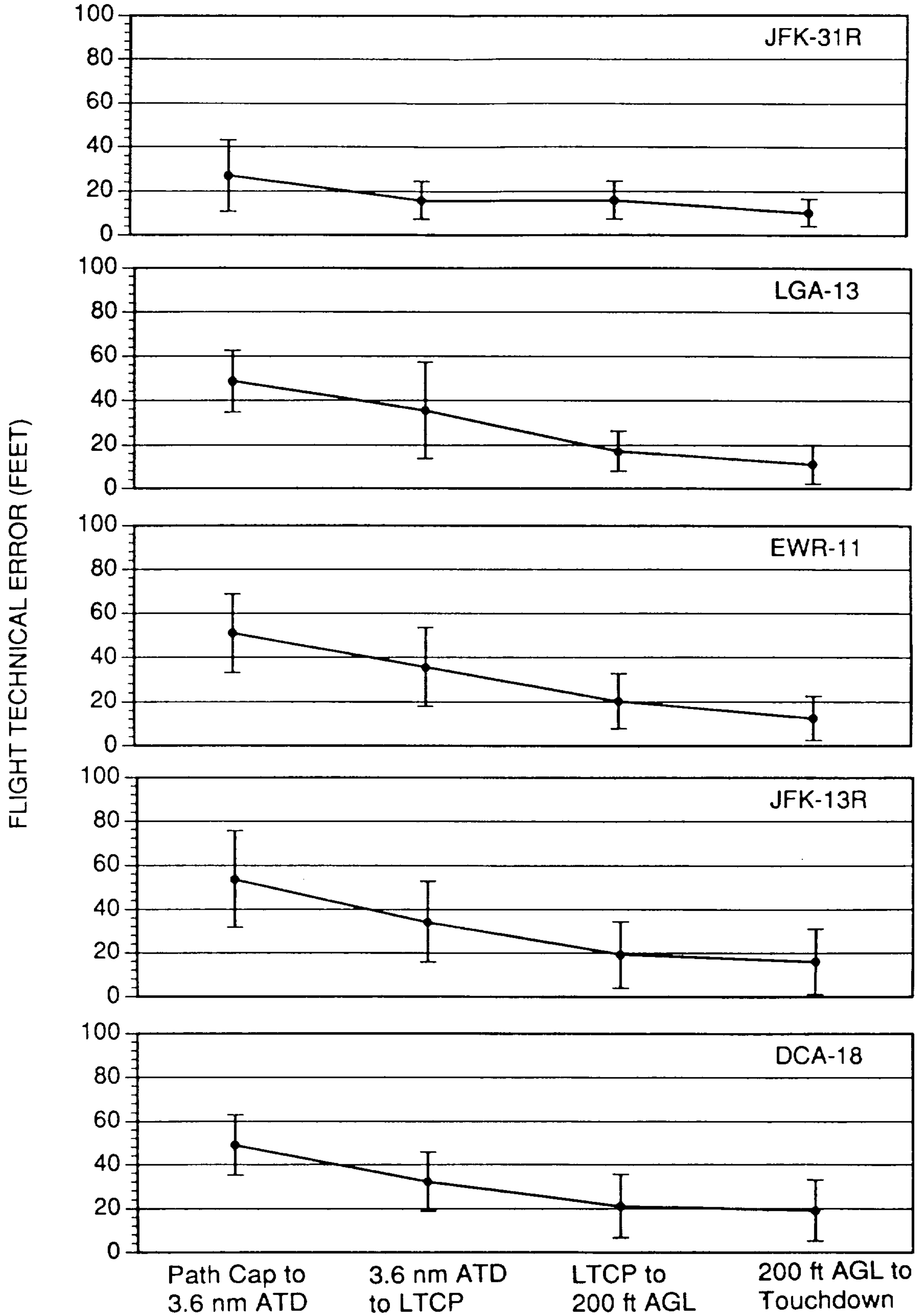
NOTE: Data point is average and bar is ± 1 standard deviation of the sample

Figure 6-12. RMS Lateral Flight Technical Error per Flight Segment



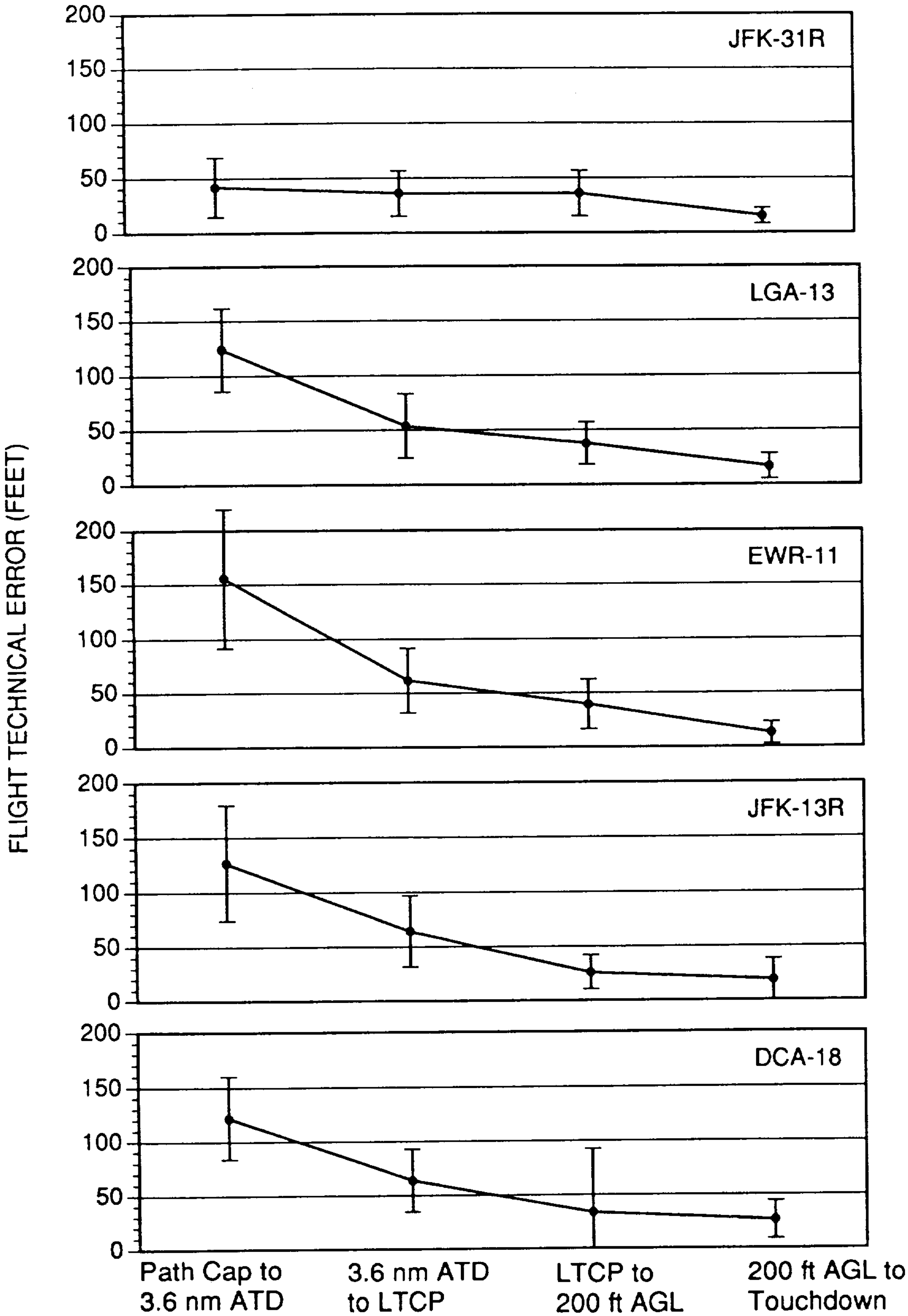
NOTE: Data point is average and bar is ± 1 standard deviation of the sample

Figure 6-13. The Maximum Lateral Flight Technical Error per Flight Segment



NOTE: Data point is average and bar is ±1 standard deviation of the sample

Figure 6-14. RMS Vertical Flight Technical Error per Flight Segment



NOTE: Data point is average and bar is ±1 standard deviation of the sample

Figure 6-15. Maximum Vertical Flight Technical Error per Flight Segment

Overall, there were no differences between the two navigation displays on either the lateral or vertical rms flight technical error. This indicates that the display mode did not have as strong an influence on the objective results as it did on the subjective results. However, the lateral rms flight technical error had a significant interaction between navigation display and approach type. Figure C-13 in Appendix C shows that the map mode had less error on DCA-18 than the HSI mode.

6.4.2.3 Maximum Bank Angle — The maximum bank angles were compared between approaches for those flight segments that included a turn and for all approaches from LTCP to touchdown. The maximum bank angles were statistically significant for all comparisons. These results are shown in Figure 6-16. The figure shows that the average maximum bank angle was as high as 20 degrees, and that the two-sigma case for the population may be as high as 30 degrees. On DCA-18, these high bank angles occurred below 200 feet and on curve radii that were smaller than permitted by FAA Order 8260.36 for Category D aircraft.

6.4.2.4 Control Activity — Control activity was statistically significant for the different approaches over all the flight segments (see Appendix C). Figure 6-17 shows the control activity averaged across pilots for the five different approaches. This shows that control activity increases (1) with an increase in CDI sensitivity and (2) a slight increase in approach complexity. The slight increase with approach complexity indicates that the pilot perception of higher workload is mostly due to mental rather than physical workload.

Control activity was significantly different for the type of navigation display between path capture and 3.62 nautical miles. There was less activity with the map display than the HSI display. This would contribute to the pilot preference for the map display, although the performance data did not show any differences between the two navigation displays.

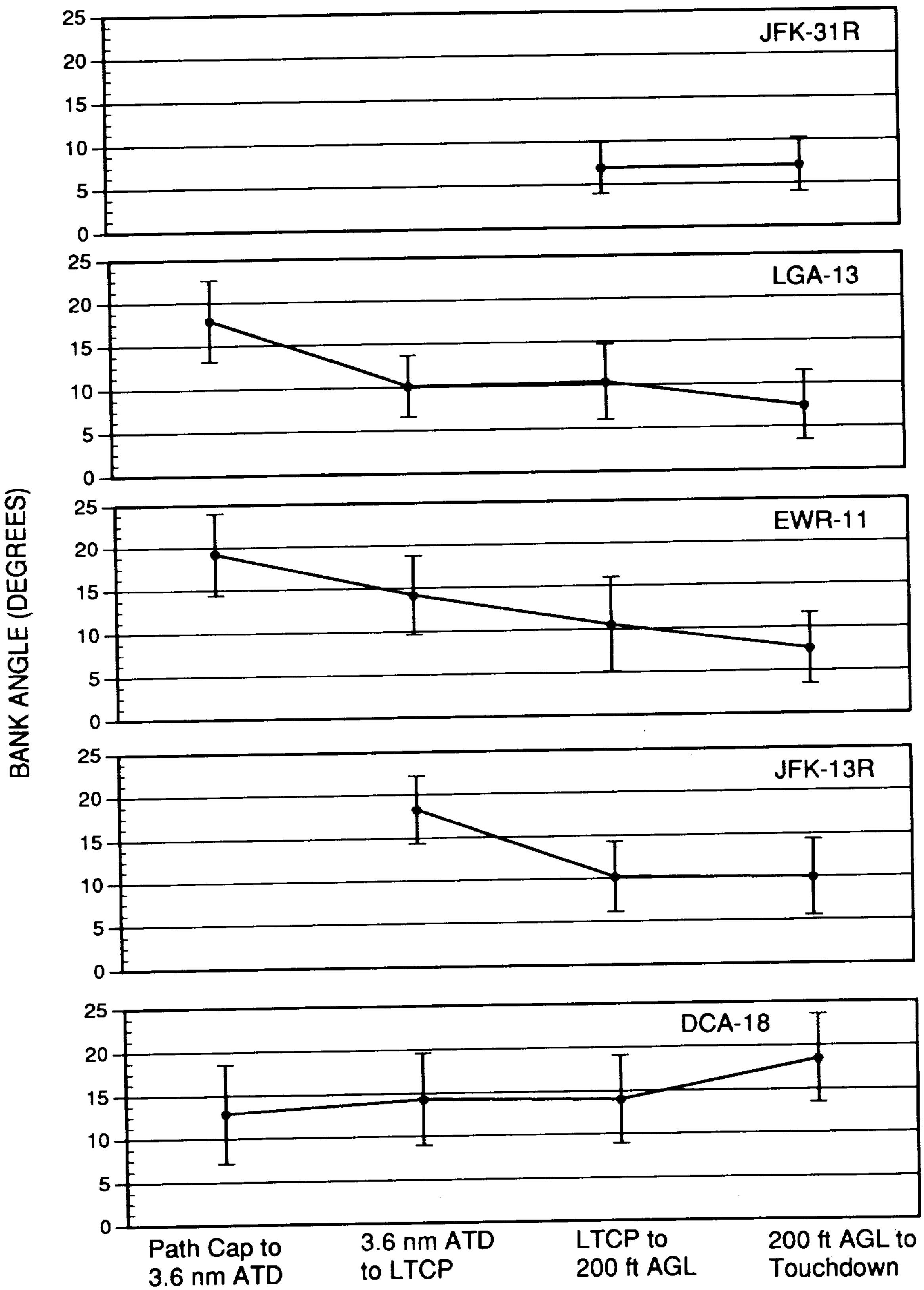
There was no difference in control activity for the two throttle modes even though the autothrottle mode did not include any throttle activity. This indicates that the pilots increased their control wheel and column activity, which improved their flight path control.

6.4.2.5 Ride Quality — Measures of ride quality are high bank angles, high lateral and vertical accelerations, and changes in direction of the acceleration. Both lateral and vertical accelerations and their changes in direction had statistically significant differences between approaches. However, their overall magnitudes were so small as to have a minimal effect upon ride quality. The largest lateral acceleration was ±0.3 g and the largest vertical acceleration was 1.3 g. The maximum number of changes that exceeded a value of 0.05 g was three per minute for both the lateral and vertical axes.

6.4.3 Performance Data at Specified Points

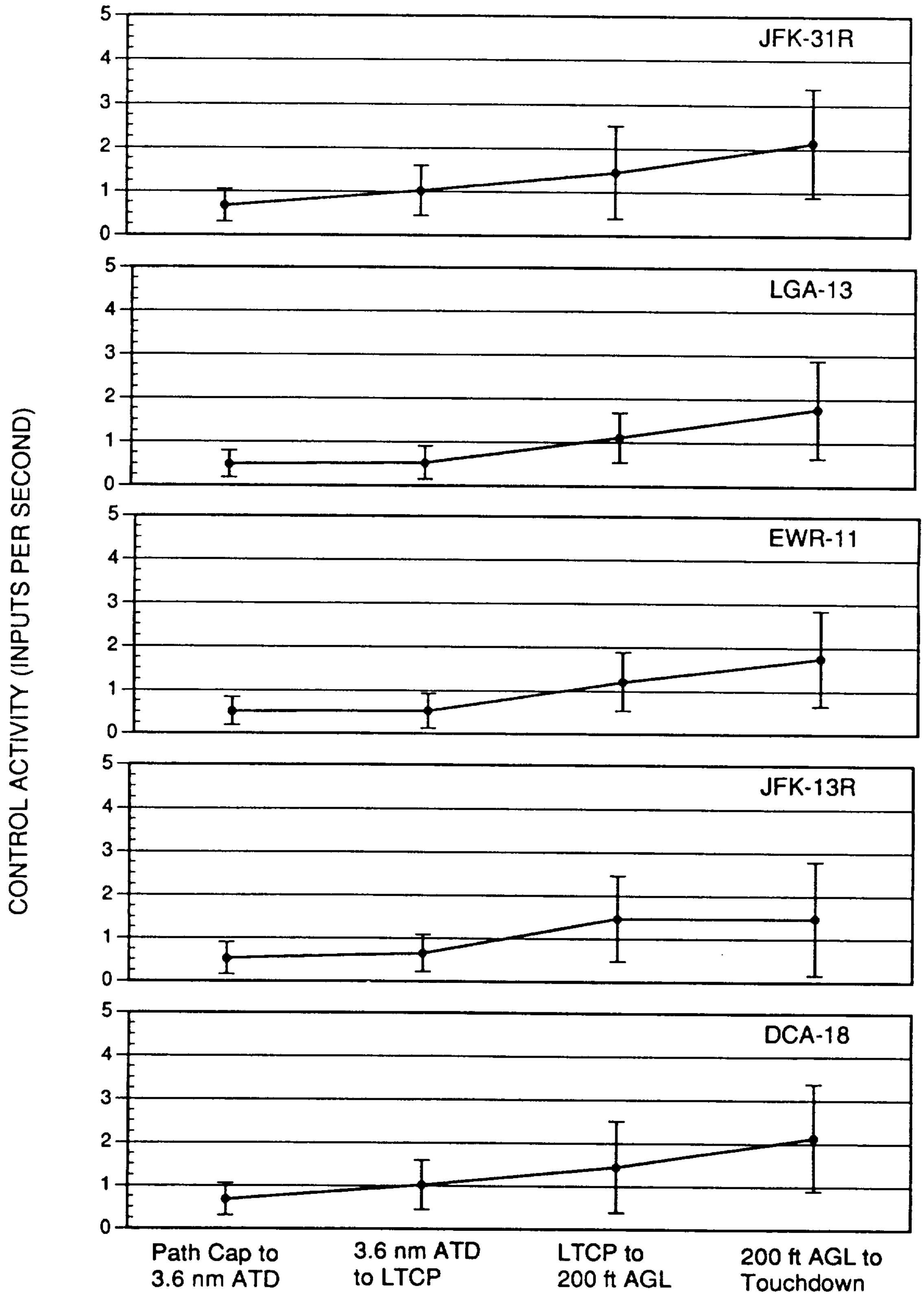
Performance was evaluated at two points along the approach path: (1) decision height or 200 feet AGL and (2) touchdown. The dependent measures included the lateral and vertical (except for touchdown) track deviations, glide path angle error relative to a 3-degree glide slope (except for touchdown), track angle error relative to the runway heading, bank angle, the longitudinal distance to the datum, airspeed error relative to the selected airspeed, vertical speed, and both lateral and vertical flight director errors. Statistical analyses were performed on the absolute values of track deviations, glide path angle, track angle, airspeed, and fight director errors. The actual values of the longitudinal position from the datum, bank angle, and vertical speed were also analyzed. Results of these analyses are presented in Appendix C.

6.4.3.1 Performance at Decision Height — At decision height, the lateral and vertical flight technical errors were significant for the different approaches. The data values, averaged across pilots, are



NOTE: Data point is average and bar is ± 1 standard deviation of the sample

Figure 6-16. Maximum Absolute Bank Angle per Flight Segment



NOTE: Data point is average across pilots and bar is ± 1 standard deviation of the sample

Figure 6-17. Amount of Control Activity per Flight Segment

plotted in Figure 6-18. However, the results for JFK-13R and DCA-18 may not be representative of performance with only MLS guidance since the visual minimum for these two approaches was 350 feet. Therefore, these results include transition from MLS guidance to outside visual. The pilot's ability to align with the runway was affected by the simulator's relatively small field of view, the absence of motion cues, the fact that the simulator was still in a turn, and the presence of a crosswind. Figure 6-19 shows the flight technical error at 350 AGL for all approaches where the pilots were entirely dependent upon MLS guidance.

The percent of trials within the implied criteria window of ± 1 dot is shown in Table 6-6 for both 200 feet and 350 feet AGL for the different approaches. The values were obtained by converting the flight technical error to an equivalent ILS course deviation sensitivity for the different runways. This figure shows that the performance in the lateral window is the same for both altitudes, indicating that the performance decrement is primarily due to tracking the curved path and not the transition to visual. However, vertical performance is better at 350 feet AGL than at 200 feet for JFK-13R and DCA-18. This indicates that vertical performance is better with the MLS guidance than after the transition to visual.

Also at decision height, there were significant differences between the approaches for the longitudinal distance from the MLS datum, the bank angle, the track angle error, and both the lateral and vertical flight director errors. Averages and standard deviations of all measures are presented in Table 6-7.

There was a significant interaction between type of navigation display and the approach. For the DCA-18 approach, the average difference in lateral error was 135 feet for the map mode and 180 feet for the HSI mode (see Appendix C.) There were no significant differences between the two display types for any of the other approaches. The throttle mode had a significant effect upon airspeed error. The average difference in speed error was 2.34 knots for autothrottles and 5.03 knots for manual throttles.

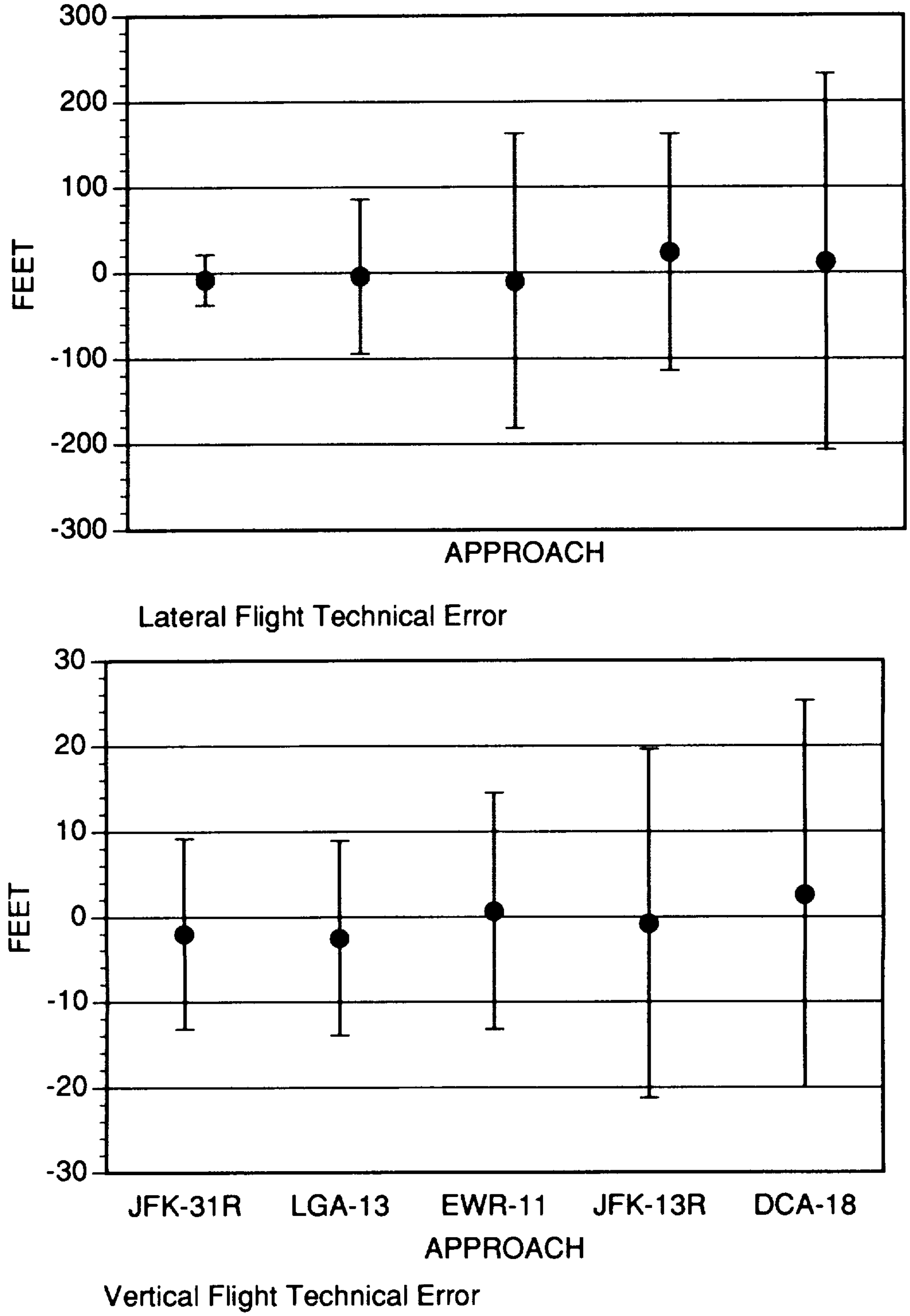
6.4.3.2 Performance at Touchdown — The lateral flight technical error and longitudinal distance from the datum were not significantly different for any of the experimental variables at touchdown. The average lateral deviation from the runway centerline was 4.47 feet with a standard deviation of 31.67, and the average longitudinal distance was 62.38 feet in front of the datum with a standard deviation of 467 feet.

However, there were significant differences between approaches for track angle error, flight path angle error, vertical speed, and pitch flight director error. There was a significant interaction between approaches and wind direction for both the flight path angle error and the vertical speed. With JFK-31R, the average sink rate was 350 feet per minute. With the remainder of the approaches, it was 530 feet per minute.

It is assumed that the touchdown results were affected by the simulator's limited outside visual cues and its lack of motion cues. The majority of the pilots were unable to "decrab" the simulator in the crosswinds or to flare the simulator on the complex approaches.

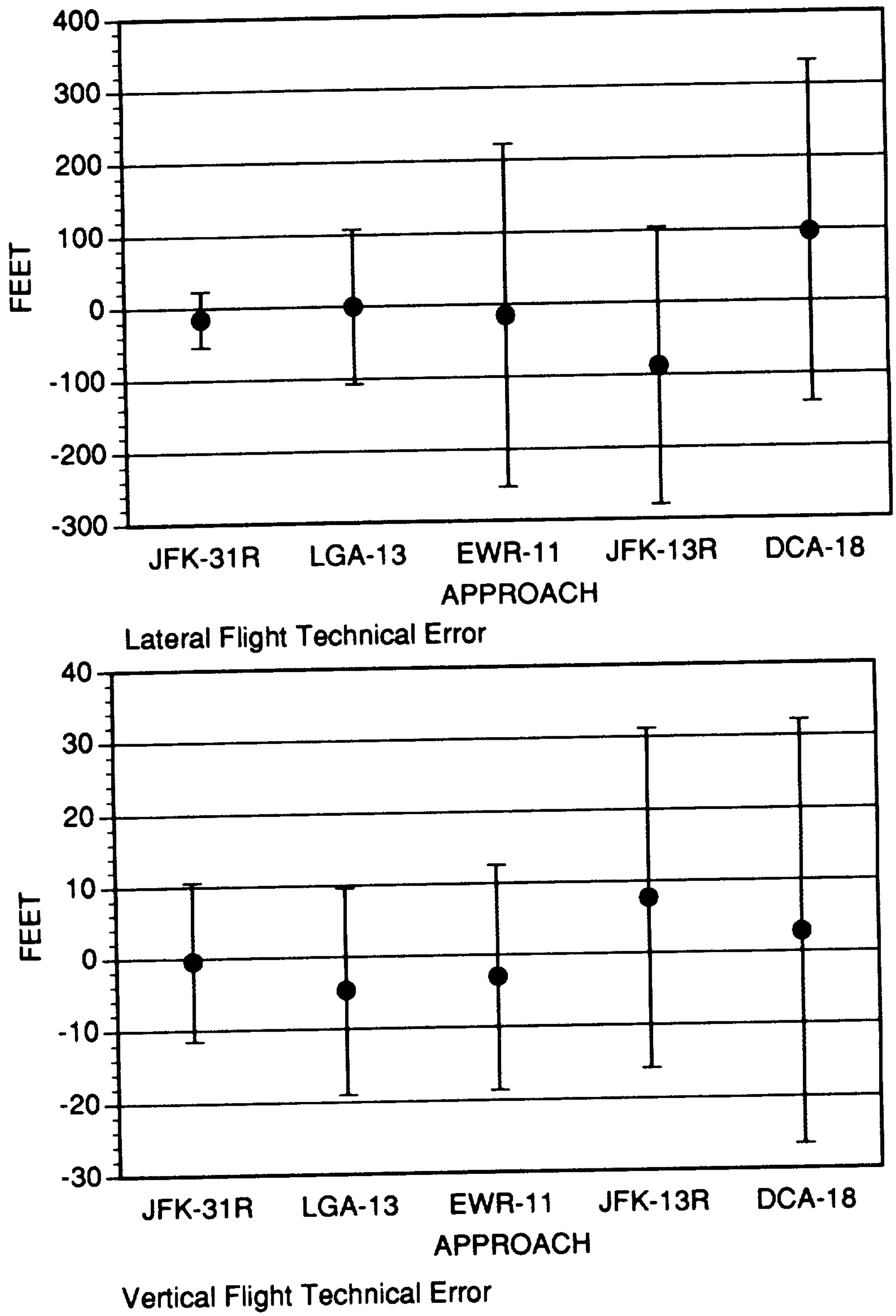
6.5 RESULTS OF THE FAILURE SCENARIOS

For the first 10 pilots, the contingencies on approach JFK-31R were inserted after path capture, and on JFK-13R and DCA-18 they were inserted below the ceiling of 450 feet. The objective results of the first 10 pilots were not analyzed for these cases. Since the failures occurred after the straight-in segment was captured, the insertion points were adjusted to occur prior to path capture on JFK-31R and prior to the initiation of the last turn on the curved approaches. As a result, 45 cases for flight director failure and 43 cases for engine fire warning were analyzed.



NOTE: Data point represents average across pilots and bar is ± 1 standard deviation of the sample

Figure 6-18. Lateral and Vertical Course Deviation at Decision Height or 200 Feet AGL



NOTE: Data point represents average across pilots and bar is ± 1 standard deviation of the sample

Figure 6-19. Lateral and Vertical Course Deviation at 350 Feet AGL

Table 6-6
Percent of Pilot Population That Would Be within the ± 1 Dot Deviation Window at Decision Height and 350 Feet AGL.

APPROACH	LATERAL WINDOW		VERTICAL WINDOW	
	200 FT	350 FT	200 FT	350 FT
JFK-31R	99.9	100	99.9	100
LGA-13	97.2	99.5	97.3	99.6
EWR-11	80.2	80.1	93.3	99.6
JFK-13R	77.6	77.6	83.4	92.9
DCA-18	73.3	75.8	71.6	95.8

Table 6-7
Performance Data at Decision Height (200 Ft AGL)
Values are the average across pilots ± 1 standard deviation of the population

PARAMETER	JFK-31R	LGA-13	EWR-11	JFK-13R	DCA-18
LATERAL FLIGHT TECHNICAL ERROR (FEET)	-8.259 ± 29.637	-4.40 ±89.82	-10.07 ± 172.02	23.49 ± 138.17	12.23 ± 219.24
LATERAL DEVIATION (DOTS)	-.0.049 ± 0.188	-0.013 ± 0.457	-0.082 ± 0.772	0.237 ± 0.786	0.096 ± 0.898
ROLL FLIGHT DIRECTOR ERROR (INCHES)	-0.019 ± 0.067	-0.008 ± 0.067	0.016 ± 0.080	-0.019 ± 0.107	-0.010 ± 0.094
VERTICAL FLIGHT TECHNICAL ERROR (FEET)	-2.03 ± 11.21	-2.529 ± 11.419	0.629 ± 13.872	-0.833 ± 20.413	2.593 ± 22.609
VERTICAL DEVIATION (DOTS)	0.058 ± 0.443	0.005 ± 0.452	0.072 ± 0.533	0.081 ± 0.717	0.082 ± 0.931
PITCH FLIGHT DIRECTOR ERROR (INCHES)	0.027 ±0.102	0.026 ± 0.115	0.045 ± 0.115	0.042 ± 0.096	0.019 ± 0.038
DISTANCE FROM DATUM (FEET)	3594 ± 222	3747 ± 218	3811 ± 262	3781 ± 390	3852 ± 436
AIRSPEED ERROR (KNOTS)	1.505 ± 3.774	2.546 ± 5.470	2.486 ± 4.493	-0.488 ± 10.582	0.411 ± 11.469
BANK ANGLE (DEGREES)	1.27 ± 3.37	0.730 ± 3.050	0.552 ± 5.576	-2.088 ± 5.986	8.076 ± 6.433
FLIGHT PATH ANGLE ERROR (DEGREES)	-0.289 ± 0.921	-0.363 ± 1.033	-0.429 ± 1.085	-0.350 ± 1.253	-0.407 ± 0.977
TRACK ANGLE ERROR (DEGREES)	0.279 ± 1.210	-0.189 ± 2.017	-0.498 ± 3.754	-1.488 ± 4.343	-4.286 ± 5.391

6.5.1 Flight Director Failure

After the flight director failure trial, the pilots were asked to compare the workload during the failure with a normal flight director approach. The results are shown in Figure 6-20 for all the approaches. There were no significant differences between the approaches. The figure shows that 52 percent of the pilots thought it was much harder and 30 percent thought it was somewhat harder. The pilots were also asked to compare it to a flight director failure on precision ILS and nonprecision VOR approaches. These results are presented in Figure 6-21. There were significant differences between the approaches for these results. These figures show that the majority of pilots thought that the flight director failure on an MLS approach is more difficult than a flight director failure on an ILS approach. In comparison with a flight director failure on a VOR approach, 53 percent thought it was more difficult. The results of both of these comparisons depend upon the complexity of the approach and the length of the final segment (i.e., the more complex or shorter the final straight segment, the more difficult). The average workload rating for a flight director failure is 6.1 as compared to an average of 3.6 for the nonfailure case. For the pilot not flying, the average workload was 5.0 as compared to 3.0 for the nonfailure case.

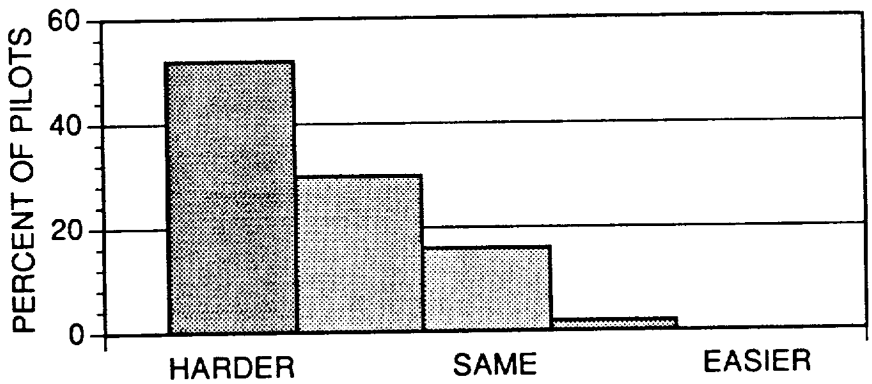
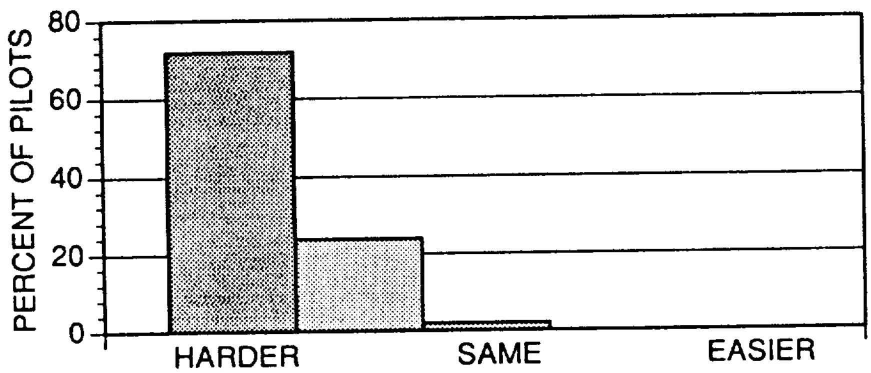
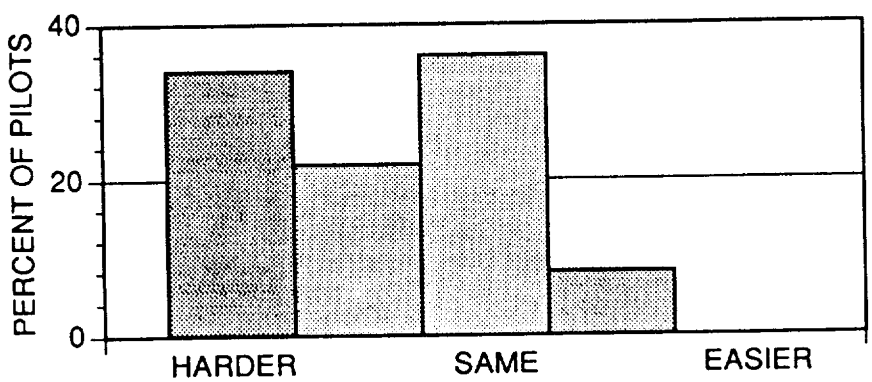


Figure 6-20. Workload Comparison of MLS Flight Director Failure Scenario With MLS Flight Director Approach



ILS COMPARISON



VOR COMPARISON

Figure 6-21. Workload Comparison of Flight Director Failure on MLS Approach With a Flight Director Failure on a Precision ILS and a Nonprecision VOR Approach

The pilots were asked a posttest question regarding what failure mode with which they would be most concerned while flying MLS curved approaches. Their responses are listed in Table 6-8. This table shows that 82 percent of the pilots thought that the flight director failure was their greatest concern, and 12 percent of the pilots said that a failure without the map display was their greatest concern.

The 45 flight director failure trials resulted in seven missed approaches, or 15.5 percent. This compares to 3.5 percent for the noncontingency trials. The distribution of these missed approaches among the approaches was uneven. There was 1 out of 7 for JFK-31R, none for LGA-13, 1 out of 10 for

Table 6-8
Pilot Comments on Failure Modes With Which They Would Be Most Concerned

	COMMENT	PERCENT (NUMBER)
1.	A FLIGHT DIRECTOR FAILURE	70% (35)
2.	A FLIGHT DIRECTOR FAILURE WITHOUT THE MAP DISPLAY	12% (6)
3.	LOSS OF THE MLS SIGNAL	6% (3)
4.	LOSS OF THE CRT'S OR MAP DISPLAY	4% (2)
5.	VALIDITY OF THE COMPUTED DATA	4% (2)
6.	ANY FAILURE	3% (1)

JFK-13R, 1 out of 6 for DCA-18, and 4 out of 10 for EWR-11. Of the seven, six occurred with the HSI display and one occurred with the map display. Therefore, the map display proved to be beneficial for approaches without a flight director.

Time-averaged data for two flight segments were analyzed for the failure scenarios. These flight segments were from the last turn completion point to decision height and from decision height to touchdown. The differences between approaches were similar to those for the noncontingency trials. There was a significant difference between the map and HSI modes for the rms lateral error. The lateral rms error averaged across pilots was 95 feet, and the standard deviation of the sample was 64 feet for the map mode. For the HSI mode, they were 256 and 316 feet, respectively. There were no differences for the other test conditions.

The performance data for a flight director failure at decision height showed that the type of navigation display was significantly different for the lateral flight technical error. The map mode average lateral error was -37.2 and the standard deviation of the sample was 140 feet, while for the HSI, they were -182.2 and 320 feet, respectively. At touchdown, the flight director failure results were similar to those for the flight director approaches.

6.5.2 Engine Fire Warning

The pilots were asked to compare the workload with an engine fire warning on an ILS precision approach and a VOR nonprecision approach. The results are presented in Figure 6-22. There were no significant differences between the approaches. The figure shows that 53 percent thought it was more difficult than an engine fire warning with an ILS approach, while only 22 percent thought it was more difficult than an engine fire warning with a VOR approach. The workload rating for the pilot flying and the pilot not flying did show significant differences between approaches. The average workload rating across pilots was 3.1 for the pilot flying and 3.3 for the pilot not flying. These are equivalent to the workload ratings for the noncontingency test conditions.

There were two missed approaches out of 49 engine fire warning trials. Four percent of the engine fire warning trials ended in a missed approach as compared to 3.5 percent for the noncontingency trials. Analysis of the time a-eraged data and the performance data at decision height and touchdown showed that the only differences between test conditions were due to the approaches.

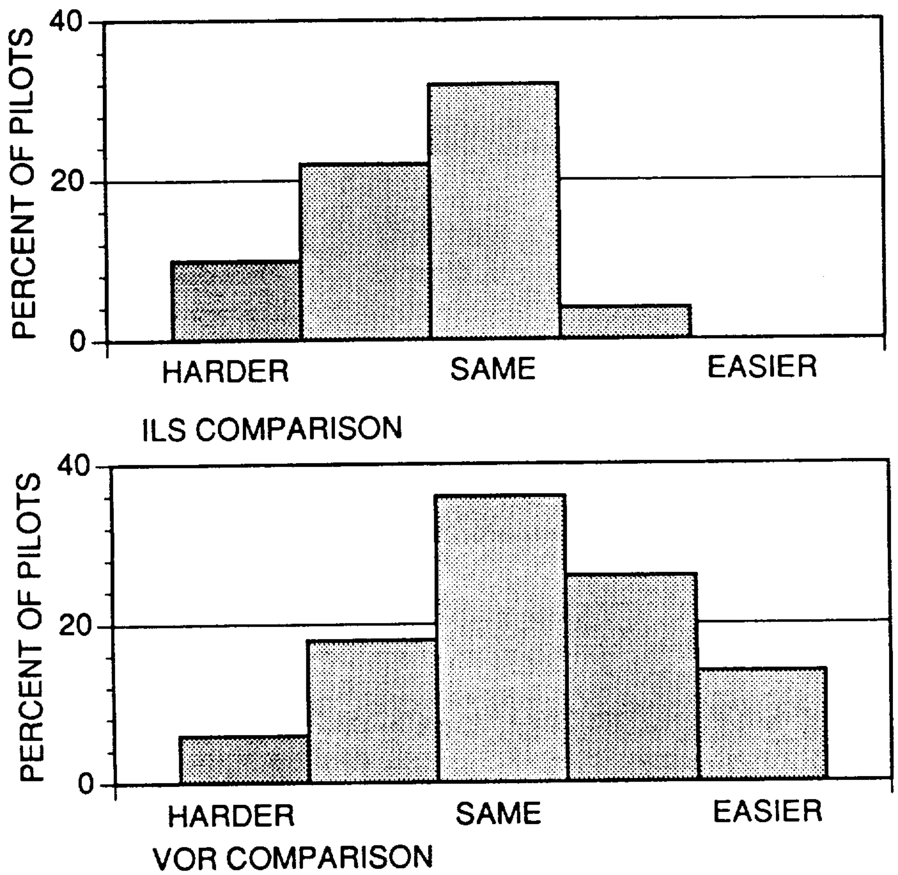


Figure 6-22. Workload Comparison of Engine Fire Warning on MLS Approach With Engine Fire Warnings on a Precision ILS and a Nonprecision VOR Approach

6.6 SUMMARY OF TEST RESULTS

The results are summarized below:

1. The objective stability criteria at decision height were acceptable for all approaches except DCA-18. For DCA-18, only half of the pilots were within a ± 8-degree bank angle and within ± 4 degrees of the runway track angle.

2. The percent of the population that would be within the ± 1-one dot lateral and vertical deviation window at decision height depends upon the curved approach. It ranged from 97 percent for LGA-13 to 72 percent for DCA-18.

3. Since the visual minimum for JFK-13R and DCA-18 was 350 feet in the simulation, the results at decision height are affected by the visual simulation and may not be representative of performance with only MLS guidance.

4. All except one flight crew thought that MLS curved approaches were operationally acceptable. The majority of pilots (52 percent) thought that the acceptability was conditional.

5. The acceptability of an approach was primarily dependent upon the length of the final straight segment. LGA-13 with a 2.7-nautical mile final was acceptable to 97 percent of the pilots, 72 percent of the pilots thought that JFK-13R with a 1.0-nautical mile final was acceptable, while only 47 percent thought that DCA-18 with an 0.6-nautical mile final was acceptable.

6. The pilots thought the radius of the turns was acceptable except for the last turn on DCA-18 (a 7,500-foot radius at 200 feet AGL) which 25 percent of the pilots thought was too steep for that low altitude. The objective results showed that the average maximum bank angle for the last turn on DCA-18 was 20 degrees, and the two-standard deviation value would be 28 degrees.
7. The majority of pilots were comfortable with the glide path changes during a turn. However, 15 percent were not comfortable with the level-off during the turn on EWR-11, and 12 percent would prefer not to have any glide path changes during a turn.
8. Overall, the pilots thought that the workload with MLS curved approaches was more difficult than an ILS precision approach but easier than a VOR nonprecision approach.
9. For all curved approaches, the average rms lateral tracking error from path capture to the last turn completion point was 250 feet, and the average maximum lateral error was 600 feet. The average vertical rms tracking error from path capture until the CDI sensitivity changed was 50 feet and the average maximum vertical error was 125 feet.
10. Only 16 percent of the pilots thought that the map mode of the navigation display was necessary for the curved approaches. The only difference in lateral performance between the map and the HSI mode of the navigation display occurred on the DCA-18 approach or with a flight director failure.
11. The results of the flight director failure contingency indicate that flight director steering commands are necessary for the curved approaches, especially without the map navigation display. A majority of the pilots (70 percent) said that the flight director is the failure mode with which they would be the most concerned.

SECTION 7
CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

The test results indicate that MLS curved approaches are suitable for a wide-body transport aircraft. Flight director steering commands are necessary for manual flight control, and a map navigation display is desirable for situational awareness. Operational acceptance of a curved approach is dependent upon the final straight segment length, the turn radii, the position of the vertical descents, and the complexity of the approach. This study showed that the operationally acceptable final segment length should be greater than 1.0 nautical mile. However, this conclusion is based on the results with two approaches at or under 1.0 nautical mile (JFK-13R and DCA-18) having a higher visual minimum than a Category I approach.

It should be noted that all the curved approaches in this evaluation included smaller turn radii and shorter final straight segment lengths than specified by FAA Order 8260.36. The approach that came the closest to meeting the requirements of the FAA Order was LGA-13. This approach had the most favorable results — nearly equivalent to the straight-in approach.

With few exceptions, the flight crews who participated in this study were capable of flying a precision curved track and able to be within a ± 1-dot decision window and stabilized at decision height (200 feet AGL).

The flight director failure contingency indicates that flight director steering commands are necessary for flying these curved approaches. When a flight director failure occurred with the HSI display, the pilots tended to lose there situational awareness, and successful completion of an approach required the assistance of the pilot not flying to suggest heading changes for course corrections. With the map display, there was more situational awareness, but the amount of time available for the pilot flying to observe the map display was limited due to the high workload.

7.2 RECOMMENDATIONS

Based on the results of this evaluation, the following recommendations are made:

1. Curved approach design criteria for wide-body aircraft should include a final segment length of greater than 1.0 nautical mile for Category I approaches, turn radii greater than 7,500 feet, a minimum of glide path changes during a turn (preferably none), and a minimum number of turns.
2. Flight director steering commands are required. If a flight director failure occurs, a missed approach should be called and an alternate straight-in approach should be requested.
3. The criteria for the course deviation display sensitivity in the minimum operational performance standards (MOPS) developed by RTCA should be changed so that it agrees with the ILS display sensitivity. This will prevent any discrete changes in display sensitivity and flight director steering commands.
4. If waypoint checks of raw data are required, there should be no more than two. Also, it is preferable that these occur prior to the final approach fix. The display of the raw data information on the navigation display should be larger and in a more obvious location.
5. Design criteria for the waypoint checks should be incorporated into RTCA's MOPS. This should include the presentation of the range and bearing data on the navigation display and the approach charts. These data should be large and easy to read. Suggestions for the approach charts include listing the data on the side or displaying it on the profile view.

6. For MLS curved approaches, the smallest range on the map display should be 5 nautical miles or less so that it can be used to assist in precision tracking.

SECTION 8
REFERENCES

1. Erkelens, L.J.J. and van Dronkelaar, J. H., "Flight Simulator Evaluation of Curved MLS Approaches with Wide-Body Aircraft," NLR CR90239L, National Aerospace Laboratory NLR, Amsterdam, June 1990.

2. "Minimum Operational Performance Standards for Airborne MLS Area Navigation Equipment" Doc. No RTCA/DO-198, Radio Technical Commission for Aeronautics, Washington, DC, March 1988.

3. Feather, J. B., "Guidance Law Simulation Studies for Complex Approaches Using the Microwave Landing System (MLS)," NASA CR-178182, National Aeronautics and Space Administration, Langley, VA, November 1986.

4. Advisory Circular 25-11, "Transport Category Airplane Electronic Display Systems," Federal Aviation Administration, U.S. Department of Transportation, Washington, DC, July 1987.

5. FAA Order 8260.36, "Civil Utilization of Microwave Landing System (MLS)," Federal Aviation Administration, U.S. Department of Transportation, Washington, DC, July 1988.

6. Advisory Circular 120-29, "Criteria for Approving Category I and Category II Landing Minima for FAR 121 Operators," Federal Aviation Administration, U.S. Department of Transportation, Washington, DC, September 1970.

7. Kelly, R. J., "Precision Approach Accuracy Considerations" presented at RTCA Special Committee 171, Radio Technical Commission for Aeronautics, Washington, DC, February 1991.

8. Wierwille, W. W. and Casali, J. G., "A Validated Rating Scale for Global Mental Workload Measurement Applications," Proceedings of the Human Factors Society 27th Annual Meeting, 129-133(b), 1983.

APPENDIX A
PILOT BRIEFING MATERIAL

APPENDIX A
PILOT BRIEFING MATERIAL

TABLE OF CONTENTS

I. OBJECTIVE

The primary objective of the wide-body evaluation program is to demonstrate the suitability of flying complex, curved path, microwave landing system (MLS) approach procedures in a wide-body aircraft. MLS provides expanded coverage allowing flexible, curved path approaches. A description of the MLS system is provided in Appendix A. As a part of this demonstration, Douglas Aircraft, under contract to the FAA/NASA (NAS1-18028), is testing guidance concepts that allow MLS curved path approaches in its newest aircraft, the MD-11. In order to accomplish the MLS demonstration, Douglas Aircraft is testing modifications to existing MD-11 electronic instrument system displays to facilitate crew procedures and situation awareness during a curved path approach.

The simulation will be conducted in a fixed-base engineering simulator located at Douglas Aircraft Company, Long Beach, California. The fixed-base simulator (FBS) is configured as an MD-11 aircraft utilizing the aerodynamic equations of that aircraft.

II. TEST DESCRIPTION

Only MLS approaches will be evaluated during this demonstration. The simulation will be initiated prior to MLS path capture. The initial conditions will be lateral navigation (or the azimuth mode if within MLS coverage), altitude hold and 210 knots. The aircraft will be configured clean and at a gross weight of 400,000 lbs. Air traffic control will have cleared the aircraft for the approach and landing. The visibility will be reduced so as to require an instrument approach (either 220-foot ceiling and 3,000-foot RVR or 320-foot ceiling and 6,000-foot RVR). The flight crew will manually fly using the flight director, manage the speed profile with either autothrottles or manual throttles, configure the aircraft, perform the landing checklist, and execute the landing or missed approach as required.

The following variables will be tested as part of this demonstration program:

(1) Five Approach Paths
(2) Manual Throttles or Autothrottles
(3) Crosswind Component (Left or Right)
(4) Navigation Display Mode (Map or Compass Rose)
(5) Contingency Modes (Engine Fire Warning or Flight Director Failure)

An autoland and five practice approaches will be flown by each crew member before the actual demonstration trials begin. The five practice approaches will enable each crew member to become familiar with the handling qualities of the MD-11 and the different approaches they will fly during the demonstration trials. The practice approaches will be flown with both manual and autothrottles.

Twelve demonstration trials will be flown by each crew member. The crew members will trade off flying the approaches. Three approaches will be flown by Pilot A, and then three approaches will be flown by Pilot B. The approach order will be randomly ordered from one pilot to the next so that it will be difficult for either pilot to gain an advantage from watching the other fly a given approach or configuration.

The simulation demonstration will take two 8-hour days for each participating crew to complete.

Approaches

Five different approaches have been designed for use in the demonstration task. The approaches (Appendix B) are a straight–in to JFK-31R; a replica of the Canarsie approach to JFK-13R; a curved approach to EWR-11 (Newark); a curved approach to LGA-13 (La Guardia); and the "river" approach to DCA-18 (National).

Mode of Operation

The curved path guidance is provided by the flight management system (FMS). The FMS computes a commanded flight path based upon the MLS signals and the approach path waypoints stored in the FMS data base. The FMS guidance algorithms provide error signals to the autopilot in order to drive the flight director bars. An MLS approach path will be line selectable on the approach page of the MCDU just like an ILS approach. The flight plan or legs page will show the waypoints, and track angle and distances like the en route legs page. Since the simulator does not have an interactive MCDU, the initial condition of a test trial will be that the approach has been selected and the autopilot (flight control computer or FCC) is armed for the approach.

The left-seat pilot (PF) will manually fly the aircraft using the flight director. The right-seat pilot will be the pilot not flying (PNF). Prior to the test trial, the two pilots will coordinate their procedures and perform the initial condition checklist. Crew coordination procedures for the approach, missed approach, flight director failure, and engine fire warning are provided in Appendix C.

The PF will either use manual throttles or autothrottles depending upon the test condition. The autothrottles will be controlled by the speed control knob on the glareshield (the flight control panel or FCP). The PF will command the PNF to select the speed reductions and add drag. (The same procedure will be performed for manual throttles since the speed control activates the speed bug on the airspeed tape.) The PNF will call out the next waypoint, track angle, and distance to it. He will be responsible for checking the bearing and distance to the MLS datum at each waypoint crossing or abeam of the waypoint intersection against the approach plate to ensure that the computed guidance is providing the correct course.

When a flight director failure or an engine fire warning occurs, the PF will be encouraged to continue the approach. If he elects to go around and is still within MLS coverage, he should continue to fly the lateral path and climb out. If he is outside of coverage or has lost guidance (RNAV FAIL), then he should turn in the direction indicated on the approach plate while climbing out. In either case the simulation will be terminated when he has climbed 1,000 feet.

III. SIMULATOR DESCRIPTION

The simulator is a wide-body, engineering development, fixed-base simulator. It is configured as a MD-11 flight deck with six-across, 8-inch by 8-inch CRT displays. An experimenter's station is located behind the left seat. The simulator is driven by an MD-11 full flight envelope, aerodynamic, and engine models. Wheel and column force loading is dynamically programmed by a McFadden controller available to the left seat only. The pedestal has operative flight controls with back-driven throttles.

The glareshield contains an emulated MD-11 flight control panel. The operable parts are the speed window, the speed control, and the autoflight switch. Rotating the speed control preselects a speed, pulling the control selects the speed, and pushing it holds the current speed. The autoflight system is engaged by the autoflight switch on the FCP and disengaged by the autoflight disconnect switch on the pilot's control wheel. The throttles contain an autothrottles disconnect and TOGA switches. Once the autothrottles are disconnected, they cannot be reengaged (*simulator limitation*).

The out-of-the-window visual scene uses a rear projection screen that is 8 feet from the left-seat pilot's eye point. The visual image is generated by a Redifon visual flight attachment (VFA) consisting of a terrain board with a 10,500-foot runway, a servo-driven color TV, associated electronics, and lighting. The VFA is capable of producing night and reduced visibility conditions.

Electronic Instrumentation System (EIS)

The flight displays are the primary flight display (PFD) and the navigation display (ND). The two center displays are redundant engine and alert displays which contain the primary engine instrumentation. (In the normal MD-11 configuration, the left center display is a system status display containing secondary engine instrumentation and system information.) Complete descriptions of the PFD, the map and approach modes of the ND, and the modifications to these displays made for the MLS curved approaches are contained in Appendix D.

Primary Flight Display

The PFD combines the function of the flight mode annunciator, the airspeed indicator, the attitude director indicator (ADI), the barometric and radio altimeters, and the vertical speed indicator. Aircraft heading is displayed below the ADI to complete the basic "T" format. The airspeed indicator displays limit speeds, as well as slat/flap and landing gear extension speeds. A filled bow tie indicator on the airspeed scale represents the selected speed and an unfilled bow tie represents a preselected speed. Preselection is set by turning the speed knob on the FCP, and arming is accomplished by pulling the speed knob. The altitude scale contains an amber wedge which indicates radio altitude. The altitude select is shown as filled circle. The approach minimum is shown as a bug and both the baroset and the approach minimum readouts are presented in the lower right corner. Either split cue or single cue flight directors are selectable as an initial test condition. Immediately below the bank angle pointer is a slip/skid indicator. MLS path deviations are shown by the horizontal and vertical deviation indicators. The flap/slat position is shown in the lower left corner. A green diamond on the heading scale indicates the drift angle.

Modifications for MLS include pointers for the azimuth and elevation deviation indicators. When curve path guidance is being controlled by the FMS the pointers are magenta. When angle-only guidance is provided the pointers are white. As a turn precursor, the azimuth or lateral pointer flashes filled three times, 5 seconds prior to entering a turn and remains filled throughout the turn. The elevation or vertical pointer flashes three times, 5 seconds prior to a descent and remains filled throughout the descent. A deviation of two dots of the azimuth pointer represents a cross-track error of 1,500 feet from path capture to an along-track distance of 23,000 feet from the MLS datum. The two-dot deviation then decreases at a 3-degree angle to 350 feet at threshold. Two dots deviation of the elevation pointer represents an altitude error of 250 feet at glide path capture. At an along-track distance of 19,000 feet from the MLS datum, the error begins to decrease at three quarters of a degree to 10 feet at threshold. This provides an equivalent sensitivity to ILS at close in ranges.

The airport identifier and the along-track distance are shown below the flap/slat indication. (This changes to the runway distance remaining after the runway threshold is crossed.) The next waypoint and the distance to go are shown to the right of the heading readout. The heading scale shows a filled magenta circle, which represents the commanded track as computed by the MLS guidance equations. When the turn precursor flashes, an unfilled magenta circle slews to the next track angle. A dotted magenta arc connects this circle with the heading indicator to show the direction of the turn.

Flight Mode Annunciator (part of the Primary Flight Display)

The flight mode annunciator (FMA) is represented by three windows at the top of the PFD. The left window is speed control, the middle is roll control, and the right is altitude control. A white box around any window indicates that either the autopilot (AP) or the autothrottles (ATS) are off but available and the pilot is manually controlling the aircraft. A white color indicates that the flight control panel (FCP) is providing control, and a magenta color indicates that the flight management system (FMS) is providing control.

Since MLS guidance is provided by the FMS until angle-only operations, both the roll and altitude windows will be in magenta until the final straight-in leg. During angle-only operations, the window annunciations will be green if autoflight is connected (representing dual flight control computers) or white if autoflight is disconnected.

THRUST Window

Since speed will be under FCP control, its window will be white. The speed window will show "THRUST" and the selected speed, unless TOGA is selected, and then it will change to "PITCH."

ROLL Window

The roll window will contain the armed modes "MLS LAND ARMED" or "MLS ARMED" above the control mode; these annunciators will be in magenta. The control mode will show "NAV1" in magenta at the start of a test run and will change to "AZIMUTH" at path capture. When angle-only guidance is provided, it will change to "AZ ANGLE" in green or white. During autoland, the control mode changes to "ALIGN" then "ROLLOUT."

PITCH Window

The altitude window will show the control mode "HOLD" with the selected altitude in magenta at the start of the test run. If autoland is armed at azimuth capture, the altitude armed mode will show "LAND ARMED" above the annunciated control mode. The control mode will change to "ELEV" at glide path capture and "DUAL LAND" will be shown to the right of it. If the approach has a segmented glide slope, i.e., two descent phases separated by a level-off, then "EL TO (specified altitude)" will be annunciated during the initial descent to provide the flight crew with a cue that a programmed level-off is part of the approach. "EL HOLD (specified altitude)" will be annunciated during the level flight phase between the two programmed descents. The control mode will change to "EL ANGLE" in green or white at the transition to angle guidance. During autoland "FLARE" then "ROLLOUT" will be shown. If go around is selected, the altitude control mode will change to "GO AROUND" in white while roll control mode will remain "AZIMUTH" in magenta.

Navigation Display

The navigation display (ND) has two modes: an approach mode (horizontal situation indicator or HSI) and a map mode. As part of the demonstration, the effect of navigation display mode on performance is being evaluated. Each simulation run will be initialized with either the approach mode or map mode selected.

Two pushbuttons, with arrows, are provided on the forward portion of the pedestal to change the range on the map mode. The arrow pointing away from the crew selects a higher range and the other selects a lower range. The map ranges are 5, 10, 20, and 40 nautical miles.

The map mode will be track oriented and shows the curved flight path, the MLS waypoints, the airport or runway, the commanded track (a magenta circle), and a bearing pointer to the MLS datum. The ground speed, true airspeed and wind direction and speed are shown in the upper left corner. The active waypoint and the distance and time to go are shown in the upper right corner. The airport identifier and the along-track distance to go are shown on the left side. The bearing and distance to the MLS datum are shown in the lower left corner. The display provides a trend vector that will predict the aircraft position in 30, 60, or 90 seconds, depending on the display range and if the current bank angle and speed are kept constant.

The approach mode shows a compass rose that is heading oriented. The course pointer is the commanded track angle and the deviation indicator indicates cross-track error. Bearing pointer 1 points to the runway threshold (the bearing/distance is shown in the lower left corner). Bearing pointer 2 points to the track angle of the next waypoint. This slews from the track angle of the active waypoint to the next waypoint 5 seconds prior to entering the turn. The other indications are the same as the map mode.

Multifunction Control Display Unit (MCDU)

Pilot interaction with the flight management system (FMS) will not be necessary in this MLS demonstration program. The multifunction control display unit of the FMS will be emulated using a flat panel display located in the forward center of the pedestal. The only page represented, as shown in Figure 1, is the active flight plan or legs page. This page provides the waypoint identifiers, the track angles, the along-track distances, the recommended airspeeds, and the waypoint altitudes of each leg. The active waypoint is in reverse video for highlighting.

FROM	DIST	SPD	ALT
043	8.1		
ASALT		210/	1760
043	6.0		
CRI		147/	1760
047	3.4		
MAJEN		147/	730
133	2.1		
13R		147/	13

-- END OF FLIGHT PLAN --

Figure 1. MCDU Page for JFK-13R or the Carnarsie Approach

Initial and Landing Checklist

INITIAL CONDITION

1. Approach Procedure.................................... **CKD** **P/PNF**
2. Landing Data.. **CKD/SET** **P/PNF**
3. Missed Approach Procedure........................ **CKD** **P/PNF**
4. Waypoint Data................................ **CROSS CKD** **P/PNF**
5. Throttles.. **CKD/SET** **P/PNF**

BEFORE LANDING

1. Gear/Lights.............................. **DOWN/4 GREEN** **P/PNF**
2. Flaps.. **FLAPS 35** **P/PNF**

Engine Fire Warning Checklist

ENGINE_ _FIRE

or

SEVERE DAMAGE

Throttle	IDLE
FUEL Switch	OFF
ENG FIRE Handle/Agent	DOWN & DISCH/CHK

IV. DAILY SCHEDULE

The simulation demonstration will take two 8-hour days for a participating crew to complete. The daily schedule is listed in Appendix E.

V. DEMONSTRATION SCHEDULE

The tentative schedule at this time is to run one or two crews a week through the MLS simulation (total 25 crews). The demonstration period will run for approximately 6 months, starting in October and running through March 1991.

VI. DATA COLLECTION DESCRIPTION

Simulator Performance Data

Simulator performance data will be collected on-line during the simulation runs. The process of data collection is "transparent" to the pilots, meaning data collection will not interfere with the tasks involved with flying the simulator. Pilots may ask to view the results of any given run, such as lateral and vertical flight track error or runway footprint. It is likely that once the crew has been trained and has flown a number of approaches, it will be able to critique it's own performance without outside aids. A complete list of the performance variables is listed in Appendix F.

Subjective Workload Assessment

In addition to performance measures, subjective workload assessments will be collected utilizing the Modified Cooper-Harper Scale. The Modified Cooper-Harper Scale utilizes a 1-to-10 rating scale with verbal descriptions of workload from a low (a rating of 1), "Operator mental effort is minimal and desired performance is easily attainable," to high (a rating of 10) "Instructed task cannot be accomplished reliably." Both pilots will give a rating after each run. This process will take just a few seconds after each run. The Modified Cooper-Harper Scale is listed in Appendix G.

APPENDIX A-A
INTRODUCTION TO MLS

Note: Briefing material is contained in this document. It is not duplicated in this report.

United States Department of Transportation
Federal Aviation Administration
Program Engineering And Maintenance Service
Washington, D. C. 20950

October 1987

APPENDIX A-B
MLS APPROACH PLATES

Note: Approach plates are shown in Section 3 of the report and are not duplicated here.

APPROACH

FLIGHT PHASE OR EVENT	PF	PNF
1. Azimuth capture	Confirm intercept	Call "azimuth active"
2. Speed reduction	Command flaps 28 and speed 165	Repeat, set, and confirm
3. Elevation capture	Confirm intercept	Call "elevation active"
4. Turn change precursor	Respond "check"	Check next waypoint on MCDU; call waypoint name, distance, and track angle
5. Crossing or abeam of waypoint	Respond "check"	Cross-check datum bearing/ distance , with the approach plate and call "waypoint check"
6. Final approach config-uration	Command gear down, flaps 50 and speed 145	Repeat, set, and confirm
7. Landing checklist	Commandlanding checklist	Read landing checklist
8. 500 feet	Respond "check"	Call "500"
9. Stabilized on approach	Call "stabilized on approach"	Respond "check"
10. 100 feet above DH	Respond "check" and look for visual reference	Call "approaching limits"
11. DH	Respond "landing" or "go around"	If no decision, call "limits"
12. 50 feet RA	Disconnect autothrottles and complete landing	Call "50" and check autothrottles disconnected

MISSED APPROACH

FLIGHT PHASE OR EVENT	PF	PNF
1. Decision to go around	Announce "go around" and command "flaps 28; check thrust"	Select go around; check FMA; check thrust; select flaps 28; and announce "flaps 28"
2. Positive climb	Command "gear up"	Select gear up and announce "gear up"
3. If remaining in MLS coverage	Continue to fly azimuth until runway threshold is crossed	Call next waypoints, distance and track
4. If outside of coverage or RNAV FAIL	Follow approach plate procedures	Read missed approach procedures from the approach plate

FLIGHT DIRECTOR FAILURE

FLIGHT PHASE OR EVENT	PF	PNF
1. Flight director bars biased out-of-view and "FD FAIL" message appears	Confirm; and continue to fly the approach with CDI data and the navigation display	Call "flight director failed"
	Command PNF to call out next heading for turn	Estimate heading of turns from wind direction and next track angle; call out to PF

ENGINE FIRE WARNING

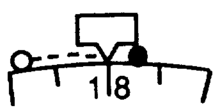
FLIGHT PHASE OR EVENT	PF	PNF
1. Master warning light and engine fire alert message	Continue to fly the approach; command PNF to set throttle to idle, shut fuel switch off, pull fire handle and turn; and check actions	Set throttle to idle; shut fuel switch off, pull fire handle and turn, observe alert messages for fire alert to go out, read engine fire checklist, and turn off master warning and caution lights

APPENDIX A-D

DESCRIPTION OF ELECTRONIC DATA INSTRUMENTATION SYSTEM

Note: Description of the MD-11 EIS displays was taken from the MD-11 Flight Crew Operating Manual. Only the modifications made for MLS are presented in this appendix.

MLS MODIFICATIONS
Primary Flight Display

NO.	CONTROL/INDICATOR	DESCRIPTION/FUNCTION
5		Vertical Deviation Display The pointer will be magenta when driven by computed MLS guidance and white when driven by angle only guidance. The pointer will flash filled five seconds prior to a glide path change and remained filled during the descent.
12		Commanded Track Bug A filled magenta circle moving on the outside of the heading tape represents the commanded MLS track angle. An unfilled magenta circle will move to the next track angle five seconds prior to a turn. This is connected with the heading index by a magenta dotted arc to indicate the direction of the turn. When the next track angle is off the tape, the value is displayed digitally at the edge of the tape.
13	**MLGA 14.1**	Tuned MLS Identification (ID) The ID of the MLS station is displayed by a magenta station identifier followed by the along track distance to the MLS datum.
15		Lateral Deviation Display The pointer will be magenta when driven by computed MLS guidance and white when driven by angle only guidance. The pointer will flash filled five seconds prior to a turn and remain filled throughout the turn.
26	**MAJEN 2.0**	Next Waypoint The next waupoint and distance to go is shown to the right of the heading indicator.

MLS MODIFICATIONS
Flight Mode Annunciator

NO.	CONTROL/INDICATOR	DESCRIPTION/FUNCTION

2

Roll Control Window

The following modes are added:

MODE	ANNUNCIATION	COLOR
Computed MLS	AZIMUTH	Magenta
Angle only MLS	AZ ANGLE	White

The following armed mode is added:

MODE	ANNUNCIATION	COLOR
MLS Land Mode	MLS LAND	Magenta

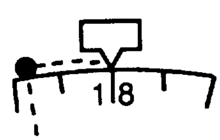
3

Altitude Control Window

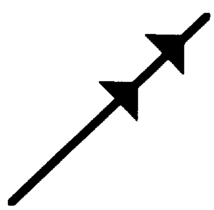
The following modes are added:

MODE	ANNUNCIATION	COLOR
Next MLS Altitude	EL TO	Magenta
MLS Hold Altitude	EL HOLD	Magenta
Computed MLS	ELEV	Magenta
MLS Angle Only	EL ANGLE	White

MLS MODIFICATIONS
Navigation Display - MAP Mode

NO.	CONTROL/INDICATOR	DESCRIPTION/FUNCTION
4A		Vertical Deviation Indicator The map mode vertical deviation is replaced with the PFD vertical deviation indicator. (See PFD for description.)
7		Bearing Pointers Only bearing pointer 1 is implemented and it points to the MLS datum.
8		Bearing Pointers Display Bearing pointer 1 source information is to the MLS datum and it should agree with the waypoint or the intersection abeam of the waypoint bearing and distance to the MLS datum
9A	MLS LGA 14.1 NM	MLS Distance and Source Identifier. The along track distance and the source identifier are displayed in magenta.
18		Commanded Track Angle The commanded track angle is shown as a filled magenta circle on the heading arc.
18		Track Display The MAP mode is magnetic track only.

MLS MODIFICATIONS
Navigation Display - APPR Mode

NO.	CONTROL/INDICATOR	DESCRIPTION/FUNCTION
4	MLS LGA 14.1 NM	MLS Distance and Source Identifier. The along track distance and the source identifier are displayed in magenta.
5		Bearing Pointers Bearing Pointer 1 is the same as the MAP mode.
		Next Track Angle Pointer Instead of the second bearing pointer, the double arrow pointer slews to the next track angle 5 seconds prior to the turn.

APPENDIX A-E
SIMULATOR PERFORMANCE DATA

HEADER INFORMATION

Subject number
Date and time
Procedure being flown
WX condition
- Ceiling
- RVR
- Wind speed
- Wind direction

Test Conditions
- Map or HSI display
- Wind model (none, left, or right)
- Flight mode (Manual, Auto, or AUTOLAND)

C.G.
Gross weight
Starting point X,Y, and Z in feet

DATA COLLECTED AT 5 HERTZ

Time reference (hundredths of a second resolution, .000, .050, .100, .150, etc.)
Current aircraft position relative to MLS datum
Guidance system position estimate
MLS position (azimuth, elevation, DME angular and distance)
Flight path angle
Magnetic track
Heading
Pitch & Roll angle
Commanded roll and pitch attitude
Commanded roll attitude error (in degrees)
Commanded pitch attitude error (in degrees)
Lateral flight technical error (plus or minus percentage deviation indication)
Vertical flight technical error (plus or minus percentage deviation indication)
Lateral flight path error (in feet)
Vertical flight path error (in feet)
Raw lateral deviation (from nose wheel antenna)
Raw vertical deviation (from nose wheel antenna)
Barometric and radar altitude
Lateral and vertical G loading at the aircraft center of gravity
Discrete position indicators for:
- Flap position
- Gear position
- Aircraft on ground (weight on wheels)
- Autopilot engaged

Speed reference selected
Indicated airspeed
Primary engine power settings
Active waypoint
Display discretes:
- Mode annunciation
  - **ROLL** AZIMUTH or AZ ANGLE
  - **PITCH** ELEV or EL ANGLE, and
  - MLS ARMED or MLS LAND ARMED
- Navigation mode (computed MLS or FMS)
- Flags and Failure indicators

Guidance mode transitions
Along track distance to go or runway remaining when aircraft is on ground

SINGLE VALUE DATA

Along track position at touchdown
Lateral position at touchdown
IAS at touchdown
Vertical rate at touchdown
IAS at decision height

DATA COLLECTED AT 20 HERTZ

Column position
Yoke position
Rudder position
Throttle position
Speed Brake position
Elevator trim

APPENDIX A-F
TEST SCHEDULE

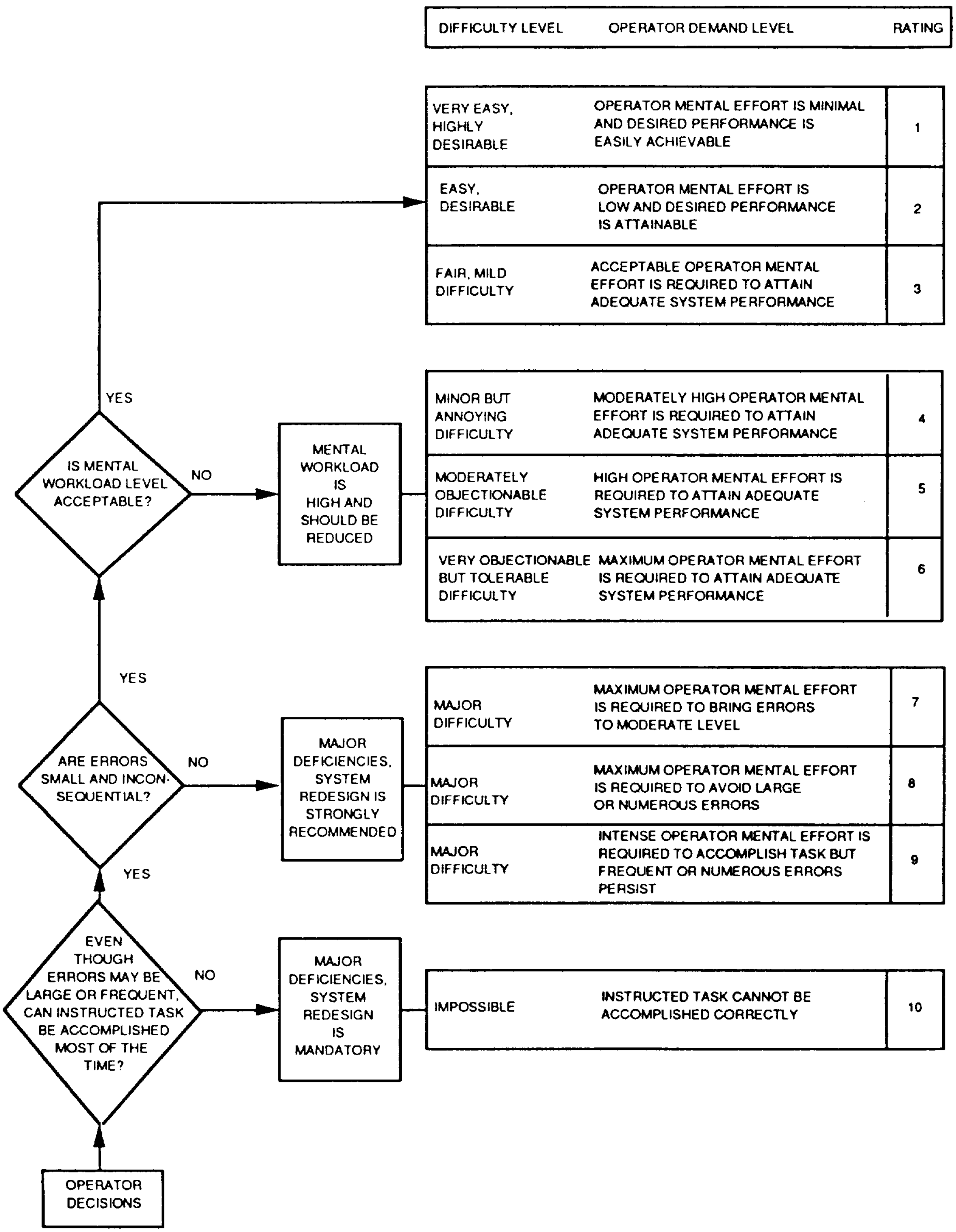
DAY ONE

TIME	ACTIVITY	DURATION
7:30	Welcome and MLS Briefing	45 Min
8:15	Test Conditions and Simulator Briefing	1 Hr
9:30	Break	15 Min
9:45	EIS and Procedures Briefing	1 Hr 30 Min
11:15	Lunch	1 Hr
12:15	Practice Trials	1 Hr
	Pilot 1....Practice 1............15 Min	
	Pilot 1....Practice 2............15 Min	
	Pilot 2....Practice 1............15 Min	
	Pilot 2....Practice 2............15 Min	
13:15	Break	15 Min
13:30	Practice Trials	1 Hr 30 Min
	Pilot 1....Practice 3............15 Min	
	Pilot 1....Practice 4............15 Min	
	Pilot 1....Practice 5............15 Min	
	Pilot 2....Practice 3............15 Min	
	Pilot 2....Practice 4............15 Min	
	Pilot 2....Practice 5............15 Min	
15:00	Recess for the Day	

DAY TWO

TIME	ACTIVITY	DURATION
8:00	Test Trials	1 Hr 30 Min
	Pilot 1...Data Run 1..........15 Min	
	Pilot 1...Data Run 2..........15 Min	
	Pilot 1...Data Run 3..........15 Min	
	Pilot 2...Data Run 1..........15 Min	
	Pilot 2...Data Run 2..........15 Min	
	Pilot 2...Data Run 3..........15 Min	
9:30	Break	15 Min
9:45	Test Trials	1 Hr 30 Min
	Pilot 1...Data Run 4..........15 Min	
	Pilot 1...Data Run 5..........15 Min	
	Pilot 1...Data Run 6..........15 Min	
	Pilot 2...Data Run 4..........15 Min	
	Pilot 2...Data Run 5..........15 Min	
	Pilot 2...Data Run 6..........15 Min	
11:15	Lunch	1 Hr
12:15	Test Trials	1 Hr 30 Min
	Pilot 1...Data Run 7..........15 Min	
	Pilot 1...Data Run 8..........15 Min	
	Pilot 1...Data Run 9..........15 Min	
	Pilot 2...Data Run 7..........15 Min	
	Pilot 2...Data Run 8..........15 Min	
	Pilot 2...Data Run 9..........15 Min	
13:45	Break	15 Min
14:00	Test Trials	1Hr 30 Min
	Pilot 1...Data Run 10........15 Min	
	Pilot 1...Data Run 11........15 Min	
	Pilot 1...Data Run 12........15 Min	
	Pilot 1...Data Run 10........15 Min	
	Pilot 2...Data Run 11........15 Min	
	Pilot 2...Data Run 12........15 Min	
15:30	Debriefing	30 Min
16:00	Adjournment	

APPENDIX A-G
MODIFIED COOPER-HARPER RATING SCALE



Reference: Wierwille, W.W. and Casali, J. G. A validated rating scale for gobal mental workload measurement applications. *Proceedings of the Human Factors Society 27th Annual Meeting, 1983, 129-133 (b)*

APPENDIX B
PILOT QUESTIONAIRES

APPENDIX B

PILOT QUESTIONNAIRES

MLS Widebody Simulator Demonstration

Pre-Program Questionnaire

Pilot Name: ______________________________ No: ________

Position: Captain First Officer *(circle one)*

Date: ______________________________

Airline: ______________________________

Current Qualifications: ______________________________

1. Approximate number of hours in transport aircraft (*list each type of aircraft, total hours and last date as captain or first officer*)?

Type of Aircraft	Captain	First Officer
Widebody		
Narrowbody		

2. Approximate number of hours of EFIS flight experience?

3. What is your opinion of MLS, especially with respect to advanced applications?

4. Do you have any previous experience in tests concerning curved approach procedures?

MLS Widebody Simulator Demonstration
JFK-31

Pilot Number:______________

Run Number:______________ Map ☐ Right ☐ Auto ☐

Date: ______________ HSI ☐ Left ☐ Man ☐

1. How do you rate the workload compared to an ILS precision approach?

☐	☐	☐	☐	☐
Much harder		About the same		Much easier

2. How do you rate the workload compared to a non precision VOR approach?

☐	☐	☐	☐	☐
Much harder		About the same		Much easier

3. Using the modified Cooper-Harper rating scale assign a workload rating for this approach.

4. Have the first officer assign a workload rating to his workload for this approach.

MLS Widebody Simulator Demonstration
LGA-13

Pilot Number:______________

Run Number:______________ Map ☐ Right ☐ Auto ☐

Date: ____________________ HSI ☐ Left ☐ Man ☐

1. Were you comfortable with the start of glide path guidance during the HUDON turn?

☐ Yes ☐ No

If "No", why?

2. Were any of the turns too steep?

☐ Yes ☐ No

If "Yes", which ones?

3. Was the final segment length adequate for the approach?

☐ Yes ☐ No

If "No", why?

4. At what point did you consider yourself established on the approach? How do you evaluate this point?

5. Given the conditions you just flew, do you consider this approach operationally acceptable as a future MLS procedure?

☐ Yes ☐ No

If "No", why?

6. How do you rate the workload compared to an ILS precision approach?

☐ Much harder ☐ ☐ About the same ☐ ☐ Much easier

7. How do you rate the workload compared to a non precision VOR approach?

☐ Much harder ☐ ☐ ☐ About the same ☐ ☐ Much easier

8. Using the modified Cooper-Harper rating scale assign a workload rating for this approach.

9. Have the first officer assign a workload rating to his workload for this approach.

MLS Widebody Simulator Demonstration

EWR-11

Pilot Number:______________

Run Number:______________ Map ☐ Right ☐ Auto ☐

Date: ______________ HSI ☐ Left ☐ Man ☐ ☐

1. Were any of the turns too steep?

   ☐ Yes ☐ No

If "Yes", which ones?

2. Were you comfortable with changing vertical path from a descent to level flight and hold during the DRINK turn?

   ☐ Yes ☐ No

If "No", why?

3. Were you comfortable with capturing the glide path during the BEERS turn?

   ☐ Yes ☐ No

If "No", why?

4. Was the final segment length adequate for the approach?

   ☐ Yes ☐ No

If "No", why?

5. At what point did you consider yourself stabilized on the approach? How do you evaluate this point?

6. Given the conditions you just flew, do you consider this approach operationally acceptable as a future MLS procedure?

   ☐ Yes ☐ No

If "NO," why?

7. How do you rate the workload compared to an ILS precision approach?

   ☐ Much harder ☐ ☐ About the same ☐ ☐ Much easier

8. How do you rate the workload compared to a non precision VOR approach?

   ☐ Much harder ☐ ☐ About the same ☐ ☐ Much easier

9. Using the modified Cooper-Harper rating scale assign a workload rating for this approach.

10. Have the first officer assign a workload rating to his workload for this approach.

MLS Widebody Simulator Demonstration
JFK-13R

Pilot Number:______________

Run Number:______________ Map ☐ Right ☐ Auto ☐

Date: ____________________ HSI ☐ Left ☐ Man ☐

1. Do you consider the turn onto final too steep?

   ☐ Yes ☐ No

2. Was the final segment length adequate for the approach?

   ☐ Yes ☐ No

If "No", why?

3. At what point did you consider yourself stabilized on the approach? How do you evaluate this point?

4. Given the conditions you just flew, do you consider this approach operationally acceptable as a future MLS procedure?

   ☐ Yes ☐ No

If "No", why?

5. How do you rate the workload compared to an ILS precision approach?

   ☐ Much harder ☐ ☐ About the same ☐ ☐ Much easier

6. How do you rate the workload compared to a non precision VOR approach?

   ☐ Much harder ☐ ☐ About the same ☐ ☐ Much easier

7. Using the modified Cooper-Harper rating scale assign a workload rating for this approach.

8. Have the first officer assign a workload rating to his workload for this approach.

MLS Widebody Simulator Demonstration
DCA-18

Pilot Number:______________

Run Number:______________ Map ☐ Right ☐ Auto ☐

Date: ____________________ HSI ☐ Left ☐ Man ☐

1. Were you comfortable with capturing the glide path during the REDUM turn?

☐ Yes ☐ No

If "No", why?

2. Were any of the turns too steep?

☐ Yes ☐ No

If "Yes", which ones?

3. Was the final segment length adequate for the approach?

☐ Yes ☐ No

If "No", why?

4. At what point did you consider yourself stabilized ed on the approach? How do you evaluate this point?

5. Given the conditions you just flew, do you consider this approach operationally acceptable as a future MLS procedure?

☐ Yes ☐ No

If "No", why?

6. How do you rate the workload compared to an ILS precision approach?

☐ Much harder ☐ ☐ About the same ☐ ☐ Much easier

7. How do you rate the workload compared to a non precision VOR approach?

☐ Much harder ☐ ☐ About the same ☐ ☐ Much easier

8. Using the modified Cooper-Harper rating scale assign a workload rating for this approach.

9. Have the first officer assign a workload rating to his workload for this approach.

MLS Widebody Simulator Demonstration
Flight Director Failure Questionnaire

Pilot Number:______________

Approach ID: ____________ Map ☐ Right ☐ Auto ☐

Run Number:______________ HSI ☐ Left ☐ Man ☐

Date: ____________________

1. What mode of the Navigation Display was used?

   ☐ Map ☐ Approach

2. How do you rate the workload compared to using the flight director on this approach?

   ☐ Much harder ☐ ☐ About the same ☐ ☐ Much easier

3. How do you rate the workload compared to a flight director failure on an ILS approach?

   ☐ Much harder ☐ ☐ About the same ☐ ☐ Much easier

4. How do you rate the workload compared to a flight director failure on a non precision VOR approach?

   ☐ Much harder ☐ ☐ About the same ☐ ☐ Much easier

5. Using the modified Cooper-Harper rating scale assign a workload rating for this approach.

6. Have the first officer assign a workload rating to his workload for this approach.

MLS Widebody Simulator Demonstration
Engine Fire Warning Questionnaire

Pilot Number:______________

Approach ID: ______________ Map ☐ Right ☐ Auto ☐

Run Number:______________ HSI ☐ Left ☐ Man ☐

Date: ______________________

1. Were you able to perform the fire warning procedures in a timely manner?

   ☐ Yes ☐ No

If "No", why?

2. How do you rate the workload compared to an engine out precision ILS approach?

☐	☐	☐	☐	☐
Much harder		About the same		Much easier

3. How do you rate the workload compared to an engine out non precision VOR approach?

☐	☐	☐	☐	☐
Much harder		About the same		Much easier

4. Using the modified Cooper-Harper rating scale assign a workload rating for this approach.

5. Have the first officer assign a workload rating to his workload for this approach.

MLS Widebody Simulator Demonstration
MAP MODE

Pilot Number:______________________________

Run Number:______________________________

Date: ______________________________

1. How often did you use the navigation display?

☐	☐	☐	☐	☐
Never		Occasionally		Frequently

2. When you did use the display, check the features you looked at:

☐ Ground Speed

☐ Wind Vector

☐ Track Readout

☐ Computed Track Command

☐ Range to Next Waypoint

☐ ETA to Next Waypoint

☐ Clock

☐ A/C Position on Flight Path Map

☐ Curved Trend Vector

☐ Map Range

☐ Along Track Distance

☐ Bearing Pointer to Runway

☐ Bearing/Distance to Runway

MLS Widebody Simulator Demonstration
APPROACH MODE

Pilot Number:____

Run Number:____

Date: ____

1. How often did you use the navigation display?

❑	❑	❑	❑	❑
Never		Occasionally		Frequently

2. When you did use the display, check the features you looked at:

- ❑ Ground Speed
- ❑ Wind Vector
- ❑ Heading Readout
- ❑ Track Angle or Drift Angle Diamond
- ❑ Range to Next Waypoint
- ❑ ETA to Next Waypoint
- ❑ Clock
- ❑ Computed Track Arrow
- ❑ Course Deviation Indicator
- ❑ Next Track Arrow
- ❑ Along Track Distance
- ❑ Bearing Pointer to Runway
- ❑ Bearing/Distance to Runway

MLS Widebody Simulator Demonstration
Post Program Questionnaire

Pilot Number:______________________________

Date: ______________________________

1. Were you satisfied with the navigation display as presented?

   ☐ Yes ☐ No *(specify your comments)*

Suggestions for improvements?

2. If no, do you have any suggested improvements for the approach charts?

3. In general, what failure mode would you be most concerned with in flying curved MLS approaches?

4. Now that you have completed this simulator program, what is your opinion of MLS curved approaches?

5. How do you rate the workload when flying MLS curved approaches compared to an ILS precision approach?

   ☐ Much harder ☐ ☐ About the same ☐ ☐ Much easier

8. How do you rate the workload when flying MLS curved approaches compared to a non precision VOR approach?

   ☐ Much harder ☐ ☐ About the same ☐ ☐ Much easier

APPENDIX C
STATISTICAL ANALYSIS OF THE DATA

APPENDIX C
STATISTICAL ANALYSIS OF THE DATA

A Chi Square contingency analysis was performed on the pilot's responses to the questions. This determined if their responses vary as a function of the experimental conditions. A repeated measures analysis of variance (ANOVA) test was performed on the objective data to determine if there were significant differences due to the experimental conditions. Those dependent measures that were significant, the standard error of the mean was obtained so that the individual treatment conditions could be compared. A probability level of 0.01 (that is, the probability of saying there is a difference when there is not) was selected as the criteria level.

Subjective Data

Results of the contingency analyses showed significant differences between the various approaches. Table C-1 presents the results of the Chis Square test for those questions that showed significant differences. The Chi Square value, the degrees of freedom and the probability level are listed. There were no significant differences for the remainder of the experimental conditions.

Table C-1.
Results of Chi Square Tests on the Subjective Responses for the Difference Between the Approaches. Only those variables that had a significance level of 0.01 or less are listed.

DEPENDENT VARIABLE	VALUE	D of F	PROB.
Comparison of workload to ILS	142.33	16	0.000
Comparison of workload to VOR	91.85	16	0.000
Workload rating of pilot flying	187.37	26	0.000
Workload rating of pilot not flying	182.67	26	0.000
Position at which pilot said he was stabilized	72.58	15	0.000
Steepness of turns	32.01	3	0.000
Final segment length	51.91	3	0.000
Operational acceptance	37.43	3	0.000

Objective Data

Three ANOVAs were performed for each of the objective performance measures. Each of these ANOVAs was a repeated measures design with one between-group variable and two within-group variables. The repeated measure was the pilots, and the between-group variable was the first and second pilot of a flight crew. The within-group variables were (1) approach and display, (2) approach and throttles, and (3) approach and wind for the three different tests.

A summary of the ANOVAs is listed in Tables C-2 through C-5 for the dependent measures over the four flight segments. Only those variables that had a significance level of 0.01 or less are listed. The F ratio, the degrees of freedom, and the probability level are given. There were no significant differences between the two groups of pilots for any of the tests. The average across pilots and the standard error of the mean are plotted for the variables that were significant. Separation of average values by more than 2 standard errors of the mean indicates that the probability level is 0.025 or less that the mean values of the two variables are the same. Figures C-1 through C-16 show these results for the dependent measures per flight segment. Tables C-6 to C-7 show the summary of the ANOVAs for the dependent measures at decision height and landing. Figures C-17 through C-23 show the plots of the averages and the standard error of the means for the dependent measures at decision height and touchdown.

Analysis of the Flight Director Failure and the Engine Fire Warning Data

The results of the Chi Square tests on the pilots' response to the questions on the flight director failure and the engine fire warning are shown in Table C-8. The results are shown for the variables that had a significance level of at least 0.05. This level was selected due to the smaller sample size for the failure conditions. For the objective measures, between-group ANOVAs were conducted since each pilot received only one test on each failure. These results are summarized in Tables C-9 through C-18. Figure C-24 shows the effect of the type of navigation display on the flight director failure.

Table C-2
Summary of Analysis of Variance Tests for the Flight Segment from Path Capture to 3.62 NM Along-Track Distance. JFK-31R was not included due to the definition of path capture. (Data are only provided for those variables with a probability level of 0.01 or less.)

DEPENDENT VARIABLE	F RATIO	D of F	PROB.
RMS lateral flight technical error			
Approach	22.29	3, 144	0.0000
Throttles	14.58	1, 48	0.0001
Average lateral error			
Approach	15.86	3, 144	0.0000
Wind	7.11	1, 48	0.0104
Maximum lateral flight technical error			
Approach	34.53	3, 144	0.0000
Throttles	20.83	1, 48	0.0000
RMS vertical flight technical error			
Approach	3.88	3, 144	0.0105
Average vertical flight technical error			
Approach vs Throttles	4.17	3, 144	0.0072
Maximum, vertical flight technical error			
Approach	14.02	3, 144	0.0000
Maximum bank angle			
Approach	267.20	3, 144	0.0000
Wind	47.70	1, 48	0.0000
Approach vs Wind	12.88	1, 48	0.0000
Total control activity			
Approach	22.93	3, 144	0.0000
Throttles	47.37	1, 46	0.0000
Display	9.18	1, 48	0.0039
Maximum lateral acceleration			
Approach	8.97	3, 144	0.0000
Number of lateral acceleration changes			
Approach	15.64	3, 144	0.0000
Maximum vertical acceleration			
Approach	8.63	3, 144	0.0000
Throttles	7.18	1, 48	0.0101
Number of vertical acceleration changes			
Approach	27.22	3, 144	0.0000

Table C-3
Summary of Analysis of Variance Tests for the Flight Segment from 3.62 NM Along-Track Distance to Last Turn Completion Point. (Data are only provided for those variables with a probability level of 0.01 or less.)

DEPENDENT VARIABLE	F RATIO	D of F	PROB.
RMS lateral flight technical error			
Approach	44.51	4, 192	0.0000
Throttles	9.17	1, 48	0.0040
Average lateral error			
Approach	4.22	4, 192	0.0027
Maximum lateral flight technical error			
Approach	68.04	4, 192	0.0000
Throttles	10.81	1, 48	0.0019
RMS vertical flight technical error			
Approach	5.84	4, 192	0.0002
Throttles	7.15	1, 48	0.0102
Average vertical flight technical error			
Approach	6.37	4, 192	0.0037
Maximum, vertical flight technical error			
Approach	15.39	4, 192	0.0000
Throttles	8.44	1, 48	0.0055
Maximum bank angle			
Approach	348.45	4, 192	0.0000
Total control activity			
Approach	38.54	4, 192	0.0000
Maximum lateral acceleration			
Approach	37.49	4, 192	0.0000
Throttles	9.01	1, 48	0.0043
Number of lateral acceleration changes			
Maximum vertical acceleration			
Approach	25.61	4, 192	0.0000
Number of vertical acceleration changes			
Approach	140.98	4, 192	0.0000

Table C-4
Summary of Analysis of Variance Tests for the Flight Segment from Last Turn Completion Point to Decision Height. (Data are only for those variables with a probability level of 0.01 or less.)

DEPENDENT VARIABLE	F RATIO	D of F	PROB.
RMS lateral flight technical error			
Approach	16.10	4, 192	0.0000
Average lateral error			
Approach	9.16	4, 192	0.0000
Maximum lateral flight technical error			
Approach	13.64	4, 192	0.0000
RMS vertical flight technical error			
Average vertical flight technical error			
Maximum, vertical flight technical error			
Maximum bank angle			
Approach	35.1	4, 192	0.0000
Total control activity			
Approach	11.48	4, 192	0.0000
Maximum lateral acceleration			
Approach	5.39	4, 192	0.0004
Wind	9.18	1, 48	0.0039
Number of lateral acceleration changes			
Maximum vertical acceleration			
Approach	26.7	4, 192	0.0000
Wind	7.14	1, 48	0.0103
Number of vertical acceleration changes			
Approach	7.71	4, 192	0.0000

Table C-5
Summary of Analysis of Variance Tests for the Flight Segment from Decision Height to Touchdown. EWR-11 was not included due to the lack of data points. (Data are only provided for those variables with a probability level of 0.01 or less.)

DEPENDENT VARIABLE	F RATIO	D of F	PROB.
RMS lateral flight technical error			
Approach	32.92	3, 144	0.0000
Wind	6.64	1, 48	0.0131
Approach vs Display	4.75	3, 144	0.0034
Average lateral error			
Wind	16.50	1, 48	0.0002
Approach vs Wind	6.34	3, 144	0.0005
Maximum lateral flight technical error			
Approach	37.34	3, 144	0.0000
RMS vertical flight technical error			
Approach	17.67	3, 144	0.0000
Average vertical flight technical error			
Approach vs Wind	6.32	3, 144	0.0005
Maximum, vertical flight technical error			
Approach	13.06	3, 144	0.0000
Throttles	7.53	1, 48	0.0085
Maximum bank angle			
Approach	45.77	3, 144	0.0000
Total control activity			
Approach	5.01	3, 144	0.0025
Maximum lateral acceleration			
Number of lateral acceleration changes			0.0016
Wind	11.23	1, 48	
Maximum vertical acceleration			
Number of vertical acceleration changes			0.0000
Wind	33.31	1, 48	

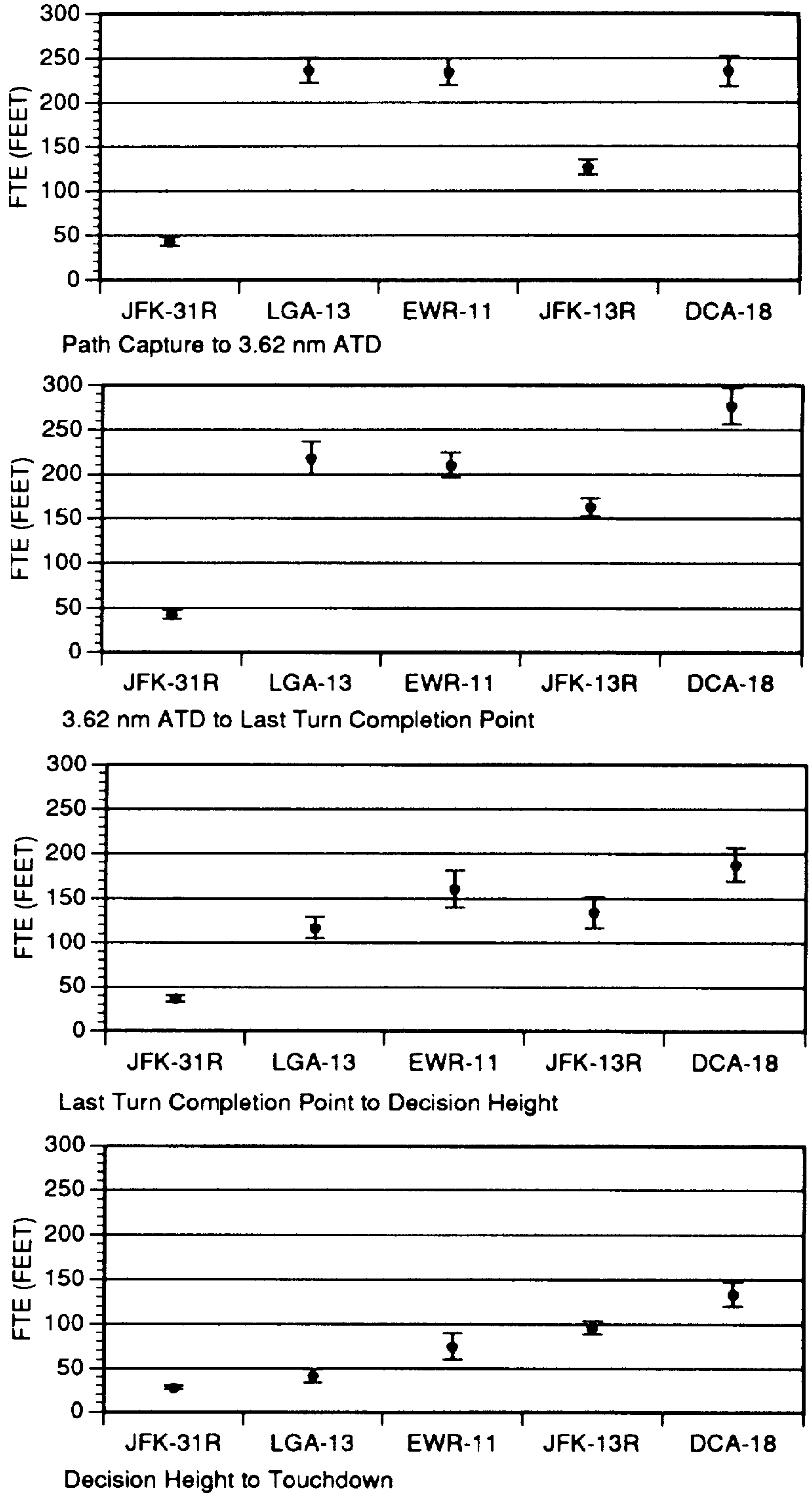


Figure C-1. RMS lateral flight technical error per flight segment for the different approaches. Data point is the average across pilots and bar is ±1 standard error of the mean.

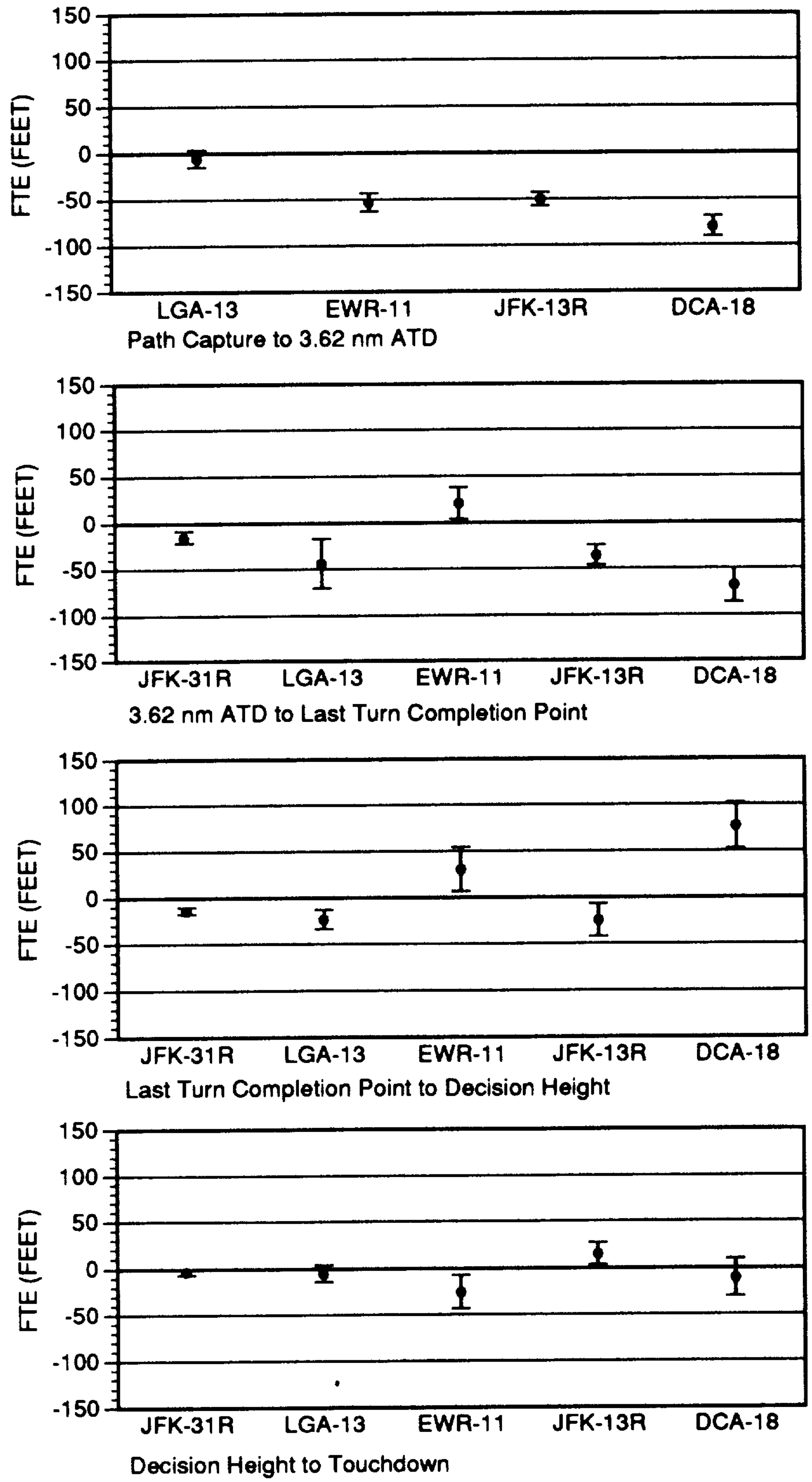


Figure C-2. Average lateral flight technical error per flight segment for the different approaches. Data point is the average across pilots and bar is ±1 standard error of the mean.

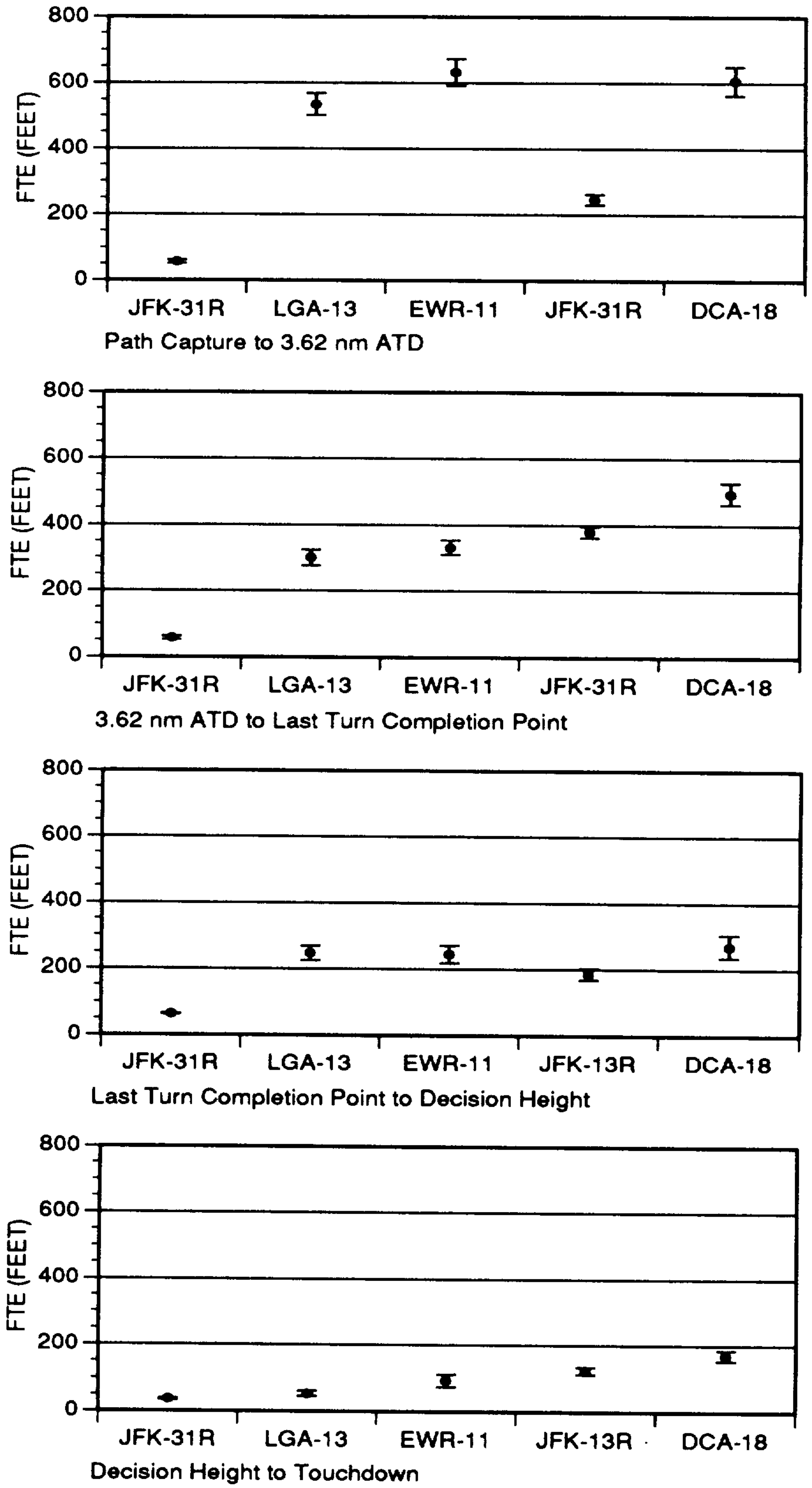


Figure C-3. Maximum absolute lateral flight technical error per flight segment for the different approaches. Data point is average across pilots and bar is ±1 standard error of the mean.

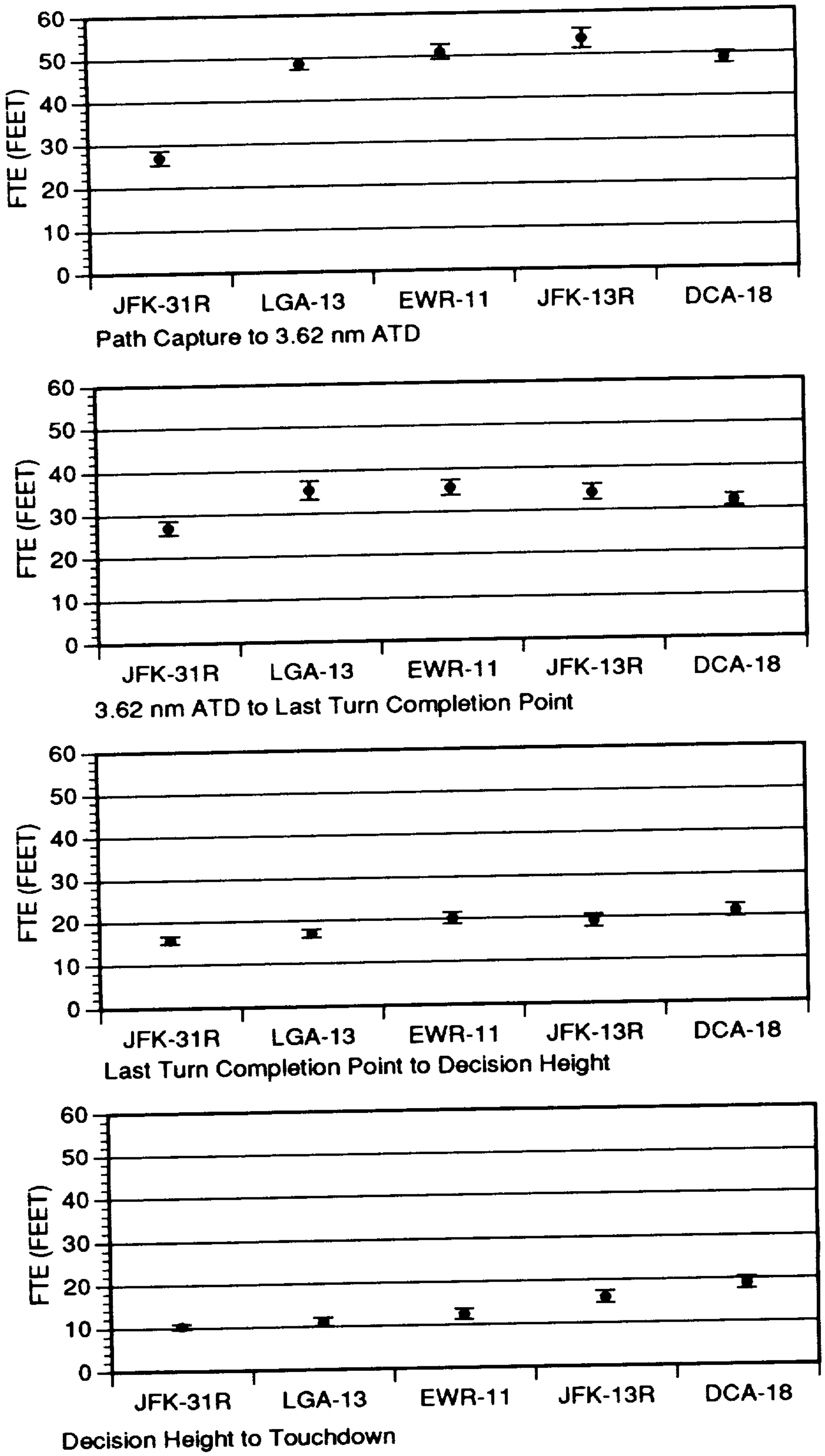


Figure C-4. RMS vertical flight technical error per flight segment for the different approaches. Data point is the average across pilots and bar is ±1 standard error of the mean.

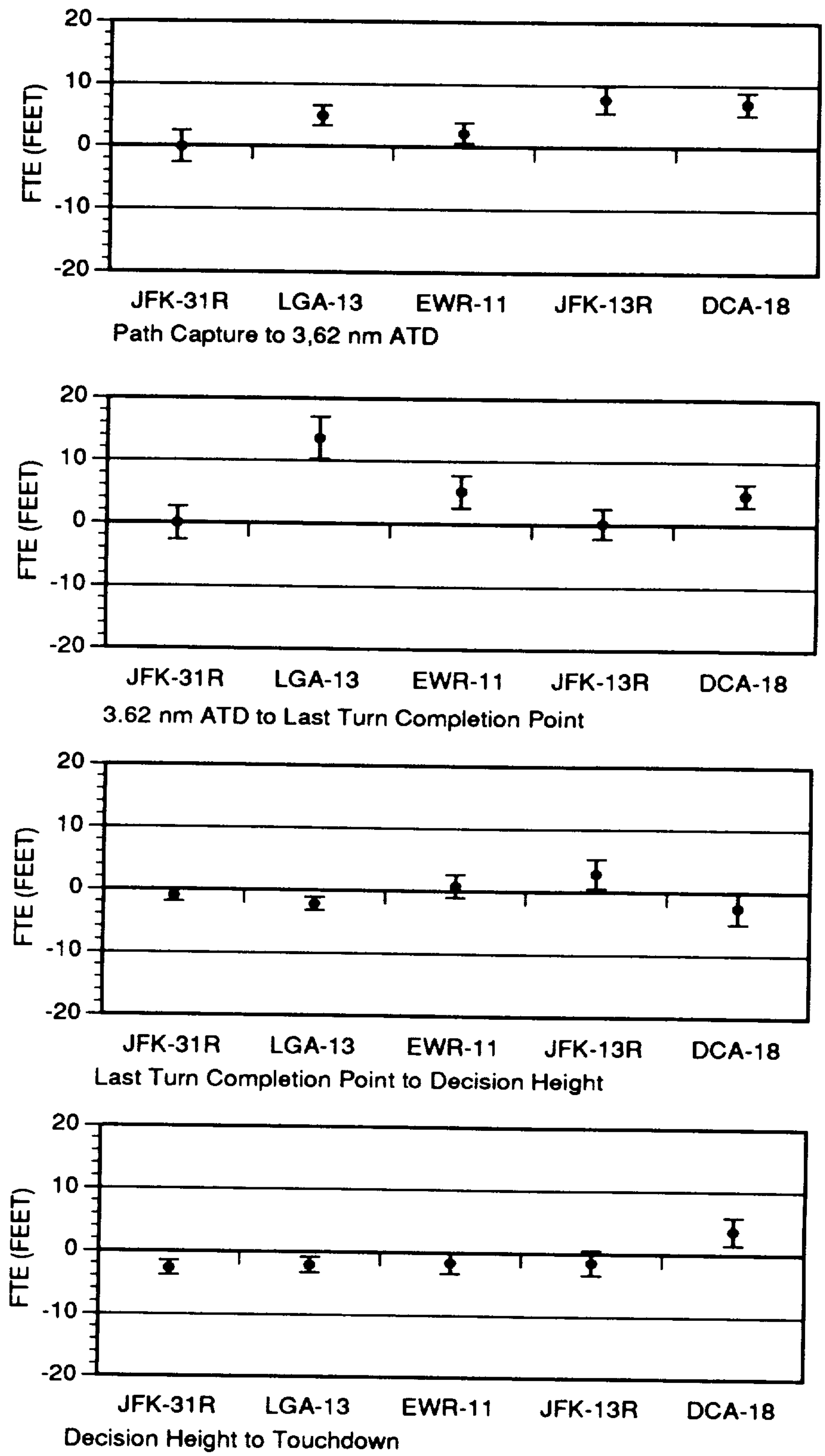


Figure C-5. Average vertical flight technical error per flight segment. Data point is the average across pilots and bar is ±1 standard error of the mean.

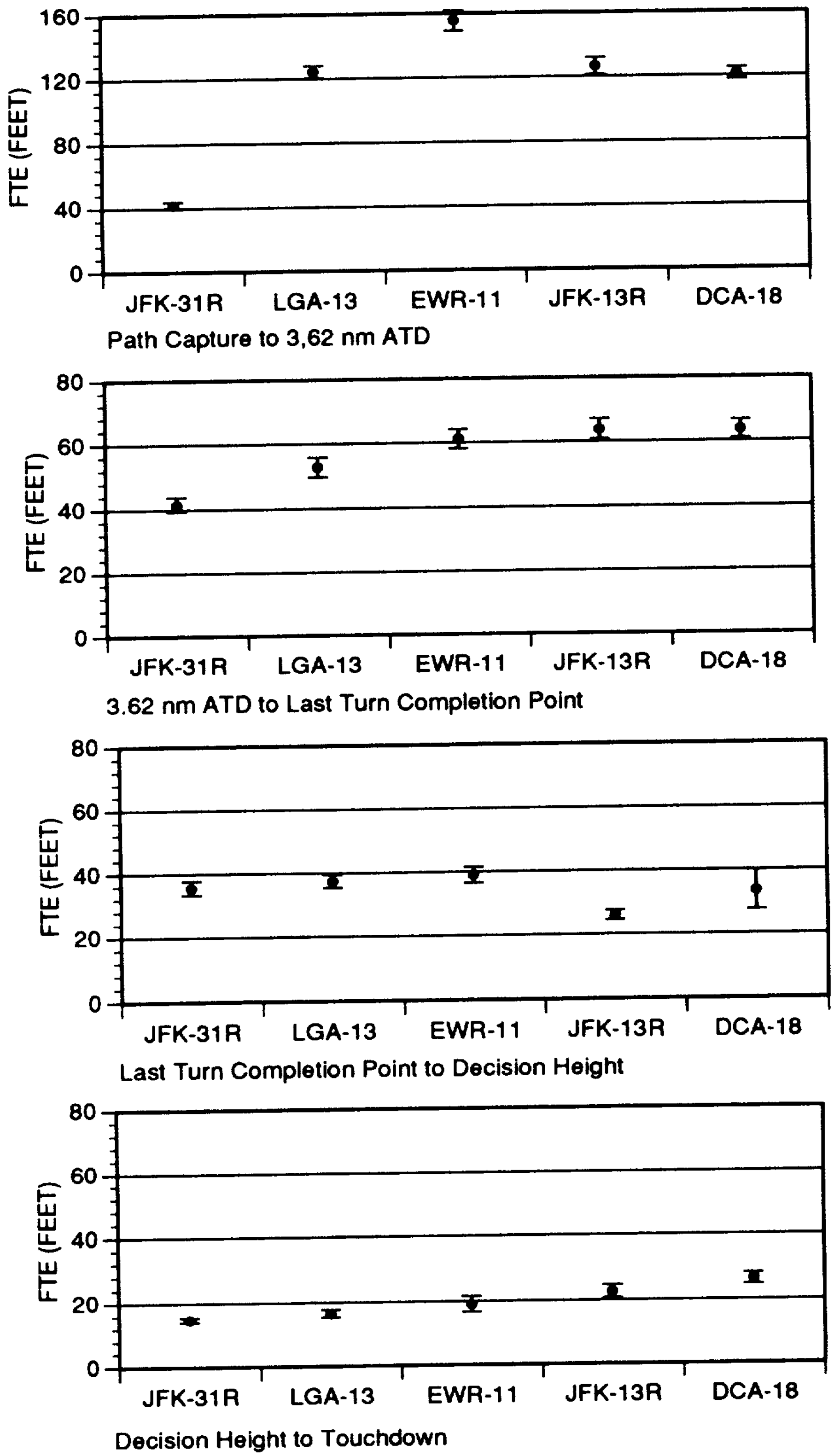


Figure C-6. Maximum vertical flight technical error per flight segment. Data point is the average across pilots and bar is ±1 standard error of the mean.

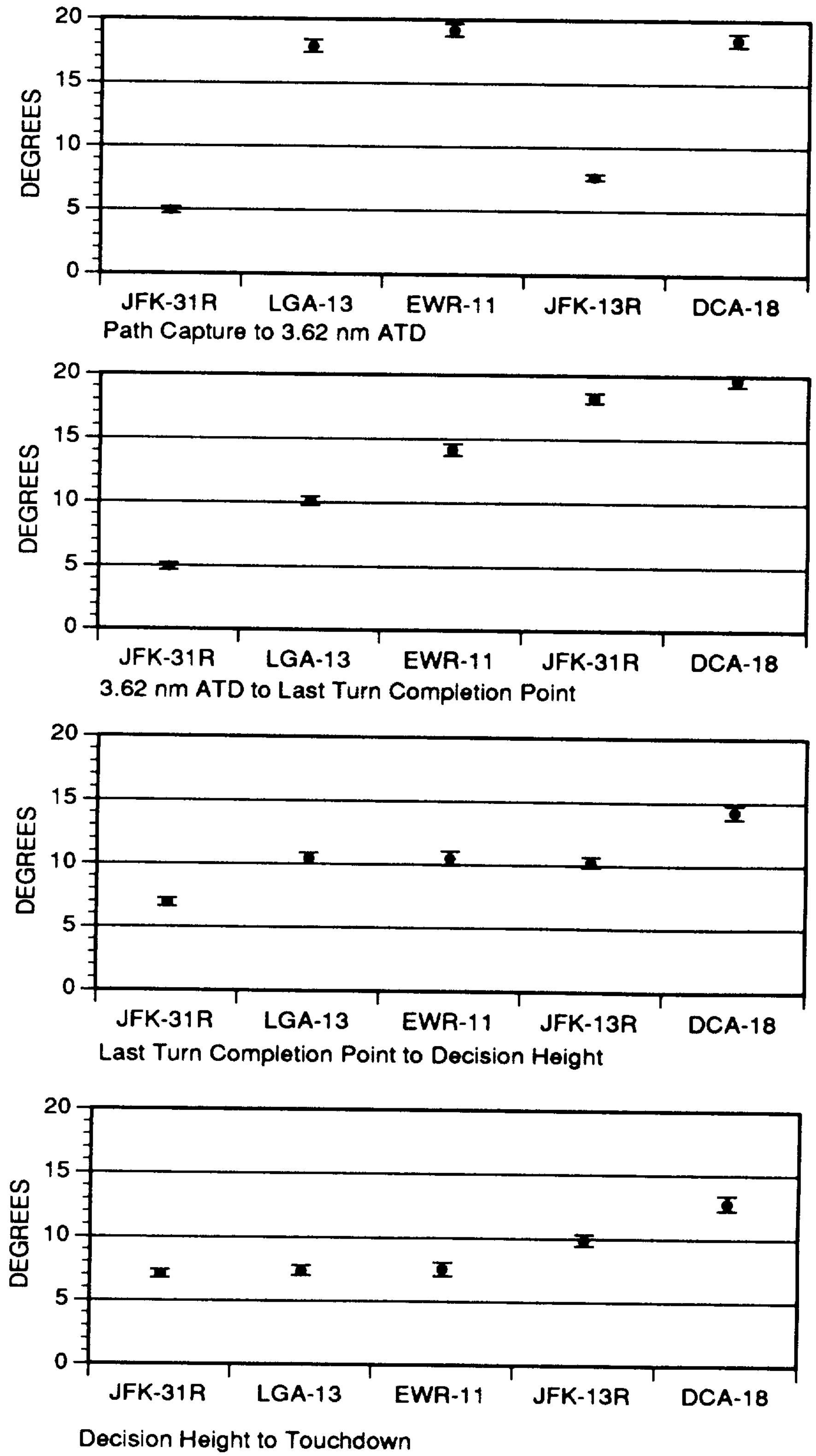


Figure C-7. Maximum bank angle for the flight segments. Data point is the average across pilots and bar is ±1 standard error of the mean.

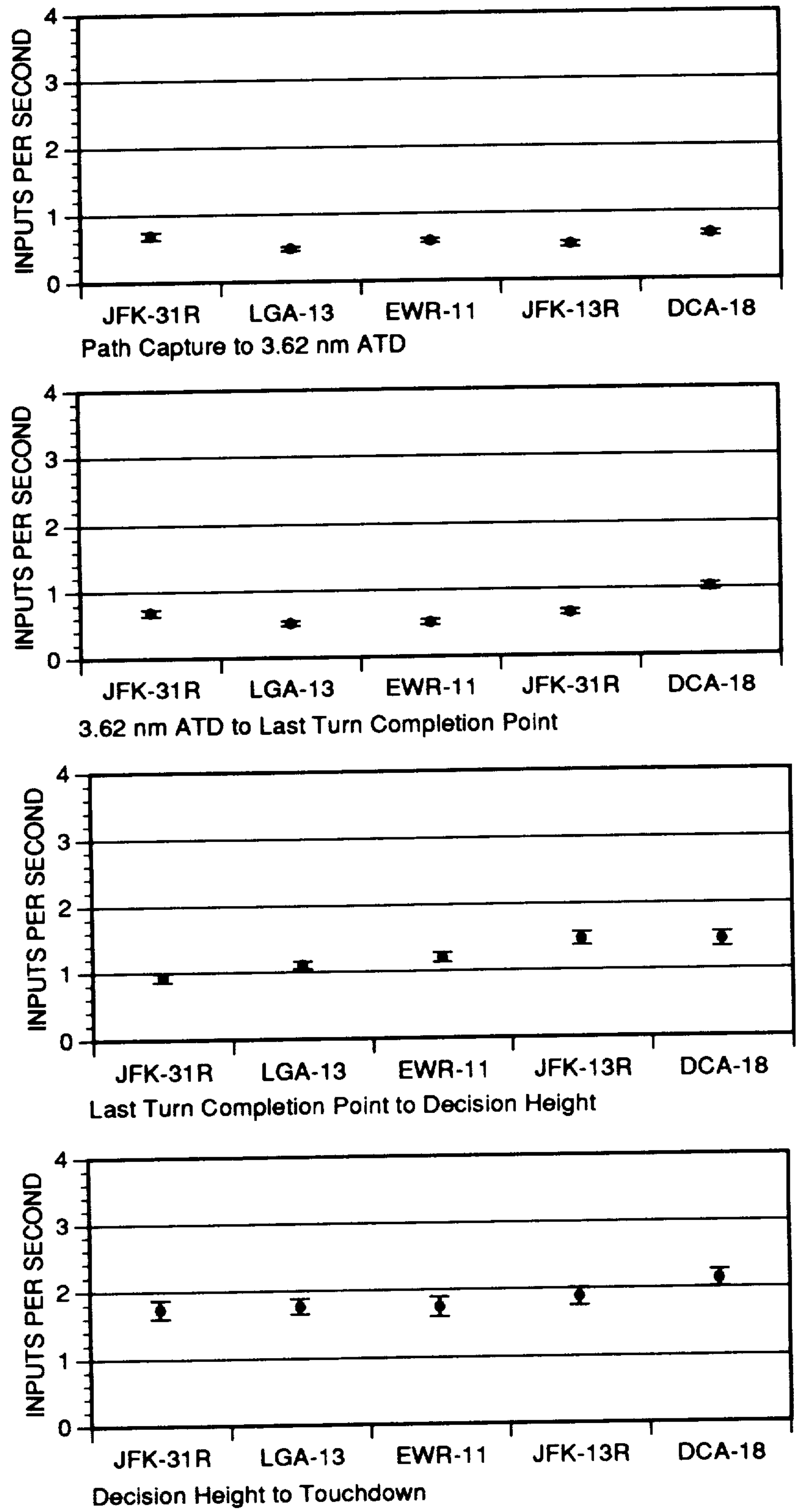


Figure C-8. Amount of control activity per flight segment. Data point is the average across pilots and bar is ±1 standard error of the mean.

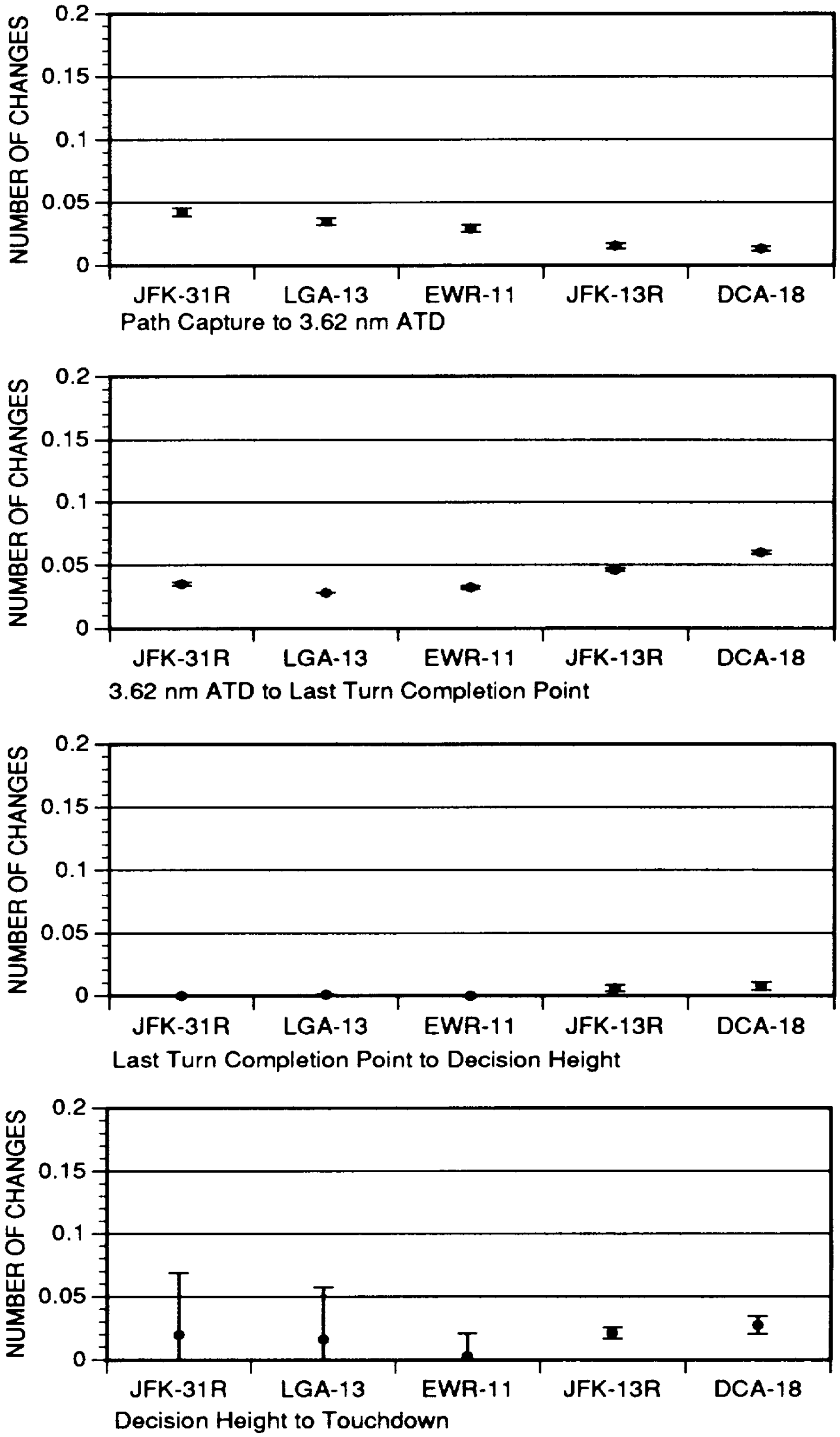


Figure C-9. Number of lateral acceleration changes greater than 0.05 g per flight segment. Data point is the average across pilots and bar is ±1 standard error of the mean.

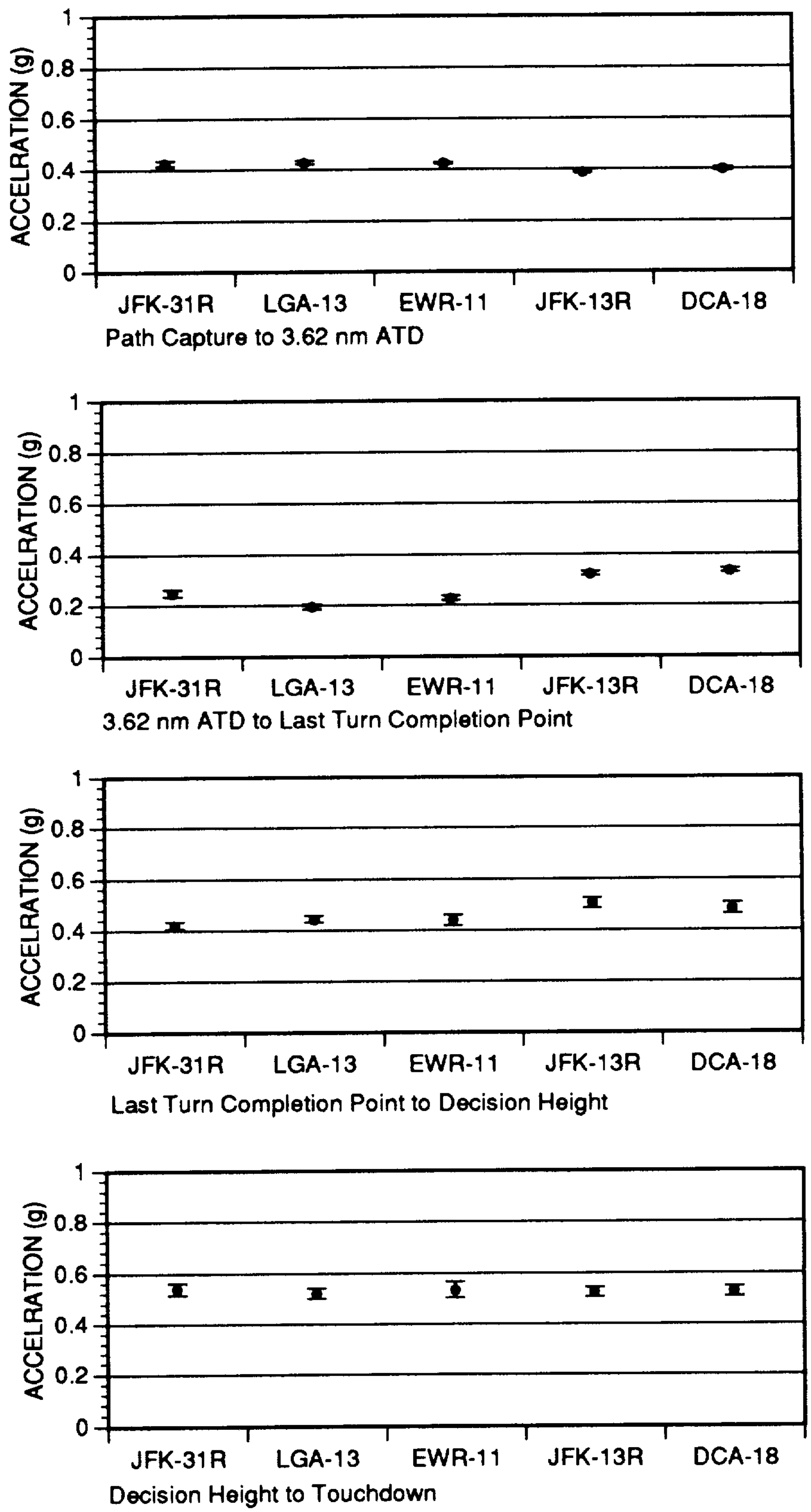


Figure C-10. Maximum lateral acceleration per flight segment. Data point is the average across pilots and bar is ±1 standard error of the mean.

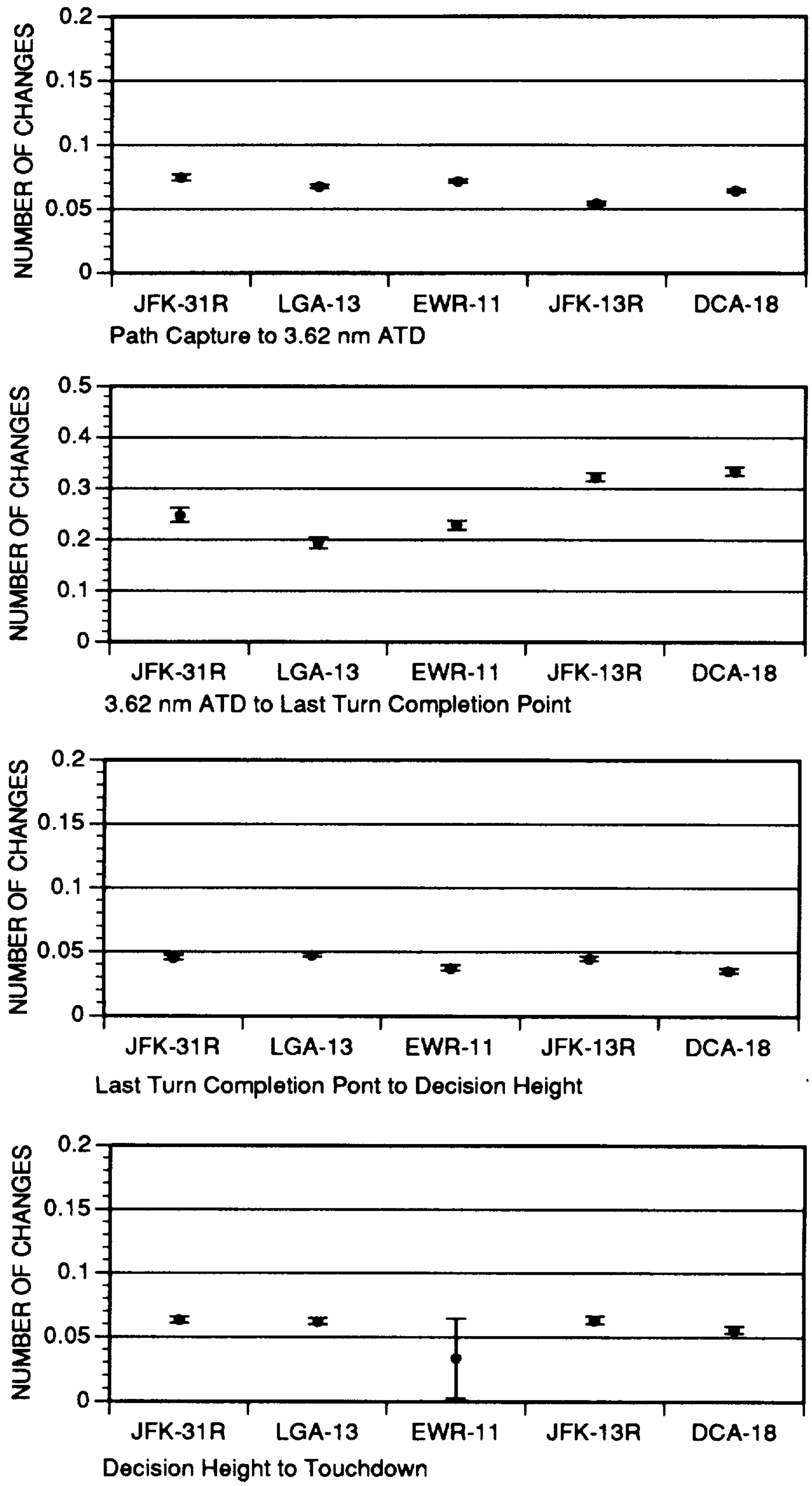


Figure C-11. Number of vertical acceleration changes greater than 0.05 g per flight segment. Data point is the average across pilots and bar is ±1 standard error of the mean.

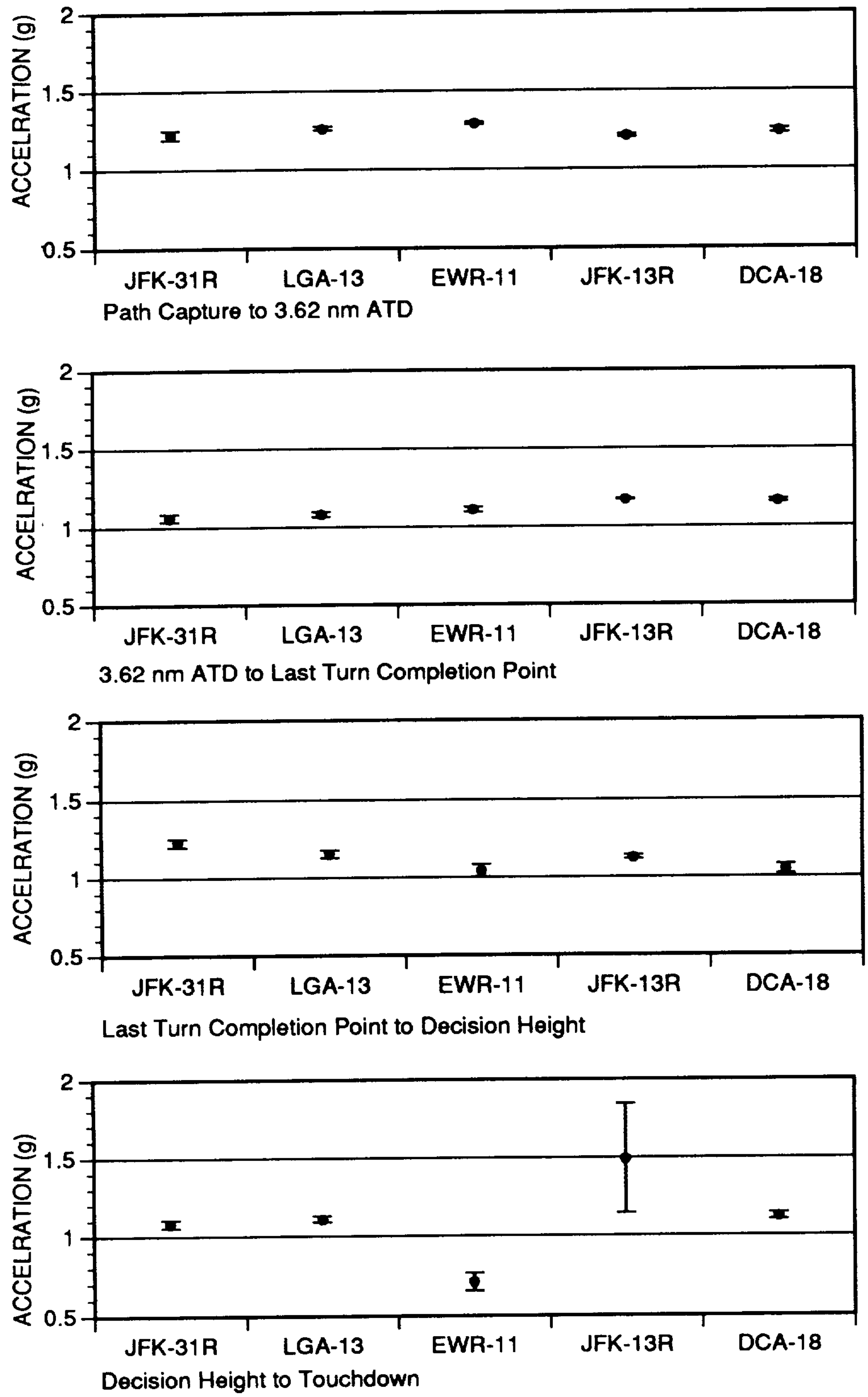
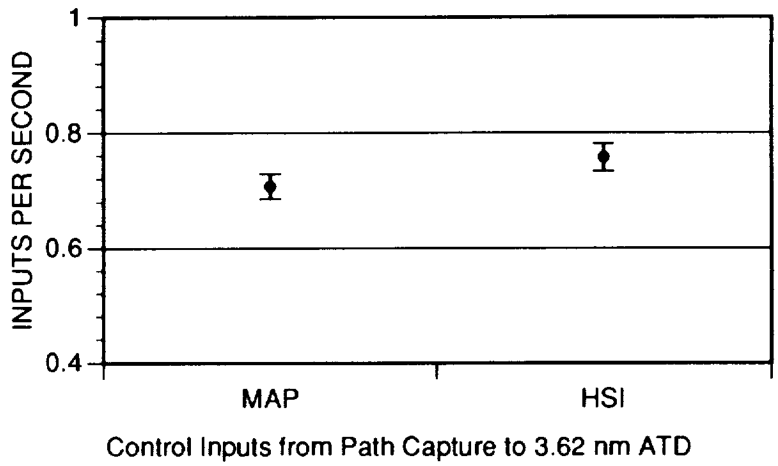


Figure C-12. Maximum vertical acceleration per flight segment. Data point is the average across pilots and bar is ±1 standard error of the mean.



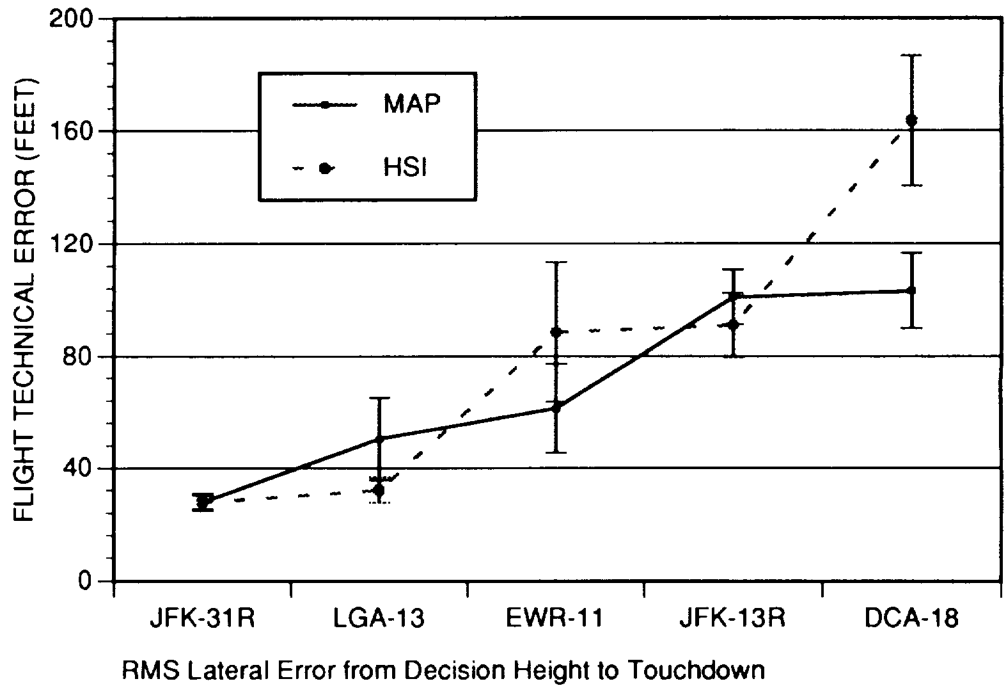
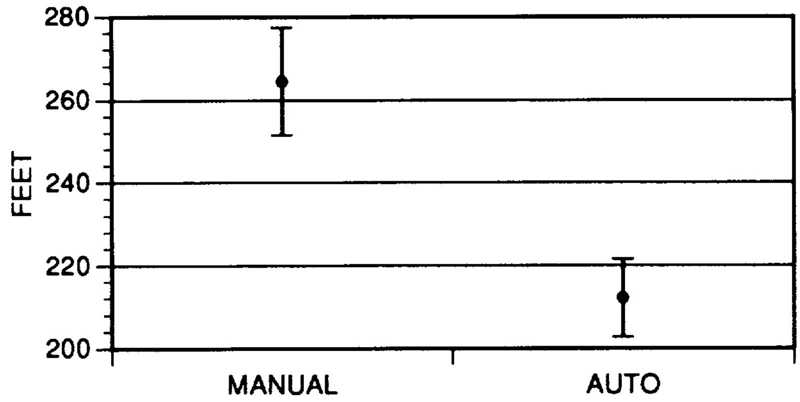
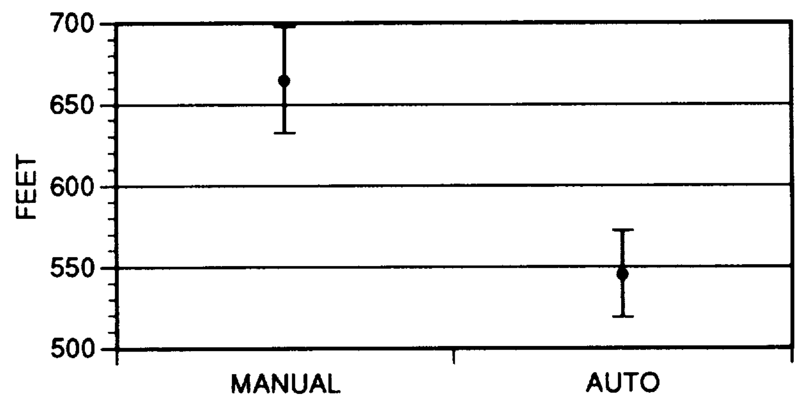


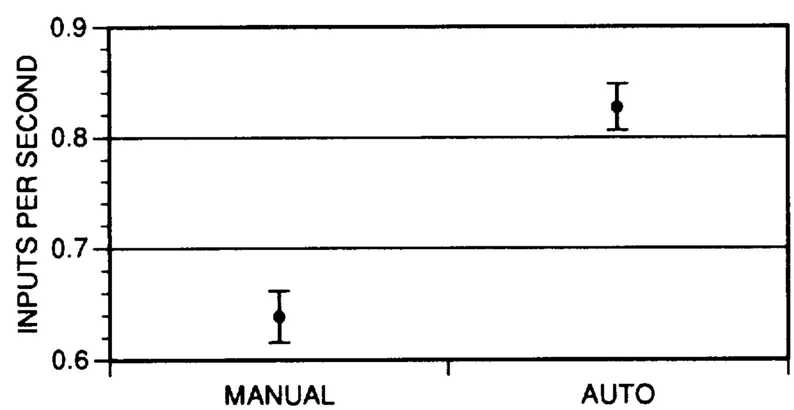
Figure C-13. The effect of the type of navigation display on the flight segment results. Data point is the average across pilots and bar is ±1 standard error of the mean.



RMS Lateral Flight Technical Error



Maximum Lateral Flight Technical Error



Control Activity

Figure C-14. Differences between throttle modes for the flight segment from path capture to 3.62 nm ATD. Data point is the average across pilots and bar is ±1 standard error of the mean.

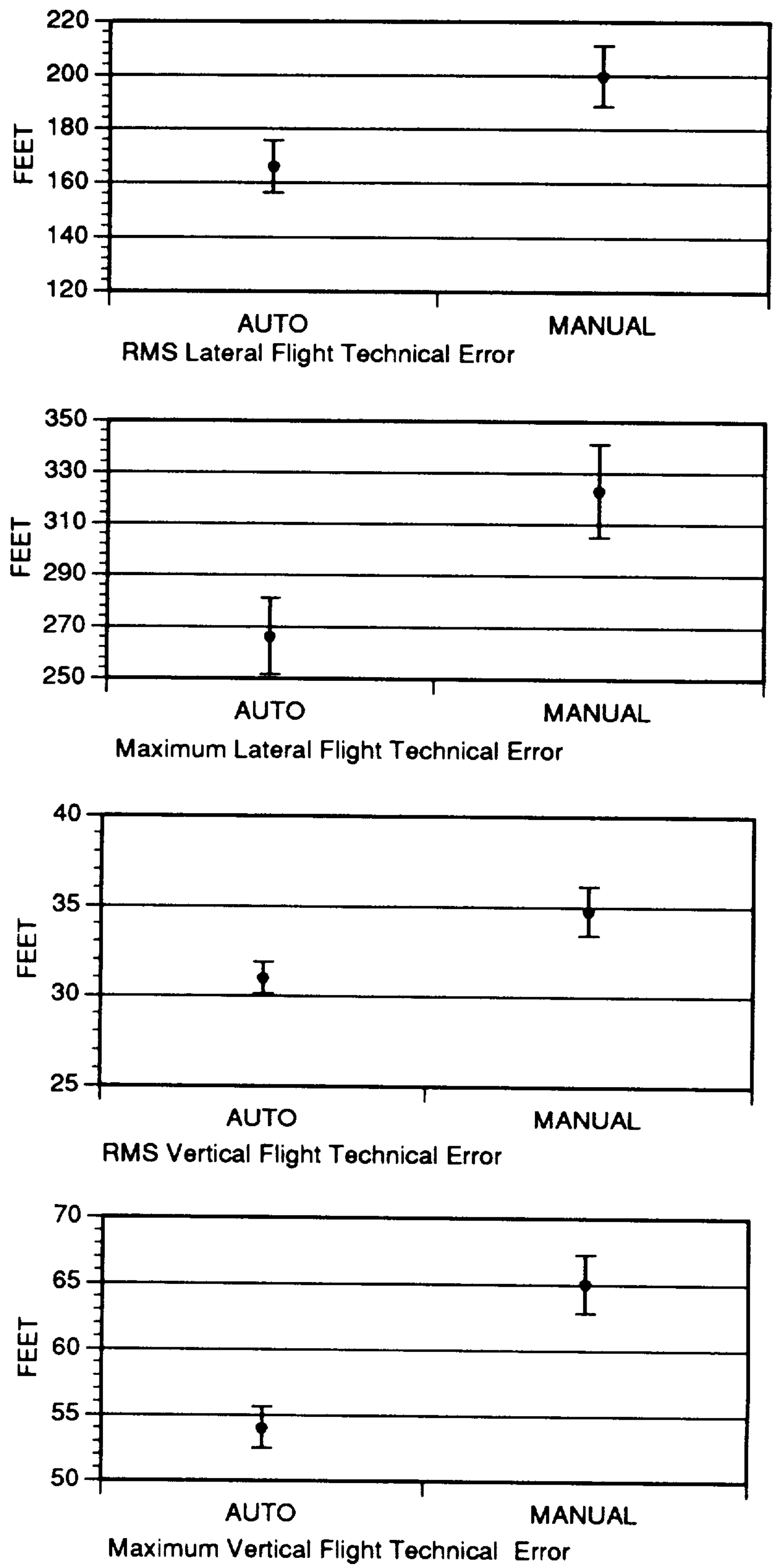


Figure C-15. The effect of throttle modes for the flight segment from 3.62 nm ATD to Last Turn Completion Point. Data point is the average across pilots and bar is ±1 standard error of the mean.

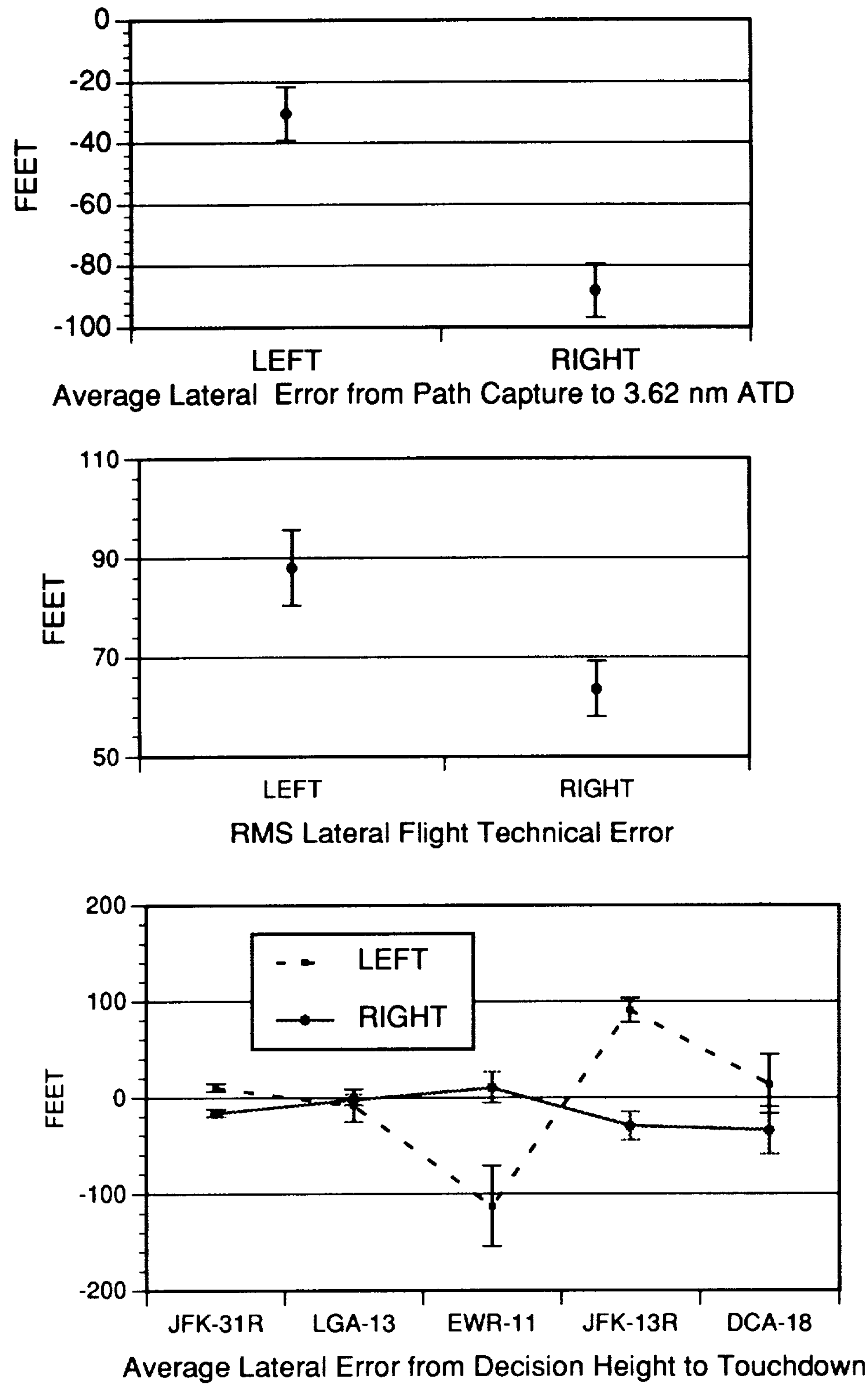


Figure C-16. The effects of the wind direction for the different flight segments. Data point is the average across pilots and bar is ±1 standard error of the mean.

Table C-6
Summary of Analysis of Variance Tests for Decision Height. (Data are only provided for those variables with a probability level of 0.01 or less.)

DEPENDENT VARIABLE	F RATIO	D of F	PROB.
Absolute lateral flight technical error			
Approach	31.89	3, 144	0.0000
Approach vs display	3.96	3, 144	0.0095
Absolute lateral course deviation			
Approach	33.32	3, 144	0.0000
Wind	11.74	1, 48	0.0013
Absolute roll flight director error			
Approach	9.25	3, 144	0.0000
Absolute vertical flight technical error			
Approach	12.51	3, 144	0.0000
Absolute vertical course deviation			
Approach	14.67	3, 144	0.0028
Throttles	9.85	1, 48	0.0000
Absolute pitch flight director error			
Approach	17.22	3, 144	0.0000
Longitudinal distance to the datum			
Approach	15.13	3, 144	0.0000
Bank Angle			
Approach	35.78	3, 144	0.0000
Approach vs wind	4.28	3, 144	0.0063
Absolute flight path angle error			
Absolute track angle error			
Approach	48.61	3, 144	0.0000
Absolute airspeed error			
Throttles	11.14	1, 48	0.0016
Vertical Speed			

Table C-7.
Summary of Analysis of Variance Tests for Touchdown. EWR-11 is not included due to the lack of data points. (Data are only provided for those variables with a probability level of 0.01 or less.)

DEPENDENT VARIABLE	F RATIO	D of F	PROB.
Absolute lateral flight technical error			
Absolute lateral course deviation			
Approach	5.11	3, 144	0.0022
Absolute roll flight director error			
Approach	4.25	3, 144	0.0066
Absolute pitch flight director error			
Approach	107.25	3, 144	0.0000
Longitudinal distance to datum			
Bank angle			
Approach	6.07	3, 144	0.0006
Absolute flight path angle error			
Approach	128.53	3, 144	0.0000
Approach vs wind	7.92	3, 144	0.0001
Absolute track angle error			
Approach	6.34	3, 144	0.0005
Absolute airspeed error			
Vertical speed			
Approach	29.86	3, 144	0.0000
Approach vs Wind	4.13	3, 144	0.0076

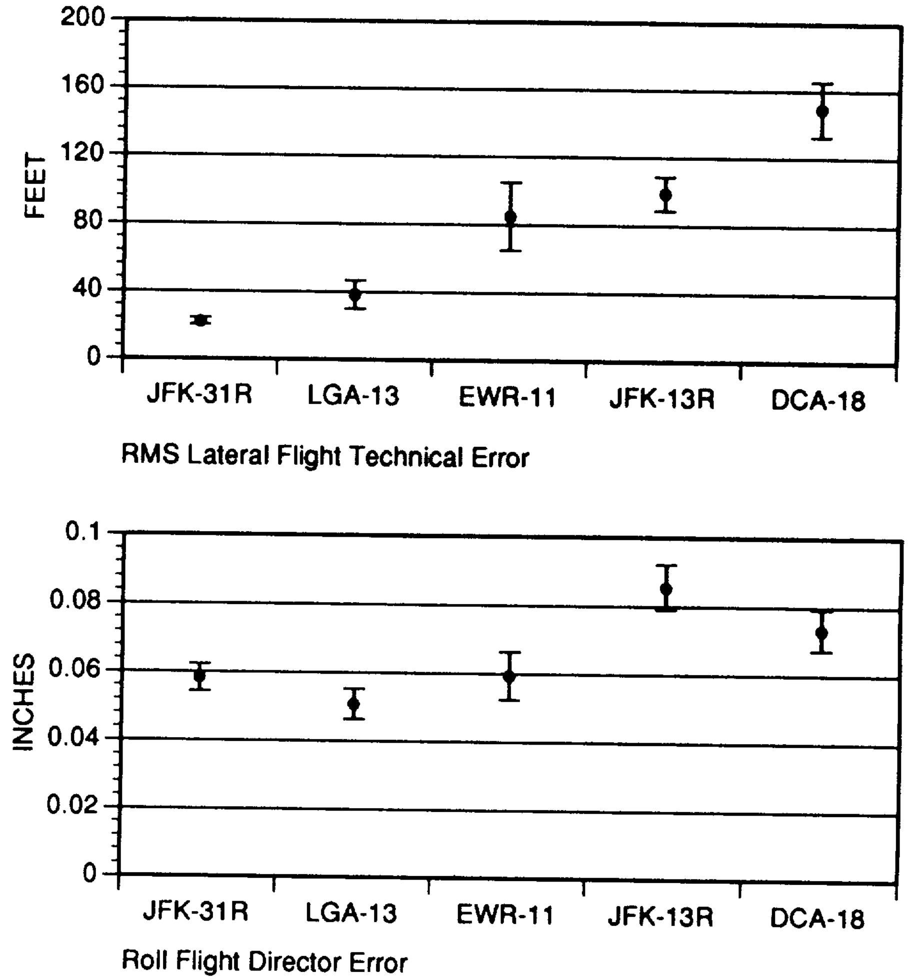


Figure C-17. Lateral errors at decision height. Data point is the average across pilots and bar is ±1 standard error of the mean.

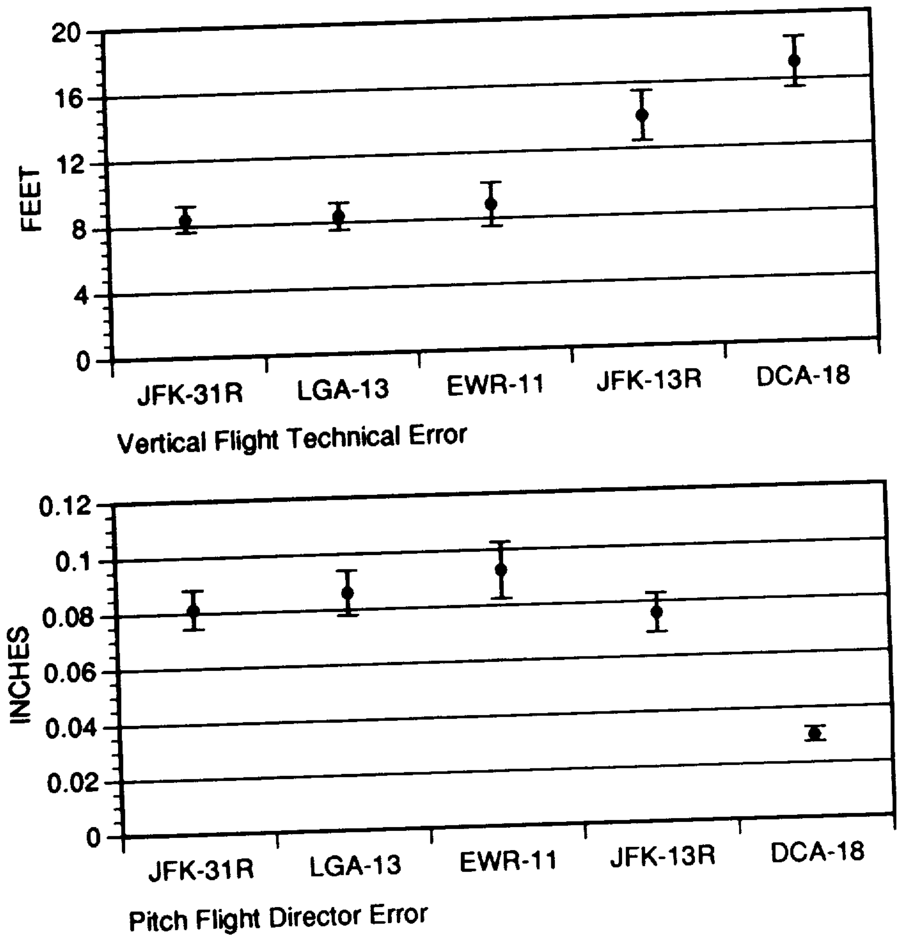


Figure C-18. Vertical errors at decision height. Data point is the average across pilots and bar is ±1 standard error of the mean.

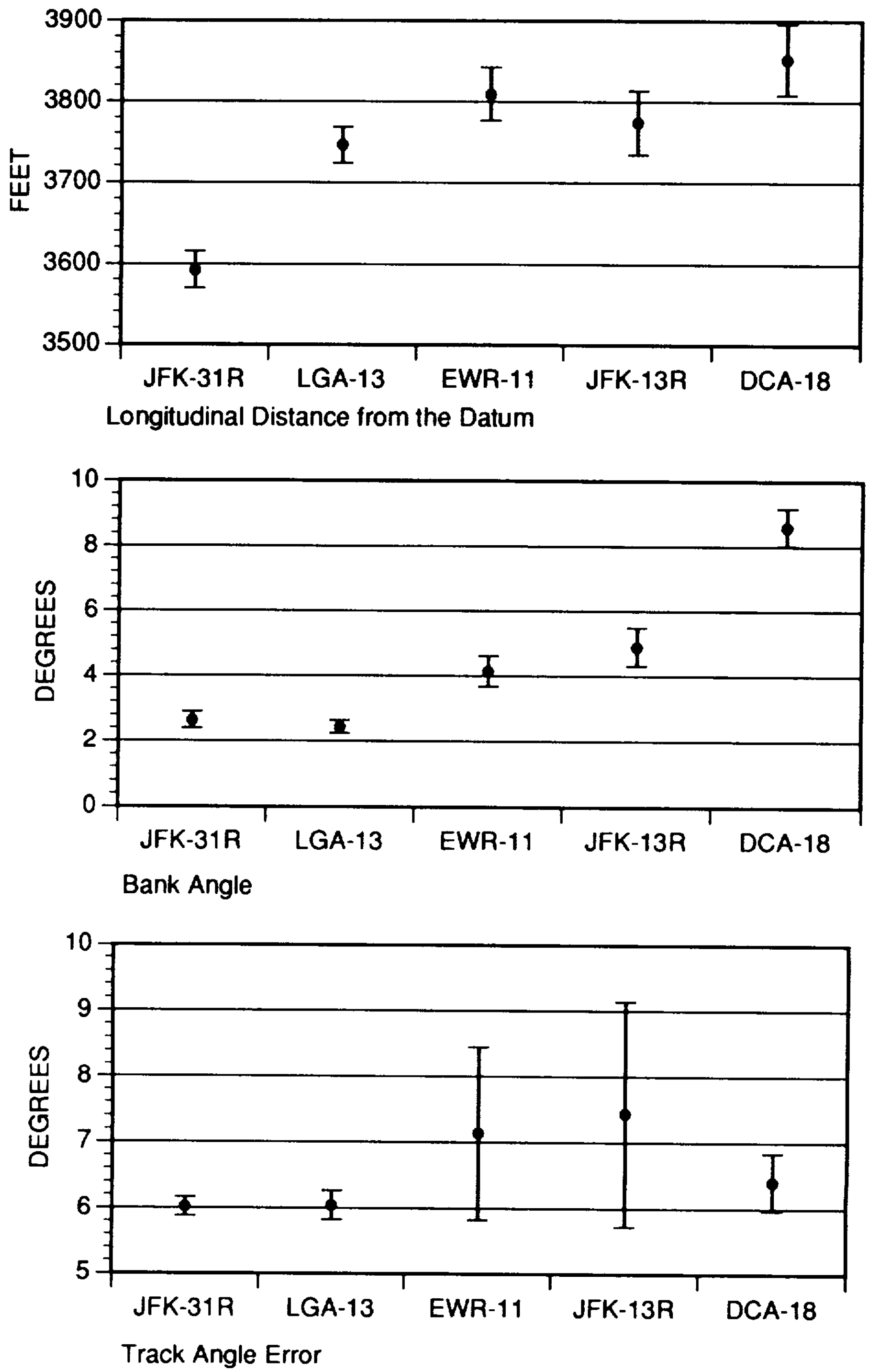
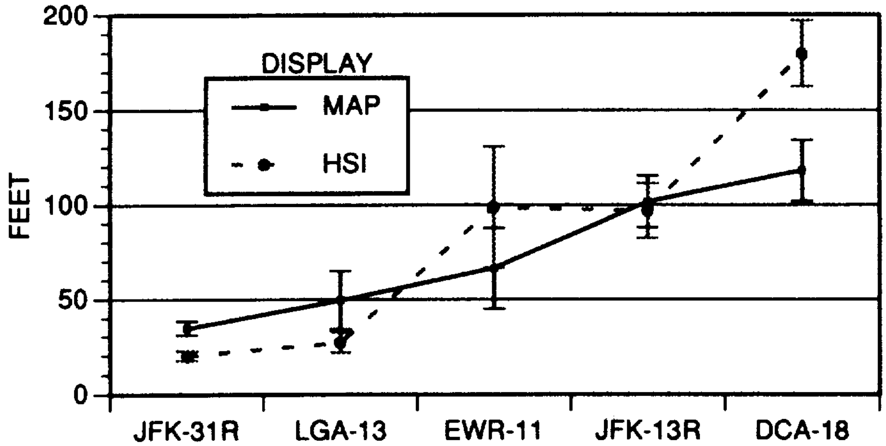
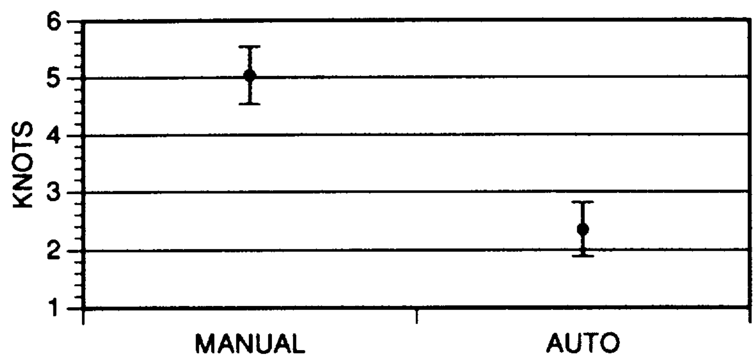


Figure C-19. Other differences between approaches at decision height. Data point is the average across pilots and bar is ±1 standard error of the mean.



Effect of Approach vs Display on Lateral Flight Technical Error



Effect of Throttles on Airspeed

Figure C-20. The effect of the other test conditions at decision height. Data point is the average across pilots and bar is ±1 standard error of the mean.

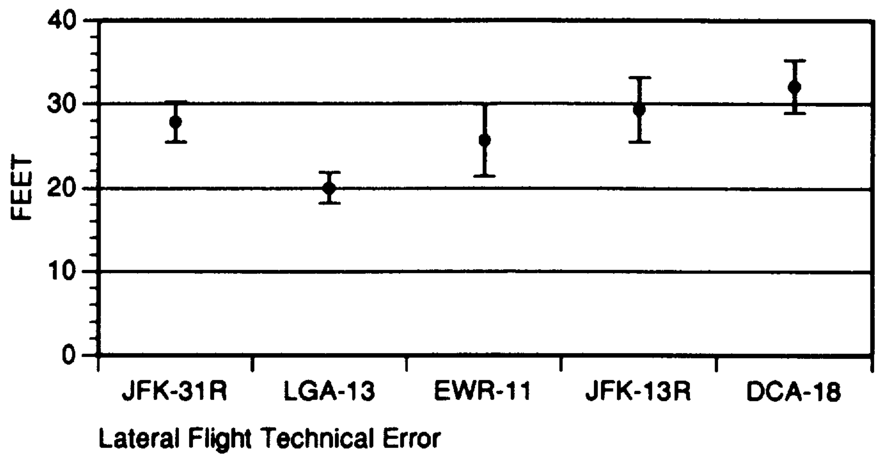


Figure C-21. The effect of approaches on track errors at touchdown. Data point is the average across pilots and bar is ±1 standard error of the mean.

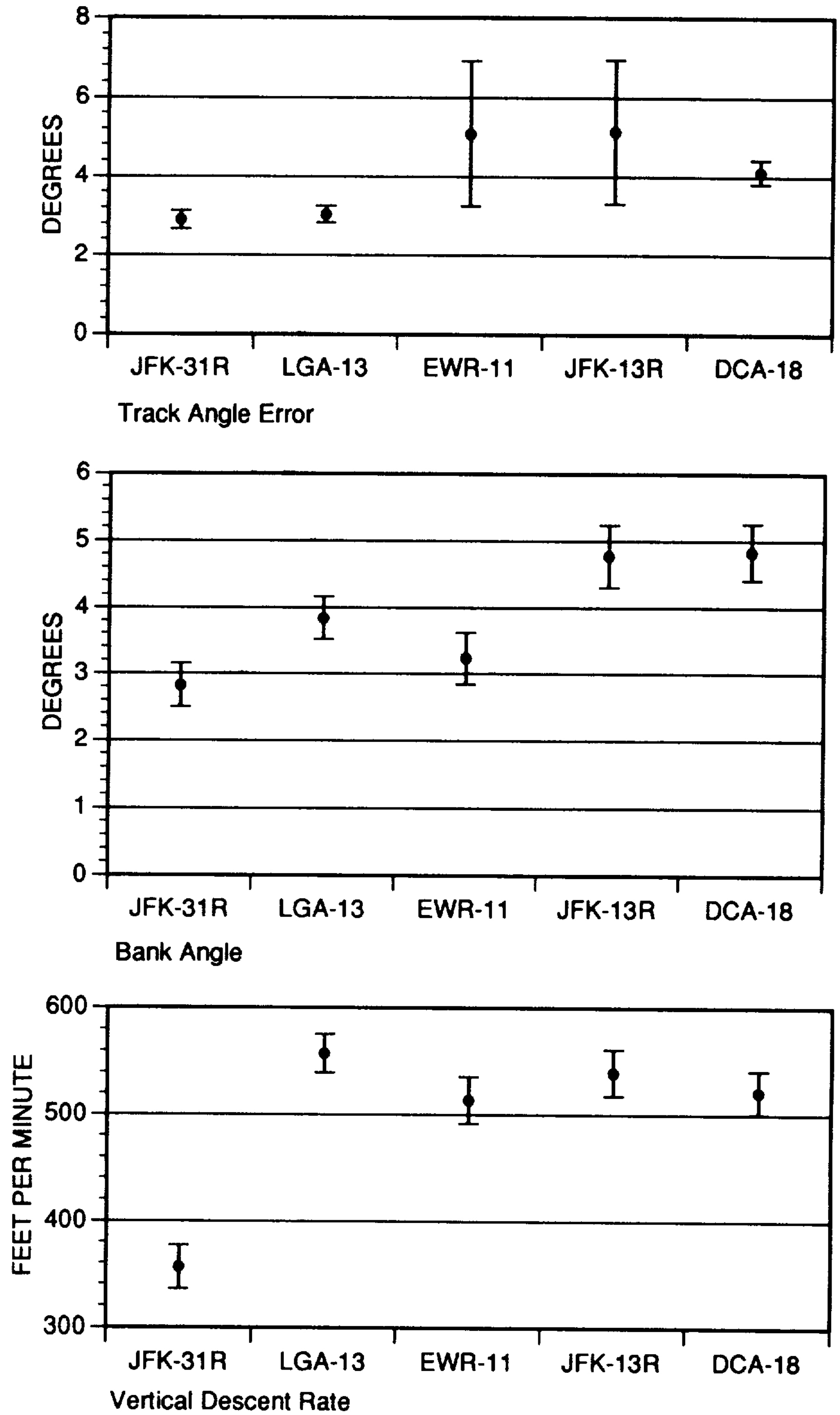


Figure C-22. Effect of approaches on other measures at touchdown. Data point is the average across pilots and bar is ±1 standard error of the mean.

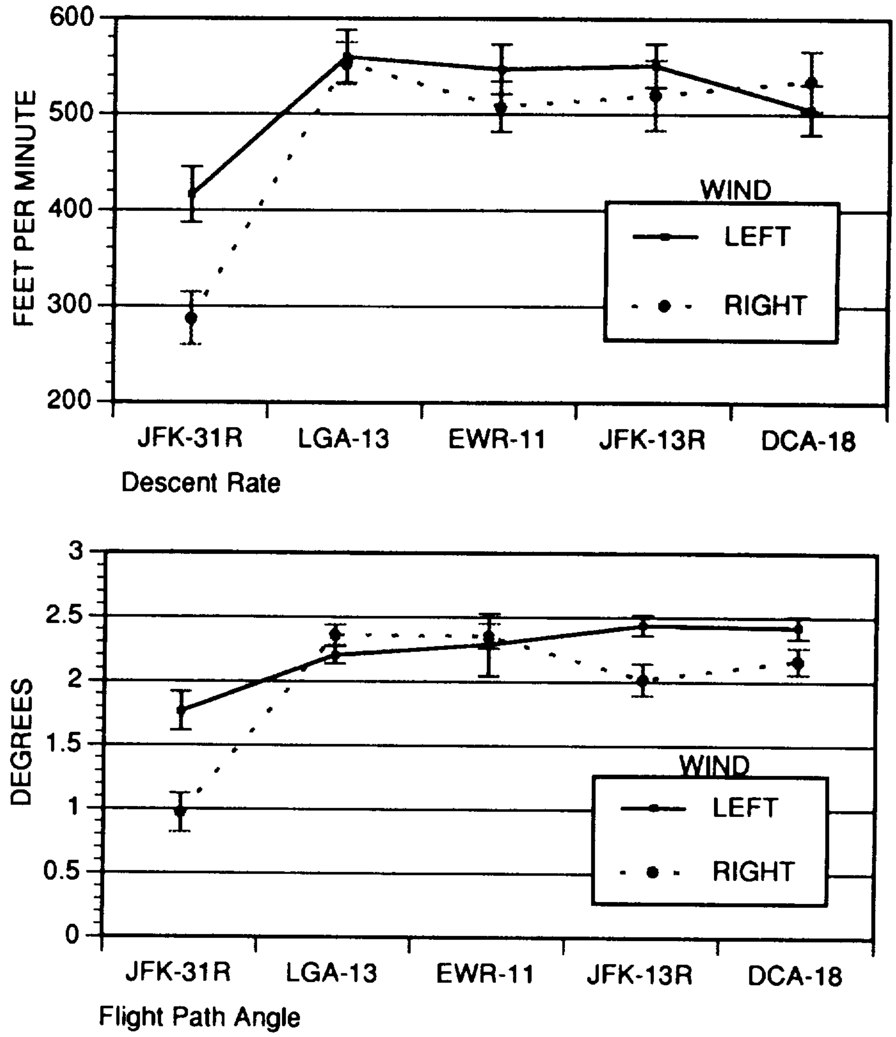


Figure C-23. Effect of approaches versus wind at touchdown. Data point is the average across pilots and bar is ±1 standard error of the mean.

Table C-8.
Results of the Chi Square Test on the Subjective Responses for the Flight Director Failure and Engine Fire Warning Contingencies. Only those variables that had a significance level of 0.05 or less are listed.

DEPENDENT VARIABLE	VALUE	D of F	PROB.
Flight Director			
Comparison of workload to failure on ILS	31.11	12	0.002
Comparison of workload to failure on VOR	39.30	12	0.000
Engine Fire Warning			
Workload rating of pilot flying	33.80	32	0.027
Workload rating of pilot not flying	48.74	32	0.029

Table C-9.
Summary of Analysis of Variance Tests for the Flight Director Failure from the Last Turn Completion Point to Decision Height. (Data are only provided for those variables with a probability level of 0.05 or less.)

DEPENDENT VARIABLE	F RATIO	D of F	PROB.
RMS lateral flight technical error			
Average lateral error Approach	2.73	4, 40	0.0366
Maximum lateral flight technical error			
RMS vertical flight technical error			
Average vertical flight technical error			
Maximum vertical flight technical error			
Maximum bank angle			
Total control activity			
Maximum lateral acceleration			
Number of lateral acceleration changes			
Maximum vertical acceleration			
Number of vertical acceleration changes			

Table C-10.
Summary of Analysis of Variance Tests for the Flight Director Failure from Decision Height to Touchdown. (Data are only provided for those variables with a probability level of 0.05 or less.)

DEPENDENT VARIABLE	F RATIO	D of F	PROB.
RMS lateral flight technical error			
Average lateral error			
Maximum lateral flight technical error			
RMS vertical flight technical error			
Average vertical flight technical error			
Maximum vertical flight technical error			
Maximum bank angle			
Approach vs Display	2.94	4, 34	0.0366
Total control activity			
Maximum lateral acceleration			
Number of lateral acceleration changes			
Maximum vertical acceleration			
Number of vertical acceleration changes			
Approach	4.09	4, 34	0.0083
Approach vs display	3.25	4, 34	0.0231

Table C-11.
Summary of Analysis of Variance Tests for the Flight Director Failure at the Last Turn Completion Point. (Data are only provided for those variables with a probability level of 0.05 or less.)

DEPENDENT VARIABLE	F RATIO	D of F	PROB.
Absolute lateral flight technical error			
Absolute lateral course deviation			
Approach	2.95	4, 35	0.0333
Absolute roll flight director error			
Absolute Vertical flight technical error			
Absolute vertical course deviation			
Absolute pitch flight director error			
Bank angle			
Absolute flight path angle error			
Absolute track angle error			
Approach	11.20	4, 35	0.0133
Absolute airspeed error			
Vertical speed			
Approach	2.86	4, 35	0.0378

Table C-12.
Summary of Analysis of Variance Tests for the Flight Director Failure at Decision Height. (Data are only provided for those variables with a probability level of 0.05 or less.)

DEPENDENT VARIABLE	F RATIO	D of F	PROB.
Absolute lateral flight technical error			
Display	5.01	1, 35	0.0317
Absolute lateral course deviation			
Display	4.66	1, 35	0.0378
Absolute roll flight director error			
Absolute vertical flight technical error			
Absolute vertical course deviation			
Absolute pitch flight director error			
Approach	4.33	4, 35	0.0060
Longitudinal distance to datum			
Bank angle			
Absolute flight path angle error			
Absolute track angle error			
Approach	4.56	4, 35	0.0045
Absolute airspeed error			
Throttles	4.88	1, 35	0.0338
Vertical speed			

Table C-13.
Summary of Analysis of Variance Tests for the Flight Director Failure at Touchdown. (Data are only provided for those variables with a probability level of 0.05 or less.)

DEPENDENT VARIABLE	F RATIO	D of F	PROB.
Absolute lateral flight technical error			
Absolute lateral course deviation			
Approach	2.95	4, 35	0.0337
Absolute roll flight director error			
Absolute vertical flight technical error			
Absolute vertical course deviation			
Absolute pitch flight director error			
Approach	5.92	4, 35	0.0010
Longitudinal distance to datum			
Bank angle			
Absolute flight path angle error			
Approach	4.33	4, 35	0.0060
Throttles	6.99	1, 35	0.0122
Approach vs throttles	6.01	4, 35	0.0000
Absolute track angle error			
Approach	11.20	4, 35	0.0000
Absolute airspeed error			
Throttles	4.88	1, 35	0.0338
Vertical speed			
Approach	2.86	4, 35	0.0378
Approach vs throttles	6.01	4, 35	0.0009

Table C-14.
Summary of Analysis of Variance Tests for the Engine Fire Warning from the Last Turn Completion Point to Decision Height. (Data are only provided for those variables with a probability level of 0.05 or less.)

DEPENDENT VARIABLE	F RATIO	D of F	PROB.
RMS lateral flight technical error			
Average lateral error			
Maximum lateral flight technical error			
RMS vertical flight technical error			
Approach	2.89	4, 28	0.0403
Average vertical flight technical error			
Maximum vertical flight technical error			
Approach	5.29	4, 28	0.0027
Maximum bank angle			
Total control activity			
Maximum lateral acceleration			
Number of lateral acceleration changes			
Maximum vertical acceleration			
Number of vertical acceleration changes			
Approach	4.61	4, 28	0.0005

Table C-15.
Summary of Analysis of Variance Tests for the Engine Fire Warning from Decision Height to Touchdown. (Data are only provided for those variables with a probability level of 0.05 or less.)

DEPENDENT VARIABLE	F RATIO	D of F	PROB.
RMS lateral flight technical error			
Average lateral error			
Maximum lateral flight technical error			
RMS vertical flight technical error			
Average vertical flight technical error			
Maximum vertical flight technical error			
Maximum bank angle			
Total control activity			
Maximum lateral acceleration			
Approach	5.57	4, 28	0.0020
Number of lateral acceleration changes			
Maximum vertical acceleration			
Approach	6.74	4, 28	0.0006
Number of vertical acceleration changes			
Approach	4.43	4, 28	0.0067

Table C-16.
Summary of Analysis of Variance Tests for Engine Fire Warning at the Last Turn Completion Point.
(Data are only provided for those variables with a probability level of 0.05 or less.)

DEPENDENT VARIABLE	F RATIO	D of F	PROB.
Absolute lateral flight technical error			
Absolute lateral course deviation			
Absolute roll flight director error			
Approach	6.12	4, 29	0.0011
Absolute vertical flight technical error			
Absolute vertical course deviation			
Approach	3.93	4, 29	0.0002
Absolute pitch flight director error			
Approach	3.07	4, 29	0.0325
Bank angle			
Approach	3.38	4, 29	0.0218
Absolute flight path angle error			
Approach	3.28	4, 29	0.0245
Absolute track angle error			
Approach	15.98	4, 29	0.0000
Display	4.91	1, 29	0.0348
Absolute airspeed error			
Throttles	6.18	1, 29	0.0189
Vertical speed			
Approach	7.85	4, 29	0.0002
Throttles	13.46	1, 29	0.0010
Approach vs throttles	5.86	4, 29	0.0014

Table C-17.
Summary of Analysis of Variance Tests for Engine Fire Warning at Decision Height. (Data are only provided for those variables with a probability level of 0.05 or less.)

DEPENDENT VARIABLE	F RATIO	D of F	PROB.
Absolute lateral flight technical error			
Absolute lateral course deviation			
Absolute roll flight director error			
Absolute vertical flight technical error			
Absolute vertical course deviation			
Absolute pitch flight director error			
Approach	3.88	4, 29	0.0044
Bank angle			
Absolute flight path angle error			
Absolute track angle error			
Approach	3.16	4, 29	0.0286
Absolute airspeed error			
Vertical speed			

Table C-18.
Summary of Analysis of Variance Tests for Engine Fire Warning at Touchdown. (Data are only provided for those variables with a probability level of 0.05 or less.)

DEPENDENT VARIABLE	F RATIO	D of F	PROB.
Absolute lateral flight technical error			
Absolute lateral course deviation			
Absolute roll flight director error			
Absolute vertical flight technical error			
Absolute vertical course deviation			
Absolute pitch flight director error			
Approach	5.52	4, 24	0.0027
Longitudinal distance to datum			
Bank angle			
Absolute flight path angle error			
Approach	8.52	4, 24	0.0002
Absolute track angle error			
Absolute airspeed error			
Vertical speed			
Approach	4.18	4, 24	0.0104

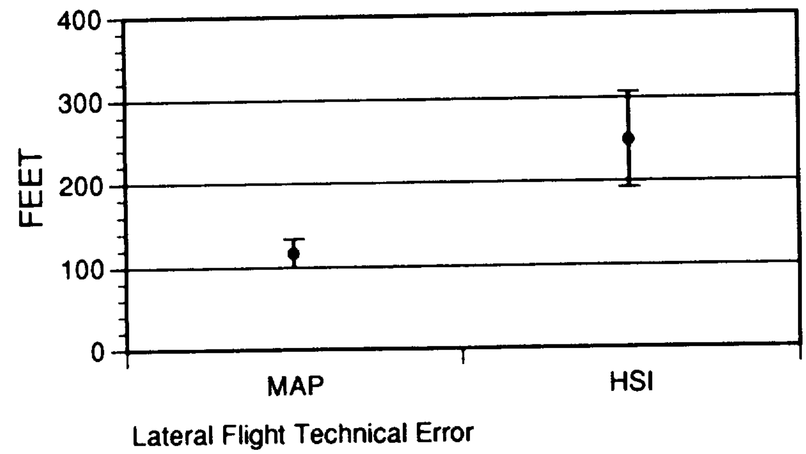


Figure C-24. The effect of navigation display type on the flight director failure at decision height. Data point is the average across pilots and bar is ±1 standard error of the mean.

*U.S. GOVERNMENT PRINTING OFFICE: 1992-627-150/60002

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	June 1992	Contractor Report

4. TITLE AND SUBTITLE
Evaluation of Microwave Landing System Approaches in a Wide-Body Transport Simulator

5. FUNDING NUMBERS
C NAS1-18028
WU 505-66-41-66

6. AUTHOR(S)
L. G. Summers and J. B. Feather

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Douglas Aircraft Company
McDonnell Douglas Corporation
Long Beach, CA 90846

8. PERFORMING ORGANIZATION REPORT NUMBER
MDC Report No. 91K0792

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Langley Research Center
Hampton, VA 23665-5225

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA CR-4450

11. SUPPLEMENTARY NOTES
Langley Technical Monitor: Charles E. Knox
Langley Contract Monitor: Cary R. Spitzer
Final Report

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited

Subject Category 04

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The objective of this study was to determine the suitability of flying complex curved approaches using the microwave landing system with a wide-body transport aircraft. Fifty pilots in crews of two participated in the evaluation using a fixed-base simulator that emulated an MD-11 aircraft. Five approaches consisting of one straight-in approach and four curved approaches were flown by the pilots using a flight director.

The test variables included (1) manual and autothrottles, (2) wind direction, and (3) type of navigation display. The navigation display was either a map or a horizontal situation indicator (HSI). A complex wind that changed direction and speed with altitude, and included moderate turbulence, was used. Visibility conditions were Cat I or better.

Subjective test data included pilot responses to questionnaires and pilot comments. Objective performance data included tracking accuracy, position error at decision height, and control activity. Results of the evaluation indicate that flying curved MLS approaches with a wide-body transport aircraft is operationally acceptable, depending upon the length of the final straight segment and the complexity of the approach.

14. SUBJECT TERMS
Microwave Landing System, Navigation, Precision Approaches

15. NUMBER OF PAGES
172

16. PRICE CODE
A08

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified		