FLIGHT TRANSPORTATION LABORATORY REPORT R86-3

FINAL APPROACH GUIDANCE USING AN ALTIMETER-AIDED LORAN-C DISPLAY SYSTEM

Norry Dogan

May 1986

MITLibraries
Document Services

Room 14-0551
77 Massachusetts Avenue
Cambridge, MA 02139
Ph: 617.253.5668 Fax: 617.253.1690
Email: docs@mit.edu
http://libraries.mit.edu/docs

DISCLAIMER OF QUALITY

Due to the condition of the original material, there are unavoidable flaws in this reproduction. We have made every effort possible to provide you with the best copy available. If you are dissatisfied with this product and find it unusable, please contact Document Services as soon as possible.

Thank you.

Appendix C - Computer Programs (pgs.97-115) contain illegible text.

ACKNOWLEDGEMENTS

This thesis is the result of work and effort that was accomplished because of the guidance and support of many individuals.

First of all, I would like to thank John K. Einhorn, Lyman R. Hazelton, Jr.,and Professor Antonio L. Elias, whose unselfish work and suggestions gave the backbone to this thesis.

Second of all, I would like to thank Professor Robert W. Simpson, NASA, and the FAA, for their interest and support through the Joint University Program.

Third of all, I would like to thank Gary Burrel for the donation of a KEA-346 altimeter for this testing.

Also, I would like to thank those people who contributed in other ways, but space only allows me to mention their names: Professor Walter M. Hollister, Professor Robert J. Hansman, Al Shaw, Don Weiner, Earle Wassmouth, and Abby Crear.

And with much appreciation and love, I want to thank my parents, whose sacrifices gave me the opportunity to study at MIT and whose confidence enabled me to succeed at it.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1 - INTRODUCTION

The goal of this thesis is to test the flyability of a display system that uses a King Radio KEAO-346 altimeter and Micrologic ML-3000 LORAN-C receiver for final approach guidance and to model the dynamics of the altimeter and the Micrologic ML-3000 LORAN-C tracking loop. The altimeter and LORAN-C receiver provide position information that provides navigation in the vertical and horizontal planes, respectively, and that is displayed as glideslope deviation and XTK deviation to the pilot.

The display system will be subject to flight tests that will have the twofold purpose of testing the flyability of the display system and of determining the dynamics of the navigation equipment. The flight tests will be a set of missed approaches to a runway with an ILS.

The testing of the flyability of the display system will be a qualitative analysis of a pilot's reaction to the display form. The analysis will consist of comments from the pilot who flies the flight tests. The flight tests will be simply a set of missed approaches to a runway with an ILS.

The system dynamics will be determined by comparing the recorded altimeter and LORAN-C navigation data with the simultaneously-recorded ILS navigation data. The glideslope angle from the ILS data will be compared to that of the arctangent of the altitude divided by the range. The localizer angle from the ILS data will be compared to that of the arctangent of the XTK error divided by the range. By also modeling the altimeter and Micrologic LORAN-C receiver dynamics, the data comparisons will provide information on not only system dynamics but also individual component dynamics. The flight tests will have the aim to excite the dynamics of the LORAN-C receiver by doing zig-zag patterns during the approach. The comparisons between the ILS and display system data will be done under the assumption that ILS dynamics are negligible with respect to the system dynamics.

LORAN-C is a hyperbolic line-of-position (LOP) system by which a receiver can be located at the intersection of two hyperbolas. This is accomplished by measuring the difference in arrival times between two pairs of pulses emitted from three fixed transmitting sites as ground waves. The transmitting stations may be designated as Master M, Slave X, and Slave Y. One hyperbola is determined by the X minus M pair of stations, the other hyperbola by the Y minus M pair of stations. Through the use of cesium clocks, each station transmits precisely-timed, pulsed RF signals. A pulse transmitted by the Master is received by Slave X, which will synchronize itself to the Master and then transmit its own pulse a fixed time later. The Slave Y station, also synchronized to the Master, will transmit a fixed time after it receives the Slave X signal, in order to avoid ambiguities. LORAN-C pulses are transmitted on a 100 kHz carrier in groups of eight pulses and with a group repetition (Master-Slave X-Slave Y) rate ranging from 10 groups per second to 25 groups per second. The pulses in a group are spaced 1000μs apart. A LORAN-C chain, which is a group of stations with one master and at least two slave stations, is distinguished from others by its group repetition interval (GRI), which is the time (in tens of microseconds) that the chain cycles through its master-slave transmission sequence. Currently, there are sixteen LORAN-C chains throughout the world. For the New England area, the common LORAN-C chain is the 9960 chain or the chain that has the GRI of 99600μs.

In practice, there are a number of ways that are used to locate oneself using LORAN-C. One method is to locate the actual time differences (TD's) given by a LORAN-C receiver on a special LORAN-C map. For modern receivers, the TD's can be displayed as latitude and longitude so that a special LORAN-C map is not required. Other methods that come as options on most modern receivers are to have the receiver display numerically the receiver's range and bearing to a recorded waypoint or to have the receiver display graphically cross-track error from a path determined by two waypoints (starting point and destination). Since LORAN-C can only provide navigation in the local horizontal plane because pulses are transmitted as ground waves, other means such as a barometric altimeter are necessary to provide vertical navigation data for final approach guidance.

Over the past two decades, because of the increase in processing power and the corresponding decrease in cost, LORAN-C has become a viable option for aircraft navigation. The increase in processing power has increased the speed by which LORAN-C signals can be locked onto and has decreased the volume of the receiver so that it can be considered as an optional piece of equipment for the cockpit panel. Airborne units can be purchased for as little as $400 per unit, exclusive of antenna and installation costs.

Errors in TD measurement are set by the signal-to-noise ratio (SNR) and by the dynamic response of the tracking loop of the user's receiver. Errors in position determination can result from warpage in the local line-of-position (LOP) or from coordinate conversions such as from TD's to lat-long. Reference 9 shows that for static tests, the repeatability accuracy in over 90% of the average area in the Northeast and Southeast United States is better than 80 meters, and that in 50% of the same coverage area, the accuracy is better than 40 meters. The dynamic response of LORAN-C is limited by the response of the receiver's tracking loops to noise and vehicle accelerations. Studies by the Department of Transportation and the State of Vermont showed that LORAN-C accuracy met FAA AC90-45A specifications (Reference 3: 'Approval of Area Navigation Systems for Use in the US National Airspace System ') for enroute, terminal area,and non-precision approach use. Non-precision approaches using LORAN-C have become more acceptable to FAA approval, as exemplified by their approvals in the recent past for LORAN-C non-precision approaches at Burlington, Vt. airport and at Hanscom Field in Bedford, Massachusetts.

The thesis will follow the methodology of the following outline. Chapter 2 will introduce the display form and the manner in which it displays the navigation information. Chapter 3 will look in detail at the flight test data-taking equipment and methodology. Chapter 4 will explain how the altimeter and LORAN-C tracking loop were modeled. Chapter 5 will show the flight test results and the analysis that was done on the results using the modeling from Chapter 4. Chapter 6 will then provide a discussion of the display's flyability and the data analysis. Appendix A will explain an experiment that was used to test the static accuracy of the altimeter; Appendix B will explain in detail the construction and certification of the flight test pallet; and Appendix C will provide the computer documentation for the computer programs used in the display and for data analysis.

CHAPTER 2 - THE DISPLAY OPERATION

2.1 NAVIGATION DATA

For testing, a Micrologic ML-3000 LORAN-C receiver and an altimeter (King Radio:KEA-346) were used to provide position information. The LORAN-C receiver was customized by the manufacturer so that a serial data stream outputted from the receiver would provide the user with time differences (TD's), time difference velocities, and the signal-to-noise ratios (SNR's).

The time difference measurements are inputted into a mathematical algorithm that approximates the hyperbolic grid system of the LOP's to a linear one around the chosen touchdown point. The algorithm (see Reference 2 for details) that converts the relative TD's (between user position and desired touchdown point) to relative East and North position is a simple first-order approximation of the hyperbolic grid. A 2x2 matrix of coefficients that are determined by the local geometry of the LOP's multiplies the relative TD values to obtain the transformation between the oblique TD-referenced coordinate system and the East-North Cartesian system. By a rotation of the axes so that the North axis is aligned with the runway and the East axis perpendicular to the runway, both along-track (range to the touchdown point) and cross-track (XTK) can be directly obtained.

The Display System uses the along-track and cross-track position in addition to altitude information from the altimeter to provide the pilot with cross-track position and glideslope-deviation information. The glideslope-deviation is the difference in altitude between the pilot's indicated altitude as given by the altimeter and the recommended altitude as given by the 3 degree tangent of the along-track distance to the touchdown point as given by the LORAN-C receiver.

2.2 DISPLAY FORM

The form of display that is used to provide the navigation information to the pilot is shown in Figure 2.1.

The cross in the center of the display in Figure 2.1 indicates the user position, and the crossing point of the horizontal and vertical indicator lines represents a point on the desired approach path as defined by the navigation data. The display is a typical pursuit display since the pilot (the center cross) pursues the crossing point of the horizontal and vertical indicator lines in order to stay near to the desired approach path.

The horizontal scale of the display gives XTK position to the pilot. The scale is divided into two regions: the central linear region between -300 feet and +300 feet (300 feet RIGHT and 300 feet LEFT) and the outer logarithmic regions between -300 feet and -3000 feet and between +300 feet and +3000 feet. The transitions at -300 feet and +300 feet from the central linear region to the outer logarithmic regions are denoted by a dot pattern that extends from the top to the bottom of the display. The spacing in the horizontal scale between 0 feet and +300 feet and between +300 feet and +3000 feet is calculated so that the slope at the +300 feet

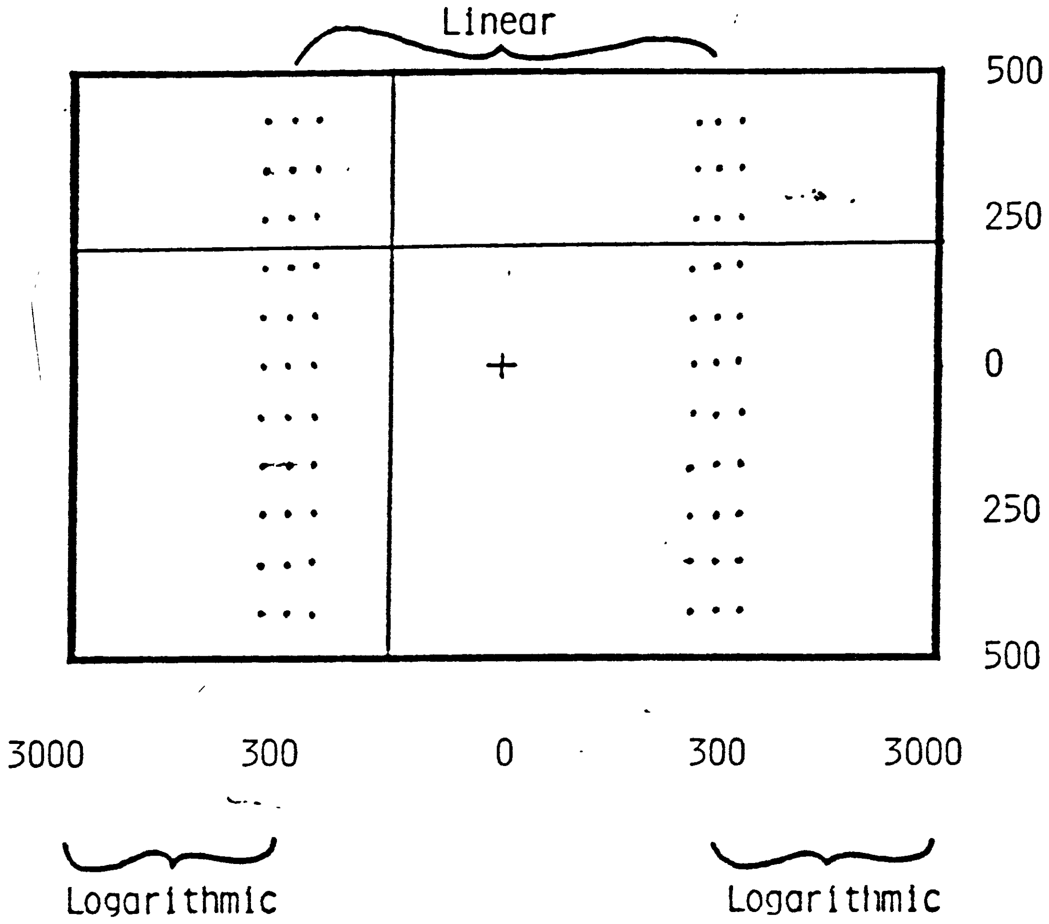


Figure 2.1 - This figure shows the manner in which navigation data is displayed to the pilot. In this case, the figure shows that the pilot - the center cross - is low and to the right of the approach path - the crossing of the vertical and horizontal indicators.

point is the same for both the linear and logarithmic regions. That is, if one were to show in cartesian coordinates (see Figure 2.2) the relationship of the distance of the XTK indicator line from the 0 ft point on the XTK scale to actual XTK distance, the straight line from 0 ft to 300 ft would have the same slope as the logarithmic curve from +300 ft to +3000 ft. This tangency would also apply for the -300 ft transition point. The reason for this tangency is so that the XTK indicator line accelerates or decelerates smoothly as it moves out of or into the logarithmic region, respectively.

The vertical scale of the display gives glideslope-deviation to the pilot in terms of feet. The glideslope deviation is the altitude difference between indicated altitude and recommended altitude. This altitude difference, physically, is the vertical distance of the airplane from the glideslope defined by the LORAN-C receiver. The display shows the altitude difference in the range +500 ft to -500 ft (500 ft BELOW glideslope to 500 ft ABOVE glideslope).

2.3 DISPLAY OPERATION

The display is designed to be used when the aircraft is downrange of the runway at which it is supposed to land and when the pilot has inputted the proper information about the destination. The proper information consists of the TD coordinates of the touchdown point, the true bearing of the runway, and the local altimeter setting. In a future commercial unit, the TD coordinates of the touchdown point and the true bearing of the runway would be stored on ROM and would simply require

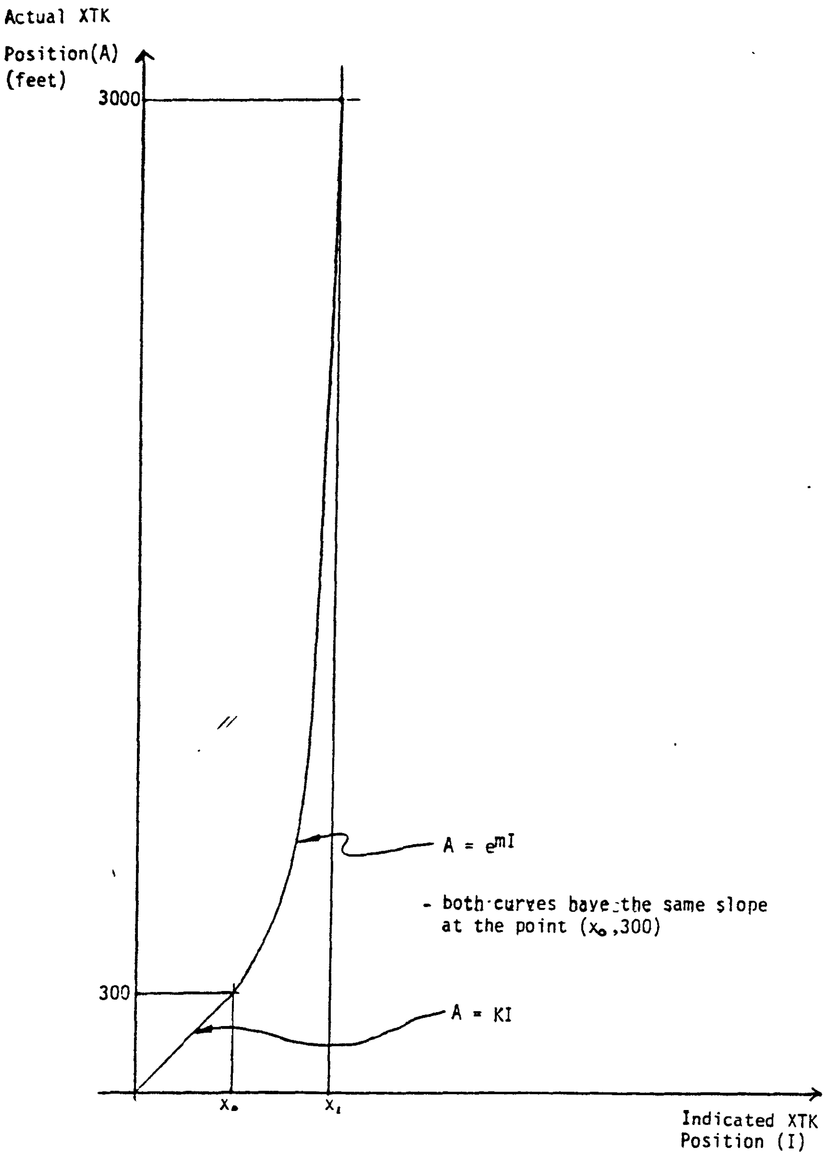


Figure 2.2 - Relationship Between Actual XTK and Indicated XTK Position

a button to be pushed by the pilot in order to be accessed. The TD coordinates of the touchdown point and the runway's true bearing are directly used by the display program, and the local altimeter setting is necessary so that the indicated altitude of the altimeter which is read by the program is the 'actual'altitude of the airplane.

When the aircraft is downrange of the runway, the pilot will use the XTK information to align the aircraft with the runway and will ignore the glideslope information until he begins his descent. The XTK indicator line provides accurate XTK position of the aircraft for all regions of the XTK scale; however, the motion of the XTK indicator line is representative of the motion of the aircraft only in the central linear region because of the non-linearity in the outer logarithmic regions. The real purpose of the outer logarithmic regions is to provide a large range of XTK indication (3000 ft LEFT and 3000 ft RIGHT), so that the pilot has initially time to react before the XTK indicator line can move from one extreme side of the display to the other extreme side. The central linear region provides the pilot with the position and motion sensitivity necessary for a good landing.

As the pilot is aligning himself with the approach path using the XTK information from the display, the glideslope indicator will begin providing glideslope deviation information once he passes the 4 nautical-mile distance-to-go point. The motion of the indicator line will then cause the pilot to react to follow the three-degree glideslope to the touchdown point. Since the glideslope scale is linear (500 ft UP to 500 ft DOWN), it provides both the aircraft's vertical deviation and velocity component relative to the three-degree glideslope. The display's glideslope deviation is found by subtracting the plane's altitude as given by the barometric altimeter from the three-degree tangent of LORAN-C-derived range.

CHAPTER 3 - FLIGHT TESTS

3.1 PURPOSE

The reasons for the flight tests were to determine the flyability of the display system outlined in Chapter 2 and to test the dynamics of the Micrologic ML-3000 LORAN-C receiver and the King Radio KEA-346 altimeter.

3.2 EQUIPMENT

The flight tests were done in a Grumman Tiger AA5B with the equipment mounted in a pallet in the back seat behind the pilot. Figure 3.1 is a block diagram showing the equipment and the flow of power and data.

The equipment was powered using two 12V gel cells. One gel cell provided direct 12V to the monitor/display, Micrologic LORAN-C receiver, and to the ILS equipment (KX-175B indicator and KI-214 head). The other gel cell provided power to an inverter that converted 12 VdC to 120 VaC. The reason for using the gel cell independently instead of placing them in parallel was to prevent noise from the inverter from feeding back and affecting the data-taking of TD's and ILS data. Even though the gel cells are rated at 20 amp-hours, past abuse had limited their life to an estimated 45 minutes at 8.4 amps. For the altimeter, a special 28V power supply (Sorensen: Model PTM 28-1.4) was used. The 28V power supply was supplied 120 VaC from the inverter, causing some AC noise to deteriorate the quality of the altitude data.

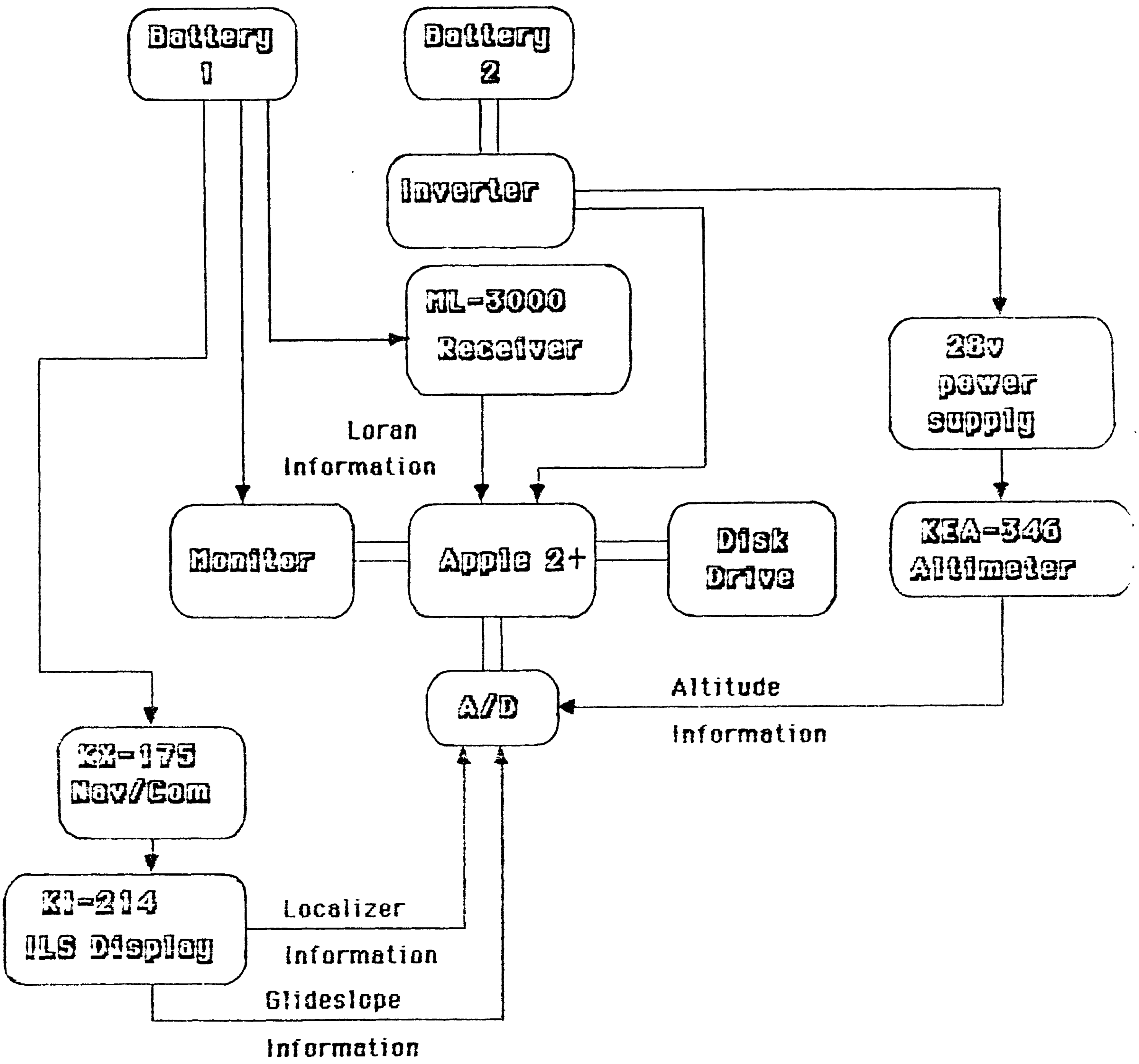


Figure 3.1 - Block Diagram of Flight Test Equipment.

The monitor/display unit was an Osborne monochrome computer monitor with a screen size of 4.5 in x 3.5 in adapted to the Apple II+ computer. The horizontal and vertical sync signals and ground of the Apple II+ were hard wired from the hardware board to a connector mounted on the back of the Apple II+ computer. Through the use of the connector, the monitor/display unit obtained the necessary video signals. The unit acted as a computer monitor for the Apple II+ computer for program editing and as a display using Apple Graphics to show the display form to the pilot during the flight tests. The monitor/display unit was mounted in a 6 in x 9 in x 5 in aluminum box with brightness and contrast controls mounted on the top of the box and vertical and horizontal controls on the side of the box. Two large sections at the front and back of the box were cut to enable a person to see the monitor screen and to mount a connector to receive the video signals from the Apple II+ computer. During the flight tests, the monitor/display unit was bolted using 0.25 inch screws to the top of the cockpit panel.

The data flow that is illustrated in Figure 3.1 consists of many parts: LORAN-C information to the Apple II+, altitude information to the Analog-to-Digital (A/D) Converter (Computer Continuum Analog Interface, Ltd.), and ILS information to the A/D. The LORAN-C information is a serial data stream from the Micrologic ML-3000 receiver that is sent to a serial data card on board the Apple II+ computer. The data stream is sent every twelfth GRI, which for the 9960 chain is approximately 1.2 seconds. The format of the data stream which is shown in Table 4.1 includes the TD's of the two slaves, the SNR's of the two slaves and the master, and the TD velocities - the rate of change of the TD's - of the two slaves. The remaining data flows shown in Figure 4.1 are all sent to the Apple II+ via the A/D converter. The A/D converter changed the analog voltage on a signal channel to a byte with a value between 0 and 255. A value of 0 corresponded to 0 volts and a value of 255 corresponded to 5 volts. For each of the three forms of information that were inputted to the A/D (and that corresponded to three different channels), buffer circuitry had to be designed and built in order to change the raw signal to one with a working range between 0V and 5V.

The localizer information was obtained by tapping the left/right error signal of the ILS autopilot output from the KI214 head. The left/right error signal is obtained by finding the difference between the DC bias of two 30Hz signals. The buffer circuitry between the ILS output signal and the A/D board is shown in Figure 3.2(a). The circuitry consists of a comparator, a two-stage low-pass filter with an approximate cutoff frequency of 0.7Hz, and a comparator/amplifier circuit. The comparator circuit finds the difference in the DC bias of the two 30 Hz signals; the low pass filter rids the signal of the 30 Hz component; and, the comparator/amplifier circuit amplifies the difference by approximately 10 (depending on the resistors' tolerances) and differences the voltage with 2.56V so that the operating range of the voltage is within the 0V to 5V range. The digitization of the resulting signal allowed a resolution of 0.049 dots/bit, where dots for the localizer refer to the angular XTK

Byte Number	Character Indentification
1	Velocity of TD1 LSB
2	Velocity of TD1 MSB
3	Time Difference 1 LSB
4	Time Difference 1 NMSB
5	Time Difference 1 MSB
6	Velocity of TD2 LSB
7	Velocity of TD2 MSB
8	Time Difference 2 LSB
9	Time Difference 2 NMSB
10	Time Difference 2 MSB
11	SNR(Master)
12	*MODE(Master)
13	SNR(TD1)
14	MODE(TD1)
15	SNR(TD2)
16	MODE(TD2)
17	Nav Status
18	Check Sum

(*MODE - Tracking Status)

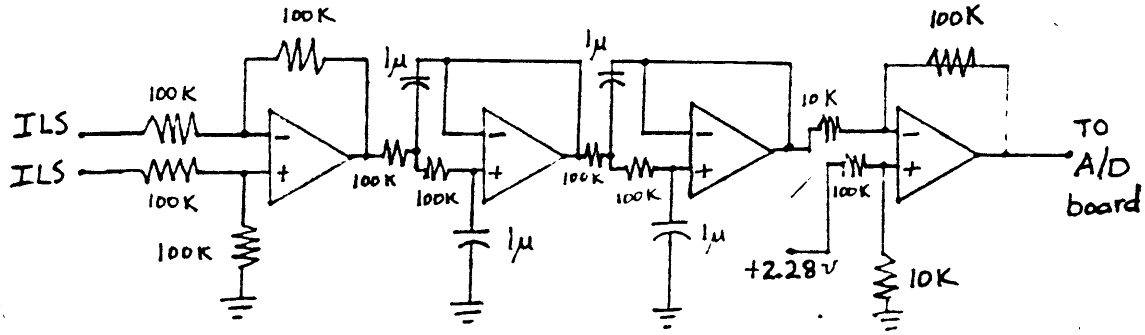
Table 3.1 - Data Stream from Micrologic ML-3000 LORAN-C Receiver.

deviation from the localizer antenna placed 1650 feet behind the runway for Runway 11 at Hanscom AFB. For Hanscom, one dot deviation is equivalent to 0.460 degrees, and full-scale deflection is 5 dots, equivalent to 350 ft deflection from the runway centerline at the threshold.

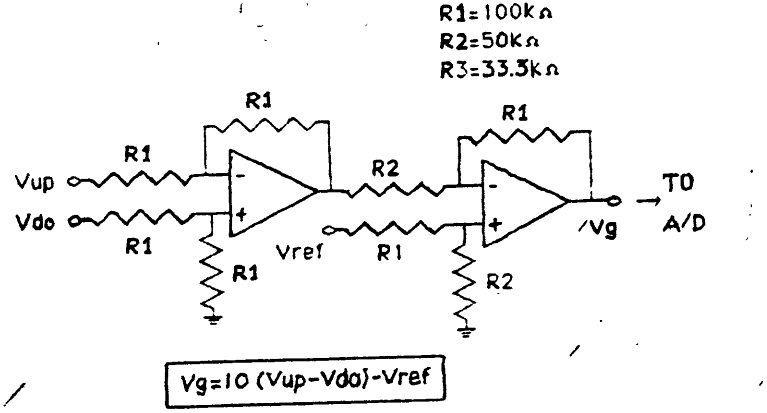
The glideslope information was obtained by tapping the up/down error signal of the ILS autopilot output from the KI 214 head. The up/down error signal was obtained by finding the difference between two DC voltages. The buffer circuitry between the ILS output signal and the A/D board is shown in Figure 3.2(b). The circuitry consists of a comparator and comparator/amplifier stage. The comparator stage finds the difference between the two DC voltages; and the comparator/amplifier stage amplifies the difference by ten and finds the difference between the amplified signal and the reference voltage of 2.56V. The digitization of the resulting signal allowed a resolution of 0.021 dots/bit, where dots for the glideslope refer to the angular deviation from a 3-degree glideslope. Full-scale deflection is 2 dots or 0.7 degrees, which is equivalent to a 300 ft deviation at the outer marker.

The altitude information was obtained by tapping the potentiometer output of the altimeter (King Radio: KEA-346). The center tap voltage of the potentiometer of the altimeter is proportional to the indicated altitude. The voltage sensitivity to indicated altitude is dependent on the voltage placed across the potentiometer so that the sensitivity was 0.47 mV/ft. Appendix A shows the results of static altitude measurements done in a high-rise building on the MIT campus, using the

(a) Localizer Data Input.



(b) Glideslope Data Input.



(c) Altimeter Data Input.

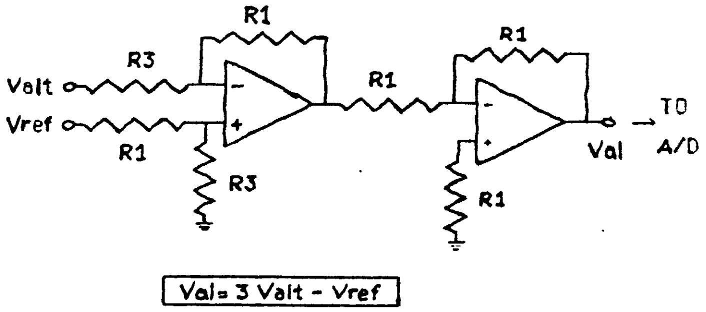


Figure 3.2 - Buffer Circuitry for A/D Data Inputs.

altimeter. The results of the testing conclude that the static error in measuring altitude after compensating for air pressure reference is within the 20 ft limit stated by the altimeter manufacturer in Figure A.4. The buffer circuitry between the altitude signal and A/D board is shown in Figure 3.2(c). The circuitry is made up of a comparator/amplifier stage and an inverter stage. The comparator/amplifier stage amplifies the altitude voltage from the potentiometer by three and finds the difference between the amplified voltage and the reference voltage of 2.56 volts. The inverter stage simply inverts the voltage from the comparator/amplifier stage so that it is of the proper polarity for the A/D to read. The digitization of the altimeter reading allowed a resolution of 13.9 ft/bit.

All the equipment was secured in an aluminum pallet in the back seat behind the pilot. Figure 3.3 shows the equipment configuration within the pallet. Figure 3.4 is a photograph of the top view of the pallet after it had been installed in the aircraft with the equipment. A LORAN-C antenna was mounted on the aircraft to receive the LORAN-C signals, and an antenna splitter was used to obtain the glideslope and localizer signals and to decouple the pallet's ILS system from that of the plane. Other than the ILS antennae, the pallet and the equipment was autonomous from the airplane's navigation and electrical equipment. Because of the size and weight of the pallet, a special airworthiness certificate was obtained that placed the aircraft in restricted category while the pallet and equipment were present. Appendix B details the pallet's construction and shows copies of Form 337, the airworthiness cetificate, and various weight and balance configurations for the aircraft.

3.3 METHODOLOGY

The flight tests were done at Hanscom Field in Bedford, Massachusetts because of its proximity and familiarity. The flight tests were a series of four missed approaches to Runway 11. Runway 11 was chosen because of the presence of an ILS. The first run was a standard approach to the runway using the aircraft's ILS. The second, third, and fourth runs were done using the display system. During the second, third, and fourth runs, the pilot intentionally flew weave patterns in order to excite the LORAN-C receiver's dynamics. During all runs, the display program ran displaying the plane's position according to the navigation data and recording all the navigation information. The program was started as the plane passed the outer marker and was stopped once it passed the first set of VASI lights. Also, the time it took for the plane to go from the outer marker to the first set of VASI lights was recorded for each run using a stopwatch. A copy of the program along with the other programs used in this report is in Appendix C.

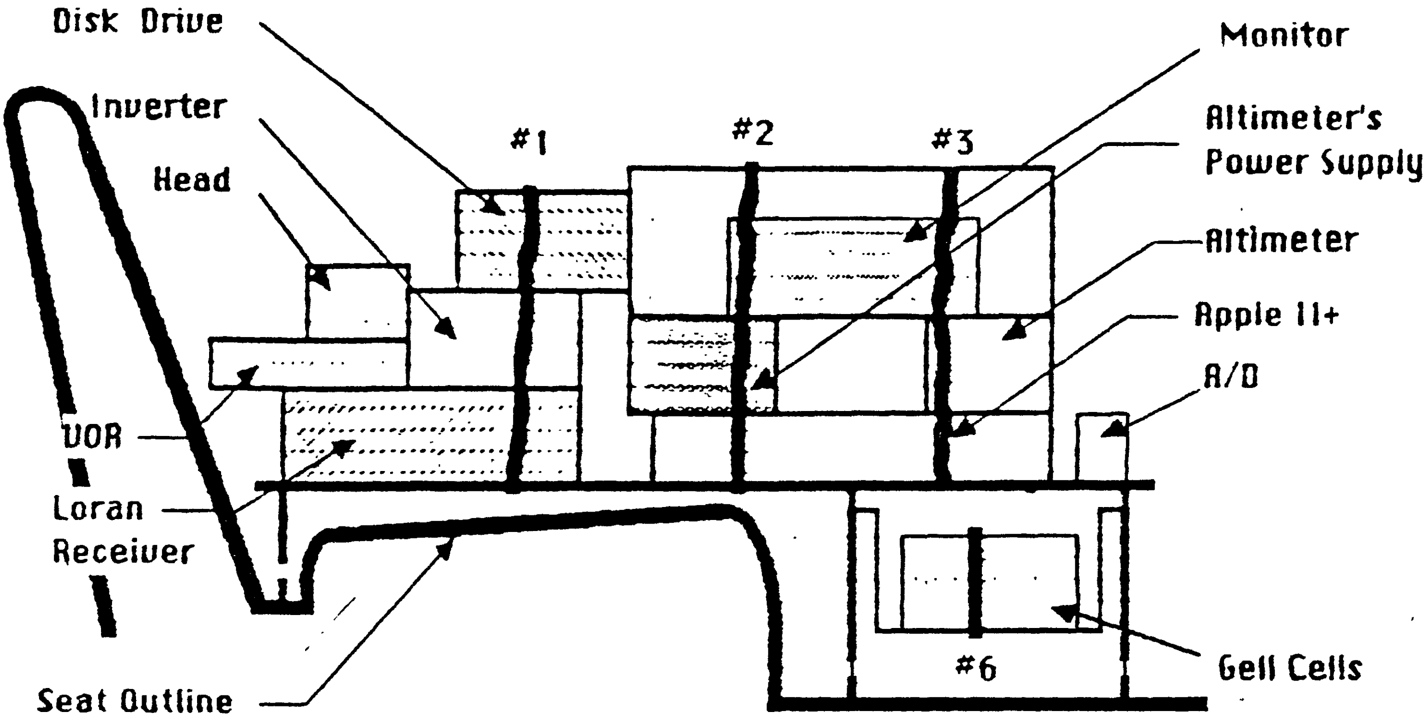


Figure 3.3 - Equipment Configuration Within Pallet.

Figure 3.4 - Top View of Pallet and Equipment in Plane.

CHAPTER 4

ALTIMETER AND LORAN-C TRACKING-LOOP MODELING

4.1 ALTIMETER

4.1.1. Static Modeling

Static errors in measuring true altitude for an altimeter can be broken up into many parts. An experiment on the MIT campus outlined in Appendix A tested the pressure sensitivity of the King Radio altimeter and its ability as a single unit to measure true altitude. The pressure sensitivity of the altimeter is the amount of pressure differential required to cause a detectable change in altitude. The experiment showed that approximately 8 feet (0.008 in Hg) of pressure difference is enough to cause a change in displayed altitude. The altimeter's ability to measure true altitude is dependent on its pressure sensitivity and the assumed relationship between measured pressure and altitude. The altimeter measured pressure without any interfacing tubing or equipment. Using a standard atmosphere model, the results showed that for the altitude range from 0 ft to 500 ft, the error in altitude measurement was within the ±20 ft stated by the manufacturer in Figure A.4 which shows the manufacturer's accuracy specifications for the King Radio KEA-346 altimeter.

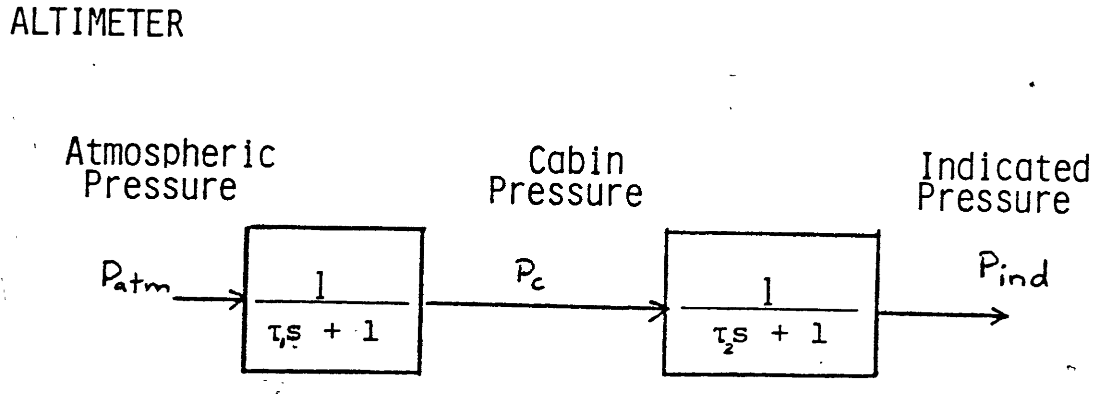
Further breakdown of the static errors of the altimeter in measuring true altitude was not attempted.

4.1.2. Dynamic Modeling

In the dynamic modeling of the altimeter, it was assumed that there were two lags: stiction and pressure lag. Stiction lag, which is because of mechanical effects in the altimeter such as the indicator needle sticking, in the altitude measurement, corresponding to pressure sensitivity in the previous section, is measured as the pressure differential required to cause a detectable change in altitude. Pressure lag in the altitude measurement occurs because the cabin pressure that is measured by the altimeter takes a finite amount of time to adjust to changes of the outside atmospheric pressure. If other means to measure the atmospheric presure such as connecting to tubing that was attached to a port to the outside were used, the amount of lag would probably differ from the pressure lag mentioned above though how the lags differed would not be known unless further testing was done on this aspect.

Both lags were modeled as first-order systems to produce a second-order model for altitude measurement, as illustrated in Figure 4.1.

A step response of the system represented in Equation 4.1 (see Figure 4.1) would have the time domain form shown in Equation 4.2.



$$\frac{P_{ind}}{P_{atm}} = \frac{1}{(\tau_1 s+1)(\tau_2 s+1)} \tag{4.1}$$

$s \equiv$Laplace variable

$\tau_1 \equiv$pressure equalization time constant (seconds)

$\tau_2 \equiv$stiction time constant (seconds)

Figure 4.1 - Dynamic Modeling of Altimeter.

$$P_{ind}(t) = 1 - [(\tfrac{v}{v-1})(e^{-\tau_1 t} - (\tfrac{1}{v})e^{-v\tau_2 t})] \tag{4.2}$$

$P_{ind} \equiv$ indicated pressure (indicated altitude)

$\tau_1 \equiv$ pressure equalization time constant

$\tau_2 \equiv$ stiction time constant

$v \equiv \frac{\tau_1}{\tau_2}$

$$P_{ind}(t) \simeq 1 - e^{-\tau_1 t} \tag{4.3}$$

Equation 4.2 can be simplified to the form in Equation 4.3 if it is assumed that τ_1 is much greater than τ_2. Physically, assuming τ_1 is greater than τ_2 is the same as assuming that the pressure lag is more significant than the stiction lag. One reason for this assumption is because of the good pressure sensitivity of the altimeter mentioned in the previous section. For an airplane flying along a three-degree glideslope at 80 knots (133 ft/sec), it would only take approximately 1.1 sec for the airplane to move a vertical distance of 8 feet so that the time constant (τ_2) associated with the stiction lag could be estimated as 0.37 sec.

4.2 LORAN-C TRACKING LOOP MODEL

The model for the tracking loop of the Micrologic ML-3000 LORAN-C receiver was taken from Reference 6. In Reference 6, Reilly discusses the manner in which a LORAN-C receiver may be changed from an analog system to a digital one. The second-order model that he discusses is shown in Equation 4.4. The parameter values shown in Equation 4.4 would not easily be obtained from LORAN-C manufacturers because of the propriety nature of the knowledge.

$$H_{cl}(s) = \frac{2\varsigma\omega_n s+\omega_n{}^2}{s^2+2\varsigma\omega_n s+\omega_n{}^2} \tag{4.4}$$

H_{cl}≡closed-loop transfer function of LORAN-C tracking loop

s ≡Laplace variable

ς ≡damping ratio

ω_n ≡natural frequency

Figure 4.2(a) shows the dynamic response of TD's for an experiment done by A. Elias (Reference 2). The experiment involved driving a car that was fitted with the Micrologic LORAN-C receiver and antennae, between two surveyed points over an open road at a speed of approximately 13 m/sec with 0.3 g's of acceleration at the start and 0.4 g's of deceleration at the end. The TD response when compared to the actual vehicle position and to the nondimensional second-order responses in Figure 4.2(b) indicates that the damping ratio of the tracking-loop model in Equation 4.4 is approximately 0.5. The result of the foregoing is that Equation 4.4 can be reduced to Equation 4.5, from which relations between the natural frequency and time response (Equation 4.6) and the natural frequency and phase angle (Equation 4.7) can be deduced.

$$H_{cl}(s) = \frac{\omega_n s + {\omega_n}^2}{s^2 + \omega_n s + {\omega_n}^2} = \frac{\sqrt{K_A} s + K_A}{s^2 + \sqrt{K_A} s + {K_A}^2} \qquad (4.5)$$

$K_A \equiv$ Loop Acceleration Constant (s^{-2})

$$(Response \quad Time) = (\frac{1}{\omega_n})(\frac{2}{\sqrt{3}}) tan^{-1}(\sqrt{3}) \simeq \frac{1.2092}{\omega_n} = \frac{1.2092}{\sqrt{K_A}} \qquad (4.6)$$

$$\phi = tan^{-1}((\frac{\omega}{\omega_n})^3) \qquad (4.7)$$

ϕ ≡phase angle (rad)

ω ≡input frequency (rad/sec)

ω_n≡loop natural frequency (rad/sec)

Analysis on the flight data wil be used to verify this model and estimate the time response of the tracking-loop.

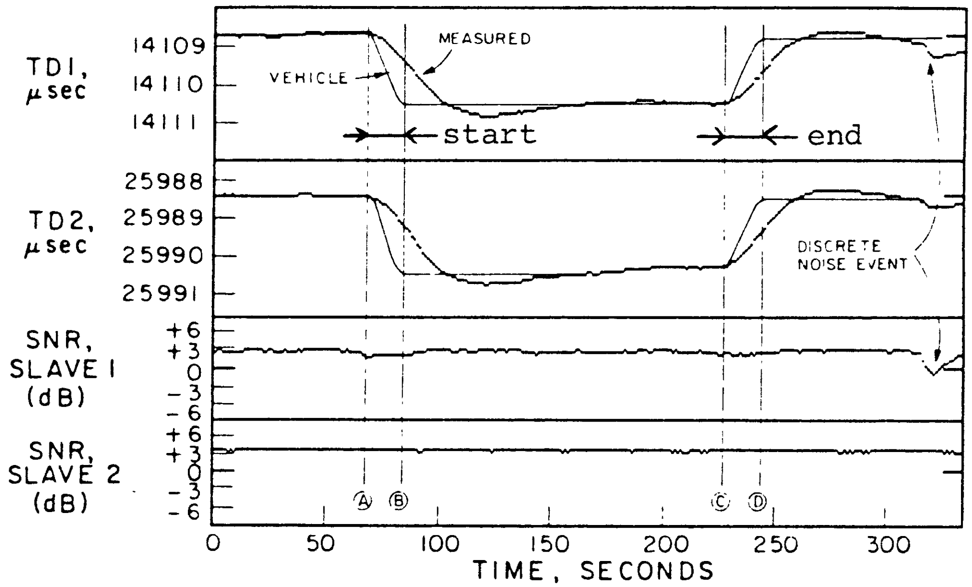


Figure 4.2(a) - TD response for car experiment (from Reference 2).

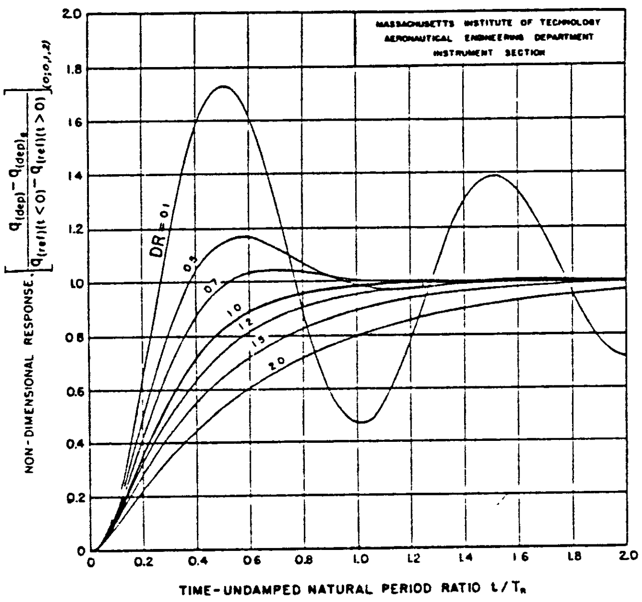


Figure 4.2(b) - Non-dimensional second-order step responses.

Figure 4.2 - Relationship between TD response and second-order system.

CHAPTER 5: FLIGHT TEST RESULTS AND ANALYSIS

5.1 FLIGHT TEST RESULTS

5.1.1 Description of Flight Tests

A series of four flights were done at Hanscom Air Force Base in Bedford, Massachusetts on December 20, 1985. Each flight was a missed approach to Runway 11 using the outer marker and first vassy as reference points. Before the outer marker was reached, the display program was prepared, and when the plane passed over the outer marker, the copilot verbally informed the flight engineer who then started the display program by pressing any key on the keyboard. During the flight, the display program not only displayed the navigation data but also recorded the LORAN-C data from the ML-3000 LORAN-C receiver, the localizer and glideslope information from the ILS, and altitude information from the King Radio altimeter. When the plane passed over the first set of VASI lights, the copilot signalled the flight engineer to stop the display program. The display program then saved all the recorded navigation into a file whose name was specified by the flight engineer. The duration of each flight test and the estimated along-track ground speed for each flight is shown in Table 5.1. The foregoing description of the flight plan for each flight was departed from for certain flights, in which air traffic at Hanscom didn't

Flight	Time (sec)	Average Approach Speed (ft/sec)
1	124	116.1
2*	93	154.8
3	113	127.4
4*	89	161.8

*Possible Error in Approach Speed

Table 5.1 - Flight Test Summary

allow us to reach the first set of VASI lights. The inaccuracies that are possible in the estimation of along-track ground speed for these cases are noted in Table 5.1.

The first flight was an ILS approach to Runway 11 with the display program recording all the navigation data; the three succeeding flights were approaches done using the display to guide the plane and record the navigation data. Unfortunately, because of a bug in the display program, the three flights done using the display had an approach angle of approximately 9.8 degrees, as will be illustrated in the following section, so that only XTK navigation was present.

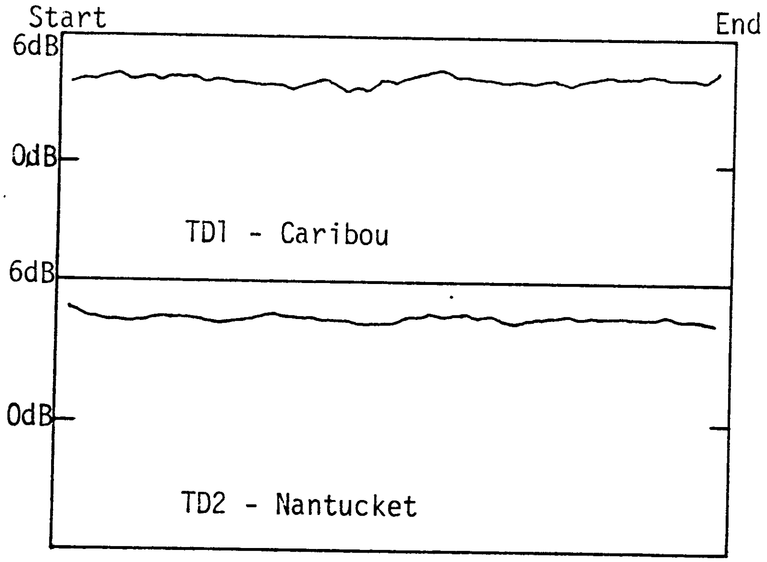
5.1.2 Plots of Flight Tests

The navigation data that was of interest was TD's, localizer angle, glideslope (ILS) angle, and altitude. The TD's were recorded with a resolution of 1/160 of a microsecond (μsec) per bit; the localizer angle with a resolution of 0.025 deg/bit; the glideslope (ILS) angle with a resolution of 0.007 deg/bit; and altitude with a resolution of 13.9 ft/bit. The reading corresponding to zero degrees deviation for both the localizer and glideslope of the ILS was measured in the laboratory.

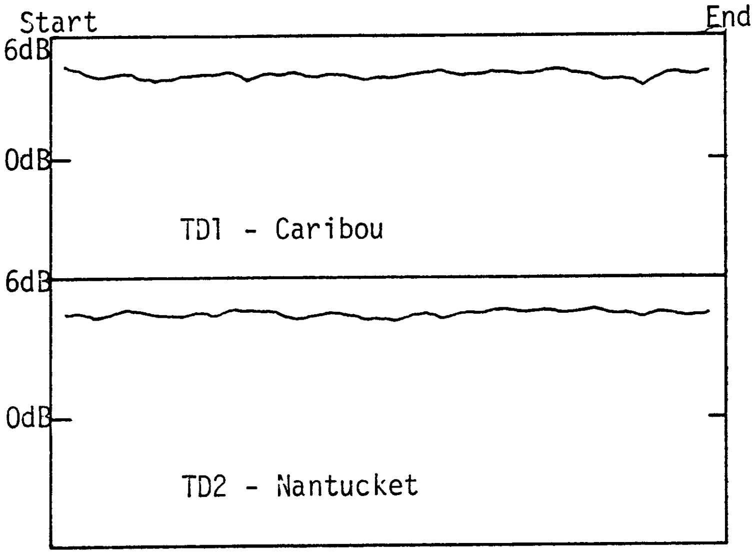
Figure 5.1 and Figure 5.2 show the signal-to-noise ratios (SNR's) for the two slave stations (Caribou and Nantucket) of the 9960 LORAN-C chain that were used for the flight testing as functions of time during the flight test.

Table 5.2 shows the SNR averages of the master (Seneca), Slave 1 (Caribou), and Slave 2 (Nantucket) for each of the flights. Slave 1's SNR on average was above 4 dB for all the flights, and Slave 2's SNR and the Master's SNR were both on average above 6 dB. In Figure 5.2 for the third approach, Slave 2's SNR showed a sharp drop at the end of the approach and Slave 1's SNR showed a sharp rise. This sudden change of SNR values is because data was taken beyond the first set of VASI lights, so that as the plane banked away from the runway in order to complete the missed approach, the plane blocked the LORAN-C antenna from receiving the Nantucket signal.

Figure 5.3(a) shows a plot of altitude vs. range for Flight 1. The plot shows indicated altitude as given by the altimeter against range as calculated from the LORAN-C data. Recommended altitude, calculated by taking a three-degree tangent of the LORAN-C-derived range, is also plotted against range to give an approximate glide path. Figure 5.3(b) shows a plot of glideslope angle against range. Both the glideslope angle from the ILS glideslope and the one from taking the arctangent of altimeter altitude over LORAN-C-derived range are plotted against range. The

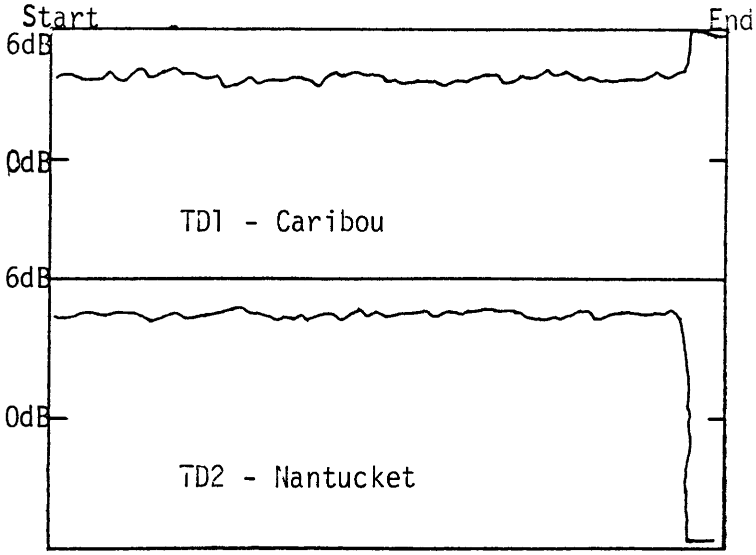


(a) - Flight 1

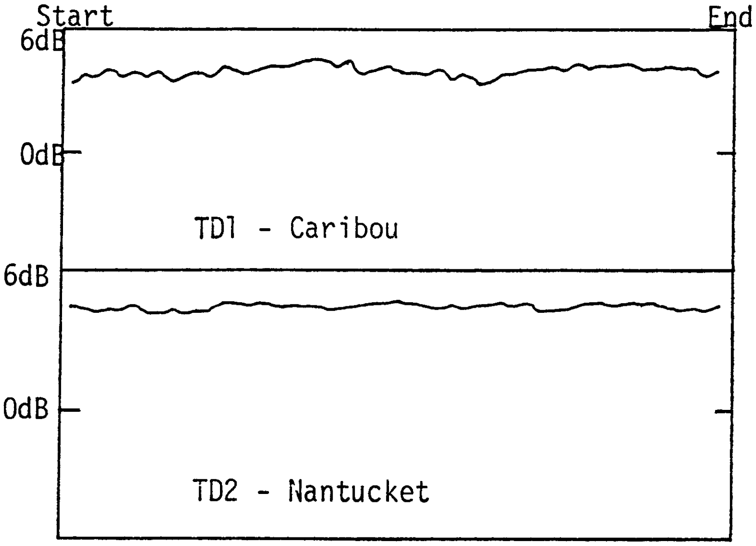


(b) - Flight 2

Figure 5.1 - SNR Plots for Flights 1 and 2



(a) - Flight 3



(b) - Flight 4

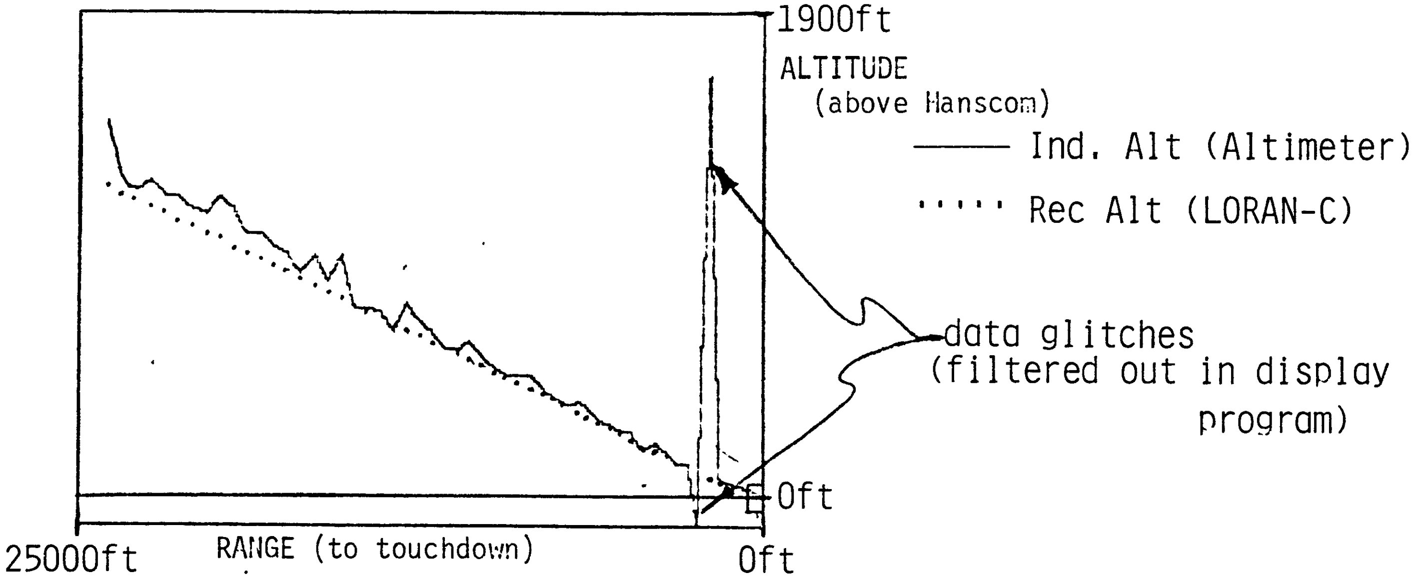
Figure 5.2 - SNR Plots for Flights 3 and 4

Flight	Slave 1 SNR (dB)	Slave 2 SNR (dB)	Master SNR (dB)
1	4.4	6.5	6.5
2	4.4	6.5	6.5
3	4.5	6.5	6.5
4	4.1	6.5	6.4

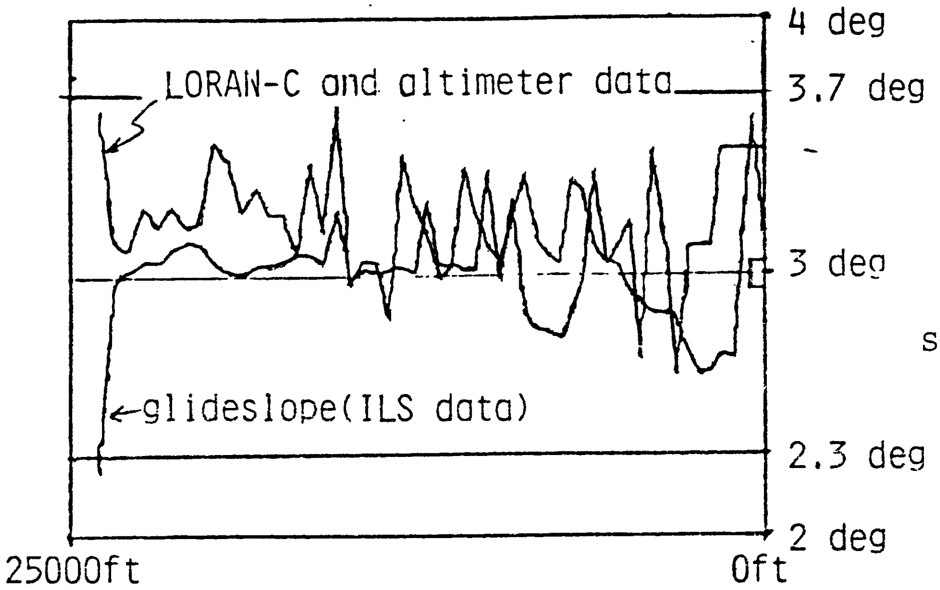
Table 5.2 - SNR Averages for Flight Tests

average difference angle between the ILS glideslope and the arctangent of altitude over range was calculated to be 0.228 degrees with a standard deviation of 0.305 degrees. An average difference angle of 0.228 degrees corresponds to differences in altitude measurement of 24 feet at a range of 1 nm from the touchdown point.

Figure 5.4 shows two plots of altitude versus range for the fourth flight to exemplify the large glideslope (9.8 degrees) that was the result of a bug in the display program. Figure 5.4(a) shows the 9.8 degree glideslope, and Figure 5.4(b) shows the 3.0 degree glideslope that should have been used. Figure 5.4(a) shows how the pilot maintained a constant altitude and then started to descend tangent to the glidepath as the altitude difference between indicated and recommended altitude came within the ±500 ft limits of the display. Because of the bug in the display program, altitude data for the second and third approaches was discarded since there was no alternate set of data to compare them to, since all the altimeter altitude data was out of the limits of the ILS glideslope.



(a) - Altitude Plot



Avg. Error Angle = 0.228 deg

Standard Deviation = 0.31 deg

(b) - Plot of ILS GS Angle and Arctangent Altitude over Range

Figure 5.3 - Altitude and Glideslope Angle vs. Range Plots for Flight 1

Figure 5.5 and Figure 5.6 show XTK vs. range for the four approaches. LORAN-C navigation information is used to provide the data for one plot; and localizer angle information is used to provide the XTK coordinate for the other plot, while the LORAN-C data is used to provide the range or along-track coordinate. Beside each plot is the average error angle between localizer angle and the arctangent of XTK over range* as given by the LORAN-C receiver and the standard deviation of the error angle.

5.1.3 Flyability

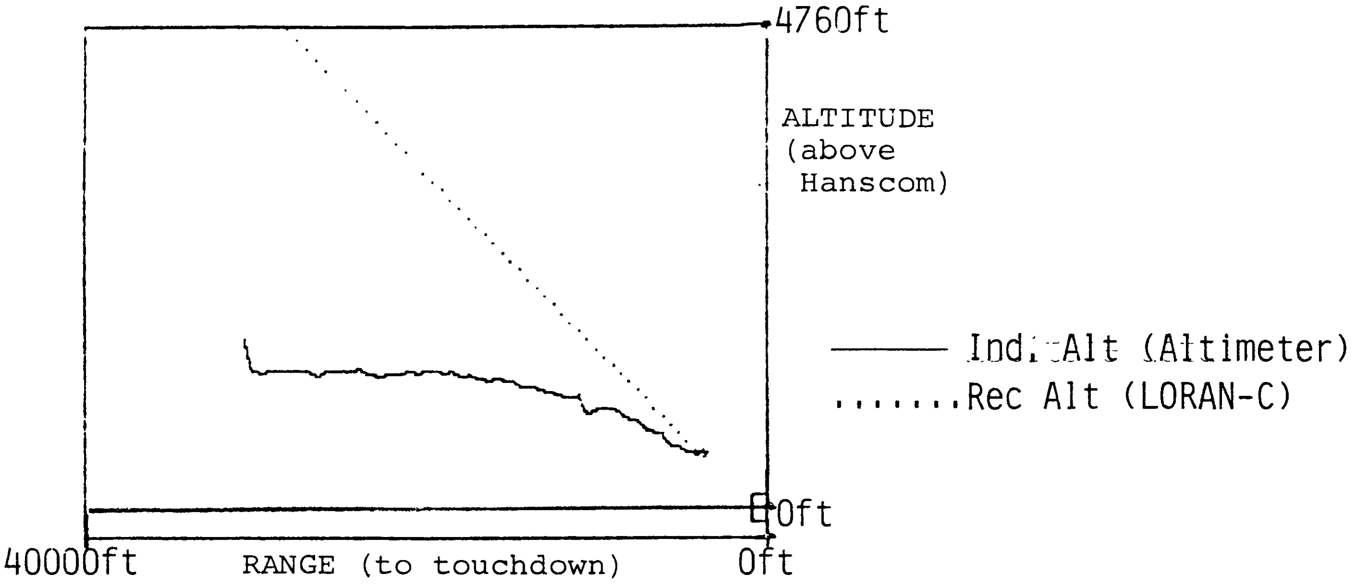
The display's flyability is determined by how well the display form and pilot's expertise interact so that the plane remains as close as possible to the approach path defined by the navigation data.

The pilot has more than 2000 hours flying experience and has flown the Grumman Tiger that was used in the testing a number of times before the flight tests occurred.

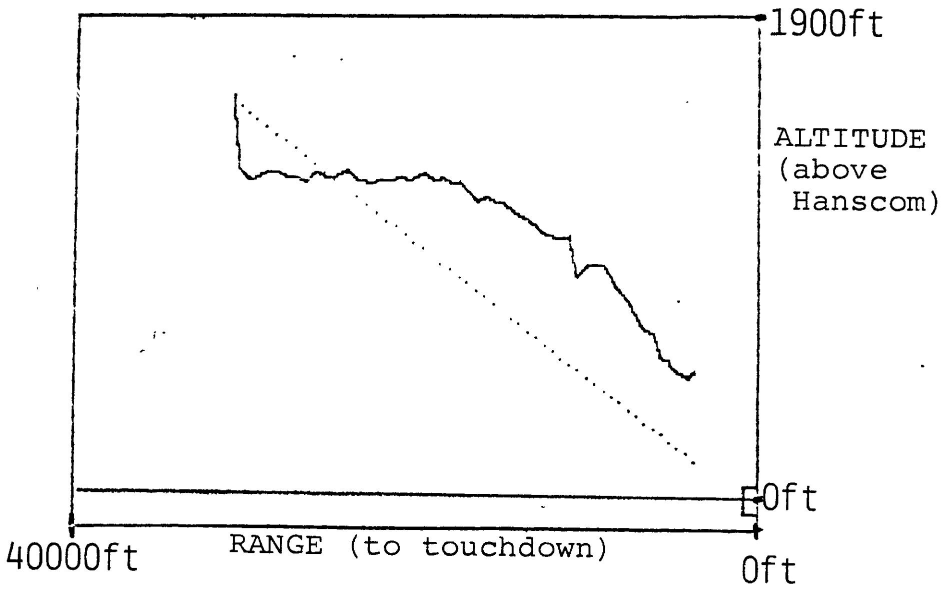
Since there was no vertical guidance because of programming bugs, there was no way to directly assess the display's flyability in this aspect; however, certain observations can be made about the ability of the display's navigation equipment to provide an accurate glideslope by referring to Figure 5.3(b). Figure 5.3(b) shows the results of comparing the ILS glideslope angle to the arctangent of altitude divided by

---

* Range in this case is equal to the range of the plane to the touchdown point plus range (7950 ft) of the touchdown point to the localizer antenna.

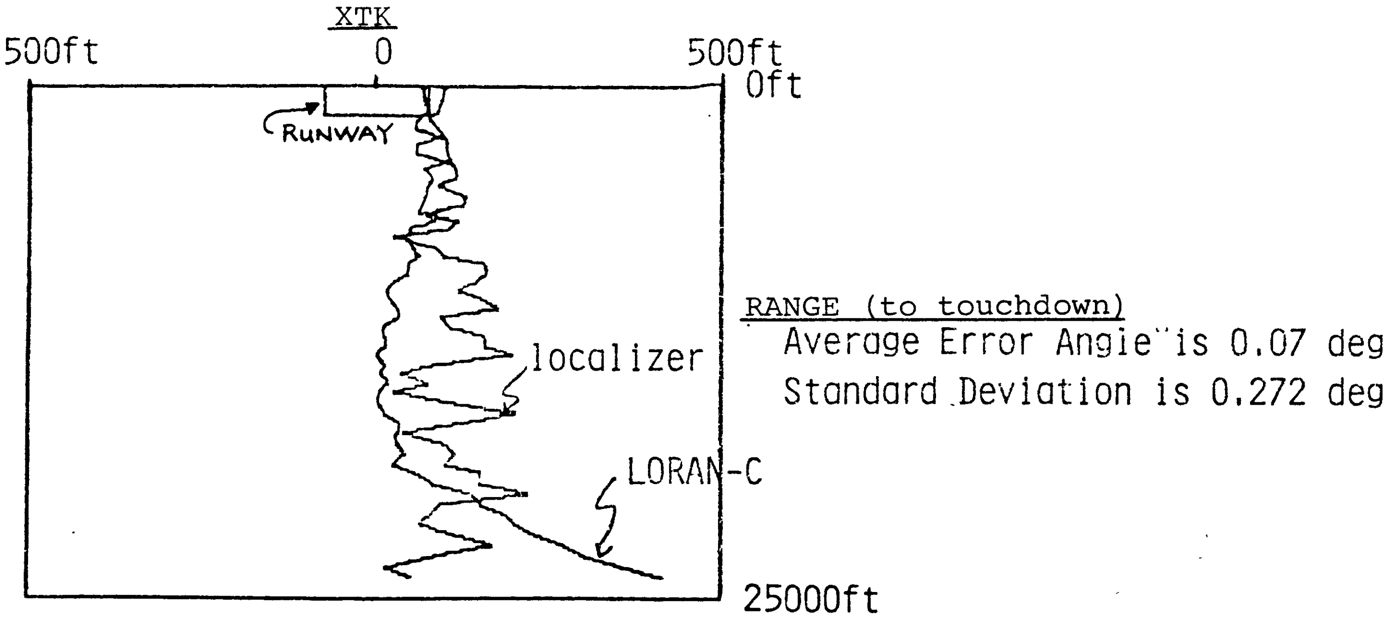


(a) - Altitude Plot with Wrong Glideslope

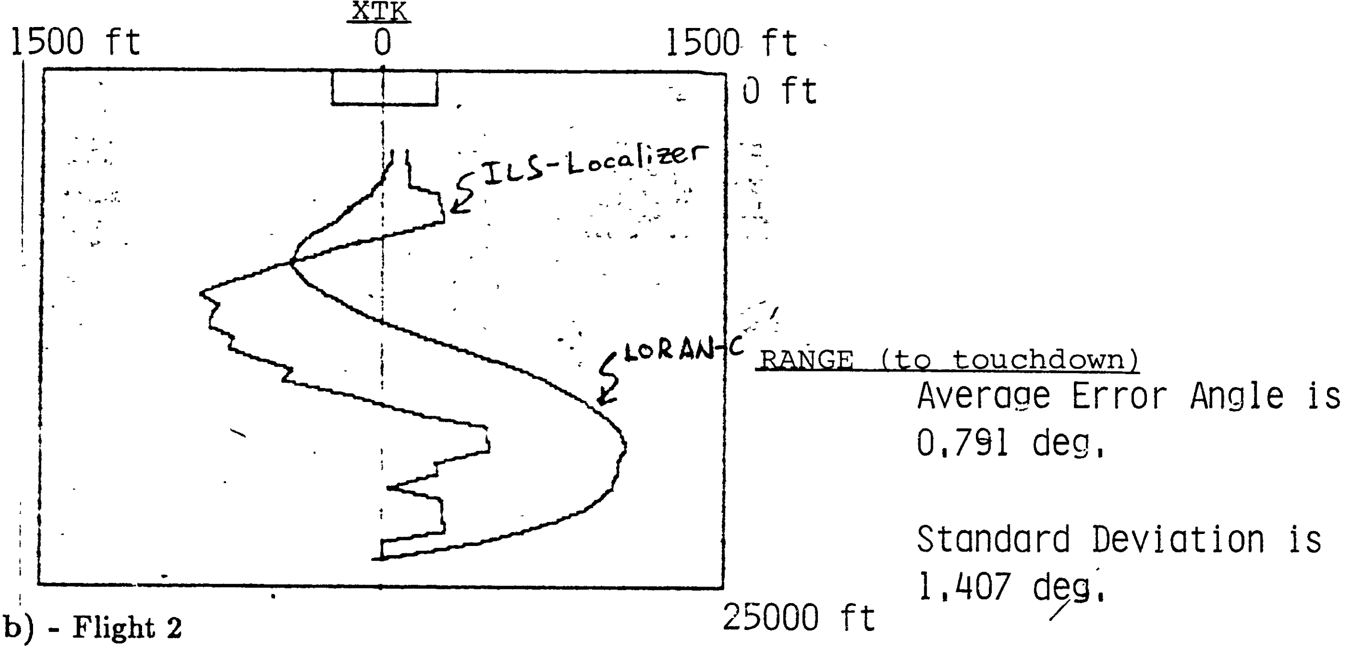


(b) - Altitude Plot with Desired Glideslope

Figure 5.4 - Altitude vs. Range Plots for Flight 4

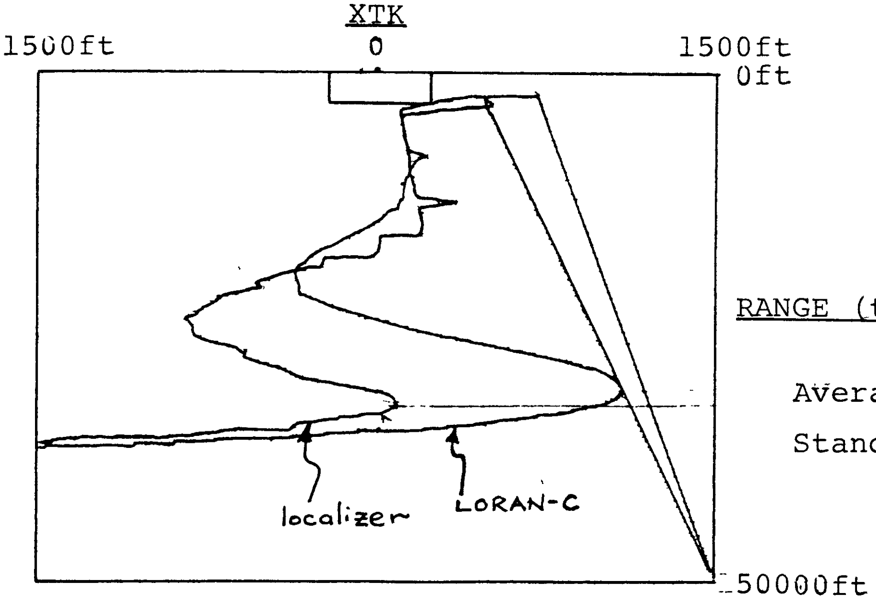


(a) - Flight 1



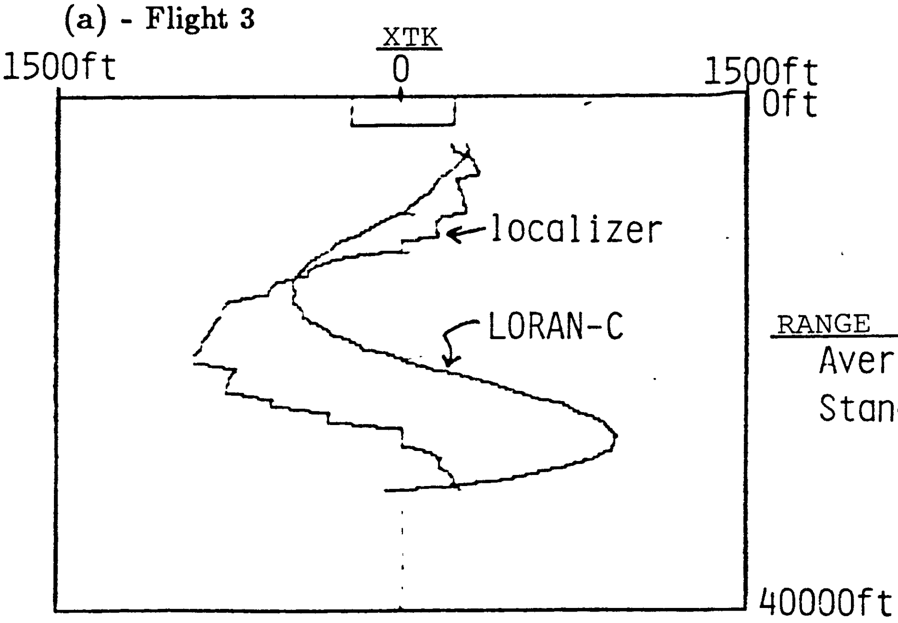
(b) - Flight 2

Figure 5.5 - XTK vs. Range Plots for Flights 1 and 2



Average Error Angle is 0.552 deg.
Standard Deviation is 0.911 deg.

(a) - Flight 3



Average Error Angle is 0.511 deg
Standard Deviation is 1.067 deg

(b) - Flight 4

Figure 5.6 - XTK vs. Range Plots for Flights 3 and 4

LORAN-C-derived range for Flight 1. Though Flight 1 used the ILS display system, Figure 5.3(b) shows that the display's altitude information and LORAN-C-derived range can provide an accuracy comparable to that of the ILS glideslope; however, since the pilot was flying the ILS glideslope, any lags in navigation information from the display may not appear until more maneuvering in the vertical plane excites the dynamics of the altimeter and LORAN-C. With respect to the display form, since the glideslope path defined by the altimeter and LORAN-C was comparable to that of the ILS glideslope, the glideslope-deviation window (see Figure 2.1) should be decreased from ±500 ft to ±200 ft so that the increased sensitivity will cause the pilot to remain closer to the glidepath and to not excite the dynamics of the LORAN-C tracking loop.

The results of maneuvering in the horizontal plane are shown in Figures 5.5 and 5.6. As long as there was no excessive maneuvering so that the LORAN-C tracking-loop dynamics were not excited, the display showed that the plane's XTK position was comparable to the ILS localizer as shown in Figure 5.5(a) for Flight 1; however, with more maneuvering that excited the dynamics of the LORAN-C tracking loops, a large delay on the order of 15 seconds occurred between the display's XTK indication and the ILS localizer, as shown in Figures 5.5(b), 5.6(a), and 5.6(b). The amount of delay experienced is determined by the acceleration of the maneuver and the tracking-loop time constant, which will be analyzed in the following section. The logarithmic outer regions acted well to keep the XTK indicator within the boundaries of the display, so that the pilot could react; however, the non-linearity of the region was disconcerting to the pilot, who expected the movement of the XTK indicator lines to be proportional to the plane's XTK velocity. The pilot also commented that the linear region was too small, since in his maneuvers in Flights 2, 3, and 4 the XTK indicator line swiftly moved from +300 ft to -300 ft; however, since the maneuvering was deliberate, the pilot's comments are applicable only if an approach with excessive maneuvering is expected. Figure 5.5(a) for Flight 1 shows that the plane was well within ±300 ft boundaries of the linear XTK region for a standard ILS approach so that as long as no excessive maneuvering is planned, the XTK indication of the display system provides navigation in the horizontal plane comparable to that of the ILS localizer.

5.2 ANALYSIS OF RESULTS

5.2.1 Serial Time Correlations

In this section, a serial time correlation analysis was done on the flight test data that was recorded, using the Data Analysis Program shown in Appendix C. For Flight 1, the ILS glideslope angle was correlated with the arctangent of the altimeter altitude divided by LORAN-C derived range. For all flights, the ILS localizer angle was correlated with the arctangent of LORAN-C-derived XTK divided by range.

Figure 5.7 illustrates the purpose of doing a serial time correlation. Line 1 and Line 2 represent two independent sets of data for measuring a particular variable over time in Figure 5.7(a). In Figure 5.7(b), if Line 2 is shifted *d* units of time forward, a correlation maximum would occur for a time shift of *d* units. The time shift corresponding to a correlation maximization would indicate that the data-taking method for Line 1 has a delay of d units with respect to that for Line 2.

For the serial time correlation analysis of the flight test data, correlation was measured with the correlation coefficient in Equation 5.l (Equation 8.5 in Reference 7) for successive time shifts. A value of +1 corresponds to perfect positive correlation, 0 to no correlation, and -1 to perfect negative correlation.

$$r = \frac{\sum(x_i-\bar{x})(y_i-\bar{y})}{\sqrt{[\sum(x_i-\bar{x})^2][\sum(y_i-\bar{y})^2]}} \tag{5.1}$$

$r \equiv$ correlation coefficient
$x_i \equiv$ individual measurement in data set 1
$\bar{x} \equiv$ mean of data set 1
$y_i \equiv$ individual measurement in data set 2
$\bar{y} \equiv$ mean of data set 2

As in Figure 5.7, the data sets to be correlated are measured over an interval of time corresponding to the interval t_b to t_e in Figure 5.7. If the data in Line 2 is shifted one unit of time forward, the measurement in Line 2 that has been shifted one unit of time beyond t_e would not have a corresponding measurement in Line 1 for the same time to be correlated against. This fact is also the case for the first point in Line 1. Thus, in order to maintain the validity of the correlation for each time shift, the end point of data set 2 for that particular shift is ignored as well as the beginning point of data set 1 for that particular shift. Thus, as further time

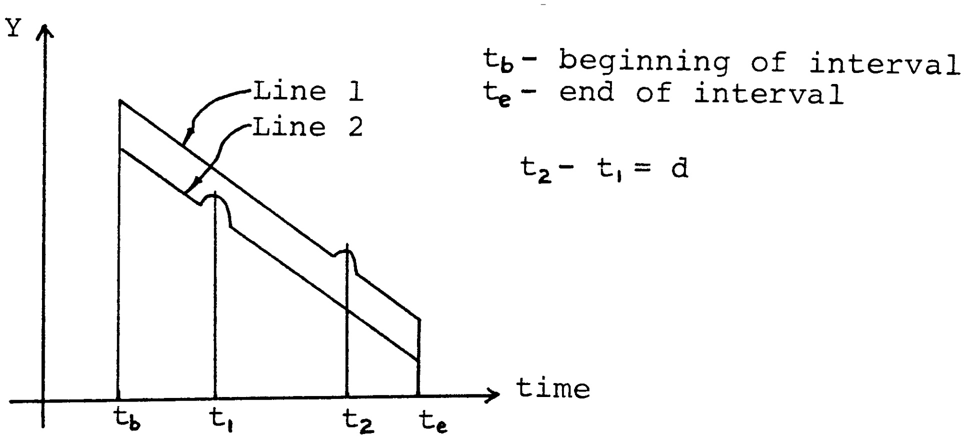


Figure 5.7(a) - Two independent sets of data: Line 1 and Line 2

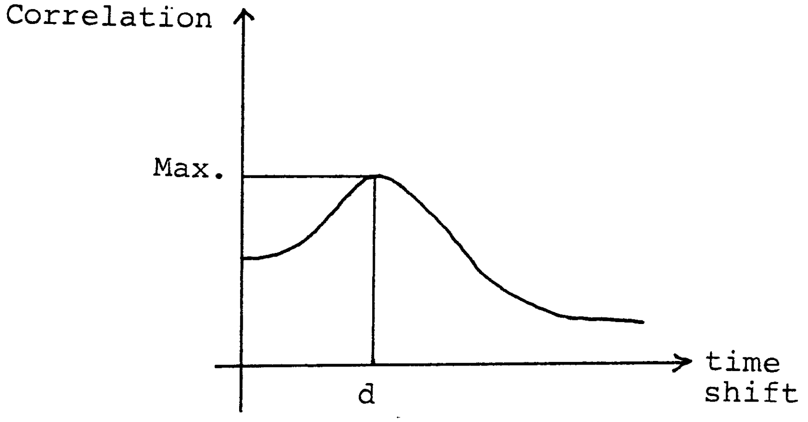


Figure 5.7(b) - Correlation max that occurs by shifting Line 2 *d* units forward

Figure 5.7 - Illustration of Serial Time Correlation

shifts occur, a smaller number of points from each data set are used to calculate the correlation coefficient for each particular time shift. For the flight test data, data set 1 would correspond to the altimeter and LORAN-C data, and data set 2 would correspond to the ILS glideslope and localizer data. The reason for that is that the ILS data is assumed to give the actual position of the plane while the altimeter and LORAN-C data is assumed to have delays.

Figure 5.8 shows the serial correlation plot for ILS glideslope angle and the arctangent of altitude divided by LORAN-C-derived range for Flight 1. A peak of 0.39 occurs at a time shift of 4.8 seconds. This low peak at first glance does not seem significant, but a student t-test on the statistic $\frac{r\sqrt{n-2}}{\sqrt{1-r^2}}$, where r is the correlation coefficient and n is the number of points, shows that the peak is statistically significant at the 95% confidence level.

Figure 5.9(a) shows the serial correlation plot for ILS localizer angle and the arctangent of LORAN-C-derived XTK divided by range for Flight 1. A maximum of 0.92 occurs at a time shift of zero.

Figure 5.9(b) shows the serial correlation plot for ILS localizer angle and the arctangent of LORAN-C-derived XTK divided by range for Flight 2. A maximum of 0.92 occurs at 13.2 seconds.

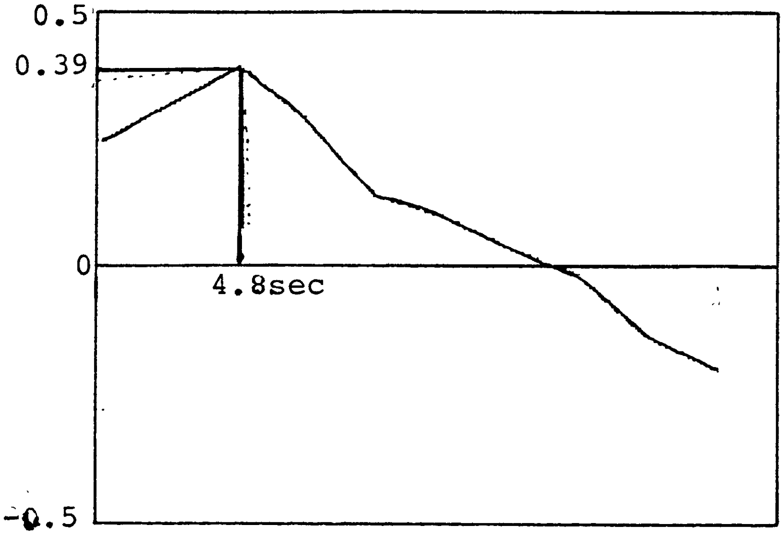
Figure 5.10(a) shows the serial correlation plot for ILS localizer angle and the arctangent of LORAN-C-derived XTK divided by range for Flight 3. There is a maximum of 0.68 at a time shift of zero.

Figure 5.10(b) shows the serial correlation plot for ILS localizer angle and the arctangent of LORAN-C-derived XTK divided by range for Flight 4. A maximum of 0.96 occurs at a time shift of 13.2 seconds.

5.2.2 Relationship between Equipment Dynamics and Delays

In Chapter 4, dynamic models were made for the altimeter and LORAN-C tracking loop. The altimeter model was theorized to be able to be represented by a first-order model (Equation 4.3). The LORAN-C tracking loop model was theorized to be similar to the one used in Reference 6 (Equation 4.5) – a second-order model with one zero and two poles.

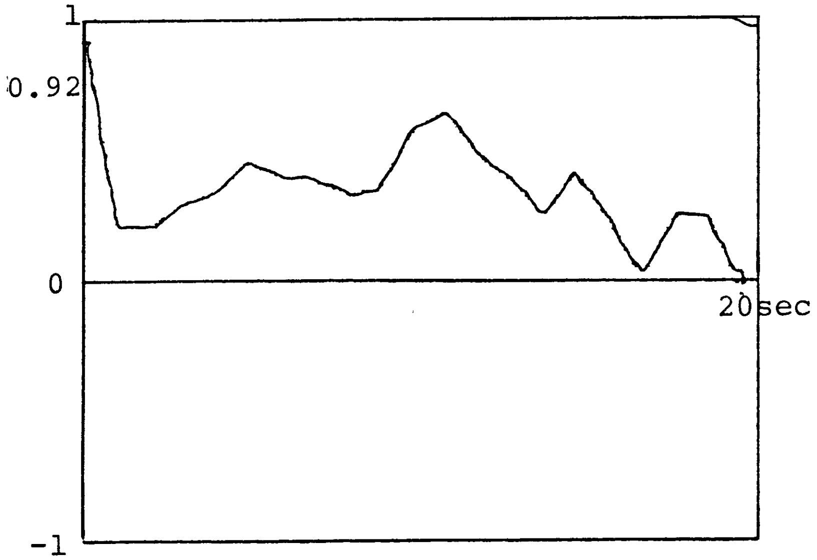
In the last section, a delay of 4.8 seconds was found to exist between the ILS glideslope angle and the arctangent of altitude divided by LORAN-C-derived range. The plane's velocity vector in the horizontal plane can be divided into two components: XTK and along-track components. The along-track component of the plane's velocity vector is relatively constant as the plane moves from the outer marker to the first set of VASI lights. With a constant along-track velocity, the range to the touchdown point then linearly decreases so that, since the LORAN-C tracking-loop model is second-order, there would be no delays in the range measurement using the TD's. The arctangent of altitude divided by LORAN-C-derived range can be approximated as altitude divided by range, since the glideslope angles are small. Since range can be thought of as true range, the delay of 4.8 seconds can be attributed to the altimeter. For a first-order system, the delay between a ramp input



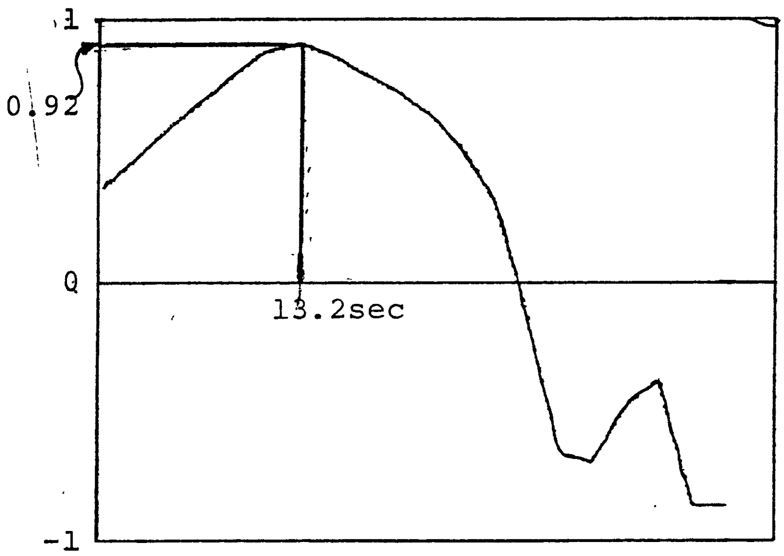
Correlation of GS angle
and arctan (h/RA)

Peak of 0.39 at 4.80S
is statistically significant
at 95% confidence level

Figure 5.8 - Serial Time Correlation Plots of Glideslope Angles for Flight 1

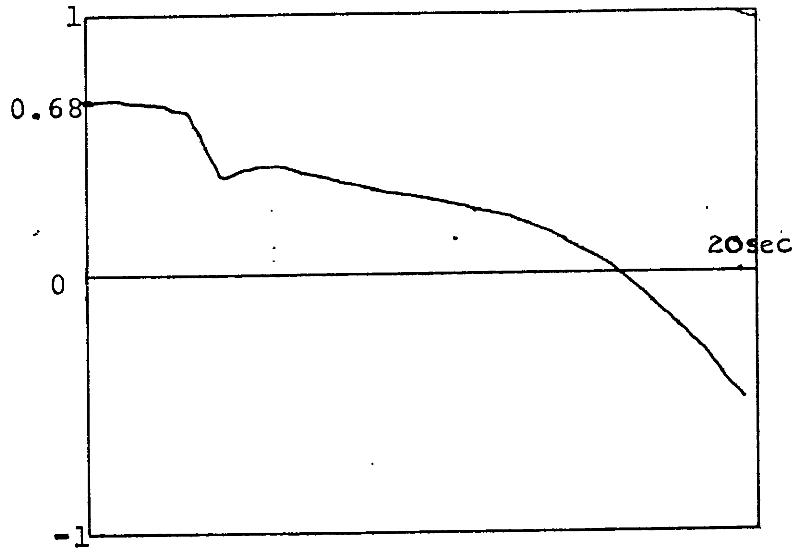


(a) - Flight 1

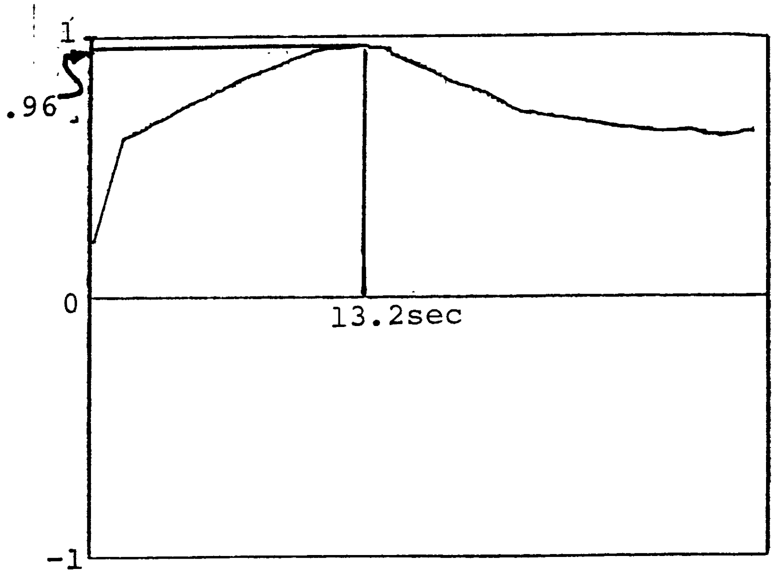


(b) - Flight 2

Figure 5.9 - Serial Time Correlation Plots of Localizer Angle and Arctangent of LORAN-C-Derived XTK and Range.



(a) - Flight 3



(b) - Flight 4

Figure 5.10 - Serial Time Correlation Plots of Localizer Angle and Arctangent of LORAN-C-Derived XTK and Range.

and the output after transients subside is equal to the time constant of that first-order system. Thus, the τ_1 in Equation 4.3 is equal to the delay of 4.8 seconds from the serial correlation analysis, which is approximately 13 times larger than τ_2 in Equation 4.2, supporting the assumption made in Section 4.1.2 that τ_1 is much greater than τ_2.

Also, in the last section, serial correlation analysis plots were done for the ILS localizer angle and the arctangent of LORAN-C-derived XTK divided by range. With a similar argument as in the last paragraph, a maximization in correlation for a particular time shift corresponds to a delay between LORAN-C-derived XTK and ILS localizer angle. Since the XTK maneuvers were sinusoidal in nature, this delay is actually a phase delay and is dependent upon the frequency of the maneuver accounting for the variety of different serial correlation plots. For Flight 1, there was little XTK maneuvering so that the XTK velocity component was relatively constant so that the maximum in correlation occurred at zero time shift as shown in Figure 5.9(a). For Flight 2, there was substantial maneuvering, and a maximum in correlation occurred at 13.2 seconds, as shown in Figure 5.9(b). For Flight 3, there was also substantial maneuvering, but the maximum in correlation occurred at zero time shift, as shown in Figure 5.10(a). The reason for the foregoing, which will be addressed in more detail subsequently, is because of the frequency of the maneuvers. For Flight 4, there was substantial maneuvering, and a maximum in correlation occurred at 13.2 seconds, as shown in Figure 5.10(b).

In order to substantiate that the time shifts corresponding to maximums in correlation are phase delays, a fast Fourier analysis, using a program shown in Appendix C was done on the localizer angle and arctangent of XTK divided by range sets of data for Flight 3, to determine the frequency components and the magnitude of the frequency components in each data set. The data sets of Flight 3 were used because of the large number of points available for analysis. The magnitudes of the frequency components for the arctangent data were then divided by the corresponding ones for the ILS data and plotted against frequency in a log-log plot in order to produce a Bode magnitude plot. This Bode magnitude plot was then compared to a theoretical one based on the LORAN-C tracking-loop model in Equation 4.5. The plots are shown in Figure 5.11 and show that the LORAN-C tracking-loop model corresponds to a second-order model with a damping ratio of 0.5 (discussed in Section 4.2) and a time constant of 18 seconds or natural frequency of 0.0672 rad/sec (using Equation 4.6).

The major frequency component of the initial XTK maneuvers that are shown in Figure 5.5(b) and Figure 5.6(b) for Flight 2 and Flight 4, respectively, have a period corresponding to 93 sec or a frequency of 0.0676 rad/sec. Using Equation 4.7, for the theoretical case a phase lag of 45.5 degrees or approximately 12 seconds should occur. This phase lag of 12 seconds corresponds well with the delay of 13.2 seconds from the serial correlation analysis for Flight 2 and Flight 4.

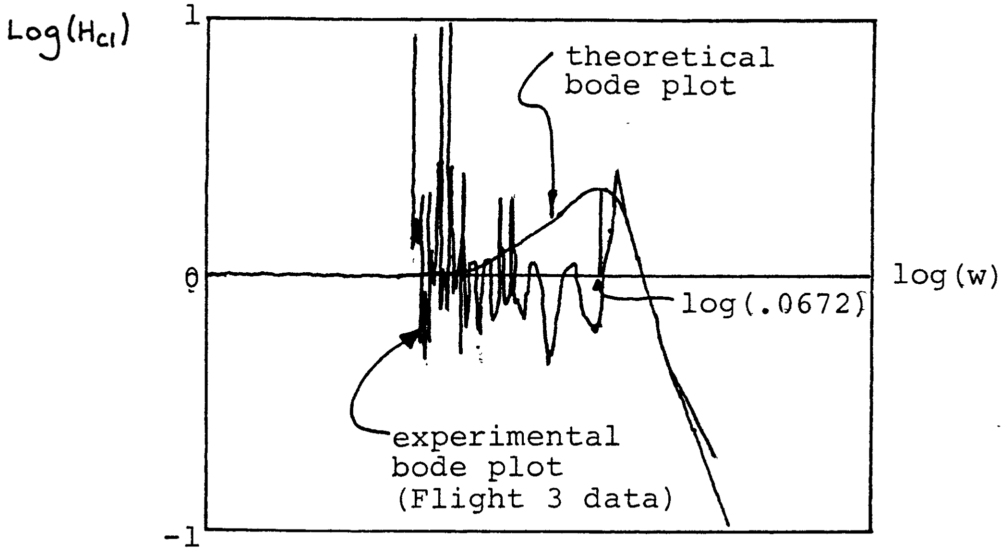


Figure 5.11 - Experimental and Theoretical Bode Plots

The major frequency components for the XTK maneuvers for flight 3 have periods of 9 seconds and 38 seconds corresponding to periods of 0.70 rad/sec and 0.16 rad/sec, respectively. Both of these frequencies are significantly out of the bandwidth of the tracking loop with a natural frequency of approximately 0.0672 rad/sec, accounting for no correlation maximizations occurring at points other than zero time shift in Figure 5.10(a).

CHAPTER 6 - CONCLUSIONS

The purpose of this report was to test the flyability of the display form discussed in Chapter 2 for final approach guidance using an altimeter and a LORAN-C receiver and to study the dynamics of the LORAN-C tracking loop.

Because of bugs in the display program, the recommended glidepath referenced by the display to give glideslope deviation had a 9.8 degree slope instead of the standard 3.0 degree, so that the vertical guidance of the display could not be directly assessed. From observations of the plot of ILS glideslope angle and the arctangent of altitude divided by LORAN-C-derived range for Flight 1 shown in Figure 5.3(b), the display's navigation equipment – King Radio KEA-346 altimeter and Micrologic ML-3000 LORAN-C receiver – provides navigation data that can produce a glidepath comparable to that of the ILS glideslope as long as there is no excessive maneuvering so that the dynamics of the LORAN-C tracking loop are not excited. The amount of maneuvering that can be done is dependent on the time constant of the tracking loop and the noise environment. In order to force the pilot to stay close to the glidepath and to prevent excitation of the LORAN-C tracking-loop dynamics, the glideslope deviation window for the display should be decreased from ± 500 ft to ± 200 ft to increase the sensitivity of changes in indicator position to changes in glideslope deviation.

The guidance in the horizontal plane provided by the display is comparable to that of the ILS localizer as long as there is no excessive maneuvering so that the LORAN-C tracking-loop dynamics are not excited. The limit of maneuvering is determined by tracking-loop time constant and the noise environment. The use of a logarithmic relation between actual XTK position and XTK indicator position in the display for XTK deviations greater than 300 ft and less than 3000 ft provides a large XTK window for the pilot to use for initial approach alignment, although the non-linearity is sometimes confusing.

The Micrologic ML-3000 LORAN-C receiver's tracking-loop dynamics can be modeled as a second-order system (Equation 4.5) with a damping ratio of 0.5 and a filter time constant of 18 seconds. There was not enough testing to provide observations on the opposing characteristics of noise (SNR's) and tracking-loop bandwidth; however, in the very good SNR environment of 4dB and above, the maneuvering was limited by the tracking-loop bandwidth of 0.011 Hz.

Further testing should implement the corrections in the display program and glideslope-deviation window to retest the flyability of the display form and should do flight tests in a variety of SNR environments using different filter time constants to obtain further experimental observations on the opposing desires of large bandwidth and low noise.

APPENDIX A - STATIC TESTING OF ALTIMETER

A.1 INTRODUCTION

A method for testing the altimeter (King Radio: KEA-346) used in the Apple Graphics Display was to compare its altitude output with a reference. The references in this case were the floors in a high-rise building located on MIT campus. The building - Tang Hall - has twenty-four stories and houses graduate students.

The testing procedure and analysis are presented in this appendix in order to substantiate the manfacturer's claims of accuracy shown in Figure A.4.

A.2 METHODOLOGY

The altimeter was used to measure the altitude of successive floors in Tang Hall. Tang Hall which is a twenty-four storey building has three elevators which all go from the ground floor to the twenty-fourth floor. An exterior drawing of Tang Hall is shown in Figure A.1.

Using one elevator for seventy minutes, two runs were made from the ground floor to the twenty-fourth floor stopping at each floor. At each floor, the wiper voltage of the altimeter that was directly proportional to the displayed altitude was recorded. At the beginning of each run, the voltage from the power supply was measured to assure that it was constant over the testing period. A diagram of the equipment is shown in Figure A.2.

A.3 ANALYSIS

A.3.1 Error Analysis

The error can be divided into two categories: error attributable to the voltage measuring instrument and error attributable to the altimeter.

The voltage measurements were done using a Fluke 8060A Multimeter. The 2-volt scale was used to measure the altimeter's wiper voltage and the 200-volt scale to measure the supply voltage (see Figure 2). The error involved with measuring on each scale is given below:

$$\text{2-volt scale : Error} = \pm[(0.04\% \text{ of reading }) + 0.0002 \text{ volts}] \tag{1}$$

$$\text{200-volt scale : Error} = \pm[(0.05\% \text{ of reading }) + 0.02 \text{ volts}] \tag{2}$$

The altitude can be calculated from the following equation that was given by the manufacturer:

$$A = 60000((V_m/V_s) - 0.05) \tag{3}$$

$A \equiv$Altitude (feet)

$V_m \equiv$Wiper Voltage (volts)

$V_s \equiv$Supply Voltage (volts)

The error in the altitude measurement because of the Fluke 8060A multimeter can be expressed by the following equation:

$$\delta A = (60000/V_s)\delta V_m + (60000V_m/V_s^2)\delta V_s \qquad (4)$$

δA ≡Altitude Error because of the Fluke 8060A multimeter (feet)
δV_m≡Wiper Voltage Error (volts)
δV_s ≡Source Voltage Error (volts)

The error attributable to the Fluke 8060A Multimeter was calculated for each altitude measurement. By comparing the difference between the altitude measurement and the actual value with the error attributable to the Fluke 8060A, an estimate of the error attributable to the altimeter was done, as shown below in Equation (5).

$$\begin{pmatrix} Calculated \\ Altitude \end{pmatrix} = A_m = A_0 + \Delta A_1 + \Delta A_2$$

$$\Delta A_1 = \mid (A_m - A_0) - \Delta A_2 \mid$$

$$\Delta A_1 = \mid (A_0 - A_m) + \Delta A_2 \mid$$

$$Therefore, \quad \Delta A_1 = \begin{pmatrix} Altitude \\ Difference \end{pmatrix} + \begin{pmatrix} Fluke \quad 8060A \\ Measurement \quad Error \end{pmatrix} \qquad (5)$$

A_0 ≡Actual Altitude (feet)
ΔA_1≡Altimeter Error (feet)
ΔA_2≡Fluke 8060A Measurement Error (feet)
(Same as δA in Equation (4))

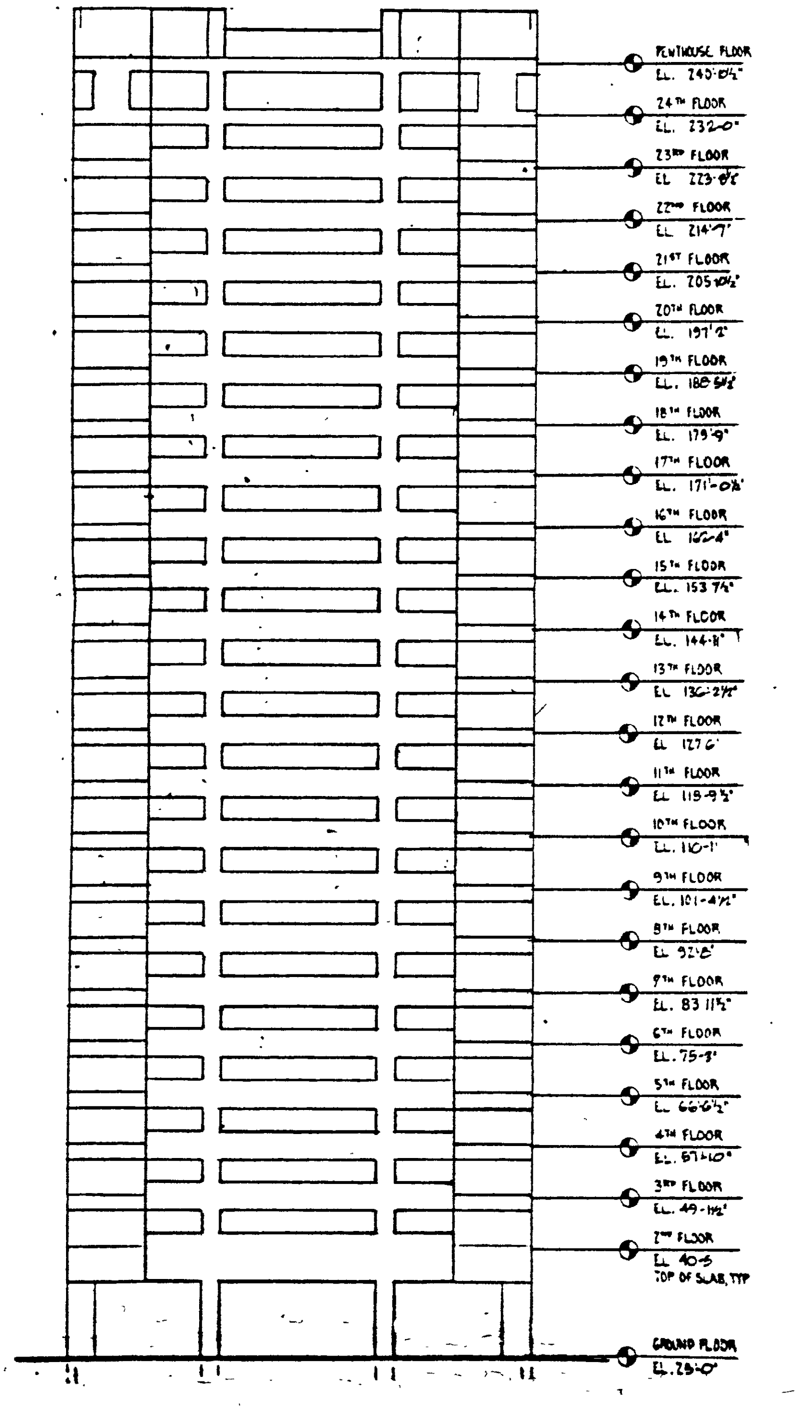


Figure A.1 - Exterior Schematic of Tang Hall.

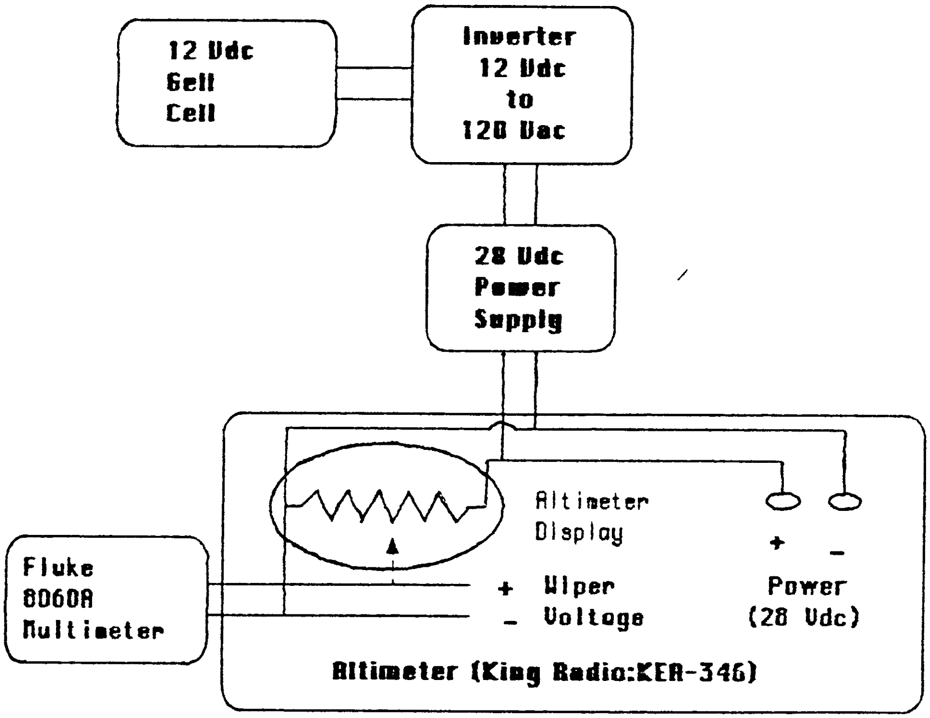


Figure A.2 - Equipment used to test the Altimeter.

A.3.2 Data Analysis

Table (A.1) shows the voltage measurements obtained from each run, their average, the corresponding altitude, and the actual altitude. The pressure setting of 30.14 inHg was obtained from a 10:00 am weather forcast, and the testing was done from 1:15 pm to 2:25 pm accounting for the large discrepancy between the actual and calculated altitudes.

Table (A.2) shows the actual and calculated altitudes referenced to the first floor of Tang. The Altitude Difference that is shown was obtained by subtracting the biased calculated altitude from the biased actual altitude. Because of the referencing to the first floor, the Fluke 8060A measurement error for a given floor was obtained by adding the Fluke 8060A measurement error for the first floor before the referencing to that of the given floor. The Altimeter Error Range was calculated by adding the bounds of the Fluke 8060A measurement error to the Altitude Difference, as shown in Equation (5).

The graph shown in Figure A.3 was done using the voltage values in Table (1) for run 1 and run 2. The graph for each run was obtained by doing a linear regression analysis of the measured voltage values. The equation used for each graph is also shown in Figure A.3.

A.4 Comments

The data in Table (A.2) shows that the error attributable to the Fluke 8060A remained relatively constant at approximately ±11 feet for all floors and that the

Floor	Run 1 (Volts)	Run 2 (Volts)	Average (Volts)	Calculated Altitude (feet)	Actual Altitude (feet)
1	1.4324	1.4316	1.4320	66.38	23.00
2	1.4375	1.4374	1.43745	78.05	40.42
3	1.4403	1.4399	1.4401	83.73	49.13
4	1.4436	1.4436	1.4436	91.22	57.83
5	1.4470	1.4472	1.4471	98.72	66.54
6	1.4510	1.4509	1.45095	106.96	75.25
7	1.4538	1.4543	1.45405	113.60	83.96
8	1.4585	1.4581	1.4583	122.70	92.67
9	1.4614	1.4647	1.46305	132.87	101.38
10	1.4659	1.4669	1.4654	137.90	110.08
11	1.4704	1.4710	1.4707	149.25	118.79
12	1.4740	1.4754	1.4747	157.82	127.50
13	1.4772	1.4788	1.4780	164.88	136.21
14	1.4804	1.4818	1.4811	171.52	144.92
15	1.4862	1.4857	1.48595	181.91	153.63
16	1.4896	1.4898	1.4897	189.94	162.33
17	1.4929	1.4938	1.49335	197.75	171.04
18	1.4964	1.4968	1.4966	204.71	179.75
19	1.4996	1.5002	1.4999	211.78	188.46
20	1.5031	1.5038	1.50345	219.38	197.17
21	1.5071	1.5087	1.5079	227.84	205.88
22	1.5110	1.5145	1.51275	239.29	214.58
23	1.5146	1.5173	1.51595	246.15	223.29
24	1.5185	1.5205	1.5195	253.95	232.00

Supply Voltage = 28.02 ± 0.034 Volts

Table (A.1) - Initial Voltage Readings and Altitude Calculations.

Floor	Biased Actual Altitude (feet)	Biased Calculated Altitude (feet)	Altitude Difference (feet)	Fluke 8060A *Meas. Error (feet)	Altimeter Error Range (feet)
1	0	0	0	±10.88	±10.88
2	17.42	11.67	5.75	±10.89	+16.64,-5.14
3	26.13	17.35	8.78	±10.90	+19.68,-2.12
4	34.83	24.84	9.99	±10.91	+20.90,-0.92
5	43.54	32.34	11.20	±10.91	+22.91,+0.29
6	52.25	40.58	11.67	±10.92	22.59,0.75
7	60.96	47.22	13.74	±10.93	24.67,2.81
8	69.67	56.32	13.35	±10.94	24.29,2.41
9	78.38	66.49	11.89	±10.96	22.85,0.93
10	87.08	71.52	15.56	±10.96	26.52,4.60
11	95.79	82.87	12.92	±10.98	23.90,1.94
12	104.50	91.44	13.06	±10.99	24.05,2.07
13	113.21	98.50	14.71	±10.99	25.70,3.72
14	121.92	105.14	16.78	±11.00	27.78,5.78
15	130.63	115.53	15.10	±11.02	26.12,4.08
16	139.33	123.56	15.77	±11.02	26.79,4.75
17	148.04	131.37	16.67	±11.03	27.70,5.64
18	156.75	138.33	18.42	±11.04	29.46,7.38
19	165.46	145.40	20.06	±11.05	31.11,9.01
20	174.17	153.00	21.17	±11.06	32.23,10.11
21	182.88	161.46	21.42	±11.07	32.49,10.35
22	191.58	172.91	18.67	±11.08	29.75,7.59
23	200.29	179.77	20.52	±11.09	31.61,9.43
24	209.00	187.37	21.63	±11.10	32.73,10.53

(*Meas. ≡ Measurement)

Table (A.2) - Errors and Biased Altitudes.

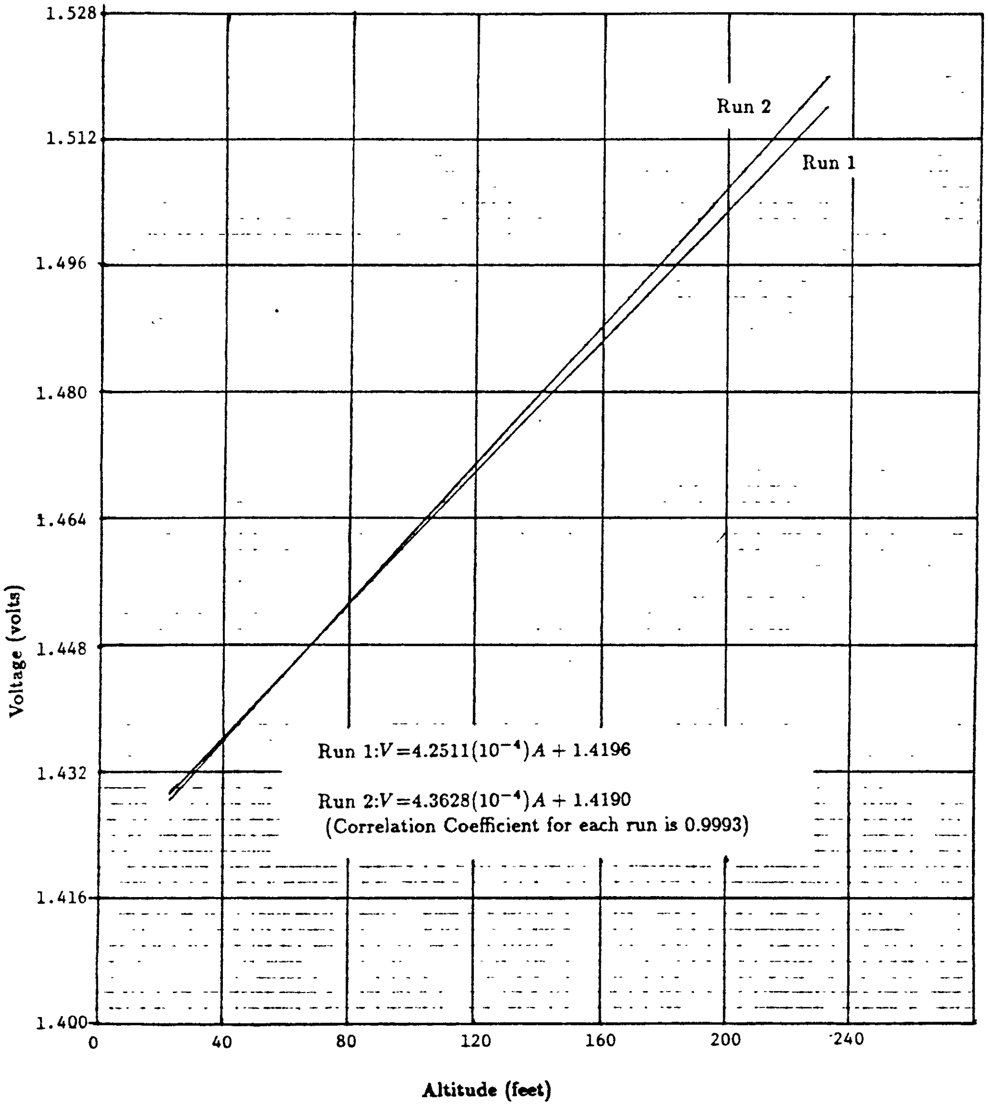


Figure A.3 - Graph of Voltage vs. Altitude for Run 1 and Run 2 in Table (1).

KING
KEA 346
SERVOED ENCODING ALTIMETER

2.5 ALTIMETER ACCURACY

Equivalent Pressure Inches of Mercury	Equivalent Pressure Millibars	Altitude Feet	Altimeter Tolerance at Room Temperature
31.0185	1050.41	-1,000	± 20
29.9213	1013.25	0	± 20
29.3846	995.08	500	± 20
28.8557	977.17	1,000	± 20
28.3345	959.52	1,500	± 25
27.8210	942.13	2,000	± 30
26.8167	908.12	3,000	± 30
25.8418	875.10	4,000	± 35
23.9782	811.99	6,000	± 40
22.2249	752.62	8,000	± 60
20.5769	696.81	10,000	± 80
19.0293	644.41	12,000	± 90
17.5773	595.24	14,000	± 100
16.2164	549.15	16,000	± 110
14.9421	506.00	18,000	± 120
13.7501	465.63	20,000	± 130
12.6363	427.91	22,000	± 140
11.1035	376.01	25,000	± 155
8.8854	300.89	30,000	± 180
7.0406	238.42	35,000	± 205
5.5380	187.54	40,000	± 230
4.3550	147.48	45,000	± 255
3.4247	115.97	50,000	± 280

Altimeter Accuracy Requirements per TSO C10b, Feb. 1, 1959

Figure A.4 - Manufacturer's Accuracy Specifications for KEA-346 Altimeter.

Altitude Difference increases from approximately 6 to 22 feet with altitude. This relatively large increase of the Altitude Difference was attributed to the altimeter since the Fluke 8060A measurement error remained relatively constant. The Altimeter Error Range reflected the increase in the Altitude Difference values with altitude by a corresponding positive shift in the Range values.

The linear regression analysis of the graphs in Figure A.3 showed that the correlation coefficient for both runs was 0.9993 not only indicating that the voltage and altitude data fit a linear relationship very well but also showing that the reference pressure remained relatively constant over the period of testing for each run.

A.5 DISCUSSION

The accuracy of the altimeter (King Radio : KEA-346) in the range from 0 to 500 feet is shown in Figure A.4 as given by the manufacturer to be ±20 feet. The data in Table (A.2) for Altimeter Error Range substantiates this claim by the manufacturer since the range ±20 feet overlaps all of the calculated ranges in Table (A.2).

The operating range of the altimeter for the Apple Graphics Display was 0 to 3000 feet; however, it was not practical to try to substantiate the manufacturer's claims over the entire operating range so that all accuracy claims above 232 feet - the altitude of the 24th floor of Tang Hall - had to be accepted as given.

APPENDIX B - FLIGHT TEST PALLET

This appendix gives detailed construction parameters of the flight test pallet, lists the airplane weight and balance calculations, and shows the FAA paperwork required to take the pallet aloft. The original form of this Appendix was written by John Einhorn for his Master of Science Thesis. Alterations to the original version were written by Norry Dogan to include the alterations to the Flight Test Pallet from that used by John Einhorn.

B.1 PALLET CONSTRUCTION

The pallet is constructed of .063 inch, 5052 sheet aluminum (ultimate sheer strength is 18 ksi, yield strength is 13 ksi, and ultimate tensile strength is 28 ksi), one inch diameter 2024-T35 aluminum rods (ultimate shear strength is 41 ksi, yield strength is 47 ksi and ultimate tensile strength is 68 ksi), 1/4 x 1 x 1 inch 6061-T6 angle aluminum (ultimate shear strength is 30 ksi, yield strength is 40 ksi, ultimate tensile strength is 45 ksi), and 3/8 inch diameter threaded steel rods.

The six legs of the pallet are made of the 2024 aluminum rods and are attached to an angle alumimum base frame by 3/8 inch diameter steel sheet metal screws. The top part of the pallet is essentially eight separate equipment compartments welded together by the Laboratory for Nuclear Science at MIT. This framework of compartments is in turn welded to an aluminum shelf which is bolted to the angle aluminum base frame by four 1/4 inch aircraft grade bolts. The basic configuration is shown in Figure B.1.

B.2 PALLET WEIGHT AND BALANCE

The weight and balance measurements for the pallet are as follows:

	Apple Graphics Display System	Langley Display System
1) Impact foam, wires, nylon, misc.	5.00 lbs	5.00 lbs
2) LORAN-C receiver	8.75 lbs	8.75 lbs
3) Two gel cells	36.00 lbs	36.00 lbs
4) Inverter	10.25 lbs	10.25 lbs
5) Monitor	(not located with pallet)	10.25 lbs
6) Apple II+	12.00 lbs	12.00 lbs
7) Disk II	4.50 lbs	4.50 lbs
8) A/D converter	1.00 lbs	1.00 lbs
9) VOR receiver	6.50 lbs	6.50 lbs
10) VOR head	3.00 lbs	3.00 lbs
11) Pallet	33.00 lbs	33.00 lbs
12) Altimeter	4.00 lbs	(not used)
13) 28V Power Supply	5.25 lbs	(not used)
14) Total weight	129.75 lbs	130.75 lbs

The center of mass is 18.125 inches from the rear of the pallet.

B.3 AIRPLANE WEIGHT AND BALANCE

The following tables use the foregoing weights and moments to give the weight and CG results for different configurations of crew and fuel. The purpose of the tables is to show that the weights and moments for the flight tests of each display system are safe and to provide the safest way for exiting and boarding the aircraft without upsetting it. All the calculations for the following tables were done using a weight balance program provided by Lyman Hazelton, Jr.

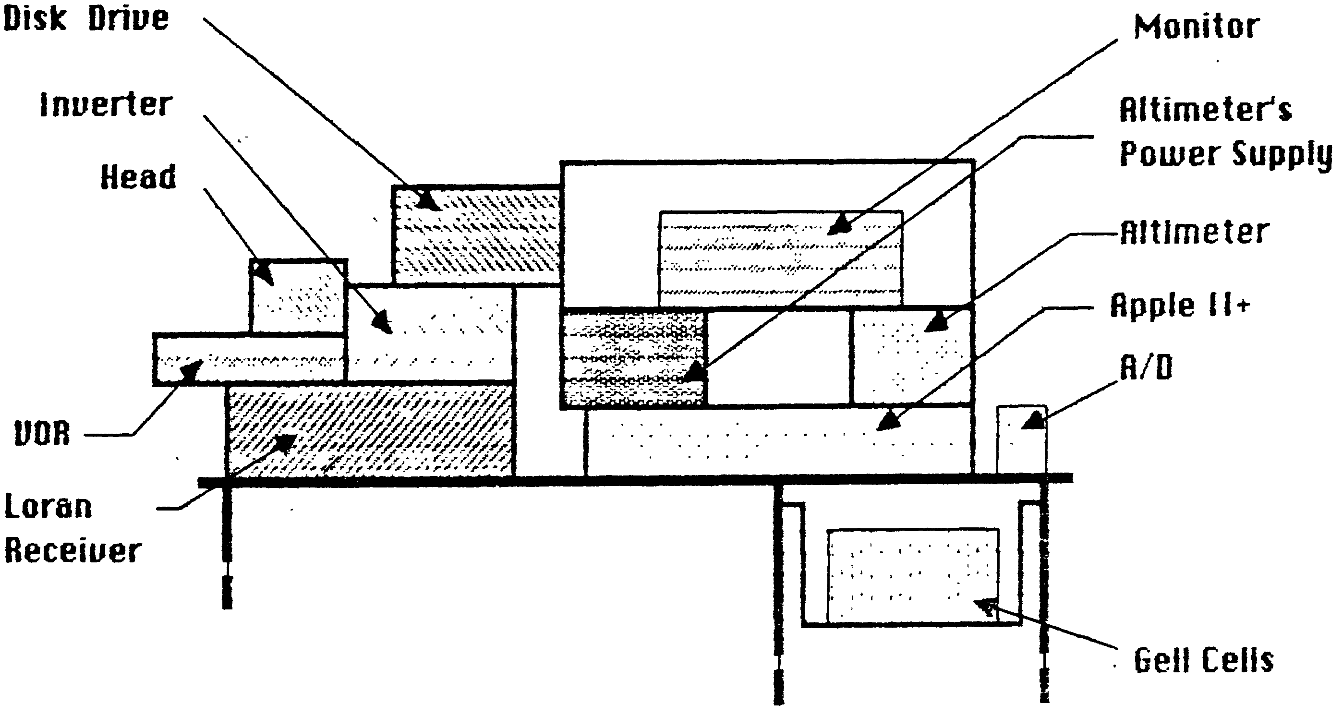


Figure B.1 - Basic Configuration of Test Pallet.

The loading and center of gravity for the airplane system are as follows:

	WEIGHT (lbs)	ARM (in)	MOMENT (in-lbs)
Empty Weight	1480	84.15	124542
Oil	11	32	325
Fuel	306	94.8	29009
Pilot	155	90.6	14043
Co-pilot	165	90.6	14949
Pallet			
(a)Apple Display System	129.75	114.93	14912.17
(b)Langley Display System	130.75	115.18	15059.79
Monitor			
(a)Apple Display System	10.25	54.6	559.65
(b)Langley Display System	(included with pallet)		
Display Hardware			
(a)Apple Display System	(see the Monitor values)		
(b)Langley Display System	3.25	54.6	177.45
Operator	165	126	20790
Rear Tie Downs	0.5	131	65
Front Tie Downs	0.42	98	41
Longerons	4	131.4	534
Cross Spar	1.3	159.4	214

The weight is given in pounds and as a percentage of the maximum allowable weight for each configuration. The total moment for each configuration is given in units of in-lbs.

The CG analysis gives the position of the CG as well as the positions of the aft and foreward (fwd) limits for each configuration. Also included in the CG analysis is a number between -1 and +1 that indicates the relative degree of centering. The -1 and +1 limits represent respectively the aft and fwd limits. Zero means that perfect centering occurred with the given configuration; a value between 0 and +1 indicates the position of the CG is fwd of the perfect centering but is still acceptable;

a value greater than +1 is to far fwd and is unacceptable. The foregoing statements are also true for values less than zero or aft of perfect centering: a value between -1 and 0 is acceptable, and a value less than -1 is unacceptable.

The foregoing tables show that the safest way to board the plane is pilot, flight engineer, and then copilot, and the safest way to exit is copilot, flight engineer, and then pilot. These methods of boarding and exiting the plane are independent of the amount of fuel present. The most dangerous configurations that occur according to the centering values in Table B.1 and Table B.2 occur when there are empty tanks and just a flight engineer and when there are full tanks and a full crew (flight engineer on the wing).

When there are full tanks and a full crew (flight engineer on the wing), the centering values indicate that there is an excessive forward moment; however, since this configuration can only occur while the plane is on the ground, the front wheel will counter the excessive moment.

When there are empty tanks and just a flight engineer, the centering value indicates that there is a large backward moment. Though this moment is not excessive, this configuration should be avoided since there is nothing to absorb an excessive backward moment except the airplane's tail.

B.4 EQUIPMENT TIE DOWN

Each piece of equipment is held to the pallet and prevented from movement in any direction by a number of means. Figure B.2 shows the pallet with equipment

Configuration	Weight (lbs)	Total Moment (in-lbs)	Fwd Limit (in)	CG Position (in)	Aft Limit (in)	Centering
Full crew Full tanks	2422 100.9%	219156.6	89.40	90.49	92.51	0.299
Full Crew Empty tanks	2116 88.2%	190147.8	84.72	89.86	92.37	-0.344
No copilot Full Tanks	2257 94.0%	204207.6	87.03	90.48	92.44	-0.275
No copilot Empty tanks	1951 81.3%	175198.8	81.60	89.80	92.28	-0.536
No pilot or copilot Full tanks	2102 87.6%	190164.6	84.48	90.47	92.36	-0.520
No pilot or copilot Empty tanks	1796 74.8%	161155.8	78.14	89.73	92.18	-0.651
No flight engineer Full tanks	2257 94.0%	198366.6	87.03	87.89	92.44	0.683
No flight engineer Empty tanks	1951 81.3%	169357.8	81.60	86.81	92.28	0.025
No copilot or flight eng. Full tanks	2092 87.2%	183417.6	84.30	87.68	92.36	0.162
No copilot or flight eng. Empty tanks	1786 74.4%	154408.8	77.89	86.46	92.17	-0.199
Pilot, copilot, flight eng. on wing Full tanks	2422 100.9%	213315.6	89.40	88.07	92.51	1.850
Pilot, copilot, flight eng. on wing Empty tanks	2116 88.2%	184306.8	84.72	87.10	92.37	0.378

Table B.1 - Weight and CG Analysis for Apple Graphics Display System.

Configuration	Weight (lbs)	Total Moment (in-lbs)	Fwd Limit (in)	CG Position (in)	Aft Limit (in)	Centering
Full crew Full tanks	2416 100.7%	218922.0	89.32	90.61	92.50	0.185
Full crew Empty tanks	2110 87.9%	189913.2	84.62	90.01	92.37	-0.391
No copilot Full tanks	2251 93.8%	203973.0	86.94	90.61	92.43	-0.337
No copilot Empty tanks	1945 81.0%	174964.2	81.47	89.96	92.28	-0.571
No pilot or copilot Full tanks	2096 87.3%	189930.0	84.37	90.62	92.36	-0.563
No pilot or copilot Empty tanks	1790 74.6%	160921.2	77.99	89.90	92.17	-0.679
No flight engineer Full tanks	2251 93.8%	198132.0	86.94	88.02	92.43	0.607
No flight engineer Empty tanks	1945 81.0%	169123.2	81.47	86.95	92.28	-0.015
No copilot or flight eng. Full tanks	2086 86.9%	183183.0	84.19	87.82	92.35	0.112
No copilot or flight eng. Empty tanks	1780 74.2%	154174.2	77.74	86.61	92.17	-0.230
Pilot, copilot, flight eng. on wing Full tanks	2416 100.7%	213081.0	89.32	88.20	92.50	1.702
Pilot, copilot, flight eng. on wing Empty tanks	2110 87.9%	184072.2	84.62	87.24	92.37	0.324

Table B.2 - Weight and CG Analysis for Langley Display System.

tie downs. Each of the equipment tie down strategies are explained below.

1) Gel cells. The gel cells (2) are padded fore and aft by impact foam. Movement is prevented fore and aft by the pallet, and movement side to side and up is prevented by 0.5 inch wide nylon webbing secured by a buckle. The tensile strength of the nylon and buckle are presented later in this appendix.

2) Apple II+. The Apple is padded above by a 0.5 inch thick sheet of impact foam. Movement fore, aft, up, and left (into airframe) is prevented by the pallet, and movement right (into Flight Test Engineer) is prevented by restraints two and three.

3) Monitor. (a) For the Apple Graphics Display System, the monitor is mounted on top of the cockpit panel by screws that also secure the top surface that exists between the base of the windshield and the top edge of the cockpit panel. (b) For the Langley Display System, the monitor is bolted in the pallet section using two 1/4 inch aircraft grade bolts where the altimeter and altimeter power supply are housed for the Apple Graphics Display System.

4) Disk drive. Movement fore and aft is prevented by the pallet. Movement left is prevented by velcro attachment to pallet and restraint number one. Movement right is prevented by velcro, restraint one, and by a 3/8 inch diameter steel rod run through two levels of the pallet.

5) Inverter. The inverter is padded fore, aft and above by impact foam. Movement fore and aft is prevented by the pallet. Movement left is prevented by restraint

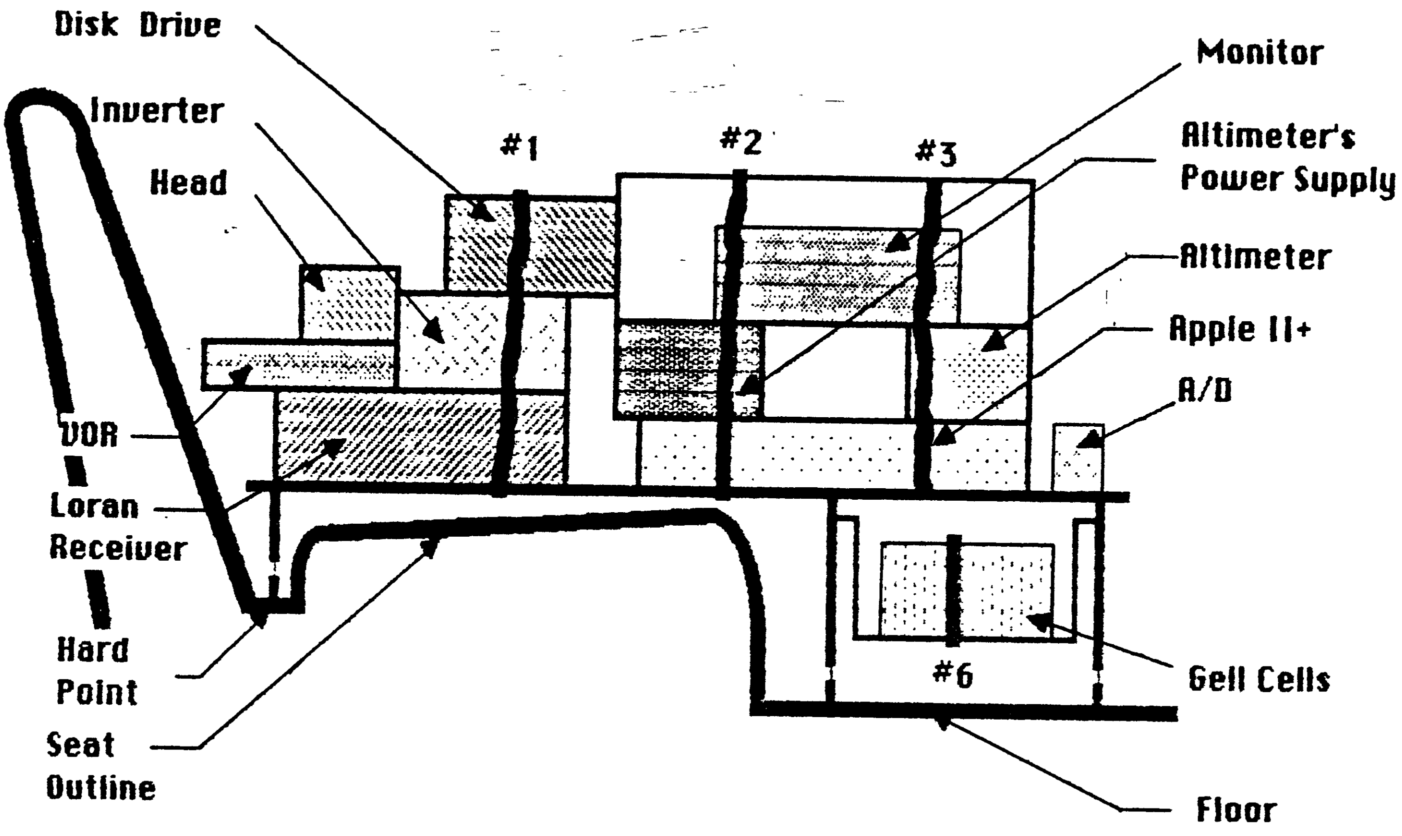


Figure B.2 - Equipment Tie Downs.

one. Movement right is prevented by restraint one and two steel rods run through two levels of the pallet.

6) VOR head. Movement fore, aft, up and left is prevented by the pallet. Movement right is prevented by a steel rod run through two sections of the pallet.

7) VOR receiver. Movement fore, aft, and up is prevented by the pallet. Movement side to side is prevented by sheet metal screw attachment to pallet through standard screw bracket in rear of receiver frame.

8) LORAN-C receiver. The LORAN is padded fore, aft and up is prevented by the pallet. Movement left is prevented by restraint number one. Movement right is prevented by restraint one and by a 1 x 1 inch aluminum L bracket secured to the pallet by sheet metal screws.

9) A/D converter is contained in its own aluminum box and attached to pallet by sheet metal screws.

10) Altimeter (Apple Graphics Display System). The pallet prevents any movement except right toward the flight engineer. Right movement is prevented by a 1x1 inch aluminum L bracket. Impact foam is placed on the top and to the right of the altimeter to act as padding.

11) Altimeter Power Supply (Apple Graphics Display System). The pallet prevents any movement except right and left. Right and left movement is prevented by the prescence of 1x1 inch aluminum L brackets at the front and back of the power supply. Impact foam is placed at the right and on the top of the power supply.

12) Langley Display (Langley Display System). The display is secured to the top of the cockpit panel using screws. This method is similar to that used to secure the monitor in the Apple Graphics Display System.

B.5 PALLET TIE DOWN

The pallet rests on the six legs which in turn rest on hard points on the plane's frame and floor. It is secured to the plane by a system of seven aluminum spars. The pallet bottom is secured at four points to seatbelt hardpoints by 1/8 x 1 x 1 inch, 6063-T5 angle aluminum (ultimate shear strength is 17 ksi, yield strength is 21 ksi, ultimate tensile strength is 27 ksi). The smallest cross-section subject to shear loads is 1/8 x 1/4 inches or .03125 square inches and will withstasnd a shear load of 531.25 pounds. Figure 3 shows the location of these spars.

The pallet top (top of monitor section) is secured by two longerons to a cross spar bolted to the rear passenger shoulder harness hardpoints. The longerons are 1/8 x 1.5 x 1.5 inch, 6063-T5 angle aluminum. The cross section subject to tensile loads is 1/8 x 1.5 inches or .1879 square inches and will withstand a tensile load of 5073.3 pounds.

The cross spar is 1/8 x 2 x 2 inches, 6061-T6 angle aluminum (ultimate shear strength is 30 ksi, yield strength is 40 ksi, ultimate tensile strength is 45 ksi). The smallest section subject to shear loads is 1/8 x 5/16 inches or .1641 square inches and will withstand a shear load of 4921.9 pounds. Figure B.4 shows the longerons and cross spar.

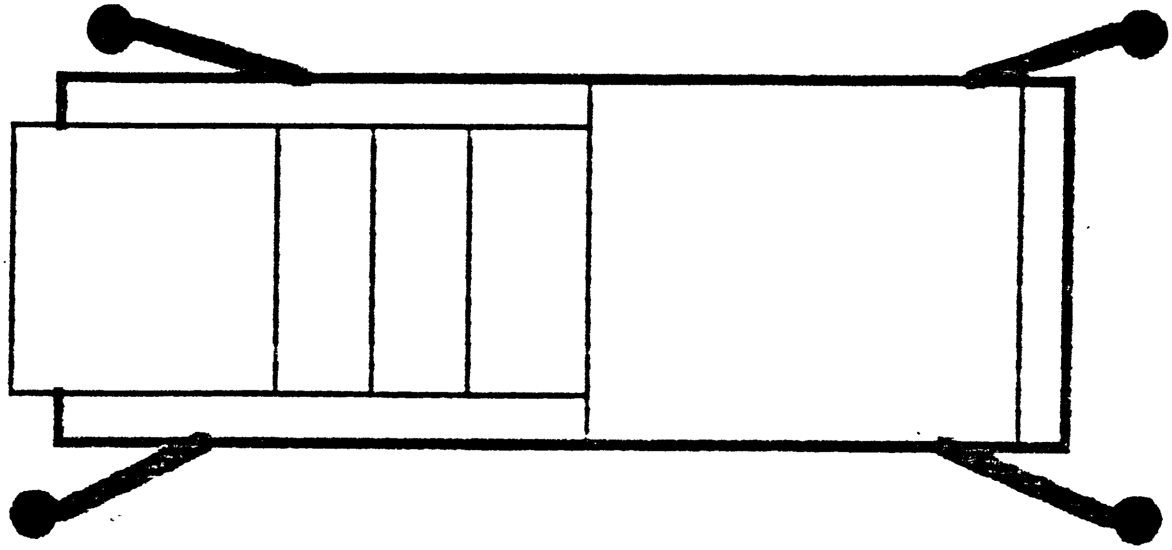


Figure B.3 - Pallet Bottom Tie Down Spars.

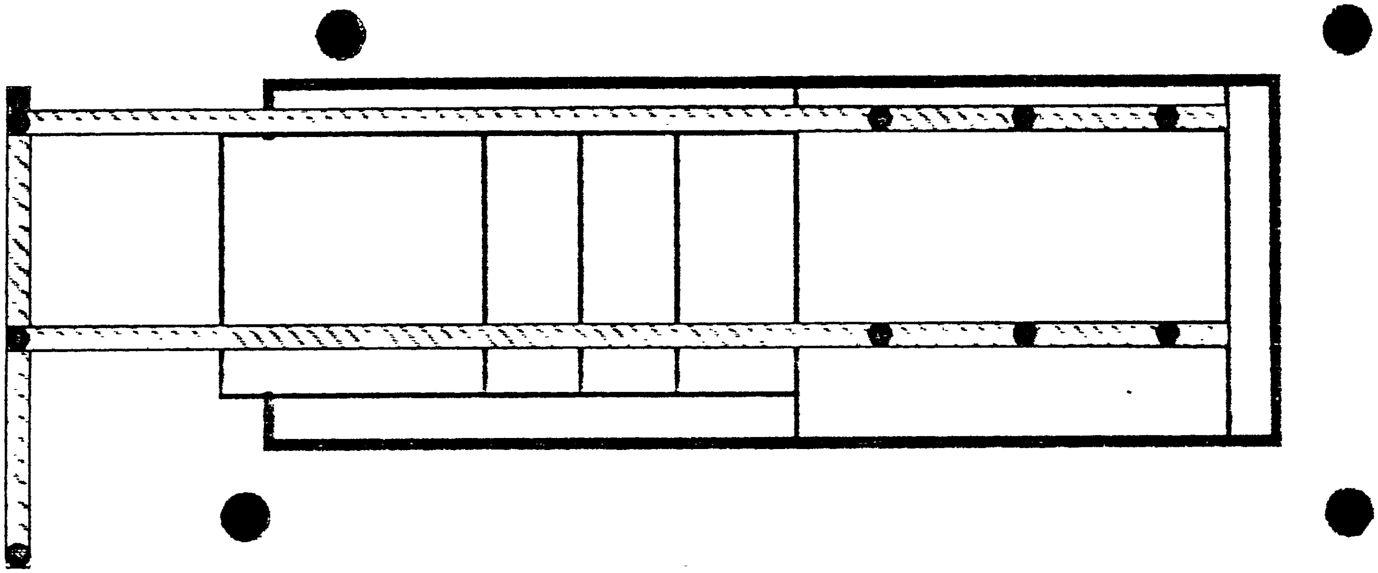


Figure B.4 - Pallet Longerons and Cross Spar.

B.5.1 Nylon Webbing

The nylon webbing is 0.5 inch wide and used primarily as mountain climbing gear. A length of this webbing was loaded on a Materials Testing System Tensile Machine in the Technology Laboratory for Advanced Composites (TELAC) at MIT and subjected to a five inch ramp stroke in two seconds. The nylon broke at 1436.25 pounds. A graph of this test is shown in Figure B.5 and is labeled as try #2. Try #1 shows a similar test with a one inch stroke. The nylon stretched the full one inch without breaking.

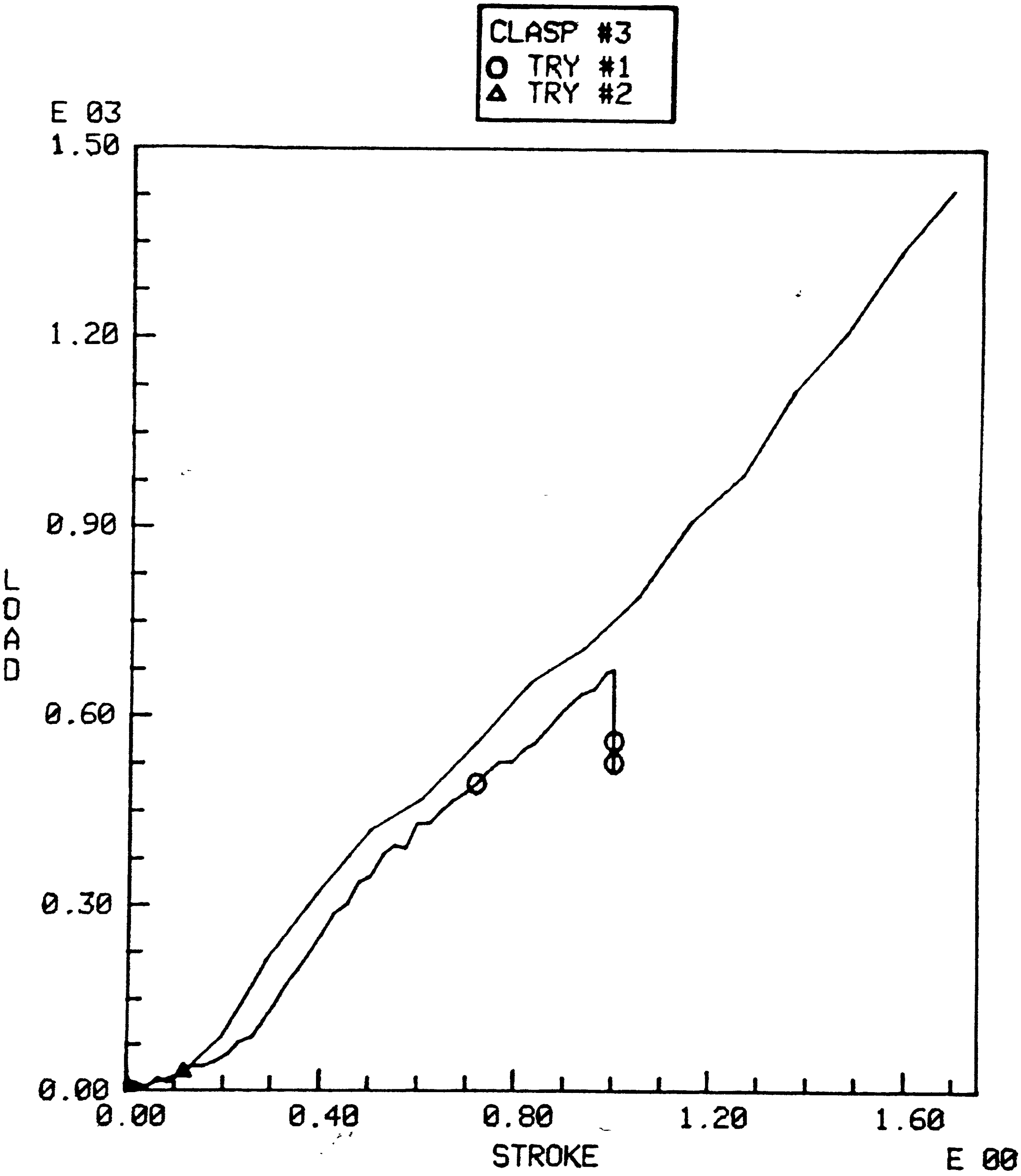


Figure B.5 - Nylon Webbing Strength Test.

B.5.2 Equipment Buckles

The nylon restraints for the equipment are held together by means of buckles, also used as mountain climbing gear. A sample buckle was loaded on an MTS tensile machine and loaded to failure. It failed at 219.84 pounds. Figure B.6 shows a graph of this test.

B.6 INSTALLATION INSTRUCTIONS

This section lists the installation procedure for the pallet.

1) Remove cushions from backs of rear two seats.

2) Position pallet bottom on seat behind pilot's seat and secure to plane with four spars.

3) Place rear seat foam cushion along seat back.

4) Slide gel cells into box, pack with foam, and secure with restraint number six.

5) Place pallet top in rear of plane along plane centerline.

6) Attach A/D box to pallet top.

7a) For the Apple Graphics Display System, place the altimeter and its power supply into their appropriate boxes; run the power cord of the altimeter power supply to the inverter; run the power leads of the altimeter to its' power supply; ground the altimeter cable to the Apple II; connect the altimeter data line to the appropriate labelled lead going to the A/D. Secure the monitor to the top of the

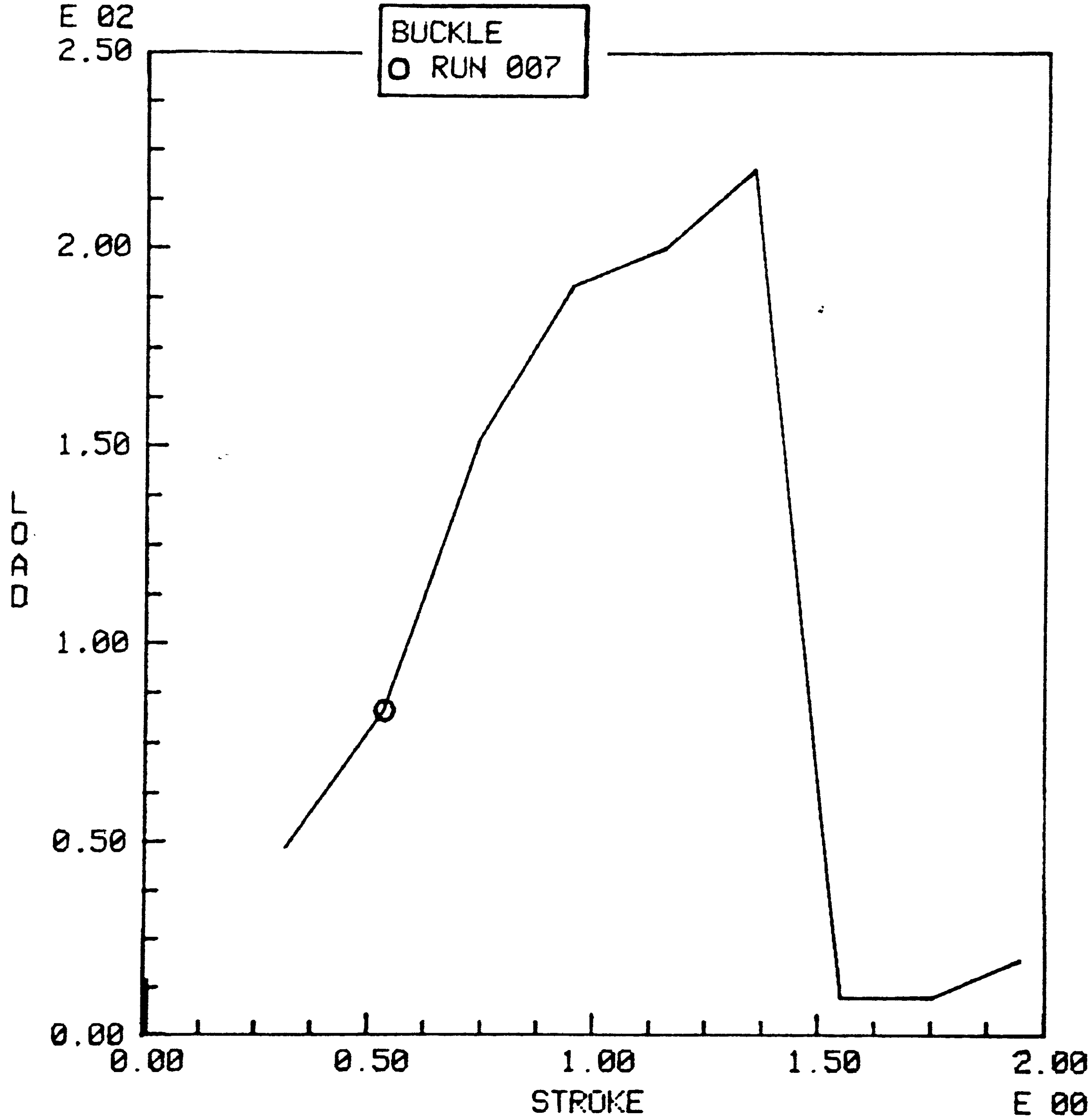


Figure B.6 - Equipment Buckle Strength Test.

cockpit panel; run the power leads and video cable back to the battery and Apple II, respectively, by passing them underneath the pilot's seat.

7b) For the Langley Display System, bolt the monitor in its appropriate place in the pallet; run its' power leads and video cable out a hole in the back of the pallet; run the power leads to the battery connections on top of the pallet; run the video cable to the Apple II. Secure the Langley Display to the top of the cockpit panel using screws; run its' power and data cable back underneath the pilot's seat to the pallet; connect the power leads to the battery connections on top of the pallet and the data cable to the Apple II.

8) Place LORAN in box, run data out line through rear hole in Apple section.

9) Put disk drive on seat behind pallet; run its' ribbon cable through the rear hole in the Apple section to the Apple II.

10) Hook A/D card ribbon cable into Apple slot #7, connect disk drive, monitor, and LORAN to proper inputs. Make sure Apple is switched on.

11) Slide Apple back into pallet and attach Apple power cord.

12) Place disk drive in box.

13) Move pallet over onto left seat and into final position. Bolt top of pallet to bottom. Replace right rear seat back cushion.

14) Slide inverter into box.

15) Slide VOR transceiver into box and secure with machine screw.

16) Slide VOR head into box.

17) Attach cables to rear of VOR transceiver, run output to VOR head and A/D converter.

18) Hook VOR and LORAN to respective antennas.

19) Attach longerons to cross spar and to monitor top. Tighten all bolts.

20) Connect LORAN and VOR to power buss on top of monitor box, making sure to ground the LORAN.

21) Connect inverter and gel cell to buss, set rear breaker then set front breaker. Turn on inverter. Plug in monitor, then the Apple, then the altimeter power supply.

22) Once all connections are correct, disengage rear and front breakers.

23) Pack Apple with foam, secure with restraints two and three.

24) Pack inverter with foam.

25) Install steel rod restraints for inverter (2 rods) and VOR head.

26) Pack LORAN with foam.

27) Place and secure restraint one.

28) Adjust and tighten all pallet restraints as necessary.

29) Installation complete.

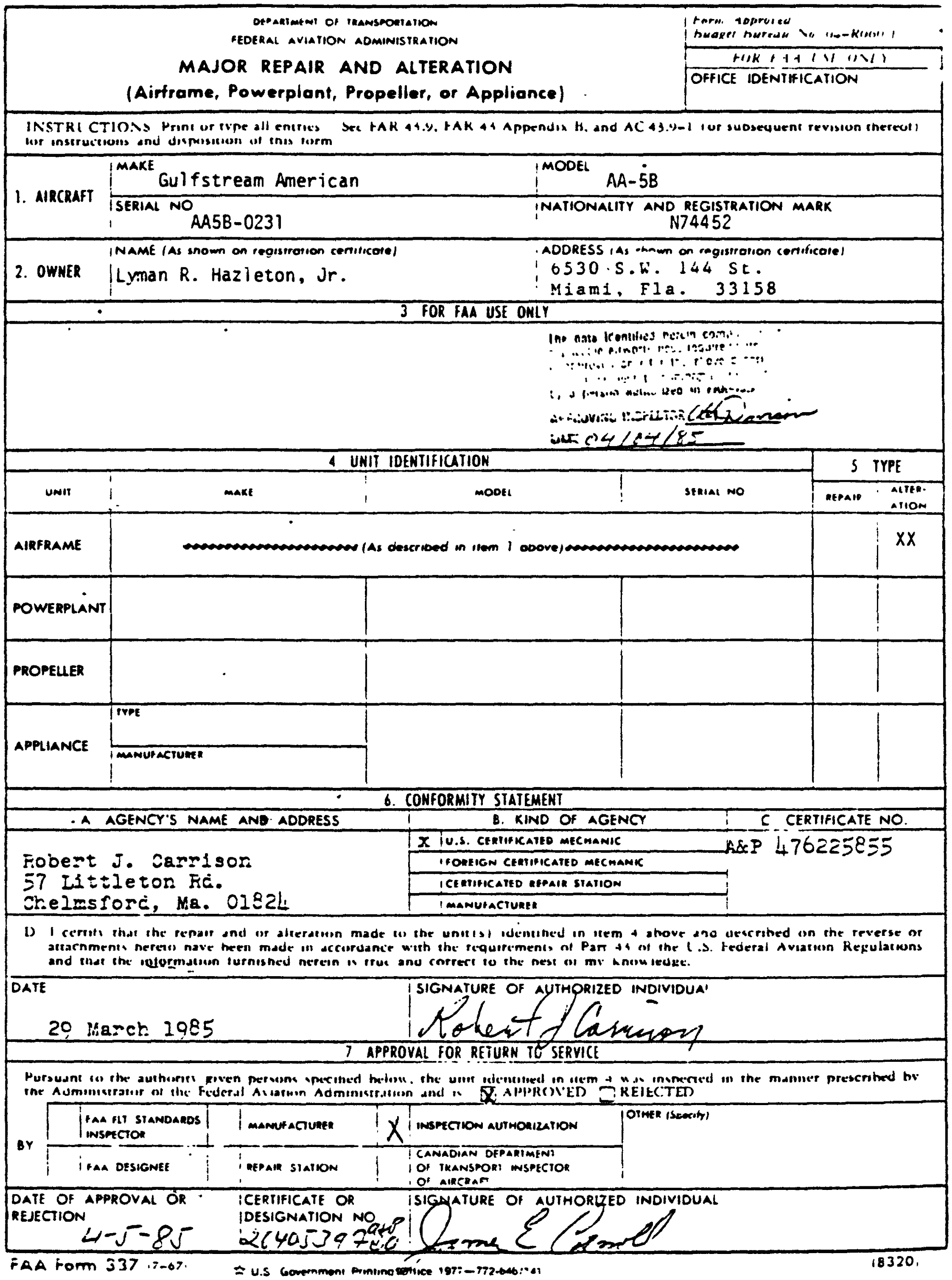
30) Turn all equipment on and test again before taxi and/or takeoff.

B.7 REMOVAL INSTRUCTIONS

Removal of pallet and equipment will be accomplished essentially in reverse order of installation. The first step will be to turn off equipment and disconnect gel cell, followed by the installation instructions in reverse order, modified as necessary for convienence.

B.8 FAA DOCUMENTATION

This section contains the FAA documentation that was sought and obtained before and flying could be done with the pallet installation. The report mentioned at the end of Form 337, "Flight Test Pallet Tie Down Strategy and Installation Instructions" has been omitted in its original form. This appendix contains all of the information contained in that report.



DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION

MAJOR REPAIR AND ALTERATION
(Airframe, Powerplant, Propeller, or Appliance)

Form Approved
Budget Bureau No. 04-R0060 1

FOR FAA USE ONLY
OFFICE IDENTIFICATION

INSTRUCTIONS Print or type all entries. See FAR 43.9, FAR 43 Appendix B, and AC 43.9-1 (or subsequent revision thereof) for instructions and disposition of this form.

1. AIRCRAFT	MAKE Gulfstream American	MODEL AA-5B
	SERIAL NO AA5B-0231	NATIONALITY AND REGISTRATION MARK N74452
2. OWNER	NAME (As shown on registration certificate) Lyman R. Hazleton, Jr.	ADDRESS (As shown on registration certificate) 6530 S.W. 144 St. Miami, Fla. 33158

3 FOR FAA USE ONLY

The data identified herein com[illegible]
[illegible]
[illegible] INSPECTOR
DATE 04/04/85

4 UNIT IDENTIFICATION — 5 TYPE

UNIT	MAKE	MODEL	SERIAL NO	REPAIR	ALTERATION
AIRFRAME	(As described in item 1 above)				XX
POWERPLANT					
PROPELLER					
APPLIANCE	TYPE MANUFACTURER				

6. CONFORMITY STATEMENT

A. AGENCY'S NAME AND ADDRESS	B. KIND OF AGENCY	C. CERTIFICATE NO.
Robert J. Carrison 57 Littleton Rd. Chelmsford, Ma. 01824	☒ U.S. CERTIFICATED MECHANIC ☐ FOREIGN CERTIFICATED MECHANIC ☐ CERTIFICATED REPAIR STATION ☐ MANUFACTURER	A&P 476225855

D I certify that the repair and/or alteration made to the unit(s) identified in item 4 above and described on the reverse or attachments hereto have been made in accordance with the requirements of Part 43 of the U.S. Federal Aviation Regulations and that the information furnished herein is true and correct to the best of my knowledge.

DATE	SIGNATURE OF AUTHORIZED INDIVIDUAL
29 March 1985	Robert J Carrison

7 APPROVAL FOR RETURN TO SERVICE

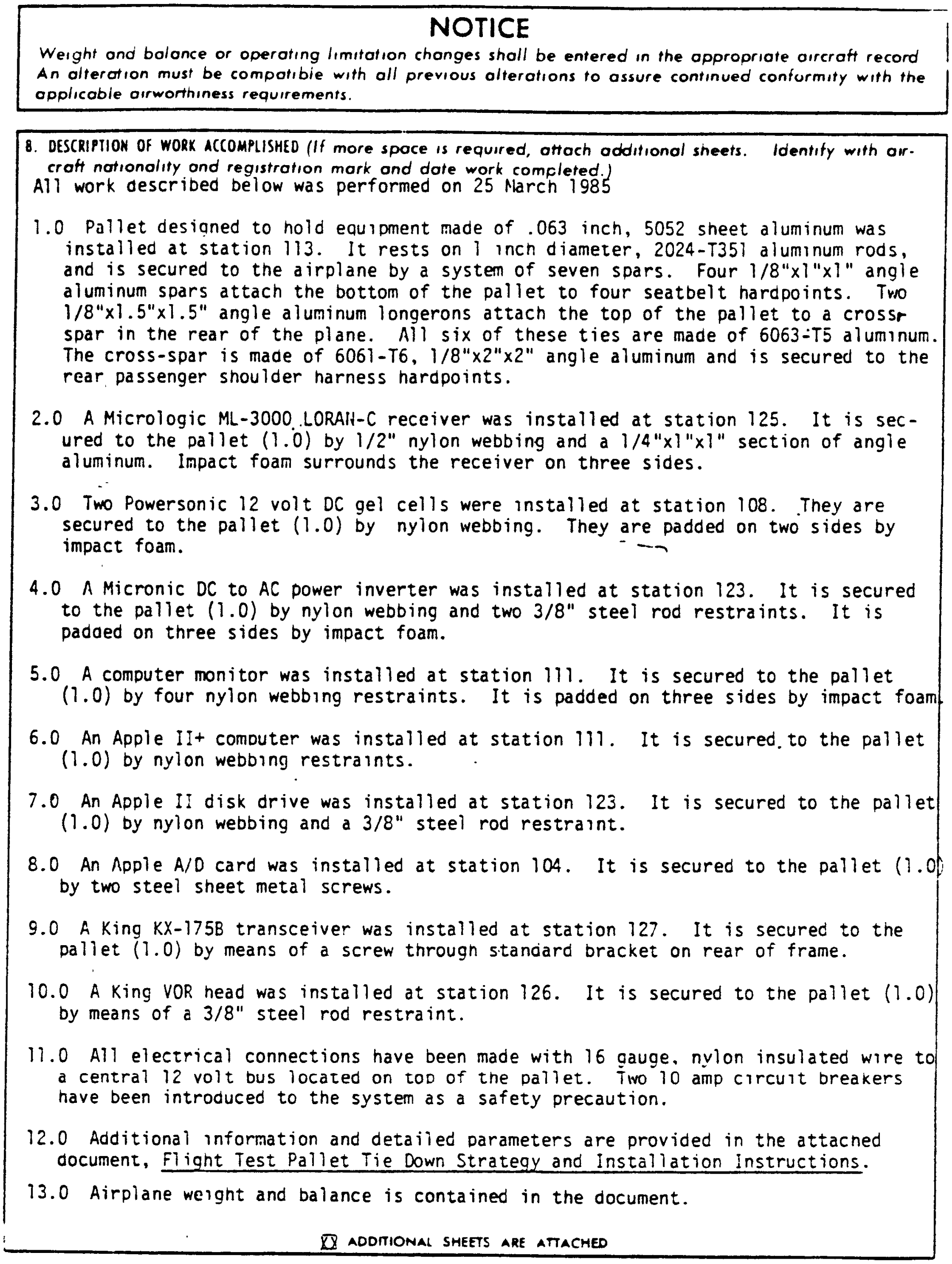
Pursuant to the authority given persons specified below, the unit identified in item 4 was inspected in the manner prescribed by the Administrator of the Federal Aviation Administration and is ☒ APPROVED ☐ REJECTED

BY	☐ FAA FLT STANDARDS INSPECTOR	☐ MANUFACTURER	☒ INSPECTION AUTHORIZATION	OTHER (Specify)
	☐ FAA DESIGNEE	☐ REPAIR STATION	☐ CANADIAN DEPARTMENT OF TRANSPORT INSPECTOR OF AIRCRAFT	

DATE OF APPROVAL OR REJECTION	CERTIFICATE OR DESIGNATION NO	SIGNATURE OF AUTHORIZED INDIVIDUAL
4-5-85	2640539 7 ACE	James E Carroll

FAA Form 337 (7-67) ☆ U.S. Government Printing Office 1977—772-646/741 (8320)

Figure B.7 - FAA Form 337, Side One.



NOTICE

Weight and balance or operating limitation changes shall be entered in the appropriate aircraft record An alteration must be compatible with all previous alterations to assure continued conformity with the applicable airworthiness requirements.

8. DESCRIPTION OF WORK ACCOMPLISHED *(If more space is required, attach additional sheets. Identify with aircraft nationality and registration mark and date work completed.)*

All work described below was performed on 25 March 1985

1.0 Pallet designed to hold equipment made of .063 inch, 5052 sheet aluminum was installed at station 113. It rests on 1 inch diameter, 2024-T351 aluminum rods, and is secured to the airplane by a system of seven spars. Four 1/8"x1"x1" angle aluminum spars attach the bottom of the pallet to four seatbelt hardpoints. Two 1/8"x1.5"x1.5" angle aluminum longerons attach the top of the pallet to a cross-spar in the rear of the plane. All six of these ties are made of 6063-T5 aluminum. The cross-spar is made of 6061-T6, 1/8"x2"x2" angle aluminum and is secured to the rear passenger shoulder harness hardpoints.

2.0 A Micrologic ML-3000 LORAN-C receiver was installed at station 125. It is secured to the pallet (1.0) by 1/2" nylon webbing and a 1/4"x1"x1" section of angle aluminum. Impact foam surrounds the receiver on three sides.

3.0 Two Powersonic 12 volt DC gel cells were installed at station 108. They are secured to the pallet (1.0) by nylon webbing. They are padded on two sides by impact foam.

4.0 A Micronic DC to AC power inverter was installed at station 123. It is secured to the pallet (1.0) by nylon webbing and two 3/8" steel rod restraints. It is padded on three sides by impact foam.

5.0 A computer monitor was installed at station 111. It is secured to the pallet (1.0) by four nylon webbing restraints. It is padded on three sides by impact foam

6.0 An Apple II+ computer was installed at station 111. It is secured to the pallet (1.0) by nylon webbing restraints.

7.0 An Apple II disk drive was installed at station 123. It is secured to the pallet (1.0) by nylon webbing and a 3/8" steel rod restraint.

8.0 An Apple A/D card was installed at station 104. It is secured to the pallet (1.0) by two steel sheet metal screws.

9.0 A King KX-175B transceiver was installed at station 127. It is secured to the pallet (1.0) by means of a screw through standard bracket on rear of frame.

10.0 A King VOR head was installed at station 126. It is secured to the pallet (1.0) by means of a 3/8" steel rod restraint.

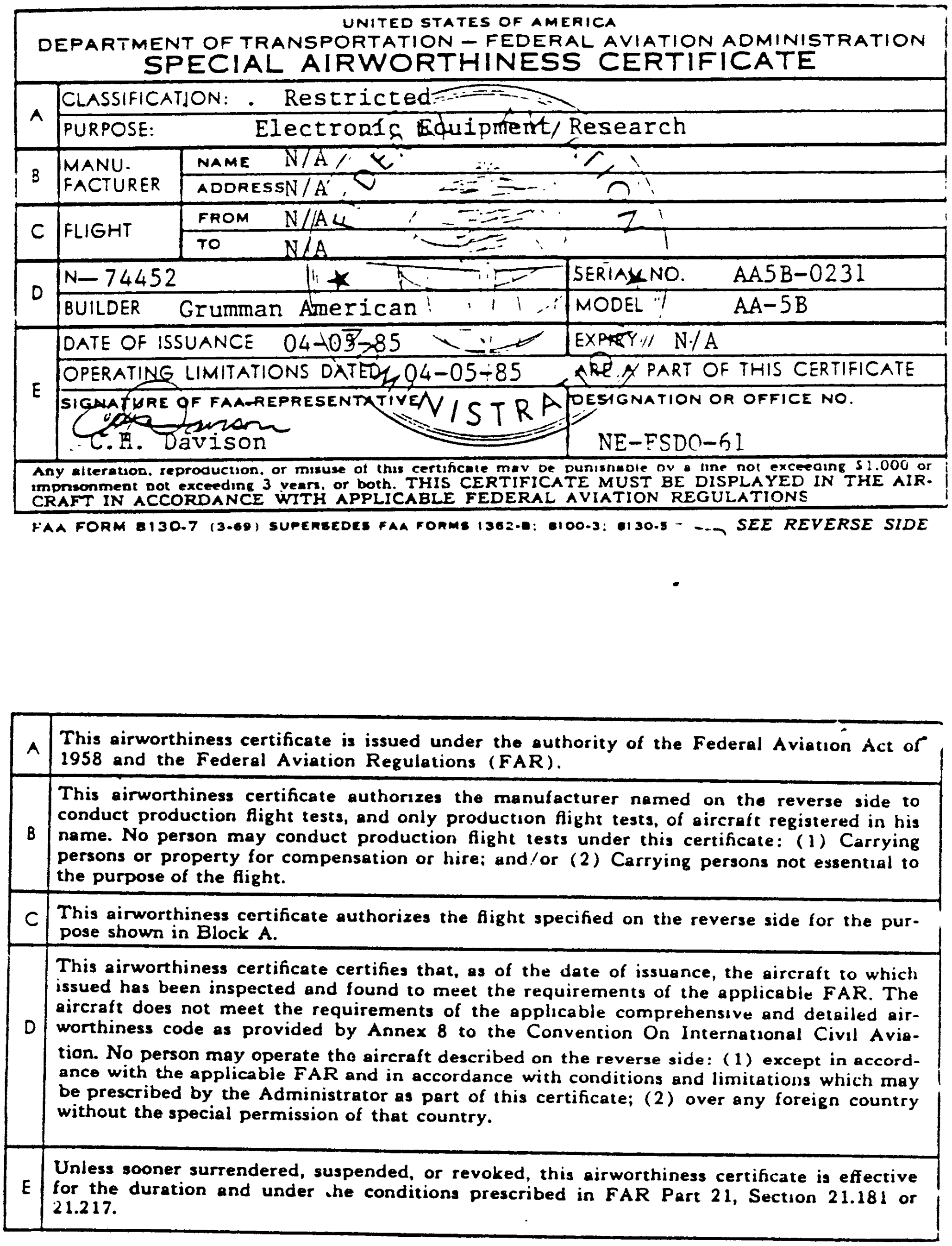
11.0 All electrical connections have been made with 16 gauge, nylon insulated wire to a central 12 volt bus located on top of the pallet. Two 10 amp circuit breakers have been introduced to the system as a safety precaution.

12.0 Additional information and detailed parameters are provided in the attached document, Flight Test Pallet Tie Down Strategy and Installation Instructions.

13.0 Airplane weight and balance is contained in the document.

☒ ADDITIONAL SHEETS ARE ATTACHED

Figure B.8 - FAA Form 337, Side Two.



UNITED STATES OF AMERICA
DEPARTMENT OF TRANSPORTATION — FEDERAL AVIATION ADMINISTRATION
SPECIAL AIRWORTHINESS CERTIFICATE

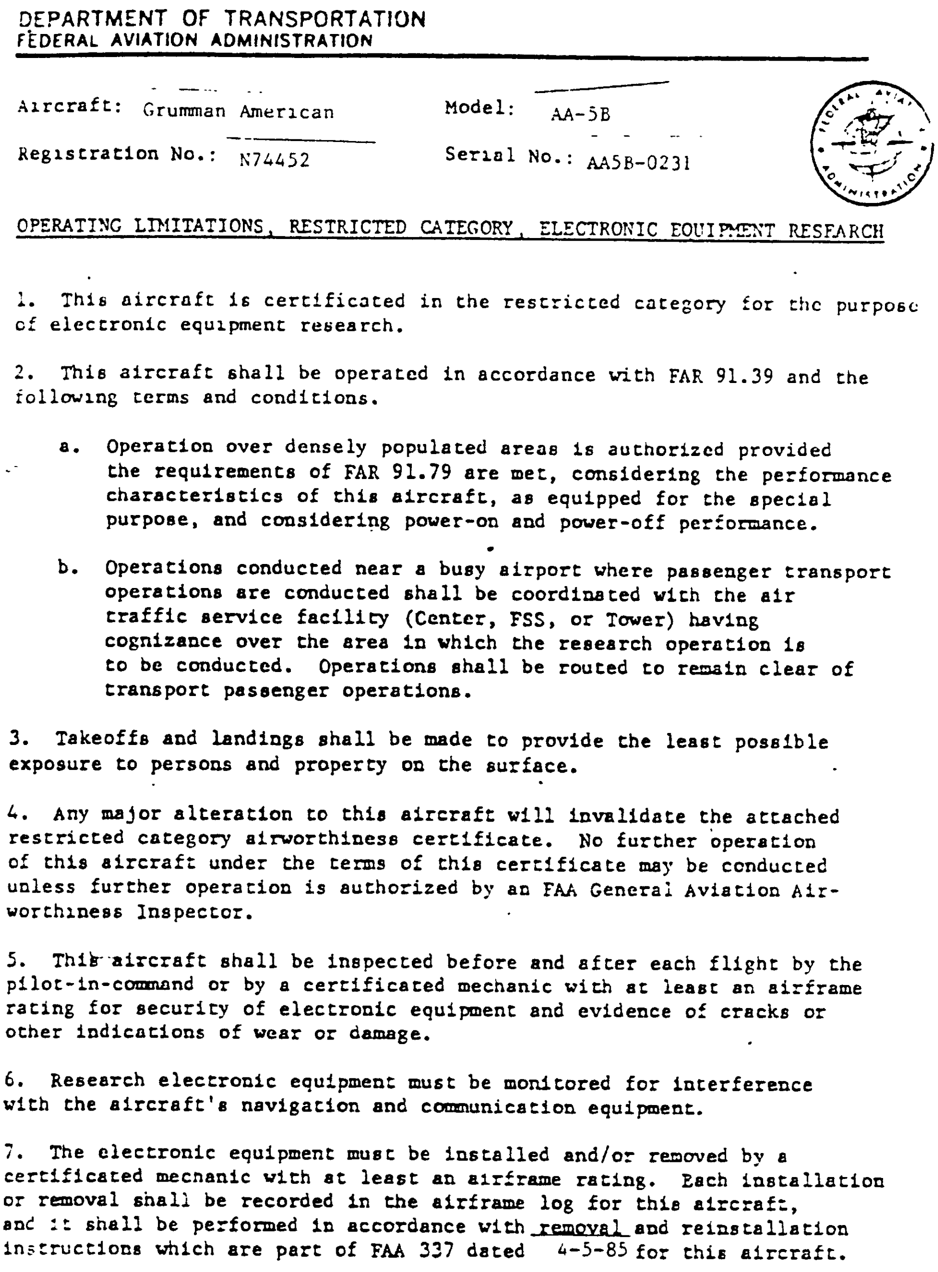
A	CLASSIFICATION:	Restricted	
	PURPOSE:	Electronic Equipment/Research	
B	MANUFACTURER	NAME N/A	
		ADDRESS N/A	
C	FLIGHT	FROM N/A	
		TO N/A	
D	N— 74452		SERIAL NO. AA5B-0231
	BUILDER Grumman American		MODEL AA-5B
E	DATE OF ISSUANCE 04-05-85		EXPIRY N/A
	OPERATING LIMITATIONS DATED 04-05-85		ARE A PART OF THIS CERTIFICATE
	SIGNATURE OF FAA-REPRESENTATIVE C.H. Davison		DESIGNATION OR OFFICE NO. NE-FSDO-61

Any alteration, reproduction, or misuse of this certificate may be punishable by a fine not exceeding $1.000 or imprisonment not exceeding 3 years, or both. THIS CERTIFICATE MUST BE DISPLAYED IN THE AIRCRAFT IN ACCORDANCE WITH APPLICABLE FEDERAL AVIATION REGULATIONS

FAA FORM 8130-7 (3-69) SUPERSEDES FAA FORMS 1362-B; 8100-3; 8130-5 — *SEE REVERSE SIDE*

A	This airworthiness certificate is issued under the authority of the Federal Aviation Act of 1958 and the Federal Aviation Regulations (FAR).
B	This airworthiness certificate authorizes the manufacturer named on the reverse side to conduct production flight tests, and only production flight tests, of aircraft registered in his name. No person may conduct production flight tests under this certificate: (1) Carrying persons or property for compensation or hire; and/or (2) Carrying persons not essential to the purpose of the flight.
C	This airworthiness certificate authorizes the flight specified on the reverse side for the purpose shown in Block A.
D	This airworthiness certificate certifies that, as of the date of issuance, the aircraft to which issued has been inspected and found to meet the requirements of the applicable FAR. The aircraft does not meet the requirements of the applicable comprehensive and detailed airworthiness code as provided by Annex 8 to the Convention On International Civil Aviation. No person may operate the aircraft described on the reverse side: (1) except in accordance with the applicable FAR and in accordance with conditions and limitations which may be prescribed by the Administrator as part of this certificate; (2) over any foreign country without the special permission of that country.
E	Unless sooner surrendered, suspended, or revoked, this airworthiness certificate is effective for the duration and under the conditions prescribed in FAR Part 21, Section 21.181 or 21.217.

Figure B.9 - Restricted Airworthiness Certificate.



DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION

Aircraft: Grumman American
Model: AA-5B
Registration No.: N74452
Serial No.: AA5B-0231

OPERATING LIMITATIONS, RESTRICTED CATEGORY, ELECTRONIC EQUIPMENT RESEARCH

1. This aircraft is certificated in the restricted category for the purpose of electronic equipment research.

2. This aircraft shall be operated in accordance with FAR 91.39 and the following terms and conditions.

a. Operation over densely populated areas is authorized provided the requirements of FAR 91.79 are met, considering the performance characteristics of this aircraft, as equipped for the special purpose, and considering power-on and power-off performance.

b. Operations conducted near a busy airport where passenger transport operations are conducted shall be coordinated with the air traffic service facility (Center, FSS, or Tower) having cognizance over the area in which the research operation is to be conducted. Operations shall be routed to remain clear of transport passenger operations.

3. Takeoffs and landings shall be made to provide the least possible exposure to persons and property on the surface.

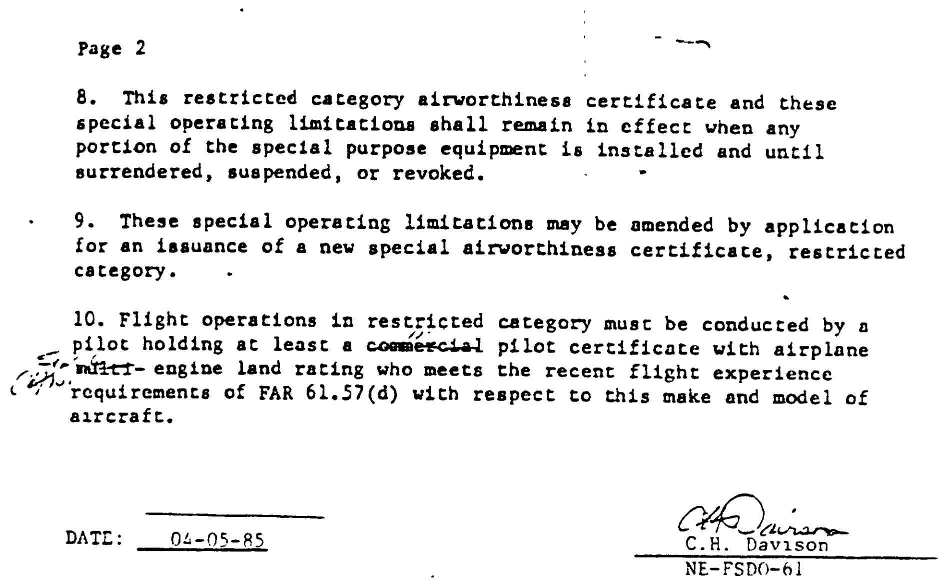
4. Any major alteration to this aircraft will invalidate the attached restricted category airworthiness certificate. No further operation of this aircraft under the terms of this certificate may be conducted unless further operation is authorized by an FAA General Aviation Airworthiness Inspector.

5. This aircraft shall be inspected before and after each flight by the pilot-in-command or by a certificated mechanic with at least an airframe rating for security of electronic equipment and evidence of cracks or other indications of wear or damage.

6. Research electronic equipment must be monitored for interference with the aircraft's navigation and communication equipment.

7. The electronic equipment must be installed and/or removed by a certificated mecnanic with at least an airframe rating. Each installation or removal shall be recorded in the airframe log for this aircraft, and it shall be performed in accordance with removal and reinstallation instructions which are part of FAA 337 dated 4-5-85 for this aircraft.

Figure B.10 - Limitations on Restricted Aircraft Operation, Page One.



Page 2

8. This restricted category airworthiness certificate and these special operating limitations shall remain in effect when any portion of the special purpose equipment is installed and until surrendered, suspended, or revoked.

9. These special operating limitations may be amended by application for an issuance of a new special airworthiness certificate, restricted category.

10. Flight operations in restricted category must be conducted by a pilot holding at least a ~~commercial~~ pilot certificate with airplane ~~multi~~- engine land rating who meets the recent flight experience requirements of FAR 61.57(d) with respect to this make and model of aircraft.

DATE: 04-05-85

C.H. Davison
NE-FSDO-61

Figure B.11 - Limitations on Restricted Aircraft Operation, Page Two.

APPENDIX C - COMPUTER PROGRAMS

C.1 DISPLAY PROGRAM

```
0  REM  LORAN-C DISPLAY PROGRAM
1  GOTO 1000
2 X =  PEEK (KB):Q1 = 0:LL = 24576: REM  WAIT STATE
3  IF  PEEK (KB) < 128 GOTO 3
4  GOTO 1460
5  REM
6  REM  HORIZONTAL AND VERTICAL LINES
10  SCALE= 1
15  XDRAW 1 AT 214,Y
20  XDRAW 2 AT X,15
25  RETURN
30  REM  BINARY LOADING ROUTINE
35  PRINT  CHR$ (4);"BLOAD LINE, A$9100"
40  PRINT  CHR$ (4);"BLOAD ASS"
45  POKE 232,00: POKE 233,145
50  POKE 0,187: POKE 1,0
60  REM
65  RETURN
70  REM  MOVE INDICATOR LINES TO NEW POSITION
75 X = IX:Y = IY: REM  OLD POSITION (IX,IY)
80  GOSUB 5
85 X = NX:Y = NY: REM  NEW POSITION (NX,NY)
90  GOSUB 5
95  RETURN
100  REM  +XTK LARGE AND +AD LARGE
105  FOR N = 1 TO 4
110 X = 204 + N:Y = 159 +/N
115  GOSUB 5
120  NEXT
125  RETURN
130  REM  +XTK LARGE AND -AD LARGE
135  FOR N = 1 TO 4
140 X = 204 + N:Y = 16 + N
145  GOSUB 5
150  NEXT
155  RETURN
160  REM  +XTK LARGE AND AD OKAY
165  FOR N = 1 TO 4
170 X = 204 + N
175  XDRAW 2 AT X,14
```

```
180  NEXT
185  XDRAW 1 AT 214,Y
190  RETURN
195  REM  -XTK LARGE AND +AD LARGE
200  FOR N = 1 TO 4
205 X = 11 + N:Y = 159 + N
210  GOSUB 5
215  NEXT
220  RETURN
225  REM  -XTK LARGE AND -AD LARGE
230  FOR N = 1 TO 4
235 X = 11 + N:Y = 16 + N
240  GOSUB 5
245  NEXT
250  RETURN
255  REM  -XTK LARGE AND AD OKAY
260  FOR N = 1 TO 4
265 X = 11 + N
270  XDRAW 2 AT X,14
275  NEXT
280  XDRAW 1 AT 214,Y
285  RETURN
290  REM  XTK OKAY AND +AD LARGE
295  FOR N = 1 TO 4
300 Y = 159 + N
305  XDRAW 1 AT 214,Y
310  NEXT
315  XDRAW 2 AT X,14
320  RETURN
325  REM  XTK OKAY AND -AD LARGE
330  FOR N = 1 TO 4
335 Y = 16 + N
340  XDRAW 1 AT 214,Y
345  NEXT
350  XDRAW 2 AT X,14
355  RETURN
360  REM  THE DISPLAY SUBROUTINE
365 X = NX:Y = NY
370  IF NX > 208 AND NY > 163 THEN  GOSUB 100
375  IF NX > 208 AND NY < 17 THEN  GOSUB 130
380  IF NX > 208 AND NY >  = 17 AND NY <  = 163 THEN  GOSUB 160
385  IF NX < 12 AND NY > 163 THEN  GOSUB 195
390  IF NX < 12 AND NY < 17 THEN  GOSUB 225
395  IF NX < 12 AND NY >  = 17 AND NY <  = 163 THEN  GOSUB 255
400  IF NX >  = 12 AND NX <  = 208 AND NY > 163 THEN  GOSUB 290
405  IF NX >  = 12 AND NX <  = 208 AND NY < 17 THEN  GOSUB 325
410  IF NX >  = 12 AND NX <  = 208 AND NY >  = 17 AND NY <  = 163 THEN  GOSUB
     5
```

```
415 NY = 90 +  INT ((75 * AD) / 500)
420  IF  ABS (XTK) < = 300 THEN NX = 110 +  INT ((50 * XTK) / 300
425  IF XTK > 300 THEN FR =  LOG (XTK / 300) /  LOG (10):NX = 160 +  INT
     (50 * FR)
430  IF XTK <  - 300 THEN XTK =  - XTK:FR =  LOG (XTK / 300) /  LOG (10):
     NX = 60 -  INT (50 * FR):XTK =  - XTK
435 X = NX:Y = NY
436  IF SE = 0 THEN  GOTO 495
437 SE = 0
438  IF SE = 0 THEN  GOTO 370
495  RETURN
1000  REM  BACKGROUND DISPLAY GRAPHICS
1001 KB =  - 16384:KS =  - 16368
1002 DL =  - 16142:DG =  - 16141:DA =  - 16140
1003  HIMEM: ~~24576~~ 24574
1004  FOR I = 1 TO 4
1005 W1 =  PEEK (DL):W2 =  PEEK (DG):W3 =  PEEK (DA)
1006  NEXT
1007 W5 =   W2
1010  HGR2
1020  REM  LOAD THE NECESSARY BINARY DATA
1030  GOSUB 30
1040  REM  VALUES OF CONSTANTS
1050 X = 110:Y = 90:NA = 0:NX = 110:NY = 90
1070  REM  DRAW THE BOUNDARY LINES
1080  FOR I = 1 TO 4
1090 X1 = 6 + I:X2 = 214 - I
1100 Y1 = 11 + I:Y2 = 169 - I
1110  HPLOT X1,Y1 TO X2,Y1 TO X2,Y2 TO X1,Y2 TO X1,Y1
1120  NEXT
1130  REM  MIDDLE MARKER
1140  FOR J = 1 TO 3
1150  HPLOT 108 + J,86 TO 108 + J,94
1160  HPLOT 106,88 + J TO 114,88 + J
1170  NEXT
1180  REM  DRAW THE XTK AND ALTITUDE INDICATOR LINES
1190  GOSUB 6
1200  REM  DOTTED BOUNDARY
1210  FOR M = 1 TO 8
1220  FOR N = 1 TO 4
1230  HPLOT (4 * N) + 50,(M * 20) - 5
1240  HPLOT (4 * N) + 150,(M * 20) - 5
1250  NEXT N
1260  FOR P = 1 TO 3
1270  HPLOT (4 * P) + 52,(M * 20) + 5
1280  HPLOT (4 * P) + 152,(M * 20) + 5
1290  NEXT P
1300  NEXT M
1310  REM  PRINT XTK NUMBERS
1320 X = 1:Y = 170: GOSUB 5330
1330 X = X + 7: GOSUB 5190
1340 X = 52: GOSUB 5330
```

```
1350 X = 108: GOSUB 5190
1360 X = 152: GOSUB 5330
1370 X = 196: GOSUB 5330
1380 X = X + 7: GOSUB 5190
1390  REM  PRINT ALTITUDE NUMBERS
1400 X = 216:Y = 11: GOSUB 5390
1410 X = 216:Y = 49: GOSUB 5430
1420 X = 216:Y = 86: GOSUB 5190
1430 X = 216:Y = 124: GOSUB 5430
1440 X = 216:Y = 158: GOSUB 5390
1450  GOTO 2
1460  REM  DATA INTAKE FOR TD'S AND ALTITUDE
1470 X =  PEEK (KS)
1480 BA =  - 28673:D$ = ""
1490 A1 = BA + 1:A2 = BA + 2:A3 = BA + 3:A4 = BA + 4:A5 = BA + 5:A6 = BA +
     6:A7 = BA + 7:A8 = BA + 8
1500 A9 = BA + 9:B0 = BA + 10:B1 = BA + 11:B2 = BA + 12:B3 = BA + 13:B4 =
     BA + 14:B5 = BA + 15:B6 = BA + 16:B7 = BA + 17:B8 = BA + 18
1505 Q1 = Q1 + 1
1510  PRINT D$;"PR#1"
1511  PRINT BA
1520  CALL  - 28640
1530  PRINT D$;"PR#0"
1540 W1 =  PEEK (DL):W2 =  PEEK (DG):W3 =  PEEK (DA):W4 = W2
1550 VM = W2:W2 = W1:W1 = W3:W3 = W4
1555  IF W4 > (W5 + 10) OR W4 < (W5 - 10) THEN VM = W5
1556 W5 = W4
1557  IF W4 > (VM + 10) OR W4 < (VM - 10) THEN W5 = VM
1560 VM = (0.006738 * VM) + 1.1063
1570  REM
1580  REM  ALTITUDE CALCULATIONS
1590  REM
1600 VS = 27.00
1610 AL = 63000 * ((VM / VS) - 0.05)
1620 AL = AL - 133: REM  HANSCOM IS 133 FT ABOVE SEA LEVEL
1890  REM  ALTITUDE DIFFERENCE WILL BE CALCULATED AFTER RANGE TO THE TOUC
     HDOWN POINT IS CALCULATED FROM THE TD VALUES.
1900  REM  CHECK LORAN DATA
1910 CS =  PEEK (A1) +  PEEK (A2) +  PEEK (A3) +  PEEK (A4) +  PEEK (A5) +
      PEEK (A6) +  PEEK (A7) +  PEEK (A8) +  PEEK (A9)
1920 CS = CS +  PEEK (B0) +  PEEK (B1) +  PEEK (B2) +  PEEK (B3) +  PEEK
     (B4) +  PEEK (B5) +  PEEK (B6) +  PEEK (B7)
1930  IF (CS - 256 *  INT (CS / 256)) <  >  PEEK (B8) THEN NA = NA + 1: GOTO
     1970
1940  IF  PEEK (B7) > 0 THEN NA = NA + 1: GOTO 1970
1950  IF NA > 0 THEN NA = 0
1960  GOTO 2030
1970  REM  TOGGLE THE SWITCH IF 5 BAD CONSECUTIVE DATA ENTRIES HAVE OCCUR
     RED
1980  IF NA < 6 THEN  GOTO 1460
1990  FOR N = 1 TO 100
1991  IF  PEEK (KB) > 128 GOTO 2350
2000 X =  PEEK ( - 16368)
2010  NEXT N
2020  GOTO 1460
```

```
2050  REM  XTK AND ALT DIFF CALCULATIONS
2060 N1 = 83.6853:N2 = 6.1147: REM  RUNWAY ANGLES WRT TRUE NORTH
2070 CE =  COS ((3.1416 / 180) * N1): REM  ROTATION MATRIX COEFFICIENTS
2080 CB =  - 1 *  COS ((3.1416 / 180) * N2)
2090 CD =  - 1 * CB
2100 CC = CE
2109 CO = 3.2808
2110 M3 =  - 101.436 * CO
2120 M4 =  - 92.927 * CO
2130 M1 =  - 191.621 * CO
2140 M2 = 171.641 * CO
2150 C1 = (CC * M1) + (CD * M3)
2160 C2 = (CC * M2) + (CD * M4)
2170 C3 = (CE * M1) + (CB * M3)
2180 C4 = (CE * M2) + (CB * M4)
2190 T1 = 0.00625 * ( PEEK (A3) + 256 *  PEEK (A4) + 65536 *  PEEK (A5))
2200 T2 = 0.00625 * ( PEEK (A8) + 256 *  PEEK (A9) + 65536 *  PEEK (B0))
2210 T1 = T1 - 14119.73
2220 T2 = T2 - 26033.25
2230 XTK = (C1 * T1) + (C2 * T2)
2240 VE = (C3 * T1) + (C4 * T2)
2250 RA2 = (XTK * XTK) + (VE * VE):RA =  SQR (RA2)
2260 AD = AL - (RA *  TAN ((3.1416 / 180) * 3.00)
2270 XTK =  INT (XTK):AD =  INT (AD)
2271 SE = 1
2272  POKE B8,W1
2273  POKE B8 + 1,W2
2274  POKE B8 + 2,W3
2280  GOSUB 360
2290  FOR J = 1 TO 20
2300  POKE LL + J - 1, PEEK (BA + J)
2310  NEXT J
2320 LL = LL + 20
2330  IF  PEEK (K2) > 128 GOTO 2350
2340  GOTO 1505
2350  TEXT
2360  INPUT "FILE NAME?";F$
2361 Q2 =  INT (Q1 / 256): POKE 24574,Q1 - 256 * Q2: POKE 24575,Q2
2370  PRINT  CHR$ (4) + "BSAVE " + F$ + ",A";24574;",L";(Q1 * 20) + 2
2380  STOP
5000  REM  NUMBER 3
5010  HPLOT X,Y TO X + 5,Y: HPLOT X + 5,Y TO X + 2,Y + 3
5020  HPLOT X + 2,Y + 3 TO X + 4,Y + 4
5030  HPLOT X + 4,Y + 4 TO X + 5,Y + 5
5040  HPLOT X + 5,Y + 5 TO X + 5,Y + 6
5050  HPLOT X + 5,Y + 6 TO X + 3,Y + 8
5060  HPLOT X + 3,Y + 8 TO X + 2,Y + 8
5070  HPLOT X + 2,Y + 8 TO X,Y + 7
5080  RETURN
```

```
5090  REM  NUMBER 5
5100  HPLOT X,Y TO X + 5,Y: HPLOT X,Y TO X,Y + 3
5110  HPLOT X,Y + 3 TO X + 2,Y + 3
5120  HPLOT X + 2,Y + 3 TO X + 4,Y + 4
5130  HPLOT X + 4,Y + 4 TO X + 5,Y + 5
5140  HPLOT X + 5,Y + 5 TO X + 5,Y + 6
5150  HPLOT X + 5,Y + 6 TO X + 3,Y + 8
5160  HPLOT X + 3,Y + 8 TO X + 2,Y + 8
5170  HPLOT X + 2,Y + 8 TO X,Y + 7
5180  RETURN
5190  REM  NUMBER 0
5200  HPLOT X + 1,Y TO X + 4,Y
5210  HPLOT X + 4,Y TO X + 5,Y + 2: HPLOT X + 5,Y + 2 TO X + 5,Y + 6
5220  HPLOT X + 5,Y + 6 TO X + 4,Y + 8: HPLOT X + 4,Y + 8 TO X + 1,Y + 8
5230  HPLOT X + 1,Y + 8 TO X,Y + 6
5240  HPLOT X,Y + 6 TO X,Y + 2
5250  HPLOT X,Y + 2 TO X + 1,Y
5260  RETURN
5270  REM  NUMBER 2
5280  HPLOT X,Y + 2 TO X + 1,Y: HPLOT X + 1,Y TO X + 4,Y
5290  HPLOT X + 4,Y TO X + 5,Y + 2
5300  HPLOT X + 5,Y + 2 TO X,Y + 8
5310  HPLOT X,Y + 8 TO X + 5,Y + 8
5320  RETURN
5330  REM  NUMBER 300
5340  GOSUB 5000
5350 X = X + 7: GOSUB 5190
5360 X = X + 7
5370  GOSUB 5190
5380  RETURN
5390  REM  NUMBER 500
5395  GOSUB 5090
5400 X = X + 7: GOSUB 5190
5410 X = X + 7: GOSUB 5190
5420  RETURN
5430  REM  NUMBER 250
5435  GOSUB 5270
5440 X = X + 7: GOSUB 5090
5450 X = X + 7: GOSUB 5190
5460  RETURN
5465  END
```

C.2 DATA ANALYSIS PROGRAM

This program was altered from an earlier version that was written by Professor Antonio Elias.

```
100  HIMEM: 36606
105 PI = 3.141592
110  GOTO 450
120 N1 =  PEEK (LL + 10):N2 =  PEEK (LL + 12):N3 =  PEEK (LL + 14)
130  IF  PEEK (LL + 1) < 128 THEN V1 = 0.025 * ( PEEK (LL) + 256 *  PEEK
     (LL + 1))
140  IF  PEEK (LL + 1) >  = 128 THEN V1 = 0.025 * ( PEEK (LL) - 256 * (25
     6 -  PEEK (LL + 1)))
150  IF  PEEK (LL + 6) < 128 THEN V2 = 0.025 * ( PEEK (LL + 5) + 256 *  PEEK
     (LL + 6))
160  IF  PEEK (LL + 6) >  = 128 THEN V2 = 0.025 * ( PEEK (LL + 5) - 256 *
     (256 -  PEEK (LL + 6)))
170 D1 = 0.00625 * ( PEEK (LL + 2) + 256 *  PEEK (LL + 3) + 65536 *  PEEK
     (LL + 4))
180 D2 = 0.00625 * ( PEEK (LL + 7) + 256 *  PEEK (LL + 8) + 65536 *  PEEK
     (LL + 9))
185 XL =  PEEK (LL + 17)
186 XG =  PEEK (LL + 18)
187 XA =  PEEK (LL + 19)
200  RETURN
450 SE = 0.6:U1 = 1:U2 = 256:U3 = 20
470 C1 =  - 101.436:C2 =  - 92.927:C3 =  - 191.621:C4 = 171.641
471 DLA = 7950
472 WW = 1000
473 ZZ = 25000
474 ST = 1
475 TH = 83.1
476 IC = 143
477 APS = 100: REM  AVERAGE APPROACH SPEED IN KNOTS
480 XB = 140:YB = 6
485 R1 = 14119.73:R2 = 26033.25
490  ONERR  GOTO 2520
500 LA = 36608:IN = 1
510  DEF  FN RO(X) =  INT (X * P + 0.5) / P
520 P = 100:KB =  - 16384:KS =  - 16368
530 D$ = ""
540 SL = 20
550 B4 =  - 28673
560  DIM AR(380)
570 DA$ =  STR$ ( PEEK ( - 21912))
580 SL$ =  STR$ ( PEEK ( - 21913))
590 VD$ =  STR$ ( PEEK ( - 21914))
600 SC = 140
```

```
600 SC = 140
610  PRINT "CLOSE": TEXT : HOME
620 LL = LA
630  HTAB 9: PRINT "LORAN-C DATA DISPLAY PROGRAM"
640  HTAB 9: PRINT "============================"
650  HTAB 5: VTAB 4: PRINT "H - PLOT HISTOGRAM"
670  HTAB 5: PRINT "G - GS/ALT PLOT"
680  HTAB 5: PRINT "M - PLOT LORAN PLOT"
710  HTAB 5: PRINT "A - COMPUTE STATISTICS"
720  HTAB 5: PRINT "X - HARD COPY LAST PLOT"
725  HTAB 5: PRINT "F - PRINT A/D"
726  HTAB 5: PRINT "L - PLOT ILS MAP"
727  HTAB 5: PRINT "B - DIFFERENTIAL ANGLES"
730  PRINT : HTAB 5: PRINT "N - FILE NAME: ";NA$;
740  PRINT : IF NA$ <  > "" THEN  HTAB 9: PRINT "FILE HAS ";NP;" DATA POI
     NTS";
750  PRINT : HTAB 5: PRINT "S - SLOT: ";SL$;" DRIVE: ";DR$;" VOL: ";VO$;
760  PRINT : HTAB 5: PRINT "C - CATALOG"
770  HTAB 5: PRINT "R - PLOT PARAMETERS"
780  PRINT : HTAB 5: PRINT "Q - QUIT PROGRAM"
790  VTAB 23: PRINT "COMMAND -> ";
800  GET CC$
810  IF CC$ = "H" THEN  GOTO 1660
830  IF CC$ = "G" THEN  GOTO 1900
840  IF CC$ = "X" THEN  GOTO 1610
845  IF CC$ = "F" THEN  GOTO 3000
847  IF CC$ = "L" THEN  GOTO 4000
848  IF CC$ = "B" THEN  GOTO 4500
850  IF CC$ = "P" THEN  GOTO 1030
860  IF CC$ = "V" THEN  GOTO 1030
870  IF CC$ = "M" THEN  GOTO 2300
880  IF CC$ = "D" THEN  GOTO 2610
890  IF CC$ = "A" THEN  GOTO 210
900  IF CC$ = "N" THEN  GOTO 970
910  IF CC$ = "S" THEN  GOTO 1470
920  IF CC$ = "C" THEN  GOTO 1560
930  IF CC$ = "R" THEN  GOTO 1340
940  IF CC$ = "Q" THEN  HOME : END
950  GOTO 610
```

```
950  GOTO 610
960  PRINT : STOP
970  INPUT "FILE NAME: ";NA$
980 F$ = NA$
990  IF NA$ = "" THEN  GOTO 1490
1000  PRINT D$ + "BLOAD ";NA$;", A36606"
1010 NP =  PEEK (LA - 2) + 256 *  PEEK (LA - 1)
1020  GOTO 610
1340  HOME :PL$ = "PLOT SPLIT":PV = SE: GOSUB 2580: IF PV > 0 AND PV < 1 THEN
     SE = PV
1350 PL$ = "PLOTTING INCREMENT":PV = IN: GOSUB 2580:IN = PV
1360 PL$ = "MAP STYLE, 0=DOTS, 1=LINES":PV = ST: GOSUB 2580:ST = PV
1370 PL$ = "TD FULL SCALE, MSEC":PV = U1: GOSUB 2580:U1 =  ABS (PV)
1380 PL$ = "TDDOT FULL SCALE, NSEC/SEC":PV = U3: GOSUB 2580:U3 =  ABS (PV
     )
1390 PL$ = "MAP FULL SCALE X(FT)":PV = WW: GOSUB 2580:WW =  ABS (PV)
1395 PL$ = "MAP FULL SCALE Y(FT)":PV = ZZ: GOSUB 2580:ZZ =  ABS (PV)
1400 PL$ = "REFERENCE TD1":PV = R1: GOSUB 2580:R1 = PV
1410 PL$ = "REFERENCE TD2":PV = R2: GOSUB 2580:R2 = PV
1420 PL$ = "A11":PV = C1: GOSUB 2580:C1 = PV
1430 PL$ = "A12":PV = C2: GOSUB 2580:C2 = PV
1440 PL$ = "A21":PV = C3: GOSUB 2580:C3 = PV
1450 PL$ = "A22":PV = C4: GOSUB 2580:C4 = PV
1455 PL$ = "THETA":PV = TH: GOSUB 2580:TH = PV
1460 PL$ = "X BIAS":PV = XB: GOSUB 2580:XB = PV
1470 PL$ = "Y BIAS":PV = YB: GOSUB 2580:YB =  ABS (PV)
1472 PL$ = "ILS CENTER":PV = IC: GOSUB 2580:IC =  ABS (PV)
1474 PL$ = "APPROACH SPEED (Kts)":PV = APS: GOSUB 2580:APS =  ABS (PV)
1475 PL$ = "MAP TO LOCALIZER ARRAY (FT)":PV = DLA: GOSUB 2580:DLA =  ABS
     (PV)
1476 PL$ = "ILS X-TRACK FULL SCALE":PV = WW: GOSUB 2580:WW =  ABS (PV)
1477 PL$ = "ILS ALONG TRACK FULL SCALE":PV = ZZ: GOSUB 2580:ZZ =  ABS (PV
     )
1480  GOTO 610
1610  REM  GRAPHICS
1615  HIMEM: 35000
1620  PRINT  CHR$ (4);" BLOAD PRINT GRAPHICS.A35000"
1625  CALL 35000, HGR2 ,1,0,1,20,0,191,0,279
1630  GOTO 610
1900  HGR2
1910  HPLOT 0,0 TO 278,0 TO 278,191 TO 0,191 TO 0,0
1915  HPLOT 278,75 TO 272,75 TO 272,115 TO 278,115
1920 WU = 190 / WW
1925 ZU = 230 / ZZ
1930 VS = 27.00: REM  SUPPLY VOLTAGE FOR ALTIMETER
1935  FOR I = 1 TO NP
1940  GOSUB 170: REM  OBTAIN TD,ILS,ALT DATA
1945 LL = LL + SL
1950 AX = C1 * (D1 - R1) + C2 * (D2 - R2)
```

```
1950 XX = C1 * (D1 - R1) + C2 * (D2 - R2)
1955 YY =  - (C3 * (D1 - R1) + C4 * (D2 - R2))
1960 KZ = XX
1965 XX = (XX *  COS (TH * PI / 180)) - (YY *  SIN (TH * PI / 180)): REM
     XTRACK
1970 YY = (KZ *  SIN (TH * PI / 180)) + (YY *  COS (TH * PI / 180))
1975 YY = YY / 0.3048: REM  RANGE IN UNITS OF FEET
1976 YY =  - YY
1980 FT = APS * (NP - I) * (6000 / 3600)
1981 FD = (74.2353 * (YY / 6076.12)) + 0.098
1985 AD = ( - 0.02094 * XG) + 2.8260
1990 AD = (AD / 4) * FD:DG = AD
1995 VM = (6.738 * (10 ^ ( - 3)) * XA) + 1.1063
2000 AI = 60000 * ((VM / VS) - 0.05)
2001 AI = AI - 133
2005 AR = YY *  TAN (3.00 * PI / 180)
2010 DA = AI - AR: REM  ALT DIFF FROM ALT AND LORAN-C RANGE CALCULATIONS
2020 X3 = X1:Y3 = Y1:X4 = X2:Y4 = Y2
2025 X1 = 272 - (YY * ZU): REM  X-COOD FOR ALT
2030 Y1 = 95 - (DA * WU): REM  Y-COOD FOR ALT
2035 X2 = 272 - (FT * ZU): REM  X-COOD FOR GS
2040 Y2 = 95 - (AD * WU): REM  Y-COOD FOR GS
2041  IF X1 < 0 THEN X1 = 0
2042  IF X2 < 0 THEN X2 = 0
2043  IF Y1 < 0 THEN Y1 = 0
2044  IF Y2 < 0 THEN Y2 = 0
2045  IF X1 > 279 THEN X1 = 279
2046  IF X2 > 279 THEN X2 = 279
2047  IF Y1 > 191 THEN Y1 = 191
2048  IF Y2 > 191 THEN Y2 = 191
2049  IF I = 1 THEN  GOTO 2055
2050  IF I > 1 THEN  GOTO 2070
2055  HPLOT X1,Y1
2060  HPLOT X2,Y2
2065  GOTO 2080
2070  HPLOT X3,Y3 TO X1,Y1: REM  LORAN DATA IS IN LINE SEGMENTS
2075  HPLOT X2,Y2: REM  GLIDESLOPE DATA IS DOTTED
2080  NEXT
2085 LL = L4
2090  GET A$: GOTO 610
2300  HGR2
2330  HPLOT 0,0 TO 278,0 TO 278,191 TO 0,191 TO 0,0
2340  HPLOT XB - 21,YB - 6 TO XB - 21,YB + 6 TO XB + 21,YB + 6 TO XB + 21
     ,YB - 6
2350 UU = 280 / WW:UZ = 190 / ZZ
2360  IF R1 < 0 THEN R1 = X1:R2 = X2
2370  FOR I = 1 TO NP
2380  GOSUB 170
2385 LL = LL + SL
2390  IF R1 = 0 THEN R1 = D1:R2 = D2
2400 XX = C1 * (D1 - R1) + C2 * (D2 - R2)
2410 YY =  - (C3 * (D1 - R1) + C4 * (D2 - R2))
```

```
2414 KZ = XX
2415 XX = XX *  COS (TH * PI / 180) - YY *  SIN (TH * PI / 180)
2416 YY = KZ *  SIN (TH * PI / 180) + YY *  COS (TH * PI / 180)
2417 XX = XX / 0.3028:YY = YY / 0.3028
2418 XX =  - XX:YY =  - YY
2420 VA = XB + UU * XX:VB = YB + UZ * YY
2430  IF VA < 0 THEN VA = 0
2440  IF VB < 0 THEN VB = 0
2450  IF VA > 279 THEN VA = 279
2460  IF VB > 191 THEN VB = 191
2470  IF I = 1 THEN  HPLOT VA,VB
2480  IF I > 1 THEN  HPLOT  TO VA,VB
2500  NEXT
2505 LL = LA
2510  GET A$: GOTO 610
2520  REM
2530  TEXT : HTAB 1: VTAB 23: CALL  - 868: HTAB 9: PRINT "";
2540 EL =  PEEK (218) + 256 *  PEEK (219):EN =  PEEK (222)
2550  IF EN = 6 THEN  PRINT "CAN'T FIND FILE ";NA$;:NA$ = "":: GOTO 2570
2560  PRINT "ERROR ";EN;" AT LINE ";EL;
2570  HTAB 39: GET A$: GOTO 610
2580  PRINT PL$;" (";PV;") : ";: INPUT "";X$: IF X$ <  > "" THEN PV =  VAL
     (X$)
2590  RETURN
3000  HTAB 5: PRINT "RAW";: HTAB 12: PRINT "CENTERED;: HTAB 23: PRINT "FR
     OMMAP";: HTAB 35: PRINT "X - TRACK"
3002  PRINT "======================================="
3005 X =  PEEK (KS)
3010 I = 0
3020 I = I + 1: IF I > NP THEN  GOTO 3500
3030  GOSUB 120
3035 CXL = XL - IC
3050 FT = ABS * (6000 / 3600) * (NP - I)
3060  IF CXL <  =  - 85 THEN XDG =  - 2.3 + .46 / 22 * (CXL + 85)
3070  IF  - 85 < CXL AND CXL <  =  - 63 THEN XDG =  - 1.84 + .46 / 21 * (
     CXL + 63)
3080  IF  - 63 < CXL AND CXL <  =  - 45 THEN XDG =  - 1.38 + .46 / 18 * (
     CXL + 45)
3090  IF  - 45 < CXL AND CXL <  =  - 28 THEN XDG =  - .92 + .46 / 17 * (C
     XL + 28)
3100  IF  - 28 < CXL AND CXL <  =  - 13 THEN XDG =  - .46 + .46 / 15 * (C
     XL + 13)
```

```
3100  IF - 28 < CXL AND CXL < = - 13 THEN XDG = - .46 + .46 / 15 * (C
     XL + 13)
3110  IF - 13 < CXL AND CXL < 0 THEN XDG = .46 / 14 * CXL
3120  IF CXL = 0 THEN XDG = 0
3130  IF 0 < CXL AND CXL < 14 THEN XDG = .46 / 14 * CXL
3140  IF 14 <  = CXL AND CXL < 28 THEN XDG = .46 + .46 / 14 * (CXL - 14)
3150  IF 28 <  = CXL AND CXL < 45 THEN XDG = .92 + .46 / 17 * (CXL - 28)
3160  IF 45 <  = CXL AND CXL < 60 THEN XDG = 1.38 + .46 / 15 * (CXL - 45)

3170  IF 60 <  = CXL AND CXL < 79 THEN XDG = 1.84 + .46 / 19 * (CXL - 60)

3180  IF 79 <  = CXL THEN XDG = 2.3 + .46 / 20 * (CXL - 79)
3200 RXDG = XDG * PI / 180
3210 XT = (FT + DLA) *  TAN (RXDG)
3220  RETURN
3400  PRINT I;: HTAB 5: PRINT XL;: HTAB 12: PRINT CXL;: HTAB 23: PRINT FT
     ;: HTAB 35: PRINT XT
3480  IF  PEEK (KB) > 128 THEN  GOTO 3500
3490  GOTO 3020
3500  GET A$: GOTO 610
4000  HGR2
4020  HPLOT 0,0 TO 278,0 TO 278,191 TO 0,191 TO 0,0
4030  HPLOT XB - 21,YB - 6 TO XB - 21,YB + 6 TO XB + 21,YB + 6 TO XB + 21
     ,YB - 6
4040  HCOLOR= 7
4050 WU = 280 / WW
4055 ZU = 190 / ZZ
4060  FOR I = 1 TO NP
4070  GOSUB 185
4080  GOSUB 3035
4085 LL = LL + SL
4090 PXT = XB + WU * XT
4100 PFT = YB + ZU * FT
4101  IF PXT < 0 THEN PXT = 0
4102  IF PFT < 0 THEN PFT = 0
4103  IF PXT > 279 THEN PXT = 279
4104  IF PFT > 191 THEN PFT = 191
4105  IF I = 1 THEN  HPLOT PXT,PFT
4110  IF I > 1 THEN  HPLOT  TO PXT,PFT
4128  NEXT
4129 LL = LA
4130  GET A$: GOTO 610
4500  HOME
4501  PR# 1
4503  PRINT  CHR$ (9);"10L"
4504  IF I > 1 THEN  GOTO 4506
4505  PRINT "This is the data for "F$
4506  PRINT "#";: HTAB 17: PRINT "LOCALIZER";: HTAB 30: PRINT "LORAN";: HTAB
     40: PRINT "DIFFERENCE"
4507  PRINT "PNT";: HTAB 17: PRINT "ANGLE";: HTAB 30: PRINT "ANGLE";: HTAB
     40: PRINT "LOC-LORAN"
4508 A1 = 0:X1 = 0:Y1 = 0:Q1 = 0
```

```
4509  FOR I = 1 TO NP
4510  GOSUB 3030
4520  GOSUB 2380
4525 YY = YY - 7950 / 3.28
4530 XS =  -  ATN (XX / YY)
4540 XS = XS * 180 / PI
4550 DX = XS - XDG
4554 DING$ = STR$ (DX)
4560  PRINT I;: HTAB 17: PRINT  LEFT$ (STRING$,5);: HTAB 30: PRINT  LEFT$
     (LING$,5);: HTAB 40: PRINT  LEFT$ (DING$,5)
4561  IF I = 1 THEN  GOTO 4565
4562  IF I = 2 THEN  GOTO 4565
4563 A1 = A1 + DX
4565 LL = LL + SL
4570  NEXT
4575 LL = LA
4580 X1 = A1 / (NP - 2)
4600  FOR I = 1 TO NP
4610  GOSUB 3030
4620  GOSUB 2380
4630  IF I = 1 THEN  GOTO 4705
4640  IF I = 2 THEN  GOTO 4705
4650 YY = YY - 7950 / 3.28
4660 XS =  -  ATN (XX / YY)
4670 XS = XS * 180 / PI
4680 DX = XS - XDG
4690 Y1 = DX - X1:Q1 = Q1 + (Y1 * Y1)
4705 LL = LL + SL
4710  NEXT
4715 SD =  SQR (Q1 / (NP - 2))
4720  PRINT "AVERAGE ERROR ANGLE = ";X1
4730  PRINT "STANDARD DEVIATION = ";SD
4750  PR# 0
4760  GET A$: GOTO 610
```

C.3 FFT AND BODE PLOT PROGRAM

This program was altered from an earlier version that was written by Professor Antonio Elias.

```
50  HIMEM: 36606
60 C1 =  - 101.436:C2 =  - 92.927:C3 =  - 191.621:C4 = 171.64
70 R1 = 14119.1829:R2 = 26032.0798
80 TH = 83.1
90 RR = 1
120  DIM X1(64),X2(64),XX(64)
130  DIM D1(64),D2(64),N1(64),N2(64),N3(64)
140 D$ =  CHR$ (4):I$ =  CHR$ (9):L$ =  CHR$ (12)
150 ZW = 150:N = 256:L = 8
151 N = 64:L = 6
155 LA = 36608:SL = 20
160 PI = 3.141592
170 DR$ =  STR$ ( PEEK ( - 21912))
180 SL$ =  STR$ ( PEEK ( - 21910))
190 VO$ =  STR$ ( PEEK ( - 21914))
200 D$ = ""
210 P1 = 30:P2 = 70
220 P3 = 145:P4 = 191
230 S1 = 50:S2 = 0.15:SC = 140
240  TEXT : HOME
250  ONERR  GOTO 940
260  HTAB 10: PRINT "LORAN ANALYSIS SYSTEM"
270  HTAB 10: PRINT "====================="
280  VTAB 4
290  HTAB 5: PRINT "F - FILE: ";NA$
300  HTAB 5: PRINT "S - SLOT: ";SL$;" DRIVE: ";DR$;" VOL: ";VO$
310  HTAB 5: PRINT "C - CATALOG"
320  PRINT
340  HTAB 5: PRINT "T - TRACES"
350  HTAB 5: PRINT "1 - FFT ARCTAN(XTK/RA)"
360  HTAB 5: PRINT "2 - FFT LOCALIZER ANGLE"
370  HTAB 5: PRINT "3 - FFT PLOT SCALE:";
380  IF BB = 0 THEN  PRINT " AUTOMATIC"
390  IF BB <  > 0 THEN  PRINT "        ";BB
395  HTAB 5: PRINT "4 - BODE MAG PLOT"
400  PRINT : HTAB 5: PRINT "Q - QUIT PROGRAM"
410  GOSUB 1020: PRINT "COMMAND -> ";
420  GET CO$
430  IF CO$ = "1" THEN  GOTO 1190
440  IF CO$ = "2" THEN  GOTO 1190
450  IF CO$ = "3" THEN  GOTO 570
460  IF CO$ = "4" THEN  GOTO 2270
461  IF CO$ = "H" THEN  GOTO 2335
470  IF CO$ = "A" THEN  GOTO 1030
```

```
480  IF CO$ = "B" THEN  GOTO 1030
490  IF CO$ = "N" THEN  GOTO 600
500  IF CO$ = "F" THEN  GOTO 650
510  IF CO$ = "S" THEN  GOTO 820
520  IF CO$ = "T" THEN  GOTO 1980
540  IF CO$ = "C" THEN  GOTO 890
550  IF CO$ = "Q" THEN  HOME : END
560  GOTO 240
570  GOSUB 1020
580  INPUT "FFT PLOT FULL SCALE: ";TP$: IF TP$ = "" THEN  GOTO 240
590 BB =  VAL (TP$): GOTO 240
600  GOSUB 1020: INPUT "NO. OF POINTS? ";TP$: IF TP$ = "" THEN  GOTO 240
610 NT =  VAL (TP$):LT =  LOG (NT) /  LOG (2)
620  IF NT <  > 2 ^  INT (LT) THEN  GOSUB 1020: PRINT NT;" NOT AN EXACT P
     OWER OF 2          -->";: GET A$: GOTO 240
630  IF NT > 256 THEN  GOSUB 1020: PRINT NT;" GREATER THAN 256
          -->";: GET A$: GOTO 240
640 N = NT:L =  INT (LT): GOTO 240
650  INPUT "FILE NAME: ";NA$
660 F$ = NA$
670  IF NA$ = "" THEN  GOTO 240
680  GOSUB 1020
690  PRINT D$ + "BLOAD ";NA$;",A36606
700 NP =  PEEK (LA - 2) + 256 *  PEEK (LA - 1)
710 NP = 64
720  GOSUB 1020
740 B1 = 0:B2 = 0
745 LL = LA
750  FOR I = 1 TO NP
754 D1(I) = 0.00625 * ( PEEK (LL + 2) + 256 *  PEEK (LL + 3) + 65536 *  PEEK
     (LL + 4))
756 D2(I) = 0.00625 * ( PEEK (LL + 7) + 256 *  PEEK (LL + 8) + 65536 *  PEEK
     (LL + 9))
760 XX = C1 * (D1(I) - R1) + C2 * (D2(I) - R2)
762 YY =  - (C3 * (D1(I) - R1) + C4 * (D2(I) - R2))
763 XZ = XX
764 XX = XZ *  COS (TH * PI / 180) - YY *  SIN (TH * PI / 180)
765 YY = XZ *  SIN (TH * PI / 180) + YY *  COS (TH * PI / 180)
766 D1(I) =  ATN (XX / YY)
767 D2(I) =  PEEK (LL + 17)
768 D2(I) = (0.0313 * D2(I)) - 4.5265
769 D2(I) = D2(I) * PI / 180
770 B1 = B1 + D1(I):B2 = B2 + D2(I)
772 LL = LL + SL
780  NEXT I
790  PRINT D$ + "CLOSE"
800 U1 = B1 / NP:U2 = B2 / NP
805 LL = LA
806  PRINT U1,U2
807  GET A$
810  GOTO 240
```

```
820  GOSUB 1020: INPUT "SLOT? ";SL$
830  GOSUB 1020: INPUT "DRIVE? ";DR$
840  GOSUB 1020: INPUT "VOLUME? ";VO$
850  IF DR$ = "" THEN DR$ =  STR$ ( PEEK ( - 21912))
860  IF SL$ = "" THEN SL$ =  STR$ ( PEEK ( - 21910))
870  IF VO$ = "" THEN VO$ =  STR$ ( PEEK ( - 21914))
880  GOTO 240
890  HOME
900  PRINT : PRINT D$ + "CATALOG,S" + SL$ + ",D" + DR$ + ",V" + VO$
910  VTAB 23: HTAB 35: PRINT "--->";
920  GET A$
930  GOTO 240
950  IF EC = 6 THEN  PRINT "FILE ";NA$;" NOT FOUND";: GOTO 1000
960  IF EC = 11 THEN  PRINT "BAD FILE NAME";: GOTO 1000
970  IF EC = 7 THEN  PRINT "CAN'T FIND VOLUME IN THAT DRIVE";: GOTO 1000
980  IF EC = 5 THEN  PRINT "PREMATURE END OF FILE";: GOTO 1000
990  PRINT "ERROR NUMBER "; PEEK (222);" AT "; PEEK (218) + 256 *  PEEK (
     219);
1000  POKE 216,0: HTAB 36: PRINT "-->";: GET A$: GOTO 240
1010  GOTO 240
1020  VTAB 23: HTAB 1: CALL  - 868: RETURN
1030 B = 0
1040  FOR I = 1 TO N
1050  IF CO$ = "A" THEN  IF B <  ABS (D1(I) - U1) THEN B =  ABS (D1(I) -
     U1)
1060  IF CO$ = "B" THEN  IF B <  ABS (D2(I) - U2) THEN B =  ABS (D2(I) -
     U2)
1070  NEXT I
1080  HGR2
1090  HPLOT 0,80 TO 256,80
1100  IF CO$ = "A" THEN  HPLOT 0,80 - (79 * ((D1(1) - U1) / B))
1110  IF CO$ = "B" THEN  HPLOT 0,80 - (79 * ((D2(1) - U2) / B))
1120  FOR Z = 2 TO N
1130  IF CO$ = "A" THEN ZZ = D1(Z) - U1
1140  IF CO$ = "B" THEN ZZ = D2(Z) - U2
1150  HPLOT  TO Z,80 - (79 * (ZZ / B))
1160  NEXT Z
1170  GOSUB 1780
1180  GOTO 240
1190  FOR Z = 1 TO N
1200  IF CO$ = "1" THEN X1(Z) = D1(Z) - U1
1210  IF CO$ = "2" THEN X1(Z) = D2(Z) - U2
1220  NEXT Z
1230  FOR Z = 0 TO N - 1
1240 X1(Z) = X1(Z) / N
1250 X2(Z) = 0
1260  NEXT Z
1270 I1 = N / 2:I2 = 1:V = 2 * PI / N
1280  FOR I = 1 TO L
1290  GOSUB 1020: PRINT "PHASE ";I;" OF ";L;
1300 I3 = 0:I4 = I1
1310  FOR K = 1 TO I2
1320 X =  INT (I3 / I1)
1330  GOSUB 1670
```

```
1340 I5 = [illegible]
1350 Z1 =  COS (V * I5)
1360 Z2 =  - SIN (V * I5)
1370  FOR M = I3 TO I4 - 1
1380 A1 = X1(M):A2 = X2(M)
1390 B1 = Z1 * X1(M + I1) - Z2 * X2(M + I1)
1400 B2 = Z2 * X1(M + I1) + Z1 * X2(M + I1)
1410 X1(M) = A1 + B1:X2(M) = A2 + B2
1420 X1(M + I1) = A1 - B1:X2(M + I1) = A2 - B2
1430  NEXT M
1440 I3 = I3 + 2 * I1:I4 = I4 + 2 * I1
1450  NEXT K
1460 I1 = I1 / 2:I2 = 2 * I2
1470  NEXT I
1480 B = 0
1490  FOR Z = 0 TO N / 2
1500 X = Z
1510  GOSUB 1750
1520 XX(Z) = X3
1530  IF X3 > B THEN B = X3
1540  NEXT Z
1545  IF RR = 7 THEN  RETURN
1550  HGR2 : HPLOT 10,150 TO 266,150
1560  FOR I = 10 TO 266 STEP 2: HPLOT I,150 TO I,152: NEXT I
1570  FOR I = 10 TO 266 STEP 16: HPLOT I,150 TO I,154: NEXT I
1580  HPLOT 10,150 TO 10,0
1590  FOR I = 0 TO 150 STEP 15: HPLOT 6,I TO 10,I: NEXT I
1600  IF BB <  > 0 THEN B = BB
1610  FOR Z = 0 TO N / 2
1620 ZX = 10 + 2 * Z:ZY = ZX + 1:ZZ = 150 - (140 * XX(Z) / B)
1630  IF ZZ < 0 THEN ZZ = 0
1640  HPLOT ZX,ZW TO ZX,ZZ TO ZY,ZZ TO ZY,ZW
1650  NEXT Z
1660  GOSUB 1780: GOTO 240
1670 Y = 0:N1 = N
1680  FOR W = 1 TO L
1690 N1 = N1 / 2
1700  IF X < N1 THEN 1730
1710 Y = Y + 2 ^ (W - 1)
1720 X = X - N1
1730  NEXT W
1740  RETURN
1750  GOSUB 1670
1760 X3 =  SQR (X1(Y) ^ 2 + X2(Y) ^ 2)
1770  RETURN
1780  GOSUB 1020: PRINT "HARD COPY? (Y/N) ";
1790  GET A$: IF A$ = "N" THEN  RETURN
1800  IF A$ <  > "Y" THEN  GOTO 1780
1810  PR# 1: PRINT : PRINT
1820  PRINT "FILE: ";NA$;", ";NP;" DATA POINTS"
1830  IF CO$ = "1" THEN  PRINT "TD1 ";
1840  IF CO$ = "2" THEN  PRINT "TD2 ";
```

```
1850  IF CO$ = "A" THEN  PRINT "EXPANDED TD1 RESIDUAL"
1860  IF CO$ = "B" THEN  PRINT "EXPANDED TD2 RESIDUAL"
1870  IF CO$ = "1" OR CO$ = "2" OR CO$ = "4" THEN  PRINT N;" POINTS FFT.
      FULL SCALE IS ";2 * B;" MICROSECONDS"
1880  IF CO$ <  > "H" THEN  GOTO 1930
1890  PRINT "   TD1";: HTAB 26: PRINT "TD2"
1900  PRINT "AV:  ";U1;: HTAB 26: PRINT U2
1910  PRINT "SD:  "; SQR (Q1 / NP);: HTAB 26: PRINT  SQR (Q2 / NP)
1920  PRINT "AV. S/N: M-> "; INT (N1 / NP);" S2-> "; INT (N2 / NP);" S3->
      "; INT (N3 / NP);
1930  IF CO$ = "T" THEN  PRINT "TD1, TD2, SNR2, SNR3"
1940  PRINT : PRINT : PRINT
1950  PRINT I$ + "G"
1960  PR# 0
1970  RETURN
1980  HGR
1990  POKE  - 16302,0
2000  HCOLOR= 7
2010  HPLOT 0,P1 TO 8,P1: HPLOT 272,P1 TO 279,P1
2020  HPLOT 0,P2 TO 8,P2: HPLOT 272,P2 TO 279,P2
2030  HPLOT 0,P1 + 0.1 * S1 TO 4,P1 + 0.1 * S1
2040  HPLOT 0,P2 + 0.1 * S1 TO 4,P2 + 0.1 * S1
2050  HPLOT 0,P3 - 255 * S2 TO 4,P3 - 255 * S2
2060  HPLOT 0,P3 TO 4,P3
2070  HPLOT 0,P4 - 255 * S2 TO 4,P4 - 255 * S2
2080  HPLOT 0,P4 TO 4,P4
2090  HPLOT 0,P1 - 0.1 * S1 TO 4,P1 - 0.1 * S1
2100  HPLOT 0,P2 - 0.1 * S1 TO 4,P2 - 0.1 * S1
2110  FOR J = 1 TO NP
2120 I = J - 1
2130 V1 = P1 + S1 * (D1(J) - U1): IF V1 < 0 THEN V1 = 1
2140 V2 = P2 + S1 * (D2(J) - U2): IF V2 < 0 THEN V2 = 1
2150 V3 = P3 - S2 * N2(J)
2160 V4 = P4 - S2 * N3(J)
2170  IF V1 > 191 THEN V1 = 191
2180  IF V2 > 191 THEN V2 = 191
2190  HPLOT I,V1
2200  IF V2 > 191 THEN V2 = 191
2210  HPLOT I,V2
2220  HPLOT I,V3
2230  HPLOT I,V4
2240  NEXT J
2250  GET A$: POKE  - 16301,0
2260  GOSUB 1780: GOTO 240
2270  HOME : INPUT "X-AXIS :";RX
2275  INPUT "Y-AXIS :";RY
2276 RR = 7
2280 WX = 280 / RX:WY = 190 / RY
2285 CO$ = "1": GOSUB 1190
2290  FOR I = 1 TO NP:N1(I) = X1(I): NEXT
2295 CO$ = "2": GOSUB 1190
2300  FOR I = 1 TO NP:N2(I) = X1(I): NEXT
2301  HOME : PRINT "PLEASE WAIT.."
```

```
2305  FOR I = 1 TO NP
2310 N3(I) =  LOG ( ABS (N1(I) / N2(I)))
2315 N3(I) = N3(I) /  LOG (10)
2320 XX(I) = (2 * PI / 113) * ((NP - I + 1) / NP)
2325 XX(I) =  LOG (XX(I)) /  LOG (10)
2326 XX(I) =  - XX(I)
2330  NEXT
2335  HGR2
2340  HPLOT 0,0 TO 0,190 TO 279,190 TO 279,0 TO 0,0
2345  HPLOT 0,95 TO 279,95
2350  FOR I = 1 TO NP
2355 PX = XX(I) * WX
2360 PY = 95 - (N3(I) * WY)
2361  IF PX < 0 THEN PX = 0: IF PX > 279 THEN PX = 278
2362  IF PY < 0 THEN PY = 0: IF PY > 190 THEN PY = 190
2365  IF I = 1 THEN  HPLOT PX,PY
2370  IF I > 1 THEN  HPLOT  TO PX,PY
2375  NEXT
2380 RR = 1
2385  GET A$: GOTO 240
2390  HPLOT V1,150 - X1(V1)
2400 V1 = 210 + SC * (D2(I) - U2)
2410  IF V1 > 279 THEN V1 = 279
2420  IF V1 < 1 THEN V1 = 1
2430  IF X1(V1) < 150 THEN X1(V1) = X1(V1) + 1
2460 Y2 = D2(I) - U2:Q2 = Q2 + (Y2 * Y2)
2470 N1 = N1 + N1(I):N2 = N2 + N2(I):N3 = N3 + N3(I)
2480  NEXT I
2490  VTAB 23: HTAB 1
2500  PRINT "AV:   ";U1;: HTAB 26: PRINT U2
2510  PRINT "SD:   "; SQR (Q1 / NP);: HTAB 26: PRINT  SQR (Q2 / NP)
2520  PRINT "AV. S/N: M-> "; INT (N1 / NP);" S2-> "; INT (N2 / NP);" S3->
      "; INT (N3 / NP);
2530  GET A$: GOSUB 1780: GOTO 240
```

REFERENCES

[1] Kayton, M., and Fried, W.R., editors, Avionics Navigation Systems , John Wiley & Sons, New York, N.Y., 1969.

[2] Elias, A.L., 'LORAN-C Approach Guidance', *Navigation*, Vol. 32, No. 1, Spring 1985.

[3] Federal Aviation Administration, *Advisory Circular 90-45A*, February 1975.

[4] Einhorn, John K., 'Probabilistic Modeling of LORAN-C for Non-Precision Approaches', MIT, Flight Transportation Laboratory Report R85-5, June 1985.

[5] Hollister, W.M., Natarajan, K., and Littlefield, J.A., 'Flight Evaluation of LORAN-C for General Aviation Area Navigation', *Navigation*, Vol. 28, No. 4, Winter 1981-1982.

[6] Reilly, R.A., 'Microminiature LORAN-C Receiver/Indicator', IEEE Transactions on Aerospace and Electronic Systems, Vol. AES-2, No. 1, pp. 74-88, January 1986.

[7] Chatfield, Christopher, Statistics for Technology, John Wiley & Sons, New York, N.Y., 1978.

[8] D'Azzo, John J., and Houpis, Constantine H., Feedback Control System Analysis and Synthesis , McGraw-Hill Book Company, New York, N.Y., 1966.

[9] Wenzel, R.J., and Slagle,D.C., 'LORAN-C Signal Stability:Northeast and Southeast U.S.', August 1983.

[10] Hughes, M., and Adams, R.J., 'An Operational Flight Test Evaluation of a LORAN-C Navigator', CG-D-9-77, March 1977.