MICROWAVE LANDING SYSTEM AREA NAVIGATION

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ABSTRACT

The International Civil Aviation Organization (ICAO) Standards and Recommended Practices (SARPS) states that the Time Reference Scanning Beam (TRSB) Microwave Landing System will supplant the existing Instrument Landing System (ILS) as the recognized international standard as early as 1995. The MLS provides the ability to determine the aircraft's position in three dimensional space over a large coverage volume in the airport terminal area. This affords the capability to navigate and execute approaches throughout this volume of coverage. This technique is known as Microwave Landing System Area Navigation (MLS RNAV). In order to assess and further develop the potential capabilities of MLS RNAV, the FAA Technical Center has undertaken the tasks of performing analytical studies, as well as the development of a prototype MLS RNAV system.

INTRODUCTION

The Microwave Landing System (MLS) is currently being implemented in the United States. The ground equipment consists of three navigation signal source elements. Lateral guidance is provided by the azimuth (AZ) transmitter, vertical guidance by the elevation angle transmitter (EL), and distance information by precision distance measuring equipment (DME/P). Airborne receivers have the built-in flexibility of having the pilot select the approach azimuth and elevation angle within certain limits. Basic MLS signal coverage provides azimuth guidance through an arc of 120°, and elevation coverage from 0.9° to 20° above the horizon. Range information is provided to at least 20 nautical miles (32 km). MLS ground equipment transmits auxiliary information in the form of data words. These data words can be interpreted by airborne receivers. The words include information about the layout of the MLS ground equipment in relation to the primary instrument runway.

The accuracy of the MLS is a significant improvement over ILS component accuracies. This fact coupled with the large coverage volume of the MLS will permit increased utility of the MLS to provide terminal area navigation and precision approach guidance. With the addition of an airborne navigation computer, an area navigation methodology based on MLS guidance is achievable. In larger aircraft, existing navigation computers and automatic flight control systems could be coupled with the MLS airborne receiver to provide the MLS RNAV capability.

In order to standardize the development of MLS RNAV and identify minimum equipment performance standards, the Radio Technical Commission for Aeronautics (RTCA) has formed a special committee, SC-151. This committee is preparing a draft document outlining the minimum operating performance standards for MLS RNAV equipment [1]. These draft minimum performance standards identify three different levels of equipment performance. The most distinctive feature of these three levels of equipment is their route construction capability. The basic level I system has only a single segment route construction capability, whereas level II allows multiple segment approaches and level III permits full curved approaches in both horizontal and vertical dimensions.
MLS RNAV SYSTEMS

In the simplest form an MLS RNAV system permits three dimensional area navigation over a single straight path. Generally, this single route segment can be located anywhere within MLS coverage. Some locations will not permit the siting of the azimuth transmitter on the runway centerline 1000 feet beyond the stop end of the runway. These siting restrictions cause the landing minima to be increased since the MLS 0° azimuth is not aligned with the runway centerline.

Using the known locations of the MLS ground components relative to the runway centerline, simple algebraic transformations of MLS guidance can be made. These transformations permit construction of synthetic guidance aligned with the runway centerline. The MLS transmitter locations which are required for the transformations are provided by the data words transmitted by the MLS.

A major advantage of MLS RNAV has already been demonstrated with the computed centerline experiments conducted last summer at Washington National Airport. Results of the computed centerline study showed pilots had no difficulty in flying computed centerline approaches to decision heights of 200 feet above ground level. Analytical studies are in progress to determine the magnitude of offset in the azimuth transmitter which can be tolerated and still retain category 1 approach minima.

The large volume of MLS coverage permits another useful application of single segment MLS RNAV. This application is called a parasite approach procedure. This application permits precision guidance to a non-instrumented intersecting runway which lies within MLS coverage. A parasite approach is graphically presented in figure 1. This permits increased flexibility in runway selection. During periods of severe crosswinds on the primary MLS runway a precision approach in more favorable wind conditions could be conducted to the intersecting runway using the parasite approach technique. Precision approaches could also be conducted during periods of maintenance or construction on the primary instrument runway.

An additional application of the parasite approach technique is depicted in figure 2. The number of helicopter IFR operations continues to increase. Mixing the helicopter with its slower approach speed with the traffic flow to the primary instrument runway tends to slow the entire traffic flow. However, using the parasite approach technique, a precision approach to an on-airfield heliport in MLS coverage could be used to separate the helicopter from the primary instrument runway traffic flow. Depending on the heliport location, category 1 approach minima could be retained for the helicopter.

The final example of an MLS RNAV application is shown in figure 3. At certain urban heliports MLS RNAV could permit lower approach minima. This could be accomplished by designing the approach around a single segment RNAV path which avoided obstacles in the terminal area. Obstacles in close proximity to the heliport could be avoided by terminating the approach to "a point in space" and then proceeding in visual conditions to the heliport.

Figure 1. Non-Instrumented, Intersecting Runway Parasite Approach

Figure 2. MLS RNAV Parasite Approach

Figure 3. MLS RNAV Point-In-Space Approach

MLS RNAV SYSTEM DESIGN

The Technical Center has designed and is building a prototype MLS RNAV system. The system will be used to evaluate the utility and accuracy of a single segment 3 dimensional RNAV system based on MLS guidance, data.
collected will be used to identify initial airspace and equipment sitting requirements. Figure 4 depicts the block diagram of the system being constructed. The system is based on the Motorola 68000 microprocessor. The only additional equipment besides the basic MLS angle receiver and DME/P interrogator is the MLS RNAV computer and cockpit control unit. All hardware and software required to support RNAV computations are housed in a single standard full size ATR container. All auxiliary information needed to support the MLS RNAV applications previously discussed are provided by either the MLS angle receiver or through pilot data entry using the cockpit control unit.

With the cockpit control unit the pilot selects the terminal waypoint (ground plane intercept point) using grid coordinates referenced to the MLS datum point. He then selects the magnetic course and elevation approach angle to be flown to the terminal waypoint. The locations of the ground transmitters are supplied through the data words received by the MLS angle receiver. Fault flag information is provided to the RNAV computer to identify periods of faulty MLS guidance.

Navigation output consists of elevation and lateral course deviation information, distance to go to the terminal waypoint and bearing to the terminal waypoint. Navigation failure information is provided to identify periods of unreliable MLS RNAV guidance. Navigation guidance information is presented using standard cockpit navigation displays consisting of a horizontal situation indicator and a digital DME readout. Future extensions of the system include implementation of command guidance flight director cues.

**ANALYTICAL STUDIES**

Extensive analytical studies targeted at characterizing the performance of an MLS RNAV system were, and continue to be conducted concurrently with the development of a prototype level I system. These studies encompass a diverse set of functional areas including the following:

1. The derivation, programming and testing of a set of algorithms for transformation of the MLS coordinate triple \((\theta, \phi, \rho)\) to the Cartesian triple \((x, y, z)\). These algorithms are referred to as MLS reconstruction algorithms.

2. The evaluation of the accuracy of the reconstruction algorithms by inputting recorded live flight data values of \(\theta, \phi, \text{ and } \rho\).

3. The analytical simulation of the effects of MLS signal source error upon MLS RNAV position determination accuracy.

4. The errors in glide path attributable to offset of the elevation transmitter.

5. The errors resulting from failure to include the complete sitting geometry in the reconstruction process.

6. The effect of system granularity errors on overall system performance.

**MLS RECONSTRUCTION ALGORITHMS**

The three ground based transmitting units, azimuth, elevation and precision distance measuring equipment define a generalized MLS coordinate system with the triple \((\theta, \phi, \rho)\). Knowing the triple and the relative positions of the ground units, it is possible to locate the position of the aircraft in 3 space. Practicality and simplicity dictate that a cartesian \((x, y, z)\) coordinate system be employed. A methodology to effect the transformation from the aforementioned MLS to cartesian coordinate system are known as an MLS construction. This methodology can be visualized by...
referring to figure 5. Here, the azimuth, elevation and DME/P units are each depicted as defining a three-dimensional geometric surface. These surfaces are respectively, a cone or plane (conical or planar azimuth), a cone (elevation), and a sphere (DME/P). The intersection of these surfaces defines the location of the aircraft. Multiple points of intersection may result in some cases, necessitating the use of a priori geometrical information to select the true unique position. A total of thirteen different reconstruction algorithms which address various degrees of complexity in ground station siting were developed by the FAA Technical Center.

![Graphical Solution](image)

Figure 5. Conical Graphical Solution

**ALGORITHM TESTING**

All of the MLS reconstruction algorithms have been subjected to extensive validation procedures. The first phase was a grid test procedure. This entailed iterating through the points in \((\theta, \phi, \rho)\) space and synthesizing the triple \((x,y,z)\) by using one of the reconstruction algorithms. This \((x,y,z)\) triple was then used to compute an MLS triple \((\theta_c, \phi_c, \rho_c)\) which was compared with the starting MLS triple.

In addition to the foregoing grid tests, the Case XI and XII algorithms were tested via simulation of single segment MLS RNAV routes. This was accomplished by playing MLS angle and range data which had been derived to simulate the single segment approaches through the reconstruction algorithms. The output from an algorithm was then compared with the original \(x, y, \) and \(z\) values.

An additional level of validation was achieved by playing live MLS angle and DME/P range data through the reconstruction algorithms. This input data was obtained in the course of executing diverse approaches and departures in an S-76 helicopter. This flight data had been recorded on magnetic tape. This data was then time synchronized and merged with ground based laser tracking data which served as an independent position check. The results of these tests are shown in figure 6.

It should be noted that differences obtained in this comparison reflect more than algorithm error. Included are signal source error, receiver performance and site alignment errors. Nevertheless, these tests, which reflect total system performance, resulted in relatively small errors.

An additional level of system simulation was performed by playing the MLS and DME/P data through the MLS RNAV system software. The entire software suite was found to consume less than .02 seconds per update cycle. Iterative solution convergence criteria were always satisfied. The timing analysis was accomplished on a PDP 11/23 minicomputer which is slower than the new prototype system's Motorola 68000 based computer.

**SIGNAL SOURCE ERROR**

Regardless of how accurate the system software is, other system limitations such as signal source error may limit the

**LIVE FLIGHT TEST RESULTS**

<table>
<thead>
<tr>
<th>PATTERN</th>
<th>ALONG TRACK ERROR</th>
<th>CROSSTRADE ERROR</th>
<th>HEIGHT ERROR</th>
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<td>STD. DEV.</td>
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<td>DEPARTURE</td>
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Figure 6
application of MLS RNAV techniques within the total volume of signal coverage. These limitations will influence the establishment of MLS RNAV Terminal Instrument Approach Procedures (TERPS). Analysis has been completed for the parallel offset approach and is currently in process for the parasite approach.

Since the \((\theta, \phi, \rho)\) to \((x,y,z)\) transformations are complex nonlinear transformations, no direct computational procedure existed for calculating the effects of signal source errors on RNAV position determination. Therefore, Monte Carlo simulation methods were employed. A closed form reconstruction algorithm, which represented the most common unit sitting was employed. The exact MLS coordinate triple \((\theta_t, \phi_t, \rho_t)\) was obtained for a particular DH, elevation angle and offset magnitude combination. Using the Monte Carlo technique, 1000 randomly perturbed triples \((\theta, \phi, \rho)\) were obtained and input to the reconstruction algorithm. The mean of each 1000 point sample was then plotted as a function of azimuth antenna offset, elevation/azimuth antenna separation and DH/glide path angle combination. Figure 7 illustrates the results obtained in crosstrack error for a 6° glide path and 300 foot DH. Note that crosstrack error increases with increasing offset values but decreases as the azimuth to elevation unit distance increases.

![Figure 7. Signal Source Error Impact on Crosstrack Position Determination](image)

**OFFSET ELEVATION ERRORS**

Another limitation which must be considered is the error in vertical position which results when the elevation angle signal pattern is conical. Figure 8 presents this error as a function of elevation angle, DH and magnitude of elevation antenna offset. Note that the vertical position error increases with increases in the elevation angle or magnitude of offset in the approach being simulated. Data shown on the graph can be used to identify the amount of offset which can be tolerated without causing an increase in Category 1 approach minima when using raw elevation guidance. In theory, Category 1 approach minima could be applied across larger offset magnitudes if the vertical position error was eliminated through computed glide path guidance.

![Figure 8. Conic Elevation Error (In Degrees) at DH Due to Elevation Antenna Offset](image)

**SITING GEOMETRY CONSIDERATIONS**

In the most general sense, the reconstructed aircraft position in cartesian space is a function of both the signal source antenna phase center location as well as the MLS triple. In many cases, some of these locations are such that simplifying assumptions may be made (e.g., colocated azimuth and DME/P antenna phase centers). In other cases, failure to include signal source locations in calculations may result in significant errors. For example, consider the case in which the colocated AZ and DME/P antennas are displaced by a significant distance in the Z direction from the elevation antenna. This is the case for sloped runways, where this difference can reach 200 feet. The proposed MLS auxiliary data words convey this information for AZ, EL and DME/P relative to the MLS datum point. Calculations reveal that failure to decode and/or employ these transmitted words result in position determination errors.

These position determination errors are plotted in the x, y, and z directions in figure 9. This figure reflects errors resulting from failure to use the elevation antenna height data words, which in this case is 80 feet. Note that the error in the z dimension is nearly the same as the missing data. This does not hold true for the case in which azimuth or DME/P antenna phase center height is missing. The error is much smaller in these cases. Nevertheless, proposals to include all of these parameters as MLS Auxiliary Data words are currently under consideration within ICAO.

**SYSTEM GRANULARITY ERRORS**

An MLS RNAV system is an inherently digital system, and as such, represents input, output and intermediate computational values to a finite resolution which is a function of the number of bits employed. This finite resolution leads to errors, known as quantization or granularity, which accumulate at each state of the system. An attempt has been
CONCLUSIONS

Several relevant conclusions can be drawn from the analytical and experimental studies conducted by the FAA Technical Center.

1. Studies and experiments conducted to date confirm the feasibility of performing single segment MLS RNAV approaches. This has been demonstrated by flying precision computed centerline approaches. It is further indicated by simulations of various single segment approaches.

2. Course width sensitivity and tailoring to be employed in MLS RNAV must be such that adequate pilot performance (flyability) is preserved and excessive consumption of airspace is avoided. This will entail optimization with respect to the parameters of system cycle rate, along track distance and approach path orientation.

3. The influence of signal source error on reconstructed position for parasite approaches requires additional analysis. The results of this analysis will contribute to the establishment of approach procedures and minima.

4. The achievement of a precise estimate of position requires use of all MLS signal source position data words. Omission of antenna z plane position data can result in significant vertical, alongtrack and crosstrack position errors. This is mitigated to a certain extent if the MLS datum point is used as the reconstruction origin.

5. Initial studies of the effects of system granularity errors indicate that the cumulative effect of these errors will have a significant effect on the total MLS RNAV system error budget.

6. The establishment of MLS RNAV approach procedures and minima will require further analyses and flight tests of the interaction of diverse parameters such as course width sensitivity, ground equipment geometry and system cycle rate.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the contributions of many individuals to this paper. Among those deserving recognition are:

- Mr. Robert Pursel
- Mrs. Min-Ju Chang
- Mr. Donald Gallagher
- Mr. John Morrow
- Mr. James D'Ottavi
- Mr. John Sackett
- Capt. Michael Webb
- Mrs. Judy Sawyer

REFERENCES