NASA CR 178032

Performance of a Commercial Transport Under Typical MLS Noise Environment

Final Report

John K. Ho
Boeing Commercial Airplane Company
Seattle, Washington

Prepared Under Contract NAS1-17635
February 1986

NASA
National Aeronautics and
Space Administration

TABLE OF CONTENTS

		Page
LIST OF FIGURES		ii
LIST OF TABLES		iii
1.0	SUMMARY	1
2.0	INTRODUCTION	2
3.0	SYMBOLS AND ABBREVIATIONS	3
4.0	RESULTS FROM EARLIER STUDY	4
5.0	AIRPLANE SIMULATION	5
5.1	Nonlinear Simulation	5
5.1.1	Airplane Model and Configuration	5
5.1.2	Automatic Flight Control Laws	6
5.1.3	MLS Error Model	6
5.1.4	MLS Simulation Results	7
5.1.5	ILS Simulation Results	7
5.1.6	Acceptability Criteria	8
5.1.7	Analysis of Results	8
5.2	Linear Covariance Analysis	9
5.2.1	Linearized Control Laws	9
5.2.2	Results of Linear Covariance Analysis	9
6.0	CONCLUSIONS	10
7.0	RECOMMENDATIONS	11
REFERENCES		12

LIST OF FIGURES

		Page
1	MLS Curved Path Segmented Approach	13
2	MLS Transmitter Antenna Arrangement and Axis System	14
3	Longitudinal Autopilot (Altitude Hold and Glide Slope Control Modes)	15
4	Lateral Autopilot (Altitude Hold and Glide Slope Control Modes)	16
5	Typical MLS Noise Outputs	17
6	X Trajectory (Run No. 3, Straight-In Approach)	18
7	Y Trajectory (Run No. 3, Straight-In Approach)	18
8	Altitude (Run No. 3, Straight-In Approach)	19
9	Pitch Angle (Run No. 3, Straight-In Approach)	19
10	Angle of Attack (Run No. 3, Straight-In Approach)	20
11	Roll Angle (Run No. 3, Straight-In Approach)	20
12	Heading Angle (Run No. 3, Straight-In Approach)	21
13	Vertical Speed (Run No. 3, Straight-In Approach)	21
14	Calibrated Airspeed (Run No. 3, Straight-In Approach)	22
15	Ground Speed (Run No. 3, Straight-In Approach)	22
16	Normal Acceleration (Run No. 3, Straight-In Approach)	23
17	Lateral Acceleration (Run No. 3, Straight-In Approach)	23
18	Contaminated Glide Slope Error (Run No. 3, Straight-In Approach)	24
19	Contaminated Localizer Angle (Run No. 3, Straight-In Approach)	24
20	Elevator Activity (Run No. 3, Straight-In Approach)	25
21	Aileron Deflection (Run No. 3, Straight-In Approach)	25
22	Upper Rudder Deflection (Run No. 3, Straight-In Approach)	26
23	Lower Rudder Deflection (Run No. 3, Straight-In Approach)	26
24	Roll Rate (Run No. 3, Straight-In Approach)	27
25	Pitch Rate (Run No. 3, Straight-In Approach)	27
26	Yaw Rate (Run No. 3, Straight-In Approach)	28
27	Beam Angle Error (Run No. 3, Straight-In Approach)	28
28	MLS Azimuth Signal (Run No. 3, Straight-In Approach)	29
29	MLS Elevation Signal (Run No. 3, Straight-In Approach)	29
30	DME Signal (Run No. 3, Straight-In Approach)	30
31	Linearized Longitudinal Autopilot (Altitude Hold and Glide Slope Control Modes)	31

LIST OF TABLES

		Page
1	Speed and Flap Setting at Different Distance From Threshold	32
2	Configuration and Initial Condition for MLS Simulations	33
3	LaRC Recommended MLS Parameter Values	34
4	Simulation Output Variables	35
5	Results of Run No. 1 (Perpendicular to Extended Runway Centerline Approach)	35
6	Results of Run No. 2 (Perpendicular to Extended Runway Centerline Approach)	36
7	Results of Run No. 3 (ILS Type Straight-In Approach)	37
8	Results of Run No. 4 (ILS Type Straight-In Approach)	38
9	Results of Run No. 5 (ILS Type Straight-In Approach)	39
10	Results of Run No. 6 (Offset Straight-In Approach)	40
11	Results of Run No. 7 (Offset Straight-In Approach)	41
12	Results of Run No. 8 (Slant Approach)	42
13	Results of Run No. 9 (Slant Approach)	43
14	Results of Run No. 10 (Glide Slope Control With MLS Noise)	44
15	Results of Run No. 11 (Glide Slope Control With ILS Noise)	46
16	Comparison Between Linear Covariance Analysis and Nonlinear Simulation (Altitude Hold)	48
17	Comparison Between Linear Covariance Analysis and Nonlinear Simulation (MLS Glide Slope)	49
18	Comparison Between Linear Covariance Analysis and Nonlinear Simulation (ILS Glide Slope)	49

1.0 SUMMARY

The purpose of this report is to evaluate the performance of a 747-200 automatic flight control system (AFCS) subjected to typical Microwave Landing System (MLS) noise. The results are compared with those in an earlier study which had the AFCS subjected to International Civil Aviation Organization (ICAO) MLS standards and recommended practices (SARPS) maximum allowable guidance error. It was found that the operable range of altitude and distance from threshold a 747 could fly under the typical MLS noise is two to three times better than with the maximum SARPS allowable noise.

In this report, the AFCS was slightly modified to allow other types of landing approaches besides Instrument Landing System (ILS) type straight-in approach. Results showed that under the altitude hold mode, acceptable longitudinal guidance under typical MLS noise was found from threshold to 77,000 ft (13 nmi) out and up to 110,000 ft (18 nmi) out for lateral guidance. For the glide slope control mode, acceptable longitudinal guidance was found at an altitude of 1,300 ft or below, and good lateral performance was found at an altitude of 4,000 ft or below. However, when the control surface activity requirement is relaxed from 1-deg rms to 2-deg rms, the airplane performed satisfactorily throughout the whole MLS coverage zone (20 nmi from threshold).

A case with typical ILS noise was also carried out and was found to have control surface activities three to four times higher than with typical MLS noise. Finally a linear covariance analysis on the longitudinal guidance is presented to compare with the nonlinear simulation.

2.0 INTRODUCTION

The purpose of this task is to evaluate the performance of a 747-200 automatic flight control system (AFCS) subjected to typical MLS noise. In 1981, a NASA contract (NAS1-16300 Task Requirement B-8) was conducted by the Boeing Flight Control Research Group. It was found that when a B747 airplane was subjected to the International Civil Aviation Organization (ICAO) MLS standards and recommended practices (SARPS) maximum allowable guidance errors, the performance was unacceptable. These ICAO SARPS guidance errors caused unacceptable deviations from 18,000 ft and beyond for longitudinal performance, and 27,000 ft and beyond for lateral performance (ref. 1). Since then, research and operational test results showed that typical MLS equipment has a noise level relatively lower than the SARPS maximum allowable noise. Therefore, the purpose of this task is to repeat some of the runs that were done in 1981, with the airplane subjected to typical MLS noise, and determine the improvement in performance of the airplane. In order to review the whole MLS coverage zone, besides the ILS type straight-in approach, some curved path segmented approach cases were examined. A comparison between the MLS and ILS performances is also included in this report. Furthermore, a linear covariance analysis on the longitudinal guidance is presented to show a cost efficient way of doing the analysis.

3.0 SYMBOLS AND ABBREVIATIONS

a	Filter Parameter
AFCS	Automatic Flight Control System
Alt Hold	Altitude Hold
AYACEL	Lateral Acceleration
AZACEL	Normal Acceleration
DME	Distance Measuring Equipment
GSE2	Contaminated Glide Slope Error
G/S	Glide Slope
H	Vertical Speed
HIC	Holding Altitude
H_R	Radio Altitude
ICAO	International Civil Aviation Organization
ILS	Instrument Landing System
LaRC	Langley Research Center
Local2	Contaminated Localizer Angle
MLS	Microwave Landing System
p	Roll Rate
q	Pitch Rate
r	Yaw Rate
rms	Root Mean Square
SARPS	Standards and Recommended Practices
VCAS	Calibrated Airspeed
X,Y,H	Rectangular Coordinates With Origin at Threshold of Runway
X_η	nth Sample From a White, Gaussian, Random Sequence
Y_η	nth Sample of MLS Noise
α	Angle of Attack
ϕ	Bank Angle
ϕ	Roll Rate
τ	Correlation Time for Filter
θ	Pitch Angle
σ_x	Standard Deviation of X_η
σ_y	Standard Deviation of Y_η
ψ	Heading Angle
ψ_{GT}	Ground Track Angle

4.0 RESULTS FROM EARLIER STUDY

An evaluation of the performance of a 747 automatic flight control system under the maximum allowable MLS guidance errors was conducted by the Boeing Flight Control Research Group in 1981. These MLS guidance errors used the maximum errors that are allowed by the ICAO MLS SARPS. Out of the three cases conducted in 1981, two of them were ILS type straight-in approaches, and the third case was a curved path segmented approach. For the two ILS type straight-in approach cases, the altitude hold mode used the barometric H as the input signal. The MLS SARPS noises were included in the guidance signals only when the airplane was on the glide slope control mode. Hence, only the glide slope portion was used in the analysis. Results showed that for distances beyond 18,000 ft from threshold, the guidance errors caused unacceptable altitude deviation, as well as pitch angle and elevator perturbations. Also, from 27,000 ft and beyond, the roll angle and aileron deflection were found to be unsatisfactory.

For the curved path segmented approach case, the initial crosstrack position was 50,000 ft from the extended runway centerline with the interception point 100,000 ft from the threshold. The airplane then flew perpendicular to the extended runway centerline and executed a 90-deg turn to capture the extended runway centerline. The altitude signal was generated by the MLS elevation and DME. However, the control law used in the report was not suitable for curved path operation, hence only the portion of the perpendicular approach was analyzed. It was found at this distance out, both longitudinal and lateral guidance caused unacceptable control surface activity as well as altitude and attitude deviations.

5.0 AIRPLANE SIMULATION

This section evaluates the performance of a 747-200 automatic flight control system (AFCS) subjected to typical MLS guidance errors. Different landing approach paths were simulated within the MLS coverage zone, each with the MLS guidance errors used as the input to the AFCS. The response of the airplane was then analyzed to determine if the performance was acceptable for each of the approach paths based on the following requirements: passenger comfort, path tracking accuracy, and control surfaces activity.

Four different types of landing approach paths were used in the simulation. The first type was a perpendicular to extended runway centerline approach, in which the airplane flew perpendicular to the extended runway centerline and then executed a 90-deg turn to capture the extended runway centerline. The second type was an equivalent ILS type approach path, in which the airplane flew straight-in towards the runway. The third type was an offset straight-in approach, in which the airplane flew parallel to the extended runway centerline and then maneuvered to capture the centerline. The fourth type was a slant approach which intercepted the extended runway centerline at an angle. Figure 1 shows the four types of landing approaches. A total of 11 runs were simulated.

The rest of the section describes the airplane model, its automatic flight control laws, and the MLS error model used in this simulation. It also includes both ILS and MLS glide slope control simulation results, the acceptability criteria, and the analysis of the results.

5.1 NONLINEAR SIMULATION

The Boeing Flight Simulation Laboratory, with its multiprocessor Harris computer system, was used for this MLS/airplane simulation. The simulation program includes the nonlinear characteristics of the airplane.

5.1.1 Airplane Model and Configuration

As the 747-200 airplane is the most common type of 747 flying today, the 747-200 AFCS was used as the basis of the simulation. A medium weight of 560,000 lb was chosen. Different speeds, ranging from 148 kn to 238 kn, along with different flap settings were used depending on the approach position. Since there is no general guideline in how a pilot should fly within the MLS coverage zone, Table 1 was used as a baseline to determine the speeds and configurations for the different simulation runs. Table 2 shows the initial conditions for each run. Some of the starting positions were intentionally displaced by a small amount from the selected course in order to eliminate initial transients due to the bias on the MLS noise.

The MLS ground transmitter antenna arrangement and the definition of the axis system used in this report can be found in Figure 2. During simulation, no antenna switching on the airplane is performed. The antenna for both the MLS angular data and DME is assumed to be colocated with the ILS glide slope antenna at the nose section.

5.1.2 Automatic Flight Control Laws

For the longitudinal guidance, two modes were simulated: altitude hold and glide slope control.

The altitude hold mode used an MLS derived altitude signal as the input to the control system. This MLS derived altitude input was calculated by the distance measuring equipment (DME) signal and the two MLS angular data (i.e., the elevation and the azimuth angles) all with noises according to Table 3. For the glide slope control mode, the contaminated glide slope angle error was used for the longitudinal guidance.

For the lateral guidance, the contaminated track angle error was used as an input to the control system. The reference point of this track angle error for ILS type straight-in approach was the threshold of the runway, and the contaminated localizer angle was used as the track angle error. For other types of landing approach simulated in this study, the reference point was the point of turn of the approach paths. Hence by converting the position of the airplane calculated by the contaminated MLS signals from the reference point to the selected course into an equivalent localizer angle error, it was used as an input to the lateral control law.

The longitudinal autopilot chosen for this study was the Sperry 247 computer with the Sperry 308 computer selected as the lateral autopilot. These two computers are commonly used on the 747-200 airplanes that are flying today with a fail passive system. Detailed information about the autopilots can be found in Reference 2. The altitude hold and glide slope portions of the control laws can be found in Figures 3 and 4.

For landing, these autopilots are designed for ILS type straight-in landing approach only. Under this MLS study, the control laws were modified slightly to allow the other types of landing approaches in order to investigate the MLS characteristic throughout the whole MLS coverage zone. Therefore, the results from the perpendicular to extended runway centerline, offset straight-in, and the slant approaches may not be the optimal performances of the airplane.

5.1.3 MLS Error Model

Many factors contribute to the lateral and longitudinal dispersion of the airplane from its selected course. These factors include wind gusts, sensor noises, and MLS signal error. In this report, the only error being considered is the MLS signal error which is the difference between the MLS receiver position outputs and the actual position of the MLS equipped airplane in space. This error is due to the inherent noise of the transmitter and receiver, equipment misalignment, and signal strength variations. NASA Langley Research Center (LaRC) has provided a MLS error model which is based on some flight test results of the Bendix MLS facility at Wallops Flight Center. This error model generates MLS noise errors by passing a white, Gaussian, random sequence through a low-pass, digital filter as described by the following equation:

$$Y_\eta = (1\text{-}a)\, Y_{\eta\text{-}1} + aX_\eta$$

where Y_η = nth sample of MLS noise

X_η = nth sample from a Gaussian random number generator with standard deviation σ_χ and zero mean.

a = filter parameter chosen to adjust the correlation time

$$= 1 - \exp\left(\frac{-\Delta T}{\tau}\right)$$

where ΔT = sample rate
τ = correlation time

The variance of Y_η is then:

$$(\sigma_y)^2 = \frac{a}{2-a} (\sigma_x)^2$$

where σ_y = standard deviation of Y_η
σ_χ = standard deviation of X_η

Table 3 shows the recommended parameter values for the LaRC MLS noise model. For the simulation runs done at the Boeing Flight Simulation Laboratory, a sample rate of 50 ms was used. Typical noise models, generated by different white, Gaussian, random sequences, scaled according to Table 3, are shown in Figure 5.

5.1.4 MLS Simulation Results

Four types of landing approaches, a total of 10 MLS runs, were simulated on the Harris computer with the AFCS subjected to typical MLS noise. Table 2 shows the initial positions, configurations, types of landing approach, and other information of each run. The time history of 28 variables were recorded and plotted for each run. Table 4 lists the 28 variables. Figures 6 through 30 show the typical responses of the 747-200 due to the MLS noise.

To interpret the simulation data, the mean and standard deviation were calculated for every thousand samples to compare with the acceptability criteria. However, the first several hundred samples of each run are left out in the analysis to enable initial transients to be ignored.

Statistics of the output variables for each of the 10 MLS runs are shown in Tables 5 through 14. Each column in the table gives the statistics of the variables for a thousand data points or 50 sec of simulation time. Some cases were run for a longer period of time than others.

5.1.5 ILS Simulation Results

The Instrument Landing System (ILS) has been used for landing guidance for the last 40 years. Over the years, it has undergone a number of improvements to increase its performance and reliability. However, due to increasing activity in the terminal area and the restricted operation possible with ILS, the International Civil Aviation Organization has decided to replace the ILS with the MLS within the next decade. Therefore, it is useful to compare the performances of the two systems.

The ILS noise model is generated by passing a white, Gaussian sequence through a low-pass, digital filter with a 0.5-sec correlation time, and then scaled with a standard deviation of 0.0443 deg and 0.0633 deg for localizer and glide slope error respectively. No bias is included in either of the noise models. The simulation results can be found in Table 15. These results, when compared with the MLS results in Table 14, show three or four times higher in magnitude.

5.1.6 Acceptability Criteria

The acceptability criteria are considered from three different aspects: path tracking accuracy, passenger comfort, and control surface activity. With the output variables roughly categorized into positions, airplane attitude angles, lateral and normal accelerations, vertical and longitudinal speeds, control surfaces activity, MLS noises, and receiver signals; all aspects of the acceptability requirements could be addressed.

In order to be consistent with the work done earlier (ref. 1), similar acceptability criteria are being used in this report. Throughout the MLS coverage zone, the MLS guidance errors have to satisfy the following requirements:

1. With regard to path tracking accuracy
   a. Altitude variation shall not exceed 25-ft rms
   b. Vertical guidance error shall not induce speed variation greater than 2-kn rms
   c. On the glide slope, at 700-ft altitude, the airplane shall not deviate from the glide path 12 ft or more
   d. The lateral tracking error is allowed to degrade with distance, at 300-ft altitude, the lateral tracking error allowed is 40 ft, and at 1300 ft altitude, the allowable error is 98 ft

2. With regard to passenger comfort
   a. Normal and lateral accelerations shall not exceed 0.05-g_n rms (1.61-ft/sec^2 rms)
   b. Sink rate variation shall not be greater than 20% of nominal rate
   c. Airplane attitude variation shall not be greater than 1-deg rms

3. With regard to control surface activity, the deflections shall not exceed 1-deg rms

5.1.7 Analysis of Results

The results which are presented in Sections 5.1.4 and 5.1.5 were compared with the acceptability criteria given in the previous section. Of all the nine altitude hold runs, Run No. 2, which is a perpendicular to extended runway centerline approach, has a 2.128-kn rms of speed variation at about 89,000 ft (15 nmi) out and a 1.636-ft/sec rms variation in normal acceleration at about 80,000 ft (13 nmi) out. Run No. 6, which is an offset straight-in approach, has a 1.095-deg rms variation in the bank angle at about 113,000 ft (19 nmi) from the threshold. These dispersions could be due to the fact that the autopilots were not designed for landing approaches other than ILS type straight-in approach. Nevertheless, they could still be considered to be marginally acceptable. The rest of the altitude hold runs show all variables have standard deviation well within the acceptable region.

On the glide slope control run (Run No. 10), the elevator has activities greater than the 1-deg rms requirement from altitude 1,300 ft and up, this variation ranges from 1.001-deg rms to 1.312-deg rms. All other variables are well within the requirements.

Run No. 11, which is a glide slope control run with typical ILS noise, when compared with Run No. 10 which is with MLS noise, was found to have variations in its variables three to four times higher than the MLS run.

5.2 LINEAR COVARIANCE ANALYSIS

The objective of the linear covariance analysis is to demonstrate a cost efficient way of determining the covariance response of the airplane due to MLS/ILS noise. MPAC, which is a program for analysis and synthesis of linear time-invariant control system, was used for this purpose. The program calculates the steady state covariance coefficient matrix of the variables in the system. These coefficients include the standard deviations of the variables and hence could be used to compare with the results from the nonlinear simulation.

5.2.1 Linearized Control Laws

Some of the gains in the AFCS are functions of position and speed of the airplane. In order to linearize the control laws, these gains are assigned with some constant values depending on the mean position and nominal speed being simulated.

Figure 30 is a linearized version of the longitudinal autopilot. In it, F1CAS and F3CAS are functions of speed. With a nominal speed of 148 kn, F1CAS and F3CAS are 1 and 0.704 respectively. GKV1 is a function of radio altitude. For the glide slope control run, GKV1 is 0.58 at 650-ft altitude. GR1 and GR2 are functions of the distance from the threshold. At 45,000 ft from the threshold, GR1 and GR2 are 0.0012 and 803.0 respectively. For the glide slope run, GR1 is 0.0046 at 650-ft altitude.

For altitude hold mode, GR1 and GR2 are reciprocals of each other. They will cancel each other in the H loop, leaving the GR2 gain directly affecting the input magnitude of the elevation noise. Since GR2 is a linear function of distance, this implies the result of one run could be scaled proportionally for other runs at different distances from the threshold.

For the glide slope control mode, the gains that are functions of distance are the GR1 and GKV1 gains. Notice that both of the gains are inside the H loop, also the aerodynamics data varies with altitude. Hence, the linear generalization that was applied to the altitude hold mode cannot be applied here.

The MLS derived altitude used in the linear covariance analysis was calculated by the noisy elevation angle together with the distance from the transmitter. The azimuth and DME noise were not included in the calculation as they are in the nonlinear simulation. This is considered acceptable because the contaminated elevation angle is the major contribution to the longitudinal guidance error.

5.2.2 Results From Linear Covariance Analysis

Three runs were analyzed with MPAC. One was the low-speed ILS type straight-in altitude hold mode at 45,000 ft from the threshold of the runway and using MLS elevation noise. The other two runs were both glide slope control mode at altitude 650 ft; one using MLS noise, and one with ILS noise. These results are then compared with the Harris nonlinear simulation Runs 5, 10, and 11 respectively. The comparison can be found in Tables 16 thru 18.

The differences between the results of the two analyses are all within 25%, except that the difference in the elevator activity is as high as 37%. This could be due to the use of a very simplified model of the actuator servo system of the elevator in the linear covariance analysis. Nevertheless, the results from the linear covariance analysis should give a good indication of the airplane performance under the influence of MLS/ILS noise. Also, a cost saving of roughly 50% could be achieved by using the linear covariance analysis to calculate the performance.

6.0 CONCLUSIONS

The simulation runs under NAS1-16300 Task B-8 have been repeated under this study using the typical MLS noise level together with the error model described in Paragraph 4.1.3. With the existing AFCS slightly modified, other approach runs which cover the whole MLS coverage zone have also been carried out. A glide slope run with typical ILS noise level is included for comparison purpose. It is concluded that:

1. The operable range of altitude and distance from threshold which the airplane could fly under typical MLS noise was two to three times better than with maximum SARPS allowable noise.

2. For altitude hold mode, with a slightly modified AFCS,
   a. Acceptable longitudinal guidance was found from threshold to 77,000 ft out (13 nmi). The criteria setting this limit is the MLS noise-induced variations in speed and normal acceleration.
   b. Acceptable lateral guidance was found from threshold to 110,000 ft out (18 nmi). The criteria setting this limit is the MLS noise-induced deviation in bank angle.

3. For glide slope mode,
   a. Acceptable longitudinal guidance was found below 1,300 ft. The criteria setting this limit is the MLS noise-induced elevator perturbation.
   b. Acceptable lateral guidance was found below 4,000 ft. The criteria setting this limit is that 4,000 ft was the maximum height being simulated in this study.

4. The ILS noise causes control surface activities three to four times higher than the MLS noise would.

7.0 RECOMMENDATIONS

The preceding sections clearly show the performance of a 747-200, with its modified AFCS, under the given MLS noise model, cannot satisfy the acceptability criteria throughout the whole MLS coverage zone. It is therefore recommended that:

1. Once a curved path approach control law is designed, the simulation should be carried out once again to examine the improvement in both longitudinal and lateral performance for these different types of curved path approach.

2. By relaxing the control surface activity requirement from 1- to 2-deg rms, the airplane could perform satisfactorily throughout the whole MLS coverage zone which is 20 nmi from the threshold.

3. When more data on the MLS noise are collected, the simulation should be carried out again using the new error model.

4. This nonlinear simulation should be carried out on other airplanes so as to get a better understanding of the MLS characteristics on a variety of airplanes.

5. For cost saving purpose, linear covariance analysis could be used as a good approximation of the airplane performance due to MLS noise.

6. The possibilities of developing guidance noise filters to make automatic flight control system more noise tolerant be investigated.

REFERENCES

1. "MLS/Airplane System Design—RF Component Design and MLS/Flight Control System Error Evaluation" Boeing Report D6-51280, December 14, 1981.

2. "Description of RFSC Simulation Software for 747 Autopilots" Boeing Report BCS-G1751, November 3, 1983.

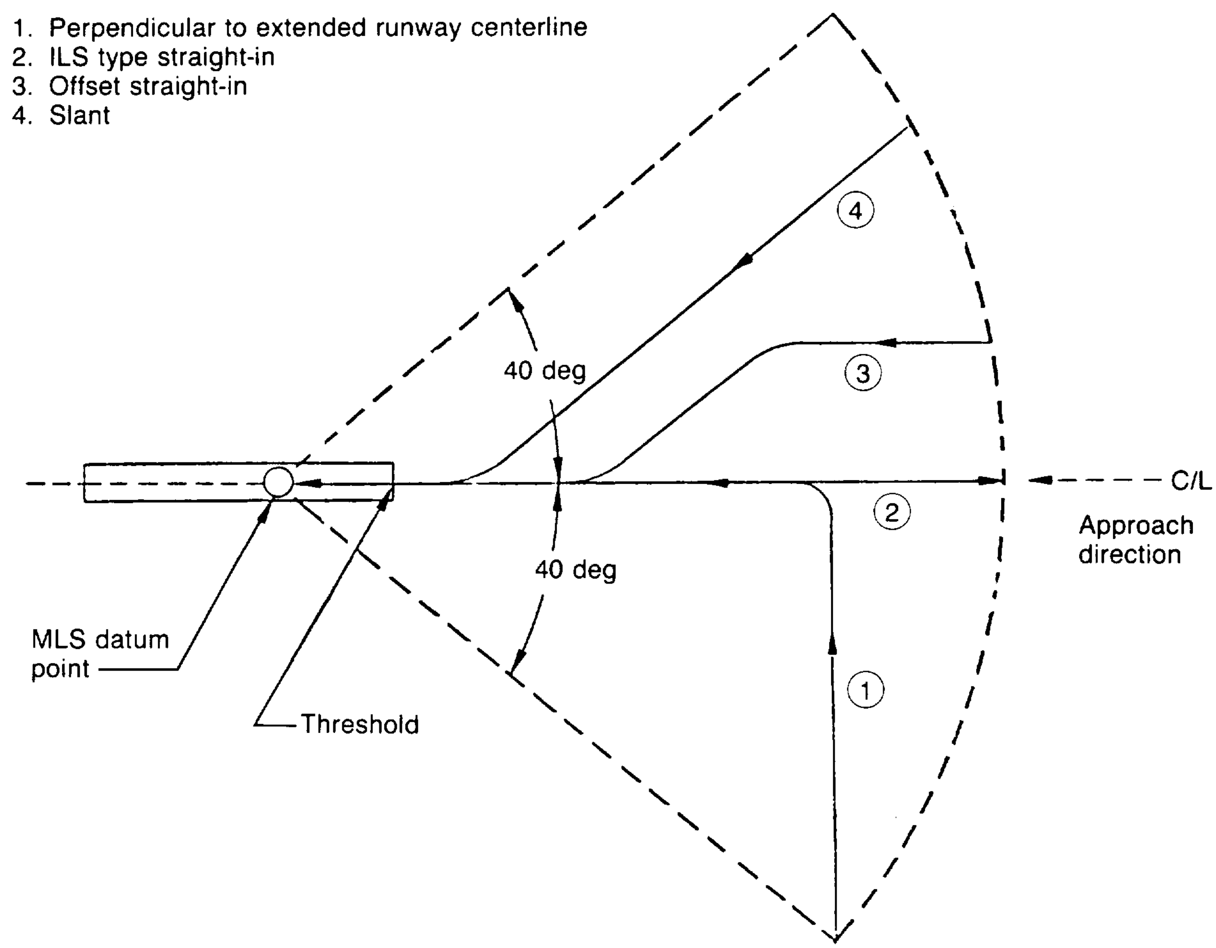


Figure 1. MLS Curved Path Segmented Approach

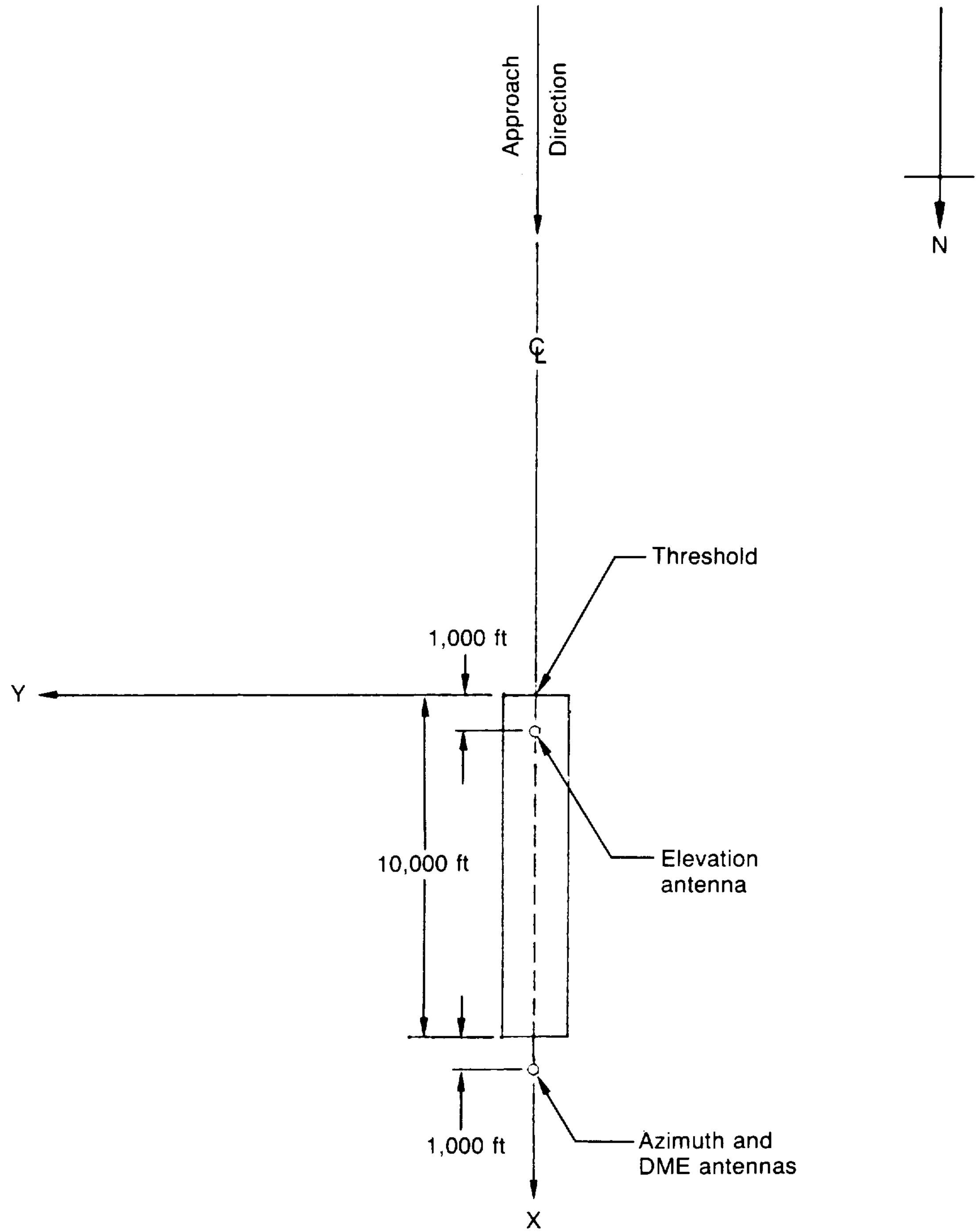


Figure 2. MLS Transmitter Antenna Arrangement and Axis System

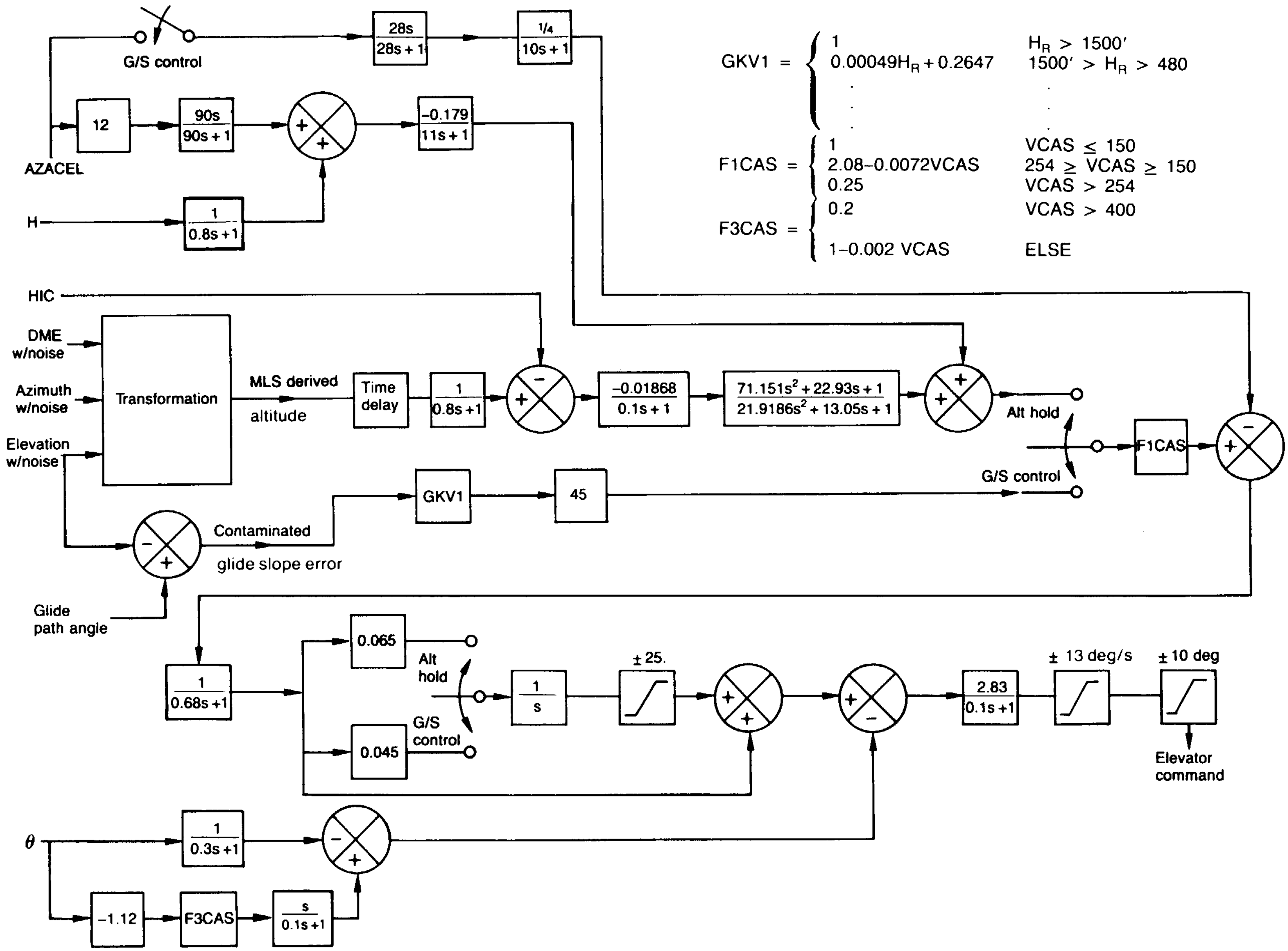


Figure 3. Longitudinal Autopilot (Altitude Hold and Glide Slope Control Modes)

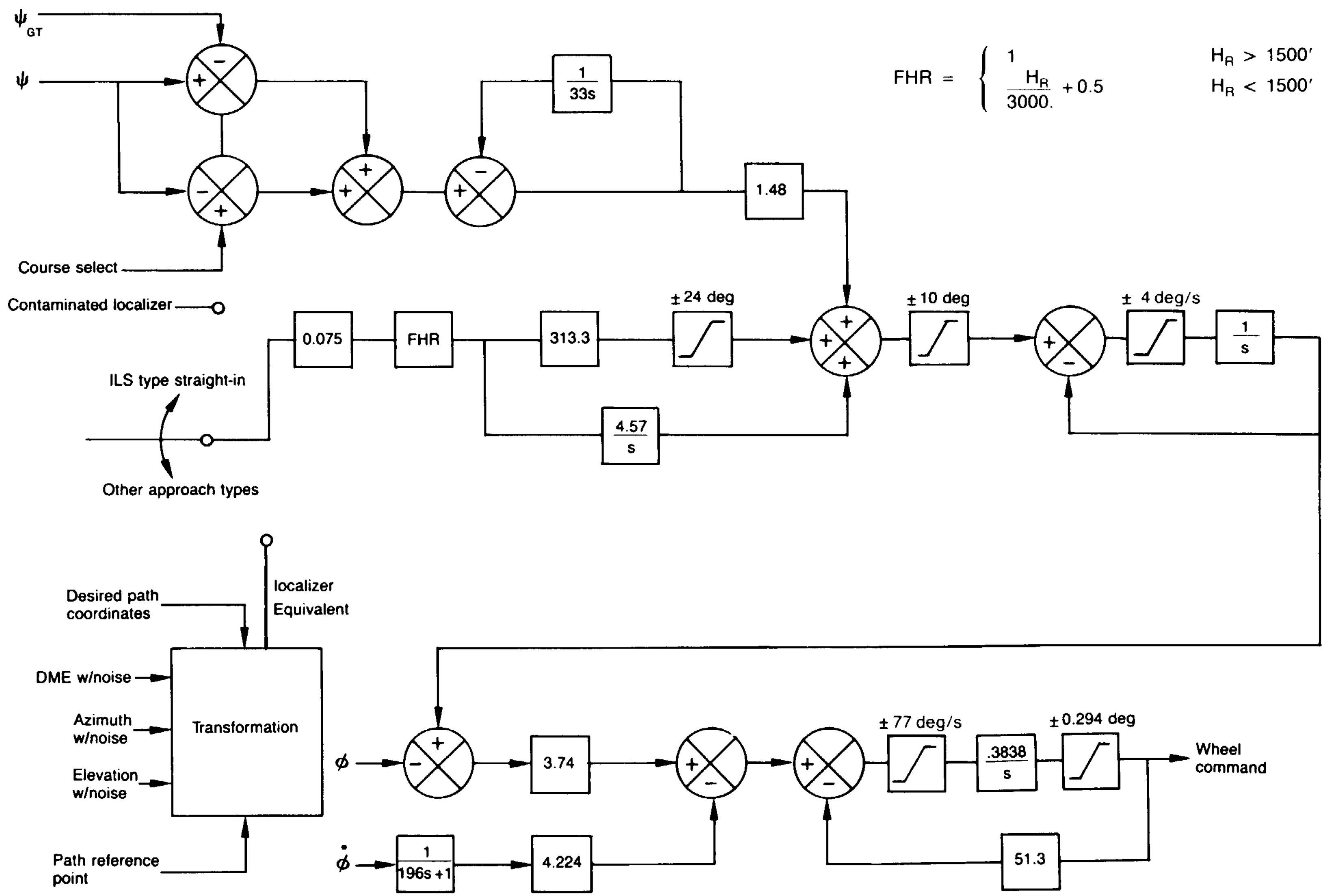


Figure 4. Lateral Autopilot (Altitude Hold and Glide Slope Control Modes)

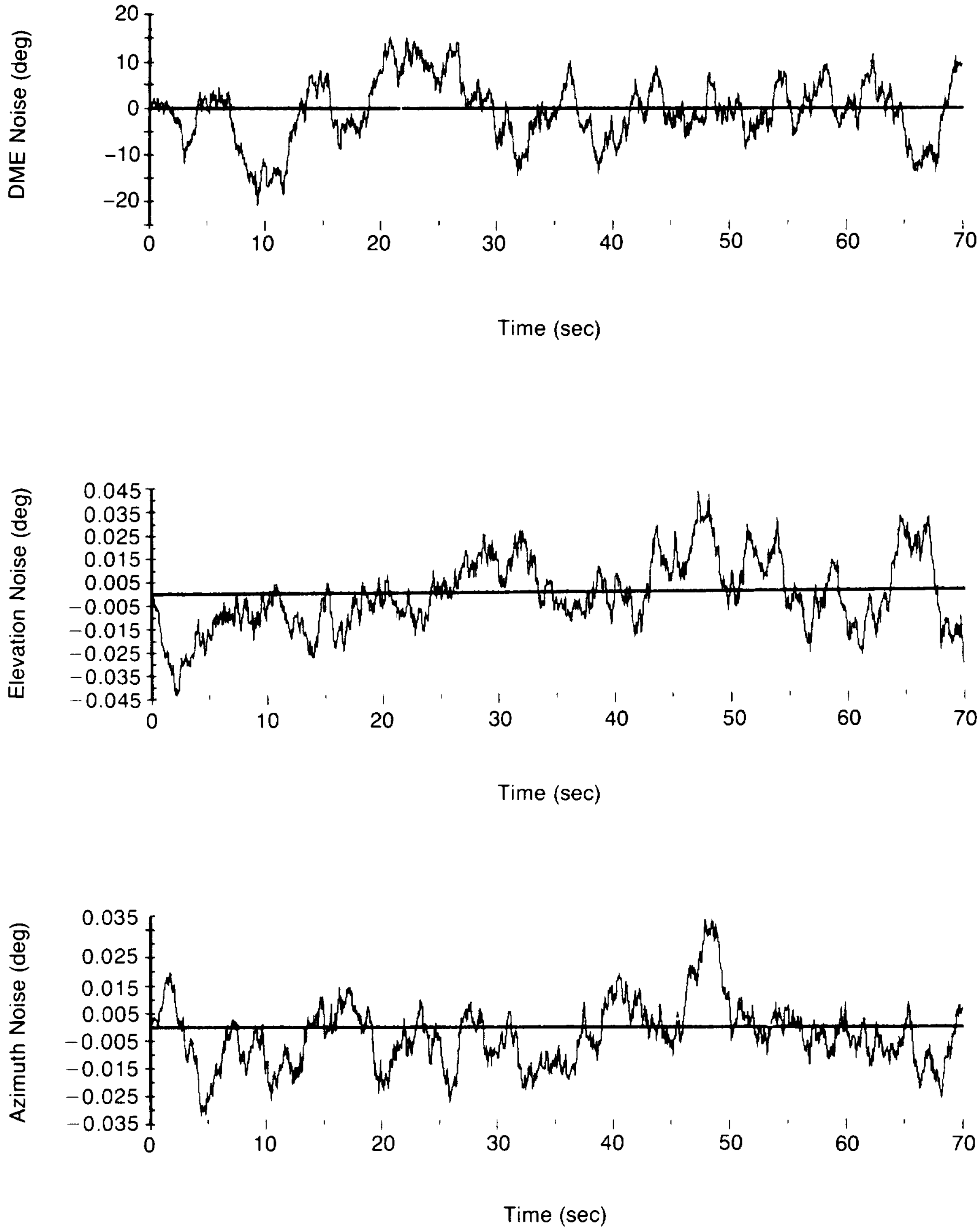


Figure 5. Typical MLS Noise Outputs

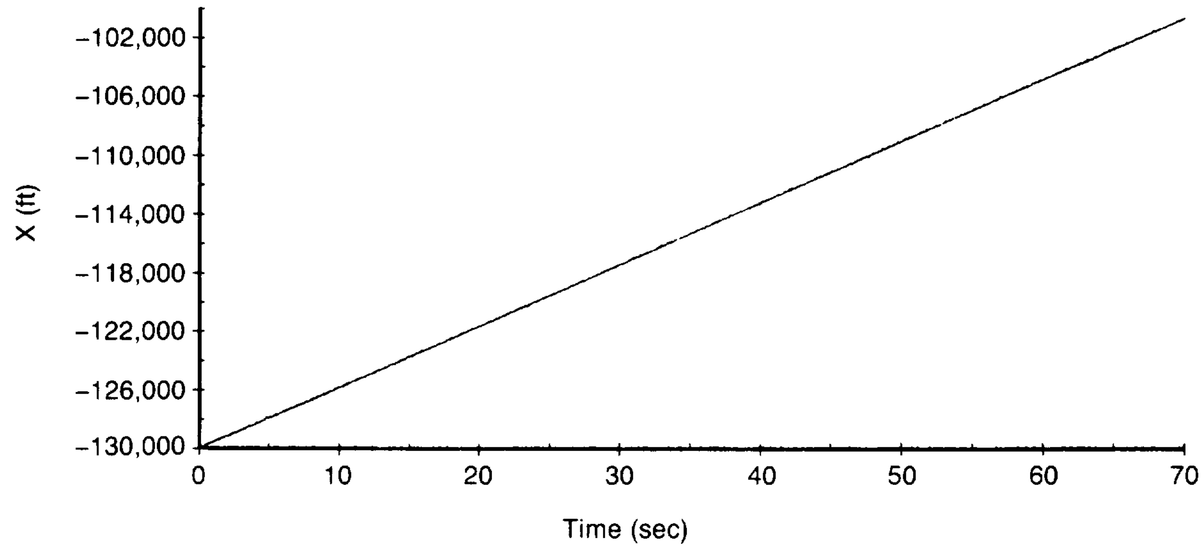


Figure 6. X Trajectory (Run No. 3, Straight-In Approach)

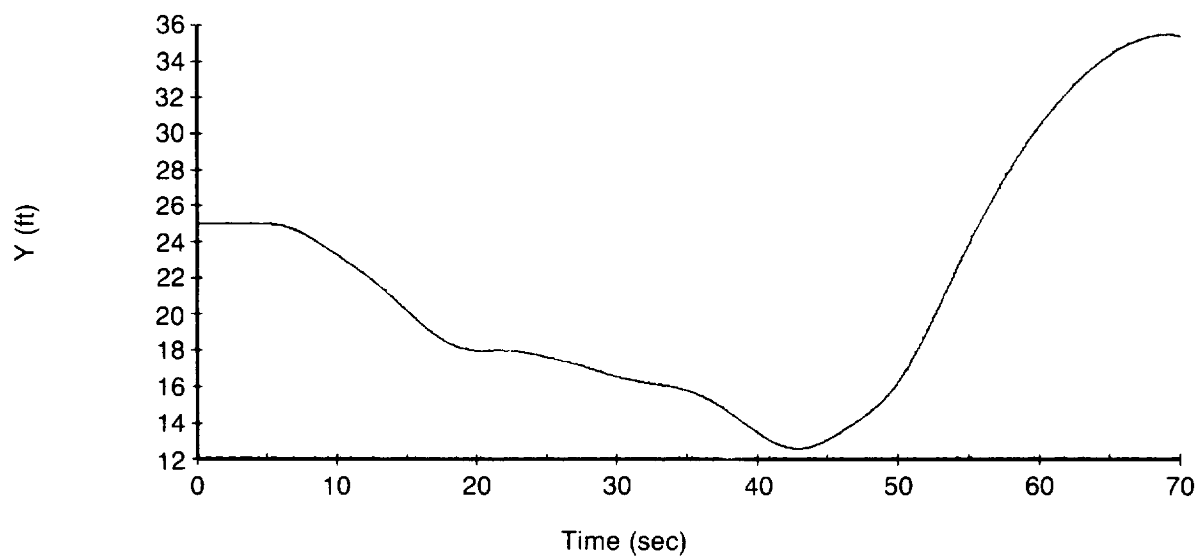


Figure 7. Y Trajectory (Run No. 3, Straight-In Approach)

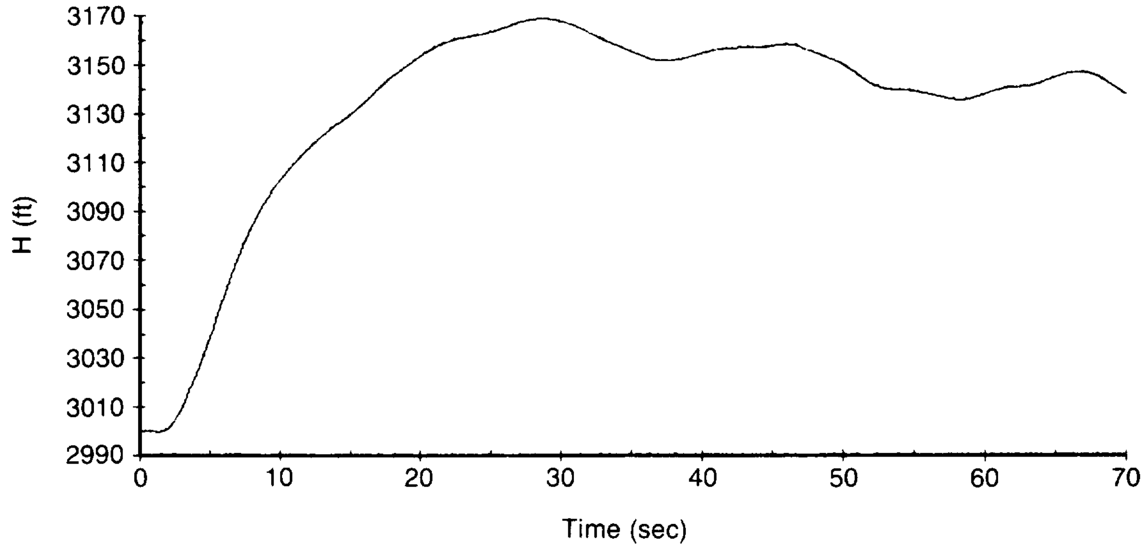


Figure 8. Altitude (Run No. 3, Straight-In Approach)

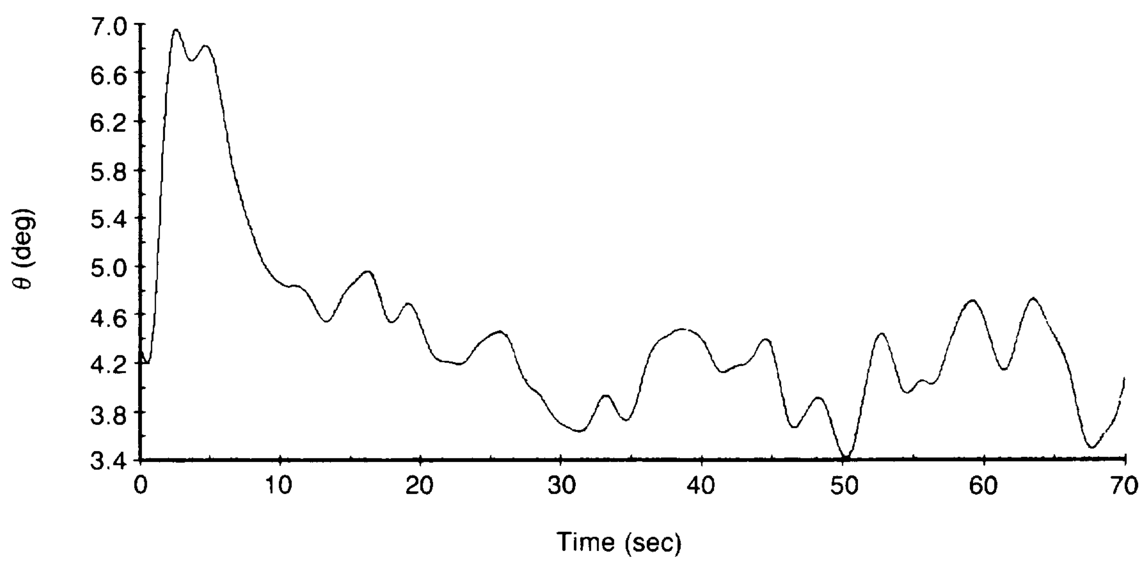


Figure 9. Pitch Angle (Run No. 3, Straight-In Approach)

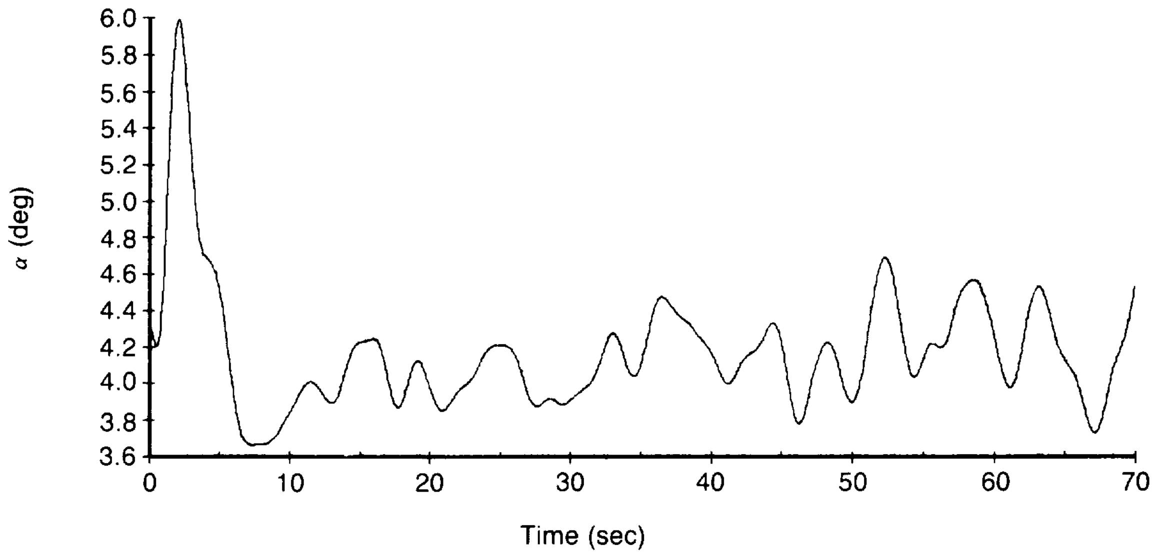


Figure 10. Angle of Attack (Run No. 3, Straight-In Approach)

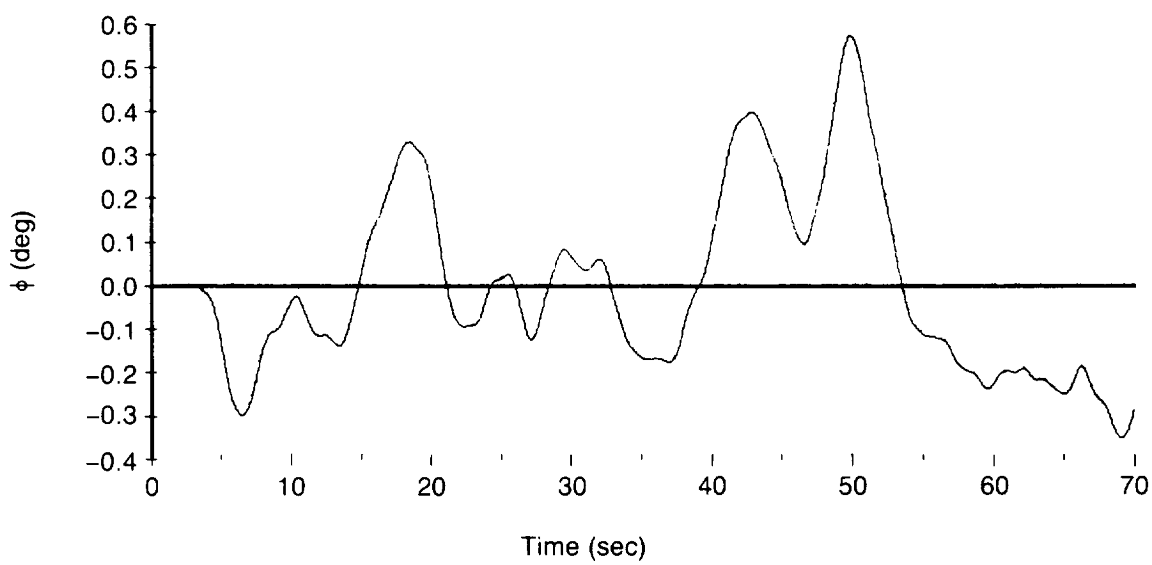


Figure 11. Roll Angle (Run No. 3, Straight-In Approach)

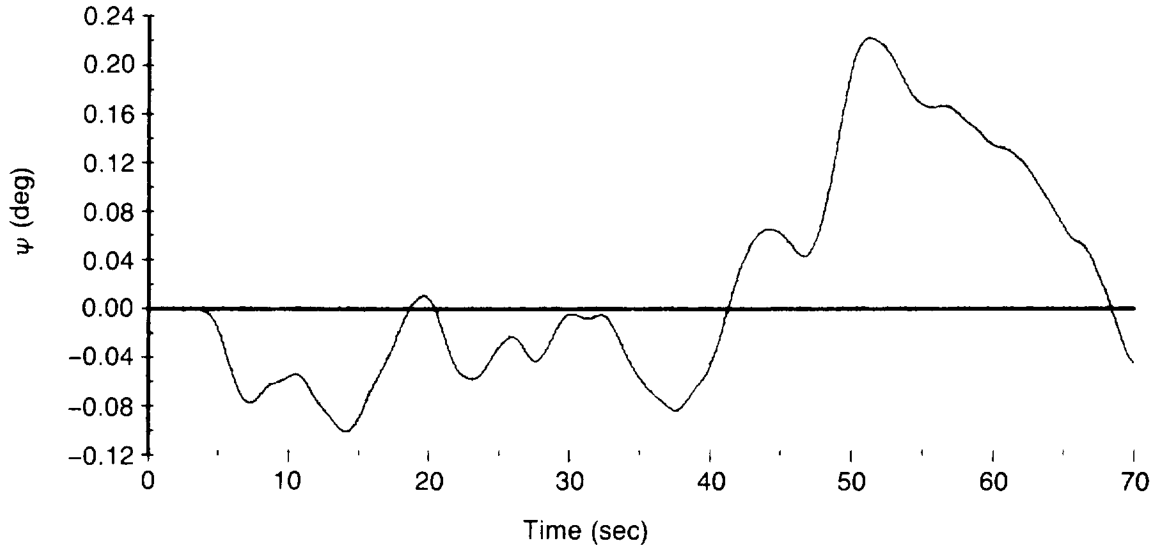


Figure 12. Heading Angle (Run No. 3, Straight-In Approach)

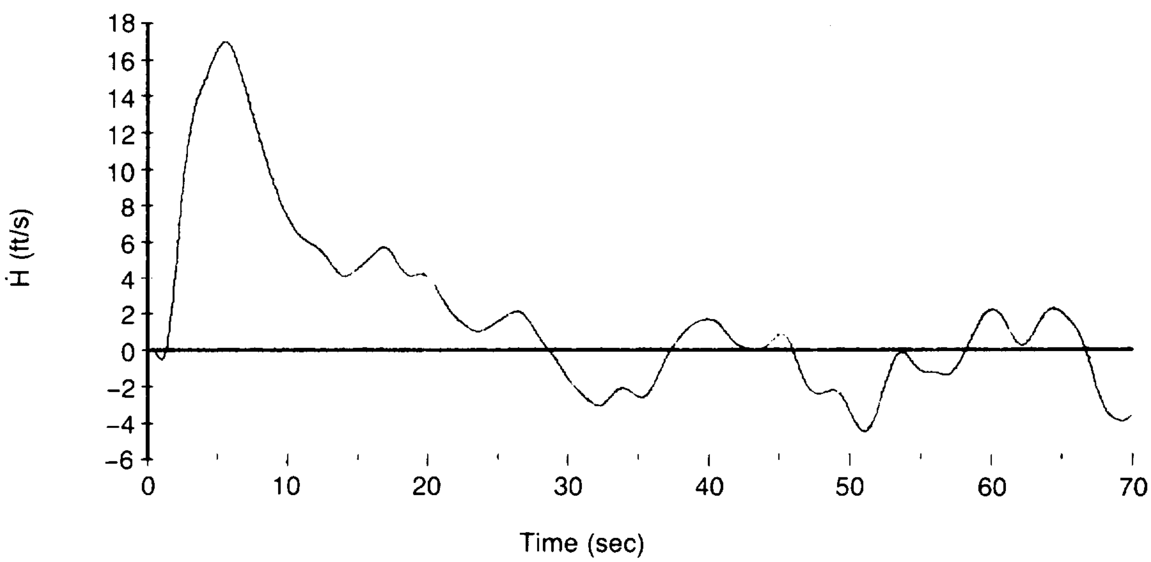


Figure 13. Vertical Speed (Run No. 3, Straight-In Approach)

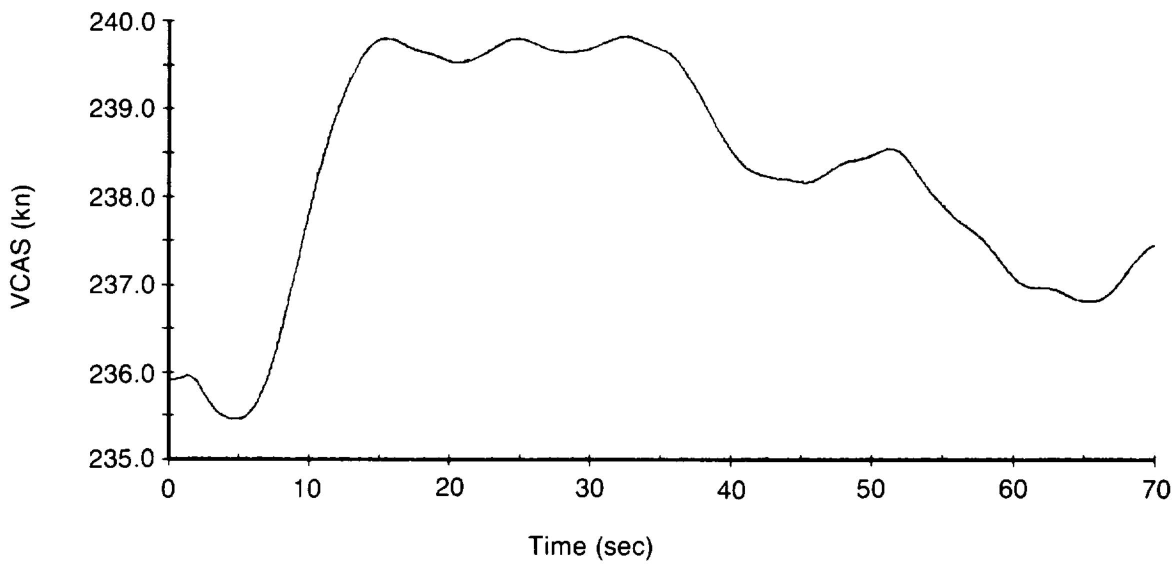


Figure 14. Calibrated Airspeed (Run No. 3, Straight-In Approach)

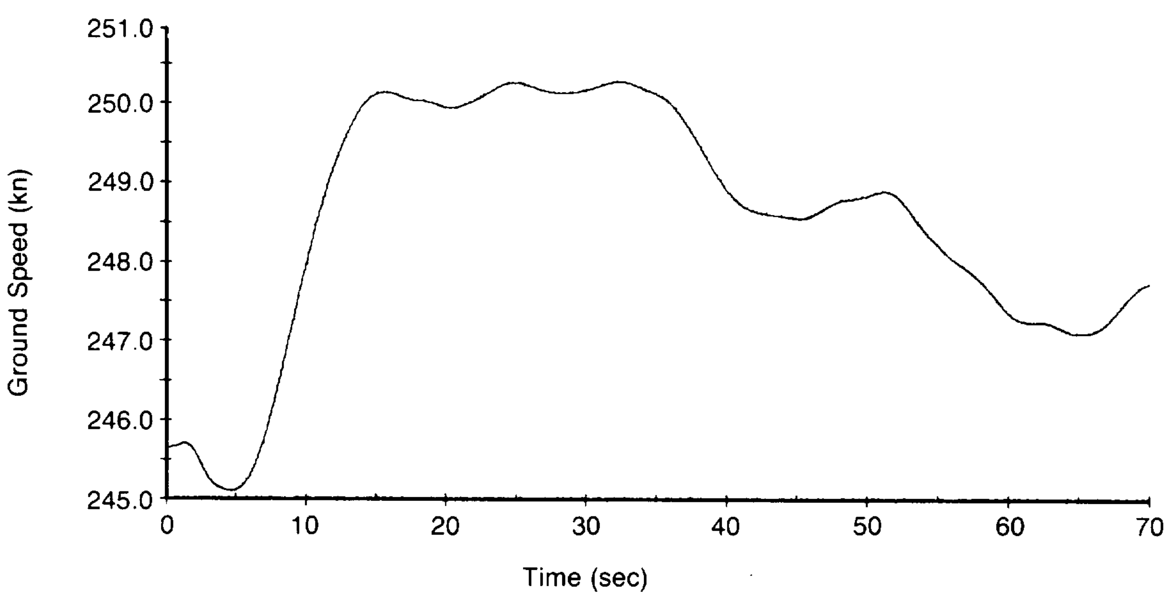


Figure 15. Ground Speed (Run No. 3, Straight-In Approach)

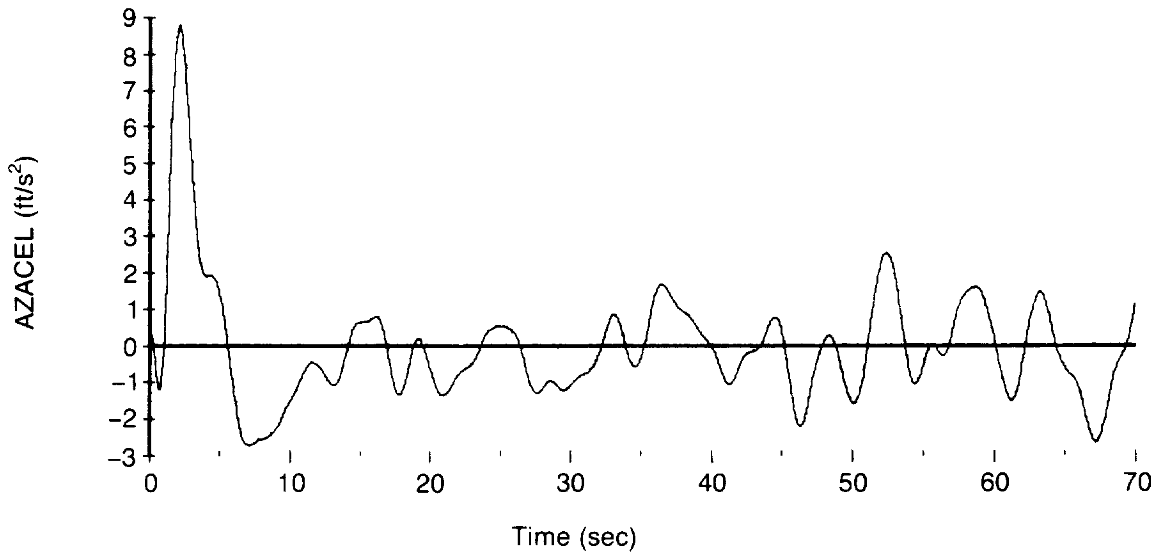


Figure 16. Normal Acceleration (Run No. 3, Straight-In Approach)

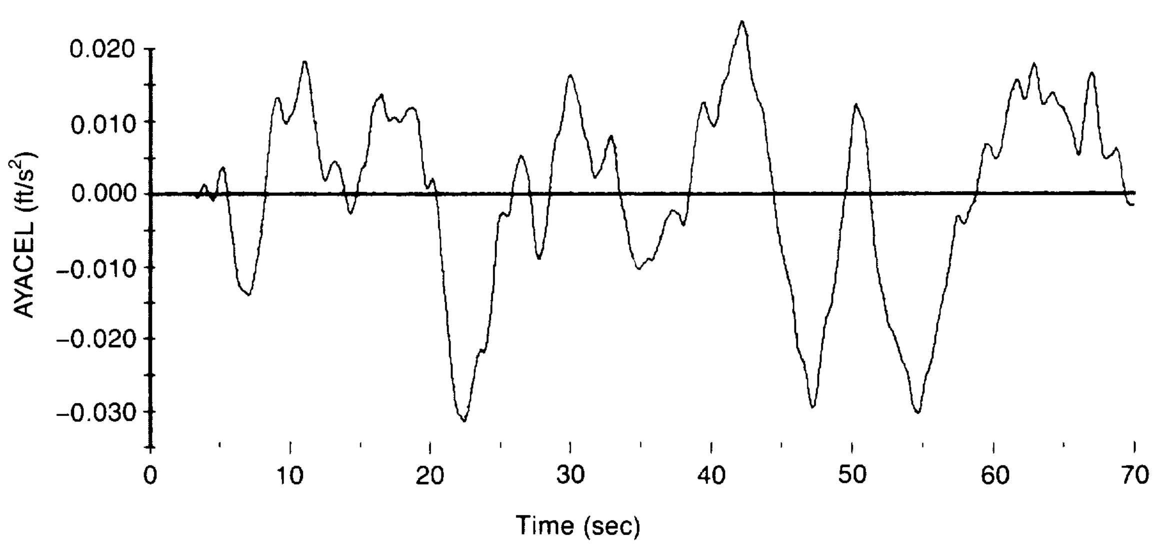


Figure 17. Lateral Acceleration (Run No. 3, Straight-In Approach)

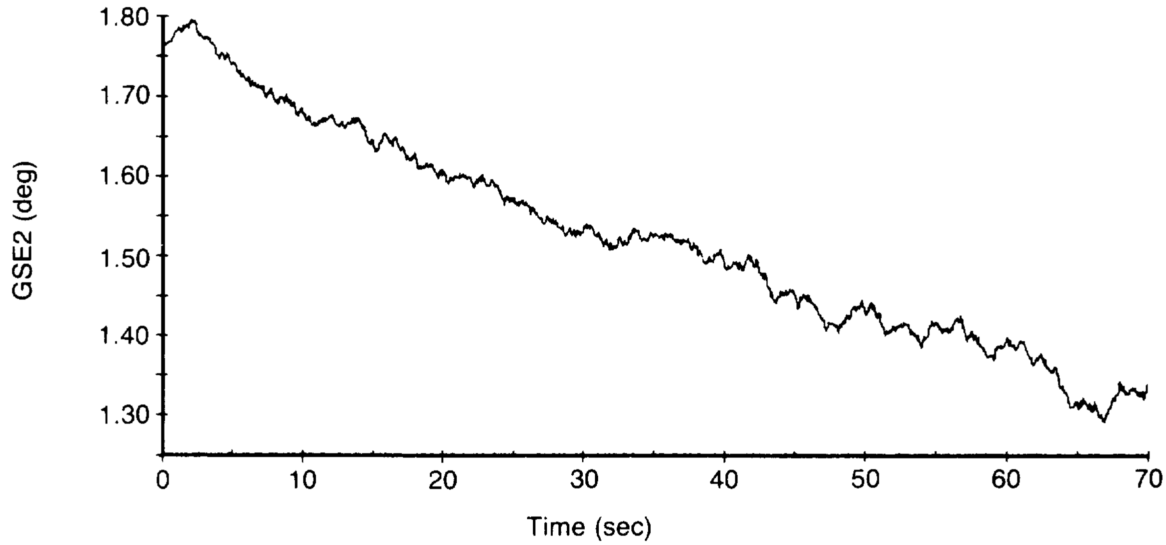


Figure 18. Contaminated Glide Slope Error (Run No. 3, Straight-In Approach)

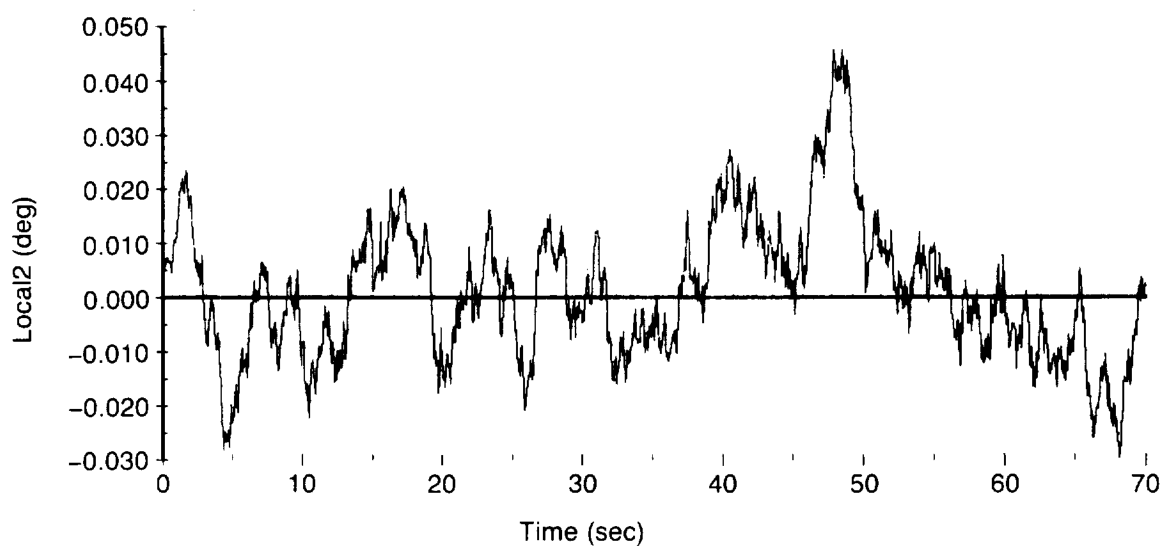


Figure 19. Contaminated Localizer Angle (Run No. 3, Straight-In Approach)

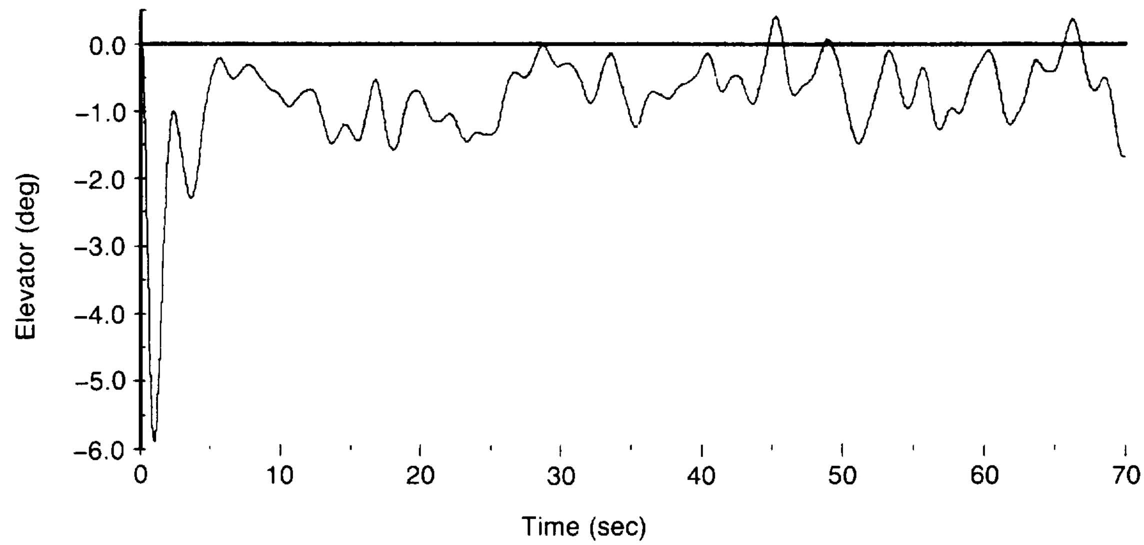


Figure 20. Elevator Activity (Run No. 3, Straight-In Approach)

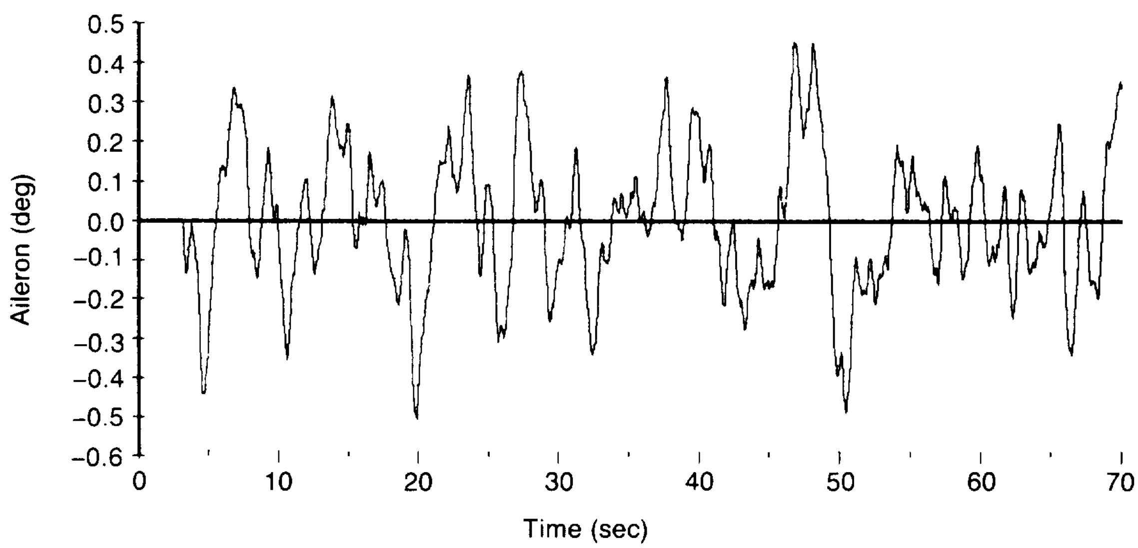


Figure 21. Aileron Deflection (Run No. 3, Straight-In Approach)

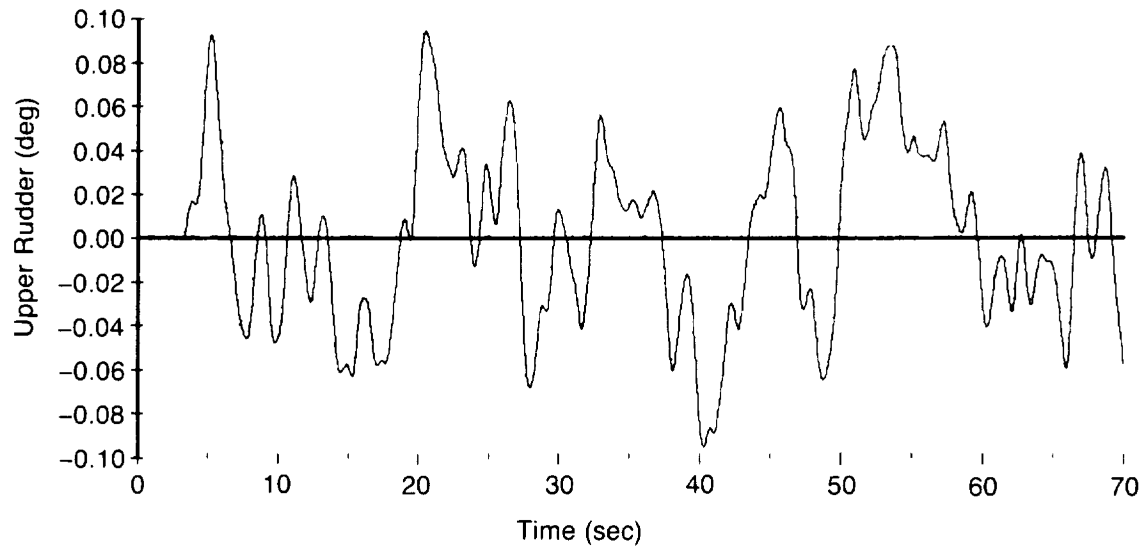


Figure 22. Upper Rudder Deflection (Run No. 3, Straight-In Approach)

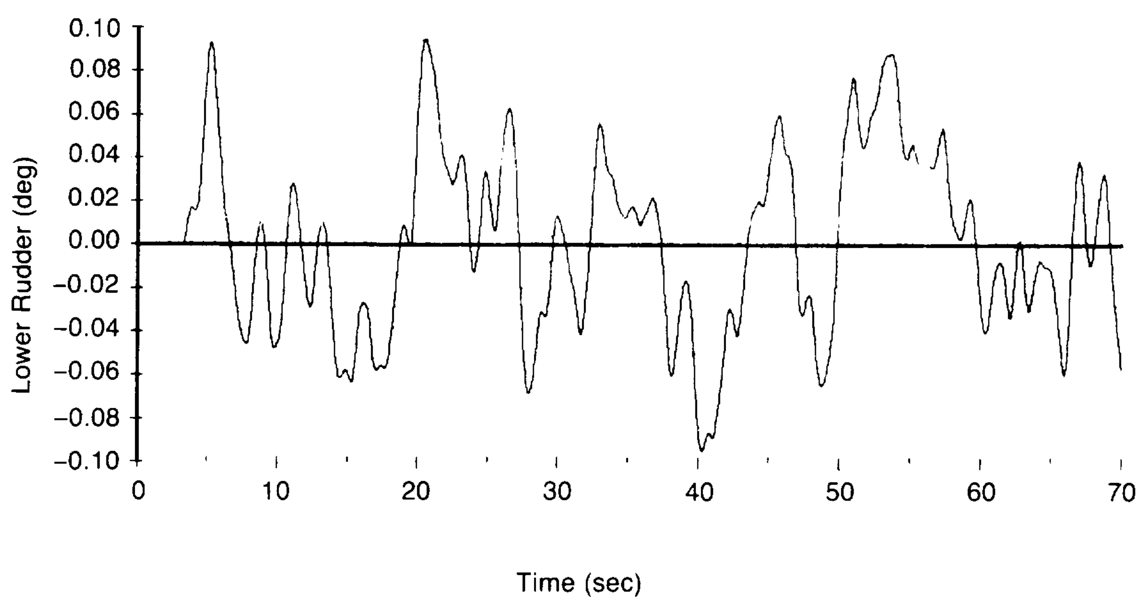


Figure 23. Lower Rudder Deflection (Run No. 3, Straight-In Approach)

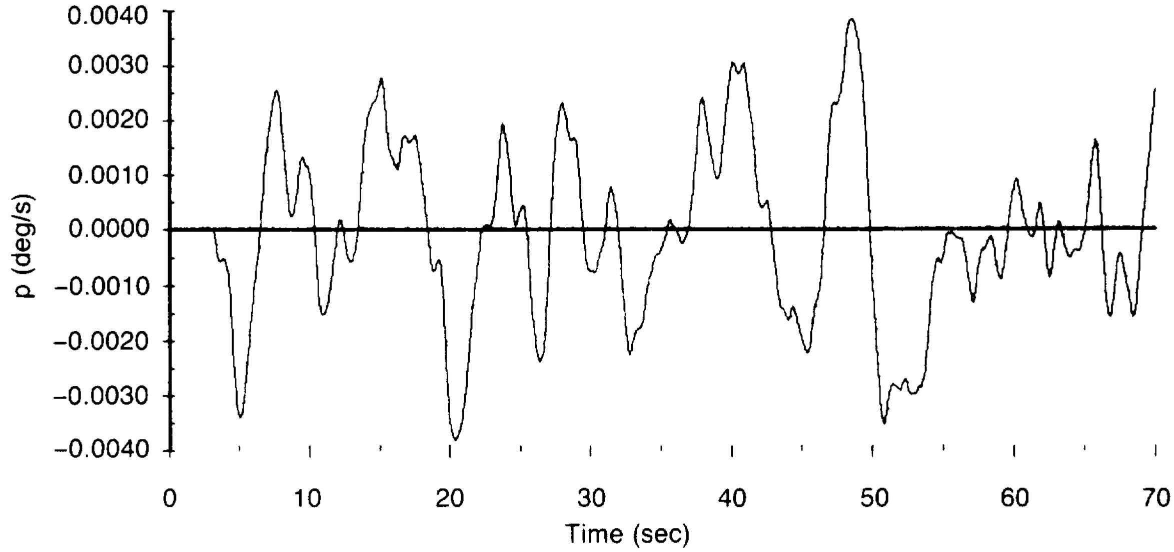


Figure 24. Roll Rate (Run No. 3, Straight-In Approach)

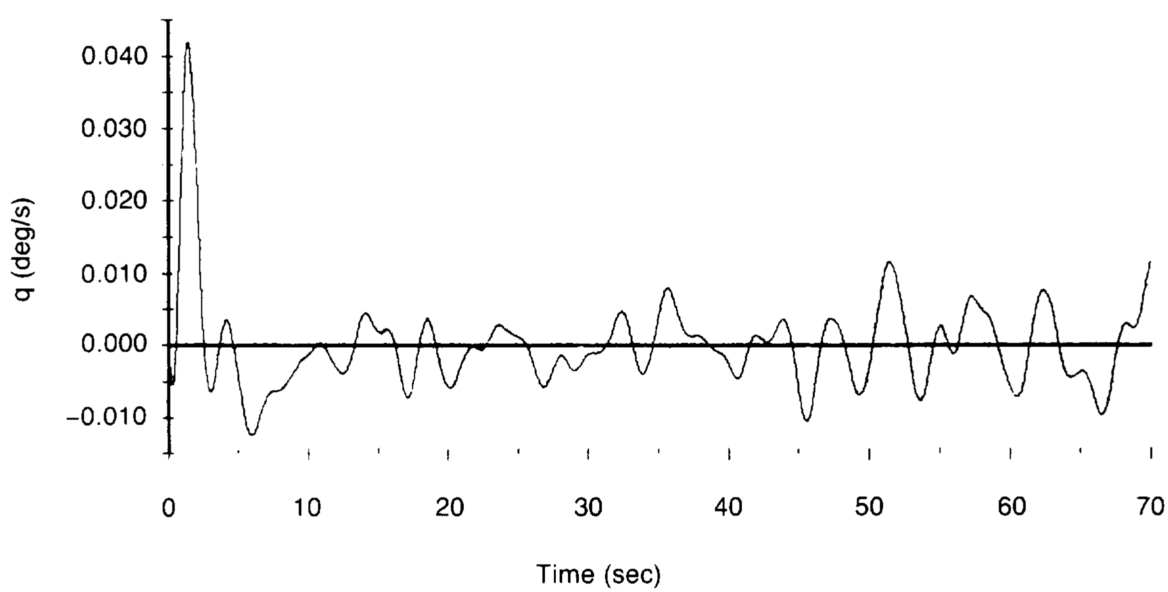


Figure 25. Pitch Rate (Run No. 3, Straight-In Approach)

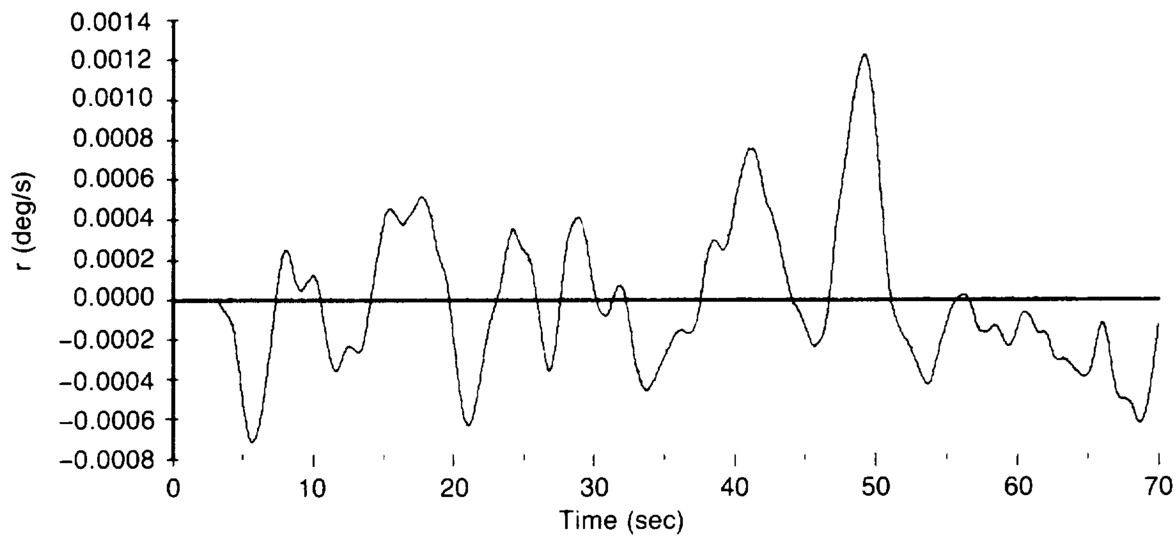


Figure 26. Yaw Rate (Run No. 3, Straight-In Approach)

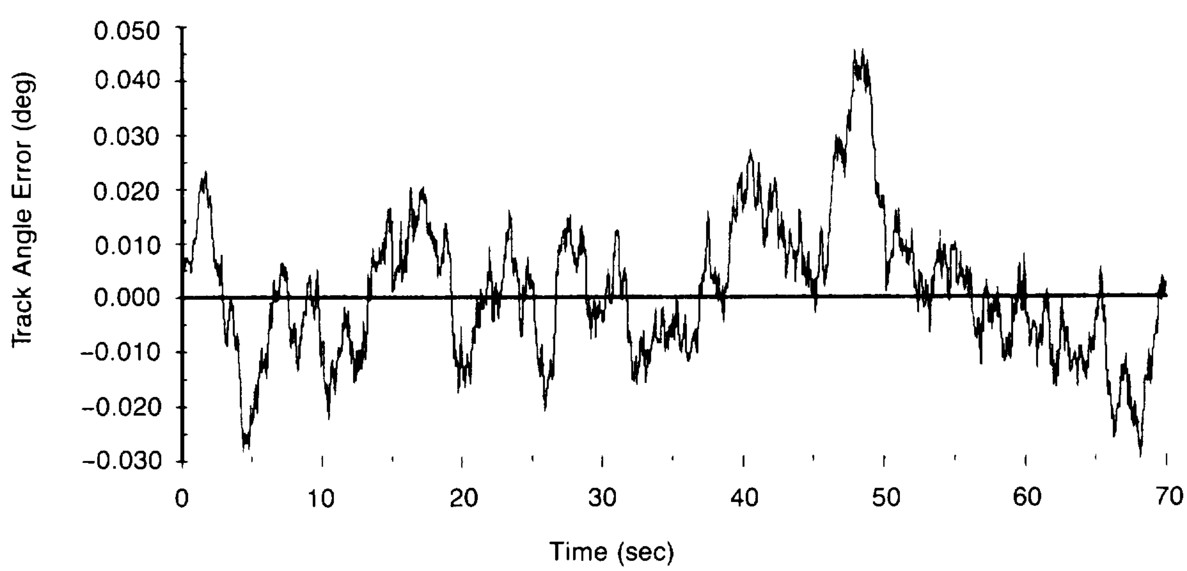


Figure 27. Beam Angle Error (Run No. 3, Straight-In Approach)

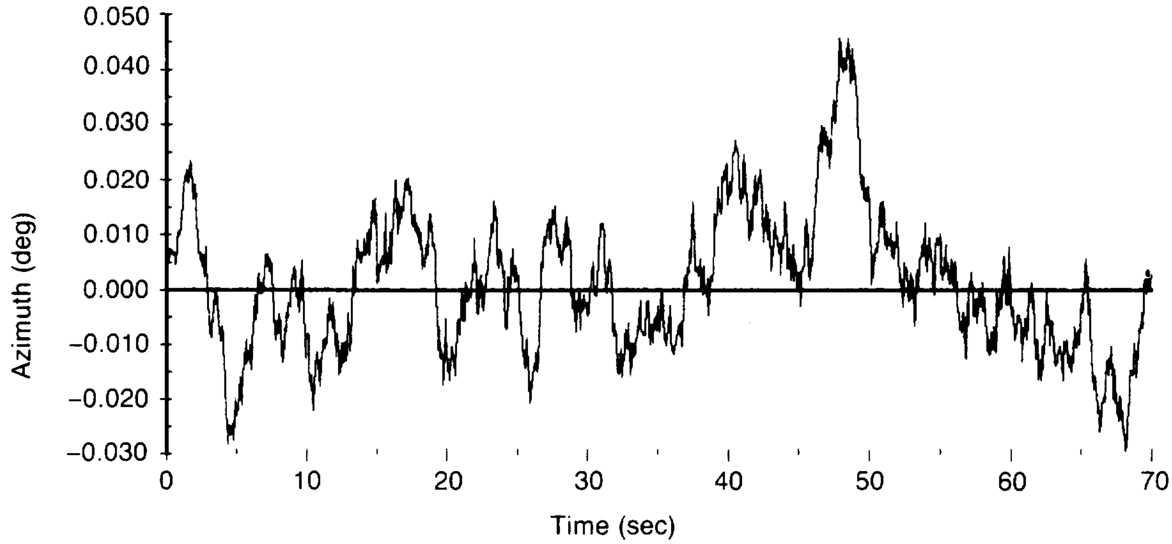


Figure 28. MLS Azimuth Signal Run (Run No. 3, Straight-In Approach)

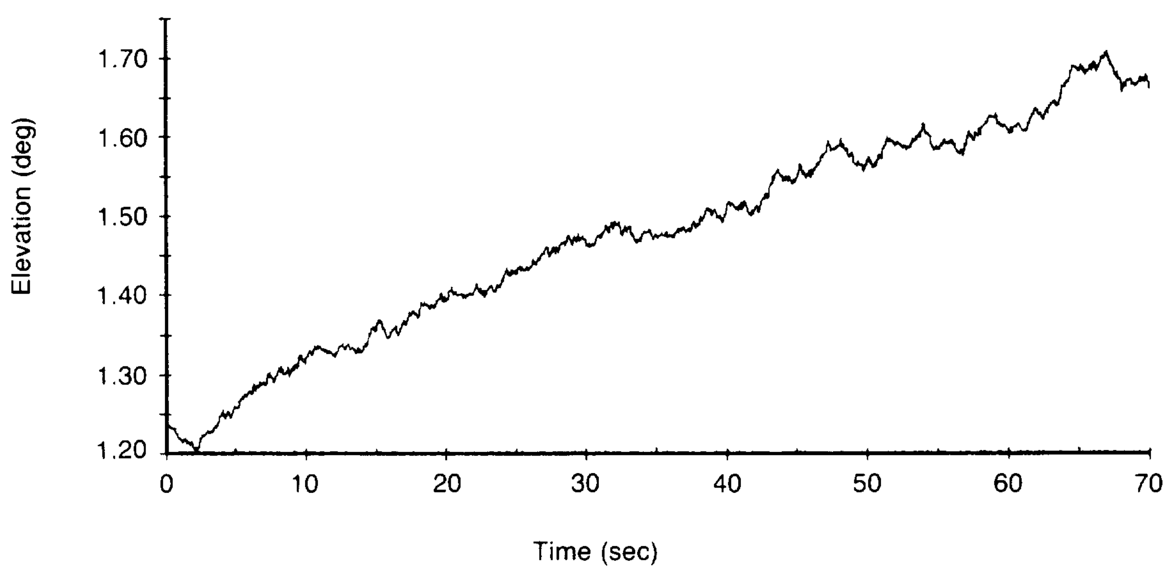


Figure 29. MLS Elevation Signal (Run No. 3, Straight-In Approach)

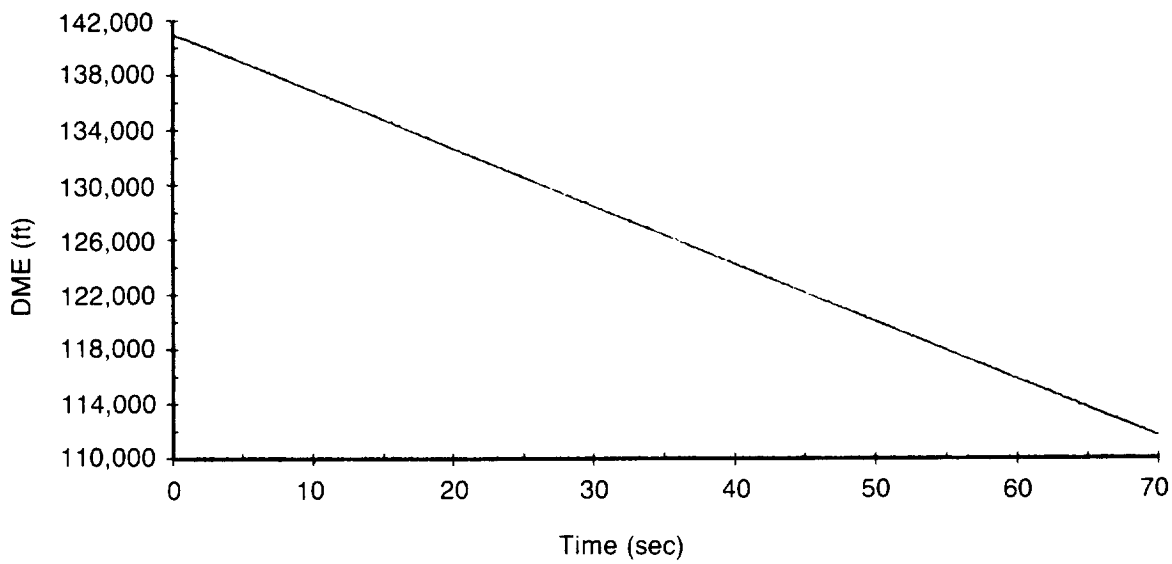
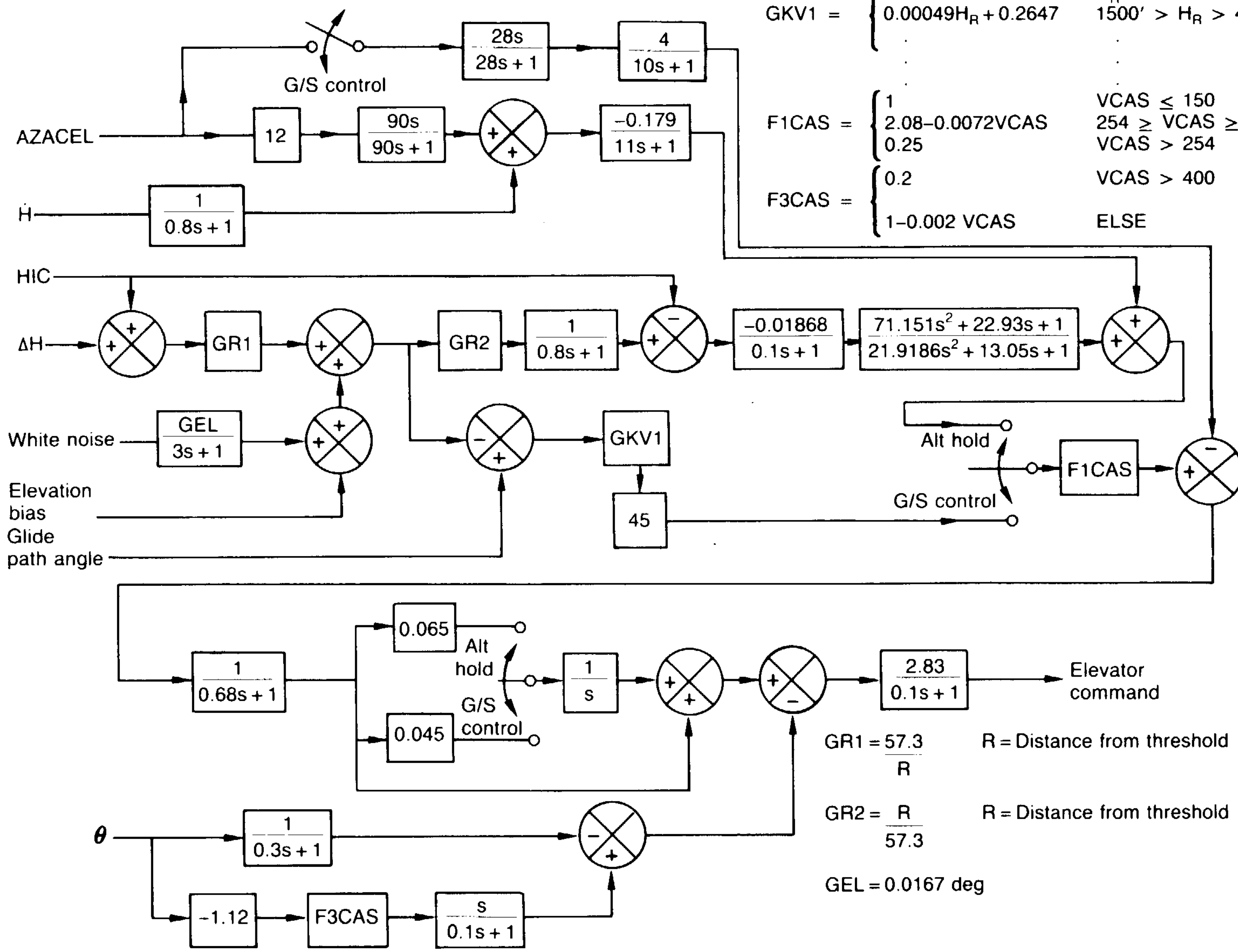


Figure 30. DME Signal (Run No. 3, Straight-In Approach)



$$GKV1 = \begin{cases} 1 & H_R > 1500' \\ 0.00049H_R + 0.2647 & 1500' > H_R > 480' \end{cases}$$

$$F1CAS = \begin{cases} 1 & VCAS \leq 150 \\ 2.08-0.0072VCAS & 254 \geq VCAS \geq 150 \\ 0.25 & VCAS > 254 \end{cases}$$

$$F3CAS = \begin{cases} 0.2 & VCAS > 400 \\ 1-0.002\ VCAS & ELSE \end{cases}$$

$GR1 = \frac{57.3}{R}$ R = Distance from threshold

$GR2 = \frac{R}{57.3}$ R = Distance from threshold

GEL = 0.0167 deg

Figure 31. Linearized Longitudinal Autopilot (Altitude Hold and Glide Slope Control Modes)

Table 1. Speed and Flap Setting at Different Distance From Threshold

MODE	DISTANCE FROM THRESHOLD	SPEED	FLAPS
Altitude hold	20 nmi	238 kn	1 deg
Altitude hold	15 nmi	200 kn	5 deg
Altitude hold	10 nmi	178 kn	10 deg
Altitude hold	5 nmi	148 kn	30 deg
Glide slope	All	148 kn	30 deg

Table 2. Configuration and Initial Condition for MLS Simulations

RUN NO.	LANDING APPROACH TYPE	STARTING POSITION FROM X	Y	H	SPEED	FLAPS	GEAR	MODE*	TABLE NO.
1	Perpendicular	−89980	90000	5000	235 kn	1 deg	up	AH	5
2	Perpendicular	−69980	70000	3000	178 kn	10 deg	up	AH	6
3	Straight-in	−130000	25	3000	235 kn	1 deg	up	AH	7
4	Straight-in	−70000	15	1500	180 kn	10 deg	up	AH	8
5	Straight-in	−56000	15	1500	148 kn	30 deg	down	AH	9
6	Offset straight-in	−130000	25025	3000	235 kn	1 deg	up	AH	10
7	Offset straight-in	−100000	50020	1500	200 kn	5 deg	up	AH	11
8	Slant	−99975	50025	1500	235 kn	1 deg	up	AH	12
9	Slant	−74980	25020	1500	200 kn	5 deg	up	AH	13
10	Straight-in	on 3 deg glide slope		4000	148 kn	30 deg	down	GS(MLS)	14
11	Straight-in	on 3 deg glide slope		4000	148 kn	30 deg	down	GS(ILS)	15

Weight of airplane : 560,000 lb
cg location : 0.25 MAC
Engine : PW-JT9D-7Q

*Modes, AH: Altitude hold
GS: Glide slope control

Table 3. LaRC Recommended MLS Parameter Values

AZIMUTH			ELEVATION			DME		
Bias, deg	Noise 1σ, deg	Correlation time, sec	Bias, deg	Noise 1σ, deg	Correlation time, sec	Bias, ft	Noise 1σ, ft	Correlation time, sec
0.0141	0.0146	3	see * below	0.0167	3	7.5	7.5	3

$$* \text{ Bias} = \begin{cases} 0.015 \text{ deg} & R \leq 9218 \text{ ft} \\ 0.025-(0.1/51482)(R-9218) & 9218 < R \leq 60700 \\ -0.075 \text{ deg} & R > 60700 \end{cases}$$

Table 4. Simulation Output Variables

1	X	15	Elevator
2	Y	16	Aileron
3	Barometric altitude	17	Rudder (upper)
4	θ	18	Rudder (lower)
5	α	19	p
6	ϕ	20	q
7	ψ	21	r
8	$\dot{H}$	22	Beam angle error
9	VCAS	23	Azimuth noise
10	Ground speed	24	Elevation noise
11	AZACEL	25	DME noise
12	AYACEL	26	MLS measured azimuth angle
13	GSE2	27	MLS measured elevation angle
14	LOCAL2	28	MLS measured DME distance

Table 5. Results of Run No. 1 (Perpendicular to Extended Runway Centerline Approach)

		AVERAGE	STANDARD DEVIATION
H	(ft)	5153	7.995
$\dot{H}$	(ft/s)		2.002
AZ	(ft/s^2)		1.079
V_{CAS}	(kn)	238.3	1.030
θ	(deg)		0.3292
α	(deg)		0.2188
Elevator	(deg)		0.4364
GSE2	(deg)		
X	(ft)	−89972	5.496
Y	(ft)	70551	
AY	(ft/s^2)		0.01479
ϕ	(deg)		0.2501
ψ	(deg)		0.07567
Aileron	(deg)		0.1930
Rudder	(deg)		0.04485
Beam error	(deg)		0.01512
Local2	(deg)		

Table 6. Results of Run No. 2 (Perpendicular to Extended Runway Centerline Approach)

		AVERAGE	STANDARD DEVIATION	AVERAGE	STANDARD DEVIATION	AVERAGE	STANDARD DEVIATION
H	(ft)	3121	20.90	3101	13.27	3091	8.170
$\dot{H}$	(ft/s)		2.131		3.290		1.839
AZ	(ft/s^2)		1.195		[1.636]		1.246
V_{CAS}	(kn)	181.7	[2.128]	178.5	0.8668	178.2	0.4465
θ	(deg)		0.5770		0.7864		0.4934
α	(deg)		0.4137		0.4846		0.3616
Elevator	(deg)		0.8405		0.9495		0.7998
GSE2	(deg)						
X	(ft)	-69979	4.794	-69987	7.046	-69989	9.430
Y	(ft)	55522		39675		23957	
AY	(ft/s^2)		0.00753		0.00901		0.01507
ϕ	(deg)		0.2610		0.3211		0.4983
ψ	(deg)		0.1057		0.1324		0.2860
Aileron	(deg)		0.2500		0.2962		0.3779
Rudder	(deg)		0.05189		0.08113		0.08541
Beam error	(deg)		0.01595		0.01718		0.03269
Local2	(deg)						

Table 7. Results of Run No. 3 (ILS Type Straight-In Approach)

		AVERAGE	STANDARD DEVIATION
H	(ft)	3152	9.915
$\dot{H}$	(ft/s)		1.946
AZ	(ft/s^2)		1.035
V_{CAS}	(kn)	238.0	1.030
θ	(deg)		0.3212
α	(deg)		0.2110
Elevator	(deg)		0.4299
GSE2	(deg)		
X	(ft)	-111120	
Y	(ft)	20.80	7.639
AY	(ft/s^2)		0.01377
ϕ	(deg)		0.2189
ψ	(deg)		0.08935
Aileron	(deg)		0.1802
Rudder	(deg)		0.04182
Beam error	(deg)		0.01326
Local2	(deg)		

Table 8. Results of Run No. 4 (ILS Type Straight-In Approach)

		AVERAGE	STANDARD DEVIATION
H	(ft)	1577	19.26
$\dot{H}$	(ft/s)		1.339
AZ	(ft/s^2)		0.7359
V_{CAS}	(kn)	183.3	1.911
θ	(deg)		0.3915
α	(deg)		0.2873
Elevator	(deg)		0.5317
GSE2	(deg)		
X	(ft)	-55707	
Y	(ft)	12.10	4.058
AY	(ft/s^2)		0.00545
ϕ	(deg)		0.1870
ψ	(deg)		0.08302
Aileron	(deg)		0.2256
Rudder	(deg)		0.05099
Beam error	(deg)		0.01318
Local2	(deg)		

Table 9. Results of Run No. 5 (ILS Type Straight-In Approach)

		AVERAGE	STANDARD DEVIATION	AVERAGE	STANDARD DEVIATION
H	(ft)	1562	5.399	1538	14.67
$\dot{H}$	(ft/s)		1.427		1.371
AZ	(ft/s^2)		0.7902		0.6857
V_{CAS}	(kn)	149.6	0.3754	149.7	0.3623
θ	(deg)		0.4497		0.4339
α	(deg)		0.3001		0.2695
Elevator	(deg)		0.7209		0.5843
GSE2	(deg)				
X	(ft)	-49320		-36417	
Y	(ft)	16.75	4.611	14.01	6.729
AY	(ft/s^2)		0.02565		0.02061
ϕ	(deg)		0.3447		0.2311
ψ	(deg)		0.1731		0.1242
Aileron	(deg)		0.3547		0.2845
Rudder	(deg)		0.08211		0.07537
Beam error	(deg)				
Local2	(deg)		0.02198		0.01852

Table 10. Results of Run No. 6 (Offset Straight-In Approach)

		AVERAGE	STANDARD DEVIATION
H	(ft)	3155	10.10
$\dot{H}$	(ft/s)		1.987
AZ	(ft/s^2)		1.061
V_{CAS}	(kn)	238.0	1.023
θ	(deg)		0.3273
α	(deg)		0.2158
Elevator	(deg)		0.4344
GSE2	(deg)		
X	(ft)	-111120	
Y	(ft)	25029	20.64
AY	(ft/s^2)		0.06471
ϕ	(deg)		[1.095]
ψ	(deg)		0.4473
Aileron	(deg)		0.7072
Rudder	(deg)		0.1961
Beam error	(deg)		0.06812
Local2	(deg)		

Table 11. Results of Run No. 7 (Offset Straight-In Approach)

		AVERAGE	STANDARD DEVIATION
H	(ft)	1634	17.81
$\dot{H}$	(ft/s)		2.161
AZ	(ft/s^2)		1.250
V_{CAS}	(kn)	203.7	1.534
θ	(deg)		0.4607
α	(deg)		0.3056
Elevator	(deg)		0.6578
GSE2	(deg)		
X	(ft)	-84166	
Y	(ft)	50016	11.80
AY	(ft/s^2)		0.01796
ϕ	(deg)		0.6133
ψ	(deg)		0.2708
Aileron	(deg)		0.5910
Rudder	(deg)		0.1329
Beam error	(deg)		0.04260
Local2	(deg)		

Table 12. Results of Run No. 8 (Slant Approach)

		AVERAGE	STANDARD DEVIATION
H	(ft)	1628	8.478
$\dot{H}$	(ft/s)		1.646
AZ	(ft/s^2)		0.8752
V_{CAS}	(kn)	237.7	1.056
θ	(deg)		0.2759
α	(deg)		0.1820
Elevator	(deg)		0.3889
GSE2	(deg)		
X	(ft)	-86890	
Y	(ft)	36993	
AY	(ft/s^2)		0.02547
ϕ	(deg)		0.3640
ψ	(deg)		0.1576
Aileron	(deg)		0.3458
Rudder	(deg)		0.08108
Beam error	(deg)		0.02613
Local2	(deg)		

Table 13. Results of Run No. 9 (Slant Approach)

		AVERAGE	STANDARD DEVIATION
H	(ft)	1589	15.39
$\dot{H}$	(ft/s)		1.458
AZ	(ft/s^2)		0.8340
V_{CAS}	(kn)	203.6	1.519
θ	(deg)		0.3196
α	(deg)		0.2214
Elevator	(deg)		0.4496
GSE2	(deg)		
X	(ft)	-63750	
Y	(ft)	13844	
AY	(ft/s^2)		0.02098
ϕ	(deg)		0.6887
ψ	(deg)		0.3114
Aileron	(deg)		0.6289
Rudder	(deg)		0.1407
Beam error	(deg)		0.05286
Local2	(deg)		

Table 14. Results of Run No. 10 (Glide Slope Control With MLS Noise)

		AVERAGE	STANDARD DEVIATION	AVERAGE	STANDARD DEVIATION	AVERAGE	STANDARD DEVIATION
H	(ft)	3480		2734		2019	
$\dot{H}$	(ft/s)	-15.99	3.108	-13.75	2.362	-14.10	1.585
AZ	(ft/s^2)		1.115		1.144		1.251
V_{CAS}	(kn)	151.5	0.8325	149.7	0.5879	149.6	0.3344
θ	(deg)		0.7448		0.7216		0.5682
α	(deg)		0.4886		0.4419		0.4664
Elevator	(deg)		[1.204]		[1.116]		[1.312]
GSE2	(deg)		0.03978		0.03145		0.01977
X	(ft)	-63253		-50009		-36951	
Y	(ft)	18.62	8.920	10.55	11.15	4.979	2.673
AY	(ft/s^2)		0.01451		0.01879		0.01824
ϕ	(deg)		0.1991		0.2300		0.2343
ψ	(deg)		0.1048		0.1362		0.1048
Aileron	(deg)		0.2652		0.2740		0.2815
Rudder	(deg)		0.05780		0.07336		0.06169
Beam error	(deg)						
Local2	(deg)		0.01385		0.01657		0.01331

Table 14. Results of Run No. 10 (Continued)

		AVERAGE	STANDARD DEVIATION	AVERAGE	STANDARD DEVIATION
H	(ft)	1322		642.1	
$\dot{H}$	(ft/s)	-13.64	1.538	-13.42	1.063
AZ	(ft/s^2)		1.114		0.7008
V_{CAS}	(kn)	149.6	0.3333	149.6	0.2605
θ	(deg)		0.5388		0.3582
α	(deg)		0.4207		0.2661
Elevator	(deg)		[1.001]		0.6460
GSE2	(deg)		0.01886		0.02242
X	(ft)	-24035		-11258	
Y	(ft)	11.04	4.494	5.091	4.202
AY	(ft/s^2)		0.02671		0.01685
ϕ	(deg)		0.3712		0.1793
ψ	(deg)		0.2054		0.0995
Aileron	(deg)		0.3520		0.2085
Rudder	(deg)		0.07725		0.05805
Beam error	(deg)				
Local2	(deg)		0.02427		0.01839

Table 15. Results of Run No. 11 (Glide Slope Control With ILS Noise)

		AVERAGE	STANDARD DEVIATION	AVERAGE	STANDARD DEVIATION	AVERAGE	STANDARD DEVIATION
H	(ft)	3366		2666		1991	
$\dot{H}$	(ft/s)	-13.93	5.998	-13.55	5.886	-13.58	4.578
AZ	(ft/s^2)		5.870		5.644		4.771
V_{CAS}	(kn)	150.0	1.075	149.3	1.174	149.4	0.6908
θ	(deg)		2.427		2.357		1.923
α	(deg)		2.163		2.089		1.731
Elevator	(deg)		5.504		5.389		5.390
GSE2	(deg)		0.05978		0.06428		0.06396
X	(ft)	-63291		-50114		-37113	
Y	(ft)	1.912	8.328	-3.361	9.340	6.870	9.485
AY	(ft/s^2)		0.04098		0.05716		0.04405
ϕ	(deg)		0.4313		0.6832		0.4737
ψ	(deg)		0.1383		0.3104		0.2287
Aileron	(deg)		1.226		1.376		1.439
Rudder	(deg)		0.2002		0.2373		0.2199
Beam error	(deg)						
Local2	(deg)		0.04632		0.05376		0.05340

Table 15. Results of Run No. 11 (Continued)

		AVERAGE	STANDARD DEVIATION	AVERAGE	STANDARD DEVIATION
H	(ft)	1324		656.5	
$\dot{H}$	(ft/s)	-13.52	6.820	-13.01	3.070
AZ	(ft/s^2)		6.439		2.547
V_{CAS}	(kn)	149.1	1.138	149.2	0.7198
θ	(deg)		2.726		1.111
α	(deg)		2.374		0.9465
Elevator	(deg)		6.406		2.804
GSE2	(deg)		0.08217		0.06670
X	(ft)	-24216		-11503	
Y	(ft)	5.031	9.930	-2.330	7.024
AY	(ft/s^2)		0.04667		0.05015
ϕ	(deg)		0.4450		0.4989
ψ	(deg)		0.2177		0.1459
Aileron	(deg)		1.112		0.8782
Rudder	(deg)		0.2109		0.2039
Beam error	(deg)				
Local2	(deg)		0.04405		0.05161

Table 16. Comparison Between Linear Covariance Analysis and Nonlinear Simulation (Altitude Hold)

VARIABLES		MPAC LINEAR COVARIANCE ANALYSIS	SCALED LINEAR COVARIANCE ANALYSIS	HARRIS NONLINEAR SIMULATION RUN NO. 5	PERCENTAGE DIFFERENCE
H	(ft)	5.836	6.3963	5.399	18
AZACEL	(ft/s^2)	0.6530	0.7157	0.7902	9
θ	(deg)	0.3787	0.4151	0.4497	8
α	(deg)	0.2568	0.2815	0.3001	6
Elevator	(deg)	0.5699	0.6246	0.7209	11
Mean height	(ft)	1,500	1,500	1,562	
Mean distance	(ft)	-45,000	-49,320	-49,320	

Weight : 560,000 lb
cg location : 25 MAC
Speed : 148 kn
Flap : 30 deg
Gear : Down

Table 17. Comparison Between Linear Covariance Analysis and Nonlinear Simulation (MLS Glide Slope)

VARIABLES		MPAC LINEAR COVARIANCE ANALYSIS	HARRIS NONLINEAR SIMULATION RUN NO. 10	PERCENTAGE DIFFERENCE
$\dot{H}$	(ft/s)	0.8521	1.063	20
AZACEL	(ft/s^2)	0.6286	0.7008	10
θ	(deg)	0.2841	0.3582	23
α	(deg)	0.2128	0.2661	20
Elevator	(deg)	0.8873	0.6460	37
Mean height	(ft)	650	642	

Weight	: 560,000 lb
cg location	: 25 MAC
Speed	: 148 kn
Flap	: 30 deg
Gear	: Down

Table 18. Comparison Between Linear Covariance Analysis and Nonlinear Simulation (ILS Glide Slope)

VARIABLES		MPAC LINEAR COVARIANCE ANALYSIS	HARRIS NONLINEAR SIMULATION RUN NO. 10	PERCENTAGE DIFFERENCE
$\dot{H}$	(ft/s)	2.623	3.070	15
AZACEL	(ft/s^2)	2.261	2.547	11
θ	(deg)	0.9460	1.111	15
α	(deg)	0.7664	0.9465	19
Elevator	(deg)	3.539	2.8040	26
Mean height	(ft)	650	657	

Weight	: 560,000 lb
cg location	: 25 MAC
Speed	: 148 kn
Flap	: 30 deg
Gear	: Down

1. Report No. NASA CR-178032	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Performance of a Commercial Transport under Typical MLS Noise Environment		5. Report Date January, 1986
		6. Performing Organization Code
7. Author(s) John K. Ho		8. Performing Organization Report No. D6-52712
9. Performing Organization Name and Address Boeing Commercial Airplane Company P.O. Box 3707 Seattle, Washington 98124		10. Work Unit No.
		11. Contract or Grant No. NAS1-17635
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546		13. Type of Report and Period Covered Contractor Report
		14. Sponsoring Agency Code 505-45-33-56

15. Supplementary Notes Langley Technical monitor:
Carey R. Spitzer
ATOPS Program Office
NASA Langley Research Center
Hampton, VA 23665-5225

William F. White APM 430
Federal Aviation Administration
800 Independence Ave. SW
Washington, D.C. 20591

16. Abstract

This document reports the performance of a 747-200 automatic flight control system (AFCS) subjected to typical Microwave Landing System (MLS) noise. The performance was then compared with the results from a previous study which had a B747 AFCS subjected to the MLS standards and recommended practices (SARPS) maximum allowable noise. A glide slope control run with Instrument Landing System (ILS) noise was also conducted. Finally, a linear covariance analysis is presented.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Microwave landing system (MLS) Automatic flight control system (AFCS) Instrument landing system (ILS)	Unclassified—Unlimited Subject Category 04

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	62	