Flight Simulation of a Wide-Body Transport Aircraft to Evaluate MLS-RNAV Procedures

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In a collaborative effort between the Federal Aviation Administration (FAA) NASA and the U.S. Air Force, a piloted simulation was conducted to look at the issues involved with flying a large, wide-body aircraft in the airport terminal area using Microwave Landing System Area Navigation (MLS)-RNAV procedures. A variety of approach paths, departure paths, and holding patterns were evaluated during the course of the study for operational use, flight technical errors, and safety. In addition, several methods for driving the horizontal situation indicator and flight director instruments were investigated along with needle sensitivity. The ultimate goal of the simulation was to develop and verify candidate paths and procedures prior to flight tests conducted in 1986/87. Subject pilots for the simulation study were provided by the FAA, NASA, the U.S. Air Force, and the airline industry.

Introduction

THE international aviation community has chosen the Microwave Landing System (MLS) to become the new standard for terminal area navigation, replacing the 40-year-old Instrument Landing System (ILS). To this end, the United States is preparing to install MLS on 1200 runways at airports across the country. Among the many advantages MLS guidance offers is the capability for generating an infinite number of paths for precision navigation during the various terminal area maneuvers. Figure 1 shows a comparison of signal coverage for MLS and ILS.

In conjunction with the Federal Aviation Administration (FAA), NASA's Langley Research Center (LaRC) has been involved in the development and testing of MLS for over a decade. Their participation in the Service Test and Evaluation Program (STEP)[1] has helped provide a data base for basic Terminal Instrument Procedures (TERPS) for narrow body, jet transport aircraft.

The FAA, charged with the responsibility for creating the TERPS standards, is working hard to develop criteria for MLS procedures. TERPS planning encompasses not only the landing phase of flight, but also an exhaustive array of approach paths, departure paths, and holding patterns. In the past, the design of these procedures has been less complex, since only a single approach or departure course was available with the ILS. However, with the capability that exists for multiple approach and departure paths using MLS, the task becomes more difficult. Compounding the problem is the anticipated ability of aircraft to fly curved or segmented paths using sophisticated airborne navigation computers.

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With complex paths, the terminal procedures designer is faced with the problems of matching up aircraft of varying size and speed with an orderly and efficient traffic flow into and out of the terminal area. Also factored into the equation are issues concerning specific runway configurations, avoidance of local terrain features, and avoidance of noise-sensitive areas.

The process of designing these new procedures could have progressed through the traditional use of flight testing alone. However, it was decided early in the project that by using flight simulation techniques considerable time and money could be saved. The distinct advantage foreseen was that researchers and pilots could take more than just a cursory look at the procedures, since simulation is generally immune to the demands placed on flight tests due to cramped aircraft schedules, balky hardware, and weather. One of the key advantages attributed to the simulation process was the ability to make changes in the parameters of a particular procedure in almost real time, something that generally cannot be done during a flight test. Another advantage was the ability to model situations not attainable in flight without incurring time or cost penalties; for example, the introduction of adverse winds to an approach scenario.

Description of Project

The profiles that were chosen for simulation fell into two categories: those required for terminal procedures development and those requiring operational evaluation. The profiles chosen for TERPS development were designed by the FAA Standards Development Branch in conjunction with the U.S. Air Force Instrument Flight Center. These were intended to encompass all of the different types of aircraft maneuvers deemed necessary for defining terminal airspace and determining obstacle clearance criteria. The profiles were generic and included the parameters (e.g., bank angle changes, pitch changes, offsets, and angular paths) expected to be needed in the construction of all envisioned complex paths. The profiles selected for operational evaluation were either designed to look at specific airport problems or represented operational scenarios useful in evaluating MLS guidance and control functions. Most of these were derivatives or combinations of the TERPS designs.

A major requirement of this project was to implement a simulation of a wide-body, jet transport aircraft with the capability of flying complex, curved paths. This entailed developing a simulation program that would combine software models representing the aircraft dynamics, MLS guidance, and an airborne area navigation system. The approach taken was to modify pre-existing programs (for the aircraft, path generation, MLS signals, and flight guidance) and integrate them into one large-scale simulation. A considerable amount of effort was expended in developing the simulation program to conduct this study.

A model of the L-1011 aircraft was chosen from a number of aircraft simulation programs resident at LaRC. This software had been developed over a period of several years, with the help of Lockheed, to investigate performance and handling qualities questions. As a result, the model was well refined.

The software to simulate the MLS guidance signals had been written by LaRC in the mid-1970's to conduct investigations into this new form of guidance and to propose operational scenarios for its use. The model had the ability to introduce errors such as would be found in an operational environment.

Software for path generation, flight navigation, and guidance had been developed previously for the STEP studies mentioned earlier. Modifications were made to this software in order to match the characteristics of the L-1011 aircraft.

Visual Motion Simulator

The Visual Motion Simulator (VMS), shown in Fig. 2, is a general-purpose simulator consisting of a two-man cockpit mounted on a six-degree-of-freedom synergistic motion base.[2,3] Motion cues were provided in the simulator by the relative extension or retraction of the six hydraulic actuators of the motion base. Washout techniques were used to return the motion base to the neutral point once the onset motion cues had been commanded.[4]

The cockpit of the VMS (Fig. 3) was designed to accommodate a generic transport aircraft configuration on the left side and a fighter or rotorcraft on the right. A programmable hydraulic-control loading system was provided for the control wheel, column, and rudder on the left side. A collimated video display provided a 60-deg, out-the-window color visual scene for both seats. A center control stand was installed, providing typical transport control features. The instrument panel contained the major instruments required to conduct flight maneuvers and navigation. The instrument complement included an electromechanical flight director and horizontal situation indicator; indicators for airspeed, altitude, vertical speed, turn and bank, and radio magnetic bearing; and the basic engine instruments. For this test, additional instrumentation was added, consisting of flight director mode indicators, a turn anticipation indicator, and digital displays for readout of distance along the track, as well as the distance direct to the azimuth site. For orientation, the bearing pointer of the horizontal situation indicator was used to indicate the bearing to the azimuth site.

Visual Landing Display System

The Visual Landing Display System (VLDS, Fig. 4) generated a realistic out-the-window landing scene for the pilots. This was deemed especially useful for providing orientation on short final approaches.

The VLDS[5] consisted of a relief-type model terrain board with representations of both metropolitan and general aviation airports. The major portion of the model was scaled at 1500:1, with a minor portion scaled at 750:1. Terrain features were "faired in" between the two sections to avoid a discernible change in appearance when traversing sections during long approach profiles. Overall board measurements were 60 ft long × 24 ft high.

The visual scene was viewed by a color television camera, fitted with a rotating optical probe, mounted on a translation system that traversed the entire model board. The image was set to represent a daytime scene, although dusk or nighttime conditions could be programmed. An adjustable skyplate was incorporated, which was used to set predetermined ceiling heights simulating variable visual conditions.

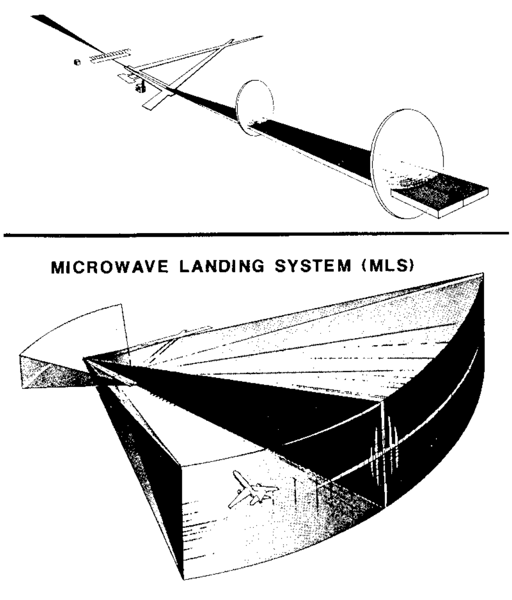

Fig. 1 Microwave vs Instrument Landing System signal coverage.

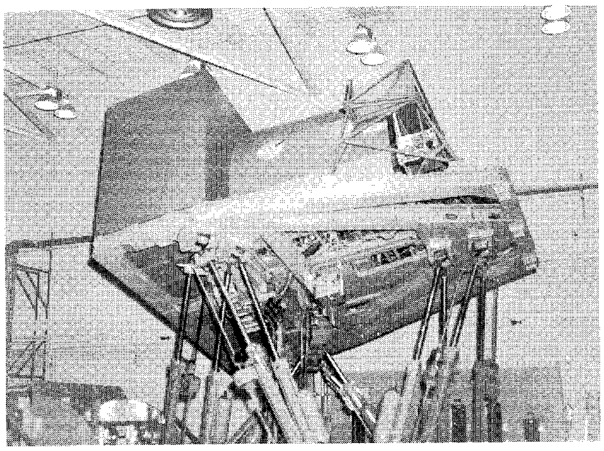

Fig. 2 Visual Motion Simulator—exterior view.

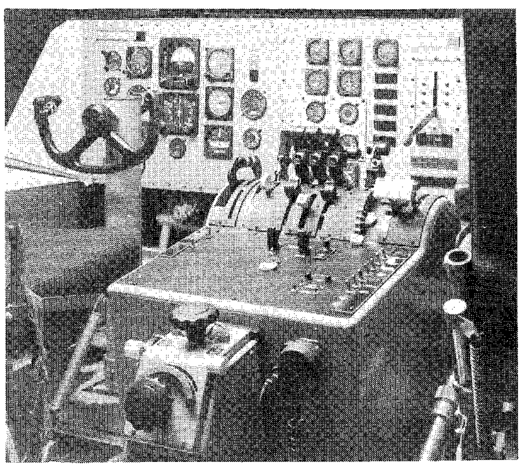

Fig. 3 Visual Motion Simulator—cockpit.

L-1011 Aircraft Model

The Lockheed L-1011 model was representative of the current generation, subsonic, commercial transport aircraft. The simulated aircraft was modeled assuming power supplied by three Rolls-Royce RB 211-22B high-bypass-ratio turbofan engines. Additional features included the flying stabilizer with a geared elevator, an extended-span wing, and an aileron active control system. Additional details of this model can be found in Refs. 6 and 7.

MLS and Guidance Model

The MLS software emulated the parameters needed for airborn derivation of azimuth, elevation, and distance. The simulation model generated "pure" MLS signals and subsequently corrupted them, using a mathematical model to duplicate system errors. Complementary aircraft guidance and navigation algorithms were employed, which accepted inputs from the MLS simulation program and processed the parameters using filtering techniques analogous to those found in airborne receivers. Linkage was made to the path generation program, where the waypoint coordinates and flight-path parameters needed to reconstruct the profile were stored. Additionally, the program provided outputs to drive the flight director and horizontal situation indicator.

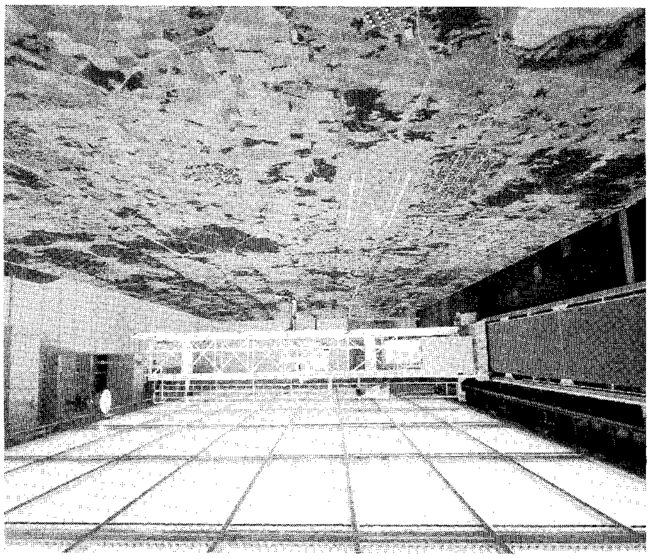

Fig. 4 Visual Landing Display System—model terrain board.

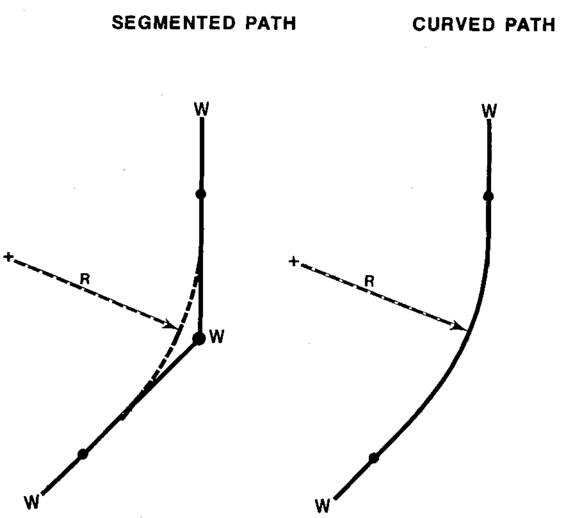

Fig. 5 Lateral flight-path construction techniques.

Path Construction

Two types of path construction techniques, which became known as "segmented" and "curved" paths, respectively, were implemented and analyzed during the simulation test.

Segmented Paths

A segmented path consisted of a path defined solely by a sequence of waypoints connected with straight lines. A course change or turn was defined by a circular "fillet" connecting two straight segments. The radius of turn was computed based on the anticipated ground speed of the aircraft at turn entry and computed to produce a mean bank angle of 15 deg under no wind conditions. Figure 5 shows the typical path construction technique.

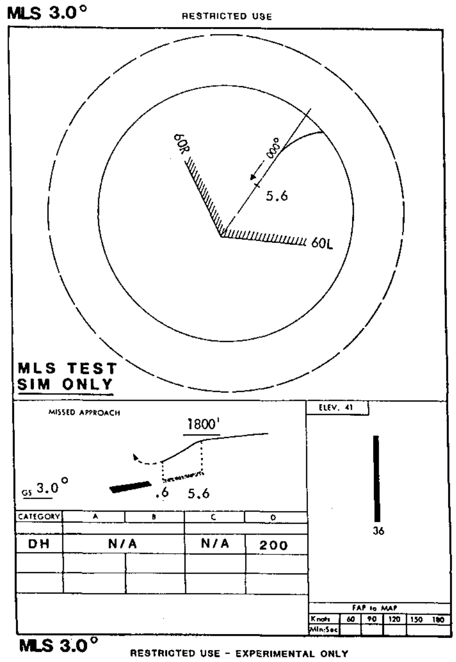

Fig. 6 Profile AA straight-in approach.

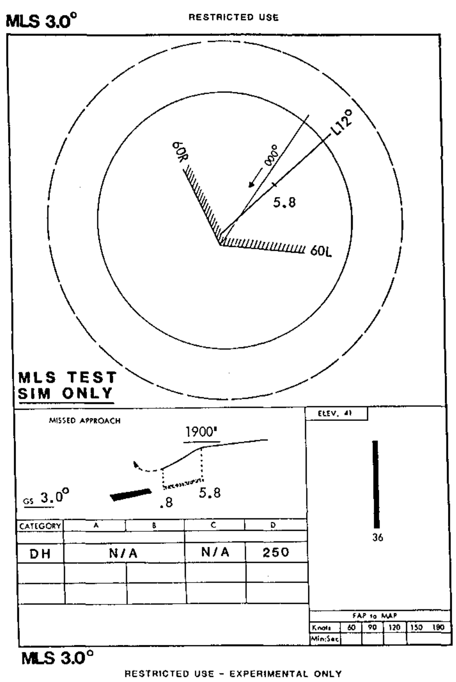

Fig. 7 Profile A offset azimuth approach (3000-ft intercept).

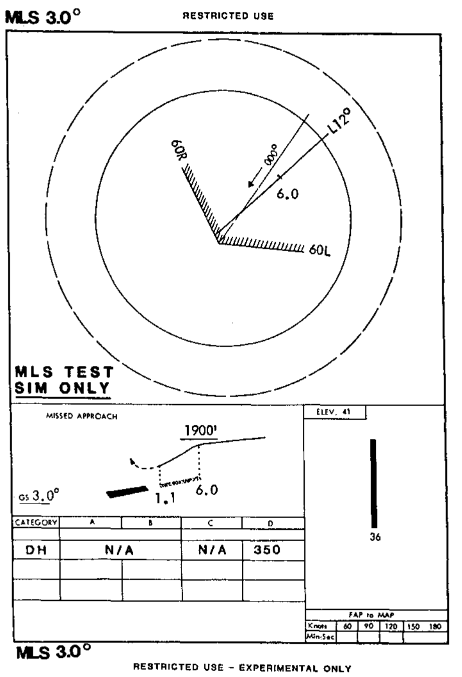

Fig. 8 Profile B offset azimuth approach (4000-ft intercept).

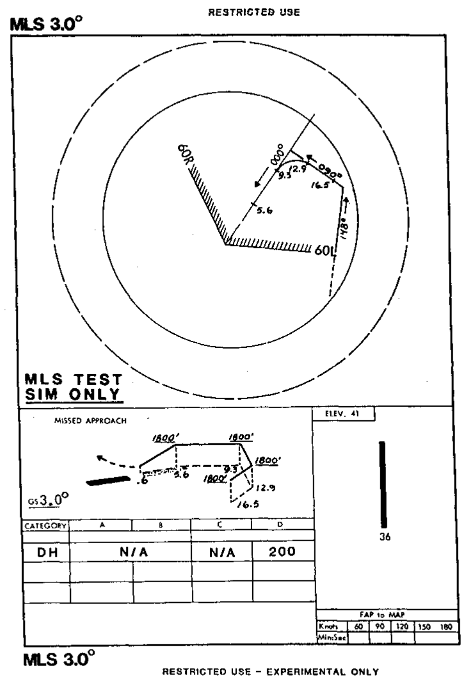

Fig. 10 Profile C.

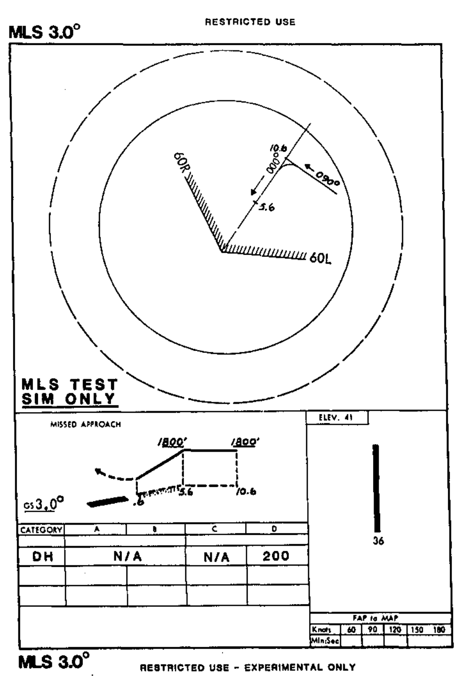

Fig. 9 Profile G1.

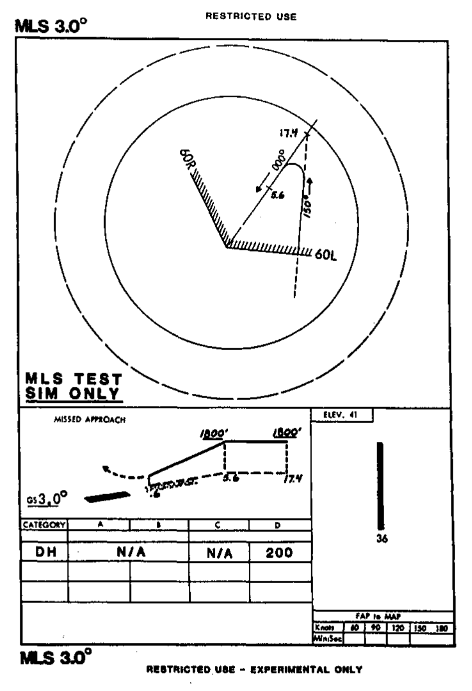

Fig. 11 Profile D1.

The vertical path for the straight-leg segments was calculated using the waypoint altitudes beginning and terminating each straight leg. Around the turn, the vertical path was calculated by taking the altitudes at the beginning and end of the fillet (computed for the lateral path above) and computing a new flight path between the two points. This generally resulted in an increased flight-path angle for this segment of the path.

One problem associated with this type of construction was that, while navigating the path, the actual ground track for an individual aircraft would vary according to its size and speed. Hence, smaller, slower aircraft would complete a turn closer to the waypoint than larger, faster ones. In addition, by not adhering to a definite ground track for the turns, adverse winds could aggravate the tracking problem, creating obstacle clearance problems.

Curved Paths

The second type of path construction, referred to as a curved path, consisted of straight-line segments connected by circular arcs, the arcs being an integral part of the path (see Fig. 5). This type of construction provided a single, precise path over the ground for all aircraft. Turns in the lateral path were defined by a fixed radius arc struck from a point located on the angle bisector passing through the charted waypoint at the apex joining the straight-line segments.

In the vertical plane, a constant-angle path was calculated from the beginning of the approach, all the way to touchdown, based on the curved-path length—not the straight-line waypoint-to-waypoint distance. This avoided the path foreshortening problem and subsequent recalculation of flight-path angle encountered with the segmented path technique.

Having a fixed ground track was deemed advantageous, especially by instrument procedures designers, since it conserved airspace while at the same time protecting the flight path from ground terrain and man-made obstacles. Another aspect favoring curved paths was that the technique minimizes the effect of adverse winds on the ground track while in the turns. However, because the path remains the same for all aircraft, regardless of their category (i.e., size and speed), an operational penalty may be imposed on some aircraft being constrained to a nonoptimum path.

Guidance Computation and Display

During the course of the project, several techniques were explored for providing the airborne guidance required to navigate the MLS paths and, subsequently, displaying this information to the pilot in a logical format. The methods chosen for testing were designed to represent a likely retrofit to present-day cockpit instrumentation. In addition, techniques suggested by the Radio Technical Commission for Aeronautics Special Committee 151 (RTCA SC-151) on Minimum Operational Performance Standards for Airborne MLS Area Nagivation Equipment were evaluated.

The cockpit guidance displays consisted of both position information, comprising lateral and vertical path deviations, and command information for path following. This information was presented, respectively, on a horizontal situation indicator (HSI) and a dual-cue flight director (F/D). A significant addition to the navigation/display system used for this test, with respect to what is commonly found in commercial aviation, was the incorporation of a course arrow on the HSI, which was automatically slewed to the desired course heading by the guidance computer. Secondary situation information, consisting of bearing and distance to the MLS azimuth station serving the runway, was displayed independently to aid in pilot orientation during the execution of complex maneuvers.

Type I Guidance

The first type of guidance tested, referred to as type I and used primarily with straight-in and segmented paths, involved the computation of lateral and vertical deviation from the straight-line paths connecting the waypoints (Fig. 5). Command information, computed by the F/D algorithms, was used to guide the aircraft along the proper course following the fillets and the descending portions of the path. (Type I guidance, as referred to here, corresponds with Levels I and II as defined by RTCA SC-151.)

This technique generally resulted in a discontinuity in the display of lateral and vertical deviation during a turn. This discontinuity was manifest in full-scale needle deflections for changes in both lateral and vertical paths, even though the F/D commanded adherence to the actual path. For the lateral path, course deviation was recalculated with respect to the new course, resulting in an immediate full-scale needle deflection or jump upon initiating a turn. This was followed by a slow return of the needle to the center upon intercepting the new course segment. The needle jump (unavoidable with this technique) could be programmed to occur either at the beginning or midpoint of the turn.

For the vertical path, a new flight-path angle had to be calculated for the course segment around a turn prior to entry. The recomputed descent profile was based on the exact distance around the turn, determined by the roll-in and roll-out points for the lateral path. This resulted in a steeper than normal flight-path angle, since the actual ground distance flown around the turn was always less than the distance to and from the charted waypoint. The problem was especially pronounced on turns having acute angles.

Type II Guidance

The second type of guidance tested, referred to as type II, consisted of lateral and vertical deviations calculated with respect to the actual three-dimensional flight path (Fig. 5). This resulted in smooth, continuous guidance throughout the turns and descents, without the full-scale needle deflections encountered with the type I deviation display, although a similar flight director algorithm was used for command information. Reference 7 provides additional information on the guidance techniques.

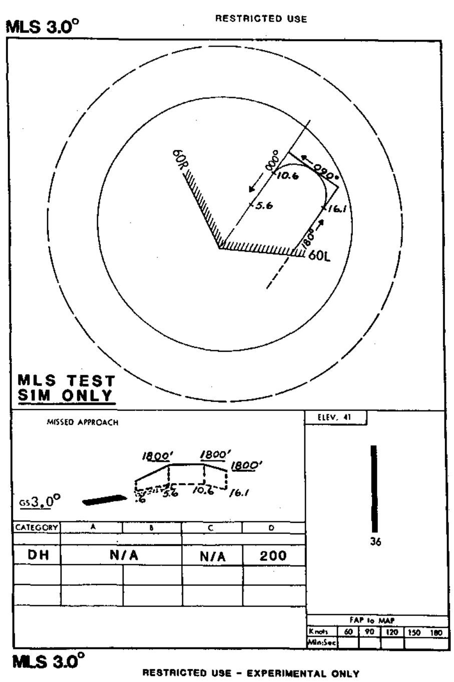

Fig. 12 Profile F1.

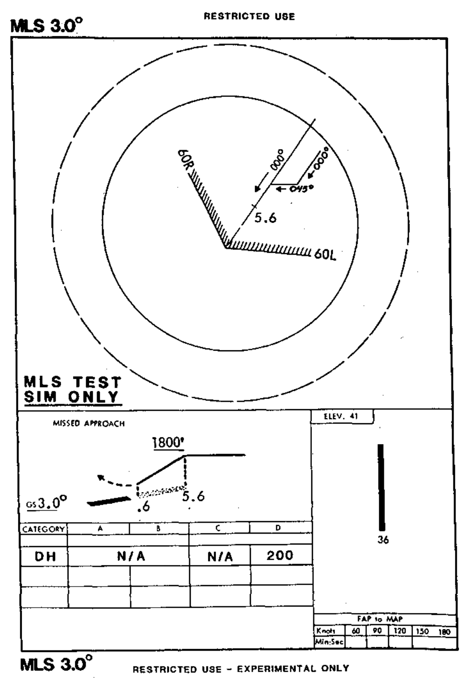

Fig. 13 Profile H1.

Experiment Discussion and Results

The approach paths that were evaluated in the simulator loosely fall into two categories: 1) simple, straight-in or angled intercept paths, and 2) complex paths, which consisted of at least one turn or course change during the approach. Each simulator run was conducted under instrument flight rules (IFR) conditions with various visability breakout conditions varying from 100 to 550 ft altitude and 0.5–3 n.mi. runway visual range.

The first profile evaluated (AA, Fig. 6) consisted of a set of conventional straight-in approaches aligned with the runway centerline for which the elevation approach angle was varied between 1.5 and 4.0 deg, in 0.5-deg increments. In addition, a 3.8-deg elevation approach angle was evaluated. For each elevation angle, two decision heights (100 and 200 ft) were evaluated. The objective of this test was to determine the maximum elevation angle to be used in the flight tests and the minimum decision height for each elevation. During the simulator study, aircraft behavioral problems were encountered as the maximum elevation angle was approached. While a maximum elevation angle of 4 deg could be flown successfully, the maximum angle used for the C-141 flight test was limited to 3.5 deg so as not to exceed the descent rate of 900 ft/min established for category D aircraft. Decision height set at 100 ft for the flight test was in accordance with category II landing minimums.

The next two profiles evaluated were similar in design and were called "offset azimuth" approaches. (They are representative of an RTCA level I capability.) The first profile (A, Fig. 7) had the intersection of the approach course and the runway centerline located 3000 ft from the threshold, while the second profile (B, Fig. 8) intercepted the centerline at 4000 ft from the threshold. Both profiles had a decision height of 250 ft. The offset azimuth angles tested varied between 4 and 16 deg and were changed in 4-deg increments. Each offset azimuth angle was tested at several elevation angles, which varied between 3 and 4 deg. The objective of these tests was to determine the maximum offset angle allowable for an acceptable landing. A second objective was to attempt to determine the relationship between offset angle, height loss, and required bank angle. For both profiles, offset azimuth angles of 12 deg were judged unsatisfactory due to the relative closeness of the intercept point on the extended runway centerline to the touch down zone. This short distance did not allow the crew sufficient time to roll the airplane level and execute an acceptable landing. A maximum offset angle of 8 deg was preferred.

The paths discussed in the following paragraphs fall under the grouping of "complex" paths. This series of paths started with a simple 90-deg turn to final and progressed to exceedingly complex ones; witness the "River Approach" to Washington National Airport. The first complex path (G1, Fig. 9) was a 90-deg intercept of the centerline from a base leg. The objective of this test was to determine the effect of course error when entering MLS coverage limits. Finally, straight-in segments were on the order of 5 n.mi. consistent with category D operations for stabilized flight.

The next complex path (C, Fig. 10) was designed to evaluate the minimum time requirements for a noncenterline, or "base leg," segment in an approach having multiple segments. The entry into the MLS coverage was designed to be at a 90-deg angle to the coverage boundary, enabling early acquisition of the MLS signal after making the transition from en route navigation. The data indicate that the minimum length of a straight (noncenterline) segment should allow for 30–45 s of stabilized flight prior to executing another maneuver. The course reversal path (D1, Fig. 11) was designed to look at the problems involved in a single, acute-angle turn. This profile was abandoned after discovering that, for the segmented guidance technique, the aircraft could not maintain a constant descent gradient along the flight path due to substantial foreshortening of the ground path vs the waypoint-to-waypoint path length upon which the flight-path computations were based.

The next profile evaluated (F1, Fig. 12) consisted of a course reversal of 180 deg, executed with a single turn defined by two waypoints. Additional variations were studied where the turn was defined through the use of three waypoints (adding one at the midpoint) and, alternatively, with the inclusion of a noncenterline segment between the two 90-deg turns. This profile was also studied to provide data on the effect of the glide-path intercept location. Tests were run with the intercept point located on the downwind leg, the base leg, and the final leg. The data revealed that all locations were satisfactory, with no preference indicated by the pilots.

The next profile evaluated (H1, Fig. 13) was a centerline "sidestep" approach. The aircraft started the approach on a course parallel to the centerline but offset from it. The objective

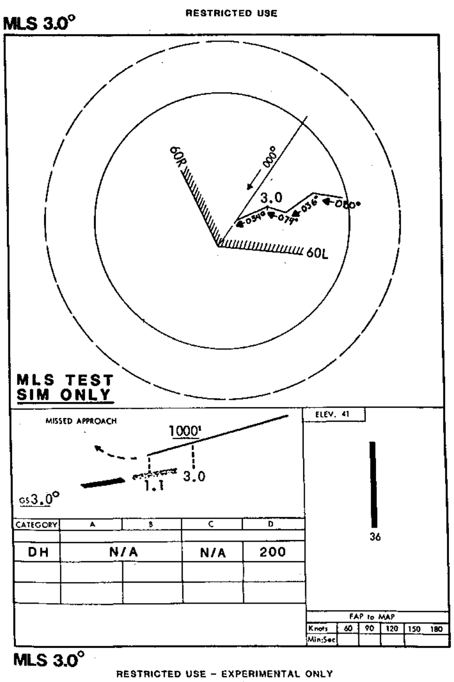

Fig. 14 Profile L.

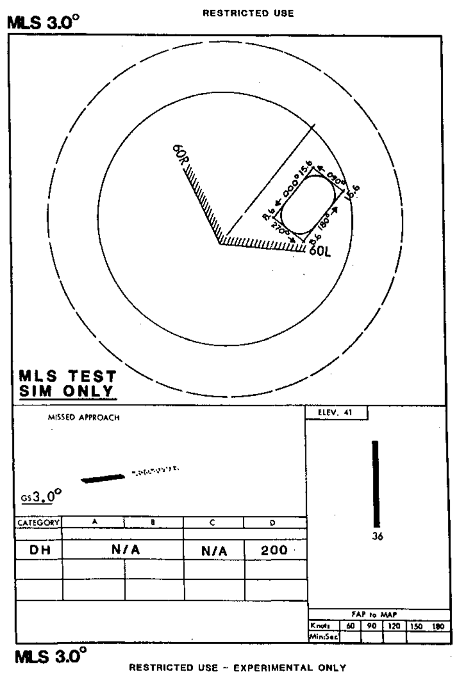

Fig. 15 Profile J.

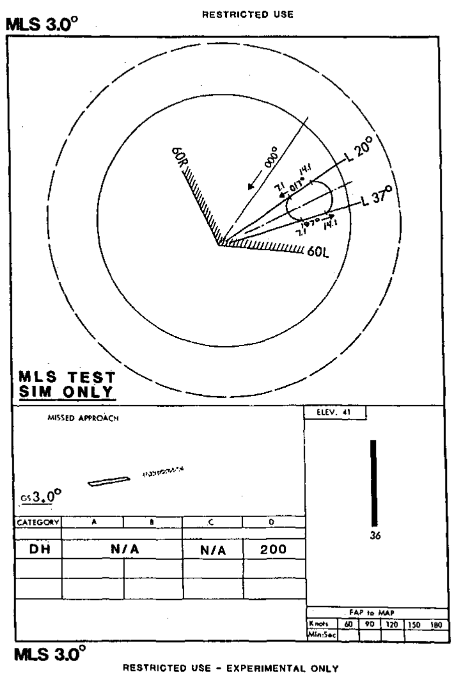

Fig. 16 Profile K.

of the test was to determine the distance required to complete the sidestep maneuver without excessive bank angle or course overshoot. As discovered with previous noncenterline segments, this distance was equated with a time range of 30–45 s. (Glide-path intercept occurred on the initial leg, thus, the aircraft was descending through both turns.)

The final complex path evaluated (L, Fig. 14) was designed to simulate the River Approach to Washington National Airport, which consists of a series of short segments and turns. This path was studied because it represented one of the most complex profiles in use today, albeit, with high minima requirements. The crews were able to fly this path using the guidance and instrumentation designed for this study, however, the workload was subjectively rated high.

Completing the study, two types of MLS-derived holding patterns were evaluated to determine the airspace and any special techniques required. The first pattern (J, Fig. 15) was a standard racetrack configuration defined by four segments created from four waypoints. The second pattern (K, Fig. 16) was created using straight segments falling along azimuth radials. This resulted in the turn at the far end having a larger turn radius than the other. Both holding patterns proved to be flyable given the guidance and instrumentation provided for this study.

The subject pilots seemed to have no trouble flying the complex paths judging from their subjective comments and the data collected.

Pilots had mixed reactions as to the display formats chosen for the lateral path tracking; however, for vertical path deviation, the continuous (type II) path method definitely was preferred. The most useful additional information presented to the pilot was considered to be along-track distance, which, corresponding with the waypoints designated on the charts, afforded a convenient means for keeping their position in a profile. The situational awareness provided by displaying the bearing and distance to the runway was also a well-liked feature.

Concluding Remarks

The benefits derived by using simulation techniques for this exercise turned out to be numerous and were not limited simply to significant savings in time and expense. Greater flexibility in developing MLS terminal procedures was afforded the designers than had previously been available. Simulation permitted rapid identification and elimination of profiles that were not feasible to fly and enabled changes in profile parameters to be made in an expeditious manner. Additional advantages noted were the ability to verify the flight-worthiness of candidate profiles prior to flight testing and the ability to acquaint project personnel with new profiles and procedures. In the future, the simulator can be used to "fly" the various terminal procedures developed, by pilots not rated in the C-141 aircraft or otherwise unable to participate in the flight test. This simulation study was a major factor in the successful completion of the flight tests that were conducted using the U.S. Air Force C-141 aircraft.

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