A THEODOLITE CONTROL PROGRAM FOR THE ACQUISITION OF

MLS FLIGHT CHECK AIRCRAFT/

A Thesis Presented to

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of the Requirements for the Degree

Master of Science

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ABSTRACT

The Ohio University MLS Evaluation and Data Collection System utilizes the manual tracking of flight measurement aircraft with a motorized theodolite. One of the most important phases of the flight evaluation of an MLS facility is the acquisition phase, in which the theodolite must be centered on the aircraft at a distance greater than ten miles. This paper describes the development of a theodolite control program intended to place the aircraft within the theodolite field of view automatically using information available from the MLS system being evaluated. This will significantly reduce the theodolite operator workload at a difficult phase of the flight evaluation procedure.
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I. INTRODUCTION AND STATEMENT OF THE PROBLEM

A. Microwave Landing Systems. Microwave Landing System (MLS) is a generic term referring to electronic systems that use microwave signals to provide precision approach and landing guidance to aircraft. MLS has existed in various stages of development since the 1950's, and several systems have been placed into service for the United States and various foreign military organizations. A few of these installations are in experimental service with air carriers and private concerns at sites where local conditions discourage the use of the conventional VHF/UHF Instrument Landing System (ILS) [1,2].

The system hereafter referred to in this article as MLS is the U.S./Australian proposed Time-Referenced Scanning Beam (TRSB) MLS. This system was chosen by the International Civil Aeronautics Organization (ICAO) in 1978 as the new world standard for all-weather landing systems. The TRSB MLS is planned to eventually replace the ILS, but this will not occur for some time, as the MLS will require more than a decade for complete implementation, and the ILS is able to meet the precision landing system requirements for the majority of sites in the U.S. and the world [3].

B. The TRSB MLS. The TRSB MLS is a precision terminal guidance system developed by the Federal Aviation Administration (FAA) to provide three-dimensional position information to landing aircraft. The MLS consists of three subsystems - azimuth, elevation and range - each corresponding roughly to an axis of the spherical coordinate system.
The azimuth and elevation subsystems are similar in that each uses a time-referenced scanning beam (TRSB) to transmit azimuth or elevation data to a common receiver in the aircraft. The TRSB is a narrow beam of C-band (5 GHz) RF energy generated by a scanning antenna array. The angle receiver in the aircraft measures the time between the 'to' and 'fro' sweeps of the beam to determine the azimuth or elevation angle of the aircraft, as depicted for azimuth in Figure 1 [4,5].

The elements of an MLS installation, except for the ranging subsystem, use a common frequency, one of two hundred 300KHz bandwidth channels between 5031 and 5091 MHz. The signal from each subsystem alternates in time with those of the other subsystems. The navigation signals are time multiplexed with other transmissions which give the aircraft receivers basic data about the MLS installation for processing of the MLS signals, and auxiliary data which can inform the flight crew of the current airport conditions and other information. Each transmission contains a preamble which allows the receiver to lock onto the signal and informs the processor of the nature of the data it is about to receive.

The preamble and the basic and auxiliary data are broadcast omnidirectionally throughout the coverage volume of the MLS installation using differential phase shift keying (DPSK), whereas the TRSB for angle guidance is highly directional and unmodulated.

Because each transmission contains an identifying preamble, the data can be transmitted in any order and over a wide range of rates,
Figure 1. TRSB Azimuth Angle Measurement. The angle receiver computes angles by measuring the time difference between received pulses. [6]
depending upon the specific characteristics of the installation. The ICAO Standards and Recommended Practices (SARPS) publications specify that the transmissions be ordered such that the aircraft receives azimuth information approximately thirteen times per second and elevation information thirty-nine times per second [7].

The high accuracy of the MLS system is achieved by use of a very narrow scanning beam. The beamwidth is typically 1 to 3 degrees for azimuth and 0.5 to 2 degrees for elevation. Multipath is controlled by the narrow beam and by receiver thresholding and signal processing [8,9].

Range information is determined at the aircraft using conventional distance measuring equipment (DME) techniques at L-band frequencies (approximately 960 MHz). The MLS uses a precision DME (DME-P) that is compatible with conventional DME (DME-N) and uses the same frequencies. The DME-P is accurate to within 40 to 100 feet, depending upon the application [10,11].

The azimuth reference for the MLS system is the centerline of the runway. To meet the specific needs of landing aircraft, the elevation angles are referenced to the touchdown point on the runway. Azimuth and range information are referenced to the stop end of the runway. Figure 2 illustrates the references used in the MLS system. (For engineering evaluation, all angles may be referenced to the phase center of the respective antennas.)

The MLS has advantages over the conventional Instrument Landing
Figure 2. MLS Reference System.
System (ILS) in that it is able to provide precision guidance over a greater range of approaches - up to thirty degrees in elevation and plus or minus sixty degrees in azimuth.\textsuperscript{1} MLS has been allocated 200 channels, compared to 40 for the ILS. The MLS is also much less susceptible to the scattering and multipath effects of local terrain and nearby buildings [12].

C. **MLS Flight Check Procedures.** The evaluation of a navigation system consists of determining the accuracy of the system. For an aircraft, it must be determined whether the aircraft is where its instruments indicate it to be.

The MLS flight check procedure consists of flying the flight check aircraft on a known path through the MLS airspace. Figure 3 shows several representative flight check patterns. The aircraft is tracked from a ground position using a precision optical tracking system and an electronic ranging system. Data from the ground reference and the MLS receivers in the aircraft are recorded simultaneously and compared to provide an immediate evaluation of the MLS performance as well as a permanent record for further study [14].

D. The Ohio University MLS Evaluation and Data Collection System. Ohio University has been involved in the flight evaluation of aircraft navigation systems for twenty years [15]. This experience helped influence the selection of Ohio University by the FAA to design and

\textsuperscript{1}The above is the Radio Technical Committee for Aeronautics (RTCA) specification. ICAO SARPS specifies plus or minus 40 degrees in azimuth and 7.5 degrees in elevation. All receivers will be provided with the capability to process the greater range of angles [13].
Pattern A. Approaches.

Pattern B. Constant Altitude Radials.

Figure 3. Potential MLS Flight Evaluation Patterns.
Pattern D. Orbits.

Figure 3. Continued.
build an MLS Evaluation and Data Collection System utilizing a light aircraft. The Ohio University system is made up of a Ground Reference System (GRS), consisting of an instrumented motorized theodolite and a ranging system, a Ground Telemetry Processor (GTP), which interfaces to the GRS, an Airborne Telemetry Processor (ATP), which interfaces to the MLS equipment in the aircraft, and a system computer, which can interface to either the GTP or the ATP, as mission requirements dictate. The ranging portion of the GRS is a Motorola Mini-Ranger III (TM), which also provides the telemetry link between the aircraft and the ground equipment. The Ohio University system is shown pictorially in Figures 4, 5 and 6. Each unit of the system is controlled by a microprocessor, and communicates with the other units of the system through serial data links [19].

Control of the theodolite during the flight check procedure is a manual operation. The theodolite operator controls the theodolite motors by means of a joystick to keep the crosshairs of the theodolite telescope centered on the aiming point on the aircraft. Due to the nature of the theodolite design, (inverted image and narrow field of view,) acquisition of the aircraft within the theodolite field of view is often a difficult and relatively time consuming task. Failure to acquire the aircraft sufficiently early in a flight check run can necessitate the termination of that run, and the repositioning of the aircraft for another run. This usually requires coordination with Air Traffic Control (ATC) and other aircraft in the area [20]. Typically, the aircraft must be acquired as early as ten miles out, [21] when the
Figure 4. MLS Data-Collection System - Configuration 1. [16]
Figure 5. MLS Data-Collection System - Configuration
Figure 6. Ground Reference System Components Pictorial. [18]
aircraft is barely visible in the theodolite, much less to the naked eye.

The high cost of manpower and flight time require that flight check time be used as efficiently as possible. It is therefore necessary that acquisition of the aircraft for tracking be accomplished smoothly and quickly.

E. A Theodolite Control Program. If it were possible to have the theodolite pointed such that the aircraft were already within the field of view before the theodolite operator began manual acquisition of the aircraft, acquisition time could be minimized. This requires an alternate method of determining the position of the aircraft. This can be done using data from the MLS system being evaluated.

Due to the nature of the Ohio University MLS Evaluation and Data Collection System design, aircraft position data derived by the airborne MLS equipment can be telemetered to the ground, and this information used to point the theodolite toward the aircraft. Under normal conditions, this information should easily place the aircraft within the theodolite's 0.75 degree field of view.2

This paper documents the development of a theodolite control program to acquire the flight check aircraft automatically and retain it in the theodolite field of view in real time. A computer simulation is used to model the responses and timing requirements of the various components of

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2The Warren-Knight WK83 theodolite field of view is specified to be 2.00 degrees, however tests documented in Appendix A show that 0.75 degree is the effective field of view with the rubber eyecup on the theodolite eyepiece [22].
the Ohio University system. The iterations of the design process are discussed and the final design and its evaluation are presented.
A. **Constraints on the Design.** The constraints on the design of a control program for positioning a tracking theodolite are the range over which it is expected to perform, the characteristics of the object it is expected to track and the capabilities of the equipment with which the control program must interact.

1. **The MLS Service Volume.** Figure 7 shows the space over which the theodolite control program must operate. This is essentially what is known as the MLS service volume - the three-dimensional space within which an aircraft is able to receive valid MLS guidance data. This space ranges in azimuth from -60 to 60 degrees with respect to the runway centerline, from 0 to 30 degrees in elevation with respect to the elevation antenna (see footnote 1) and to a range of 20 nautical miles from the stop end of the runway (or, more specifically, the location of the MLS DME antenna) [23].

2. **The Aircraft.** The control program must be able to point the theodolite at a single-engine, light aircraft traveling at 120 to 135 knots within the MLS Service volume, generally over one of the flight paths depicted in Figure 3. Other motions of the aircraft are due to air turbulence and pilot-aircraft interaction. Extensive data on these variables are available as a result of Ohio University ILS flight evaluation activity [24]. An example of these data is given in Figure 8. Data such as these can be considered to be worst-case data, since they also contain the effect of perturbations in the ILS path.
Figure 7. The MLS Service Volume.
Figure 8. Effect of Air Turbulence and Pilot-Aircraft Interaction. Pilot was flying a straight-in approach on a 3° glidepath at 135 knots.
3. **The Theodolite.** The control program must drive a motorized theodolite (see Figure 6) which is capable of movement at the rates given in Table 1 and whose response to control signals is virtually instantaneous when referenced to a theodolite command update rate of 5 Hz. The basis for the 5 Hz update rate is explained later in this section. The theodolite has a field of view of 0.75 degree. Measurement of the theodolite rates, response and field of view is detailed in Appendix A.

The optimum theodolite location for most flight measurement activities is at the edge of the runway, abeam the elevation antenna. Several criteria dictate the choice of this location. The strongest factors are those affecting measurement accuracy. These are theodolite angular rates, and geometric dilution of precision (GDOP).

Figure 9 illustrates the locus of points within which the theodolite would be unable to track the flight check aircraft to the runway threshold.\(^3\) The shape of this locus is determined by the equation,

\[
Y = \frac{K + \sqrt{K^2 - 4X}}{2}
\]

where

\[
K = \frac{\text{Vel} \times 6076.1155}{\text{Theorate} \times 20 \times \pi}
\]

where X and Y are in feet, Theorate is the theodolite angular rate in degrees per second and Vel is the speed of the aircraft in knots. A similar locus exists in the vertical plane containing the runway.

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\(^3\)Cat I MLS evaluations require that MLS data be evaluated to the runway threshold. The MLS approach reference datum point is specified by ICAO SARPS to be fifty feet above the centerline at the threshold [25].
### ACQUISITION Mode

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<th>Elevation</th>
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<tr>
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<tr>
<td>Counterclockwise</td>
<td>-1.43</td>
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### MANUAL Mode

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<th>Azimuth</th>
<th>Elevation</th>
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<td>1.44</td>
</tr>
<tr>
<td>Counterclockwise</td>
<td>-1.34</td>
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Table 1. Nominal theodolite tracking rates in degrees per second.
Figure 9. Locus of Points Within Which the Theodolite Would be Unable to Track Azimuthally An Aircraft Crossing the Threshold at 135 Knots. The runway shown is 150' by 8000'. Maximum theodolite rate is 1.42 degrees per second.
centerline. It is interesting to note that the loci intersect along the extended centerline of the runway. Along this line, the axis of a theodolite pointed at an approaching aircraft would be collinear with the trajectory of the aircraft, and any angular change measured would be due to departures of the aircraft from its trajectory, due to air turbulence or pilot technique.

GDOP in this application can be stated as; The resolution of an object's position by the theodolite is inversely proportional to the distance of the theodolite from the object. Thus, to achieve the greatest accuracy in determining aircraft position, the theodolite should be as close to the aircraft as possible.

Based on the above arguments, the optimum location for the theodolite would therefore be on the runway centerline a few hundred feet from the threshold. Since it is undesirable to close an active runway for MLS evaluations, the edge of the runway or runway shoulder near the elevation antenna is a practical compromise that can be used with little sacrifice in theodolite accuracy.

The fact that power for the theodolite, GTP and system computer is available at the elevation transmitter site contributes to the desirability of this location.

4. System Hardware. The theodolite control program will be implemented in BASIC on an Hewlett Packard (TM) HP 9826 microcomputer, which serves as the Ohio University MLS Evaluation and Data Collection
System's System Computer. The HP 9826 version of BASIC combines all of the traditional advantages of programming in BASIC with advantages of even higher-level languages, such as formatted input and output (I/O) and fast mathematics operations, due to a separate internal mathematics processor [26]. This results in a relatively fast BASIC that is capable of I/O operations with a wide variety of devices.

The HP 9826 is connected to the MLS Evaluation System through an RS-232 connection to either the GTP or the ATP. Through this connection the computer is able to receive MLS and theodolite position information and to send commands to the theodolite at a rate of 960 ASCII characters per second (9600 Baud) [27]. Figures 4 and 5 illustrate the communication links among the MLS system hardware elements.

The software for the GTP and ATP is designed so that the system computer can send the GTP or ATP a single-character command and the GTP/ATP will respond by sending the contents of the appropriate data buffer to the computer. For example, if the computer sends a "1" to the GTP, the GTP will respond by sending a thirty-one character message to the computer containing the current theodolite azimuth and elevation, the Miniranger slant range to the aircraft, and the date and time that information was valid. To command the theodolite, the computer sends the GTP or ATP a "2" to which is appended the desired theodolite azimuth and elevation. The GTP, when in acquisition mode, will then drive each theodolite axis to within ±0.03 degree of that position and hold position within ±0.03 degree.
Tests of this data link have shown that a maximum MLS position-theodolite command turnaround rate of five messages per second can be expected. This rate is based solely on I/O characteristics. Therefore if the theodolite control program can be designed to run in less than 0.2 second, operations can be pipelined such that I/O and computation occur simultaneously and the theodolite command is updated at the maximum rate allowed by I/O considerations. This has been done, and is discussed below.

5. Available Data. The theodolite control program will have the following information available for its use: MLS azimuth antenna position (AX,AY,AZ), MLS elevation antenna position (EX,EY,EZ), theodolite position (TX,TY,TZ), MLS azimuth and elevation (MLSAZ and MLSEL), theodolite azimuth and elevation and Miniranger range (Theorange). The labels in parentheses are the variable names assigned to these values in the control program. MLS range may not be available at every MLS installation; therefore the theodolite control program must be able to function without it. MLS antenna and theodolite positions are referenced to the centerline of the runway at the threshold, as illustrated in Figure 10.

B. Details of the Theodolite Control Program. The block diagram of the theodolite control program is shown in Figure 11. This program was developed in Waterloo BASIC (WBASIC) on the Ohio University IBM 4341 computer [28]. Waterloo BASIC was used because it interacts well with the IBM VM/CMS operating environment and because it is easily translated into HP 9826 BASIC, which is used in the measurement system.
Figure 10. Range Coordinate System.
Figure 11. Theodolite Control Program Block Diagram.
1. **The Coordinate Converter.** Working from output to input through the theodolite control program, the first major module is the coordinate converter, which generates the theodolite command. The use of a coordinate conversion algorithm was one of the major considerations in the design of the theodolite control program, because coordinate conversion requires the most complex and time-consuming processor operations and because coordinate conversion has a significant effect upon the overall accuracy of the system. Table 2 shows the results of the investigation of the effect of sending MLS data directly to the theodolite with no coordinate conversion. In this table, AZERR and ELERR are the theodolite error in degrees, relative to the true position of the aircraft. AZERRF and ELERRF are the theodolite error in percent, relative to the theodolite field of view (0.75 degree). Typical MLS antenna and theodolite positions and a runway length of eight thousand feet were assumed. Note that although the errors are tolerable in elevation, they are quite unacceptable in azimuth. Errors within one nautical mile of the threshold are not weighted very heavily, since the theodolite control program is primarily an aircraft acquisition aid, and not for close-in automatic tracking. A total error in each axis of thirty percent or less of the theodolite field of view is considered to be acceptable for the purposes of this design. Figure 12 relates this error to the theodolite's 0.75 degree field of view. Note that a root sum squared error of greater than fifty percent would place the aircraft completely out of the theodolite field of view.

Three algorithms were developed to handle the coordinate conversion. The second two algorithms are improvements of the first. They are
\[(TX, TY, TZ) = (-1000, 100, 0)\]
\[(EX, EY, EZ) = (-1000, 400, 0)\]
\[(AX, AY, AZ) = (-8000, 0, 0)\]

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Table 2. Theodolite Pointing Error Resulting From No Conversion of Aircraft Position Coordinates. AZERR and ELERR are in degrees. AZERRF and ELERRF are in percent of the theodolite of view.
Figure 12. Allowable Error Related to Theodolite Field of View.
evaluated separately because they are somewhat more complex, and will therefore make different demands upon the system computer processing time. The accuracies of the three algorithms are compared in Table 3. The values in Table 3 are in percent of the theodolite field of view. No data is given for AZERRF2 because the second algorithm only computes a new value for the theodolite elevation. The data in Table 3 are computed closer to the threshold than is required for the purposes of acquisition, to emphasize the accuracies of the algorithms.

Figure 13 illustrates the geometries used in the derivation of the coordinate conversion algorithms. The first algorithm makes the assumption that the distance between the MLS elevation antenna and the flight check aircraft is the same as the distance between the theodolite and the aircraft.

As is shown in Figure 13, the MLS azimuth radial determines one line of position (LOP) for the flight check aircraft. The circle whose radius is

$$RT = \sqrt{\text{Theorange}^2 - ZT^2}$$

about the theodolite is the other LOP. This circle is formed by projecting the intersection of the cone formed by revolution of MLSEL about the theodolite and the plane $Z = ZT$ onto the plane $Z = TZ$. The two intersections of these two LOP's designate two possible positions of the aircraft. The fact that MLS elevation data are not available behind the elevation antenna rules out the position closest to the stop end of the runway and therefore leaves only one valid position for the aircraft.
\[(TX,TY,TZ) = (-1000, 100, 0)\]
\[(EX,EY,EZ) = (-1000, 400, 0)\]
\[(AX,AY,AZ) = (-8000, 0, 0)\]

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</tbody>
</table>

Table 3. Theodolite Pointing Error in Percent of Theodolite Field of View Resulting from Coordinate Conversion Algorithms.
Figure 13. Coordinate Conversion Geometries.
The coordinate conversion algorithm consists of the simultaneous solution of the equations

\[ xT^2 + yT^2 = RT^2 \]

and

\[ \tan(MLSAZ) = \frac{YA}{XA} \]

where

\[ RT = \sqrt{\text{Theorange}^2 - ZT^2} \]

\[ ZT = \text{Theorange} \times \sin(MLSEL) + EZ - TZ \]

and

\[ XA = XT + TX - AX \]

\[ YA = YT + TY - AY \]

This results in a quadratic of the form

\[ XT = \frac{-b + \sqrt{b^2 - 4ac}}{2a} \]

where

\[ a = 1 + \tan^2(MLSAZ) \]

\[ b = 2\tan(MLSAZ) \times (AY - TY + (TX - AX) \times \tan(MLSAZ)) \]

and

\[ c = \tan(MLSAZ)(TX - AX)(\tan(MLSAZ)(TX - AX) + 2(AY - TY)) \]

\[ + (AY^2 - TY^2 - RT^2) \]

The root

\[ XT = \frac{-b - \sqrt{b^2 - 4ac}}{2a} \]

is not valid because MLS elevation data are not available behind the elevation antenna, as explained previously. Once XT is known, YT is computed from

\[ YT = (XT + TX - AX) \times \tan(MLSAZ) + AY - TY \]

The second algorithm uses the results of the first algorithm to calculate an approximate value for the range from the elevation antenna.
to the aircraft, and thus arrive at an updated value for ZT, the elevation of the aircraft with respect to the theodolite. The equation;

\[ \text{Elrange} = \sqrt{(X_{T} + X_{I} - E_{X})^2 + (Y_{T} + Y_{I} - E_{Y})^2 + (Z_{T} + Z_{I} - E_{Z})^2} \]

computes the range. The new value for ZT becomes

\[ Z_{T} = \text{Elrange} \times \sin(\text{MLSEL}) + E_{Z} - T_{Z} \]

The third algorithm incorporates all of the steps of the first and second algorithms and goes one step further. This algorithm uses the new ZT from the second algorithm to recompute c of the quadratic polynomial and solve for a new XT and YT.

Once XT, YT and ZT are known, THEOAZ and THEOEL are computed using the equations;

\[ \text{THEOAZ} = \tan^{-1}(Y_{T}/X_{T}) \]
\[ \text{THEOEL} = \tan^{-1}(Z_{T}/\sqrt{X_{T}^2 + Y_{T}^2}) \]

The effect of each algorithm upon system computer timing was checked by incorporating each algorithm into the complete control system, less the I/O portions, and checking the time required for each iteration on the HP 9826.\textsuperscript{4} The time required for the first algorithm averaged 0.12 second. The second algorithm averaged 0.14 second and the third 0.19 second. Based on the data in Table 3 and the requirement for an iteration time of less than 0.2 second, the second algorithm was selected as most suitable for the coordinate converter, because it provides the required accuracy and its execution time is such that I/O can be added to the control program and total execution time kept under 0.2 second.

\textsuperscript{4} The I/O could not be included in the control portion at this writing due to the lack of availability of MLS receivers.
2. **The Interpolator.** The Coordinate Converter receives information from a program module called the Interpolator. Due to the time-multiplexed nature of the MLS system and the data links between the ATP, GTP and the System Computer, each item of position data is valid for a different point in time. The Interpolator predicts the aircraft's position at the time the theodolite will have completed the next command. This prediction is the result of a linear interpolation based upon the preceding two data points for each item. The Interpolator uses the algorithm

\[ P' = P_n + \left( \frac{T_{n'} - T_n}{T_n - T_{n-1}} \right) (P_n - P_{n-1}) \]

where

- \( P' \) is the estimated position
- \( P_n \) is the last known position
- \( P_{n-1} \) is the position preceding the last known position
- \( T_{n'} \) is the time of the estimated position \( P' \)
- \( T_n \) is the time of \( P_n \)
- \( T_{n-1} \) is the time of \( P_{n-1} \)

The above algorithm is applied three times, once each to the MLS azimuth, MLS elevation and Miniranger range position components. The result is all three position components referenced to a common point in time.

3. **The Updater.** The Interpolator module requires the concurrent use of past and present data. Because it is possible for one of
the position buffers in the GTP or ATP to contain identical information for two successive iterations of the theodolite control program, it is necessary to check for this condition to prevent a divide by zero failure of the Interpolator. This is the reason for the Updater.

The function of the Updater can be described symbolically as:

Compare \( T_{n+1} \) to \( T_n \)

If different:

\[
\begin{align*}
P_n & \rightarrow P_{n-1} \\
P_{n+1} & \rightarrow P_n \\
T_n & \rightarrow T_{n-1} \\
T_{n+1} & \rightarrow T_n
\end{align*}
\]

If equal, continue.

As in the Interpolator, the Updater operates on the MLS azimuth and elevation and Miniranger range position components.

4. The Time Generator. The last module in the theodolite control program is the Time Generator. The function of the Time Generator is to predict the time for which the next theodolite command will be valid. The Time Generator does this by taking the time of the last theodolite position message and adding the iteration time of the theodolite control program and an experimentally determined lead constant. The iteration time is recomputed each iteration.
III. EVALUATION OF THE THEODOLITE CONTROL PROGRAM

The two primary criteria used to evaluate the performance of the theodolite control program were the ability of the theodolite, under the control of the theodolite control program, to acquire the aircraft, and its ability to track the aircraft within the MLS service volume. The automatic tracking is just as important as initial acquisition, because the theodolite must remain centered on the aircraft until the operator is ready to begin manual tracking.

Because MLS receivers are not yet available to Ohio University and because the software controlling the interchange of telemetry data between the ATP and GTP has not been completed, it was impossible to evaluate the performance of the theodolite control program on the actual hardware for which it was designed. The Evaluation of the theodolite control program was therefore performed by simulation on the Ohio University IBM 4341 computer.

The purpose of the simulation was to evaluate the performance of the theodolite control program under actual flight conditions, e.g., to simulate the performance of the theodolite control program while acquiring and tracking an aircraft on standard MLS evaluation flight patterns.

The simulation is performed by the sequential execution of several program modules, as illustrated in Figure 14. The most important of

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5 The Miniranger was found to have a design flaw in the data-link software, which is being corrected by Motorola at this writing.
FLTPATH
Generates aircraft trajectories

MLSDATA
Simulates time multiplexing of MLS signals

JVMACQ
Simulates theodolite control program, GTP, theodolite and system computer

JVMPLT
Creates plot files

Figure 14. Theodolite Control Program Evaluation Sequence.
these is JVMACQ. This program, written in Waterloo BASIC, contains the basic theodolite control program and a subroutine which simulates the GRS (Miniranger and theodolite) and GTP. A copy of JVMACQ is found in Appendix B.

Aircraft position data used by JVMACQ is generated by a FORTRAN program called FLTPATH. FLTPATH generates aircraft position coordinates referenced to the theodolite and to the MLS transmitting antennas for the loci of points that comprise patterns A, B and D. The output of FLTPATH is in the same format as data produced by the GTP, and is stored in disk files named <RUNIDENT> FPDATA and <RUNIDENT> MLSTDATA pending use by other program modules. The source code and theory of operation of FLTPATH are documented in Appendix C.

For the purposes of simulation, the MLS data output by FLTPATH is processed by another FORTRAN program called MLSDATA. MLSDATA, found in Appendix D, separates the azimuth, elevation and range components of the FLTPATH MLS data and samples them alternately with respect to time. This is to simulate the time-multiplexed nature of actual MLS data, and is necessary to properly test the Interpolator and Updater modules of the theodolite control program, described above. The data output by MLSDATA has three time tags, one each for azimuth, elevation and range, compared to one time tag common to all three components output by FLTPATH. The output of MLSDATA is stored in a disk file called <RUNIDENT> MLSDATA.

During its execution, and after initialization, JVMACQ reads MLS azimuth and elevation and Miniranger range from <RUNIDENT> FPDATA and
MLSDATA disk files, performs the Updater and Interpolator functions, and generates the theodolite command through the Coordinate Converter. The theodolite command is stored in an output disk file THEOCOM, and is also sent to the THEOUPDATE subroutine. THEOUPDATE contains algorithms which simulate the dynamics of the theodolite and GTP and update the current theodolite position. The current theodolite position is then written with a time tag into a file called THEODATA.

The data produced during the simulation was evaluated by comparing the data in the FPDATA (where the aircraft really was), THEOCOM (where the control program commanded the theodolite to point), and THEODATA (where the theodolite actually pointed) files. This was accomplished graphically by plotting the three data sets on the same graph. Two plots were made for each simulation, one of azimuth versus time, and the other of elevation versus time. These plots not only show clearly the performance of the theodolite control program, but also demonstrate the performance that can be expected from the theodolite and GTP in the manual tracking mode.

The plots from the simulations are shown in Figures 15-20. Figures 15 and 16 are of Pattern A data. (See Figure 3.) Figures 17 and 18 are of Pattern B and Figures 19 and 20 are of Pattern D. The data in Figures 15-18 begin ten nautical miles from the DME antenna (stop end of the runway) and terminate at the runway threshold. (There is no difference in the ability of the theodolite to acquire the air-
Figure 15. Azimuth Data for a Pattern A Approach. Pattern is a 3° glidepath, 0° azimuth radial, beginning 10 nm from the DME antenna and terminating at the runway threshold.
Figure 16. Elevation Data for a Pattern A Approach. Pattern is a 3° glidepath, 0° azimuth radial, beginning 10 nm from the DME antenna and terminating at the runway threshold.
Figure 17. Azimuth Data for a Pattern B Approach. Pattern was 0° azimuth radial, 1000' AGL, beginning 10 nm from the DME antenna and terminating at the runway threshold.
Figure 18. Elevation Data for a Pattern B Approach. Pattern was 0° azimuth radial, 1000' AGL, beginning 10 nm from the DME antenna and terminating at the runway threshold.
Figure 19. Azimuth Data for Pattern D flown at a radius of 5 nm from the DME Antenna at an Altitude of 1000' AGL.
Figure 20. Elevation Data for Pattern D Flown at a Radius of 5 nm from the DME Antenna at an Altitude of 1000' AGL.
craft at five, ten, fifteen or twenty miles. Ten miles was used for a starting point instead of fifteen to reduce the volume of data to be plotted and to expand slightly the scale of the plots.) The dashed lines in the plots indicate the boundaries of the theodolite field of view.

The plots show two things: first, the theodolite moves directly to point to the aircraft, and second, the theodolite is able to keep the aircraft well within the field of view throughout most of the MLS airspace. In fact, when the theodolite is unable to track the aircraft, as in Figure 17, the loss of track is due to the limit of the theodolite rate, and not to the control program.
This paper has presented the development of a theodolite control program for use with the Ohio University MLS Evaluation and Data Collection System in the acquisition of MLS flight check aircraft. Key conclusions reached as a result of this research are:

1. Computer simulation has demonstrated that the program described in Chapter II provides satisfactory, practical capability for the acquisition of MLS evaluation aircraft within the MLS airspace.

2. Several algorithms (described in Chapter II and Appendix C) were developed to perform the MLS-to-theodolite referenced coordinate conversions. The execution time of these algorithms is proportional to their accuracy.

3. The theodolite tracking ability is related to the theodolite angular rate, aircraft flight path, and the aircraft velocity.

Other results of this effort are:

1. Theodolite rates, field of view and response characteristics have been quantitatively defined.

2. A program to simulate MLS flight check patterns was developed.

The theodolite control program was developed in WBASIC, and has been only partially implemented in HP 9826 BASIC, due to related hardware and software unavailability. In the final implementation, there are several factors which should be considered:
1. Three coordinate conversion algorithms were developed. Their execution time is proportional to their accuracy. The user should check system timing to make sure he is getting the maximum possible accuracy for the execution time he has available.

2. A constant K was provided in the theodolite control program to adjust for the time required for computation and transfer of data between the GTP and the system computer. Adjustment of this constant will have the effect of centering the theodolite on the target aircraft.

3. In operational use of the theodolite control program, the theodolite operator should return the theodolite to ACQUISITION mode as soon as possible to insure that acquisition is completed prior to the beginning of the next run. (The theodolite may require one minute or more to reach the starting point of a run.) In doing so, the operator should make sure the theodolite motor cables will not become snarled by the theodolite rotation.

4. It is recommended that an I/O command be established in the GTP such that the theodolite control program can receive all the information it requires in a single I/O transaction. This would include MLS azimuth and elevation, Mini-ranger range and the associated time tags. The recommendation is that this command be combined with a theodolite position command, such that immediately upon receipt of the theodolite command, the GTP will begin loading the next position message into the system computer input buffer, while at the same time driving the theodolite to the commanded position.
5. It is recommended that the implementation of the theodolite control program in machine language or compiled BASIC be studied. The resulting savings in time would allow the possible inclusion of additional features. The on-screen display of the theodolite and aircraft positions and acquisition status (TRACKING, UNABLE TO TRACK, AIRCRAFT RATE TOO HIGH, etc.) are features that should be considered.
V. ACKNOWLEDGEMENTS

The work reported in this thesis was supported by the Avionics Engineering Center of Ohio University. Dr. Robert W. Lilley, associate director, served as research advisor. Dr. Richard H. McFarland, director, served as thesis advisor. Their guidance and encouragement were invaluable during this effort. Acknowledgement is made to the entire staff of the Avionics Engineering Center who helped in many different ways.

This thesis is dedicated to my parents, John V. and Abbie L. Matthews, and to Carla A. Ryan, for their constant love, support and encouragement.
VI. REFERENCES


[20]. "Flight Check," Avionics Engineering Center, Ohio University, Athens, OH.
[21]. Op cit., Lilley, McFarland and Phipps, p.3.
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VII. BIBLIOGRAPHY


A. Technical Memorandum:

"Measurement of Theodolite Physical and Dynamic Characteristics"

Abstract

Field of view, tracking rates and dynamic response of the motorized instrumented theodolite used with the Ohio University MLS Evaluation and Data Collection System are measured.
I. Introduction

This paper documents measurement of the characteristics of the instrumented motorized theodolite of the Ground Reference Subsystem (GRS) of the Ohio University MLS Evaluation and Data Collection System [29,30]. The parameters measured were the theodolite field of view, tracking rates and response to control signals.

The theodolite is a Warren-Knight WK 83 modified by the addition of motors with optical shaft encoders to provide precision joystick control and digital position output. The motor control system and the physical modifications to the theodolite are documented in references 29 and 30. The theodolite operates in conjunction with the Ground Telemetry Processor (GTP) subsystem of the MLS Data Collection System [31].

II. Theodolite Field of View

The field of view was measured by pointing the theodolite so that a reference object was located at the edge of the theodolite field of view. The theodolite position was recorded. The theodolite was then turned until the object was at the opposite edge of the field of view, and the position again recorded. The difference between the two measurements is the theodolite field of view. It was noted when making the measurements that pressing the eye tighter against the eyepiece increases the field of view. The field of view measured with "comfortable" eye pressure against the eyepiece is 0.75 degree. The field of view with the eye pressed tightly against the eyepiece is 1.00 degree.
It was noted that by moving one's eye about on the rubber eyecup, a 2.00 degree field of view could be achieved, but this would not be practicable when tracking a moving object. When the rubber eyecup was removed from the eyepiece, the full 2.00 degree field of view was easily achieved. This is the figure specified in the Warren-Knight theodolite literature [32]. With the rubber eyecup in place, the 0.75 degree measurement will be considered to be the nominal theodolite field of view.

III. Theodolite Tracking Rates

The tracking rate measured is the maximum rate at which the theodolite motors can change the theodolite position while the GTP is in the ACQUISITION and MANUAL TRACKING modes. The rates were measured using the HP9826 System Computer to process and record the data. The theodolite rate data is shown in figures A-1, A-2 and A-3. These figures display the GTP clock time at which each piece of data is recorded, the theodolite position at that time, the instantaneous rate computed over the interval from the preceding measurement, the average rate computed from data occurring after the theodolite has achieved a rate greater than 1.00 degree per second, and the maximum instantaneous rate measured during the move. The rate and position data are recorded for each axis. The reader will note that the rates are different for each axis, direction and mode. Nominal theodolite rates derived from the data are given in Table A-1.
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Figure A-1. Theodolite tracking rates in ACQUISITION mode.
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Figure A-2. Azimuth tracking rates in MANUAL mode.
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Figure A-3. Elevation tracking rates in MANUAL mode.
### ACQUISITION Mode

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### MANUAL Mode

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Table A-1. Nominal theodolite tracking rates in degrees per second.
IV. Theodolite Response to Control Signals

The theodolite response to control signals was measured by driving the theodolite motor control lines with TTL level signals from a function generator. The theodolite motor controller was configured such that a TTL "0" induces no theodolite motion and a TTL "1" commands maximum rate of motion in the direction corresponding to the command input. In order to simulate computer control with a function generator, the function generator output was applied directly to the input of the differential amplifier that drives the theodolite controller output transistors. Data are captured from the auxiliary data port of the GTP.

Figures A-4 - A-9 are plots of the theodolite response to a 0.6 Hz square wave. The square waves are illustrated in Figure A-11. Theodolite position is sampled at a rate of 15 Hz with a resolution of 0.01 degree. The effect of the solid-state motor controller is evidenced by the sharpness of the corners on the plots. The occasional rounding that is seen is due primarily to the relatively low sampling rate rather than to any actual rounding in the response. This is particularly evident in Figures A-6 and A-9. The positive trend in Figures A-6 and A-9 is due to a slight asymmetry in the square wave driving the theodolite motor controller. Time, on the X-axis in these plots, is arbitrary, in seconds since GTP start-up.

Figure A-10 illustrates the response of the theodolite to an impulse occurring at a rate of 0.6 Hz. The impulse consistently induces a theodolite movement of approximately 0.03 degree. This is significant in that it implies that the theodolite can be accurately positioned to within four percent of the theodolite field of view.
Figure A-4. Response to control signals - clockwise azimuth.
Figure A-5. Response to control signals - counterclockwise azimuth.
Figure A-6. Response to control signals - oscillating azimuth.
Figure A-7. Response to control signals - increasing elevation.
Figure A-8. Response to control signals - decreasing elevation.
Figure A-9. Response to control signals - oscillating elevation.
Figure A-10. Azimuth response to impulses.
V. Theodolite Response to Positioning Commands

The software controlling the GTP microprocessor has been designed so that a theodolite positioning command can be given to the GTP by the HP9826 System Computer, and the GTP will drive the theodolite to within \( \pm 0.03 \) degree of that position at the rate determined in Section III. The GTP will then keep the theodolite within 0.03 degree of the commanded position until another position is commanded or the ACQUISITION mode is switched off.

Figures A-12 and A-13 show the theodolite response when commanded to move from 10.00 to 12.52 degrees in azimuth and elevation. Again, most of the rounding seen is due to the relatively low output sampling rate of 11 Hz. Additional rounding can be attributed to the 0.03 degree deadband in the GTP theodolite positioning program. This deadband was placed in the program to reduce chatter and resulting gear wear due to offset in the theodolite motor controller power supplies and a consequent tendency for the theodolite to drift slowly when idle. Figure A-14 is a listing of the response data plotted in Figures A-11 and A-12.

Figures A-15 and A-16 illustrate the theodolite response when commanded to move from 12.52 to 10.00 degrees in azimuth and elevation. Again, the slight irregularities at the corners are due more to the method of recording data than to the system being studied. Figure A-17 is a listing of the data plotted in Figures A-15 and A-16.
a) Input to theodolite controller for Figures 4 and 7.

b) Input to theodolite controller for Figures 5 and 8.

c) Input to theodolite controller for Figures 6 and 9.

d) Input to theodolite controller for Figure 10.

Figure A-11. Function generator inputs to the theodolite motor controller.
Figure A-12. Theodolite response to acquisition commands - clockwise azimuth.
Figure A-13. Theodolite response to acquisition commands - increasing elevation.
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Figure A-14. Theodolite response to acquisition commands - listing of data.
Figure A-15. Theodolite response to acquisition commands - counterclockwise azimuth.
Figure A-16. Theodolite response to acquisition commands - decreasing elevation.
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Figure A-17. Theodolite response to acquisition commands - listing of data.
VI. Acknowledgements

The author acknowledges advice given by Dr. Robert Lilley in preparation of this report and assistance given by Kim Constantikes in making the theodolite measurements.
Appendix B. Program listing for the Waterloo BASIC theodolite control program, including THEOUPDATE subroutine which models the theodolite and GTP.
SIMULATES THEODOLITE CONTROL PROGRAM

ON ERR GOTO 1620
ON ATTN GOTO 1620
ON EOF GOTO 1870
OPEN 120,'AA MLSDATA C',INPUT
OPEN 121,'AA FPDATA C',INPUT
OPEN 122, 'AA THEODATA C', OUTPUT
OPEN 126, 'AA THEODOM C', OUTPUT
OPEN 128, 'AA XYZDATA C', INPUT

INITIALIZE CONSTANTS

XYZS = 1111.1111

INPUT 128, USING XVZ$, TX, TY, TZ
INPUT 128, USING XYZS, AX, AY, AZ
INPUT 128, USING XYZS, EX, EY, EZ
FTMET = 0.3048

CONVERT TO METERS
AX = AX*FTMET
AY = AY*FTMET
AZ = AZ*FTMET
EX = EX*FTMET
EY = EY*FTMET
EZ = EZ*FTMET
TX = TX*FTMET
TY = TY*FTMET
TZ = TZ*FTMET

INITIALIZE CONSTANTS FOR THEOUPDATE SUBROUTINE

TCWAZRATE=1.27
TCCWAZRATE=-1.43
TPELRATE=1.3
TNELRATE=-1.39
THEOWINDOW=0.375
HPTIME=0.20
TCWAZINC=TCWAZRATE*HPTIME
TCCWAZINC=TCCWAZRATE*HPTIME
TPELINC=TPELRATE*HPTIME
TNELINC=TNELRATE*HPTIME

LEAD CONSTANT FOR TIME

K=0.00
THEOaz=0.0
THEOel=0.0

I/O FORMATS

MLS$=11111111111111111111111111111111111111111111
GTPS=00000000000000000000000000000000000000000000
TERMS=11111111111111111111111111111111111111111111

DYNAMIC INITIALIZATION

INPUT #20, USING MLS$, AZMINP, AZSECP, MLSAZP, ELMINP, ELSECP, MLSELP &
& RANMINP, RANSECP, MLRSANP
TMLSAZP=AZMINP*60 + AZSECP/1000
TMLSELP=ELMINP*60 + ELSECP/1000
TMLSRANP=RANMINP*60 + RANSECP/1000
INPUT #20, USING MLS$
INPUT #20, USING MLS$
INPUT #20, USING MLS$, AZMIN, AZSEC, MLSAZ, ELMIN, ELSEC, MLSEL, &
& RANMIN, RANSEC, MLRSAN
00730 TMLSZ = AZMIN*60 + AZSEC/1000
00740 TMLSEL = ELMIN*60 + ELSEC/1000
00750 TMLSRAN = RANMIN*60 + RANSEC/1000
00760 INPUT #20, USING MLS$
00770 INPUT #20, USING MLS$
00780 FOR I = 1 TO 6
00790 INPUT #21, USING GTP$, TMINP, TTHEOP, DUMMYAZ, DUMMYEL, THEORANGE
00800 NEXT I
00810 TTHEOP = TMINP*60 + TTHEOP/1000
00820 MLSAZ=MLSAZ/100
00830 MLSZP=MLSZP/100
00840 MLSAZP=MLSAZP/100
00850 MLSZP=MLSZP/100
00860 TMLSSCAL=MLSZ
00870 TMLSSCAL=MLSZ
00880 GOSUB 1960
00890 I
00900 I
00910 I
00920 INPUT #20, USING MLS$, AZMINN, AZSECN, MLSAZN, ELMINN, ELSECN, MLSZPN, &
00930 & RANMINN, RANSECN, MLRSANN
00940 TMLSZN = AZMINN*60 + AZSECN/1000
00950 TMLSELN = ELMINN*60 + ELSECN/1000
00960 TMLSRANN = RANMINN*60 + RANSECN/1000
00970 MLSAZN=MLSAZN/100
00980 MLSZPN=MLSZPN/100
00990
01000 IF TMLSZN=TMLSZ THEN GOTO 1050
01010 MLSAZP=MLSAZ
01020 MLSZ=MLSZN
01030 TMLSAZ=TMLSAZN
01040
01050 IF TMLSELN=TMLSEL THEN GOTO 1100
01060 MLSZP=MLSZ
01070 MLSZ=MLSZPN
01080 TMLSAZN=TMLSAZN
01090
01100 IF TMLSRANN=TMLSRAN THEN GOTO 1160
01110 MLRSANP=MLRSAN
01120 MLRSAN=MLRSANP
01130 TMLSRANP=TMLSRAN
01140 TMLSRAN=TMLSRANN
01150
01160 INPUT #21, USING GTP$ , TMIN, TTHEO, DUMMYAZ , DUMMYEL , THEORANGE
01170 TTHEO = TMIN*60 + TTHEO/1000
01180 HPTIME = TTHEO - TTHEOP
01190 TMINP = TMIN
01200 I
01210 I
01220 I
01230 I
01240 TMLSSCAL = TTHEO + HPTIME + K
01250 MLSAZ1=MLSAZ+(TMLSSCAL-TMLSAZ)*(MLSAZ-MLSAZP)/(TMLSAZ-TMLSAZP)
01260 MLSZ1=MLSZ+(TMLSSCAL-TMLZ)*(MLSZ-MLSZP)/(TMLZ-TMLZP)
01270 MLRSAN1=MLRSAN+(TMLSSCAL-MLRSANP)*(MLRSAN-MLRSANP)/(MLRSANP-MLRSAN)
01280 THEORAN1=THEORANGE+(TMLSSCAL-THEORANGE)*(THEORANGE-THEORANGE)/(THEORANGE-THEORANGE)
01290 TTHEOP=TTHEO
01300 THEOREANGE=THEOREANGE
01310 I
01320 I
01330 I
01340 XT, YT, ZT ARE IN METERS
01350 ZT = THEORAN1 * SIN (RAD (MLSEL1)) + EZ - TZ
01360 A = 1 + TAN (RAD (MLSAZ1))**2
01370 B = 2 * TAN (RAD (MLSAZ1)) * (AY - TY + (TX - AX) * TAN (RAD (MLSAZ1)))
01380 C = TAN (RAD (MLSAZ1)) * (TX - AX) * (TAN (RAD (MLSAZ1)) * (TX - AX) + &
01390 & Z2 = (AY - TY)**2 + (AY - TY)**2 + (ZT - EZ)**2
01400 D = 1 + (AY - TY)**2 + (AY - TY)**2 + (ZT - EZ)**2
01410 XT = (-B + SQRT(B**2 - 4 * A * C)) / (2 * A)
01420 YT = (XT + TX - AX) * TAN (RAD (MLSAZ1)) + AY - TY
01430 I
01440 ELRANGE = SQRT ((XT+TX-EX)**2+(YT+TY-EY)**2+(ZT+TZ-EZ)**2)
01450 ZT = ELRANGE * SIN(RAD(MLSEL1)) + EZ - TZ
01460 THEOCOMAZ = DEG(ATNZ(YT,XT))
01470 IF THEOCOMAZ < 0 THEN THEOCOMAZ = THEOCOMAZ + 360
01480 THEOCOMEL = DEG(ATNZ(ZT,SQR(XT**2+YT**2)))
01490 GOSUB 1960 1 GOSUB THEOUPDATE
01500 I
01510 I
01520 OUTPUT SECTION
01530 I
01540 TMIN = INT(TTHEO/60)
01550 TSEC = REM(TTHEO,60) * 1000
01560 PRINT #22, USING GTP$ , TMIN, TSEC, THEOAZ*100, THEOEL*100, THEORANGE
01570 PRINT #26, USING GTP$, TMIN, TSEC, THEOCOMAZ*100, THEOCOMEL*100
01580 GO TO 920 I GOTO MLSUPDATER
01590 I
01600 I IN CASE OF ERROR...
01610 I
01620 PRINT 'TMLSAZ', 'TMLSEL', 'TMLSRAN', 'TMIN'
01630 PRINT TMLSAZ, TMLSEL, TMLSRAN, TMIN
01640 PRINT 'MLSAZ', 'MLSEL', 'MLSRAN'
01650 PRINT MLSAZ, MLSEL, MLSRAN
01660 PRINT 'TMLSAZP', 'TMLSELP', 'TMLSRANP'
01670 PRINT TMLSAZP, TMLSELP, TMLSRANP
01680 PRINT 'MLSAZP', 'MLSELP', 'MLSRANP'
01690 PRINT MLSAZP, MLSELP, MLSRANP
01700 PRINT 'TMLSAZN', 'TMLSELN', 'TMLSRANN'
01710 PRINT TMLSAZN, TMLSELN, TMLSRANN
01720 PRINT 'MLSAZN', 'MLSELN', 'MLSRANN'
01730 PRINT MLSAZN, MLSELN, MLSRANN
01740 PRINT 'TMLSA1', 'TMLSEL1', 'TMLSRAN1'
01750 PRINT TMLSA1, TMLSEL1, TMLSRAN1
01760 PRINT 'MLSA1', 'MLSEL1', 'MLSRAN1'
01770 PRINT MLSA1, MLSEL1, MLSRAN1
01780 PRINT 'TMLSAZ', 'TMLSEL', 'TMLSRAN'
01790 PRINT TMLSAZ, TMLSEL, TMLSRAN
01800 PRINT 'MLSAZ', 'MLSEL', 'MLSRAN'
01810 PRINT MLSAZ, MLSEL, MLSRAN
01820 PRINT XT, YT, ZT
01830 PRINT A, B, C
01840 I
01850 I WIND UP PROGRAM
01860 I
01870 CLOSE #20
01880 CLOSE #21
01890 CLOSE #22
01900 CLOSE #26
01910 CLOSE #28
01920 STOP
01930 I
01940 I SUBROUTINE THEOUPDATE
01950 I
01960 IF THEOCOMAZ-THEOAZ>180 THEN THEOAZ=THEOAZ+360
01970 IF THEOCOMAZ - THEOAZ < -180 THEN THEOAZ = THEOAZ - 360
01980 IF (O< THEOCOMAZ-THEOAZ) AND (THEOCOMAZ-THEOAZ<=TCWAZINC)
01990 THEOAZ=THEOCOMAZ
02000 ELSE IF (TCMAZINC<=THEOCOMAZ-THEOAZ) AND (THEOCOMAZ-THEOAZ<0)
02010 THEOAZ=THEOCOMAZ
02020 ELSE IF THEOCOMAZ-THEOAZ>TCWAZINC
02030 THEOAZ=THEOAZ+TCWAZINC
02040 ELSE
02050 IF THEOAZ=THEOAZ+TCWAZINC
02060 ENDIF
02070 IF THEOAZ >= 360 THEN THEOAZ = THEOAZ - 360
02080 IF THEOAZ < 0 THEN THEOAZ = THEOAZ + 360
02090 I
02100 IF (O< THEOCOMEL-THEOEL) AND (THEOCOMEL-THEOEL<=TPELINC)
02110 THEOEL=THEOCOMEL
02120 ELSE IF (TPELINC<=THEOCOMEL-THEOEL) AND (THEOCOMEL-THEOEL<0)
02130 THEOEL=THEOCOMEL
02140 ELSE IF THEOCOMEL-THEOEL>TPELINC
02150 THEOEL=THEOEL+TPELINC
02160
02160 ELSE
02170 THEDEL=THEDEL+TNELINC
02180 ENDIF
02190 I
02200 I
02210 RETURN
02220 END
Appendix C. Technical Memorandum: "Program FLTPATH"

Abstract

A FORTRAN program to simulate the trajectories of flight check aircraft on Patterns A, B and D. Output is in the same format as that used by the Ohio University Ground Telemetry Processor (GTP).
I. Introduction

The development of hardware and software for MLS test and evaluation gives rise to a need to simulate portions of the MLS system and its environment for the purpose of testing the hardware and debugging the software. The Fortran program FLTPATH meets a portion of that need by providing for simulation of the flight path of an aircraft through the MLS service volume. FLTPATH simulates the flight of an aircraft over standard flight check patterns. The output of the program is in a format compatible with the output of the Ohio University MLS flight check hardware. Instructions and examples for use of the program on the Ohio University Computer System are included.

II. Description

A. Flight Patterns. FLTPATH is a Fortran program which generates the loci of points in space which will be referenced as Patterns A, B and D. These patterns have been used successfully in systematic evaluations of the spatial structure of the ILS signal. FLTPATH generates these patterns in the format that may be adapted for MLS evaluations.

B. The Reference System. The flight patterns are assumed to be flown with the pilot using the MLS signal to provide guidance information. Thus, all patterns are referenced to the physical locations of the MLS transmitting antennas. Since the aircraft is optically tracked from the ground by an instrumented theodolite, the output of FLTPATH is referenced to the physical location of the theodolite, simulating the
output of the Ohio University MLS Data Collection System Ground Telem­etry Processor (GTP). [33] The locations of the theodolite and the MLS hardware are referenced to the centerline of the runway at the threshold. Figure C-1 illustrates the various reference systems used in FLTPATH.

C. Pattern A. Pattern A is basically a straight-in approach to landing. The pilot approaches the runway at fixed azimuth and elevation angles. The run is terminated a few feet above the runway. Pattern A is illustrated in Figure C-2a. Pattern A generally starts 10 nm from the azimuth/DME antenna.

D. Pattern B. Pattern B checks the vertical structure of the MLS signal. The pilot flies at a constant altitude along a fixed azimuth radial, intercepting the entire range of MLS elevation angles, as illustrated in Figure C-2b. Pattern B generally starts 15 nm out.

E. Pattern D. Pattern D checks the lateral/orbital structure of the MLS signal. The pilot flies a partial orbit about the azimuth antenna at a constant altitude and range. In order to evaluate the clearance and out-of-coverage-indication (OCI) portions of the MLS azimuth signal, pattern D covers angles as wide as from -65 to +65 degrees in azimuth with respect to the runway centerline, as shown in Figure C-2c.

F. The Equations. FLTPATH uses three subroutines to perform the necessary coordinate conversions. The first, MLSCRT, converts the aircraft position from MLS-referenced spherical coordinates to cartesian coordinates referenced to the theodolite. Because of the triple-origin
Figure C-1. FLTPATH Range Coordinate System.
Pattern A. Approaches.

Pattern B. Constant Altitude Radials.

Figure C-2. Potential MLS Flight Evaluation Patterns.
Pattern D. Orbits.

Figure C-2. Continued.
nature of the MLS coordinate system, an iterative-approximation algorithm is used to convert the aircraft position to cartesian coordinates. The iterative approach eliminates the need to solve a complicated polynomial containing four roots. The three iterations used here are sufficient to keep errors below 0.1 percent throughout the practical range of the MLS.

The long form of the equations is:

\[
\begin{align*}
XA_1 &= RA \cdot \cos(AA) \\
YA_1 &= RA \cdot \sin(AA) \\
XE_1 &= XA + AX - EX \\
YE_1 &= YA + AY - EY \\
ZE_1 &= \tan(EE) \cdot \sqrt{XE_1^2 + YE_1^2} \\
ZA_1 &= ZE_1 + EZ - AZ \\
XA_2 &= \cos(AA) \cdot \sqrt{RA^2 - ZA_1^2} \\
YA_2 &= \sin(AA) \cdot \sqrt{RA^2 - ZA_1^2} \\
XE_2 &= XA_2 + AX - EX \\
YE_2 &= YA_2 + AY - EY \\
ZE_2 &= \tan(EE) \cdot \sqrt{XE_2^2 + YE_2^2} \\
ZA_2 &= ZE_2 + EZ - AZ \\
XA_3 &= \cos(AA) \cdot \sqrt{RA^2 - ZA_2^2} \\
YA_3 &= \sin(AA) \cdot \sqrt{RA^2 - ZA_2^2} \\
XE_3 &= XA_3 + AX - EX \\
YE_3 &= YA_3 + AY - EY \\
ZE_3 &= \tan(EE) \cdot \sqrt{XE_3^2 + YE_3^2}
\end{align*}
\]
\[ X_T = X_E + E_X - T_X \]
\[ Y_T = Y_E + E_Y - T_Y \]
\[ Z_T = Z_E + E_Z - T_Z \]

where \((R_A, A_A, E_E)\) are the MLS range, azimuth and elevation of the aircraft referenced to the azimuth/DME and elevation antennas, respectively. \((X_T, Y_T, Z_T)\) are the cartesian coordinates of the aircraft referenced to the theodolite. \((A_X, A_Y, A_Z), (E_X, E_Y, E_Z)\) and \((T_X, T_Y, T_Z)\) are the cartesian coordinates of the azimuth and elevation antennas and the theodolite referenced to the runway threshold. The above equations reduce to:

\[ X_E_1 = \cos(A_A) \ast R_A + A_X - E_X \]
\[ Y_E_1 = \sin(A_A) \ast R_A + A_Y - E_Y \]
\[ Z_A_1 = \tan(E_E) \ast \sqrt{X_E^2 + Y_E^2 + E_Z - A_Z} \]

\[ X_E_2 = \cos(A_A) \ast \sqrt{R_A^2 - Z_A^2} + A_X - E_X \]
\[ Y_E_2 = \sin(A_A) \ast \sqrt{R_A^2 - Z_A^2} + A_Y - E_Y \]
\[ Z_A_2 = \tan(E_E) \ast X_E^2 + Y_E^2 + E_Z - A_Z \]

\[ X_E_3 = \cos(A_A) \ast \sqrt{R_A^2 - Z_A^2} + A_X - E_X \]
\[ Y_E_3 = \sin(A_A) \ast \sqrt{R_A^2 - Z_A^2} + A_Y - E_Y \]
\[ Z_T = \tan(E_E) \ast \sqrt{X_E^2 + Y_E^2 + E_Z - T_Z} \]
\[ X_T = X_E_3 + E_X - T_X \]
\[ Y_T = Y_E_3 + E_Y - T_Y \]

Subroutine CRTMLS converts the aircraft position from cartesian coordinates referenced to the theodolite to MLS coordinates. The equations are:
\[ XA = XT - AX + TX \]
\[ YA = YT - AY + TY \]
\[ ZA = ZT - AZ + TZ \]
\[ ZE = ZT - EZ + TZ \]
\[ RA = \sqrt{XA^2 + YA^2 + ZA^2} \]
\[ AA = \tan^{-1}(YA / XA) \]
\[ EE = \tan \left( \frac{ZE}{\sqrt{(XA + AX - EX)^2 + (YA + AY - EY)^2}} \right) \]

The last subroutine, CRTHEO, is a standard cartesian-to-spherical coordinate conversion, with both coordinate systems referenced to the theodolite. The equations are:

\[ RT = \sqrt{XT^2 + YT^2 + ZT^2} \]
\[ AT = \tan^{-1}(YT/XT) \]
\[ ET = \tan^{-1}(ZT/\sqrt{XT^2 + YT^2}) \]

G. The Paths. Since ideal patterns A and B are straight lines in space, the flight paths for these patterns are generated in cartesian coordinates. From the input information, the start and stop points for the pattern are computed. From the input aircraft velocity and the set time interval between data points, the incremental distance the aircraft travels along the path is computed. From this the X, Y and Z increments are calculated. The program then enters a loop wherein the (X,Y,Z) position is updated, CRTHEO is called to convert the data to theodolite coordinates, and the data are output.

Pattern D is based upon altitude and range, and is therefore worked in cylindrical coordinates. From the given aircraft velocity and
range, the azimuthal rate in degrees per second is computed. This is converted into the azimuth increment based on the required data rate. The program then enters a loop wherein the azimuth is updated, the X,Y, and Z coordinates are computed, (Z is constant), CRTHEO is called and the data are output.

The output of FLTPATH is in the same format as data output by the Ohio University GTP. A sample of the output is included in the Addenda, along with a complete listing of the program and the terminal input and output for a sample run.

III. Operation

FLTPATH FORTRAN is most conveniently run by invoking the executive program FLTPATH EXEC. The correct form is:

`FLTPATH <RUNIDENT>`

FLTPATH EXEC sets the file definitions needed to run FLTPATH. Files 5 and 6 are used for the terminal input and output. Files 7 and 10 are used to pass the input parameters from one run to another, helping to reduce the amount of manual input. Files 8, 9 and 12 are the output files. FLTPATH EXEC gives Files 7 and 10 the name RANGE COORD A. File 8 is named `<RUNIDENT> FPDATA C`, File 9 is named `<RUNIDENT> XYZDATA C`, and File 12 is named `<RUNIDENT> MLSTDATA C`.

FLTPATH FORTRAN is well documented by comments within the code. During execution, the user is prompted for all information necessary to run the program and control the output.
The user is presented with a series of options. The first concern is the use of File 7. If previously prepared range coordinate data are to be used, they will be read from the file RANGE COORD A upon a "Y" or "YES" response by the user. Otherwise the user will be prompted for the locations of the azimuth and elevation antennas and theodolite, and the aircraft velocity. When entering numerical data, it is important that the decimal point be included in all numbers. Otherwise, the computer may set the number incorrectly.

Following the input of the range coordinates, the data are displayed at the terminal and the user is asked to verify the accuracy of the data. If the response is not "Y" or "YES", the user will be prompted to reenter the data.

When the accuracy of the range data has been established, the user has the option of updating the input file with the current data.

The user is then asked to enter A, B or D, according to which pattern he wishes to generate, and the information necessary to generate that pattern.

The final option the operator has in the execution of FLTPATH is whether to output the cartesian coordinates of the aircraft, \((XT, YT, ZT)\). These coordinates are produced at an intermediate point in the execution of the program. This option was used to debug the program, and has been left in the code in case such data may be needed in the future. File \(<\text{RUNIDENT}>\) XYZDATA will be generated regardless of whether the cartesian
aircraft coordinates are output, and will contain a complete record of
the input parameters for that run.

Files 8 and 12 are output in the following format:

DDDHHHMMSSSTHTAAATEEETHRRRRREEEG

which is used by the GTP. DDD represents the day, HH the hours, MM the
minutes, SSTHT the seconds multiplied by one thousand, (THT stands for
tenths, hundredths, thousandths,) AAATH and EEETH the azimuth and eleva-
tion multiplied by one hundred, and RRRRR the range in meters. EEE and
G are used by the GTP to record event mark and GO/NOGO data.

There are some constants in the source code of FLTPATH, of which
the user should be aware. The first is TT. This is the time increment
between data points, and controls the data rate of the output. TT =
1./15. is equivalent to 15 Hz. The constant RO in the sections for pat-
terns A and B controls the starting point of the pattern. RO = 10.*
6076.1155 feet is equivalent to 10 nautical miles from the azimuth/DME
antenna. AAO in the section for pattern D controls the start and end
points for the orbit. AAO = -65. will generate an orbit of 130 degrees,
from -65 to +65 degrees. The user will note that the length of the out-
put files is directly proportional to these constants.

IV. Acknowledgments

The writer thanks Dr. Robert Lilley for his assistance in the
definition of the flight check patterns and GTP characteristics and the
preparation of this report.
VI. Addenda

A. FLTPATH FORTRAN
B. FLTPATH EXEC
C. RANGE COORD
D. RUN1 FPDATA
E. RUN1 MLSTDATA
F. RUN1 XYZDATA
G. RUN1 CONSOLE
Addendum A. FLTPATH Fortran.
GET SYSTEM PARAMETERS

WRITE(6,538)
READ(5,528)Y
IF ( Y.EQ.YES ) GO TO 20
15 WRITE(6,510)
WRITE(6,511)
WRITE(6,525)
WRITE(5,512)
READ(5,521)TX
WRITE(5,513)
READ(5,521)TY
WRITE(6,514)
READ(5,521)TZ
WRITE(6,515)
READ(5,521)AX
WRITE(6,516)
READ(5,521)AY
WRITE(6,517)
READ(5,521)AZ
WRITE(6,518)
READ(5,521)EX
WRITE(6,519)
READ(5,521)EY
WRITE(6,520)
READ(5,521)EZ
WRITE(6,526)
READ(5,521)V
GO TO 10
20 READ(7,521)TX
READ(7,521)TY
READ(7,521)TZ
READ(7,521)AX
READ(7,521)AY
READ(7,521)AZ
READ(7,521)EX
READ(7,521)EY
READ(7,521)EZ
READ(7,521)V
10 WRITE(6,527)
READ(5,528)PAT

ECHO PARAMETERS TO SCREEN

WRITE(6,522)TX,TY,TZ
WRITE(6,523)AX,AY,AZ
WRITE(6,524)EX,EY,EZ
WRITE(6,530)V
WRITE(6,529)PAT

CHECK DATA

WRITE(6,536)
READ(5,528)Y
IF ( Y.NE.YES ) GO TO 15
WRITE(9,522)TX,TY,TZ
WRITE(9,523)AX,AY,AZ
WRITE(9,524)EX,EY,EZ
WRITE(9,530)V
WRITE(9,529)PAT

SAVE DATA?

WRITE(6,537)
READ(5,528)Y
IF ( Y.NE:YES ) GO TO 25
WRITE(10,521)TX
WRITE(10,521)TY
WRITE (10, 521) TZ
WRITE (10, 521) AX
WRITE (10, 521) AY
WRITE (10, 521) AZ
WRITE (10, 521) EX
WRITE (10, 521) EY
WRITE (10, 521) EZ
WRITE (10, 521) Y

C LONG XYZ DATA OUTPUT DESIRED?
25 WRITE (6, 539)
READ (5, 528) Y

******************************************************************************

DETERMINE BRANCHING

IF ( PAT.EQ. PAT(1) ) GO TO 100
IF ( PAT.EQ. PAT(2) ) GO TO 200
IF ( PAT.EQ. PAT(4) ) GO TO 400
WRITE (6, 531)
GO TO 10

******************************************************************************

FOR PATTERN A

100 CONTINUE

GET PATH PARAMETERS

WRITE (6, 532)
READ (5, 521) GPA
WRITE (9, 532) GPA
GPA = GPA * RADCON
WRITE (6, 533)
READ (5, 521) RAD
WRITE (9, 533) RAD
RAD = RAD * RADCON

COMPUTE STARTING POINT

RO = 10.0 * 6076.1155
CALL MLSORT( RAD, GPA, RO, XTO, YTO, ZTO, AX, AY, AZ, EX, EY, EZ, TX, TY, TZ)

COMPUTE END POINT

RF = - AX
CALL MLSORT( RAD, GPA, RF, XTF, YTF, ZTF, AX, AY, AZ, EX, EY, EZ, TX, TY, TZ)

COMPUTE INCREMENTS

D = SQRT( (XTF - XTO)**2 + (YTF - YTO)**2 + (ZTF - ZTO)**2 )
DD = V * 6076.1155 * TT / 3600
XX = DD * (XTF - XTO) / D
YY = DD * (YTF - YTO) / D
ZZ = DD * (ZTF - ZTO) / D

COMPUTE NUMBER OF POINTS

Q = D / DD
J = INT(Q)

RECORD SIMULATION CONDITIONS ON OUTPUT

WRITE (9, 600) XTO, YTO, ZTO, XTF, YTF, ZTF
WRITE (9, 601) D, DD, Q, XX, YY, ZZ
WRITE (9, 603)
INITIALIZE SYSTEM

ITH = 0.
ITM = 0.
TS = 0.
XT = XTO
YT = YTO
ZT = ZTO

COMPUTE POINTS ON PATH

DO 199 l=1,J
101 CALL CRTH(0,XT,YT,ZT,AT,ET,RT)
IAT = INT(AT * 100 / RADCON)
IET = INT(ET * 100 / RADCON)
RT = RT / 3.28084
IRT = INT(IRT)
ITS = INT(TS * 1000)
WRITE(8,540)ITM,ITS,IAT,IET,IRT
CALL CRTHLS(XT,YT,ZT,AA,EE,RA,AX,AY,AZ,EX,EY,EZ,TX,TY,TZ)
IAA = INT(AA * 100 / RADCON)
IEE = INT(EE * 100 / RADCON)
RA = RA / 3.28084
IRA = INT(IRA)
WRITE(12,540)ITM,ITS,IAA,IEE,IRA
IF ( Y.NE.YES ) GO TO 110
WRITE(9,602)TS,XT,YT,ZT

110 XT = XT + XX
YT = YT + YY
ZT = ZT + ZZ
CALL TIME(TT,ITH,ITM,TS)
199 CONTINUE
GO TO 999

***********************************************************************
FOR PATTERN B

200 CONTINUE

GET PATH PARAMETERS

WRITE(6,534)
READ(5,521)ALT
WRITE(9,534)ALT
WRITE(6,533)
READ(5,521)RAD
WRITE(9,533)RAD
RAD = RAD * RADCON

COMPUTE STARTING POINT

RO = 10.0 * 6076.1166
ZTO = ALT - TZ
PRO = SQRT ( RO**2 - ZTO**2 )
XTO = PRO * COS( RAD ) + AX - TX
YTO = PRO * SIN( RAD ) + AY - TY

COMPUTE END POINT

ZTF = ZTO
XTF = - TX
YTF = - TY

COMPUTE INCREMENTS

D = SQRT( (XTF-XTO)**2 + (YTF-YTO)**2 + (ZTF-ZTO)**2 )
DD = V * 6076.1155 * TT / 3600
XX = DD * (XTF - XTO) / D
YY = DD * (YTF - YTO) / D
ZZ = DD * (ZTF - ZTO) / D

COMPUTE NUMBER OF POINTS

Q = D / DD
J = INT(Q)

RECORD SIMULATION CONDITIONS ON OUTPUT

WRITE(9,600)XTO,YTO,ZTO,XTF,YTF,ZTF
WRITE(9,601)DD,Q,XX,YY,ZZ
WRITE(9,603)

INITIALIZE SYSTEM

ITH = 0.
ITM = 0.
TS = 0.
XT = XTO
YT = YTO
ZT = ZTO

COMPUTE POINTS ON PATH

DO 299 l=1,J
  CALL CRTHEO(XT,YT,ZT,AT,ET,RT)
  IAT = INT(AT * 100 / RADCON)
  IET = INT(ET * 100 / RADCON)
  RT = RT / 3.28084
  IRT = INT(RT)
  ITS = INT(TS * 1000)
  WRITE(8,540)ITM,ITS,IAT,IET,IRT
  CALL CRTMLS(XT,YT,ZT,AA,EE,RA,AX,AY,AZ,EX,EY,EZ,TX,TY,TZ)
  IAA = INT(AA * 100 / RADCON)
  IEE = INT(EE * 100 / RADCON)
  RA = RA / 3.28084
  IRA = INT(RA)
  WRITE(12,540)ITM,ITS,IAA,IEE,IRA
  IF ( Y.NE.YES ) GO TO 210
  WRITE(9,602)TS,XT,YT,ZT
  210 XT = XT + XX
       YT = YT + YY
       ZT = ZT + ZZ
       CALL TIMECTT(ITH,ITM,TS)
  299 CONTINUE

FOR PATTERN 0

400 CONTINUE

GET PATH PARAMETERS

WRITE(6,534)
READ(5,521)ALT
WRITE(9,534)ALT
WRITE(6,535)
READ(5,521)RA
WRITE(9,535)RA
RA = RA * 6076.1155

START AND STOP POINTS

AAO = -65.0
AAF = -AAO

COMPUTE INCREMENTS

D = AAF - AAO
DO = V * 6076.1155 * TT / (20.0 * PI * RA)

COMPUTE NUMBER OF POINTS

Q = D / DD
J = INT(Q)

RECORD SIMULATION CONDITIONS ON OUTPUT

WRITE(9,601)D,DD,Q,XX,YY,ZZ
WRITE(9,603)

INITIALIZE SYSTEM

ITH = 0.
ITM = 0.
TS = 0.
AA = AA0
AA = AA * RADCON
DD = DD * RADCON
PRA = SQRT( RA**2 - ALT**2 )

COMPUTE POINTS ON PATH

DO 499 I=1,J
XT = PRA * COS( AA ) + AX - TX
YT = PRA * SIN( AA ) + AY - TY
ZT = ALT - TZ
401 CALL CRTHEOeXT,YT,ZT,AT,ET,RT)
IAT = INT(AT * 100 / RADCON)
IET = INT(ET * 100 / RADCON)
RT = RT / 3.28084
IRT = INT(RT)
IT = INT(TS * 1000)
WRITE(8,540)ITM,ITS,IAT,IET,IRT
CALL CRTMS(XT,YT,ZT,AA,EE,RA,AX,AY,AZ,EX,EY,EZ,TX,TY,TZ)
IAT = INT(AA * 100 / RADCON)
IET = INT(EE * 100 / RADCON)
RA = RA / 3.28084
IRA = INT(RA)
WRITE(12,540)ITM,ITS,IAA,IEE,IRA
IF ( Y.NE.YES ) GO TO 410
WRITE(9,602)TS,XT,YT,ZT
410 AA = AA + DD
CALL TIME(TT,ITH,ITM,TS)
499 CONTINUE

***********************************************************************

510 FORMAT('ENTER THE LOCATIONS OF THE THEODOLITE AND THE AZIMUTH')
511 FORMAT(' AND ELEVATION ANTENNAS, WITH RESPECT TO THRESHOLD.')
525 FORMAT(' UNITS ARE IN FEET. INCLUDE DECIMAL PLACE.//')
512 FORMAT('//+ /TX=')
513 FORMAT('+ /TY=')
514 FORMAT('+ /TZ=')
515 FORMAT('+ /AX=')
516 FORMAT('+ /AY=')
517 FORMAT('+ /AZ=')
518 FORMAT('+ /EX=')
519 FORMAT('+ /EY=')
520 FORMAT('+ /EZ=')
521 FORMAT(F10.3)
522 FORMAT(' THEODOLITE POSN = (',F10.3,'),(',F10.3,')')
523 FORMAT(' AZ ANT POSN = (',F10.3,'),(',F10.3,')')
524 FORMAT(' EL ANT POSN = (',F10.3,'),(',F10.3,')')
526 FORMAT(' ENTER AIRCRAFT VELOCITY IN KNOTS. V=')
527 FORMAT(' ENTER DESIRED FLIGHT CHECK PATTERN. (A, B, OR D)')
528 FORMAT(A1)
529 FORMAT(' PATTERN ',A1)
530 FORMAT(' AIRCRAFT VELOCITY = ',F7.2,' KNOTS')
ENTER A, B OR D.

ARE THE ABOVE PARAMETERS CORRECT? (Y/N)

DO YOU WISH TO UPDATE INPUT CONDITIONS? (Y/N)

DO YOU WISH TO USE PREVIOUS COORDINATES? (Y/N)

DO YOU WISH XYZDATA OUTPUT? (Y/N)

OUTPUT FORMATS

Enter A, B or D.

FORMAT (10, 15, 15, 15, 15, 10)

XTO = F10.3, YTO = F10.3, ZTO = F10.3

XT = XE + EX - TX
YT = YE + EY - TY
RETURN

CONVERTS FROM MLS TYPE SPHERICAL COORDINATES TO CARTESIAN COORDINATES REFERENCED TO THE THEODOLITE.

WARNING: MLS COORDINATES ARE NOT CONVENTIONAL SPHERICAL.

XE = RA * COS(AA) + AX - EX
YE = RA * SIN(AA) + AY - EY
ZA = TAN(EE) * SQRT(XE**2 + YE**2) + EZ - AZ
XE = SQRT(RA**2 - ZA**2) * COS(AA) + AX - EX
YE = SQRT(RA**2 - ZA**2) * SIN(AA) + AY - EY
ZA = TAN(EE) * SQRT(XE**2 + YE**2) + EZ - AZ
XE = SQRT(RA**2 - ZA**2) * COS(AA) + AX - EX
YE = SQRT(RA**2 - ZA**2) * SIN(AA) + AY - EY
ZT = TAN(EE) * SQRT(XE**2 + YE**2) + EZ - T
XT = XE + EX - TX
YT = YE + EY - TY
RETURN

END

CONVERTS FROM CARTESIAN COORDINATES TO SPHERICAL COORDINATES WITH COMMON REFERENCE (THEODOLITE).

PI = 3.141592654
RT = SQRT(XT**2 + YT**2 + ZT**2)
AT = ATAN(YT/XT)
IF (YT < 0.0) AND (XT < 0.0) AT = AT + PI
IF (YT < 0.0) AND (YT < 0.0) AT = AT + PI
IF (XT < 0.0) AND (XT < 0.0) AT = AT + PI
ET = ATAN(ZT/SQRT(XT**2 + YT**2))
RETURN

END

CONVERTS FROM CARTESIAN COORDINATES TO SPHERICAL COORDINATES WITH COMMON REFERENCE (THEODOLITE).

PI = 3.141592654
RT = SQRT(XT**2 + YT**2 + ZT**2)
AT = ATAN(YT/XT)
IF (YT < 0.0) AND (XT < 0.0) AT = AT + PI
IF (YT < 0.0) AND (YT < 0.0) AT = AT + PI
IF (XT < 0.0) AND (XT < 0.0) AT = AT + PI
ET = ATAN(ZT/SQRT(XT**2 + YT**2))
RETURN

END
CONVERTS FROM THEODOLITE REFERENCED CARTESIAN COORDINATES TO MLS TYPE SPHERICAL COORDINATES.

\[\begin{align*}
XA &= XT - AX + TX \\
YA &= YT - AY + TY \\
ZA &= ZT - AZ + TZ \\
ZE &= ZT - EZ + TZ \\
RA &= \sqrt{(XA)^2 + (YA)^2 + (ZA)^2} \\
AA &= \text{ATAN}(YA / XA) \\
EE &= \text{ATAN}(ZE / \sqrt{(XA + AX - EX)^2 + (YA + AY - EY)^2})
\end{align*}\]

RETURN
END

SUBROUTINE TIME(TT,ITH,ITM,TS)
SIMULATES DIGITAL CLOCK. UPDATES TIME BY INCREMENT TT.

\[\begin{align*}
TS &= TS + TT \\
\text{IF } (TS \text{ LT } 60.) & \text{ GO TO 10} \\
TS &= TS - 60. \\
ITM &= ITM + 1. \\
\text{IF } (ITM \text{ LT } 60.) & \text{ GO TO 10} \\
ITM &= ITM - 60. \\
ITH &= ITH + 1.
\end{align*}\]

10 CONTINUE
RETURN
END
Addendum B. FLTPATH EXEC.
Addendum C. RANGE COORD.
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Addendum E. RUN1 MLSTDATA.
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AZ ANT POSN = (-8000.000, 0.0, 0.0)  
EL ANT POSN = (-1000.000, 400.000, 0.0)  
AIRCRAFT VELOCITY = 135.00 KNOTS

PATTERN A

ENTER GLIDE PATH ANGLE. GPA = 3.000
ENTER RADIAL IN DEGREES. RAD = 0.0

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Addendum F. RUN1 XYZDATA.
R: T=0.01/0.01 13:48:25
FLTPATH RUN1
F1 5 TERMINAL
F1 6 TERMINAL
F1 7 DISK RANGE COORD *
F1 8 DISK RUN1 FPDATA C
F1 9 DISK RUN1 XYDATA C
F1 10 DISK RANGE COORD A ( LRECL 80 BLKSIZE 80 RECFM F )
F1 12 DISK RUN1 MLSTDATA C
LOAD FLTPATH ( START CLEAR NOMAP )
EXECUTION BEGINS...

RANGE COORDINATE SYSTEM

\[ \begin{align*}
(AX,AY,AZ) & : A \\
T & : (TX,TY,TZ) \\
E & : (EX,EY,EZ)
\end{align*} \]

DO YOU WISH TO USE PREVIOUS COORDINATES? (Y/N)
Y
ENTER DESIRED FLIGHT CHECK PATTERN. (A, B, OR D)
A
THEODOLITE POSN = ( -1000.000, 400.000, 0.0 )
AZ ANT POSN = ( -8000.000, 0.0, 0.0 )
EL ANT POSN = ( -1000.000, 400.000, 0.0 )
AIRCRAFT VELOCITY = 135.00 KNOTS
PATTERN A
ARE THE ABOVE PARAMETERS CORRECT? (Y/N)
Y
DO YOU WISH TO UPDATE INPUT CONDITIONS? (Y/N)
N
DO YOU WISH XYZDATA OUTPUT? (Y/N)
Y
ENTER GLIDE PATH ANGLE. GPA = 3.00
ENTER RADIAL IN DEGREES. RAD = 0.00

OUTPUT STORED ON C-DISK AS RUN1 FPDATA C, RUN1 XYDATA C AND RUN1 MLSTDA
R: T=2.29/2.72 13:50:51

Addendum G. RUN1 CONSOLE.
Appendix D. Program listing for MLSDATA FORTRAN, which modifies simulated MLS data output by FLTPATH to simulate the time-multiplexed nature of actual MLS data.
SAMPLES INPUT FILE WITH RESPECT TO TIME TO SIMULATE
TIME MULTIPLEXED MLS DATA.

INPUT ON FI 12
OUTPUT ON FI 13

INPUT IS IN SAME FORMAT AS USED FOR GTP THEODOLITE DATA.

LAST REVISION FEBRUARY 2, 1983

10 READ(12,540,END=999)TMLSEL,MLSAZ,MLSEL,MLSRAN
TMLSAZ = TMLSEL
TMLSRN = TMLSEL
WRITE(13,550)TMLSAZ,MLSAZ,TMLSEL,MLSEL,TMLSRN,MLSRAN
20 READ(12,540,END=999)TMLSEL,DUMMY1,MLSEL,DUMMY2
WRITE(13,550)TMLSAZ,MLSAZ,TMLSEL,MLSEL,TMLSRN,MLSRAN
30 READ(12,540,END=999)TMLSEL,DUMMY1,MLSEL,MLSRAN
TMLSRN = TMLSEL
WRITE(13,550)TMLSAZ,MLSAZ,TMLSEL,MLSEL,TMLSRN,MLSRAN
40 READ(12,540,END=999)TMLSEL,MLSAZ,MLSEL,DUMMY2
TMLSAZ = TMLSEL
WRITE(13,550)TMLSAZ,MLSAZ,TMLSEL,MLSEL,TMLSRN,MLSRAN
50 READ(12,540,END=999)TMLSEL,DUMMY1,MLSEL,MLSRAN
TMLSRN = TMLSEL
WRITE(13,550)TMLSAZ,MLSAZ,TMLSEL,MLSEL,TMLSRN,MLSRAN
60 READ(12,540,END=999)TMLSEL,DUMMY1,MLSEL,DUMMY2
WRITE(13,550)TMLSAZ,MLSAZ,TMLSEL,MLSEL,TMLSRN,MLSRAN
GO TO 10
540 FORMAT('000000',16,15,15,15,'00001')
550 FORMAT('000000',16,15,'000000',16,15,'000000',16,15)
999 STOP
END