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REVIEW OF OPERATIONAL ASPECTS OF INITIAL EXPERIMENTS UTILIZING THE U.S. MLS

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SUMMARY

An exercise to support the Federal Aviation Administration in demonstrating the U.S. candidate for an international microwave landing system (MLS) was satisfactorily accomplished at the National Aviation Facilities Experimental Center in May 1976. It was demonstrated that in automatic three-dimensional (3-D) flight, the volumetric signal coverage of the MLS can be exploited to enable a commercial carrier class airplane to perform complex curved, descending paths with precision turns into short final approaches terminating in landing and roll-out, even when subjected to strong and gusty tail- and cross-wind components and severe wind shear. The avionics technique used in the demonstration for processing and utilization of the MLS signals is illustrative of application to future system design.

Of equal importance were the advanced displays that allowed the flight crew and observers to follow the flight situation and aircraft tracking performance very accurately from the aft flight deck of the Terminal Configured Vehicle Program Boeing 737 research airplane without outside reference. Elements of these displays enabled the pilots to proceed after take-off toward the initial way point of the flight profiles, where automatic 3-D flight was initiated. During the initial phase of automatic 3-D navigation, elements of the displays were driven by conventional navigation signals. Upon entering the MLS coverage region, MLS signals were used to drive the display elements for monitoring of the automatic control system performance during transition from conventional RNAV to MLS RNAV; curved, descending flight; flare; touchdown; and roll-out. Of greater importance, particularly with respect to implications for future systems, the displays enabled the pilots, when traffic situations or their interruptions occurred, to control manually for diversionary maneuvers. The situation presented by the displays was clear enough to allow the pilots to perform the appropriate maneuvers readily in the RNAV environment to reenter the desired profiles with precision. Such capability is lacking today in commercial operations and will be required for acceptance of complex, close-in maneuvers in the future. In addition, the pilots flew several manually controlled approaches using the same display formats that had been used for monitoring purposes during the automatic flights. Data for these manual approaches indicate that the performance compares favorably with the performance achieved under automatic flight control.

INTRODUCTION

The growing congestion associated with the rapid expansion of air travel and the noise impact of the jet fleet on airport neighbors have led to technology developments in ground and airborne electronic systems and in noise suppression. In this area, the Department of Transportation (DOT) and the Federal Aviation Administration (FAA) have undertaken an effort to upgrade the air traffic control system. This revised system, known as the Upgraded Third-Generation Air Traffic Control System (UG3RD ATCS), has the following features (ref. 1):

(1) Intermittent positive control
(2) Discrete address beacon system
(3) Area navigation
(4) Microwave landing system
(5) Upgraded air traffic control automation
(6) Airport surface traffic control
(7) Wake-vortex avoidance system
(8) Aeronautical satellites for transoceanic flight
(9) Automation of flight service stations

It is recognized that additional development and evaluation activities should make maximum use of the potential of these system developments. In formulating the joint DOT-NASA Civil Aviation Research and Development Policy Study Report (ref. 2, p. 6-28) the question of U.S. Government conduct or support of demonstration programs in civil aviation is introduced with:

> "Demonstration programs are needed to prove out new systems and technologies, to assess market potentials, or to remove major institutional constraints temporarily. Demonstration programs are experiments designed to embrace new concepts, procedures, regulations, or the blending of new technologies into existing systems. These programs should collect information and required data in a real-world environment involving the ultimate users of the system. . . ."

In recognition of this need, the NASA Langley Research Center has implemented the Terminal Configured Vehicle (TCV) Program (ref. 3). Its goal is to identify, evaluate, and demonstrate aircraft and flight management technology that will improve the efficiency and acceptability of conventional aircraft in terminal-area operations. The reason for emphasis on terminal-area operations (fig. 1) is that this region is recognized as the system bottleneck as well as the major area of possible unfavorable impact with the community environment.

The TCV Program is conducting analytical, simulation, and flight test research which will support improvements in (1) terminal-area capacity and efficiency, (2) approach and landing capability in adverse weather, and (3) operating procedures to reduce noise impact. In this research, major emphasis is being placed on the development of advanced concepts for applications to avionics and displays for aircraft operations in the UG3RD and post UG3RD ATCS's. Particular emphasis is being placed on operations in an MLS environment. One example of this effort is the participation of NASA through its TCV Program with the FAA in the demonstration of the U.S. national microwave landing system to the

All Weather Operations Panel of the International Civil Aviation Organization (ICAO). This demonstration took place at the FAA's National Aviation Facilities Experimental Center (NAFEC) in May 1976 (ref. 4). During this demonstration the MLS was utilized to provide the TCV Boeing 737 research airplane with guidance for automatic control during transition from conventional RNAV to MLS RNAV in curved, descending flight; flare; touchdown; and roll-out. The purpose of this paper is to describe some of the operational aspects of the demonstration. Flight profiles, system configuration, displays, and operating procedures used in the demonstration are described, and preliminary results of flight data analysis are discussed. Recent experiences with manually controlled flight in the NAFEC MLS environment are also discussed.

ABBREVIATIONS AND SYMBOLS

AFD	aft flight deck
ATC	air traffic control
AWOP	All Weather Operations Panel
Az	azimuth angle from MLS azimuth beam
C-band	5000-MHz frequency signal
CWS	control wheel steering
DME	distance measuring equipment
DME/DME	dual DME navigation mode
DOT	Department of Transportation
EADI	electronic attitude director indicator
EHSI	electronic horizontal situation indicator
El	elevation angle
EL1	elevation angle from MLS glide slope beam
EL2	elevation angle from MLS flare beam
FAA	Federal Aviation Administration
GCA	Ground Controlled Approach
ICAO	International Civil Aviation Organization
IDD	inertially smoothed DME/DME navigation mode

ILS	instrument landing system
INS	inertial platform
K_u	15,000-MHz frequency signal
LAT	latitude
LAT_{ORIGIN}	latitude of origin of MLS runway-referenced coordinates
LONG	longitude
$LONG_{ORIGIN}$	longitude of origin of MLS runway-referenced coordinates
MLS	microwave landing system
MLS RNAV	navigation in the MLS environment
NAFEC	National Aviation Facilities Experimental Center
NASA	National Aeronautics and Space Administration
NCDU	navigation control/display unit
R	range measurement
RNAV	area navigation
RSFS	Research Support Flight System
TCV	Terminal Configured Vehicle
UG3RD ATCS	Upgraded Third-Generation Air Traffic Control System
VFR	visual flight rules
V_E	east velocity
V_N	north velocity
$\dot{h}$	altitude rate or sink rate
h_{msl}	altitude above mean sea level
h_{td}	altitude above desired touchdown point
x,y,z	aircraft position in runway-referenced coordinates
$\dot{y}$	cross runway velocity
$\ddot{y}$	cross runway acceleration

ΔLAT	latitude deviation of aircraft from origin of runway-referenced coordinate system
ΔLONG	longitude deviation of aircraft from origin of runway-referenced coordinate system
β	angle of glide-path deviation
η	angle of lateral-path deviation
θ	aircraft pitch angle
ϕ	aircraft roll angle
ψ	aircraft yaw angle
3-D	three-dimensional navigation mode (3 positions)
4-D	four-dimensional navigation mode (3 positions and velocity or time schedule)

TCV PROGRAM OVERVIEW

It has been recognized that new ATC equipment and procedures cannot solve the problems that they are intended to solve unless the airborne systems and flight procedures are developed to take full advantage of the capabilities of the ground-based facilities. The airborne system is considered to be the basic airframe and equipment, the flight-control systems (automatic and piloted modes), the displays for monitoring or pilot control, and the crew as manager and operator of the system. Because of the urgent need to develop the required airborne system capability, the NASA Langley Research Center has implemented a long-term research effort known as the Terminal Configured Vehicle Program. The program is conducting analytical, simulation, and flight-test work to develop advanced flight-control capability for

- 4-D RNAV and transition to MLS
- Precision, curved, steep, decelerating, and time-sequenced approaches utilizing MLS
- Zero-visibility landings through turnoff

This capability will be developed by means of

- Advanced automatic controls
- Advanced pilot displays for monitoring and control
- Reduced crew workload
- Improved interfaces of avionics, aircraft, and crew
- Advanced airframe configurations

The primary facility used in the flight research is the Research Support Flight System (RSFS). The system consists of a Boeing 737 airplane (fig. 2) equipped with onboard reprogrammable all-digital integrated navigation, guidance, control, and display systems.

RSFS Description

A cutaway view of the airplane shown in figure 3 illustrates the palletized installation of the RSFS avionics and depicts a second cockpit for research (aft flight deck, AFD). The value of the RSFS for research purposes is enhanced by several notable design features:

(a) The system functions are controllable and variable through software.

(b) The hardware is easily removed, modified, repaired, and installed.

(c) Flight station changes are readily accomplished in the research cockpit, which has a fly-by-wire implementation for control of the airplane.

The arrangement of the AFD is shown in the photograph of figure 4. The center area of the cockpit is seen to resemble a conventional 737 cockpit, whereas the area immediately in front of the pilot and copilot has been opened up by removing the wheel and wheel column and replacing them with "brolly handle" controllers. This open area has been utilized as the location for advanced electronic displays. The displays illustrated in figure 4 consist of an electronic attitude director indicator (EADI) at the top, the electronic horizontal situation indicator (EHSI) in the middle, and the navigation control display unit (NCDU) at the bottom. A control mode select panel is shown located at the top of the instrument panel and centered between the two pilots. The display system is all digital and can be readily reprogramed with regard to formats and symbology for research purposes. The NCDU is used to call up preplanned routes and flight profile information or for entering new or revised information to be displayed. Inserted information and flight progress information can be called up on the NCDU for review. The EADI instrument provides basic attitude information to control the airplane; the EHSI shows the horizontal plan of the flight, either with a heading-up or north-up mode, and the flight progress. The display formats and their functions will be described in more detail in a later section of this paper.

TCV Program Goals

The basic goals of the TCV Program are illustrated in figure 5. As seen in this figure, operations in the MLS environment can, perhaps with proper controls and displays, allow operators to take advantage of steep, decelerating curved approaches with close-in capture which result in shorter common paths. These paths can be planned for reduced noise over heavily populated areas and for increased airport capacity. Onboard precision navigation and guidance systems including displays are required for 3-D and 4-D navigation and for sequencing and closer lateral runway spacing. Displays are under development with the intent of achieving lower visibility operations in this future environment with sufficient confidence that they become routine. Finally, programmed turnoffs at relatively high speed should clear the runway to allow operations to proceed with perhaps 40 to 45 seconds between aircraft, should the vortex wake problems be solved.

U.S. MICROWAVE LANDING SYSTEM

In 1977, the ICAO is scheduled to select a new international standard approach and landing guidance system that will replace both the instrument landing system (ILS) at civil airports and the ground controlled approach (GCA) at military airports (ref. 5). The ICAO All Weather Operations Panel is presently evaluating candidate microwave landing systems submitted by Australia, Britain, France, West Germany, and the United States. All candidate systems operate in the microwave region, which is expected to serve the full range of aircraft operating in all-weather conditions.

The U.S. MLS basically transmits three time-reference scanning fan-shaped radio beams from the runway, as illustrated in figure 6. One beam scans ±60° from side to side of the runway center at a rate of 13½ times per second to provide azimuth (Az) referencing. The second beam scans up 20° and down to a reference plane parallel to the runway surface at a rate of 40 times per second to provide basic glide slope guidance (EL1). The third beam, which scans up 7½° and down to the same plane parallel to the runway at a rate of 40 times per second, is used for flare guidance (EL2). A fourth nonscanning fan-shaped beam transmitted from a distance measuring equipment (DME) site provides ranging information. This DME beam is transmitted at a rate of 40 times per second and has an angular coverage of 120° in azimuth and 20° in elevation. Time reference means that receiving equipment onboard the aircraft will measure the time difference between successive "to" and "fro" sweeps of the scanning beams to determine aircraft position relative to the runway center line and to a preselected glide path. This time-difference measurement technique gives rise to the designation of the U.S. MLS as a Time Reference Scanning Beam MLS.

JOINT FAA/NASA ICAO DEMONSTRATION AGREEMENT

Early in the TCV Program, a joint NASA/FAA agreement recognized the long-term objectives of the NASA Program, and NASA agreed to provide use of the TCV airplane for support of specific FAA system evaluations, including that of the MLS. In July 1975, at the request of the FAA, NASA agreed to participate in a flight demonstration of the U.S. MLS capabilities to the All Weather Operations Panel (AWOP) of ICAO at NAFEC. The ground rules adopted for the demonstration were

(1) Fly 3-D automatic, curved, descending approaches with RSFS navigation control laws used for the curved-path portions and with MLS guidance substituted for inertial platform (INS) guidance.

(2) Make transition from curved-path portions to short, straight final approaches and land with the RSFS autoland control laws modified to use MLS guidance substituted for INS and ILS guidance.

(3) Perform flares using EL2 and/or radio altimeter signals.

(4) Perform roll-out using MLS guidance.

(5) Modify the RSFS displays to accept MLS derived information. These displays include (a) horizontal situation, (b) curved trend vector, and (c) center-line and glide-path deviations.

All the capabilities implied by the ground rules were to be demonstrated in an automatic mode without use of the inertial smoothing technique which is a basic part of the conventional RSFS. The FAA asked that no acceleration signals be used to augment the MLS data if possible. However, the FAA stated that the use of body-mounted accelerometers or direct measurement of INS acceleration signals were permissible if parameters of this type were needed for the basic control systems. The FAA also stated that the use of attitude data from the INS was permissible in lieu of attitude from high-quality vertical and directional attitude reference systems for display purposes. The philosophical approach taken by Langley Research Center was to make minimum modifications in the existing navigation guidance and control systems and to derive all necessary parameters from the MLS data for interface with these systems.

DEMONSTRATION FLIGHT PROFILES

The flight profiles selected for the demonstration are shown in figure 7 superimposed on a photograph of the NAFEC area. The two profiles shown in this figure are designated as a 130° azimuth capture and an S-turn azimuth capture. Each flight profile contains a 3 n. mi. straight final approach representative of many VFR approaches being flown at the present time at congested airports near heavily populated areas. These profiles, which can be used to provide alleviation of noise over populated areas, are also illustrative of the types of curved paths that have potential for increasing airport capacity in an advanced ATC environment.

A more detailed description of flight events along the demonstration profiles is given in figures 8 and 9. As seen in figure 8, take-off was from runway 22 with the airplane controlled manually from the front cockpit during take-off. Shortly after take-off, control was shifted to the aft cockpit, where a control wheel steering (CWS) mode had been selected by the AFD pilot. Prior to encountering the first way point, the AFD pilot selected a 3-D automatic RNAV mode for airplane control. This control mode used inertially smoothed DME/DME (IDD) as the source of guidance information. Altitude was maintained at 1220 m (4000 ft) until the way point indicated by "Begin 3° descent" was passed. From this point the airplane continued descending at 3° until flare was initiated. After crossing the Az boundary and approximately 15 seconds after crossing the EL1 boundary, the pilot received an indication of valid MLS data, at which time he selected the MLS RNAV mode which used MLS data as the source of guidance information. This latter event is noted as "MLS enable" in figure 8. Just prior to entering the final turn, the pilot switched to Land Arm. The airplane continued to fly under the MLS RNAV mode until both selected glide slope and lateral path were acquired; then the control of the airplane was switched to autoland, which then controlled the aircraft along the 3 n. mi. final approach. At an altitude consistent with the sink rate and altitude criteria of the flare laws in the flight control system, flare was initiated. Flare was executed using EL2 and DME data as the source of vertical guidance information on most of the touchdowns. On a few flights during the demonstration, a radio altimeter was used as the source of vertical guidance information for comparison purposes.

The events along the S-turn profile are very similar to the events of the 130° azimuth capture profile, as shown in figure 9. It may be noted that the S-turn profile resulted in a greater time period of MLS RNAV than did the 130° profile. On touch-and-go approaches, control was switched from aft flight deck automatic control to front flight deck manual control for the take-off portion of repeat flights. On landings that continued to a full stop, roll-out was conducted in an automatic mode that used the Az beam for runway center-line guidance information.

RSFS CONFIGURATION FOR THE ICAO DEMONSTRATION

The basic configuration of the RSFS that was used during the ICAO Demonstration is illustrated in figure 10. It should be noted that the original RSFS was not configured to use MLS data for navigation, guidance, or control. The principal task to which NASA addressed its efforts was the integration of the MLS signals into the navigation, guidance, and control laws and display formats of the original RSFS that had been designed to use INS, DME, ILS, and radio altimeter data. The major development effort involved with the configuration of figure 10 was directed at aircraft antenna design and location, interface of the MLS receiver with the RSFS, and design of the MLS guidance signal processor. Wherever possible, the functions of this signal processor were designed to permit integration of MLS derived navigation, guidance, and control parameters with existing laws of the navigation and guidance computer and the autoland computer with minimal modifications to these computers. Minor changes were made to the existing display formats, with features added to indicate validity of MLS signals and to improve the perspective runway format.

MLS Processor

Details of the MLS processor are illustrated in figure 11. As shown in this figure, the inputs to the MLS processor from the MLS receiver are Az, R, EL1, and EL2. These signals were prefiltered to remove extraneous noise and then transformed to a runway-referenced coordinate frame which produced position data (x,y,z) relative to the selected glide-path intercept point.

The function of the closed-loop estimator of figure 11 was to produce estimates of position and velocity parameters required for interface with the navigation and guidance computer, the autoland computer, and the displays. The Air

Data input to the closed-loop estimator consisted of calibrated airspeed and sink rate as derived from a barometric altimeter. These two pieces of data were used to initialize the closed-loop estimator. The Accelerations input to the closed-loop estimator was used to produce the quality of velocity data required in the flight control system. These acceleration data were extracted from the INS during the ICAO Demonstration. However, on subsequent flights this Accelerations input was derived from body-mounted accelerometers, with no notable degradation of flight performance. A description of the closed-loop estimator outputs is given in the following paragraphs.

MLS Processed Signals for Navigation and Guidance

The MLS processor outputs to the navigation and guidance computer are indicated in figure 12. The parameters derived from MLS data for navigation are ΔLAT and ΔLONG, which are latitude and longitude deviations from the origin of the MLS runway-referenced coordinate frame. The terms LAT_{ORIGIN} and $LONG_{ORIGIN}$ in figure 12 are the latitude and longitude values for the origin of the runway-referenced coordinate frame. These latitude and longitude origin values are known a priori and stored in the navigation computer. It is then a simple task to determine the aircraft latitude and longitude, as indicated by the equations in figure 12. The MLS processor outputs used for guidance are latitude LAT, longitude LONG, altitude to mean sea level h_{msl}, north velocity V_N, east velocity V_E, and sink rate $\dot{h}$. These MLS processor outputs and way points defining the desired flight path which are prestored in the navigation and guidance computer are then operated upon by the RSFS guidance laws to produce path correction commands to the autopilot while operating in an automatic RNAV mode.

MLS Processed Signals for Autoland

The MLS processor outputs to the autoland computer as shown in figure 13 are glide-path-angle deviation β, lateral-path-angle deviation η, altitude to touchdown h_{td}, vertical velocity, or sink rate $\dot{h}$, and cross runway velocity $\dot{y}$. These inputs to the autoland guidance laws are processed in the autoland computer along with a prestored runway heading during the final approach to produce pitch and roll commands to the autopilot. It should be noted here that airspeed is controlled by the autothrottle according to a preset airspeed selected by the pilot.

MLS Processed Signals Used for Displays

Before discussing the MLS processor outputs used for driving the displays, it is appropriate to describe the EHSI and EADI display formats used during the MLS demonstration. The photograph of figure 14 shows the arrangement of the electronic displays in the research cockpit. The display system consists of the electronic attitude director indicator (EADI) at the top, an electronic horizontal situation indicator (EHSI) in the middle, and the navigation control display unit (NCDU) at the bottom. The EADI provides basic attitude information used to control the airplane. The EADI format of figure 14 shows an en route format, with the star and circle symbology providing information on the position of the airplane relative to a programed flight profile. Details of the EADI symbology used for approach to landing will be discussed later.

The EHSI format of figure 14 shows a horizontal view of the preprogramed flight path and obstacles, such as the towers shown in the display. The present position of the airplane is indicated by the apex of the triangle symbol. The dashed trend vector in front of the airplane symbol is predictive information and represents where the airplane will be in 30, 60, and 90 seconds if it maintains the current turn rate. The map also shows way points along with the path and ground navigation aids. The current track angle is displayed at the top of the screen. The moving time box shown in the photograph can be displayed if the pilot wishes to fly a 4-D path manually or automatically.

The NCDU is used by the pilot to call up or revise preplanned routes and flight profiles. Flight progress information can also be called up on the NCDU for review.

The EADI format used for the automatic approach and landing mode is shown in the photograph of figure 15. This format provides basic attitude information in both pitch and roll. Lines of pitch angle in 5° increments are indicated above and below the horizon, and the roll pointer at the top of the display shows bank angles of 10°, 20°, 30°, and 45°. The reference airplane symbol is biased 5° up to reduce clutter in the middle of the screen. Flight-path angle is displayed in the form of two wedge-shaped symbols that move vertically as a function of flight-path angle and laterally as a function of drift angle. Flight-path acceleration is displayed by the rectangular-shaped symbol that is just to the left of the flight-path symbols. Deviation from the vertical and lateral paths is displayed by the movement of the autoland box symbol in relation to the boresight dot of the reference airplane symbol. When desired, a computer-generated perspective runway with extended center line (ref. 6) can be displayed for approach situation information. The triangle symbol on the horizon gives present track-angle information. The box-shaped symbols on the horizon represent 10° track increments from the runway heading and are plotted relative to the junction of the rearward extended runway center line and the horizon. The pilot uses the track angle and relative track symbology to establish his path intercept for runway alinement. The computer-generated runway symbology shows good registration with the real runway, shown by the forward-looking television image. Time of day is displayed in the top left-hand corner so that video tapes of the displays can be correlated with the onboard data system. Radio altitude is displayed in the top right-hand side of the screen.

The MLS processor outputs used to drive these display symbols are indicated in figure 16 as north velocity V_N, east velocity V_E, sink rate $\dot{h}$, lateral-path deviation η, glide-path deviation ϵ, latitude LAT, and longitude LONG. The display symbols which are driven from these parameters are flight-path angle wedges, which indicate the projected touchdown point; trend vector, which indicates the predicted flight path of the aircraft; aircraft position; ground speed; lateral-path and glide-path deviations; and a computer-generated perspective runway with an extended center line. Additional inputs to the display computations as shown in figure 16 are cross runway acceleration $\ddot{y}$, which is used to stabilize the trend vector; and pitch θ, roll ϕ, and yaw ψ, which are used to correct the perspective runway symbol for aircraft attitude changes. The acceleration and attitude inputs were derived from the inertial platform during the ICAO Demonstration. During later flights the acceleration inputs were measured from body-mounted accelerometers and transformed to an inertial reference frame.

RSFS Reconfiguration Summary

Changes to the RSFS configuration for the ICAO Demonstration may be seen by comparing figure 17 with figure 3. As shown in figure 17, three antenna locations were selected for the demonstration. The C-band antennas on the tail and lower aft fuselage were used for diagnostic purposes during the development flights. The C- and K_u-band antennas located above the front cabin were the primary antennas used for guidance. The cabin-mounted C-band antenna was used to receive Az, EL1, and R signals, and the K_u-band antenna was the receiving antenna for EL2 signals. The MLS receivers, processor, and special MLS signal recorders are shown located just in front of the aft flight deck. Special in-flight diagnostic oscillographs and a backup MLS receiver are shown located at the right rear of the airplane.

OVERVIEW OF FLIGHT RESULTS

During the development, demonstration, and post-demonstration data-collection flights in the NAFEC MLS environment, 208 automatic approaches and 205 automatic flares were flown. These flares were terminated in touch-and-go maneuvers and full-stop landings that included automatic roll-out operations. During the demonstration flights, final approaches of 3 n. mi. were achieved. Following the demonstration, shorter final automatically controlled approaches of 2 n. mi. were flown. Manually controlled flights conducted after the demonstration included 41 approaches with final segments of 3, $1\frac{1}{2}$, and 1 n. mi. Reduction of flight data gathered on these flights is underway. Analysis of these data is expected to result in an assessment of path tracking accuracy; speed control system performance; display format utility for monitoring aircraft path tracking performance and for interpretation of flight situation and usefulness in changes in flight plans; wind shear and turbulence conditions during all flight phases; quality of the MLS signals in terms of precision and multipath characteristics; and total performance of the navigation, guidance, and flight control systems. However, a limited amount of quantitative data has been reduced and the results will be summarized here. In addition, qualitative comments of pilots and observers regarding overall airplane performance will be discussed.

Automatic Flight Control Performance

An example of path tracking accuracy during the demonstration flights of May 20, 1976, is shown in figures 18 and 19. The data of these two figures were obtained through a comparison of unprocessed MLS Az, EL1, EL2, and R signals with phototheodolite tracking data. The ordinates of figure 18 are in degrees and each abscissa is in nautical miles, as measured from the MLS Az and DME transmitter site. In figure 18, it can be seen that the azimuth error is quite small throughout the approach and is usually less than 0.05°. The error in elevation (EL1 reference) is somewhat larger but appears to be of the order of 0.05° along most of the final approach. The abscissa scales of figure 19 are the same as for figure 18. The upper plot of this figure has range signal error along the ordinate; the lower plot has degrees of elevation (flare signal) error along its ordinate. The range-error plot of figure 19 shows a bias of approximately 8 m (25 ft), with maximum errors appearing to be of the ord_r of 15 m (50 ft). The elevation error shown in this figure agrees well with the elevation error in figure 18. In fact, these two elevation-error plots agree so well that it is highly probable that the major portion of this error may be attributable to phototheodolite error rather than errors in either EL1 or EL2 signals. The source of this error is under study. The growth of EL1 and EL2 error in the vicinity of the runway threshold can be attributed chiefly to the geometry of the phototheodolite sites.

Flight-path deviations for the same flight as in figures 18 and 19 are shown in the plots of figure 20. The upper plot of this figure shows the lateral-path deviation that occurred from final turn into the final approach fix through touchdown and roll-out. These lateral deviations are typically less than 15 m (50 ft). The lower plot of figure 20 is representative of the glide-path deviations experienced during the demonstration flights. These deviations were usually less than 6 m (20 ft). The growth of glide-path deviation starting at 1.3 n. mi. is due to the flare maneuver.

An example of the effects of wind shear along the flight track on tracking performance during final approach is shown in figure 21. The plot on the left of figure 21 shows an ideal 3° glide slope (dashed line) and the glide-slope performance (solid line) achieved when the airplane was subjected to the influence of the evident wind shear shown in the calibrated-airspeed plot on the right of this figure. The airspeed plot shows variations in the tail wind component of approximately 20 knots. An examination of this plot indicates that the airplane experienced a wind shear gradient along the flight path of approximately 15 knots over an altitude range of 8 m (25 ft). Examination of the glide-slope performance plot shows that the flight deviations were quite small and of the order of 3 m (10 ft) or less. This performance is considered to be excellent for such severe wind conditions. Other wind conditions experienced during the demonstration flights include strong gusts, tail wind components of 20 to 25 knots, and 20-knot cross-wind components.

No conclusions may be made at this time regarding correlations among airspeed at flare initiation, mean tail winds during flare, sink rates at touchdown, and touchdown dispersion. Analysis is underway to develop correlation criteria for the results of these flights and the data gathered during the development and demonstration flights. However, it can be noted that touchdown dispersion data obtained for EL2 flares and radio altimeter flares appear to have similar characteristics. These dispersion data are considered to compare favorably with performance of commercial airlines. Following the ICAO

Demonstration, several automatic approaches were successfully flown with acceleration data sensed from body-mounted accelerometers instead of from the INS. During these latter flights the final approach was shortened to 2 n. mi.

Display Utilization

In exploiting the MLS capabilities in an RNAV and MLS environment and in utilizing profiles such as those demonstrated before the ICAO, it is essential that the flight crew be continually oriented with respect to its flight and navigation situation. Today's aircraft flight instrumentation is not considered operationally adequate, either for monitoring automatic flight or for contingency reversion to manual control in the environment anticipated, that is, close-in, curved, descending, precision approach profiles with very low visibility and in proximity to other traffic. Consequently, the advanced electronic display system has been provided in the aft flight deck of the TCV airplane with which to explore and develop this all-important interface of the pilot with his environment.

During the ICAO Demonstration, the ability to observe the position of the airplane at all times and its tracking performance by means of the displays was as impressive as the automatic operation itself. After take-off, the displays permitted the pilots to position the airplane manually for a smooth, maneuverless transition to 3-D automatic flight into the first way point of the automatic profile. Also, during the development flights prior to the demonstration, numerous interruptions in flying the profiles were encountered. Several diversions due to intrusion of traffic were encountered, and there were many programing errors and malfunctions of various kinds that led the pilot to take over. The displays, in combination with control wheel steering, resulted in effortless navigation during reprograming or redirected flight and facilitated expeditious maneuvering by the pilots to reenter the desired patterns without lost time or excessive airspace for orientation and without the need for vectoring from the ground. The EADI symbology provided an effective means of monitoring flight progress on the final approach. In particular, the excellent registration of the computer-generated perspective runway with the television-generated image of the real-world runway established confidence in the potential utility of computer-generated runway symbology for monitoring landing operations.

The implications for the future are clear with respect to automatic flight. Advanced displays will have to be provided to

Maintain crew orientation

Permit manual maneuvering within constraints in airspace, fuel, and time in order to cope with diversions due to traffic, weather, or loss of automatic capability

Permit continued controlled navigation when new clearances and/or flight profiles must be defined

Manually Controlled Approaches

Upon completion of the automatic flights related to the ICAO Demonstration, additional flights were conducted to evaluate display effectiveness for manually controlled flight along the same profiles, since this is considered to be the best way to evaluate display information for monitoring purposes and takeover if necessary. The runway symbology and track information relative to the runway presented in the EADI appear to be effective means of integrating horizontal information into the vertical situation display for the landing approaches. The runway and relative-track symbology aid the pilot in maintaining a current mental picture of his situation relative to the runway.

The velocity vector control mode was used during the approaches. In this mode, the pilot commands pitch rate by pulling or pushing the panel-mounted controllers. When the pilot perceives that the desired flight-path angle has been reached, he releases the controllers and the system maintains that flight-path angle. The pilot also commands roll rate by rotating the panel-mounted controllers. When he attains the desired track angle relative to the runway, he releases the controllers with wings level and that track angle is maintained until further inputs are made.

During the manual approaches the pilot's task was to capture and hold the localizer center line while maintaining the 3° glide-slope center line. Several approaches with 3 n. mi. finals were flown using the runway and relative-track symbology as primary information for capturing and holding the localizer center line. The resulting lateral errors were less than 5 m (15 ft) at the 30-m (100-ft) altitude window. This small error indicates that the pilot was able to make the localizer offset correction quickly and come through this window with satisfactorily stable attitudes and conditions. The vertical errors at the 30-m window were less than 2 m (6 ft).

Flight-path deviations for a typical manually controlled approach are shown in the plots of figure 22. The upper plot of this figure shows the lateral-path deviations that occurred from the final approach fix to an altitude of 30 m (100 ft). The lateral deviation at the final approach fix is approximately 30 m. This offset was easily handled by the pilot, and as indicated by the plot, the lateral deviations were reduced to 3 m (10 ft) or less prior to flare initiation. The lower plot of figure 22 is illustrative of the glide-path deviations during these approaches. The maximum vertical deviation is seen to be 6 m (20 ft).

The manual approach performance achieved with the runway and relative-track symbology is very encouraging considering that these were the first close-in approaches flown by these pilots. The performance data for these manual approaches compare very favorably with the flight director criteria for glide slope and localizer performance stated in reference 7 for Category I and Category II approach conditions. Additional manual approaches with final segments of $1\frac{1}{2}$ and 1 n. mi. were successfully flown. Quantitative data relating to these latter approaches are not available at this time.

CONCLUDING REMARKS

The system development effort undertaken by NASA in support of the ICAO Demonstration presented NASA with the opportunity to gain experience with the U.S. MLS characteristics and an opportunity to develop operational techniques for utilization of this system in a real-world environment. The demonstration also provided an opportunity for a wide and varied audience to observe proof of concept of the MLS in flight and to witness presentations of the techniques used to integrate the MLS capability into an existing avionics system on a commercial carrier class airplane.

The flights demonstrated the utility of the wide area coverage of the MLS for curved, descending paths commencing with a standard RNAV approach into a terminal area and continuation of this approach throughout the MLS coverage area and onto the runway. The ability to fly precision curved navigation paths with use of MLS signals highlights the potential of this system for design of noise alleviation and high-capacity flight paths in a terminal area. During these flights, transition from a curved path to the final approach was executed smoothly, with lateral excursions of the order of 15 m (50 ft). These small excursions, or overshoots, indicate that an 800-m (2500-ft) separation of final approach paths, and therefore runway separation, is a reasonable goal.

These flights also demonstrated the feasibility of shorter final approaches for terminal-area operations during very low visibility conditions. Shorter final approaches coupled with improved ATC techniques give promise of shorter common paths for merging aircraft and therefore a potential for increased airport capacity. Flare performance using the MLS flare beam (EL2) was seen to compare favorably with that accomplished when conventional radio altimeter techniques were used; and use of the MLS for roll-out demonstrated the potential for improved guidance on the runway.

Advanced display concepts developed under the TCV Program were shown to be compatible with the MLS, and the accuracy of the MLS signals permitted these displays to be used to their fullest advantage by the pilots both in monitoring and controlling with precision the close-in flight profiles. Also, the EHSI proved to be of significant value for execution of flight plan changes or manual performance of diversionary maneuvers.

It should be noted that the demonstration flights were conducted under severe wind conditions which would ordinarily have required runway assignment changes for final approaches or rerouting to other airports in the cases of commercial airline traffic. Atmospheric conditions included high winds with strong gusts resulting in tail wind components of 20 to 25 knots, cross-wind components of 20 knots, steady tail quartering winds of 20 to 25 knots, and shears in excess of 50 knots per 30 m (100 ft).

Problems currently existing in terminal-area operations of the civil air transportation system can be expected to intensify in the future. New flight procedures and advancements in flight control, navigation, and guidance systems designed to take maximum advantage of MLS, and other advanced ATC equipment, offer potential solutions to these problems as well as economic advantage. The development and demonstration of these advantages is an urgent requirement. The NASA Terminal Configured Vehicle Program has demonstrated through flight research during the ICAO evaluation period that the TCV research airplane and its advanced equipment can effectively utilize the MLS capabilities for improved terminal-area operations.

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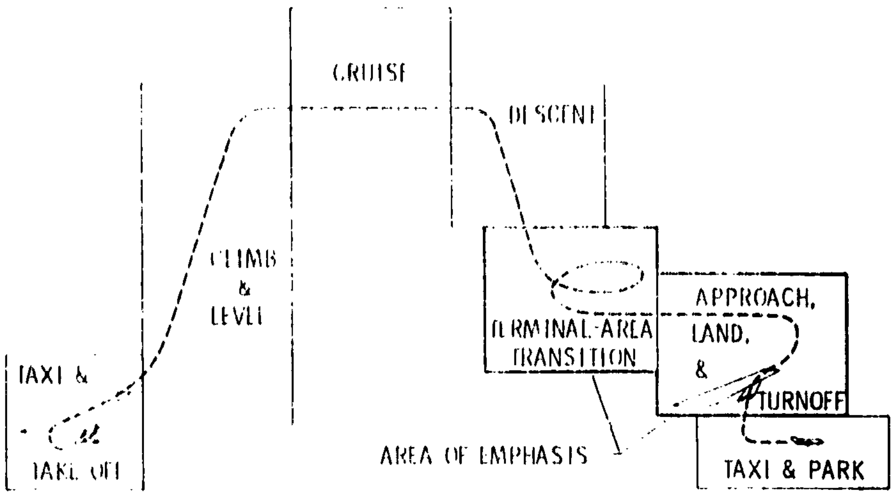

Figure 1.- Flight modes and areas of emphasis in Terminal Configured Vehicle Program.

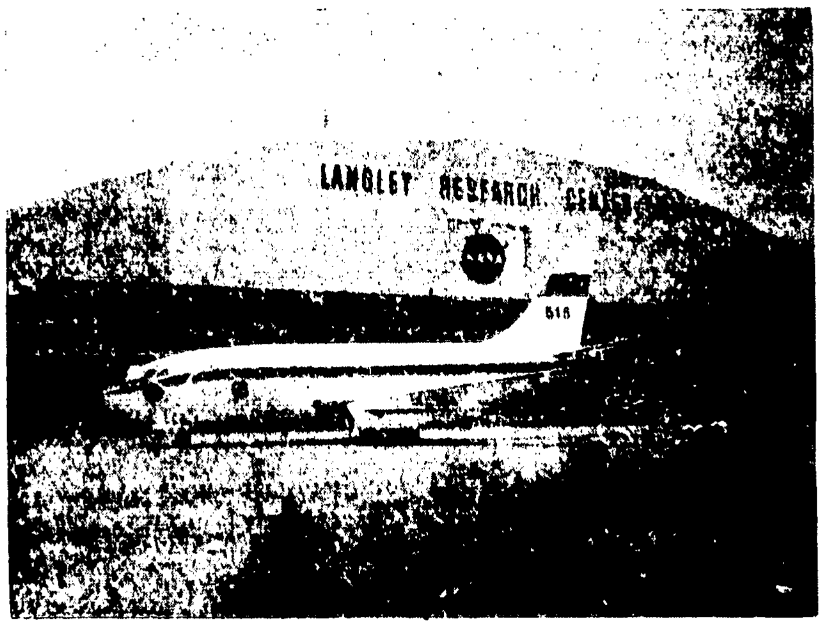

Figure 2.- Terminal Configured Vehicle Program research airplane.

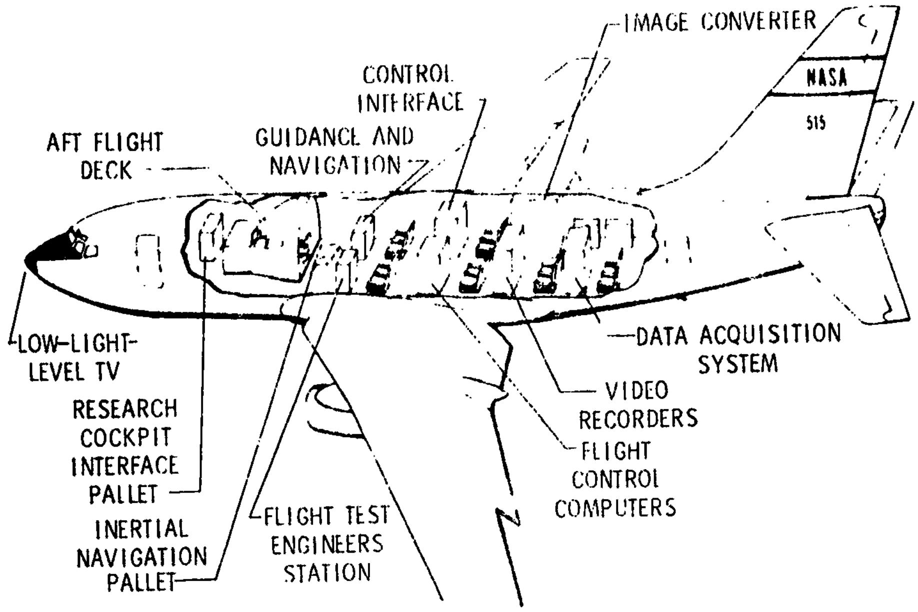

Figure 3.- Research Support Flight System internal arrangement.

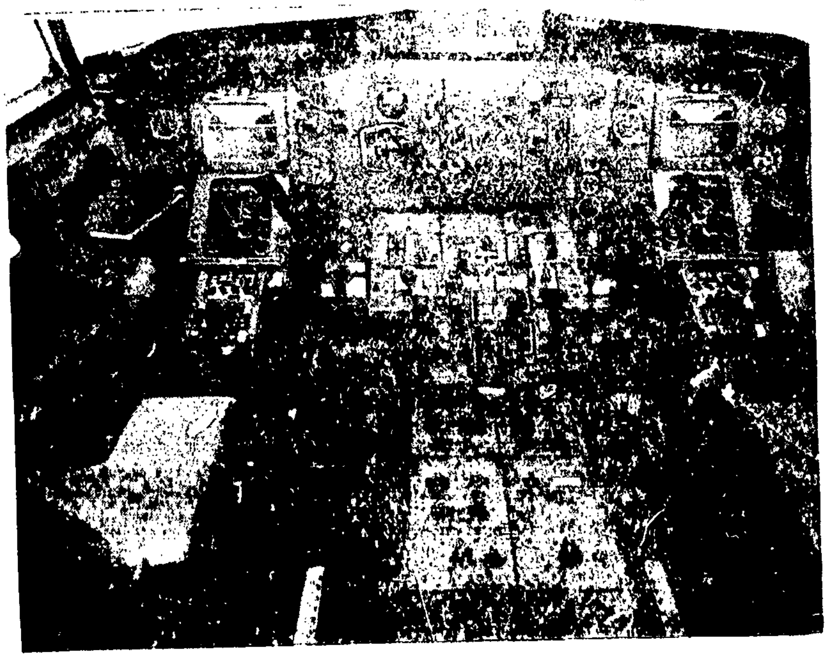

Figure 4.- Aft flight deck display arrangement.

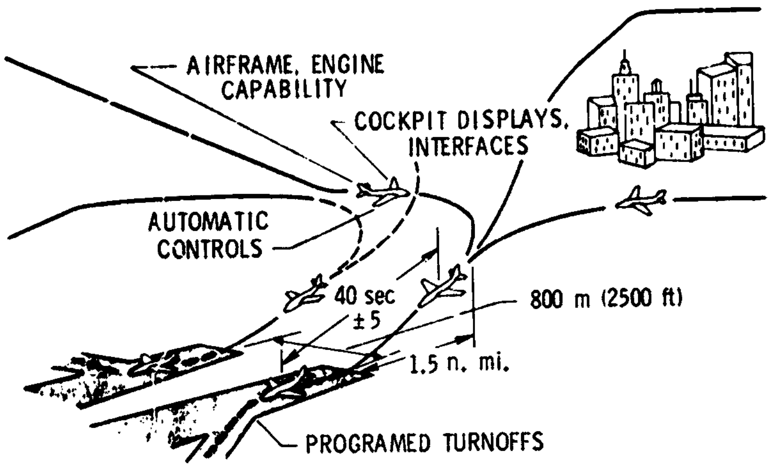

Figure 5.- Terminal Configured Vehicle operational goals.

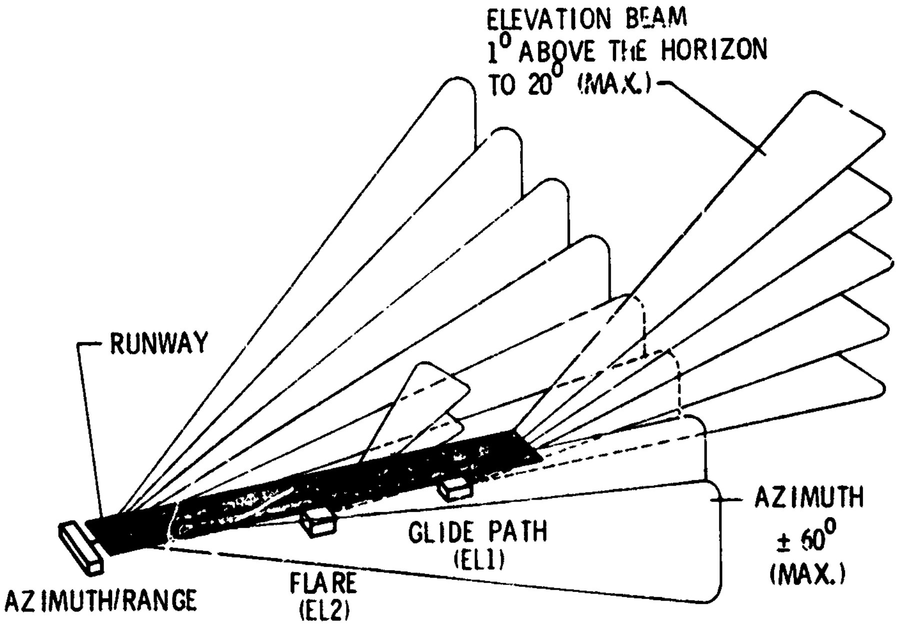

Figure 6.- Microwave landing system.

Figure 7.- ICAO Demonstration profiles at NAFEC.

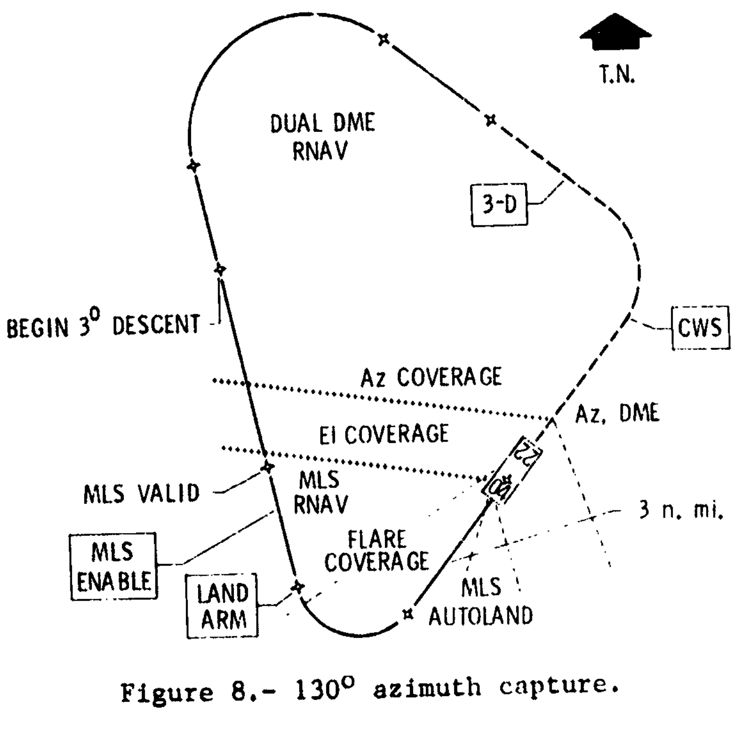

Figure 8.- 130° azimuth capture.

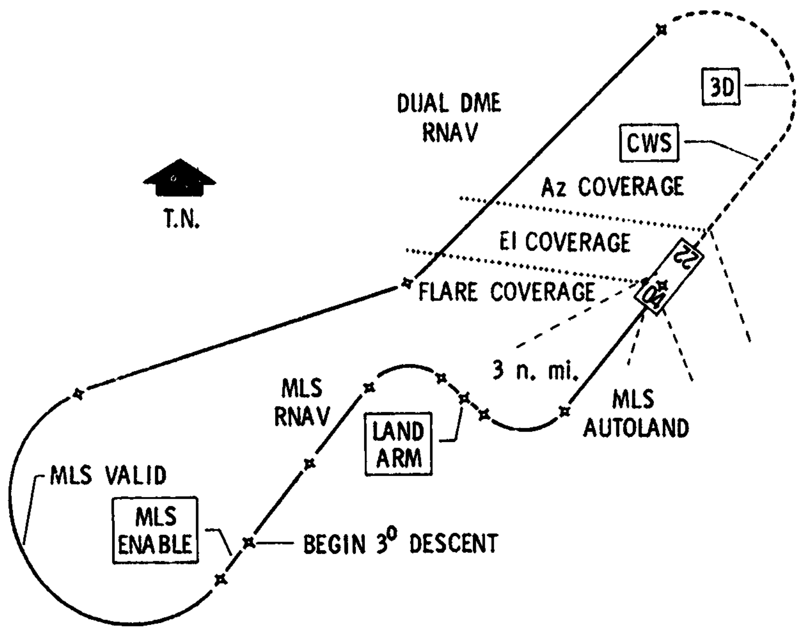

Figure 9.- S-turn azimuth capture.

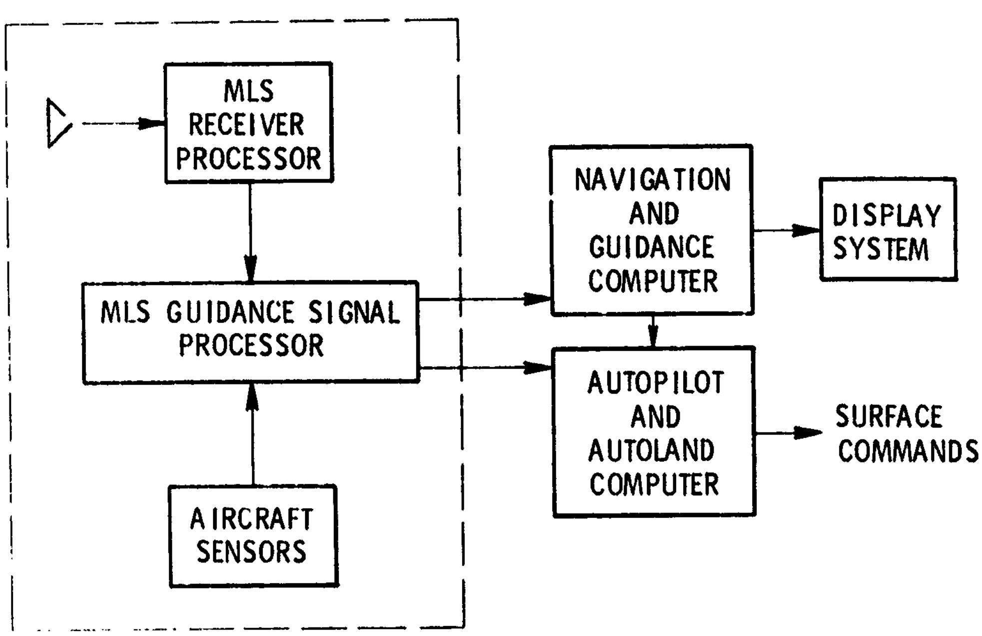

Figure 10.- MLS integration with TCV airplane.

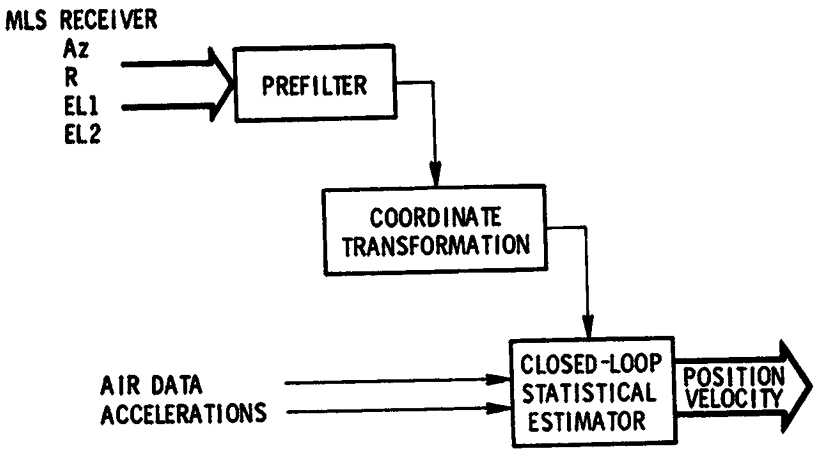

Figure 11.- Major functions of MLS processor.

NAVIGATION

$$LAT = LAT_{ORIGIN} + \Delta LAT$$
$$LONG = LONG_{ORIGIN} + \Delta LONG$$

GUIDANCE

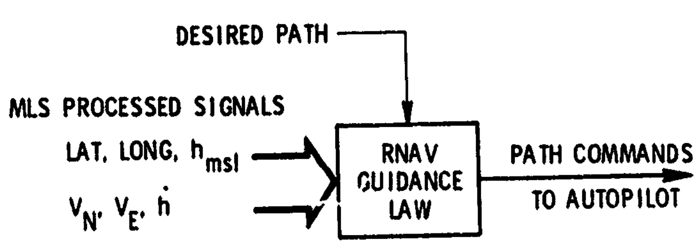

Figure 12.- MLS processed signal use for navigation and guidance.

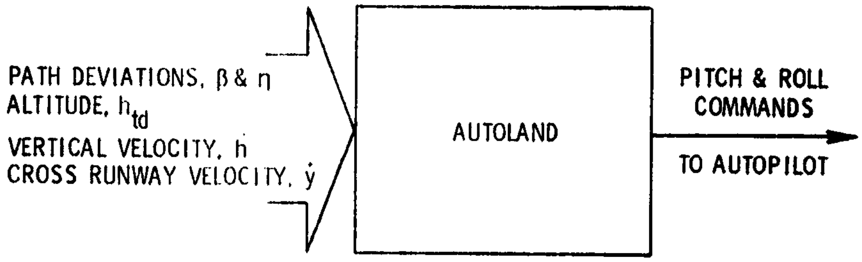

Figure 13.- MLS processed signal use for autoland computer.

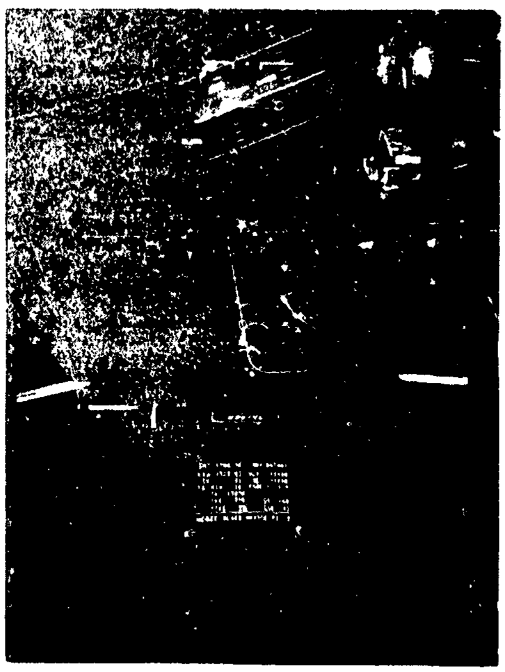

Figure 14.- EADI and EHSI displays.

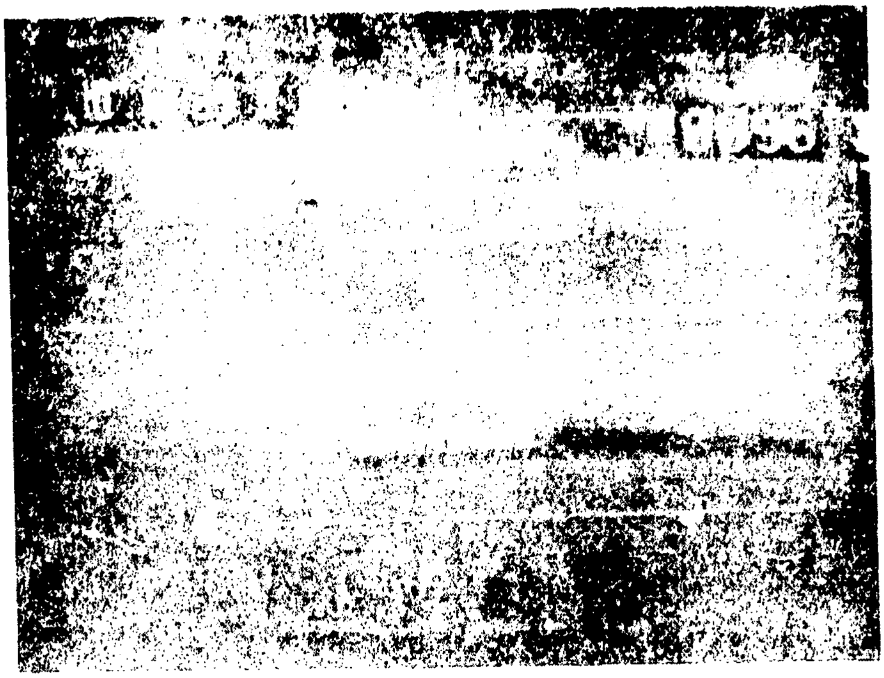

Figure 15.- EADI symbology.

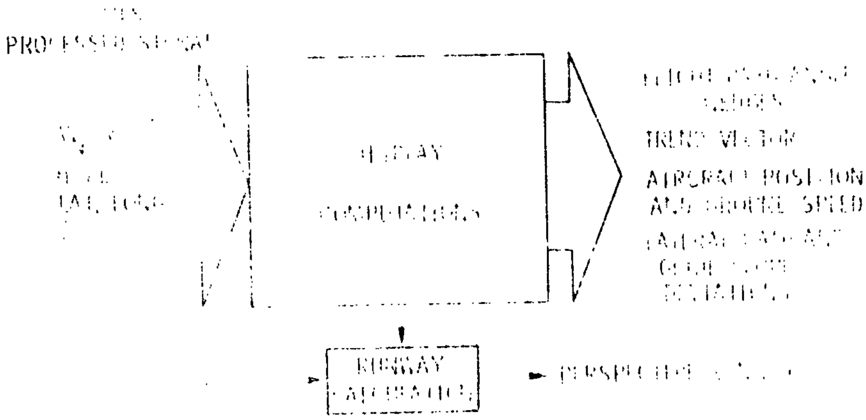

Figure 16.- MLS processed signal use for displays.

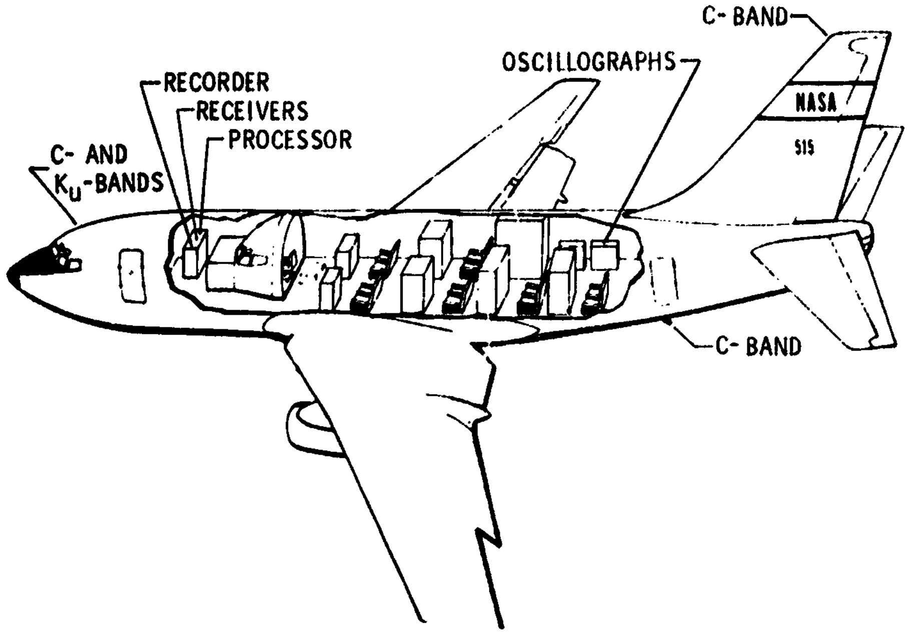

Figure 17.- Research Support Flight System internal arrangements with MLS.

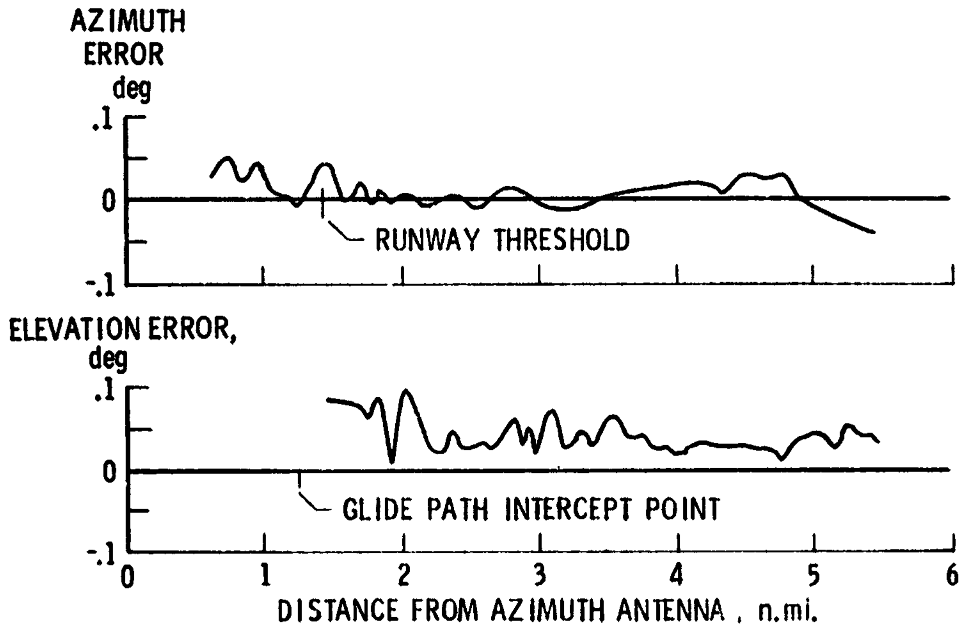

Figure 18.- Typical azimuth and elevation signal errors.

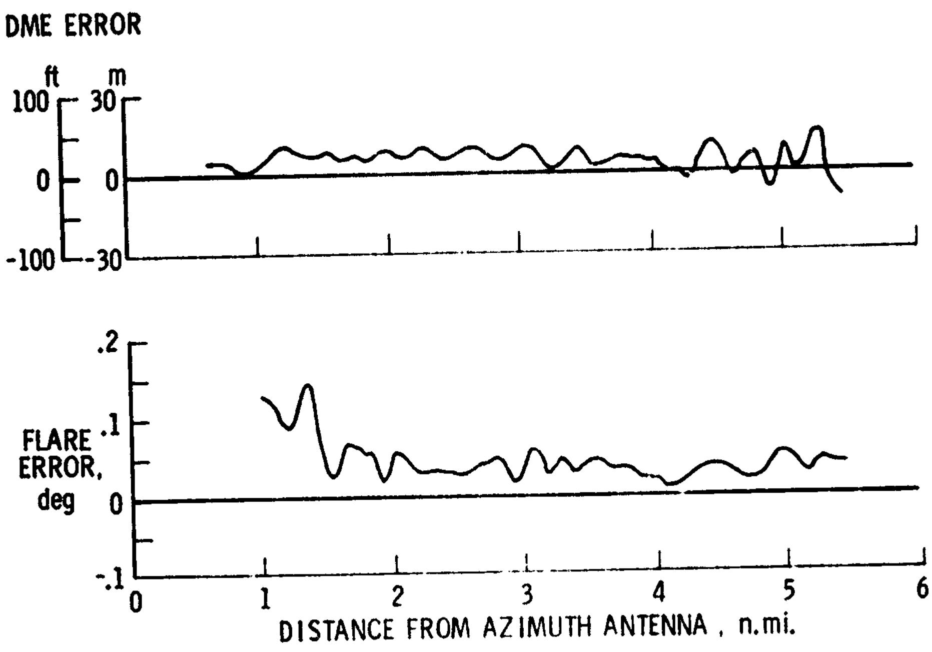

Figure 19.- Typical DME and flare signal errors.

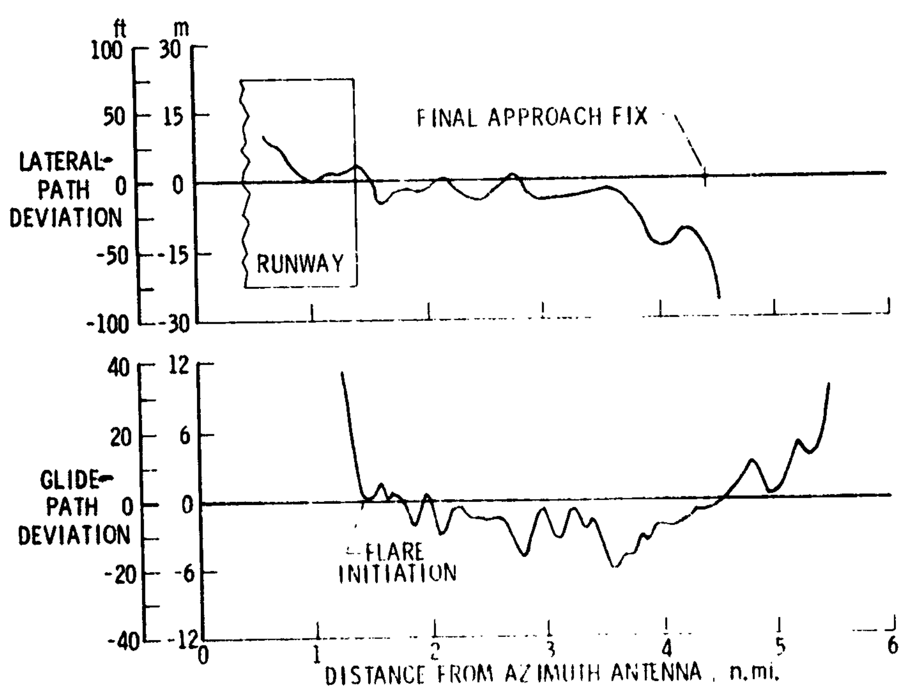

Figure 20.- Typical autoland flight-path deviations.

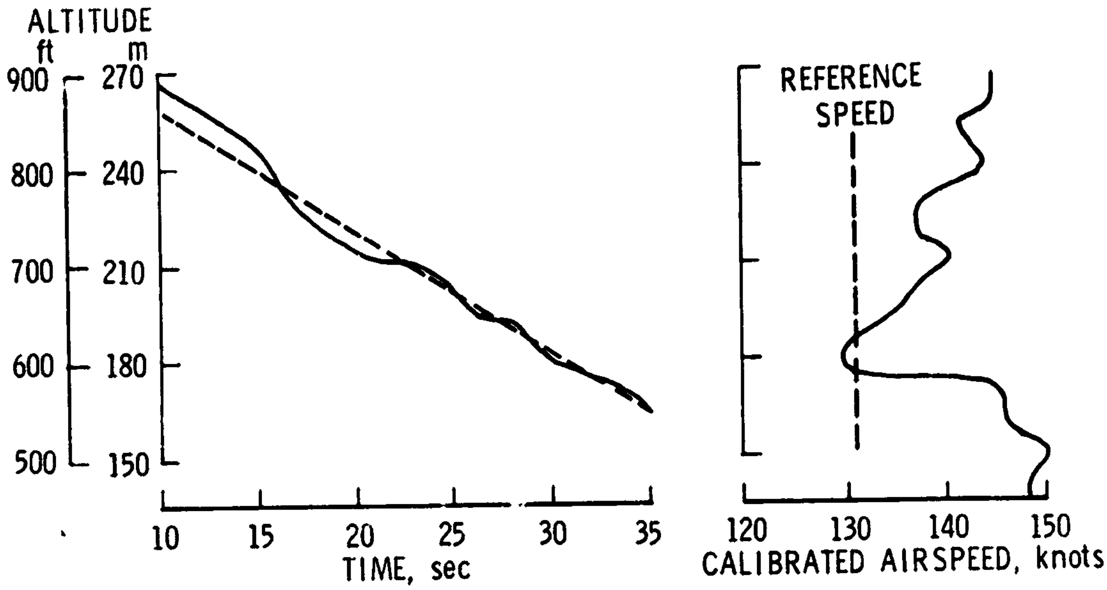

Figure 21.- Typical autoland shear performance.

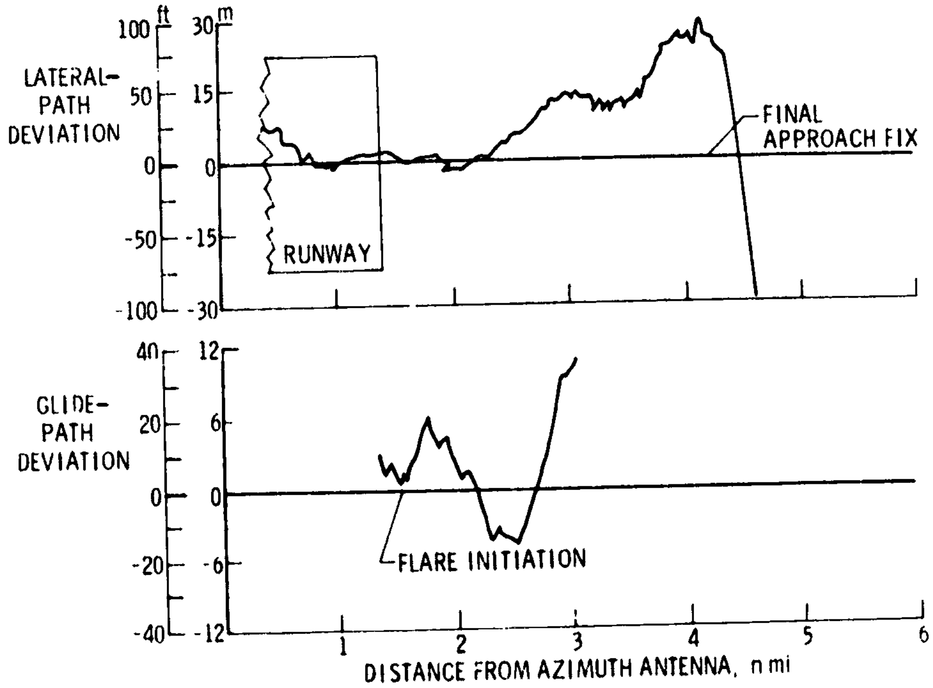

Figure 22.- Typical manual control flight-path deviations.