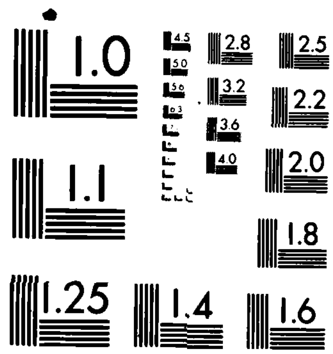
AD-A139 871 CONUS LORAN-C ERROR BUDGET: FLIGHT TEST(U) SYSTEMS CONTROL TECHNOLOGY INC WEST PALM BEACH FL L D KING ET AL DEC 83 DOT/FAA/PM-83/32 1/2

UNCLASSIFIED DTFA01-83-C-20041 F/G 17/7 NL



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

AD-A139871

DOT/FAA/PM-83/32

Program Engineering &
Maintenance Service
Washington, D.C. 20591

CONUS LORAN-C ERROR BUDGET

Larry D. King
Edwin D. McConkey
Kristen J. Venezia

December 1983

Final Report

NOTICE

Technical Report Documentation Page

1. Report No. DOT/FAA/PM-83/32	2. Government Accession No.	3. Recipient's Catalog No. December 1983
4. Title and Subtitle CONUS Loran-C Error Budget		5. Report Date
		6. Performing Organization Code
7. Author(s) L.D. King, K.J. Venezia and E.D. McConkey		8. Performing Organization Report No.
9. Performing Organization Name and Address Systems Control Technology, Inc. 2326 S. Congress Ave., Suite 2A West Palm Beach, Florida 33406		10. Work Unit No. (TRAIS) DTFA01-83-C-20041
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address Department of Transportation Federal Aviation Administration 800 Independence Avenue, S.W. Washington, D.C. 20591		13. Type of Report and Period Covered FINAL REPORT
		14. Sponsoring Agency Code FAA APM-420
15. Supplementary Notes		

16. Abstract

This report contains the description and results of a Loran-C flight test program conducted in the continental United States (CONUS). The data collection period was during July 1983. The purpose of the program was to collect Loran-C signal coverage and accuracy data representative of low altitude, low speed operations typical of helicopters and general aviation aircraft.

The test aircraft used was a Beechcraft Queen Air, Model 65. The aircraft was configured with a data collection palate and multipin electrical connectors located in the aircraft cabin. A Teledyne TDL-711 navigation receiver was used in the test, utilizing an E-field antenna mounted on the top of the fuselage. A microprocessor controlled data collection system, utilizing a scanning DME and other aircraft navigation instruments, was used to record data and establish aircraft reference position.

Route segments, totaling over 9500 nm covering much of CONUS, were flown during the project. Data were recorded on all route segments. Over 12,000 data points were used in the accuracy analysis. Calibration procedures, used at five locations, reduced errors throughout an area within a 75 nm radius of the calibration point.

17. Key Words Navigation Flight Test Loran-C		18. Distribution Statement Document is available to the U.S. Public through the National Technical Information Service, Springfield, VA 22161	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 118	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF TABLES

1.0 EXECUTIVE SUMMARY

1.1 INTRODUCTION

This report contains a description and results of a Loran-C flight test program that was conducted in the continental United States (CONUS). The project was performed during July 1983. The purpose was to collect Loran-C signal coverage and accuracy data representative of low altitude, low speed operations typical of helicopters and general aviation aircraft.

1.2 TEST EQUIPMENT

The test aircraft was a Beechcraft Queen Air, Model 65. The aircraft was leased by the contractor and configured as a navigation test vehicle with a data collection palate and multipin electrical connectors located in the aircraft cabin. The connectors provide 28V DC, 115V/400Hz AC power and signals from several aircraft navigation instruments.

A Teledyne TDL-711 navigation receiver was used in the project. The equipment consisted of a receiver/processor unit, a control/display unit and an antenna unit. The antenna was an eighteen inch whip E-field type that was mounted on the top of the fuselage. The control/display unit was located on the aircraft console and was operated by the flight crew during the test. The course deviation signal and a system warning flag were displayed on a conventional course deviation indicator located on the pilot's flight instruments.

1.3 TEST AREA

Route segments, totaling over 9500 nm and covering much of CONUS, were flown during the project. Specific segments are listed in Table 1.1. The route segments were chosen in such a manner that all stations in each of the four U.S. Loran-C chains were used at some time during the test.

In addition to the enroute segments, five calibration segments were flown to specifically evaluate the effectiveness of using area calibration procedures in a localized area. The size of the area that was examined was a 75 nm radius from the calibration point. The pattern flown in these tests resembled a tilted figure-eight and is shown in Figure 1.1. Calibration segments were flown at London, KY, Burlington, VT, Muskegon, MI, Fresno, CA, and Lafayette, LA.

Table 1.1 Flight Test Segments

Segment	Origin	Destination
1	West Palm Beach, FL	London, KY
2	London, KY	Atlantic City, NJ
3	Atlantic City, NJ	Burlington, VT
4	Burlington, VT	Flint, MI
5	Flint, MI	Muskegon, MI
6	Muskegon, MI	Kansas City, MO
7	Kansas City, MO	Rapid City, SD
8	Rapid City, SD	Billings, MT
9	Billings, MT	Portland, OR
10	Portland, OR	Medford, OR
11	Medford, OR	Fresno, CA
12	Fresno, CA	Phoenix, AZ
13	Phoenix, AZ	Lubbock, TX
14	Lubbock, TX	San Antonio, TX
15	San Antonio, TX	Lafayette, LA
16	Lafayette, LA	Tallahassee, FL
17	Tallahassee, FL	West Palm Beach, FL

1.4 ENROUTE NAVIGATION AVAILABILITY AND ACCURACY

Navigation data were recorded on a microprocessor based data collector which stored a number of position related parameters on cassette tape. The following parameters were recorded:

Aircraft Instrument Parameters

- VOR bearing
- DME distance (aircraft DME)
- heading
- altitude
- time (data collector clock)
- course deviation and flag

Reference Aircraft Positioning System

- DME distances (scanning DME)
- cochannel VOR frequency
- time tag (corresponds to time of the distance measurement)

Loran-C Navigation Parameters

- distance to waypoint
- desired track
- latitude/longitude
- Loran-C triad and transmitter signal data

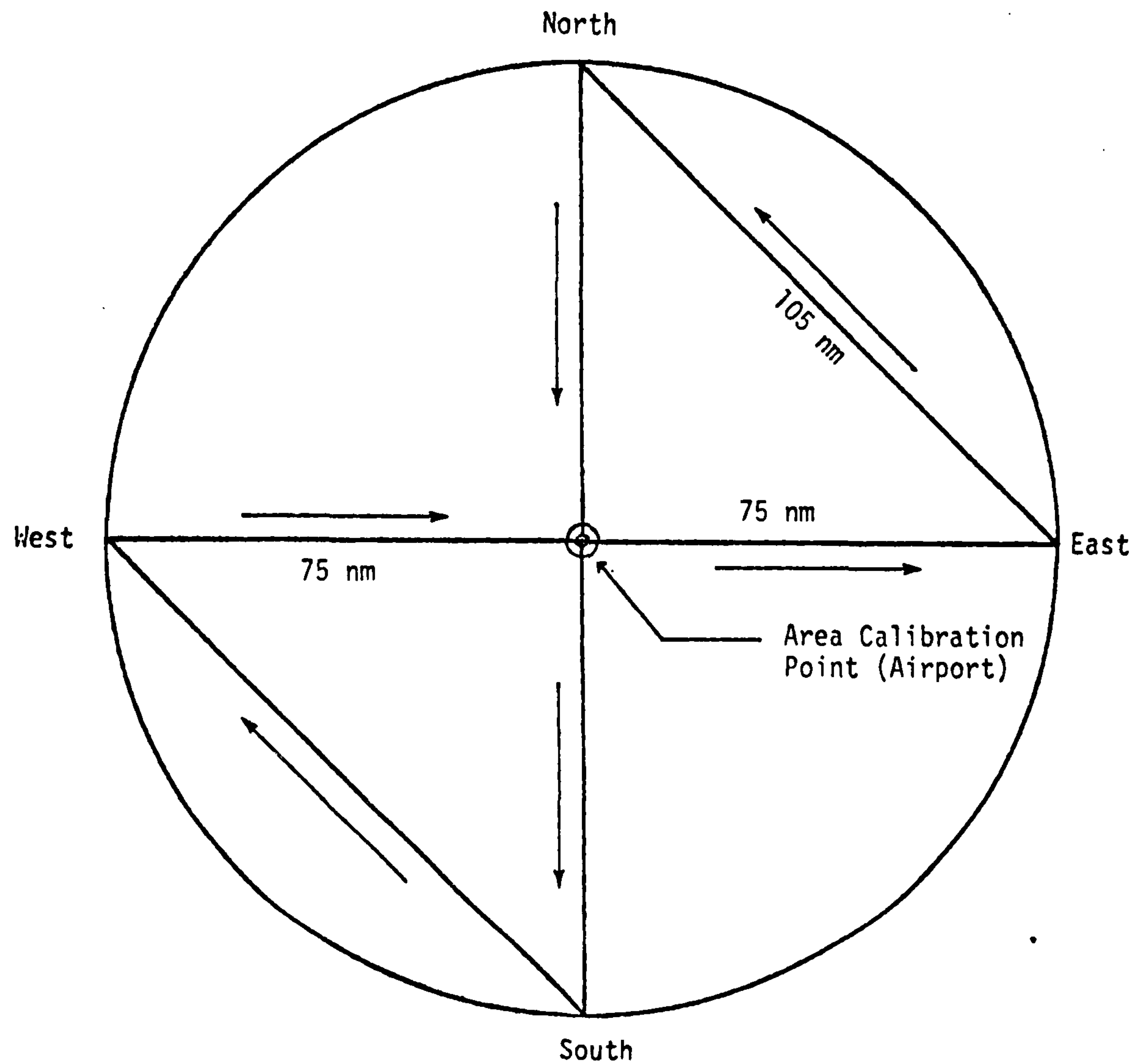


Figure 1.1 Area Calibration Pattern (75 nm Radius of Validity)

Aircraft position was established during post flight data processing from the multiple DME distance measurements (up to seven per second) provided by the scanning DME. Navigation accuracy was determined by comparing the Loran-C position and navigation parameters with corresponding parameters derived from the DME position reference system.

The flight test and subsequent analysis of the recorded data produced the following results:

- Loran-C signals were received on all segments of the test, even those in the "midcontinental gap" area. However, the Loran-C geometry is very poor in some of these areas, particularly in the southwestern United States, which produced large navigation errors.

- Navigation errors measured during the enroute phase of the test, in areas of both good and poor geometry, were worse than the enroute requirements of FAA Advisory Circular 90-45A for the non-VOR/DME systems. In areas of good geometry only, navigation errors were better than the requirements of AC 90-45A.

- The largest source of navigation error was due to propagation modeling error. These errors are transformed into navigation errors by the coordinate conversion process and tend to look like bias errors in a given operational area.

- Cycle errors, caused by misidentification of the third cycle zero crossing of the Loran-C signal, were observed on three separate occasions during the test. Two of these occurrences happened in areas of good Loran-C coverage near London, KY and Lafayette, LA. The other occurrence happened in a poor Loran-C coverage area near Albuquerque, NM.

- Outages at the Loran-C transmitters, both of a momentary nature and of longer duration, were correlated with outages of the airborne receiver. In most instances, the momentary outages produced no operationally significant effect upon navigation. In one instance, however, a momentary outage on the master signal caused the cycle error observed near London, KY.

- A few short duration receiver outages were correlated with rain and thunderstorm activity. These outages were probably caused by electrical interference and/or precipitation static. In general these outages were not operationally significant.

- Flight technical errors recorded during the test were quite small, 0.4 nm (2σ).

1.5 CALIBRATION TEST RESULTS

At five locations, a calibration procedure permitted the operator to insert a correction factor into the receiver to remove system bias errors at the calibration point. The following results were obtained during these tests:

- The calibration procedure reduced navigation errors throughout the 75 nm radius calibration point. After calibration, errors were reduced to a level where both enroute and terminal area requirements of AC 90-45A were met at all test locations. In addition, the accuracy very nearly met the requirements for non-precision approach throughout the calibration area.

- Time difference errors of the Loran-C lines of position were derived from a comparison of the Loran-C position and the DME reference position. In some areas and in some directions of flight, these errors were dependent upon the distance to the calibration point. In other segments, there was no significant relationship between these errors and the distance from the calibration point.

- In some calibration tests the correction factor, which was inserted on the ground at a known location, did not totally remove all time difference error at the calibration point as determined from the airborne measurements. These differences may be due to errors in the reference point location or local disturbances in the Loran-C grid near the calibration point. The differences, measuring over 1 μs in some instances, could produce operationally significant navigation errors if Loran-C were to be used for instrument approach procedures.

2.0 TEST DESCRIPTION AND PROCEDURES

2.1 PURPOSE OF THE TESTS

The purpose of the project was to collect Loran-C data and develop error budgets which emphasize low altitude operations typical of general aviation aircraft and helicopters. Enroute data was collected across the continental United States "touching" as many of the forty-eight contiguous states as possible. Over 9500 nm were flown and more than 78 hours of Loran-C data were collected. The testing period was from 5 July 1983 to 15 July 1983.

2.2 TEST OBJECTIVES

The objective of this project was to collect and analyze Loran-C performance data in the CONUS enroute structure. The specific objectives of this flight test were defined as follows:

- Collect data that is representative of general aviation (GA) operations.

  General aviation, including helicopter operators, is expected to be the major user of Loran-C in domestic airspace. The contractor utilized a general aviation aircraft, a Beechcraft Queen Air, for this purpose. The Loran-C data were collected at altitudes typically flown by GA aircraft with speeds and dynamic maneuvers typical of GA aircraft.

- Collect data over a broad geographical area of the domestic U.S.

  Four Loran-C chains are in operation in CONUS, three in the eastern and middle eastern states and one in the western states. The test route called for utilizing all Loran-C stations in all four Loran-C chains.

- Collect data in both good and poor coverage areas.

  Coverage was limited by the lack of available signals, poor geometry of the Loran-C lines of position, and local noise.

- Collect data to reveal the bias error characteristics of Loran-C time differences.

  In previous tests of Loran-C systems a constant bias error had been noted as being a characteristic of the system. The test route provided for a detailed examination of this bias error in five diverse locations.

- Collect data that can be processed to produce Loran-C error budgets.

  In order to produce error budget information, both Loran-C data and reference aircraft position data must be available to the analyst. The data collection system provided a means of recording both Loran-C data from an airborne receiver and position reference data from TACAN and DME stations operated by the FAA and the U.S. Department of Defense. No transmitters or transponders were needed to be put in place to establish the reference position of the aircraft.

- Process the recorded data to produce Loran-C error budget data.

  The contractor developed computer programs and analysis procedures in previous error budget programs for this specific purpose. These programs were fully compatible with the FAA error budget requirements.

2.3 TEST LOCATIONS

The extensive navigation coverage provided by a limited number of Loran-C transmitters made test location selection a complex process. Signal bias errors and even coverage varied from location to location depending on such factors as local topography, transmitter geometry and localized electromagnetic disturbances. Test locations were chosen to include many geographically diverse situations in areas of both good and bad geometry. For the purposes of this test one "round-robin" route covering most of CONUS was flown. The Loran-C airborne system was tested over a 7000 nautical mile route. Five locations had also been chosen for area calibration flights. Each of these flights covered approximately 500 nm within a 75 nm radius of the test location. In total, approximately 9,500 nautical miles of Loran-C data were collected. In order to minimize the number of ATC directed course deviations, all enroute segments followed the Victor Airway structure. The overall route of flight is depicted in Figure 2.1 while specific enroute procedures which were followed are more fully discussed in Section 2.4. As shown in Figure 2.1, the major test locations were:

West Palm Beach, FL	Rapid City, SD
London, KY	Eugene, OR
Atlantic City, NJ	Fresno, CA
Burlington, VT	Phoenix, AZ
Muskegon, MI	San Antonio, TX
Kansas City, MO	Lafayette, LA

Of the major test locations, the five places which were utilized for area calibration test sites were as follows:

London, KY

Burlington, VT

Muskegon, MI

Fresno, CA

Lafayette, LA

A list of the VOR/VORTAC stations used during the flight test are presented in Table 2.1

Table 2.1 VOR/VORTAC Stations Used During CONUS Loran-C Flight Test

IDENTIFIER	LOCATION	IDENTIFIER	LOCATION
ABQ	Albuquerque, NM	LCH	Lake Charles, LA
ACH	Anton Chico, NM	LFT	Lafayette, LA
ACY	Atlantic City, NJ	LIN	Linden, CA
AHN	Athens, GA	LMN	Lamoni, IA
BAE	Badger, WI	LNK	Lincoln, NE
BFL	Bakersfield, CA	LOZ	London, KY
BGS	Big Springs, TX	LWS	Lewiston, ID
BIL	Billings, MT	MAI	Marianna, FL
BLF	Bluefield, WV	MFR	Medford, OR
BLH	Blythe, CA	MKC	Kansas City, MO
BPT	Beaumont, TX	MKG	Muskegon, MI
BRG	Whitesburg, KY	MOL	Montebello, VA
BTV	Burlington, VT	MSO	Missoula, MT
BUF	Buffalo, NY	MSY	New Orleans, LA
BXK	Buckeye, AZ	OLU	Columbus, NE
CCC	Calverton, NY	ONL	Oneill, NE
CEW	Crestview, FL	ORL	Orlando, FL
DBN	Dublin, GA	ORW	Norwich, CT
DLS	The Dalles, OR	OTM	Ottumwa, IA
DPK	Deer Park, NY	OTO	Otto, NM
DRU	Drummond, MT	OTT	Nottingham, MD
ECK	Peck, MI	PBI	Palm Beach, FL
EEN	Keene, NH	PHP	Philip, SD
ELA	Eagle Lake, TX	PHX	Phoenix, AZ
ENO	Kenton, DE	PIR	Pierre, SD
EUG	Eugene, OR	PMD	Palmdale, CA
FAT	Fresno, CA	PSC	Pasco, WA
FJS	Fort Jones, CA	PSP	Palm Spring, CA
FNT	Flint, MI	PWE	Pawnee City, NE
GDM	Gardner, MA	RAP	Rapid City, SD
GEF	Greenville, FL	RBL	Red Bluff, CA
GFL	Glen Falls, NY	ROC	Rochester, NY
GPT	Gulfport, MS	SAC	Sacramento, CA
GVE	Gordonsville, VA	SAT	San Antonio, TX
HLN	Helena, MT	SHR	Sheridan, WY
HOB	Hobbs, NM	SJI	Semmes, AL
HRS	Harris, GA	SJN	Saint Johns, AZ
HYM	Hyman, TX	SJT	San Angelo, TX
IAP	Portland, OR	SYR	Syracuse, NY
IOW	Iowa City, IA	TAY	Taylor, FL
ISL	Winner, SD	TLH	Tallahassee, FL
JAX	Jacksonville, FL	TXO	Texico, NM
JCT	Junction, TX	TYS	Knoxville, TN
JVL	Janesville, WI	UCA	Utica, NY
LBB	Lubbock, TX	YXU	London, CN

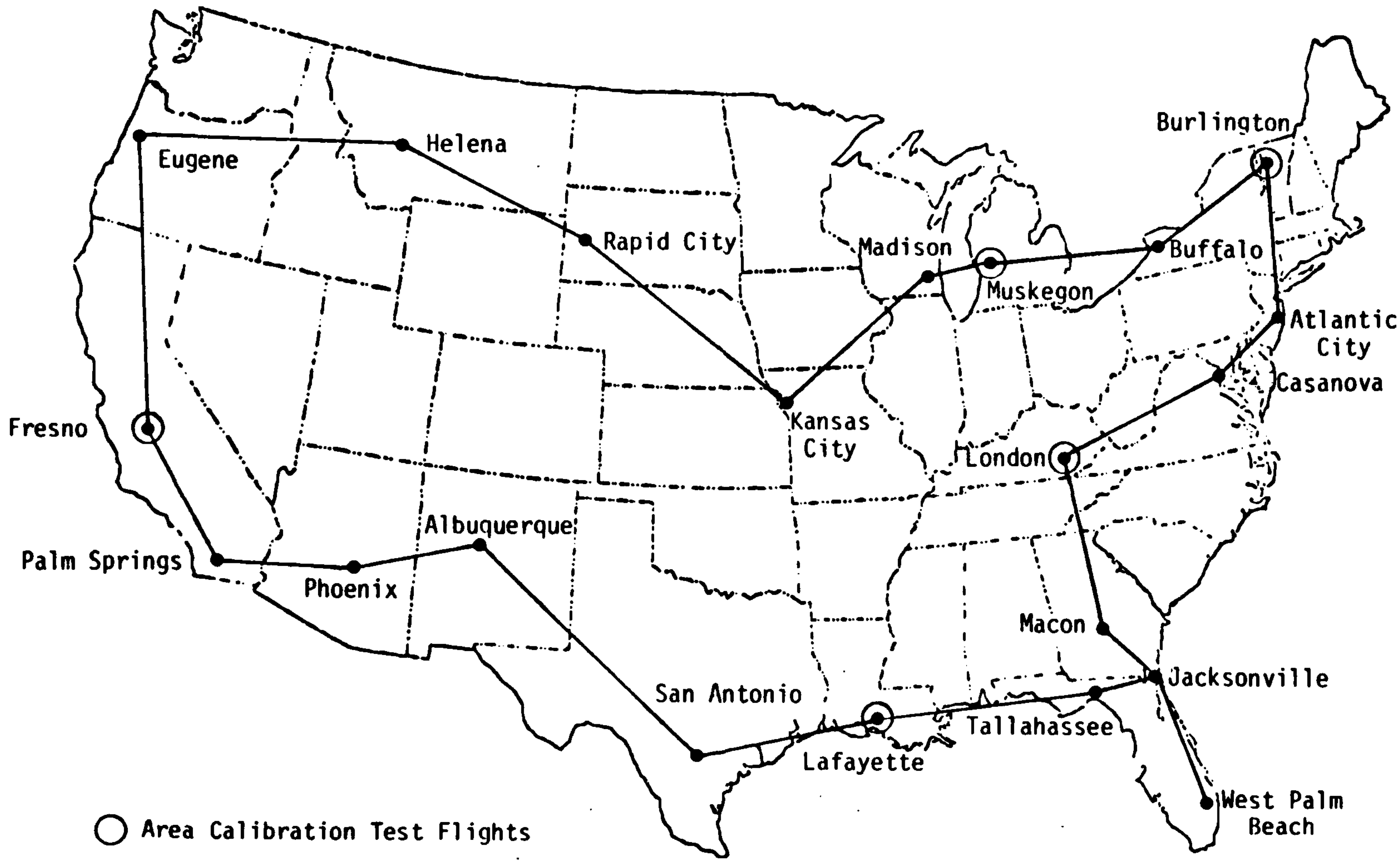


Figure 2.1 Loran-C Flight Test Route

Navigation system check-out flights and pilot training were conducted in the vicinity of Palm Beach International Airport in West Palm Beach, Florida. Data acquisition system calibration was also conducted in the Palm Beach area utilizing visual reference data and DME cross correlation.

2.4 FLIGHT TEST ROUTES AND PROCEDURES

Presently, data exists from previous Loran-C flight tests conducted in the United States in the following areas:

- London, KY (private data)
- Atlantic City, NJ
- State of Vermont
- Reno, Nevada and the surrounding area
- Areas of Colorado
- Klamath Falls, OR
- Transition data collected during the Alaska Loran-C flight test (Figure 2.2)

The flight test route covered virtually all "new ground" while at the same time duplicating some previous test locations for data validation purposes. Certain locations such as London, KY were ideal because of station geometry for tests like the area calibration. Many previously untested areas in the Great Lakes region, the West Coast area and the Southeast/Central parts of the United States were investigated.

2.4.1 CONUS Flight Test Routes and Procedures

The flight test route utilized all four United States based Loran-C chains. They were: the Southeast Chain, Northeast Chain, Great Lakes Chain and the West Coast Chain. Figures 2.3 through 2.6 depict the expected coverage from the four Loran-C chains as defined by the United Stated Coast Guard (USCG). Correlating Figure 2.1 with Figures 2.3 through 2.6 it is apparent that there were places along the flight test route where there is no published Loran-C coverage. For example, areas in the Rapid City, SD region and in the San Antonio, TX area were without accurate Loran coverage per se. This is not to say that Loran signals could not be received in these areas, but it was observed that Loran navigation in these general areas were not accurate or reliable. Other areas such as London, KY and Muskegon, MI were in excellent Loran-C coverage areas. In fact, navigation in the London, KY area was accomplished using the Southeast, Northeast, and Great Lakes chains.

The flight test route was designed to include as many geographically diverse station geometry situations as possible. The flight test route

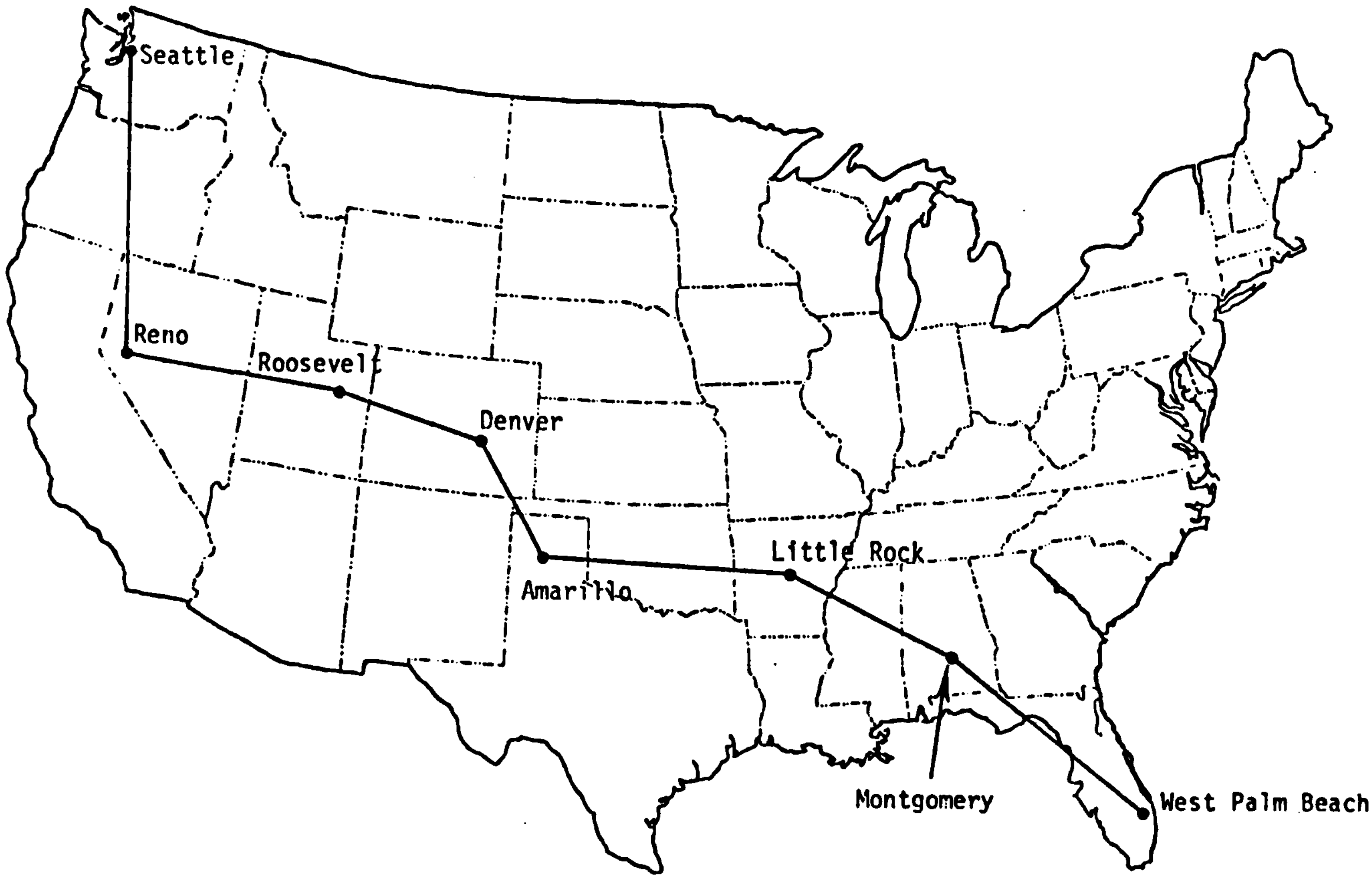


Figure 2.2 Transition Flight Test Route (W. Palm Beach to Seattle)

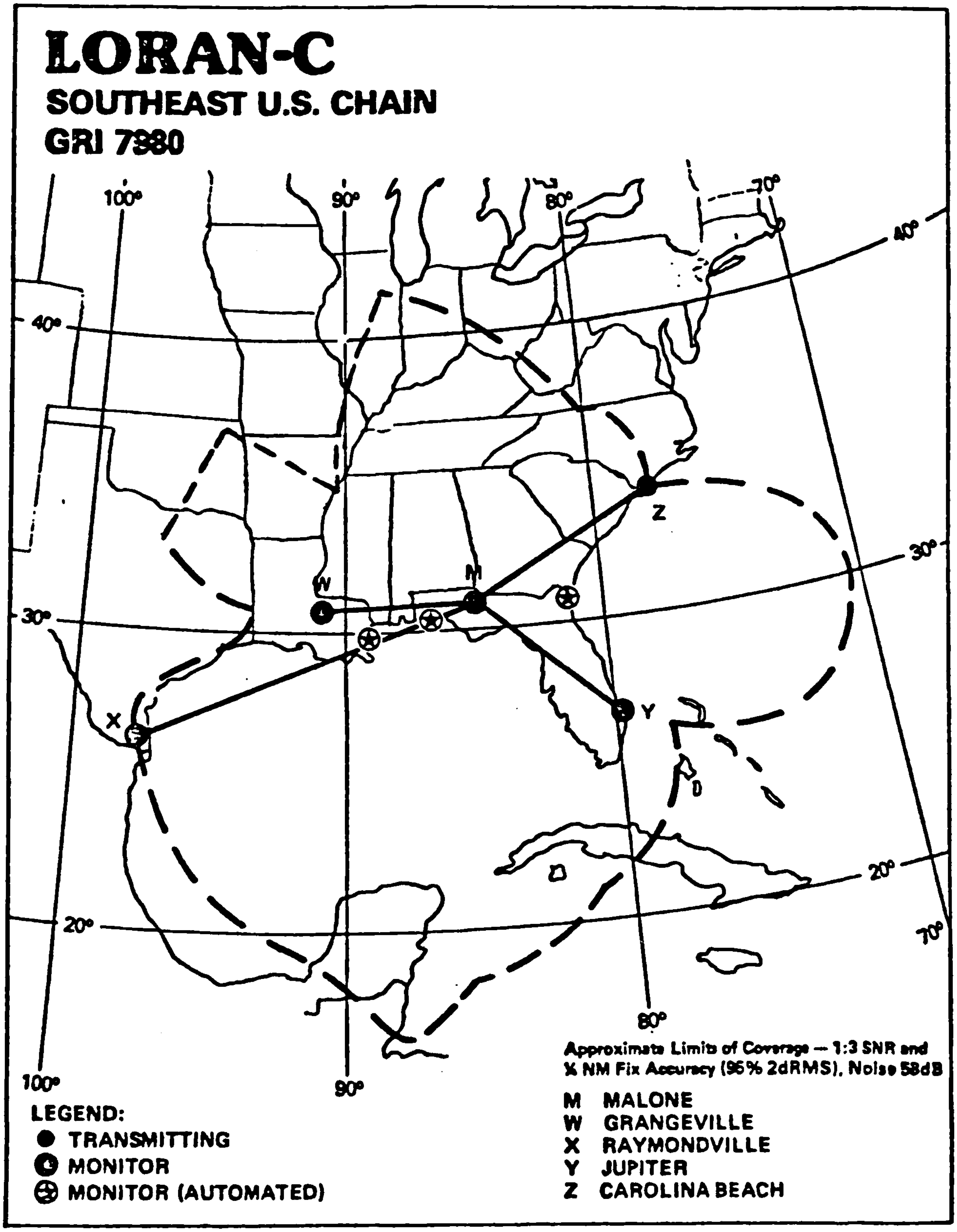


Figure 2.3 Loran-C Southeast U.S. Chain Coverage[2]

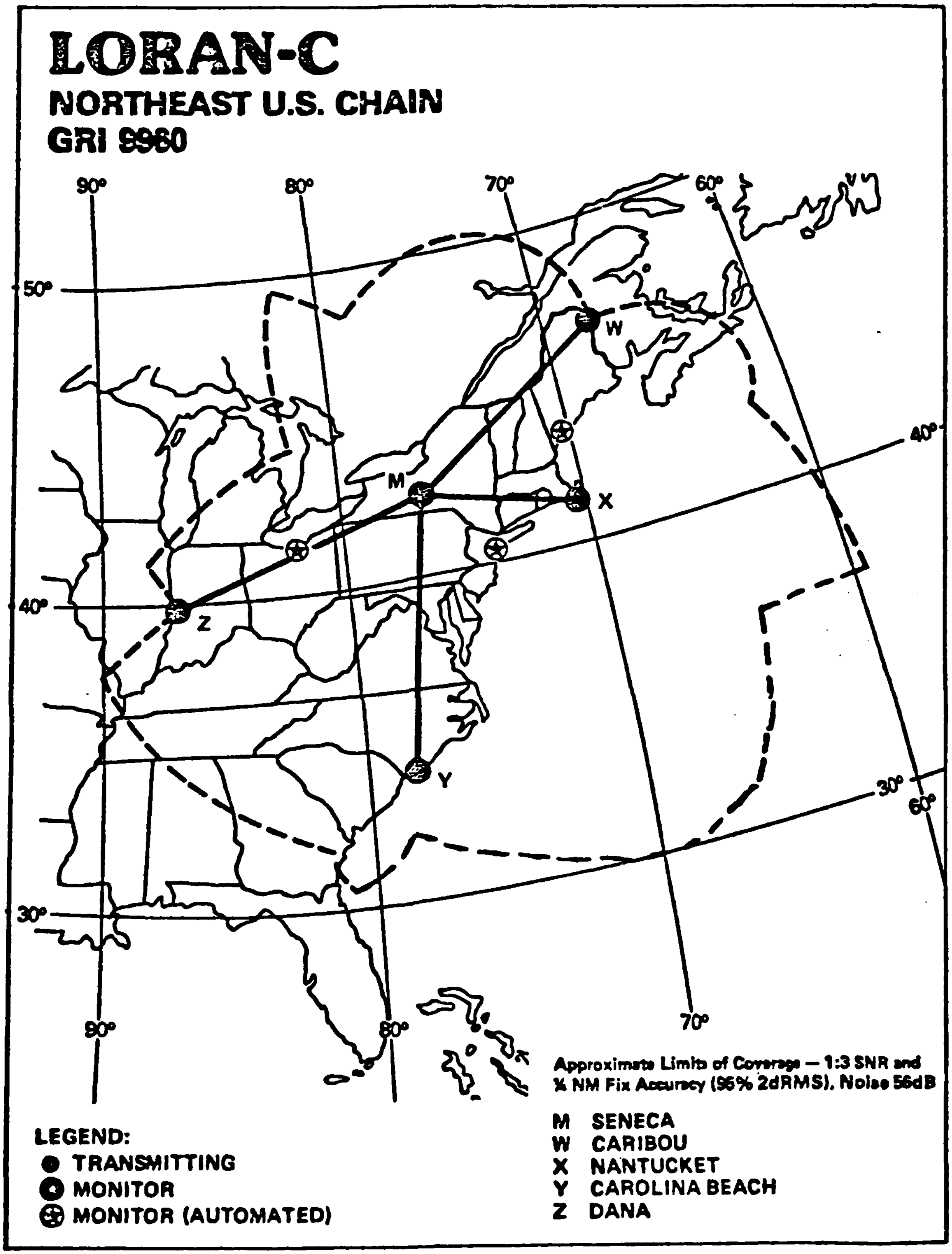


Figure 2.4 Loran-C Northeast U.S. Chain Coverage[2]

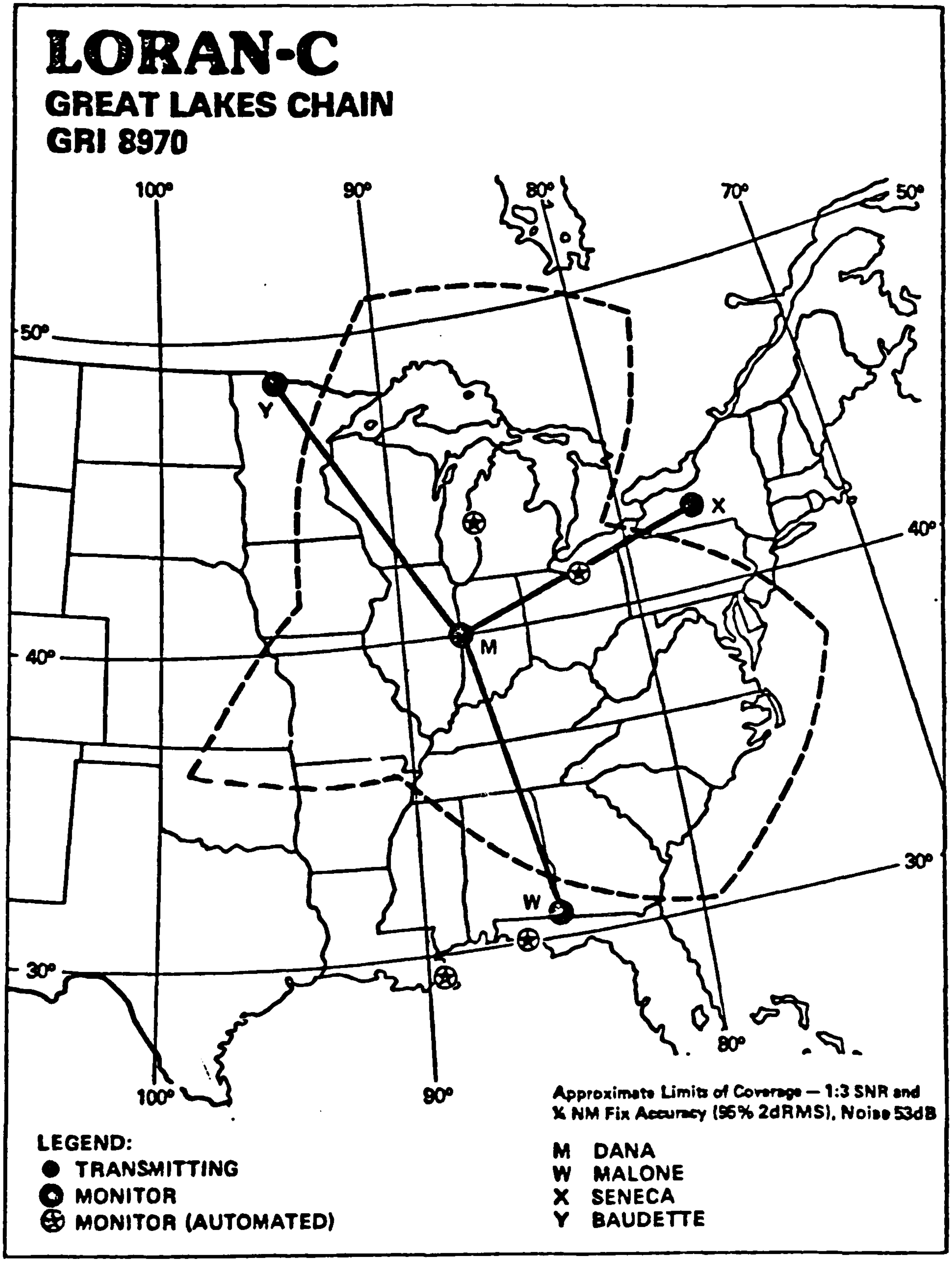


Figure 2.5 Loran-C U.S. Great Lakes Chain Coverage[2]

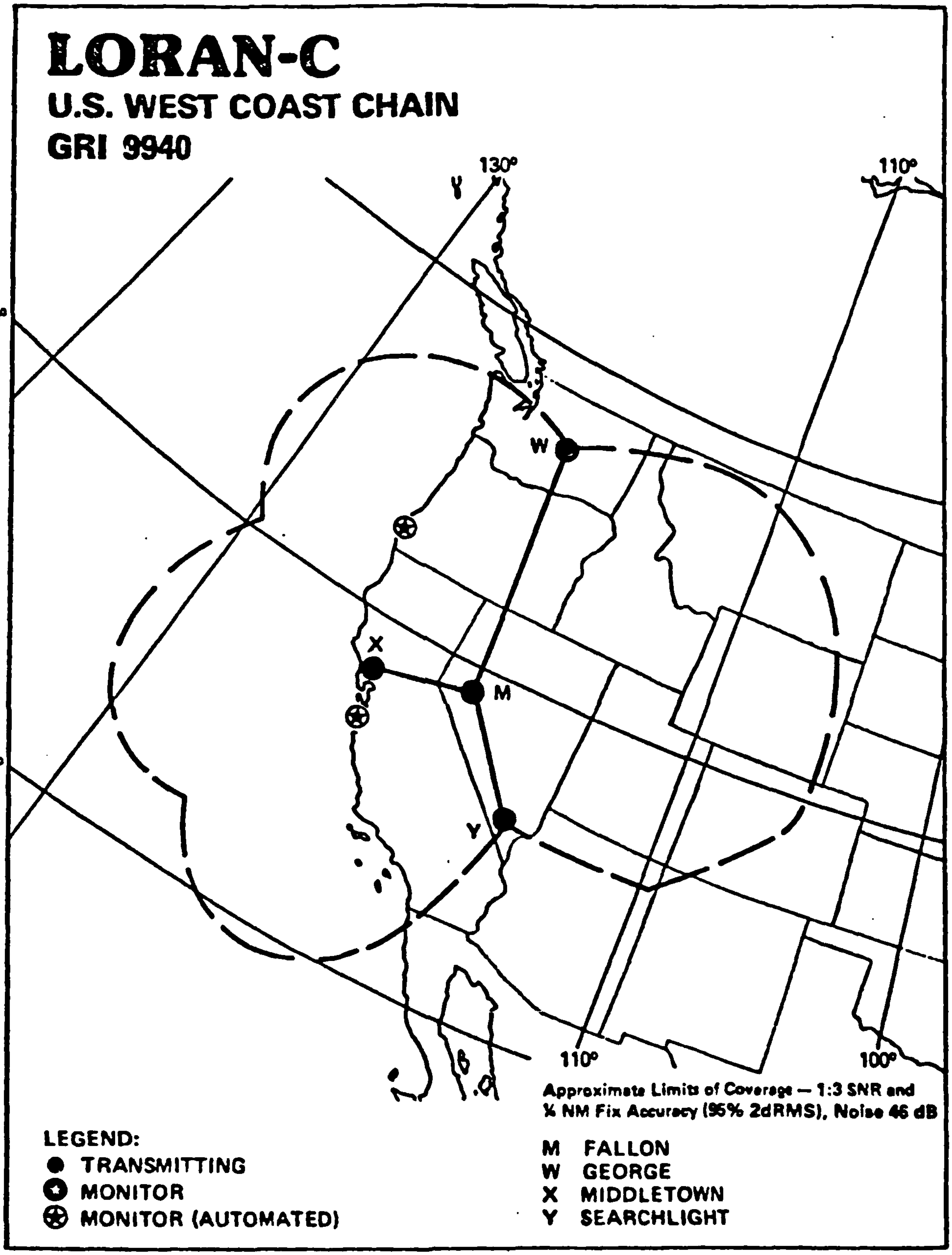


Figure 2.6 Loran-C U.S. West Coast Chain Coverage[2]

covered areas of both good and bad transmitter geometry as well as areas where signal-to-noise ratios (SNRs) are thought to be low. Table 2.2 shows the areas along the test route of marginal Geometrical Dilution of Precision (GDOP) and SNR conditions. Certain station geometries and triad combinations were selected to reflect both good and bad navigation conditions. Table 2.2 presents the worst case situations along the route. As mentioned earlier, areas such as Rapid City, SD and San Antonio, TX are large distances from one or more Loran-C stations. Therefore, the GDOP was generally high and the SNRs were usually low on one or more stations. Other areas like Eugene, OR and Gila Bend, NM were right on the baseline extension of a master and secondary station. It was unlikely that reliable navigation signals would be obtained in areas such as these. When poor navigation signals were obtained, other triad combinations were utilized within a chain to yield different station geometries for a given area.

Throughout the course of the flight test route, chain-to-chain transitions were made periodically. The test route was designed so that many practical chain/triad combinations were available. Data were collected throughout each chain-to-chain transition so that bias error data could be correlated. Table 2.3 shows the four chain-to-chain transition areas for the flight test route flown. As presented in Table 2.3, the chain-to-chain transitions in the London, KY and Buffalo, NY areas were in good signal coverage areas from both chains. On the other hand, the transitions in the Rapid City, SD and San Antonio, TX areas were not in good Loran-C coverage areas. In fact, both were outside of the published USCG Loran-C coverage areas (see Figures 2.3 through 2.6).

Master dependent and master independent errors in the same geographic area within a chain were investigated using the Southeast Chain. The TDL-711 system that was utilized for the program had a master independent triad (Grangeville-Jupiter-Carolina Beach) programmed into one of the specialized PROMS. The objective of this test was to determine the bias shift over the same geographic area using a master dependent triad and a master independent triad. To this end, a flight was flown between West Palm Beach, Florida and Jacksonville, Florida in the master dependent mode utilizing Malone (master), Jupiter and Carolina Beach as the primary triad. This segment, which was approximately 240 nm in length, should have yielded the amount of data necessary to make a valid error budget comparison. The results of this investigation are discussed in Section 6.0.

Table 2.2 Areas of Marginal GDOP and SNR Conditions

LOCATION/AREA	SNR'S			GDOP	TRIAD	COMMENTS
	Master	Sec-1	Sec-2		M Sec-1 Sec-2	
Palm Beach, FL				High	Malone, Jupiter, Carolina Bch.	Baseline Extension
Burlington, VT			Marginal		Seneca, Caribou, Dana	
Buffalo, NY			Marginal		Dana, Senca, Baudette	
Kansas City, MO		Marginal		High	Dana, Seneca, Baudette	Large Distance from Seneca
Kansas City, MO to Rapid City, SD	Marginal*	Low			Dana, Malone, Baudette	Large Distance from Malone and Dana (near Rapid City)
Rapid City, SD				**Marginal**	Fallon, George, Searchlight	Large Distance from all Stations
Eugene, OR				High	Fallon, George, Searchlight	Baseline Extension from Fallon and Searchlight
San Francisco, CA (60 nm North)				High	Fallon, George, Middletown	Caseline Extension from Fallon and Middletown
Gila Bend, NM				High	Fallon, Middletown, Searchlight	Baseline Extension from Fallon and Searchlight
Gila Bend, NM to Albuquerque, NM				High	Fallon, Middletown, Searchlight	See Gila Bend, NM
Albuquerque, NM to San Antonio, TX	Low	Low		High	Fallon, George, Searchlight	Large Distance from Station
San Antonio, TX 200 nm out				High	Malone, Grangeville, Raymondville	Poor Geometry

/NOTE/*SNR Marginal Near Rapid City, SD

Table 2.3 Chain-to-Chain Transitions

TRANSITION AREA	FROM	TO	COMMENTS
London, KY	Southeast Chain (7980)	Northeast Chain (9960)	Transition made in good coverage area from both chains
Buffalo, NY	Northeast Chain (9960)	Great Lakes Chain (8970)	Transition made in good coverage area from both chains
Rapid City, SD	Great Lakes Chain (8970)	West Coast Chain (9940)	Transition made in poor coverage area from both chains
San Antonio, TX	West Coast Chain (9940)	Southeast Chain (7980)	Transition made in poor coverage area from both chains

2.4.2 Correlation Flight Test Routes and Procedures

The area calibration tests were conducted at five different test locations. Each test utilized a different Loran-C chain/triad configuration. There were two important reasons for the area calibration tests; first, to determine how TD corrections can be used for Loran-C approaches in the future; second, to determine how far from the area calibration point the TD corrections are valid. For the purposes of this test a 75 nm radius was examined in all directions. The pattern, depicted in Figure 2.7, was designed to investigate all quadrants within a 75 nm radius of the area calibration point. These results are discussed in Section 6.0.

2.5 FLIGHT CREW

Two subject pilots were available for this test effort. All of the pilots were commercial and instrument rated, and all had previous experience flying long range navigation equipment. Table 2.4 presents a breakdown of the flight hours and qualifications for each pilot.

Table 2.4 Project Pilot Experience

PILOT	TOTAL TIME	COMM.	INST.	ATR	PREVIOUS LONG RANGE NAVIGATIONAL EXP.
A	35,000 hours	✓	✓	✓	Omega, Loran-C
B	35,000 hours	✓	✓	✓	Omega, Loran-C

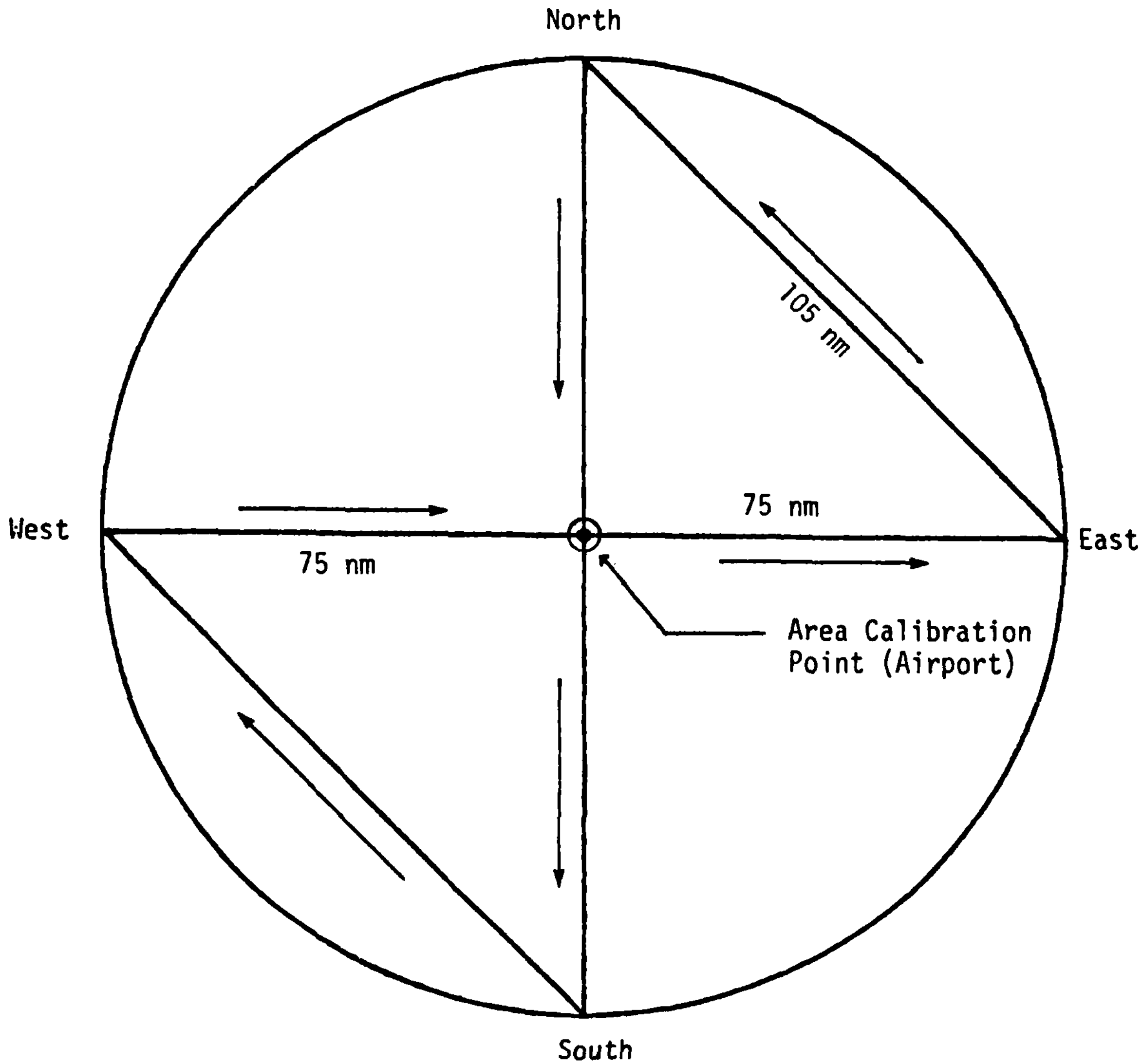


Figure 2.7 Area Calibration Pattern (75 nm Radius of Validity)

All enroute and approach segments were flown by the primary subject pilot. The copilot acted as safety observer and was also responsible for ATC communications and data entry into the TDL-711 Loran-C system. The flight test observer was tasked with operation of the data acquisition system and the manual logging of unusual flight situations, such as deviations due to weather or ATC requests.

2.6 FLIGHT LOGS

A flight log of significant events was kept for each enroute segment and subsequent approach. The log was kept by the safety pilot/observer. The log served to record pilot blunders, Loran-C operational performance, ATC deviations, CDU indications, weather conditions, and malfunctions. The logs were used, when necessary, to outline the conditions under which each enroute segment and approach was flown and to verify events and data. Figure 2.8 presents the sample Loran-C flight log utilized during the flight test program.

LORAN-C FLIGHT LOG

Date: ______________ Pilot: ______________ Depart A/P: ______________ Segment#: ______________

Depart. Time: ______________ Co-Pilot: ______________ DSTN A/P: ______________ Triad: ______________

Engineer: ______________ Area Cal : Yes No

LEG #	W/P # (Name)	TO / FROM	TIME PASSING FROM W/P	REQUESTED		ATC DEVIATIONS	COMMENTS	SNR or TD's
				ALTITUDE	V-AIRWAY			

Figure 2.8 Flight Log

3.0 TEST VEHICLE AND EQUIPMENT

3.1 TEST AIRCRAFT

The test aircraft chosen for these flights was a Beechcraft Queen Air 65. This vehicle was chosen for its economy, large cabin space and gross weight payload capability. Data acquisition equipment was well within maximum gross weight limits with a full load of fuel, full crew and required test support personnel. Aircraft range as currently configured is approximately 6 hours plus reserve. All flight legs were planned to be approximately 4.5 hours in length leaving an adequate margin for unexpected flight conditions.

The Queen Air was leased by the contractor and was dedicated to this program during the data collection segment of the flight test schedule. The subject pilots were familiar with the operation of this aircraft, reducing the need for additional pilot familiarization flights. The aircraft was equipped with an EDO Century III autopilot system, a Collins FD-105 flight director system, dual communication radios, dual VOR navigation radios, KNC-610 RNAV system and an altitude encoding transponder. VOR/DME navigation system outputs were displayed on the FD-105 flight director system consisting of a horizontal situation indicator (HSI) and attitude direction indicator (ADI) with a command steering display. During the data collection activity, a dedicated course deviation indicator (CDI) display was utilized to display Loran-C steering commands at all times. The safety observer monitored aircraft position by conventional VOR navigation using a standard CDI display on the right side of the front instrument panel. The TDL-711 control display unit was mounted in the center console between the two pilots.

The aircraft was equipped with static wicks manufactured by TCO Manufacturing, Inc. Three wicks were installed on each control surface which provided more than the adequate number of static discharge points. The static wicks are very lightweight and designed to discharge static in the 100 kHz range.

3.2 TELEDYNE TDL-711 LORAN-C RECEIVER/PROCESSOR

The Loran-C airborne system used for the flight test program was a Teledyne TDL-711 micro-navigator system consisting of an E-field vertical antenna; a receiver/computer unit mounted on the data acquisition rack; a control display unit (CDU) mounted on the aircraft's center console; and a CDI in the center of the pilot's instrument panel to display Loran-C course deviation.

The control display unit, shown in Figure 3.1, was the operator's interface with the Loran-C system. It displays position information both in latitude/longitude and time differences; shows which waypoint, or waypoint pair, has been selected; displays all navigation and test modes; and shows the information being entered through the keyboard.

There are six decimal points for use with the data shown in each upper display window (two of the six in each are shown in Figure 3.1).

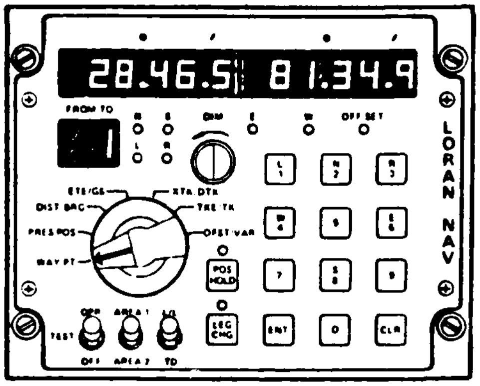


Figure 3.1 TDL-711 Control Display Unit [1]

These same decimal points are also used to warn the crew of non-standard Loran-C system operation. All the decimal points blink when the processor is operating in the master independent mode (the master signal is unusable or non-existent and a third secondary has been added to the computations, with one of the secondaries selected as master). They remain on steadily when navigation information (and thus, the computed position) is unusable.

The rotary data selector switch chooses the information to be displayed:

- "WAY PT": the selected waypoint position is displayed, or the coordinates to be entered for the selected waypoint are shown
- "PRES POS": position displays present position or allows entry of present position
- "DIST/BRG": displays, in the left and right windows, range and bearing to the selected "TO" waypoint in the "FROM-TO" window
- "ETE/GS": the processor shows time to go to the "TO" waypoint and present ground speed
- "XTK/DTK": shows crosstrack distance on the left and desired track angle on the right
- "TKE/TK": displays track angle error and track angle
- "OFST/VAR": shows the current parallel offset distance (or allows selection of a new offset), and lets the operator either see the current magnetic variation, if any, or enter a new variation.

The "MODE SELECTOR", (lower left corner) is a three position switch which, at the operator's discretion, either shuts off power to the system, initiates the self-test sequence, or puts the system into normal operation.

One of two pre-programed coverage areas can be chosen with the area switch*. This switch selects the triad (a three-station set of master and secondaries) which is to be used for position computation and navigation. All of the programmable read only memory chips (PROMs) for all test coverage areas were available in the system. The "L/L-TD" switch chooses the mode of the selected position display or entry - latitude/longitude or time differences.

Pressing the "POS HOLD" switch stores the aircraft's present position at the moment it is depressed. If the rotary data selector is in the "PRES POS" mode, the displays will freeze. In any event, position continues to be updated once per second. The indicator light stays on until the switch is pressed a second time.

To effect a leg change, the "LEG CHG" switch is depressed and the next waypoint pair is entered using the keyboard. On the TDL-711, the leg change light will flash when the "TO" waypoint has been reached, and the new waypoint "FROM-TO" pair must be entered manually. There is no automatic leg change function. The selected waypoint pair appears in the "FROM-TO" window.

The keyboard is for information entry. Certain keys have double functions depending on the position of the rotary data selector switch. The "ENT" key inserts the keyboard entry into the processor. the "CLR" key is used to clear keyboard entry errors.

The "N" and "S" lights indicate latitude, and the "E" and "W" longitude. Whenever an offset course has been entered, the "OFFSET" light remains on.

When the aircraft is left or right of desired track, when the track angle error is left or right of desired track heading, or when the offset course is left or right of nominal, the "L" or "R" lights will be on to indicate the direction of displacement.

The "DIM" control regulates all CDU lights except the "OFFSET", "LEG CHG", and "POS HOLD" indicators. They are controlled with the cockpit dimmer controls.

Certain internal diagnostic functions can be summoned with coded key entry sequences.

The output of the Loran-C navigator drives a deviation indicator (CDI), giving linear deviation from the selected "TO" waypoint course. Full scale deflection left or right of center is 1.28 nautical miles.

/NOTE/*
This particular Loran-C unit was modified with Teledyne's 16 triad option.

The "TO" flag indicates that the aircraft is located short of the "TO" waypoint. The "FROM" flag indicates a position beyond the "TO" waypoint. The red "NAV" flag indicates that steering commands are invalid.

The Loran-C receiver is designed to run a remote display unit (RDU), and the information it provides to that remote display can be externally programmed through the PROM.

3.3 MULTIPLE DME POSITIONING SYSTEM

The multiple DME positioning system used was a Rockwell-Collins DME-700. The DME-700 transmits pulsed signals to a ground station and receives responses from the station. Range was determined by measuring the signal propagation time from the aircraft to the station and back to the aircraft. The DME-700 is capable of operating in several modes including: standby, single channel, diversity, and scan (which was utilized for the purpose of this test). The scan mode provides a capability to service up to five stations at a high rate, and scan the other 274 channels for valid replies at the same time. The DME-700 obtains serial digital control information on one of two ARINC 429 input data buses. The control information also instructs the DME as to what mode of operation to use. The DME-700 delivers serial digital distance data over two ARINC 429 output data buses. DME data (distance and frequency) from the five closest DME stations are delivered via the data output buses at a one second rate. Depending on the number of stations, data from an additional 15 (fifteen) DME stations can also be delivered via the data output buses.

3.4 DATA ACQUISITION AND RECORDING SYSTEM

The data acquisition package utilized during the flight test program consisted of seven major components. They were as follows:

- MFE 452B Cassette Recorder
- Collins DME-700
- VOR Digital Converter
- Dynamic Pressure TAS System
- Microcomputer Chassis, Logic and Interface Boards
- Keyboard and Alphanumeric Display
- Loran-C Receiver Processor Unit (RPU)

The appropriate data parameters were digitally recorded on the MFE 452B cassette recorder. These data were recorded from three distinct sources via the microcomputer logic and interface boards. The three sources were as follows: Collins DME-700, analog voltages representing aircraft systems and the Teledyne TDL-711 system RPU. The operator/system interface components consisted of a keyboard, alphanumeric display and a CRT console, to be used for post-flight quick-look data dumps. The primary power for the data acquisition system was 28 VDC.

3.5 SYSTEM CHECKOUT AND CALIBRATION

The Loran-C navigation system and the airborne data acquisition system were checked out in a series of calibration flights in the West Palm Beach area prior to beginning flights for data collection. At the same time, the crew utilized the navigation equipment and became proficient in its operation. The training series consisted of local enroute flights and approaches.

Operational validation and calibration of the ground truth and data acquisition system was accomplished in the West Palm Beach area. The calibration flights consisted of two phases: an enroute test phase (approximately two hours) and a local area transition phase (approximately one hour). Automatic DME selection functions were tested as well as the accuracy of the multilateration ground truth system. Details of the ground truth and data acquisition system are discussed in Section 4.2 and Appendix C.

Total flight time required for the familiarization/calibration tests was approximately three hours. Operationally, the calibration tests were conducted using the procedures and guidelines laid down for the overall flight test.

4.0 DATA PROCESSING AND PROCEDURES

The data obtained during the flight test consisted of digital data recordings on magnetic tape and observations of the pilots and flight test observer. The digital data recording system, used in the test, recorded three generic types of navigation and aircraft system data. These types were:

- analog voltage or phase angle data
- DME digital data
- TDL-711 Loran-C digital data

All data were time tagged by the data collector clock to the nearest 0.01 second. Data were recorded at a 1 Hz rate on magnetic tape cassettes. The format of the data recorded by the airborne instrumentation system is presented in Appendix A. During the flight testing data were recorded continuously. In all, 90 cassettes of test data were obtained. Due to the large amount of data, processing was performed at a 0.1 Hz rate, thereby providing data at ten second intervals.

All flight test data were processed with the contractor's microcomputer system. The system consisted of a North Star Horizon microcomputer system controlled by a Zilog Z-80 microprocessor. The system had four 5.25 inch floppy disk drives, a line printer, a digitizer tablet, and a small, flatbed incremental plotter.

All digital data were transmitted from the airborne data recorder to the North Star computer and stored on floppy disks. Data processing programs were written in North Star Basic or Z-80 Assembler.

4.1 CHARACTERISTICS OF THE DATA

The following analog data were recorded during the test and utilized in the data reduction procedure:

- dynamic pressure (indicated airspeed)
- altitude reference } potentiometer voltages
- altitude wiper } potentiometer voltages
- aircraft heading synchro
- CDI indicator voltage
- CDI flag voltage

Each of the analog channels was calibrated in the contractor's laboratory and in ground tests installed in the aircraft.

Seven DME data channels from the Rockwell-Collins DME-700 were obtained each second. Each channel contained a time tag, co-channel VOR frequency and DME distance. In areas where there were five or more DME stations available, the DME-700 provided DME measurements from five separate stations. The additional two channels contained data from two of the five channels taken about a half second later. When fewer than five stations were available, the DME-700 provided repeated measurements from the available stations to complete the seven channels of data.

The TDL-711 Loran-C navigator was equipped with a specialized programmable, read only memory (PROM) for providing a considerable amount of Loran-C receiver information through the remote display unit (RDU) data line. The navigator output 157 bytes of internal navigator data in binary format (see Appendix B). The Loran-C information was divided into three general categories; display replica data, Loran-C signal processing data and Loran-C navigation data. Specific parameters recorded in these categories were:

Display replica data

- CDU annunciators
- left hand digital display
- right hand digital display
- from/to waypoint display
- decimal points and other CDU lamps
- distance to waypoint register for display
- ground speed register for display
- CDU mode switch selector position

Loran-C signal processing data

- time difference A
- time difference B
- Loran-C track status
- Loran-C signal-to-noise ratio
- Loran-C station blink status
- Loran-C envelope detection status
- Loran-C envelope numbers
- triad in use
- group repetition intervals (GRIs) per CDI update

Loran-C navigation data

- Loran-C latitude and longitude
- crosstrack error
- to/from waypoint numbers
- to/from waypoint latitude and longitude
- parallel offset value
- magnetic variation value
- CDI scale factor

4.2 GROUND TRUTH DATA PROCESSING

The ground truth data processing consisted of converting the DME measurements from the DME-700 into aircraft position. The processing of the DME information to determine aircraft position was the most time consuming aspect of the data processing. The major elements of the procedure are shown in the block diagram in Figure 4.1

The procedure began by providing an initial estimate of the aircraft's position. This was generally provided by using the latitude and longitude coordinates of the nearest VOR facility or an airport reference point. Next, the DME information was read from the floppy disk containing the test data. The DME frequency (or more correctly, the VOR co-channel frequency) was used to identify the station being received. A data file of DME stations, their coordinates, altitude, magnetic variation and their co-channel VOR frequency was maintained for this purpose.

The aircraft position estimate and the DME station coordinates were used to compute a corresponding DME distance. A spherical earth model with the Sodano formula for earth oblateness was utilized for this purpose.

The recorded DME distance was corrected for the slant range error and compared with the computed DME distance. The difference was called the DME residual error. The residual error was passed to a mean square estimator of northing and easting corrections. Details of the estimation procedure are contained in Appendix C.

If the easting and northing corrections to the position estimate were sufficiently small, the aircraft position estimate was conditionally accepted as the aircraft's true position. The criteria used for acceptance was:

$$|\Delta \text{East}| + |\Delta \text{North}| < .01 \text{ nm}$$

where ΔE is easting correction
ΔN is northing correction

The condition on the acceptance of the point was that the root mean square value of the sum of the residuals be less than some threshold value. For these tests the threshold was set at 0.08nm, which is 5% of the alongtrack error criteria set forth in Advisory Circular 90-45A. When Loran-C was measured against position fixes from the DME system which meet this criteria, the DME position error contributed negligible error with reference to AC 90-45A criteria.

If the aircraft position was accepted, the data were placed in an output file for future use in the analysis of Loran-C accuracy. Furthermore, the coordinates were used to compute an estimate of wind. The aircraft's next position estimate for the next record time (usually 10 seconds later) was made from heading, airspeed and wind values by

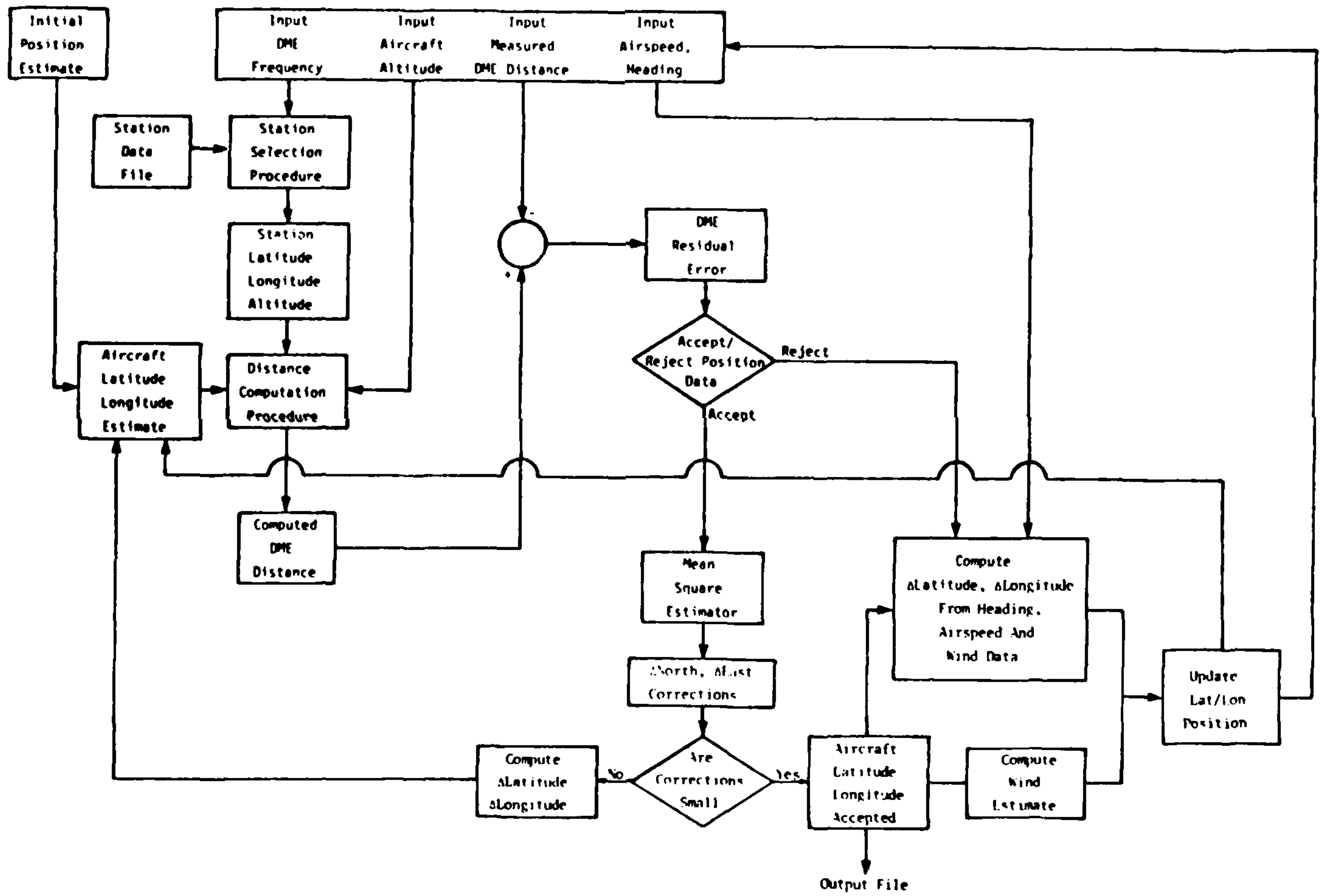


Figure 4.1 DME Positioning System Block Diagram

dead reckoning procedures. If the point was rejected for any reason, the original aircraft position estimate was updated by dead reckoning to the next record time and the procedure was repeated.

In addition to the residual criteria, the DME data had to pass four additional tests. These were:

- a sufficient number of DME stations
- a theoretical position fix accuracy (DRMS value) which exceeded the 0.3 nm threshold
- the correction procedure had to converge in 20 or less iterations
- the denominator of the least square estimator had to be non-zero.

An expression for the theoretical position fixing accuracy (or DRMS) of the DME system is contained in Appendix C.

4.3 LORAN-C ACCURACY

Through the use of the aircraft's true position, and the navigation and Loran-C data recorded from the Loran-C navigator, many accuracy parameters were determined. These included:

- easting and northing position errors
- Loran-C time difference errors
- total system alongtrack and crosstrack errors
- navigation sensor alongtrack and crosstrack errors
- navigation computer alongtrack and crosstrack errors
- flight technical error

A diagram defining these error relationships is shown in Figure 4.2. The navigator RDU data stream provided Loran-C derived latitude and longitude, crosstrack deviation (flight technical error -- FTE) and distance to waypoint (DTW) data. From these parameters, and the waypoints which define the approach course, the other error components were calculated:

Given:	$\left.\begin{matrix} LAT_D \\ LON_D \end{matrix}\right\}$		latitude/longitude derived from the DME data
	$\left.\begin{matrix} LAT_L \\ LON_L \end{matrix}\right\}$		latitude/longitude derived by the navigator
	FTE	-	Loran-C flight technical error - recorded data
	DTW	-	Loran-C distance to waypoint
	$\left.\begin{matrix} LAT_{TO}, LON_{TO} \\ LAT_{FR}, LON_{FR} \end{matrix}\right\}$		coordinates of the "TO" and "FROM" waypoints

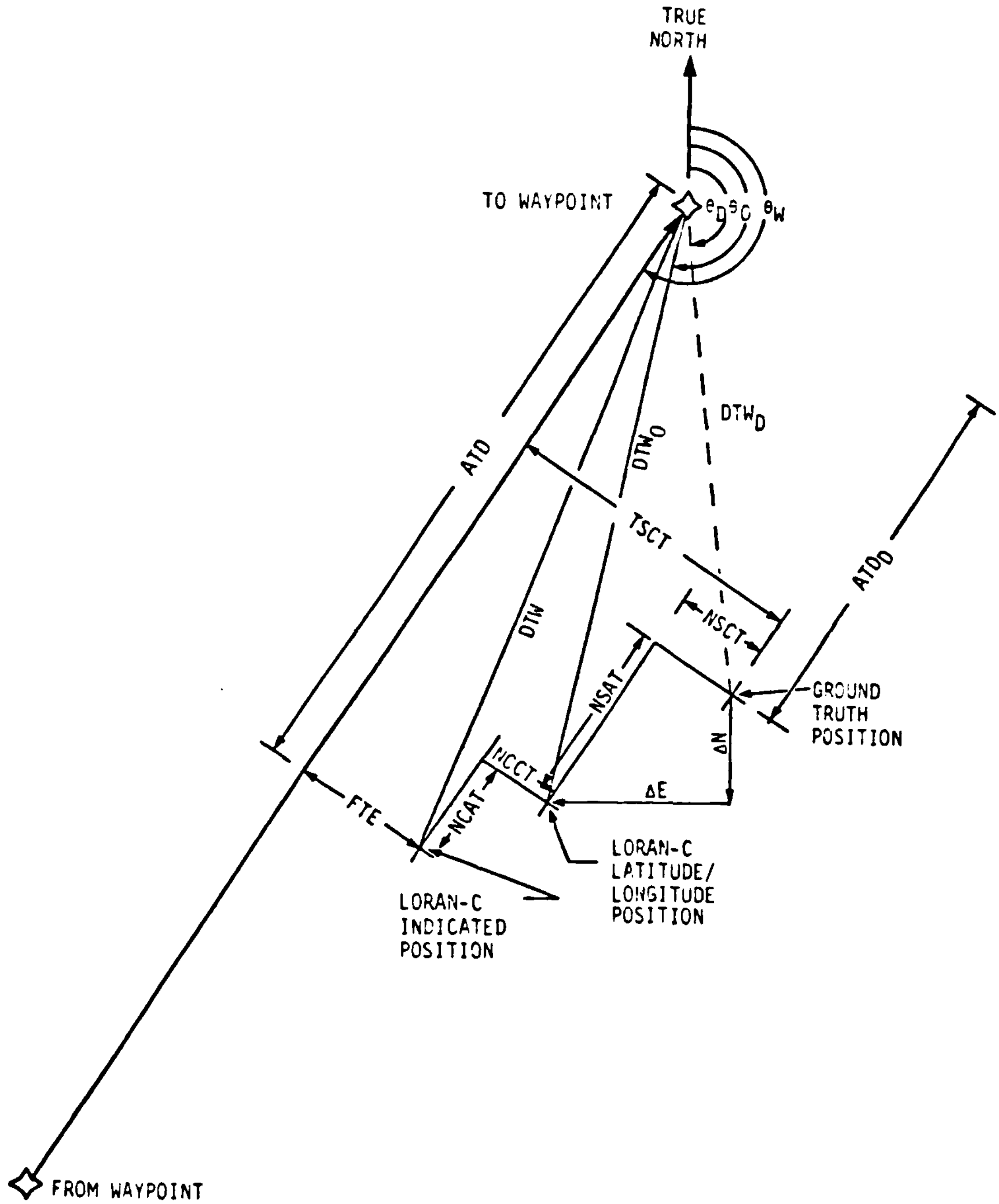


Figure 4.2 Loran-C System Error Geometry

Find: $\left.\begin{matrix}\Delta N \\ \Delta E\end{matrix}\right\}$ Loran-C navigation northing error and easting error

TSCT - Total system crosstrack error (aircraft position relative to intended course)

ATD - Alongtrack distance

$\left.\begin{matrix}\text{NSAT} \\ \text{NSCT}\end{matrix}\right\}$ Loran-C navigation sensor error in alongtrack and crosstrack coordinates

Step 1: Find northing and easting errors

$$\Delta N = LAT_L - LAT_D$$
$$\Delta E = (LON_L - LON_D) \cos (LAT_D)$$

Step 2: Define course geometry

The angle θ_w was the reciprocal angle of the desired course between the "FROM" waypoint and the "TO" waypoint. This angle was calculated using the great circle bearing equation in Appendix C with the "TO" waypoint and "FROM" waypoint coordinates used as input data.

Step 3: Find true aircraft position

The angle θ_D was the reciprocal angle of the aircraft's bearing to the "TO" waypoint as measured from the aircraft's true position. The true distance to waypoint, DTW_D, and the angle θ_D were calculated using great circle distance and bearing equations in Appendix C with the "TO" waypoint coordinates used as input data. Then TSCT and ATD were determined as follows:

$$TSCT = DTW_D \cdot \text{Sin} (\theta_w - \theta_D)$$
$$ATD_D = DTW_D \cdot \text{COS} (\theta_w - \theta_D)$$

Step 4: Find track-related Loran-C position

FTE and DTW were given

$$ATD^2 = DTW^2 - FTE^2$$

Step 5: Find navigation computer errors

The values θ_L and DTW_L were computed using the "TO" waypoint coordinates and the navigator's latitude, longitude coordinates in the great circle distance and bearing equations in Appendix C. The navigation computer errors were then defined using the following equations:

$$NCAT = ATD - DTW_L \cdot \cos(\theta_w - \theta_L)$$
$$NCCT = DTW_L \cdot \sin(\theta_w - \theta_L) - FTE$$

Step 6: Find navigation sensor errors

The navigation sensor errors were found by subtracting computer error and flight technical error (in the crosstrack case) from the total system error.

4.4 TIME DIFFERENCE ACCURACY

Time difference (TD) errors were computed at each point where valid Loran-C and DME position data were available. The procedure involved reversing the coordinate conversion process performed by the TDL-711 navigator. Using the true aircraft position from the DME system, distance to Loran-C station values were computed for a spheroidal earth model. The procedure for this computation was taken from FAA Advisory Circular 90-45A, Appendix J. However, earth radii used in the procedure were taken from Reference 3, which uses the World Geodetic System - 1972 Datum. These values are:

equatorial radius (a)	=	6,378,135.00 meters
polar radius (b)	=	6,356,750.500 meters
flattening (f)	=	(a-b)/a = 1/298.26

Once the distance to the station was determined, the propagation time delay for the distance traveled was computed. The primary factor delay was found by dividing the distance traveled by the speed of light at the earth's surface for a standard atmosphere. The speed of light values were taken from Reference 3 by dividing the speed of light in free space (299.792458 meters/ μsec) by the surface index of refraction for the standard atmosphere (1.000338). The speed of propagation at the surface of the earth is 299.6911624 meters/ μsecond.

Time difference errors were evaluated by computing time difference values from the true aircraft position and substracting the recorded time difference value obtained from the TDL-711 data output. The TD errors determined in this manner represented the difference between TDs that would provide zero position error and those TDs actually recorded. As such, they represented either the inability of the receiver to properly measure TDs from the available signal-in-space (receiver errors), the inability of the navigator to appropriately model the propagation characteristics of the Loran-C signal (modeling error), the inability of the coordinate conversion procedure to converge on a latitude/longitude solution (computer processing error), or the inability of the ground truth positioning system to accurately determine the aircraft's position (reference system error).

The computer processing procedure was validated by inserting recorded Loran-C coordinates in the model and computing time differences. The time differences obtained agreed with those recorded during the test to better than .03 microseconds, which was considered to be excellent agreement. The remaining sources of TD errors (receiver error, modeling error and reference system error) are discussed in detail in Section 6.

4.5 STATISTICAL DATA PROCESSING

The error components were evaluated statistically by computing their mean values and standard deviations according to standard formulas:

mean value of N samples $x_1, x_2, \ldots x_n$

$$\bar{X} = \frac{1}{N} \sum x_i$$

standard deviation of those samples

$$\sigma_x = \sqrt{\frac{\sum x_i^2 - N\bar{X}^2}{N - 1}}$$

Regression equations and correlation equations were utilized to establish the correlation distance of Loran-C errors at the area calibration test locations. The regression equation was utilized to fit a straight line as a function of distance from the location. The form of this equation was:

$$\hat{e} = A + B \cdot d$$

where

- $\hat{e}$ was the time difference error estimator
- d was the distance from the specified location along a given direction
- A, B were constants formed by the regression equation

The constants A and B were found by evaluating the following equations:

$$B = \frac{N \sum e_i \cdot d_i - \sum e_i \cdot \sum d_i}{N \sum d_i^2 - (\sum d_i)^2}$$

$$A = \frac{\sum e_i - B \sum d_i}{N} = \bar{E} - B\bar{D}$$

where

N was the number of data samples,

e_i and d_i were corresponding error and distance samples,
and $\sum$ represented the summation of N samples.

$\overline{E}$ and $\overline{D}$ were the mean values of the error and distance samples respectively.

An estimate of the correlation coefficient for the time difference error as a function of distance from the specified location was given by the equation:

$$r = \frac{\Sigma(d_i - \overline{D}) \cdot \Sigma(e_i - \overline{E})}{(\Sigma(d_i - \overline{D})^2 \cdot \Sigma(e_i - \overline{E})^2)^{\frac{1}{2}}}$$

where

r was the estimate of the correlation coefficient and,

$$\left.\begin{array}{l} d_i \\ e_i \\ D \\ E \end{array}\right\} \text{were defined previously}$$

4.6 FIXED SITE LORAN-C DATA

Fixed site Loran-C data were obtained from the United States Coast Guard (USCG) ground monitoring stations at Dunbar Forest, MI, New Orleans, LA and Point Pinos, CA. The automatic monitor at Dunbar Forest and Point Pinos monitors/controls the X and Y legs of the Great Lakes chain and the West Coast Chain, respectively. The data obtained from these monitor systems were in two different forms. For example, TDs were averaged over a 7.5 minute interval over a 24 hour period along the X and Y legs of the Great Lakes chain. If the TDs were found to be out of tolerance by more than ± 50 nano-seconds, then a manual correction was input into the appropriate chain leg. Corrections were on the order of 20 nano-seconds. In addition to averaging, the TDs were integrated over a 7.5 minute interval to yield long term trends in TDs. All of the results were plotted on standard 8 1/2 x 11 paper. The monitor system at New Orleans and Point Pinos were automatically operated in the same manner as the Dunbar Forest monitor. The New Orleans monitor station monitors/controls the W and X legs of the Southeast U.S. chain. In addition, station outage data during the flight test period were obtained for the Northeast, Southeast and Great Lakes Loran-C chains. These data contained momentary outages as well as longer term outages lasting one minute or more. Station outage data were not obtained for the West Coast Chain.

5.0 OPERATIONAL ANALYSIS

5.1 GENERAL

As found in this test and previous Loran-C tests with the TDL-711, the system has been designed reasonably well from the pilot's point of view. Most of the features or modes were, at one time or another, used by each of the subject pilots. Most of the time the pilots preferred to keep the digital display readout in the XTE mode in order to fine tune their steering performance, since this readout was to .01 nm. On occasion the pilots used the distance to waypoint mode in order to maintain cognizance of their alongtrack position, and used the CDI needle for crosstrack steering. In any event, in the majority of situations the Loran-C signal stability was good enough that pilot FTE, or steering error, was quite low. Even when flying the CDI, needle movement was only affected by aircraft heading or wind, and did not exhibit the significant variations often encountered with either flying VOR radials, or, to a lesser extent, when flying VOR/DME RNAV. It is to be expected that the FTE error budget in a Loran-C RNAV system will be substantially lower than the values currently used for the enroute and terminal phases of VOR/DME RNAV system certifications.

For the purpose of explaining the following operational situations the system was considered to be "locked-on" to the Loran-C signal if the decimal point warning lights on the Loran-C control/display unit were extinquished. This was the normal indication that the system is producing valid present position information. When the system was locked-on and the flag indicator on the course deviation indicator was out of view, the system was considered to be producing valid navigation information in terms of course deviation and distance to waypoint. If the system had been locked-on and the decimal point warning lights appeared on the control display unit, the system was considered to have lost one or more of the Loran-C signals. The term "lose-lock" is used to describe this situation.

Four operationally significant circumstances were observed during the conduct of these tests. All four problems have been observed and documented in previous tests (References 4 & 5). When initiating a leg change (i.e., changing from a waypoint 1-2 leg to a waypoint 2-3 leg), a period of several seconds was required, during which time the CDI needle was centered and the flag was in view. In an enroute environment, where course changes between legs are usually moderate, this denial of steering information is not critical. However, if this situation occurred in a terminal area situation where course changes of up to 90° can be expected, this system characteristic could possibly result in undesirable airspace utilization under conditions where airspace is at a premium. The principal cause of this problem is the saturation of the computer currently used in the TDL-711. Use of a faster computer or more optimized software design should reduce this "dead" time to a more desirable level.

The second problem is of a potentially more serious nature, and has also been observed previously. On several occasions, such as flying into Kansas City, MO, the Loran-C accuracy markedly degraded, with no overt indication to the pilot that such a situation existed. In some cases the Loran-C accuracy diverged from a value of approximatey 1 nm to a value approaching 7 nm. From the pilot's point of view the system is performing perfectly (i.e., the system is locked-on with an adequate set of signal strengths, the CDI flag is pulled out of view, and CDI steering signals are available). However, without some supplemental position fixing aid such as VOR and DME, or visual fixes, the pilot is not aware that his guidance could be in error by 7 nm.

The cause for these errors has been traced to difficulties associated with tracking the correct Loran-C cycle in the receiver front end. This cycle slip problem is discussed later in this report (Section 6.0). Operational procedures to identify this problem and to eliminate or reduce the possibility of it occurring should be investigated.

The third problem has also been observed and documented in previous tests (References 4 & 5). The TDL-711 system offers a diagnostic mode which can be utilized to display certain internal navigator data such as signal-to-noise ratios (SNRs) and other important signal data. This mode is entered by moving the selector to the LEG CHG position and then entering a specified series of keystrokes. On several occasions when the pilot tried to exit the diagnostic mode, the system displays would become frozen. To resume normal navigation the system had to be reinitialized inflight.

The fourth type of problem occurred on one occasion. For reasons unknown, when a leg change (LEG CHG) was initiated, the CDI needle moved full left than right repeatedly. Again the displays were frozen and the system required reinitialization before navigation could be resumed. Both problems are likely related to software in the navigator.

Finally, some short duration navigation outages were noted on several occasions. These outages produced a loss of navigation for periods of 30 to 60 seconds. Post flight data analysis revealed that these outages were caused by momentary Loran-C transmitter outages and low signal-to-noise ratio values on one or more of the received signals. Often these outages occurred during periods of rain and thunderstorm activity in the vicinity of the aircraft. It is believed that some of these outages were caused by precipitation static. The aircraft was equipped with static wicks on the control surfaces to disipate skin currents, however, these wicks may not have been totally effective in eliminating signal reception problems caused by precipitation static. Specific occurrences of navigator outages are discussed in Sections 6.1.1 through 6.1.17 and Section 6.2.1.

5.2 ENROUTE SEGMENTS

During the enroute transition phase of testing, no "mid-continent gap" was encountered per se. Although at times signals were weak and coverage was poor, the navigator continued to operate and provide good guidance for most of the flight. There were times when the system lost the signal for brief periods of time enroute but these occurances were limited.

Several problems were experienced on the east coast of the United States while flying the enroute segments. On the first segment from West Palm Beach, FL to London, KY the system repeatedly "lost-lock". This might be attributed to the local thunderstorm activity encountered while enroute. The severe lightening associated with these storms could have possibly caused a great deal of interference in the 100 kHz range.

On the segment from London, KY to Atlantic City, NJ the system "lost-lock" for forty-five (45) minutes outside of London. The system did not acquire adequate signals for the remainder of the flight. Similarly the same problem was experienced on the flight from Atlantic City, NJ to Burlington, Vt; the only difference being the system "lost-lock" when triads were changed and the system never "locked-on" again. The SNRs for all of the stations were quite low when the system was trying to acquire the new triad. Note in both cases the system did "lock-on" on the ground, after landing, using the same triad. This problem was studied during the post flight data analysis activities and it is believed that a procedural change in operating the navigation set during triad changes would eliminate or reduce the occurrence of this problem. The procedure for acquiring new triads would include a step to reset the mode selector to the OFF or TEST position to initialize data in the navigator memory locations.

5.3 AREA CALIBRATION TESTS

With only a few exceptions the Loran-C unit performed flawlessly during the area calibration tests. During the conduct of these tests all four U.S. Loran-C chains were utilized. In all five area calibration tests the aircraft was area calibrated at a predetermined location and after the completion of each flight the aircraft was returned to the same location. In each case the recorded position and time difference values were the same at the start and completion of each area calibration flight. When area calibrated, the TDL-711 performs with remarkable accuracy and repeatability. On two of the tests the system "lost-lock" for brief time periods (30-120 seconds). This occurred three times during the London, KY test and twice during the Muskegon, MI test. At London, KY the system "lost-lock" due to a momentary outage of the Dana station. One of the "lost-lock" occurrences at Muskegon, MI was due to a momentary station outage and the other was due to low signal to noise ratios on all stations. No other noticeable problems were experienced except for some known accuracy degradation west of Lafayette, LA due to poor geometry.

6.0 TEST RESULTS

This section contains an analysis of the signal coverage and accuracy data recorded during the CONUS Loran-C flight test. The analysis is divided into:

- enroute system performance
- area calibration system performance
- DME positioning system performance
- statistical evaluation of calibration data
- navigation computer accuracy
- flight technical error
- overall system performance

Loran-C system accuracy was derived from the data recorded by the data acquisition system and processed according to the methods described in Section 4. Position derived from the scanning DME system was used as the aircraft reference standard. The accuracy analysis provided the following measures of system performance:

Total system crosstrack error	- based on the reference system position relative to desired aircraft track.
Total system alongtrack error	- based on a comparison of the Loran-C distance to waypoint versus the reference system derived distance to waypoint.
Navigation system error	- based upon a comparison of the Loran-C derived latitude and longitude and the reference system derived latitude and longitude. Several measures of this error are contained in the data including root mean square radial error (DRMS), easting error, northing error, and navigation system alongtrack and crosstrack error (easting and northing error resolved in aircraft alongtrack and crosstrack coordinates).

Navigation computer error	- based on a comparison of distance to waypoint and crosstrack deviation derived from the Loran-C position and similar parameters recorded from the output of the navigation system.
Flight technical error	- based on the course deviations observed on the signal to the pilot's course deviation indicator.

The recorded data were processed at ten second intervals. The resolution of the data contributed to quantization of the accuracy data. The following resolution limits were in effect:

latitude	- 0.1 arc minutes (.10 nm)
longitude	- 0.1 arc minutes (.07-.08 nm)
distance to waypoint	- .10 nm
crosstrack deviation	- .02 nm

During the enroute portion of the flight test, data were available at 51% of the data records. For the area calibration portion of the flight test, data were available at 86% of the data records. The data were edited to delete portions of the flight when the Loran-C system was not being used for navigation. These include situations such as terminal area maneuvering, ATC requested diversions from desired track and weather avoidance. Also included are those times when the aircraft was maneuvering to intercept a new course at route turn points.

6.1 ENROUTE SYSTEM PERFORMANCE

This section contains a discussion of the performance of the TDL-711 Loran-C system as it operated during the enroute phase of the CONUS flight test. Specific operational situations which occurred with regard to geometry, signal coverage, and weather are discussed for each segment of the flight test. Also, the time-difference errors, DRMS values and total system crosstrack and alongtrack errors were analyzed.

The Teledyne TDL-711 model Loran-C used for this project was developed a number of years ago and was considered an older model relative to other receivers which have recently been developed. Some of the characteristics of the TDL-711 system which should be noted were:

- fairly slow computation
- only used three stations - two time differences
- only tracked one chain
- used a comparatively simple propagation model - it used no correction for a secondary phase factor

Some beneficial features to the flight test of this Loran-C system were:

- it was designed for airborne use
- it had an RDU data output compatible with the data collector

These two characteristics of the TDL-711 system made it appropriate to achieve the objectives of Section 2.0.

During the flight test, the operational procedures related to the 16 triad option of the Loran-C unit were not clearly understood. Upon switching from one triad to another, while enroute, it was found that the Loran-C system ignored the selection and continued using the previous triad or failed to provide navigation altogether. The procedure for triad selection was not clear in the Loran-C unit instructions. After several attempts at airborne triad changes failed, the procedure was modified to assure reinitialization of the unit. It was determined that putting the Loran-C unit into the test mode of operation prior to a change in triad improved airborne acquisition. If this procedure had been followed in the earlier segments, it is believed that the selection of a different triad would have resulted in the appropriate Loran-C system operation.

6.1.1 Segment #1 - Palm Beach, FL to London, KY (Figure 6.1)

During the flight from Palm Beach, FL (PBI) to London, KY (LOZ) bad weather in the form of rain, thunder and lightning was encountered. This resulted, at times, in abnormal operations of the Loran-C receiver.

The Southeast U.S. chain was used for this flight. Taking off from PBI, the receiver did not acquire the preferred triad of Malone-Jupiter-Carolina Beach. Instead the backup station (Grangeville) was used by the receiver in place of the Jupiter station. This problem was described in Section 6.1.

At three different times during this segment there was a significant loss of the Loran-C signals. These outages were up to 20 minutes long:

- before Orlando-operator initiated triad change
- after Jacksonville-operator initiated triad change due to large errors in the region of the Malone-Grangeville baseline extension
- fourteen miles from London-receiver would not reacquire

There were also three occurrences of minor signal loss. These were times when all the decimal points on the CDU display came on for approximately 1-6 minutes indicating loss of navigation. Two (2) outages occurred due to a momentary master outage. This was not operationally significant. Another outage occurred due to a secondary outage (Carolina Beach) for approximately ten (10) minutes. Two successive momentary outages on the Carolina Beach station caused the system to lose signals on all stations. This was operationally significant as it affected navigation capability during the approach to London, KY.

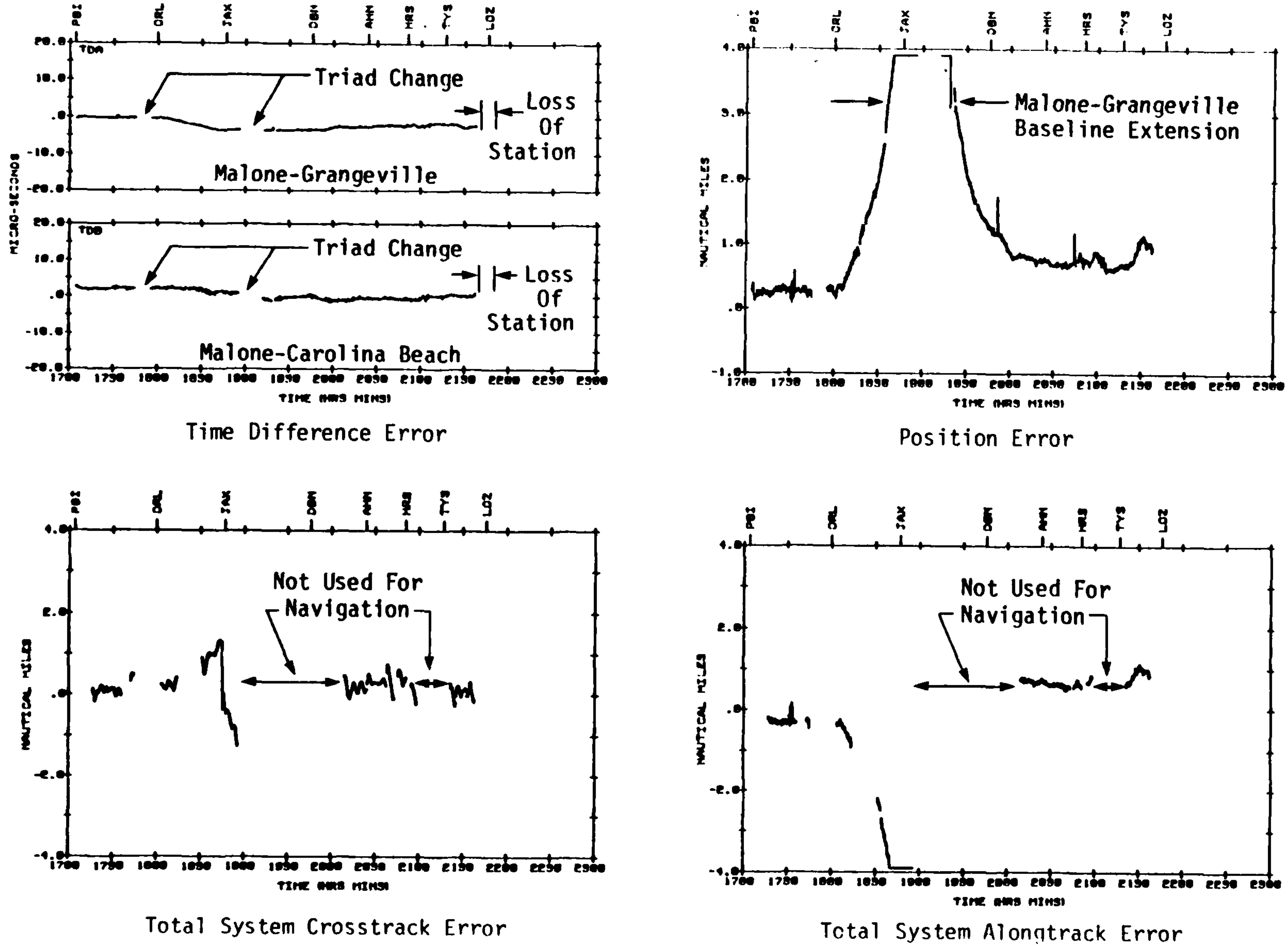


Figure 6.1 Loran-C System Errors, Palm Beach, FL To London, KY (July 5, 1983)

The bad weather encountered throughout most of the segment caused static to be heard, periodically, over the communication radios. Some short duration flags (approximately 1 min.) may have been due to precipitation static.

The selected triad used between Orlando, FL (ORL) and Dublin, GA (DBN) showed poor geometry characteristics. During this leg the flight path crossed the baseline extension of Malone-Grangeville.

The time difference errors observed throughout this segment showed no significant problems. For the Malone-Grangeville station pair (TDA), the TD errors were very smooth over the entire segment, varying between 0.0 and -3.0 microseconds (μs). The errors for the Malone-Carolina Beach station pair (TDB) were also quite smooth. These errors varied between 0.0 and +3.0 μs.

The position error plot dramatically shows the effect of the baseline extension crossing between ORL and DBN. The error values between PBI and ORL are very small (approx. 0.2 nm). Between ORL and DBN the errors increased to over +4.0 nm. Between Athens, GA (AHN) and LOZ the error values were slightly higher than the earlier PBI to ORL leg, approximately +0.6 to +1.0 nm.

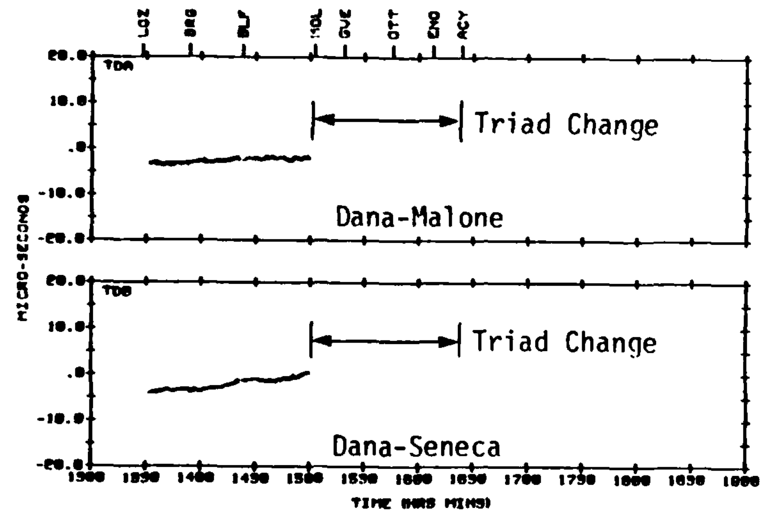
Due to the numerous deviations from track caused by weather, a limited amount of data were available for crosstrack and alongtrack errors. Disregarding the baseline extension area, between ORL and DBN, the crosstrack error was small, generally less than $\pm$0.5 nm. The alongtrack error was small during the PBI to ORL leg (less than +0.5 nm), increasing during the Dublin to London leg to approximately +0.5 to +0.9 nm.

6.1.2 Segment #2 - London, KY to Atlantic City, NJ (Figure 6.2)

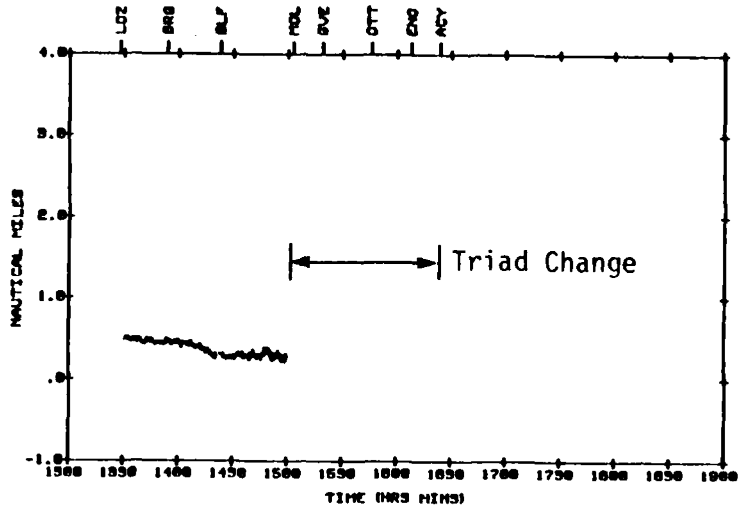
During this segment the Great Lakes chain was used (Dana-Malone-Seneca). Near Montebello, VA (MOL) the Northeast chain of Seneca-Carolina Beach-Dana was selected. However, the system would not acquire the station signals. Several present position updates were entered over VOR stations in an attempt to reaquire Loran-C navigation, but these attempts failed. The reason for this problem was discussed in Section 6.1. Prior to this, there was a momentary outage near Bluefield, WV (BLF). This outage was caused by indications on the Malone and Seneca signals, blinking of the seventh and eighth pulses, that the chain was not operating within specified operational standards.

The TD errors for both the Dana-Malone station pair (TDA) and the Dana-Seneca station pair (TDB) were very smooth. The TDA error had a gradual change from -4.0 to -2.0 μs between London and Montebello. The TDB errors showed an decreasing trend from -4.0 to 0.0 μs.

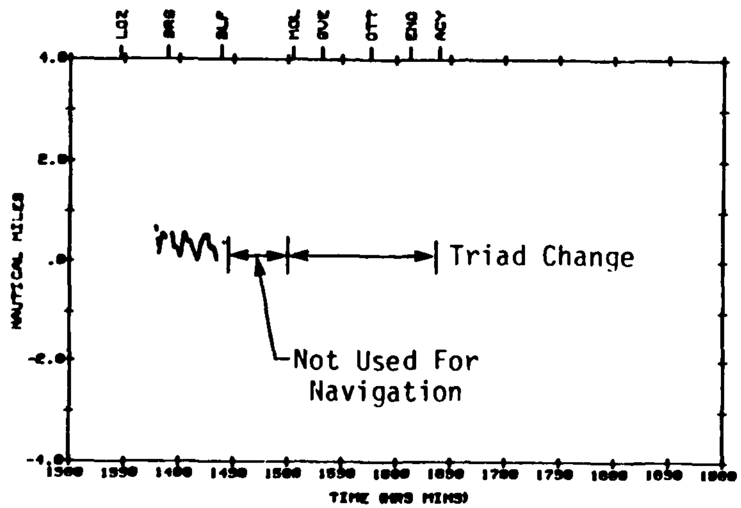
The position error values decreased slightly from +0.5 to +0.2 nm. This reflects the change in TDB error and the good geometry of the lines of position.



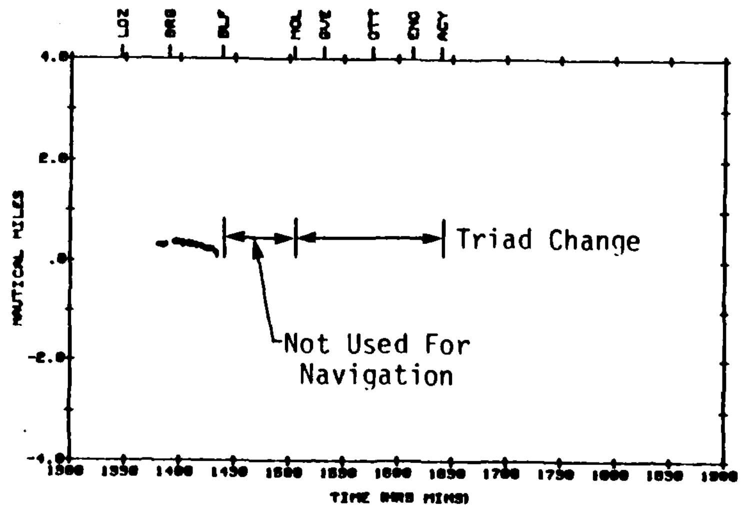
Time Difference Error



Position Error



Total System Crosstrack Error



Total System Alongtrack Error

Figure 6.2 Loran-C System Errors, London KY to Atlantic City, NJ (July 6, 1983)

The crosstrack and alongtrack errors were small. The crosstrack errors varied from 0.0 to +0.5 nm, while the alongtrack errors varied between +0.2 to +0.3 nm. There is no data during the first 10 minutes of this segment due to poor DME coverage of the position reference system.

6.1.3 Segment #3 - Atlantic City, NJ to Burlington, VT (Figure 6.3)

Initially, the Northeast U.S. chain (Seneca-Nantucket-Carolina Beach) was used during this segment. Upon switching to the Northeast chain (Seneca-Caribou-Nantucket) near Gardner, CT, the Loran-C system did not acquire the station signals for the remaining part of the segment. This problem was discussed in Section 6.1.

The TD errors for the station pair Seneca-Nantucket (TDA) were between +2.0 to +3.0 μs, with some roughness observed over Long Island. For the station pair Seneca-Carolina Beach (TDB), the TD errors were small, between -2.0 and +1.0 μs. The variation in TD errors might possibly be due to coastline effects.

The position error values were between +0.2 and +0.4 nm. The errors began to increase near Gardner, CT due to the fact that the system was operating on the back side of the Seneca-Nantucket baseline.

The crosstrack and alongtrack error values were small. The crosstrack errors varied between ±0.2 nm; while alongtrack errors stayed constant at approximately +0.2 nm.

6.1.4 Burlington, VT to Flint, MI (Figure 6.4)

Throughout the first half of this segment the Seneca-Caribou-Nantucket triad of the Northeast U.S. chain was used, transitioning to the Great Lakes chain (Dana-Seneca-Baudette) for the later part of the segment. Upon transitioning to the Great Lakes chain, the system did not acquire the new triad for about one hour, between Buffalo, NY and London, Ont. This initial outage was due to bad geometry from the Seneca-Nantucket baseline extension. Between Burlington, VT and Glens Falls, NY there were inconsistent DME measurements of the position reference system. This is believed to be caused by signal reflections off Lake Champlain from the Plattsburg, Burlington and Valcour stations. For these reasons, data from part of the Burlington, VT, Glens Falls, NY segment were deleted from the analysis.

The TD errors for station pair Seneca-Caribou (TDA) increased in magnitude from +0.0 to -6.0 μs between Burlington and Rochester, NY. The TD error (following the triad change) for station pair Dana-Seneca (TDA) was essentially zero. The large change in TDA error was caused by propagation modeling error. The use of time difference measurements has a cancellation effect upon propagation model error in the center of the triad coverage area. When operating near either the master or the secondary station this cancellation effect does not occur.

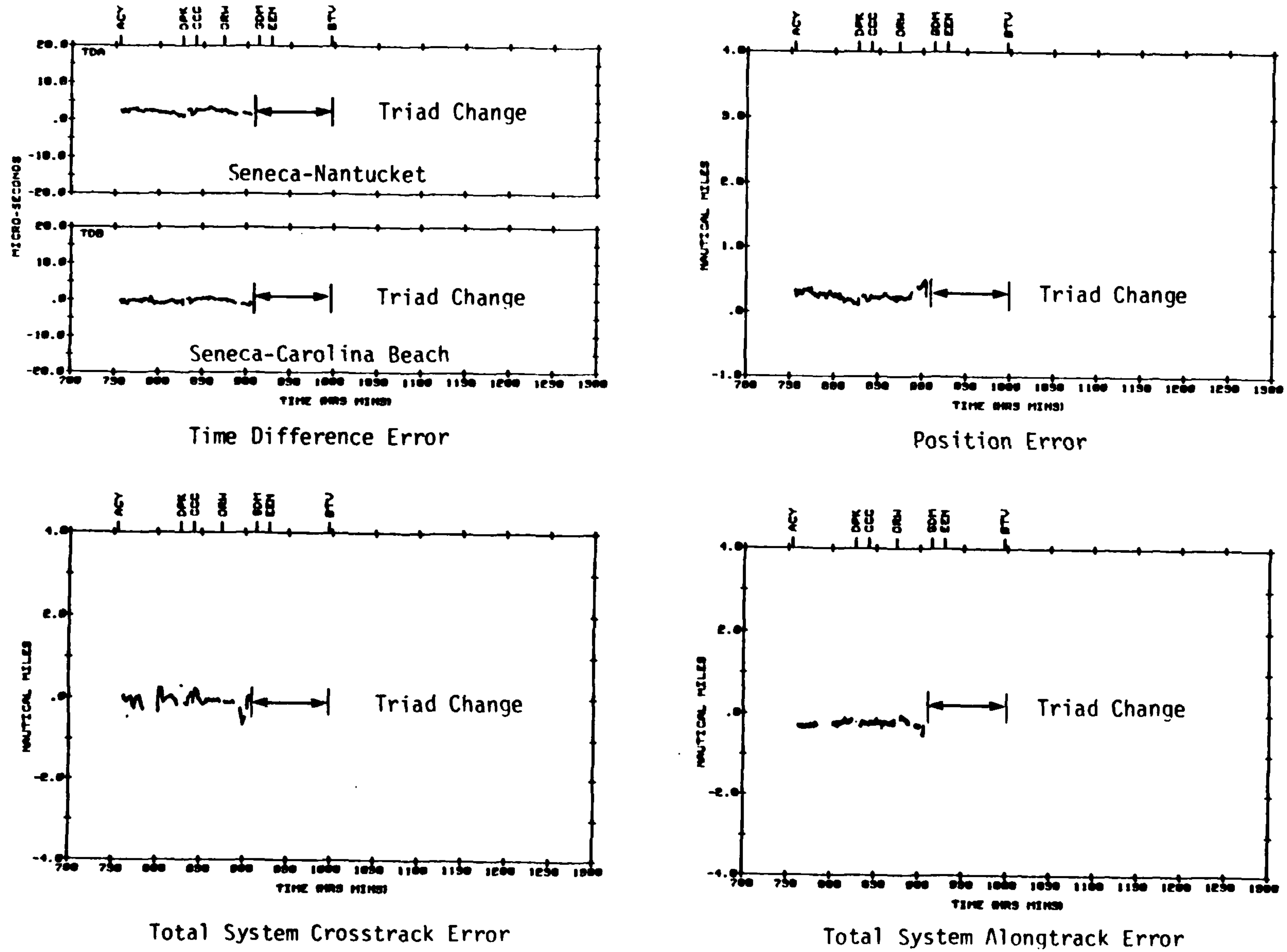


Figure 6.3 Loran-C System Errors, Atlantic City, NJ To Burlington, VT (July 7, 1983)

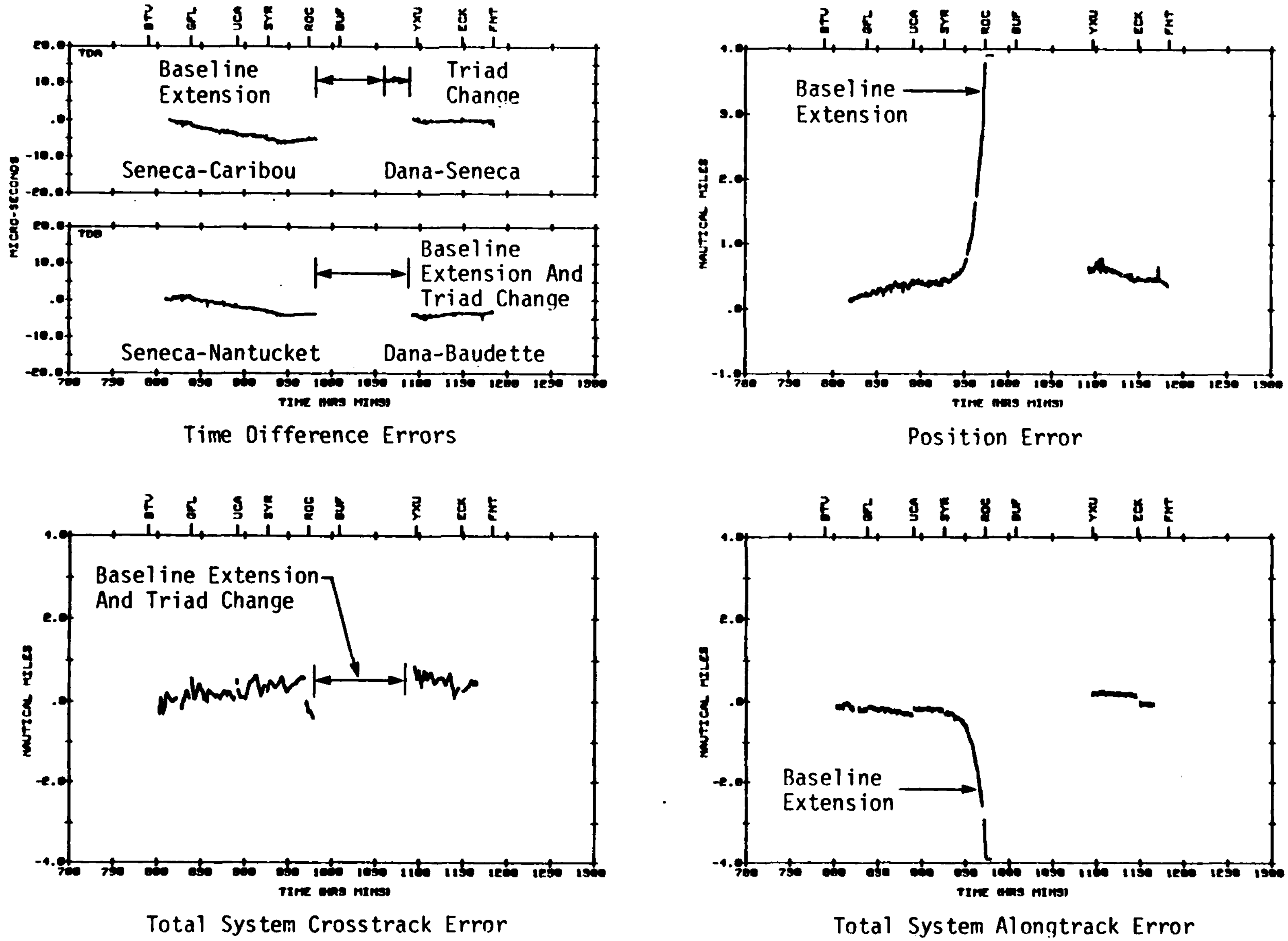


Figure 6.4 Loran-C System Errors, Burlington, VT To Flint, MI (July 8, 1983)

The Seneca-Nantucket TD errors (TDB) increased in magnitude from +1.0 to -4.0 μs. For the station pair Dana-Baudette (following the triad change) the TD errors (TDB) decreased in magnitude from -4.0 to -2.0 μs.

The position error values were small near Glens Falls, NY, increasing to about +0.5 nm between Syracuse, NY and Rochester, NY. A dramatic increase was observed near Rochester, NY due to poor geometry caused by the Seneca-Nantucket baseline extension. Following the triad change the position error values descreased from approximately +0.7 nm near London, Ont. to +0.4 nm near Flint, MI.

The crosstrack error, using the Northeast chain, increased from +0.2 nm to +0.4 nm as the aircraft approached the baseline extension area. Following the triad change, the crosstrack error decreased from +0.5 nm to +0.3 nm near Flint, MI.

The alongtrack error, using the Northeast chain, was small (approximately +0.2 nm) with a rapid increase near the baseline extension area. Following the triad change the alongtrack error was constant, approximately +0.2 nm, for the remainder of the segment.

6.1.5 Segment #5 - Flint, MI to Muskegon, MI (Figure 6.5)

During this short segment the Dana-Seneca-Baudette triad of the Great Lakes chain was used with no problem encountered.

The TD errors for the Dana-Seneca station pair (TDA) increased in magnitude from 0.0 to -2.0 μs. For the station pair of Dana-Baudette (TDB), the TD errors remained fairly constant at approximately -2.5 μs.

The position error values were small, remaining constant at about +0.3 nm.

For this segment the crosstrack error values were erratic and large (approximately 1.0 nm). The reason for this occurrence is unknown. However, the alongtrack error values were very small, varying between 0.0 and 0.1 nm.

6.1.6 Segment #6 - Muskegon, MI to Kansas City, MO (Figure 6.6)

During this segment the Dana-Seneca-Baudette triad of the Great Lakes chain was used, transitioning to Dana-Malone-Baudette. However, during this transition, the Loran-C system continued using Dana-Seneca-Baudette, never responding to the triad change. This problem was discussed in Section 6.1. There was one momentary system outage for 30 seconds at approximately 9:00. At this time there was a momentary outage of the master, Dana, recorded in the U.S. Coast Guard records.

The TD error values were fairly smooth throughout the segment. For the station pair Dana-Seneca (TDA), the errors gradually increased in magnitude from -0.2 to -0.4 μs. The errors for the station pair Dana-Baudette (TDB) were slightly erratic between Badger, WI (BAE) and Janesville, WI (JVL). Otherwise, the TDB errors gradually descreased in magnitude from -0.3 to 0.1 μs.

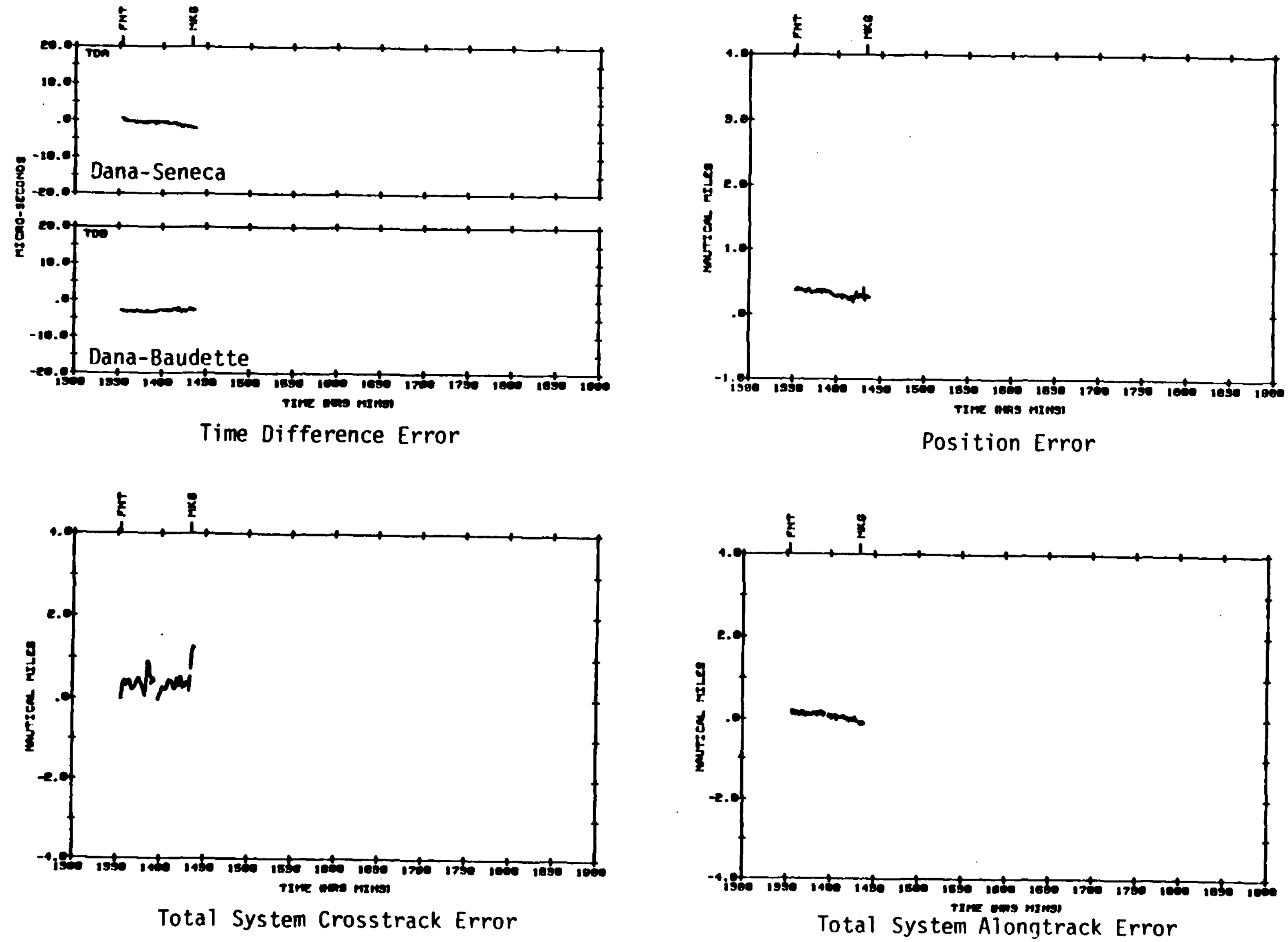


Figure 6.5 Loran-C System Errors, Flint, MI To Muskegon, MI (July 8, 1983)

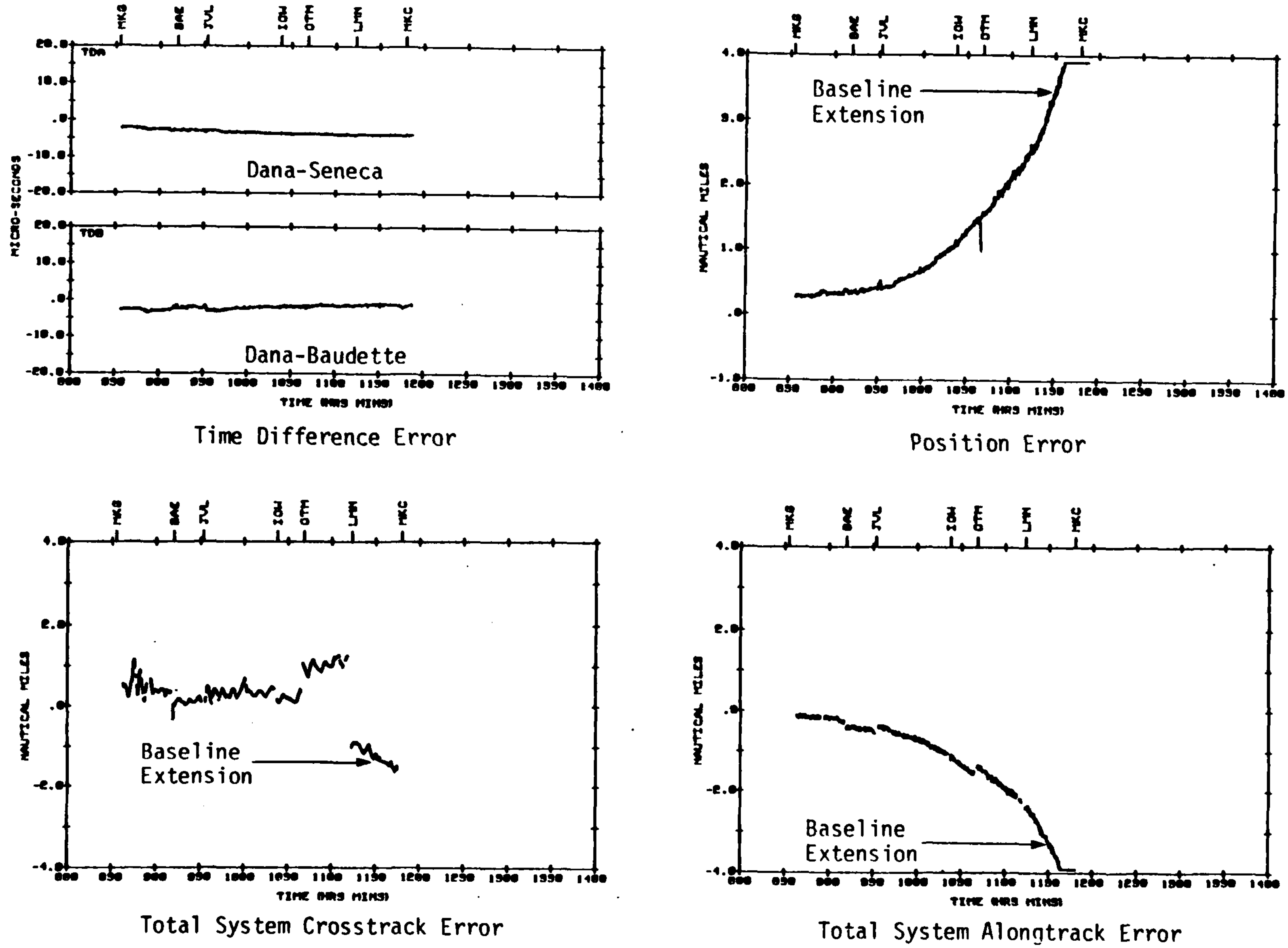


Figure 6.6 Loran-C System Errors, Muskegon, MI To Kansas City, MO (July 9, 1983)

The position error values steadily increased at a rapid rate, from +0.2 nm to greater than +4.0 nm, as the aircraft approached the baseline extension of the Dana-Seneca station pair near Kansas City, MO.

The crosstrack error values were very erratic, varying between 0.0 and +1.2 nm, gradually increasing in magnitude to approximately +3.0 nm upon approaching the Dana-Seneca baseline extension. The alongtrack errors are not as erratic as the crosstrack error; however, the alongtrack errors gradually increased in magnitude from -0.1 to greater than +4 nm. Again, this was due to the proximity of the Dana-Seneca baseline extension.

6.1.7 Segment #7 - Kansas City, MO to Rapid City, SD (Figure 6.7)

The Dana-Malone-Baudette triad of the Great Lakes chain was used throughout this segment. The only trouble encountered was a momentary outage at approximately 13:15, due to a loss of the master, Dana. This segment was flown in an area were there is little to no published Loran-C coverage. As can be observed from the error plots (especially position error), the Loran-C errors progressively got worse approaching Rapid City.

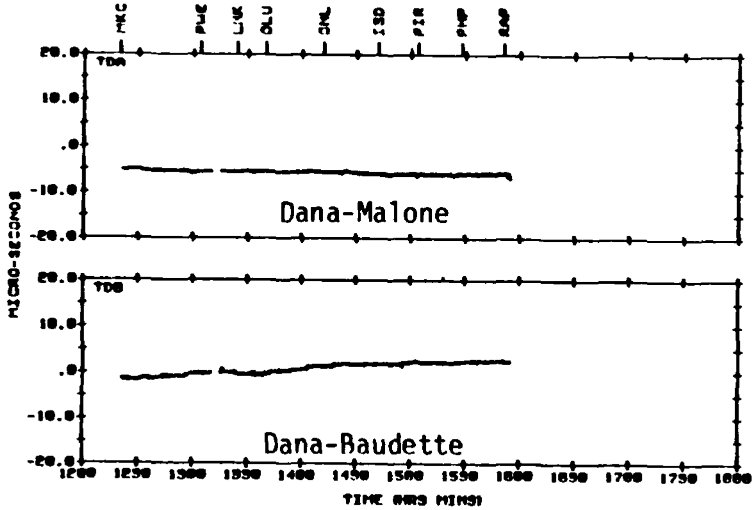
The TD errors were very smooth. For the Dana-Malone pair, the (TDA) errors remained fairly constant, increasing slightly from +0.0 to +1.0 μs. The TD errors for Dana-Baudette (TDB) showed a decrease, then an increase in magnitude from -2.0 to +2.5 μs. This is due to propagation modeling error.

The decreasing navigation capability is again apparent on the position error plot. As can be seen, the error values increased from +1.0 to +3.9 nm at Rapid City.

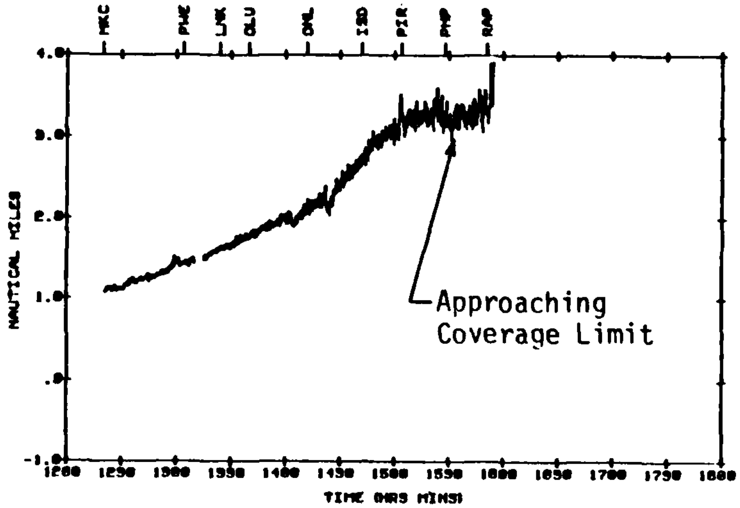
Erratic crosstrack and alongtrack errors occurred throughout the flight segment. The alongtrack error values increased in magnitude from -1.0 to -3.0 nm at Pierre VOR. At this point the crosstrack errors decreased abruptly in magnitude to approximately ±0.2 nm. Then there was an abrupt increase in magnitude to approximately ∓1.0 nm, fluctuating between -0.6 and -1.0 nm to Rapid City. These fluctuations are due to course changes in the flight plan reflecting differing components of position error in the alongtrack and crosstrack directions as the course changes.

The alongtrack errors behaved in a similar manner. These errors remained between +0.5 and -1.0 nm up until reaching Pierre VOR. At this point the alongtrack errors increased abruptly to approximately +3.0 nm. The errors fluctuated between +2.8 and +3.2 nm for the remainder of the segment to Rapid City, SD.

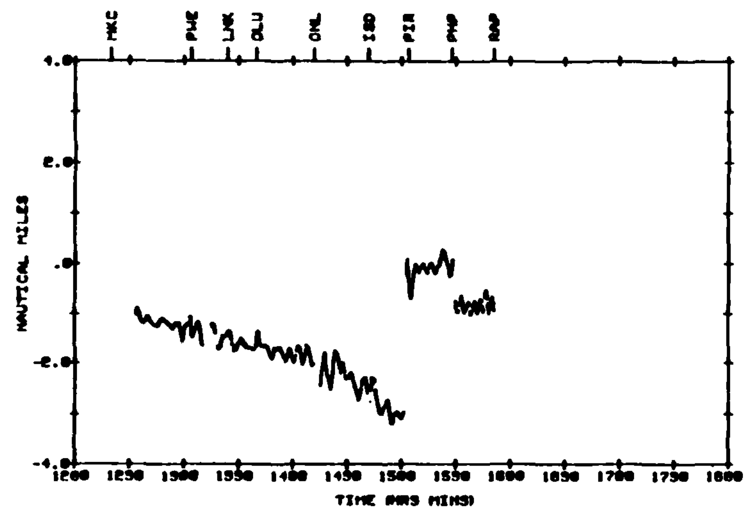
All the changes in errors along this segment can be attributed to the poor signal coverage geometry which occurred in this part of the country. This has been referred to as the "mid-continent gap".



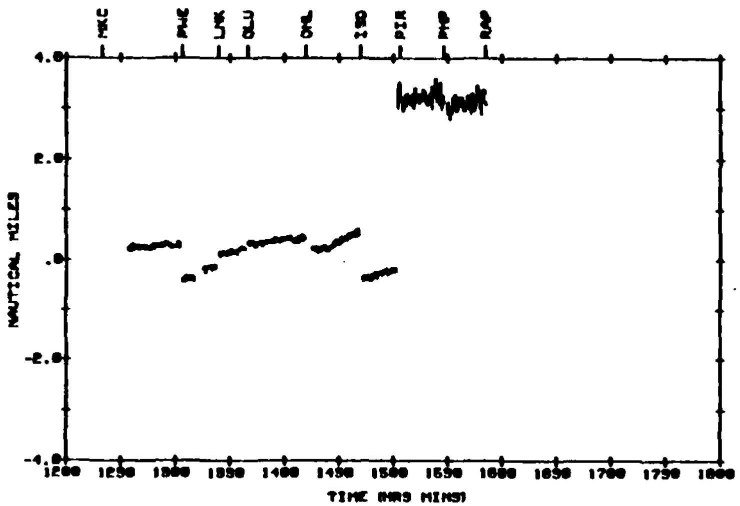
Time Difference Error



Position Error



Total System Crosstrack Error



Total System Alongtrack Error

Figure 6.7 Loran-C System Errors, Kansas City, MO To Rapid City, SD (July 9, 1983)

6.1.8 Segment #8 - Rapid City, SD to Billings, MT (Figure 6.8)

Upon leaving Rapid City, the West Coast Chain, Fallon-George-Searchlight triad, was used. Bad weather was encountered during this segment. As a result, various offsets were used as the aircraft progressed to Billings, MT.

The TD errors for the station pair Fallon-George (TDA) were small (approximately +1.0 μs), increasing slightly to approximately +2.0 to +2.5 μs, possibly due to weather. Between the times 17:15 and 17:30 the TD errors became erratic, fluctuating between +1.0 and -1.0 μs. This could have resulted from terrain effects over mountainous areas or roughness in the DME position reference data.

The TD errors for the station pair Fallon-Searchlight (TDB) were constant, approximately -1.0 μs, for the entire segment. Again, there was some roughness at about 17:15 to 17:30.

The position error values were very erratic, varying from +0.1 to +1.0 nm. The roughness observed can be attributed to roughness in the TD measurements. For much of the later half of this segment, offsets of 10, 12 and 13 nm were used to avoid weather.

A limited amount of crosstrack and alongtrack data were available due to the avoidance of bad weather. The crosstrack error values fluctuated between +0.2 and -0.6 nm. The alongtrack error values fluctuated between ±0.5 nm.

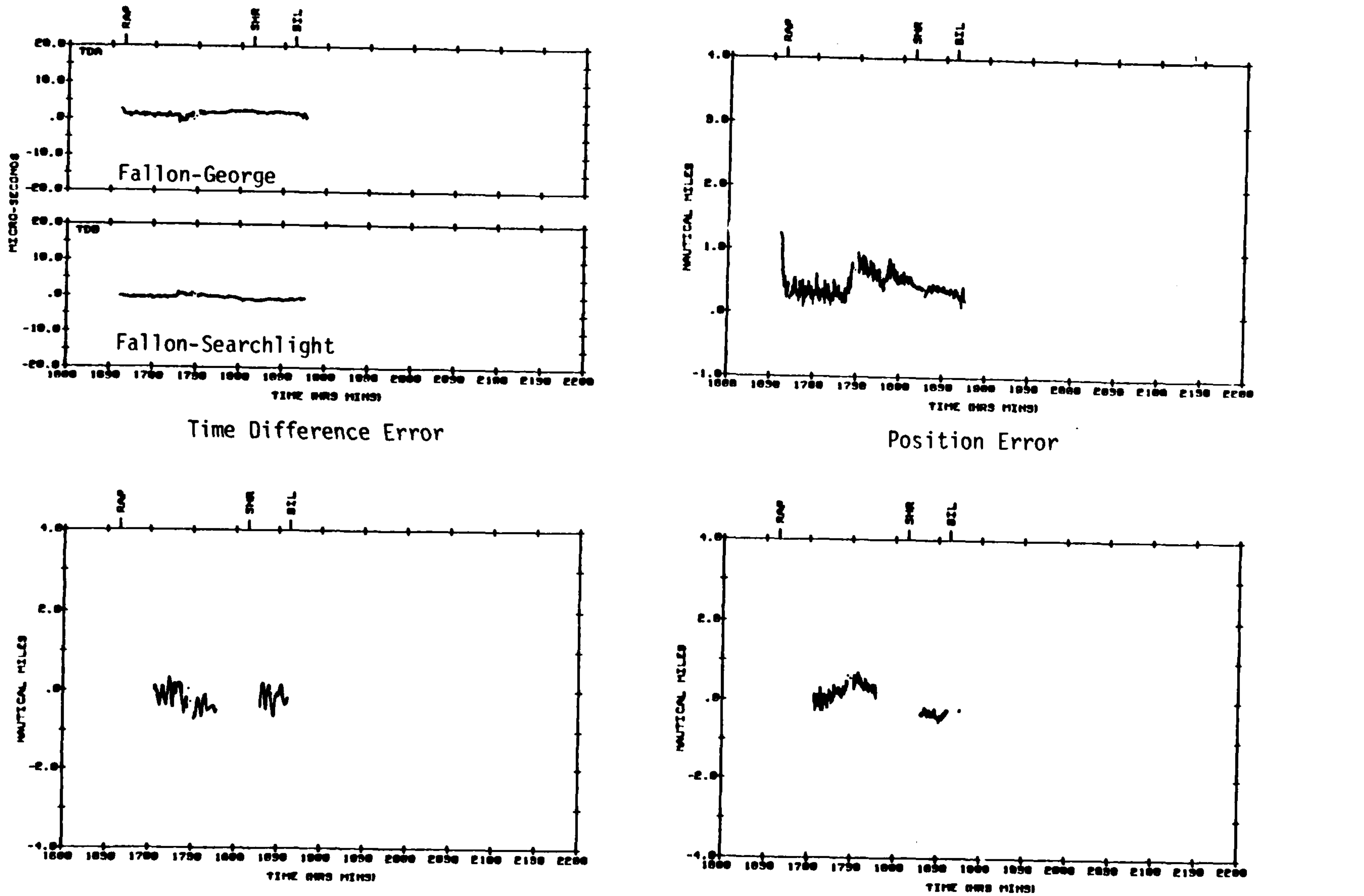
6.1.9 Segment #9 - Billings, MT to Portland, OR (Figure 6.9)

The West Coast chain, Fallon-George-Searchlight triad, continued to be used on this segment. The Loran-C system operated well with only two short momentary outages, each lasting only 30-60 seconds. Momentary outage data was not recorded by the U.S. Coast Guard for the West Coast chain.

The TD errors for the station pair Fallon-George (TDA) gradually increased from +2.0 to +5.0 μs. Propagation modeling error, as the aircraft approached George on this segment, contributed to this increase in TD error.

The TD errors for the station pair Fallon-Searchlight (TDB) decreased in magnitude slightly from -2.0 to 0.0 μs, then increased in magnitude to approximately +4.0 μs for the remaining part of the segment. The mountainous terrain may have contributed to this increase in TD error magnitude.

The position error plot was very erratic, gradually increasing from approximately +0.5 nm to greater than +4.0 nm. This increase in DRMS was due to the poor geometry of the Fallon-Searchlight baseline extension.



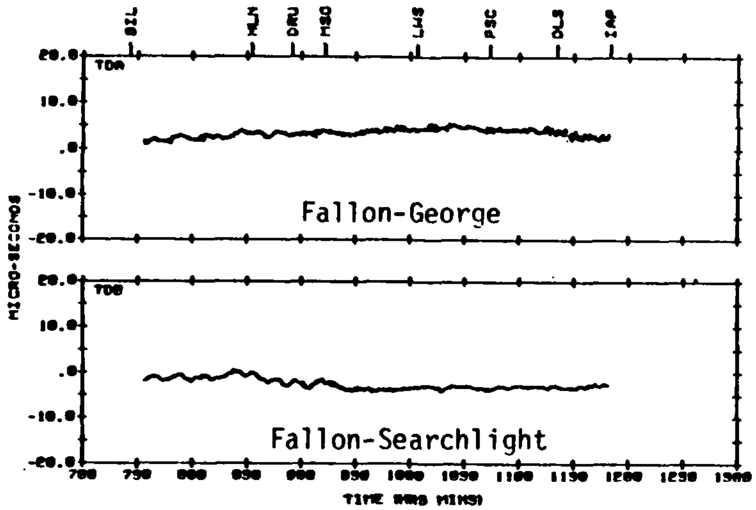
Time Difference Error

Position Error

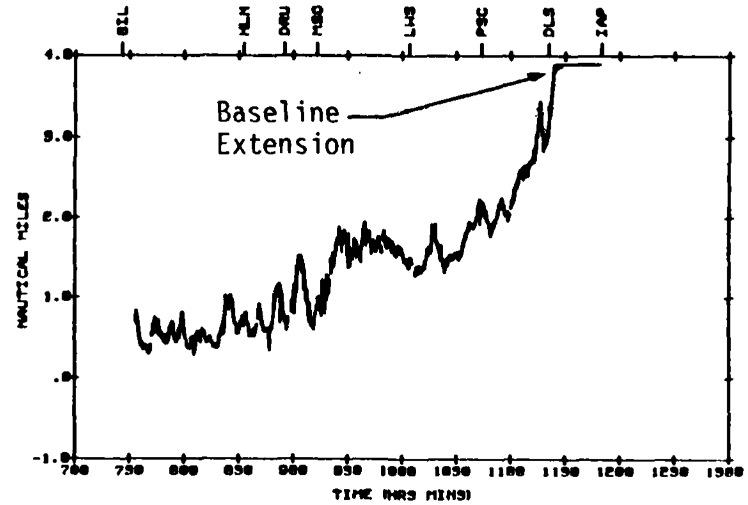
Total System Crosstrack Error

Total System Alongtrack Error

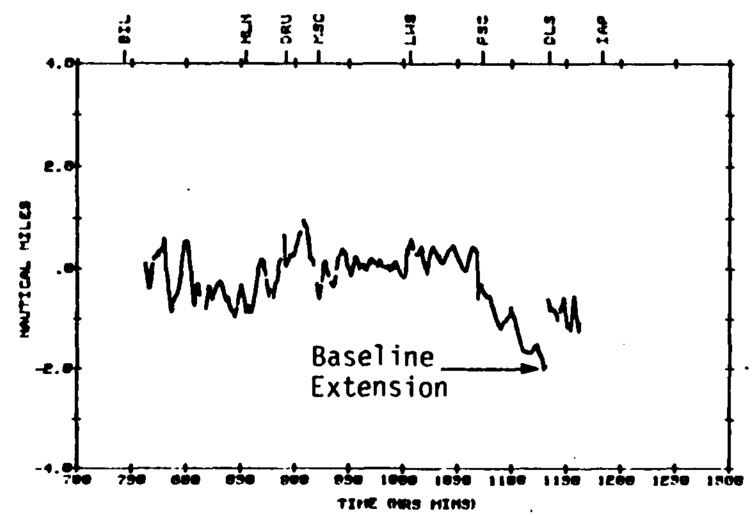
Figure 6.8 Loran-C System Errors, Rapid City, SD To Billings, MT (July 9, 1983)



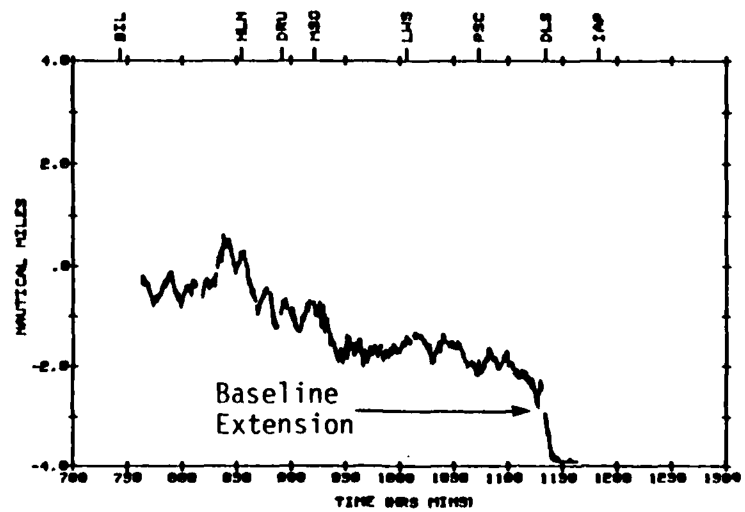
Time Difference Error



Position Error



Total System Crosstrack Error



Total System Alongtrack Error

Figure 6.9 Loran-C System Errors, Billings, MT To Portland, OR (July 11, 1983)

The crosstrack errors fluctuated between +1.0 to -1.0 nm throughout most of this segment. Toward the end of the segment the errors increased in magnitude to approximately -2.0 nm. Then the errors abruptly decreased in magnitude to -0.5 nm, fluctuating around -1.0 nm near Portland, OR.

The alongtrack errors again showed the presence of the Fallon-Searchlight baseline extension. Initially the alongtrack errors varied between -0.1 and -0.9 nm. Then the errors increased to +0.5 nm. From this point on, the error magnitude gradually increased to values exeeding -4.0 nm.

6.1.10 Segment #10 - Portland, OR to Medford, OR (Figure 6.10)

During this segment the West Coast chain, Fallon-George-Middletown triad, was used.

The TD errors were fairly smooth throughout the entire segment. For the station pair Fallon-George (TDA), the TD errors gradually decreased from +2.5 to 0.0 μs. The station pair Fallon-Middletown (TDB) had fairly constant TD errors, between ±0.5 μs.

The position errors were also fairly smooth, decreasing from +0.2 to 0.0 nm.

Error values for crosstrack fluctuated between +0.8 to -0.5 nm, while the alongtrack errors were smooth, varying from +0.1 to -0.6 nm.

6.1.11 Segment #11 - Medford, OR to Fresno, CA (Figure 6.11)

Again, the West Coast chain, Fallon-George-Middletown triad, was used. Upon leaving Medford, the Loran-C system did not provide navigation until approximately twenty minutes into this flight segment. Toward the later part of the segment, the Fallon-George baseline extension was approached resulting in a dramatic increase in all position related error components.

The TD errors for both the Fallon-George (TDA) and Fallon-Middletown (TDB) station pairs increased in magnitude as the aircraft progressed through the flight segment. The TDA errors varied from 0 to -5.0 μs, while the TDB errors varied from 0 to +5.0 μs. Both changes are attributed to propagation modeling error as the aircraft left the vicinity of the George transmitter and flew toward the Middletown station.

The position errors dramatically increased from 0.0 to greater than +4.0 nm. This was due to the proximity of the Fallon-George baseline extension as the aircraft approached Fresno, CA.

Crosstrack error values fluctuated between ±0.5 nm before sharply increasing in magnitude to approximately -2.0 nm, due to the baseline extension. The alongtrack errors varied from -0.1 to -0.9 nm before a dramatic increase in error (greater than +4.0 nm), again due to the presence of the baseline extension.

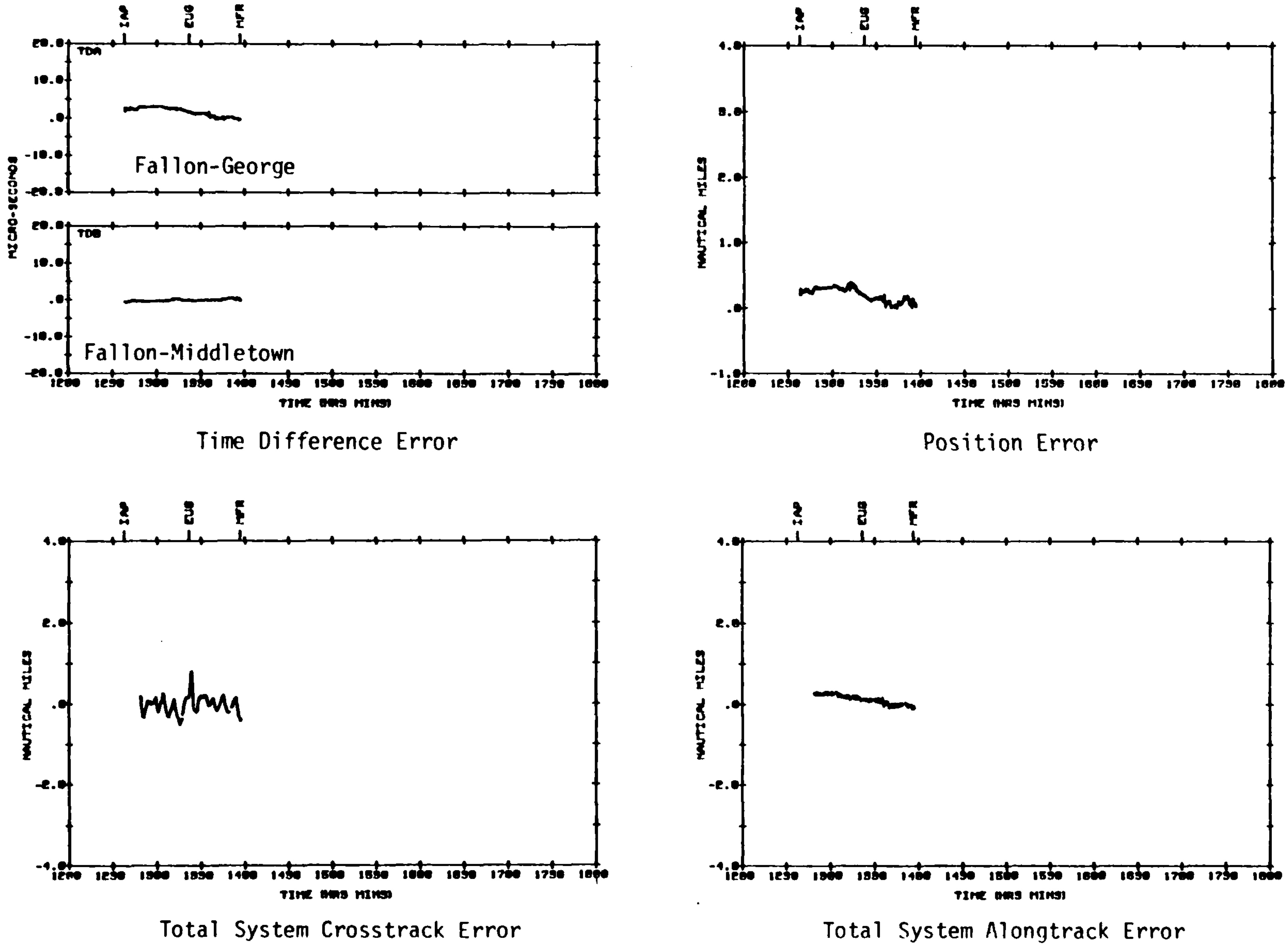


Figure 6.10 Loran-C System Errors, Portland, OR To Medford, OR (July 11, 1983)

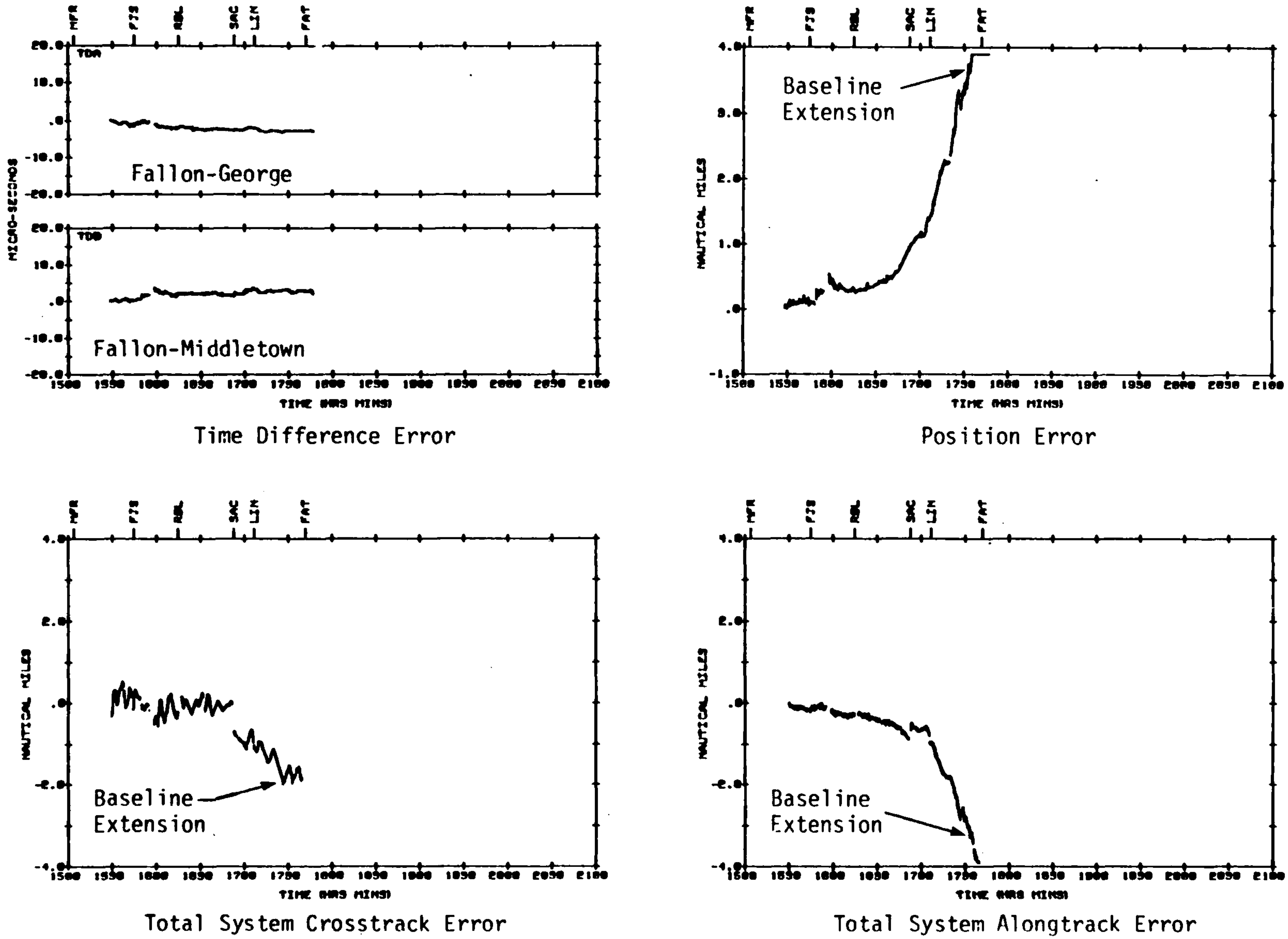


Figure 6.11 Loran-C System Errors, Medford, OR To Fresno, CA (July 11, 1983)

6.1.12 Segment #12 - Fresno, CA to Phoenix, AZ (Figure 6.12)

The West Coast Chain, Fallon-Middletown-Searchlight triad, was used for this entire segment. During this segment the aircraft flew across the Fallon-Searchlight baseline extension. At this time the Loran-C system became erratic and navigation was not available. When the system resumed navigation, large errors were apparent. This situation continued for the rest of the flight segment.

The TD errors were fairly smooth throughout this segment. For the station pair Fallon-Middletown (TDA), the TD errors decreased from +5.0 to -2.0 μs. For the station pair Fallon-Searchlight (TDB), the TD errors increased from -0.5 to +4.0 μs. There was some roughness in the TDB error data at about 7:00 hours. This could be due to poor DME measurements.

The position error plot graphically illustrates the effect of the Fallon-Searchlight baseline extension on the Loran-C system. The position errors are initially small (approximately +0.4 nm). These errors reached values as large as +1.0 nm before there was a dramatic increase in position error (+4.0 nm).

This type of behavior also was observed for the crosstrack and alongtrack errors. The crosstrack error fluctuated between 0 and -1.0 nm, then increased in magnitude to approximately -3.0 nm. Following this, the crosstrack error decreased sharply to approximately +0.2 nm.

The alongtrack errors are fairly smooth, starting at +0.5 nm and increasing in magnitude to -1.0 nm. At this point the alongtrack errors dramatically increased in magnitude to values greater than -4.0 nm. Again, this is due to the presence of the baseline extension.

6.1.13 Segment #13 - Phoenix, AZ to Lubbock, TX (Figure 6.13)

This segment was flown in an area where there was very little published Loran-C coverage. This resulted in large errors for all position related error components. Initially the West Coast Chain, Fallon-George-Searchlight triad, was used. (When the system locked on it indicated a position of the aircraft which was in error.) Another West Coast Chain triad combination of Fallon-Middletown-Searchlight was selected, but to no avail. The system never transitioned to this triad and continued to use Fallon-George-Searchlight. In addition to the poor Loran-C station geometry, there was also bad weather encountered as the aircraft reached Texas. At this point the Southeast Chain, Malone-Grangeville-Raymondville triad, was selected. Again, the Loran-C system would not respond to triad selector changes. This problem was discussed in Section 6.1.

During the later part of this segment the Loran-C system lost the George signal momentarily. This could have been due to precipitation static. As bad weather was encountered, static was heard over the VHF radios. When the George signal was reaquired, there was a large cycle error, causing the TD errors for the Fallon-George station pair (TDA) to

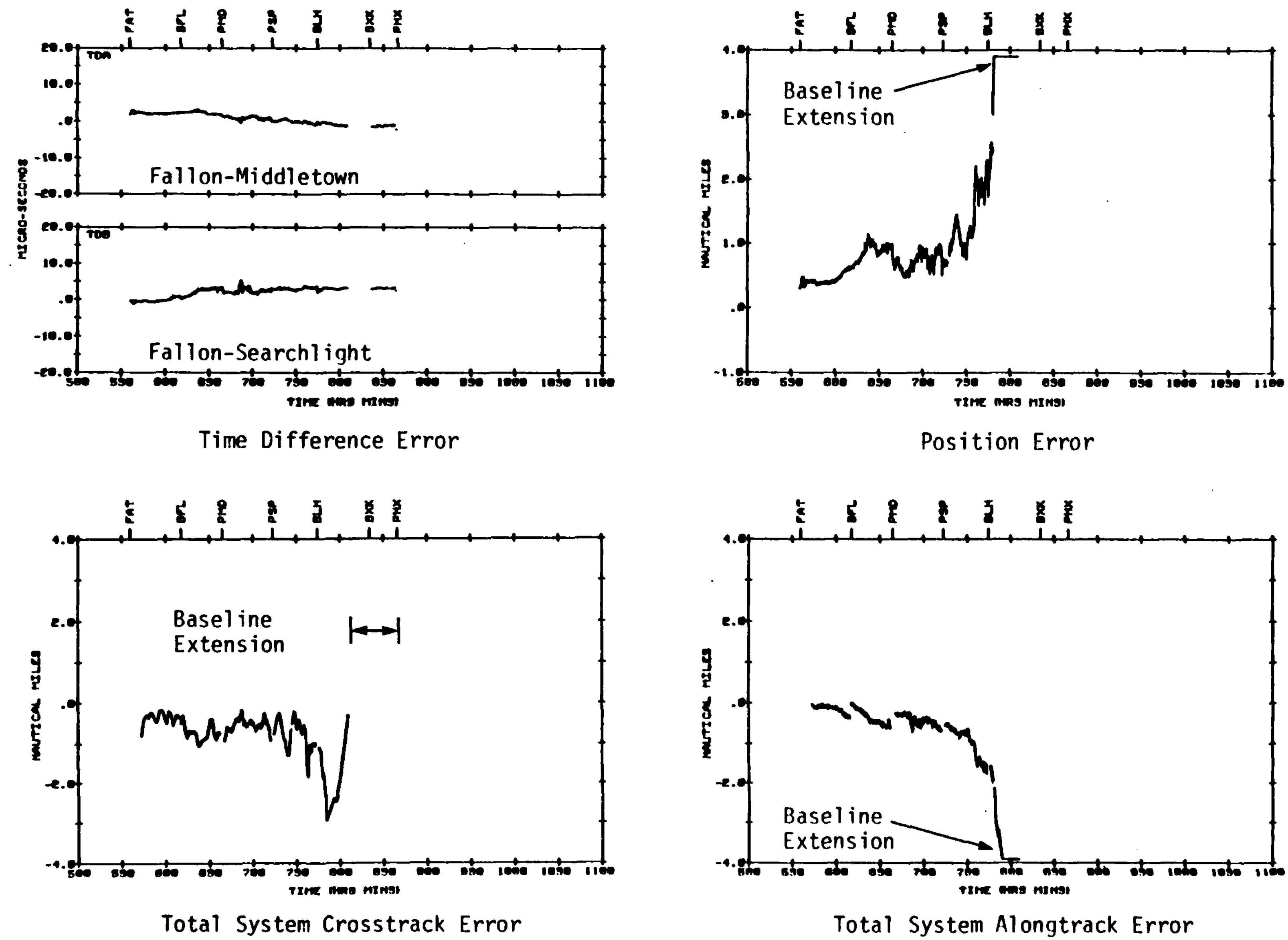


Figure 6.12 Loran-C System Errors, Fresno, CA To Phoenix AZ (July 13, 1983)

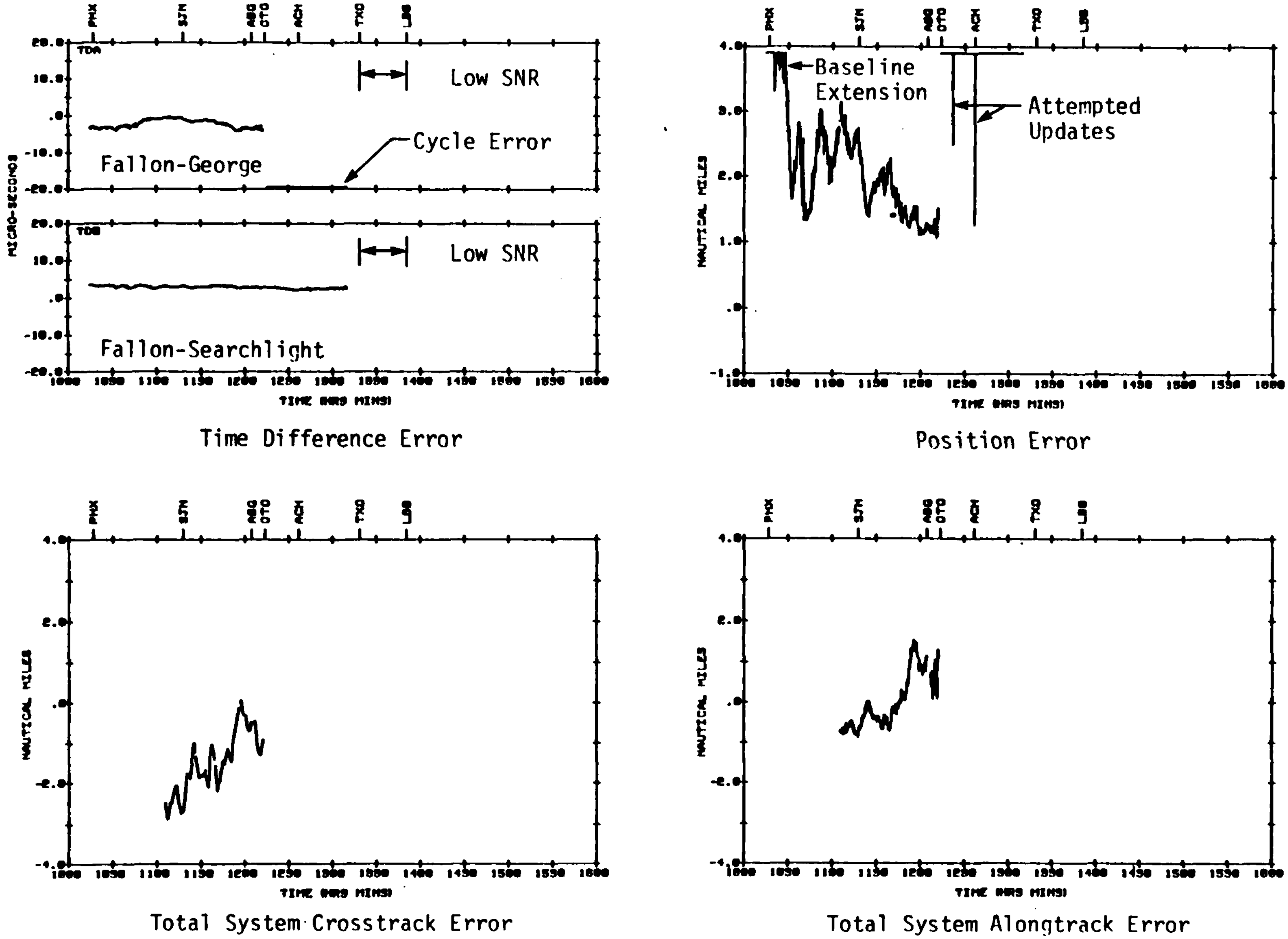


Figure 6.13 Loran-C System Errors, Phoenix AZ To Lubbock, TX (July 13, 1983)

be extremely large (-30 μs). At this time the envelope-cycle-difference and signal-to-noise ratio values measured in the receiver were at reasonable levels indicating nominal signal reception.

The TD errors for the Fallon-Searchlight station pair (TDB) were fairly constant throughout, varying between +2.0 and +3.0 μs.

The position errors show the poor coverage experienced during this segment. The errors fluctuated from greater than +4.0 nm down to +1.0 nm before the cycle error in the George signal occurred. At this point the errors were extremely large (+4.0 nm).

The crosstrack and alongtrack error plots also illustrate the poor coverage received in this area. The crosstrack error values gradually decreased in magnitude from -3.0 to 0.0 nm. The errors for alongtrack decreased, then increased, in magnitude from -1.0 to +1.5 nm.

6.1.14 Segment #14 - Lubbock, TX to San Antonio, TX (Figure 6.14)

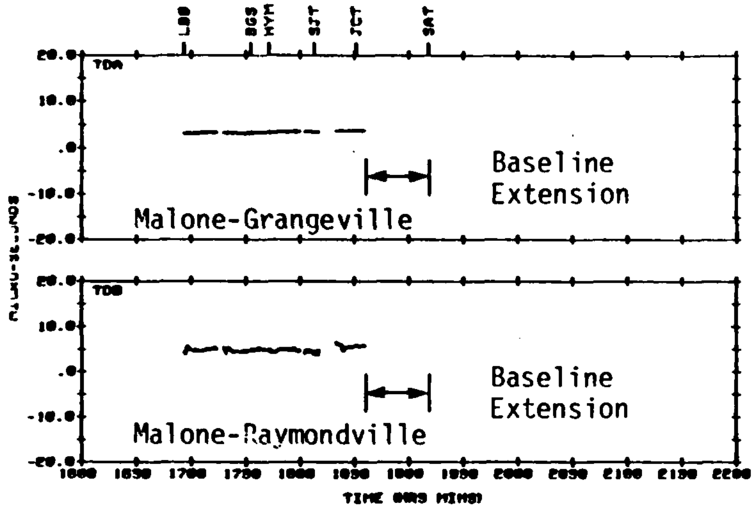
Upon leaving Lubbock the Southeast Chain, Malone-Grangeville-Raymondville triad, was chosen. During this segment poor Loran-C geometry was again experienced. Initially the Loran-C system had a northing error of +4.0 nm and an easting error of +3.0 nm. Alongtrack error was as large as +10.0 nm at one point during this flight segment. As the aircraft approached the vicinity of San Antonio, TX the system was affected by the Malone-Grangeville baseline extension. This prevented the receiver from providing navigation for the rest of the segment to San Antonio, TX.

The TD errors for the station pair Malone-Grangeville (TDA) were fairly constant at approximately +3.5 μs. The TD errors for the station pair Malone-Raymondville (TDB) fluctuated between +4.0 and +6.5 μs.

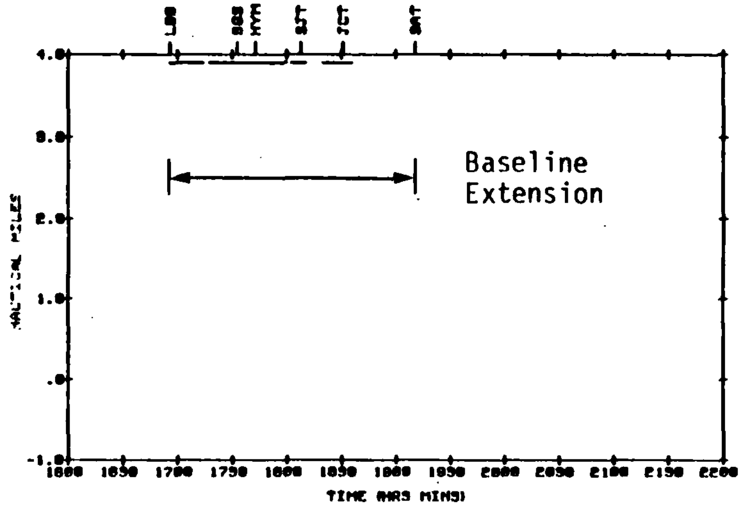
The position errors were totally out of limits throughout the whole segment (+4.0 nm). The crosstrack and alongtrack errors were also out of limits for the entire segment. However, crosstrack error, for a short time, had values between approximately -0.2 and +0.8 nm.

6.1.15 Segment #15 - San Antonio, TX to Lafayette, LA (Figure 6.15)

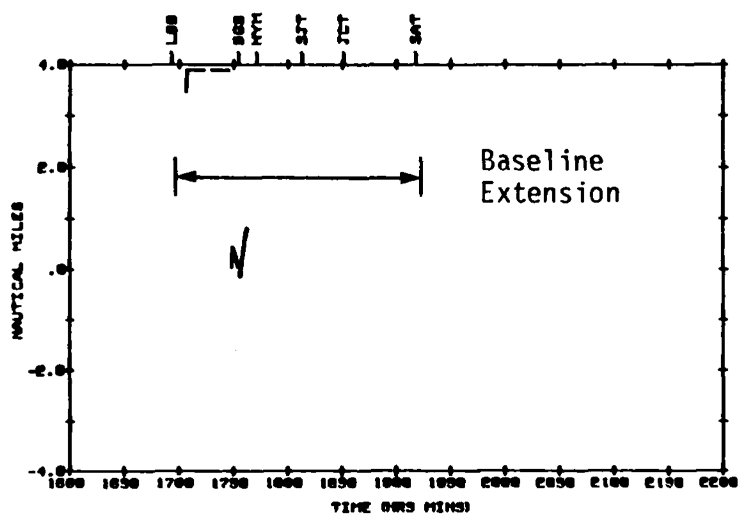
Throughout this segment, as with the previous segment, the Loran-C system was affected by the poor station geometry and the Malone-Grangeville baseline extension. Several chain triad combinations were selected before departure, none of which allowed the Loran-C system to acquire. Using the Southeast Chain, Malone-Grangeville-Raymondville triad, the measured time-difference for the station pair Malone-Grangeville was 10997 μs. This is less than the theoretically minimum TD value of 11000 μs. This situation is due to propagation model error. When the system finally provided navigation, the indicated present position was approximately +6.0 nm in error in crosstrack. Following this, a triad change was made to Malone-Raymondville-Jupiter. However, as previously discussed, the Loran-C system ignored this change and continued to use Malone-Grangeville-Raymondville. Throughout this entire segment the Loran-C system was not adequate for navigation.



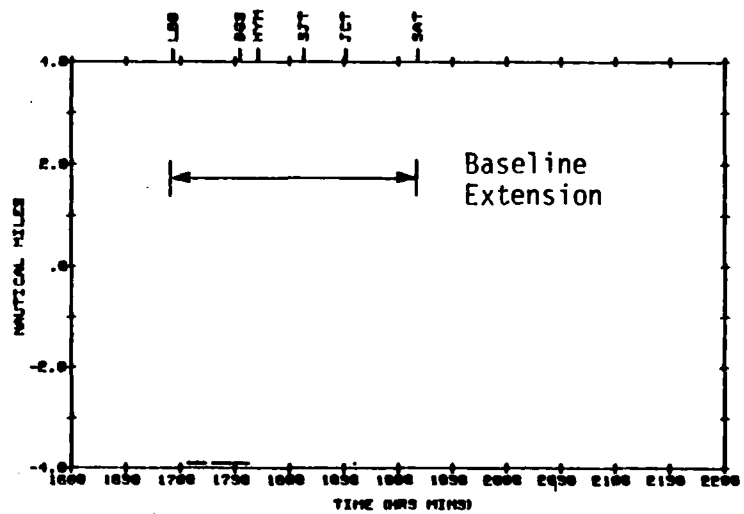
Time Difference Error



Position Error



Total System Crosstrack Error



Total System Alongtrack Error

Figure 6.14 Lorán-C System Errors, Lubbock, TX To San Antonio, TX (July 13, 1983)

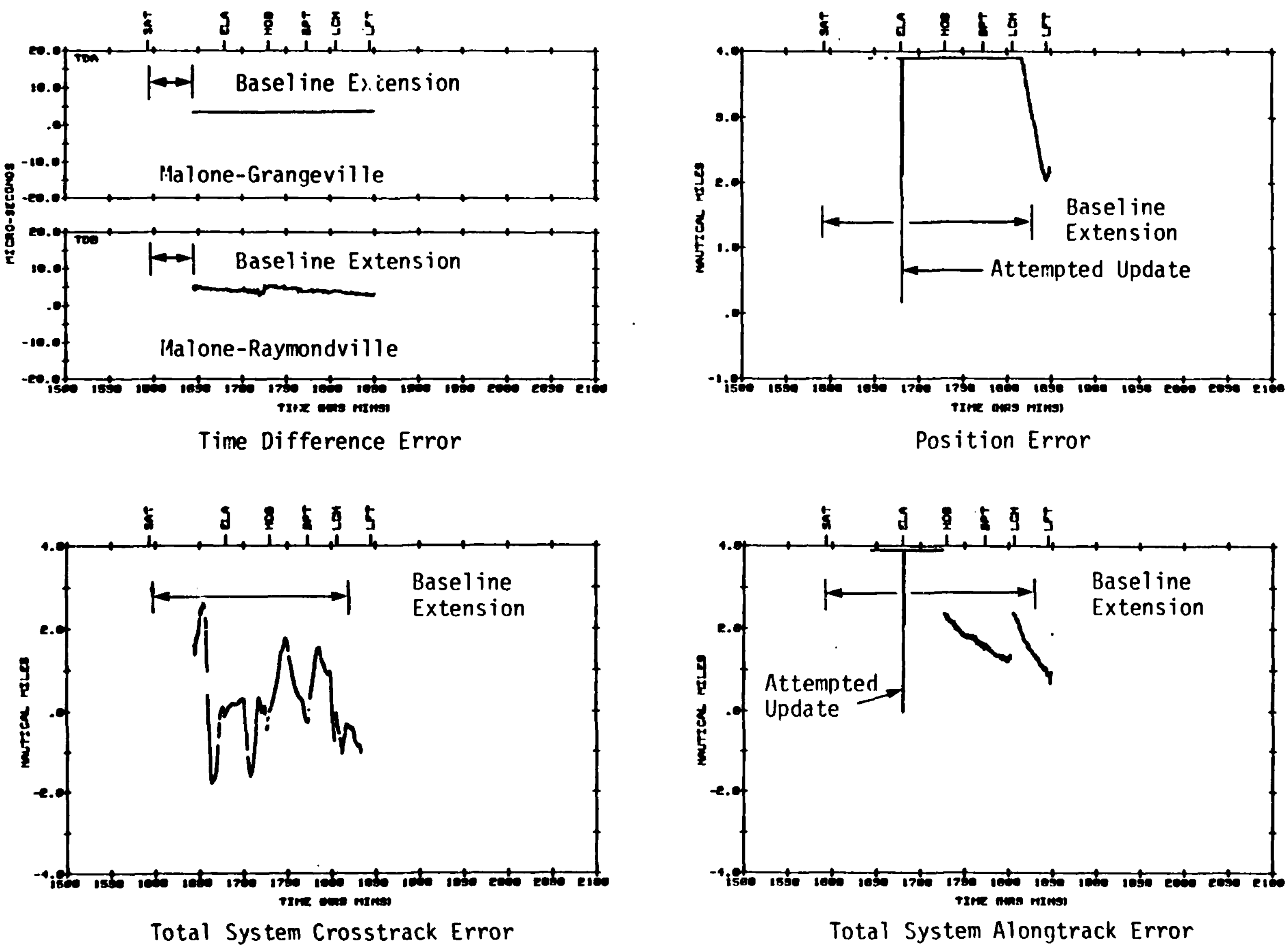


Figure 6.15 Loran-C System Errors, San Antonio, TX To Lafayette, LA (July 14, 1983)

The TD errors for the station pair Malone-Grangeville (TDA) were constant at approximately +4.0 μs. These TD errors remained constant due to the baseline extension. The TD errors for the station pair Malone-Raymondville (TDB) varied from +5.0 to +3.0 μs.

The position errors were out of limits (+4.0 nm) for the entire segment, due to the proximity of the baseline extension. These errors began to decrease toward the end of the segment reaching a value of +2.0 nm.

The affects of the baseline extension were also observed in the crosstrack and alongtrack error plots. The crosstrack errors fluctuated abruptly between +3.0 and -2.0 nm. The alongtrack errors were out of limits for part of the flight segment, decreasing to values between +2.0 and +0.5 nm toward the later half of the segment.

6.1.16 Segment #16 - Lafayette, LA to Tallahassee, FL (Figure 6.16)

During this segment the Southeast Chain, Malone-Raymondville-Jupiter triad, was used. A cycle error on the Jupiter station was observed during the data processing. The envelope number for this station measured in the receiver was low indicating an envelope-cycle-difference of approximately -2.7 μs. The receiver was unable to correctly identify the correct cycle for the entire flight segment.

The TD errors for the station pair Malone-Raymondville (TDA) decreased then increased in magnitude from +3.5 to -4.0 μs. The TD errors for the station pair Malone-Jupiter (TDB) shows the cycle error on the signal from the Jupiter transmitter. These errors are approximately +10.0 μs, decreasing slightly to approximately +6.0 μs.

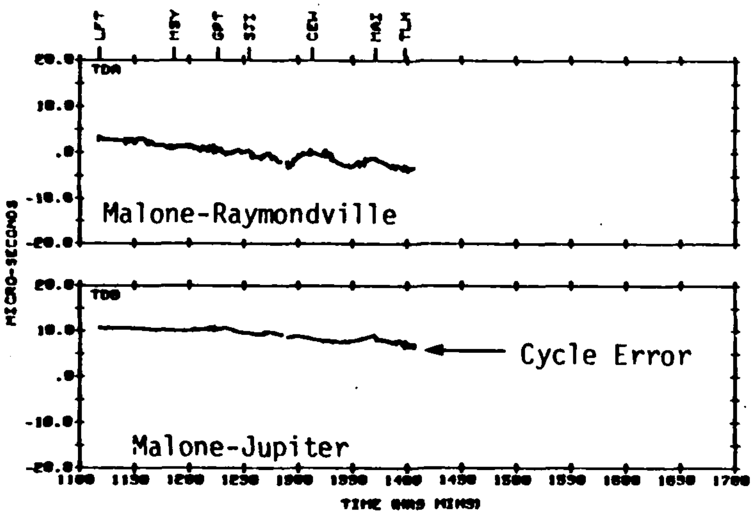
The position errors were very large (+4.0 nm). This segment should have experienced good station geometry. The reasons for the large position errors were due to the cycle error in the Malone-Jupiter time difference measurement, which was not apparent to the pilots.

The crosstrack and alongtrack errors had large values due to the cycle error. The crosstrack error values decreased in magnitude from errors greater than -4.0 nm, then increased in magnitude from 0.0 to +1.0 nm. The alongtrack errors are variable, ranging between -2.0 to +0.6 nm.

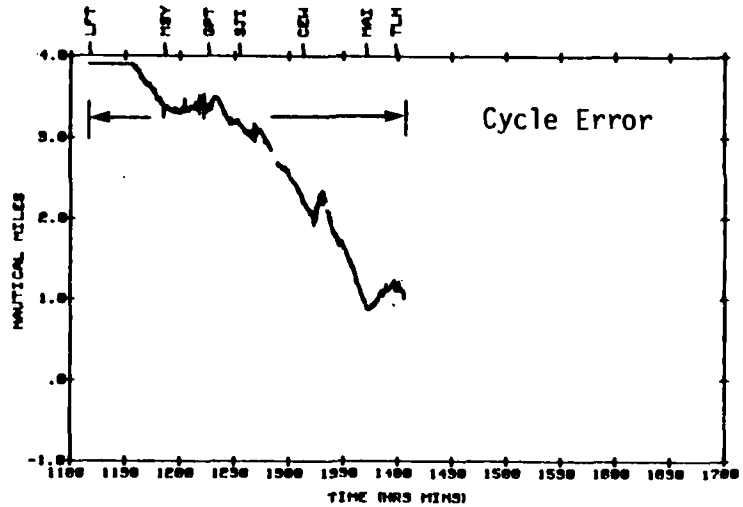
6.1.17 Segment #17 - Tallahassee, FL to Palm Beach, FL (Figure 6.17)

The TDL-711 Loran-C receiver has the capability to use a master independent triad for position computation. The master signal is still needed to identify the secondaries during the acquisition procedure.

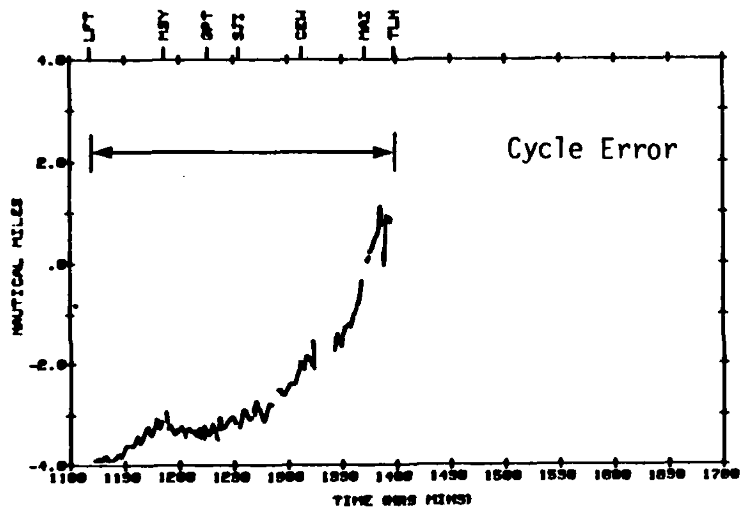
This segment was flown to obtain data from the Loran-C system in the master independent mode, Grangeville-Jupiter-Carolina Beach triad. However, the receiver initially acquired the Southeast Chain, Malone-Raymondville-Jupiter triad. For a brief time during this segment (16:54) an offset was used to avoid weather. At approximately 17:16, a transition to the master independent mode using Grangeville-Jupiter-



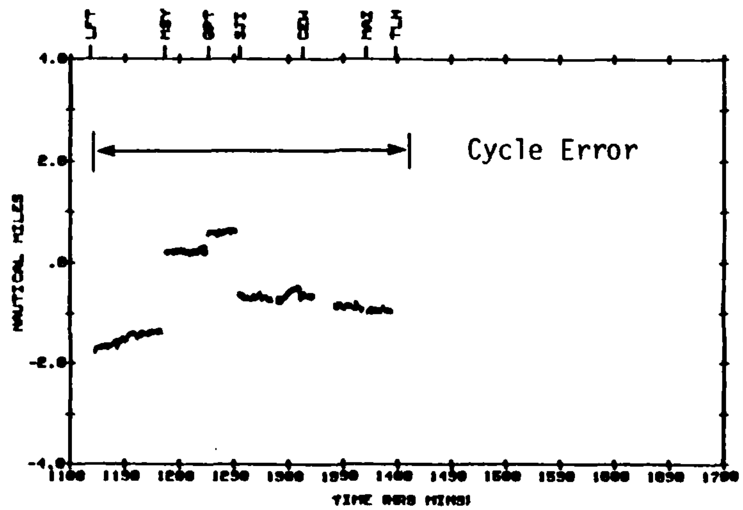
Time Difference Error



Position Error

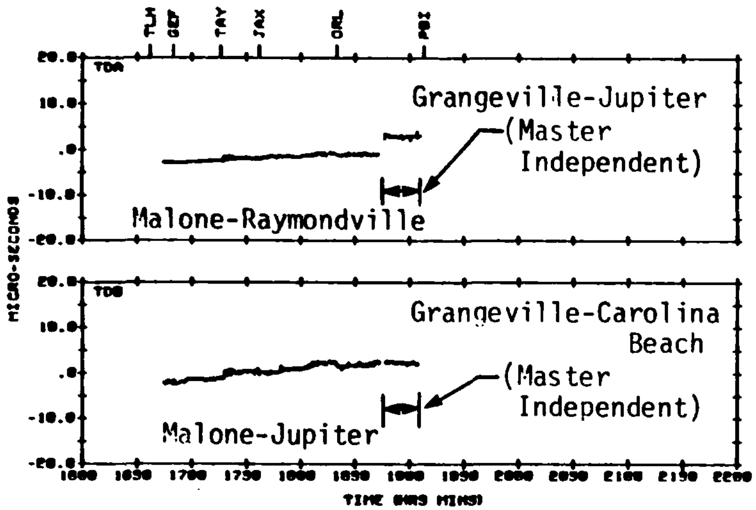


Total System Crosstrack Error

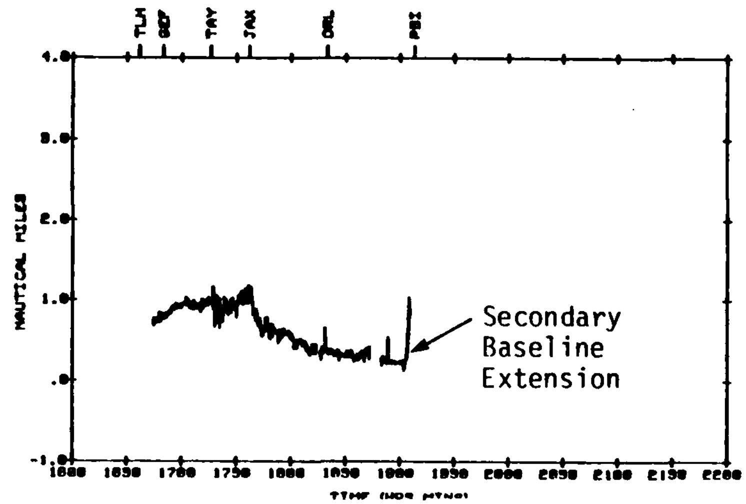


Total System Alongtrack Error

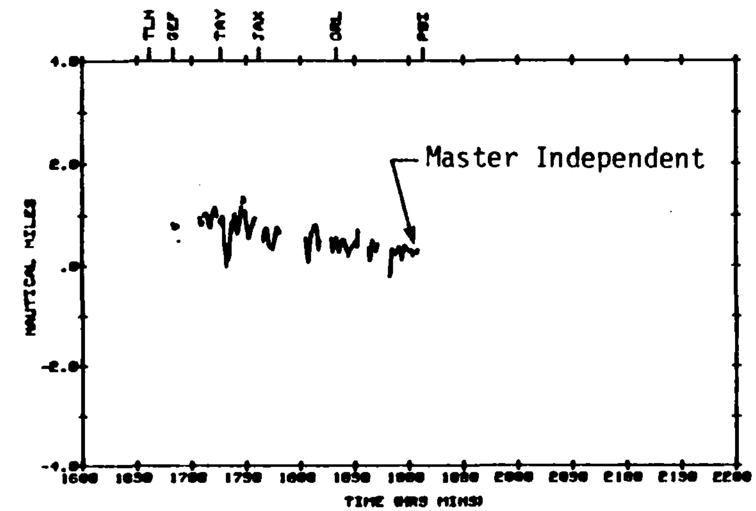
Figure 6.16 Loran-C System Errors, Lafayette, LA To Tallahassee, FL (July 15, 1983)



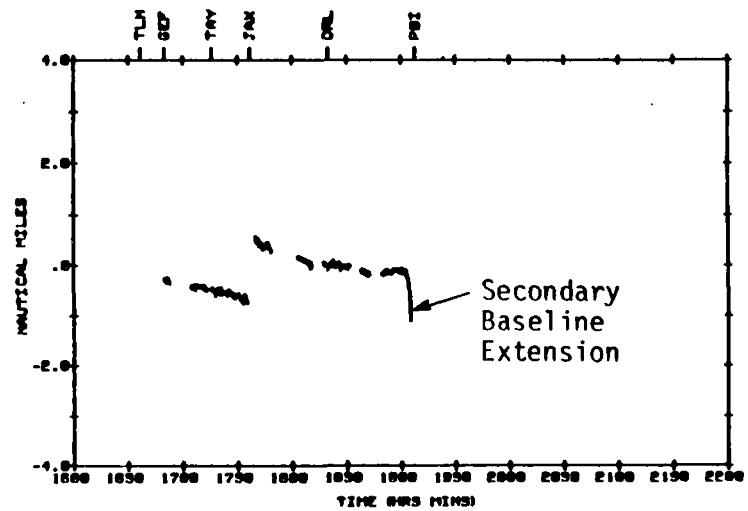
Time Difference Error



Position Error



Total System Crosstrack Error



Total System Alongtrack Error

Figure 6.17 Loran-C System Errors, Tallahassee, FL To Palm Beach, FL (July 15, 1983)

Carolina Beach was attempted, but to no avail. Again, some parallel offsets were used to avoid weather. At approximately 18:50, the Loran-C system was able to transition to the master independent mode using Grangeville-Jupiter-Carolina Beach. These stations were used for the remainder of the flight to Palm Beach, FL.

The TD error for the station pair Malone-Raymondville (TDA) gradually decreased in magnitude from -6.0 to -1.0 μs. Some of the roughness observed may be attributed to the thunderstorm activity encountered during this segment. Upon switching to the master independent mode, the TD errors for the station pair Grangeville-Jupiter (TDA) remained fairly constant throughout the rest of the segment at approximately +2.5 μs.

The TD errors for the station pair Malone-Jupiter (TDB) varied from -2.5 to +2.5 μs. Again, some of the roughness observed may be attributed to the thunderstorm activity encountered. The errors associated with the Grangeville-Carolina Beach station pair (TDB) were of the same magnitude as the TD errors of the previous station pair (Malone-Jupiter). These errors were fairly constant throughout the rest of the segment at approximately +2.0 μs.

The position error plot was very rough. These values fluctuated between +1.0 and 0.0 nm, with a gradual decreasing trend from +0.8 to 0.0 nm. As the segment was ending, the aircraft was just beginning to approach the Jupiter-Carolina Beach baseline extension. This is illustrated by the abrupt increase in position error at the end of the plot.

The crosstrack errors fluctuated between +1.2 and -0.2 nm, gradually decreasing along the flight segment. The alongtrack errors were smoother, varying between 0.0 and -1.0 nm. Again, the presence of the Jupiter-Carolina Beach baseline extension can be observed at the end of this plot.

6.2 AREA CALIBRATION SYSTEM PERFORMANCE

At various locations along the evaluation route, area calibration flights were conducted. Five different locations were chosen, each utilizing a different Loran-C chain/triad configuration. For the purposes of this test, a 75 nm radius was examined in all directions from a given airport. The pattern flown is described in Section 2.4.2.

The five locations which were utilized for area calibration evaluation were:

London, KY

Burlington, VT

Muskegon, MI

Fresno, CA

Lafayette, LA

There were two reasons for conducting these area calibration tests:

1) Determine how far from the area calibration point the TD corrections are valid.

2) Determine the best possible method to determine TD correction factors.

6.2.1 Area Calibration TD Error Evaluation

Prior to takeoff on each calibration flight, the plane was taxied to a predetermined location on the airport. From the approach plate, the latitude/longitude of this location was determined and entered as the present position into the Loran-C unit. The coordinate selector switch on the CDU was set to TD (time-difference) and the TD values associated with the latitude/longitude were entered into the Loran-C CDU. The Loran-C navigator determined a correction factor which zeroed out the position bias error present at that particular location. This procedure was referred to as ground calibration.

During the data reduction phase of the program, a corresponding correction factor was computed and applied to the time difference readings obtained from the data in order to determine corrected time difference values. This correction factor was determined by computing the theoretical time difference values from the known calibration location or the airport and subtracting the actual time difference measurements recorded at the calibration location. Since the theoretical time difference values were computed from a propagation model that was used in the Loran-C navigator, the correction factor calculated by the Loran-C navigator and the correction factor computed for data reduction purposes were the same values.

The data from these area calibration test flights were analyzed by plotting the TD errors as a function of the distance from the area calibration location (Figures 6.18 through 6.22). These TD errors were computed in the same manner as in Section 4.4. TDA and TDB were plotted separately. Although the evaluation pattern flown was similar to that depicted in Section 2.4.2, the East to West portion of the pattern was plotted on one plot and the North to South portion was plotted on another. The Fresno area calibration evaluation was flown from the South to the North instead of North to South. The East/West plots depict the aircraft traveling from the calibration location to the East, then traveling from the West back to the calibration location prior to landing.

What was anticipated from this data was a linear trend, starting from 0.0 μs at the calibration location, gradually increasing to larger TD error values as the distance from this location increased.

6.2.2 London, KY Area Calibration Test (Figure 6.18)

It was observed from the East/West plot that, in spite of ground calibration, the TD errors were not zero as the aircraft overflew the calibration point. This was not expected, since the TD correction factors were entered into the Loran-C system just prior to takeoff. The North/South plot showed the same anomaly, as the airplane passed

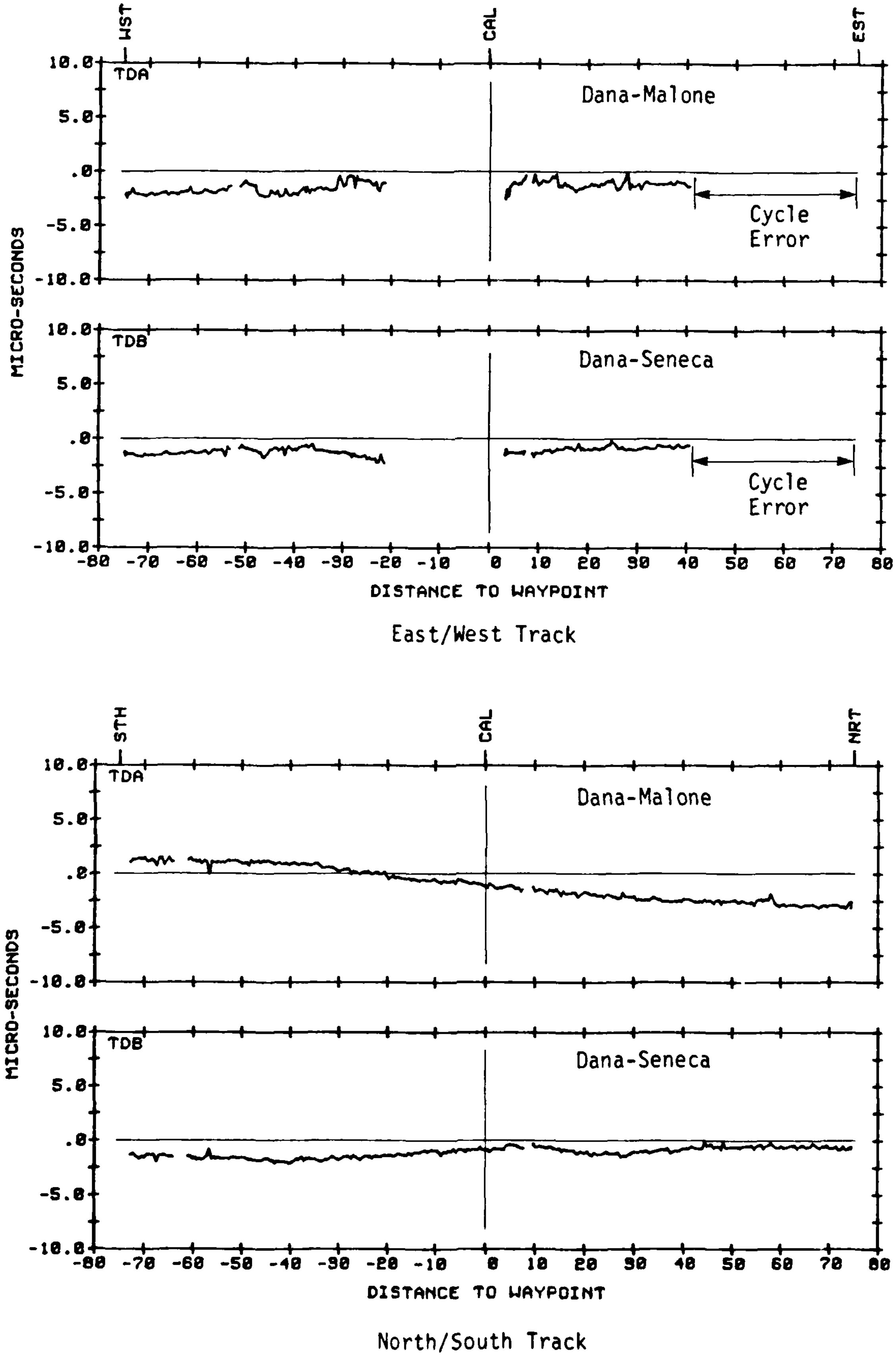


Figure 6.18 Area Calibration TD Errors, London, KY (July 6, 1983)

over the calibration location. At this time the TDA (Dana-Malone) and TDB (Dana-Seneca) errors were approximately -1.0 and -0.5 μs, respectively. The gap in data observed around the calibration location was due to a lack of DME data.

Several reasons for non-zero TD errors at the calibration point are possible. They include the following:

- erroneous latitude/longitude coordinates for the calibration point
- local propagation anomalies in the vicinity of the calibration point
- errors in the DME position reference system

A specific cause for the non-zero TD error could not be determined by examining the flight test data.

The Great Lakes chain, Dana-Malone-Seneca triad, was used throughout the calibration test. At various times during this test the Loran-C system did not acquire the appropriate station signals. These occurrences lasted, at the most, for one minute. It was observed from the data, and from U.S. Coast Guard records, that the station at Dana momentarily went off the air during these times.

As the airplane traveled toward the East waypoint, there was a cycle error in the Loran-C receiver. This occurred 35 miles from the East waypoint and continued for approximately 95 miles. As a result the TDA and TDB errors increased in magnitude (-10.0 μs). This caused a position error of about 1.5 nm, primarily in the alongtrack direction. The cycle error occurred after one of the momentary outages on the Dana station. This cycle error was not apparent to the pilots. Envelope numbers were analyzed in the post flight data. The numbers for Malone and Seneca were within the nominal range prior to the cycle error. After the cycle error occurred, the envelope numbers are significantly higher than normal.

In general, the TDB errors appeared to be greater in magnitude near the West waypoint (-1.5 μs), decreasing slightly then increasing again upon approaching the calibration location (-2.0 μs), while the TDA errors decreased from -2.5 to -0.5 μs. Traveling from the calibration location to the East, the TDA errors decreased from -2.5 to -1.0 μs., while the TDB errors decreased from -1.5 to -0.5 μs during this time.

As the aircraft proceeded North to South, a linear trend of TDA and TDB error was observed. The TDA errors decreased in magnitude from -2.5 μs then increased in magnitude to +1.0 μs, crossing 0.0 μs approximately 20 miles after passing the calibration location. The TDB errors increased in magnitude as the aircraft traveled North to South (-0.5 to -1.5 μs), never crossing 0.0 μs.

6.2.3 Burlington, VT Area Calibration Test (Figure 6.19)

The calibration test performed at Burlington, VT (BTV) used the Northeast Chain, Seneca-Caribou-Nantucket triad. Again, a similar

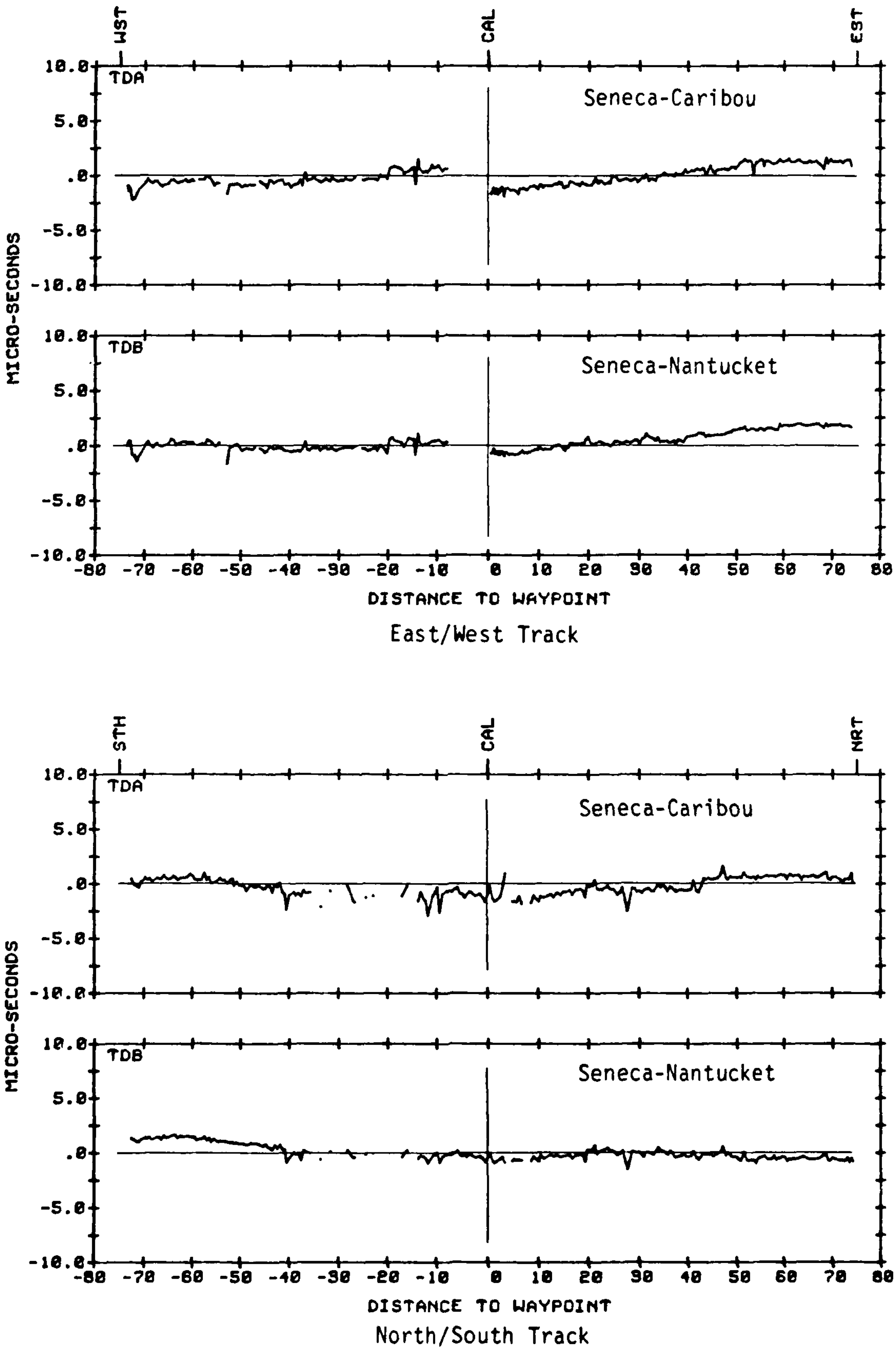


Figure 6.19 Area Calibration TD Errors, Burlington, VT (July 7, 1983)

anomaly occurred here as it did in the previous calibration test. The TD errors were not zero when the aircraft was flying over the calibration location. In addition there appears to be a slight shift in both TD errors in the East/West track near the calibration point. This could be due to effects on the Loran-C signal due to Lake Champlain or errors in the DME reference position caused by DME signal reflections from the lake. As the aircraft passed over the airport on the North/South track, the TD errors were approximately -1.0 μs. This compared well with the -0.5 to -1.0 μs errors experience during takeoff on the East leg, but it differed from the +0.5 to +1.0 μs error as the aircraft approached Burlington from the West.

In the East/West direction, the TD errors had a gradual increasing trend (to values between 1.5 and 2.0 μs at a distance of 75 nm from the calibration point) traveling East from the calibration location, for both TDA (Seneca-Caribou) and TDB (Seneca-Nantucket). To the West, TDA errors gradually increased in magnitude, to 2.0 μs at a distance approximately 70 nm from the calibration point, while TDB remained fairly constant (approximately 0.0 μs).

In the North/South direction, the TDA errors went from approximately +0.5 μs at the North waypoint to -0.5 μs near the calibration location, back to +0.5 μs near the South waypoint. The TDB errors were approximately 0.0 μs for most of this leg. Within 35 miles of the South waypoint the TDB errors increased to approximately +1.5 μs.

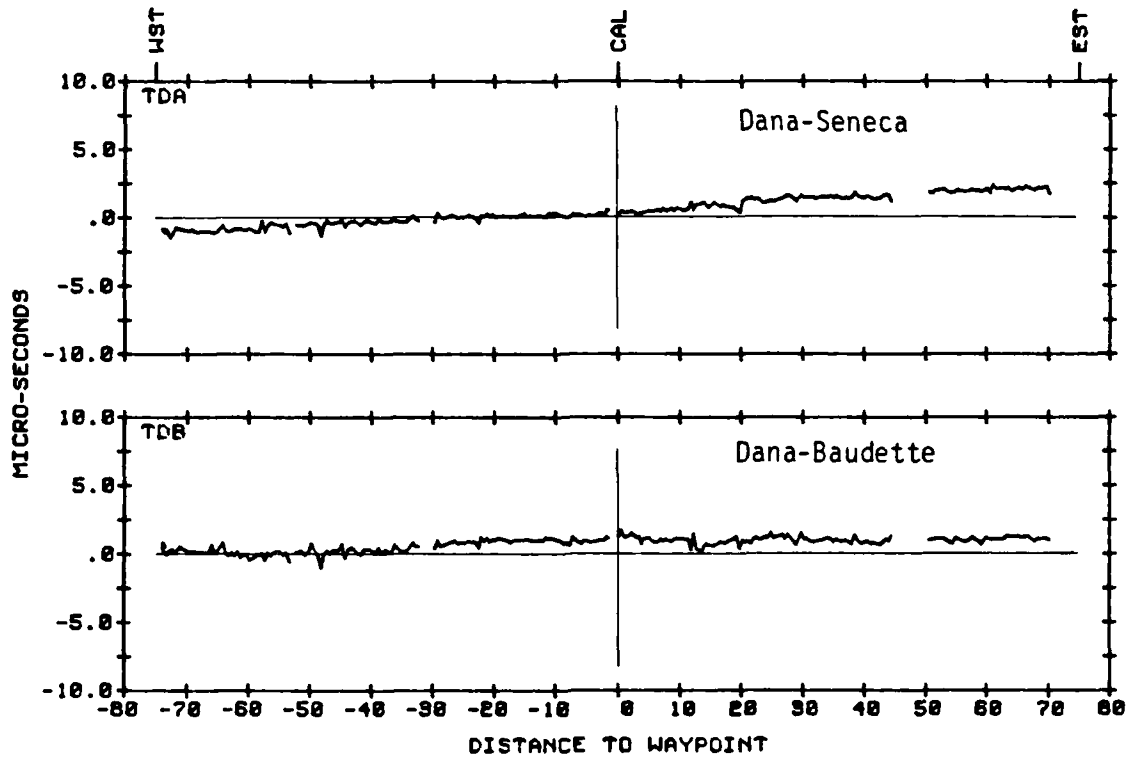
The gaps in the data that were observed were due to inadequate DME data.

6.2.4 Muskegon, MI Area Calibration Test (Figure 6.20)

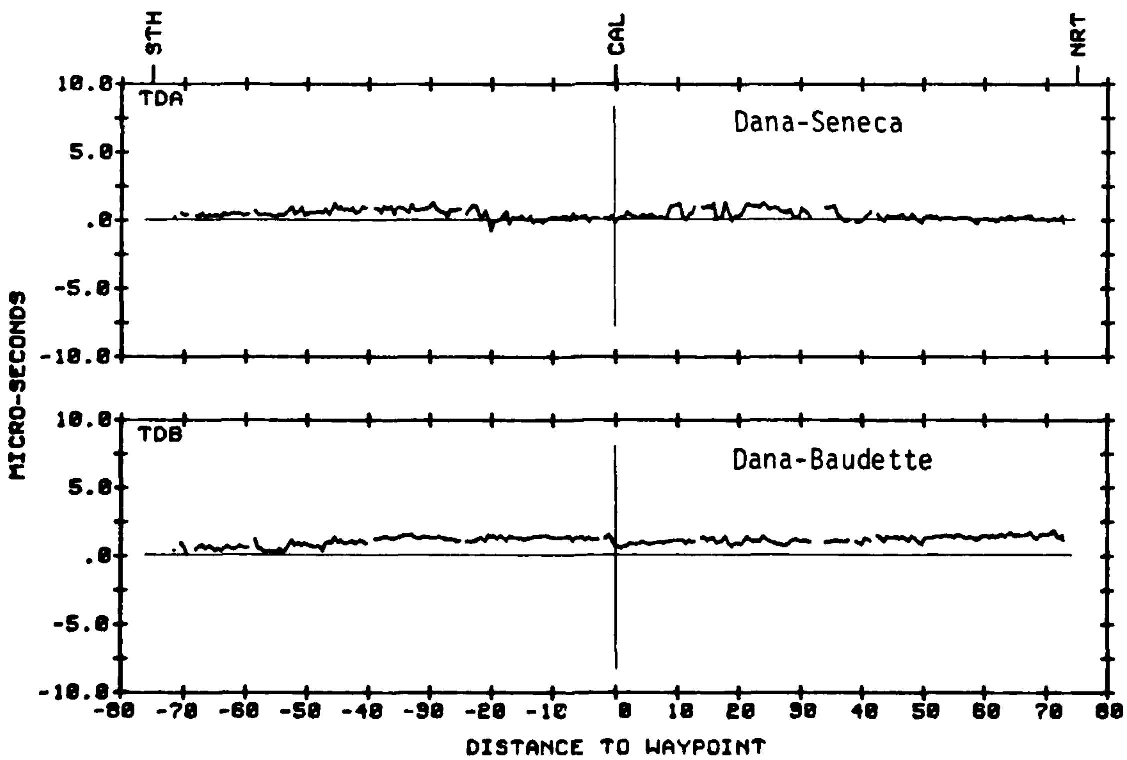
During this calibration test the Great Lakes chain, Dana-Seneca-Baudette, was used. The calibration procedure removed most of the TDA error as shown in both the East/West and North/South tracks. However, about +1.5 μs error remained in TDB as shown by both tracks. As with the Burlington flight, the West-Cal leg was flown over a fresh water lake. The Muskegon data did not exhibit a shift like that seen at Burlington.

The East/West TD error plots showed a linear trend in TD errors with an increase in distance from the calibration location. The TDA error was approximately +.25 μs during ground calibration, increasing to +2.5 μs at the East waypoint and +1.5 μs at the West waypoint. The TDB error was larger at the calibration location (+2.0 μs) than at either the East (+1.5 μs) or West (+1.0 μs) waypoints. The TDB errors exhibit a decreasing trend as the aircraft was further away from the calibration location.

The TD errors were fairly constant during transition from North to South. The TDA errors were approximately +0.5 μs and the TDB errors were approximately +1.5 μs. As the airplane was passing over the calibration location, the TDA error was 0.0 μs and the TDB error was +1.0 μs.



East/West Track



North/South Track

Figure 6.20 Area Calibration TD Errors, Muskegon, MI (July 8, 1983)

There were two times during this calibration test when the Loran-C system momentarily lost the station signals. One occurrence was due to a momentary station outage and one was due to low signal to noise ratios on all stations. These outages lasted for less than one minute each time.

6.2.5 Fresno, CA Area Calibration Test (Figure 6.21)

The West Coast chain, Fallon-Middleton-Searchlight triad, was used throughout this test. As shown in Figure 6.21, the calibration procedure removed the error in TDA as the aircraft passed over the calibration point on both the East/West and North/South tracks. However, about -1.0 μs of error remained for TDB.

A linear trend was observed for TDA from the calibration location (approximately 0.5 μs) to the East waypoint (approximately -1.5 μs), crossing 0.0 μs about 30 miles from the airport. The TDB error was -0.25 μs near the calibration point, decreasing to 0.0 μs as the airplane proceeded toward the East waypoint. As the airplane traveled from the West, the TD errors decreased from -1.0 μs and -1.5 μs to +0.5 μs and -0.5 μs for TDA and TDB, respectively.

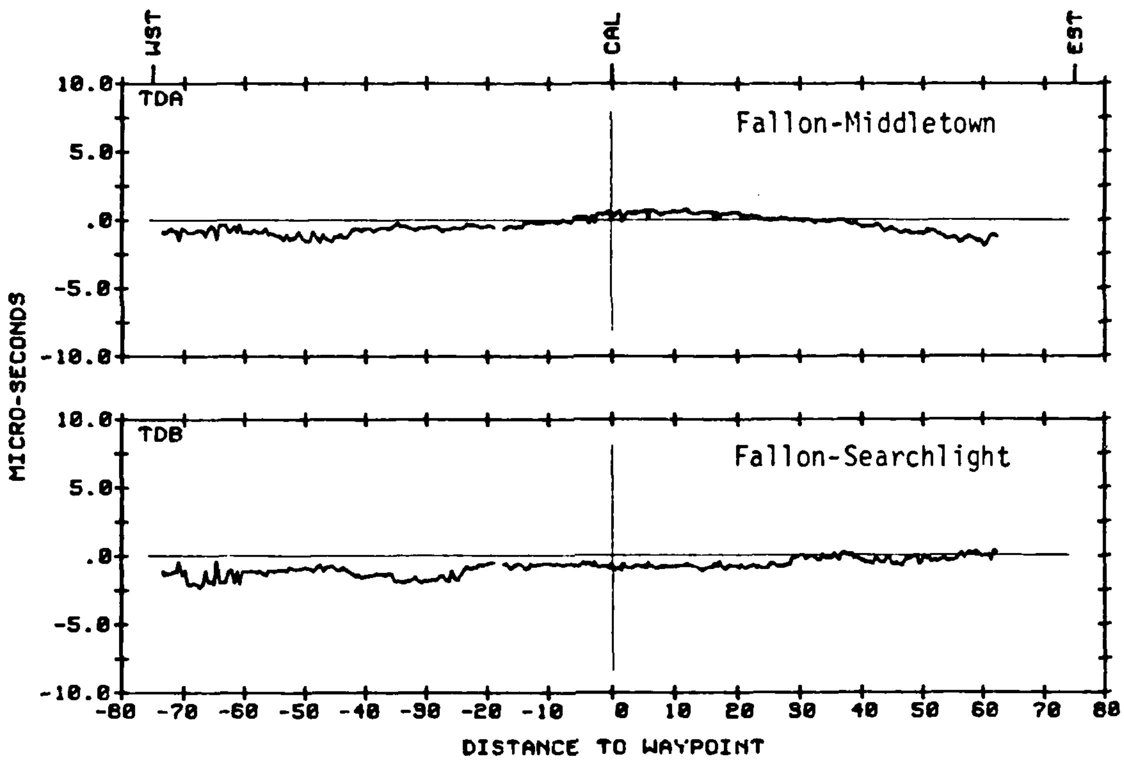
The North/South plots showed a more linear trend of the TD errors than has been observed previously. The TDA errors were -2.0 μs 75 nm south of the calibration location, decreased to approximately 0.0 μs near the calibration location, then increased to -0.5 μs 75 nm north of the calibration location. This same trend was observed for the TDB errors, the farther from the calibration location the larger the TD errors. However, the TD error plot did not cross the 0.0 μs axis at the calibration location.

6.2.6 Lafayette, LA Area Calibration Test (Figure 6.22)

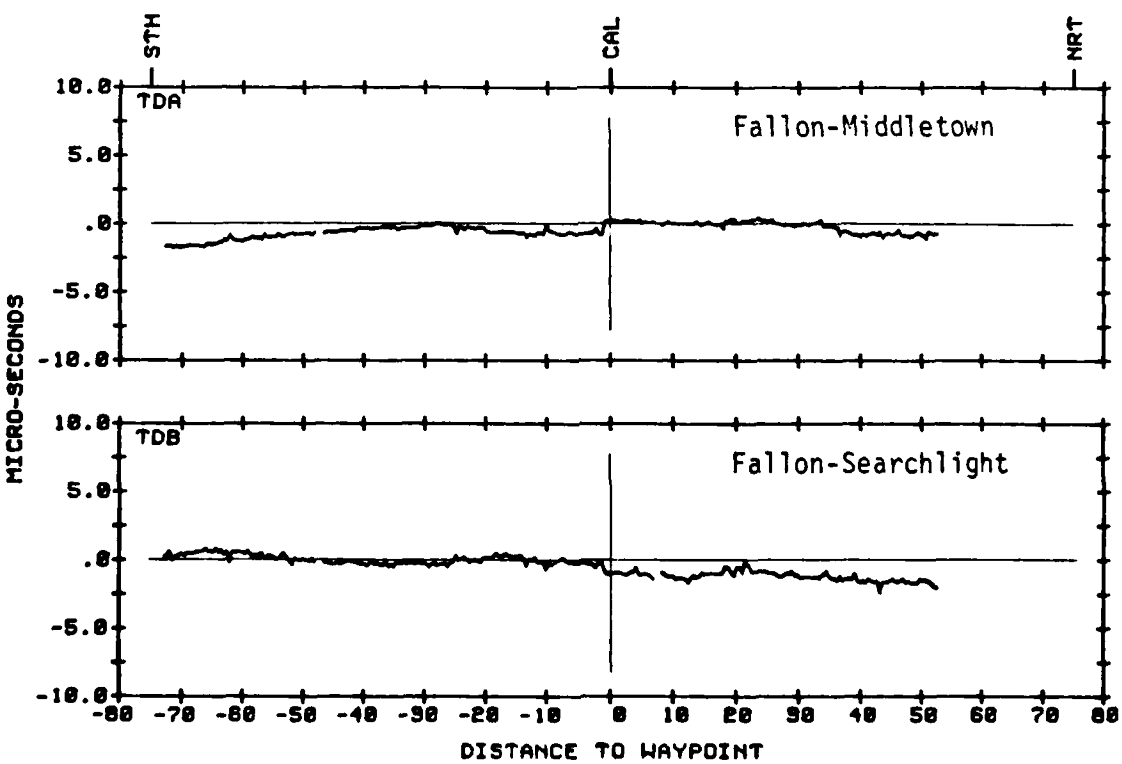
During this test the Southeast chain, Malone-Raymondville-Jupiter triad, was used. As shown in the plots of Figure 6.22, the calibration procedure effectively reduced the TD errors at the calibration point at Lafayette. Both TDA and TDB errors were at, or near, zero at the CAL waypoint on both the East/West and North/South tracks. The errors also exhibit a linear trend increasing in magnitude as the distance from the calibration point increased.

In the East/West direction, the TDA errors (Malone-Raymondville) increased from 0.0 μs at the calibration location to -2.0 μs at the East waypoint and +1.5 μs at the West waypoint. The TDB errors (Malone-Jupiter) remained fairly constant near 0.0 μs, increasing slightly to -0.25 μs to the East and less than +0.25 μs to the West.

In the North/South direction, the TD error plots were not as linear. The TDA errors increased from 0.0 μs at the calibration location to -0.5 μs at the North waypoint and -1.5 μs at the South waypoint. The TDB errors increased from 0.0 μs at the calibration location to -0.5 μs to the North and to the South. Due to temporary



East/West Track



North/South Track

Figure 6.21 Area Calibration TD Errors, Fresno, CA (July 12, 1983)

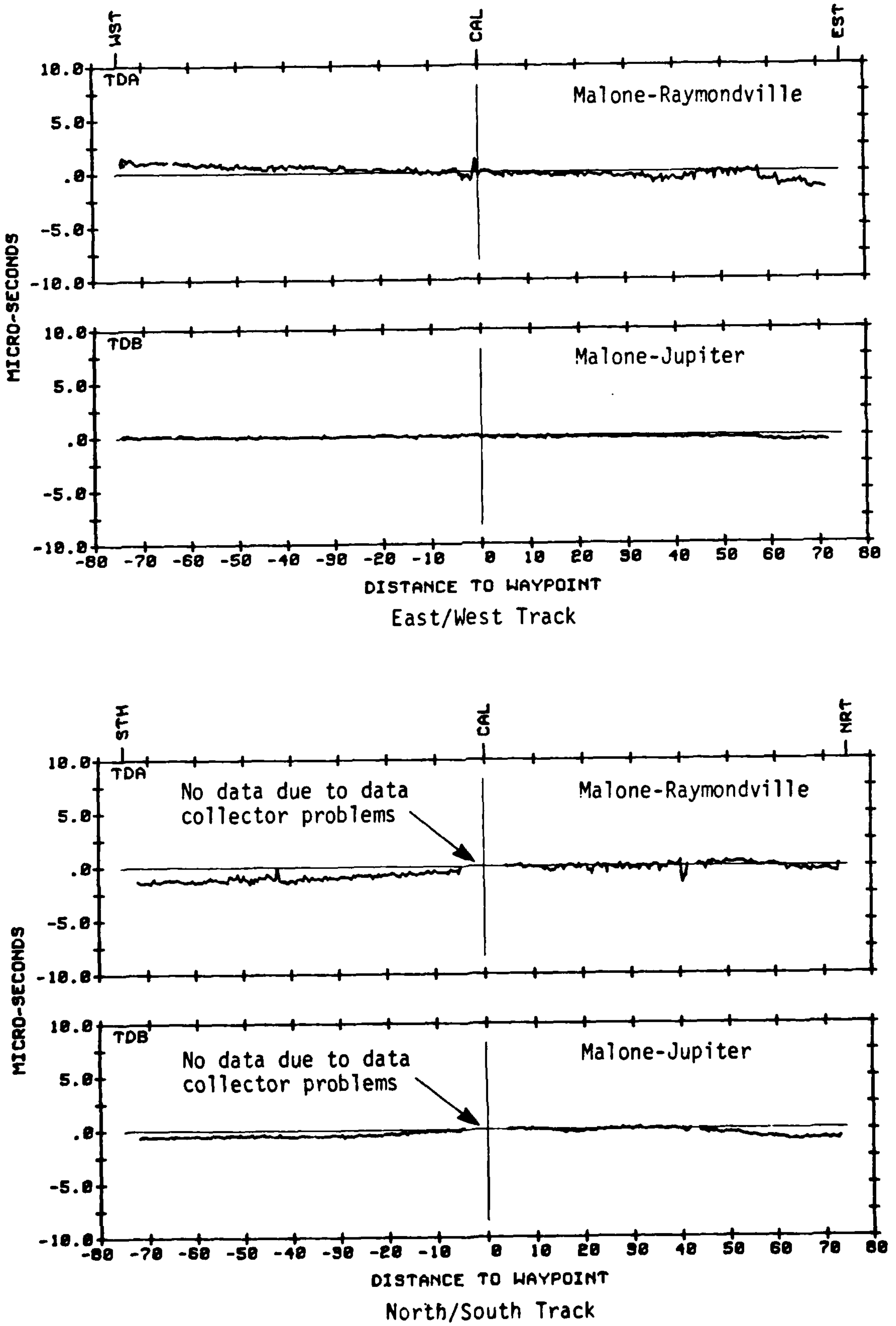


Figure 6.22 Area Calibration TD Errors, Lafayette, LA (July 15, 1983)

problems with the data collector, no data was recorded during in-flight measurements over the calibration location.

At three points during this test the Loran-C system momentarily lost navigation capability. During these times it was observed that the SNR values for the station at Raymondville were relatively low. These occurrences were brief (less than one minute).

For each of the previous area calibration tests flown except for Lafayette, LA, there was some difference between the TD errors on the ground and in the air. Further testing and analysis must be performed before any specific reason can be given for this situation. Also, it should be noted at these locations, that the TD errors were not zero upon departure. This is significant because the TD correction factors were entered into the Loran-C system just prior to departure. This could have been due to local signal anomalies during the time when the TD correction factors were to be entered into the Loran-C system. For each test it was observed that, after landing, the Loran-C system displayed the same latitude and longitude as before taking off at the calibration point.

6.3 DME POSITIONING SYSTEM PERFORMANCE

During most enroute segments and area calibration flights four to six DME distance values were recorded. On takeoff and landing and in a few areas in Montana and Oregon there were periods when fewer than three DME distances were available. Since there were ample stations with suitable geometry in most areas of the test, reception of signals from at least three DME stations with suitable geometry was established as a minimum criterion for acceptance of a DME derived aircraft position.

At locations where three or more measurements were used to establish the aircraft position, the root mean square value of the DME residuals usually provided an effective means for identification and rejection of occasionally erroneous DME data. When a large residual error was observed, the station with the largest error was dropped from the positioning solution and a new position solution was obtained. If the new solution met accuracy criteria it was accepted and the dropped station was flagged. This procedure provided an effective means of identifying position errors in the DME station data base.

Bias errors in the DME measurements, caused by transponder delay errors, also affected the accuracy of the DME positioning system. Since the DME positioning system was considered to be sufficiently accurate to establish the enroute and area calibration performance of the Loran-C system, no effort was made in the data reduction process to reduce position errors caused by DME bias errors.

On some occasions there was a lack of DME data due to bad DME geometry, high residuals, or reception of signals from less than three DME stations. In these instances no position solution could be derived for the specified data record. This situation occurred about 4% of the records during the enroute segments and 3% of the records during the area calibration flights. These records were dropped from the analysis due to lack of position data.

The overall availability of satisfactory DME derived position during the enroute segments was 96.4%. For the area calibration tests the availability was 97.3%. The two segments with the lowest availability were Medford, OR to Fresno, CA (81.4%) and Lubbock, TX to San Antonio TX (86.5%). Availability on all other segments, including area calibration flights, exceeded 90%.

6.4 STATISTICAL EVALUATION OF CALIBRATION DATA

The time difference errors obtained during the correlation flights were evaluated regarding their relationship with the distance to the calibration point. The errors were fitted statistically, in a least squares sense, to a line of the form

$$e = A + B \cdot d$$

where e is the time difference error estimate
d is the distance from the calibration point
A, B are constants determined by the least squares estimation procedure (Section 4.5)

The constants A and B have some physical significance. The value of A represents the error estimate value at the calibration point. It therefore, represents the difference between the ground calibration and the airborne calibration values. The constant B represents the change in the time difference error per unit of distance from the calibration point.

One additional parameter, the correlation coefficient, was evaluated regarding the degree to which the time difference error data are related to the distance to calibration point. This parameter varies between -1 and +1. A magnitude near 1 indicates a strong relationship exists between the errors and the distance to the calibration point. A correlation value near zero indicates little or no linear relationship between the error and distance (although other relationships may exist). The sign of the correlation coefficient indicates whether the error increases with increasing distance or decreases with increasing distance. The sign of the correlation coefficient is the same as the sign of the constant B. The constants A and B, the correlation coefficients, and the standard error of the estimator for the five calibration locations are presented in Table 6.1.

The statistical data in Table 6.1 clearly indicates a varied pattern of calibration point differences and dependence upon distance to the calibration point regarding the time difference errors. Magnitudes of the estimator equation zero crossing value (the constant A) range from very small values (0.04 μs) up to values over 1 μs (-1.23 μs) indicating some significant differences between ground calibration and airborne calibration values. In the areas that were flown in the calibration tests, these differences were not significant in terms of position error because of favorable geometry in the Loran-C lines of position. In these areas 1 μs error in time difference would produce less than one half mile of position

Table 6.1 Calibration Error Estimation Parameters

Location	Dir.	Status	Constant Term A(μs)	Linear Term B (μs/100 nm)	Correlation Coefficient	Standard Error Se(μs)
London, KY	E/W	Dana-Malone	-1.23	+0.92	.63	.42
	N/S	Dana-Malone	-0.86	-3.46	-.98	.31
	E/W	Dana-Seneca	-0.99	+0.50	.49	.32
	N/S	Dana-Seneca	-1.10	+0.85	.80	.27
Burlington, VT	E/W	Seneca-Caribou	-0.19	+1.22	.61	.68
	N/S	Seneca-Caribou	-0.27	+0.34	.19	.79
	E/W	Seneca-Nantucket	-0.23	+1.27	.69	.57
	N/S	Seneca-Nantucket	+0.11	-1.16	-.76	.45
Muskegon, MI	E/W	Dana-Seneca	+0.59	+2.33	.98	.21
	N/S	Dana-Seneca	+0.45	-0.30	-.34	.35
	E/W	Dana-Baudette	+0.79	+0.80	.72	.32
	N/S	Dana-Baudette	+1.14	+0.45	.58	.27
Fresno, CA	E/W	Fallon-Middletown	-0.37	+0.35	.21	.63
	N/S	Fallon-Middletown	-0.40	+0.71	.50	.45
	E/W	Fallon-Searchlight	-0.74	+1.12	.79	.35
	N/S	Fallon-Searchlight	-0.65	-1.70	-.89	.31
Lafayette, LA	E/W	Malone-Raymondville	+0.04	-1.33	-.88	.29
	N/S	Malone-Raymondville	-0.52	+1.07	.82	.31
	E/W	Malone-Jupiter	-0.06	-0.36	-.86	.09
	N/S	Malone-Jupiter	-0.34	+0.06	.08	.31

error. In areas where poor geometry was evident, these differences between ground and airborne calibration could produce operationally significant position errors during a instrument approach procedure.

In some areas, and some directions of flight, the time difference errors were very strongly related to the distance from the calibration point. Several locations had correlation coefficients with a magnitude exceeding 0.8. Other areas had errors which were not strongly related to distance to the calibration point. In these instances the error was nearly constant throughout the calibration segment.

An evaluation of the "goodness of fit" of the linear estimator can be observed from the standard error column of Table 6.1. The standard error represents the variation of the error about the linear estimation. The standard error values range from a low of 0.09 μs at Lafayette to 0.79 μs at Burlington indicating a good fit at all locations.

In summary, the time difference errors appear to be consistent within the 75 nm radius utilized during the flight test at all test locations. The differences between local calibrations performed at ground level, and those measured in the air using the position reference system are of some concern. Differences of over one microsecond, as observed in this test, would produce operationally significant navigation errors during final approach in areas with poor Loran-C geometry, that is areas with large geometrical dilution of precision (GDOP).

The specific cause of these calibration differences could not be determined from the information obtained during the data collection. A number of possible explanations are presented in the following list:

- local pertibations in the Loran-C grid at the ground calibration point

- survey errors in determining the latitude and longitude coordinates of the ground calibration point

- lags in the airborne measured time difference values caused by filtering and signal smoothing in the Loran-C position determination algorithms

- resolution of the recorded Loran-C position (0.1 minutes of arc) and errors in the scanning DME position reference system

6.5 NAVIGATION COMPUTER ACCURACY

Statistical values for navigation computer error in alongtrack and crosstrack coordinates were evaluated for the seventeen flight segments and five area calibration tests. The errors were characteristically small and produced, to some extent, by filtering and smoothing of the Loran-C guidance data and computer algorithms.

The mean values and standard deviations for the seventeen flight segments are as follows:

	MEAN	STANDARD DEVIATION
Navigation computer crosstrack error	.00 nm	.01 nm
Navigation computer alongtrack error	-.05 nm	.06 nm

The mean values and standard deviations for the five area calibration tests are as follows:

	MEAN	STANDARD DEVIATION
Navigation computer crosstrack error	.00 nm	.01 nm
Navigation computer alongtrack error	-.05 nm	.05 nm

6.6 FLIGHT TECHNICAL ERROR

Flight technical error, based on the deviation signal presented to the pilot, was evaluated for the seventeen enroute segments and the five area calibration tests. The errors were small in terms of deflection values (+5 dots was full scale). The deviation signal presented to the pilot had a high sensitivity of $\pm$1.28 nm full scale (or 3.9 dots per nm). Due to this high sensitivity, even though the deflections appear large, the flight technical error is fairly small in terms of nautical miles.

For the seventeen enroute segments the statistical values were found to be:

	MEAN	STANDARD DEVIATION
Loran-C Flight Technical Error	.02 nm (.08 dots)	.18 nm (.71 dots)

For the five area calibration tests the statistical values were found to be:

	MEAN	STANDARD DEVIATION
Loran-C Flight Technical Error	.03 nm (.12 dots)	.17 nm (.67 dots)

6.7 OVERALL SYSTEM PERFORMANCE

6.7.1 Overall Enroute System Performance

Total system alongtrack and crosstrack error plots for the seventeen enroute flight segment were described and shown in Section 6.1. The alongtrack plots have a smooth (filtered) appearance due to the resolution of the distance to waypoint information and the position filtering resulting from the short (1 sec) update rate of the Loran-C navigator.

The crosstrack data shown in Section 6.1 exhibits a smooth but oscillatory behavior. Since the crosstrack error represents the actual position of the aircraft with respect to desired track, the smooth character of the data is expected. The oscillatory nature of the data is believed to be a result of filtering the crosstrack deviation by the receiver/processor to produce a smooth deviation signal for the pilot or autopilot.

A summary of the statistical errors in terms of the mean, standard deviation, and the mean plus/minus two standard deviation are presented in Table 6.2. Also shown in Table 6.2 are the area navigation accuracy requirements in FAA Advisory Circular 90-45A for non-VOR/DME area navigation systems. It can be observed that the Loran-C crosstrack accuracy experienced during the flight test nearly meets the AC 90-45A requirements, only exeeding it by 0.10 nm. However, the alongtrack error exceeds the requirement by 0.96 nm.

There are various problem areas that are of some concern. These are:

- system outages due to the failure of the system to switch to a new chain/triad combination while being selected enroute.
- large errors due to a lack of reliable navigation during times when the receiver was experiencing poor station geometry.
- increasing errors due to a lack of reliable navigation in areas were station signal strength is low (mid-continent gap).

6.7.2 Overall Area Calibration System Performance

Total system alongtrack and crosstrack error plots for the five area calibration flights are shown in Appendix D. The alongtrack plots have the same filtered appearance as the alongtrack plots for the enroute segments. Again, this is due to the resolution of the Loran-C system used.

The crosstrack data shown in Appendix D exhibits the same smooth but oscillatory behavior as the crosstrack data for the enroute segments. This is due to the same characteristics discussed in the previous section.

A summary of the error statistics in terms of the mean, standard deviation, and the mean plus/minus two standard deviations are presented in Table 6.3 for each of the five area calibration flights, while Table 6.4 depicts the aggregate error statistics for all calibration flights. Also shown in Tables 6.3 and 6.4 and in Figure 6.23 are the area navigation accuracy requirements for non-precision approach in FAA Advisory Circular 90-45A for non-VOR/DME area navigation systems. It can be observed that, with one exception, the Loran-C alongtrack and crosstrack accuracy experienced during the area calibration test meet or very closely meet the AC 90-45A criteria for non-precision approach. The exception is the total system crosstrack error at Burlington, VT. This error exceeds the requirement by 0.24 nm.

A problem area of great concern was the cycle error experienced in the London, KY area calibration test. As noted in Table 6.3, these data were deleted from the London error statistics. These errors would place the accuracy of the Loran-C system well outside the non-precision approach accuracy limits of AC 90-45A.

Table 6.2 Loran-C Enroute Accuracy Aggregation

Error Quantity	Mean ($\overline{X}$)	Standard Deviation (σ)	$\overline{X}-2\sigma$	$\overline{X}+2\sigma$	AC90-45A Requirements	$\overline{X}-2\sigma$ Δ	$\overline{X}+2\sigma$ Δ
Northing Error	-0.35	1.14	-2.63	1.93			
Easting Error	0.06	1.08	-2.10	2.22			
DRMS	1.20	1.08	--	--			
TSCT	-0.42	1.09	-2.60	1.76	2.50	-0.10	0.74
TSAT	-0.38	1.04	-2.46	1.70	1.50	-0.96	-0.20
NSCT	-0.49	1.08	-2.65	1.67			
NSAT	-0.33	1.04	-2.41	1.75			
NCCT	0.00	0.01	-0.02	0.02			
NCAT	-0.05	0.06	-0.17	0.07			
FTE	0.03	0.17	-0.31	0.37			
TD-A	-0.61	10.56	-21.73	20.51			
TD-B	1.56	8.90	-16.24	19.36			
CTD	0.07	0.18	-0.29	0.43			

/NOTE/ Based on 8233 Data Points
All values are in nautical miles

DRMS - Root Mean Square Radial Error
TSCT - Total System Crosstrack
TSAT - Total System Alongtrack
NSCT - Navigation System Crosstrack
NSAT - Navigation System Alongtrack
NCCT - Navigation Computer Crosstrack
NCAT - Navigation Computer Alongtrack
FTE - Flight Technical Error
TD-A - Time-Difference A
TD-B - Time-Difference B
CTD - Crosstrack Deviation

Table 6.3 Loran-C Area Calibration Accuracy

London Area Calibration*

Error Quantity	Mean ($\bar{X}$)	Standard Deviation (σ)	$\bar{X}-2\sigma$	$\bar{X}+2\sigma$	AC90-45A Requirements	$\bar{X}-2\sigma$ Δ	$\bar{X}+2\sigma$ Δ
DRMS	0.21	0.05	--	--	--	--	--
TSCT	0.05	0.21	-0.37	0.47	$\pm$0.60	0.23	0.13
TSAT	-0.05	0.15	-0.35	0.25	$\pm$0.30	-0.05	0.05
FTE	0.01	0.17	0.35	0.33	--	--	--
TD-A	-1.00	1.37	-3.74	1.74	--	--	--
TD-B	-1.09	0.43	-1.95	-0.23	--	--	--

*Data from portions of the flight with cycle errors have been deleted

Burlington Area Calibration

Error Quantity	Mean ($\bar{X}$)	Standard Deviation (σ)	$\bar{X}-2\sigma$	$\bar{X}+2\sigma$	AC90-45A Requirements	$\bar{X}-2\sigma$ Δ	$\bar{X}+2\sigma$ Δ
DRMS	0.13	0.06	--	--	--	--	--
TSCT	0.14	0.35	-0.56	0.84	$\pm$0.60	0.04	-0.24
TSAT	-0.01	0.09	-0.19	0.17	$\pm$0.30	0.11	0.13
FTE	0.08	0.25	-0.42	0.58	--	--	--
TD-A	0.06	0.87	-1.68	1.80	--	--	--
TD-B	0.47	0.80	-1.13	2.07	--	--	--

Muskegon Area Calibration

Error Quantity	Mean ($\bar{X}$)	Standard Deviation (σ)	$\bar{X}-2\sigma$	$\bar{X}+2\sigma$	AC90-45A Requirements	$\bar{X}-2\sigma$ Δ	$\bar{X}+2\sigma$ Δ
DRMS	0.13	0.05	--	--	--	--	--
TSCT	0.04	0.17	-0.30	0.38	$\pm$0.60	0.30	0.22
TSAT	-0.04	0.10	-0.24	0.16	$\pm$0.30	0.06	0.14
FTE	0.03	0.12	-0.21	0.27	--	--	--
TD-A	0.58	0.87	-1.16	2.32	--	--	--
TD-B	0.92	0.51	-0.10	1.94	--	--	--

Fresno Area Calibration

Error Quantity	Mean ($\bar{X}$)	Standard Deviation (σ)	$\bar{X}-2\sigma$	$\bar{X}+2\sigma$	AC90-45A Requirements	$\bar{X}-2\sigma$ Δ	$\bar{X}+2\sigma$ Δ
DRMS	0.17	0.09	--	--	--	--	--
TSCT	0.06	0.19	-0.32	0.44	$\pm$0.60	0.28	0.16
TSAT	-0.04	0.17	-0.38	0.30	$\pm$0.30	-0.08	0.00
FTE	0.01	0.17	-0.33	0.35	--	--	--
TD-A	-0.55	0.64	-1.83	0.73	--	--	--
TD-B	-0.60	0.86	-2.32	1.12	--	--	--

Lafayette Area Calibration

Error Quantity	Mean ($\bar{X}$)	Standard Deviation (σ)	$\bar{X}-2\sigma$	$\bar{X}+2\sigma$	AC90-45A Requirements	$\bar{X}-2\sigma$ Δ	$\bar{X}+2\sigma$ Δ
DRMS	0.13	0.11	--	--	--	--	--
TSCT	0.03	0.15	0.27	0.33	$\pm$0.60	0.33	0.27
TSAT	-0.02	0.15	-0.32	0.28	$\pm$0.30	-0.02	0.02
FTE	0.01	0.12	-0.23	0.25	--	--	--
TD-A	-0.21	0.66	-1.53	1.11	--	--	--
TD-B	-0.20	0.30	-0.80	0.40	--	--	--

/NOTE/ All values are in nautical miles.

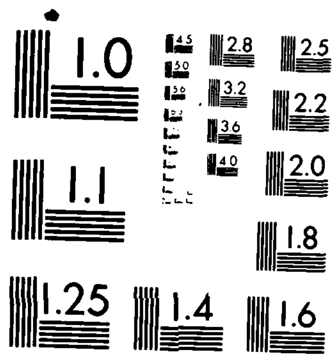
AD-A139 871 CONUS LORAN-C ERROR BUDGET: FLIGHT TEST(U) SYSTEMS CONTROL TECHNOLOGY INC WEST PALM BEACH FL L D KING ET AL DEC 83 DOT/FAA/PM-83/32 2/2

UNCLASSIFIED DTFA01-83-C-20041 F/G 17/7 NL

END

FILMED

DTIC



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963-A

Table 6.4 Loran-C Area Calibration Accuracy Aggregation

Error Quantity	Mean ($\overline{X}$)	Standard Deviation (σ)	$\overline{X}-2\sigma$	$\overline{X}+2\sigma$	AC90-45A Requirements	$\overline{X}-2\sigma$ Δ	$\overline{X}+2\sigma$ Δ
DRMS	0.15	0.08	--	--	--	--	--
TSCT	0.06	0.23	-0.40	0.52	$\pm$0.60	0.20	0.08
TSAT	-0.03	0.14	-0.31	0.25	$\pm$0.30	-0.01	0.05
FTE	0.02	0.18	-0.34	0.38	--	--	--
TD-A	-0.20	1.04	-2.28	1.88	--	--	--
TD-B	-0.07	0.94	-1.95	1.81	--	--	--

/NOTE/ All values are in nautical miles

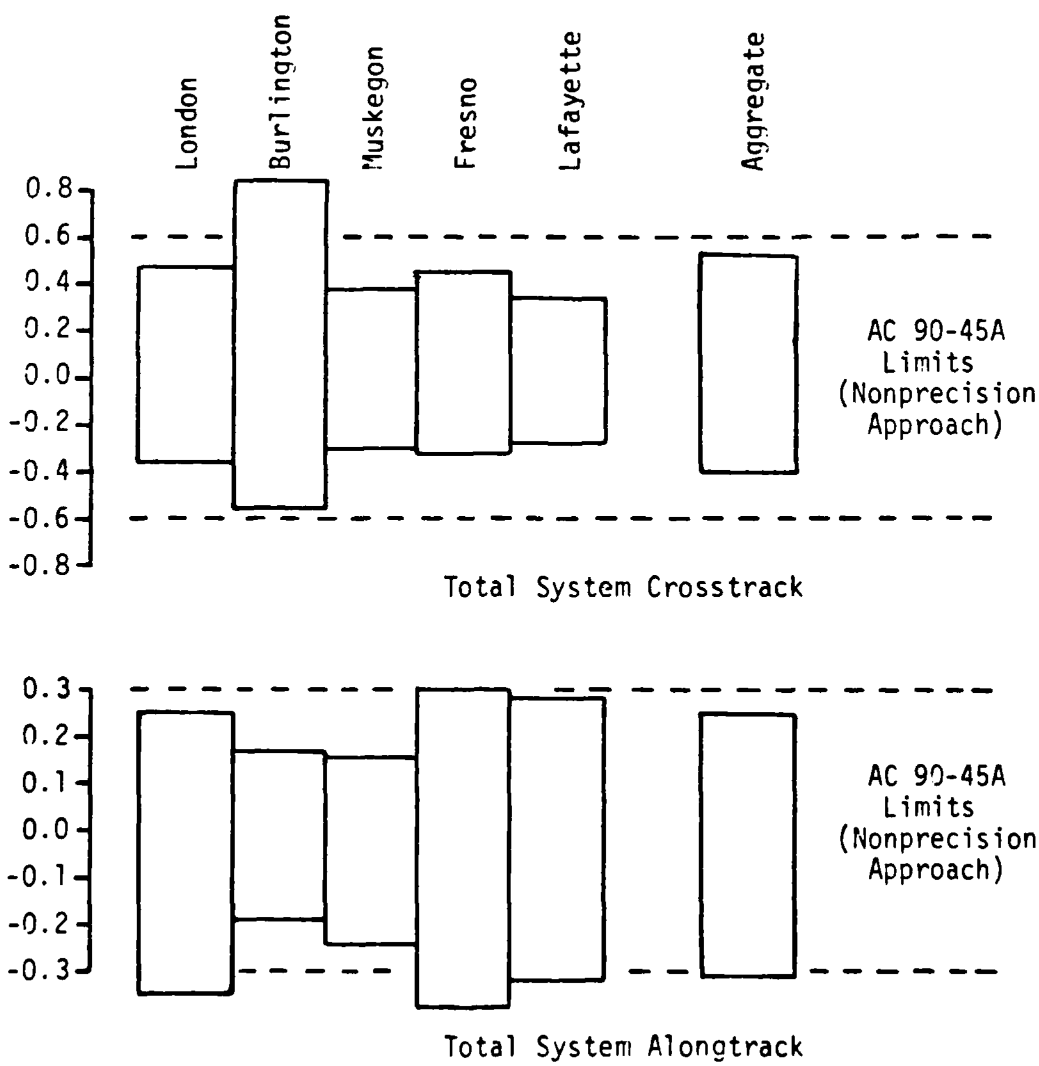


Figure 6.29 Mean $\pm 2\sigma$ Errors for the Calibration Flights

7.0 CONCLUSIONS

The following conclusions were developed from the flight test of the Teledyne TDL-711 Loran-C navigation system in CONUS:

- During the enroute phase of the flight test total system crosstrack errors were slightly larger (0.10 nm) than current enroute accuracy standards contained in the Federal Aviation Advisory Circular 90-45A for non-VOR/DME systems. Total system alongtrack errors were also larger (0.96 nm) than the current standard. These data were measured in areas of both good and poor Loran-C coverage areas as defined by the U.S. Coast Guard.

- During the calibration flights in which the Loran-C position was corrected at a known ground reference point, total system alongtrack and crosstrack errors were better than AC 90-45A enroute and terminal accuracy standards.

- The major source of Loran-C system error is propagation model error (time difference error). This error is converted to positional and navigational errors by the coordinate conversion procedure.

- Flight technical errors of about 0.4 nm (2σ) were measured on both enroute and calibration flights.

- Alongtrack and crosstrack computational errors were negligible throughout the test.

- Cycle errors were observed on three separate occasions during this test. Two of these occurrences happened in good Loran-C signal coverage areas near London, KY and Lafayette, LA. One occurrence happened in a poor signal coverage area near Albuquerque, NM. The flight crew was not aware of these errors during the test as the navigation system indicated normal operation.

- The navigation system produced very large errors in the baseline extension areas. These errors were recognized by the flight crew by comparing Loran-C position with information from VOR/DME receivers. In many instances, the Loran-C navigation system did not produce any indication to the crew that its information was not accurate during operations near the baseline extensions.

- Momentary system outages occurred during thunderstorm and rain activity. These outages are believed to have been caused by precipitation static. The outages were not significant in most instances.

- System outages occurred during times when Loran-C transmitters were experiencing momentary or longer outages. In one instance, a momentary outage on the Dana station appears to have triggered a cycle error in the navigator.

REFERENCES

1. Anonymous, "TDL-711 Loran Micro Navigator - Operations Manual", Offshore Navigation, Inc., July, 1978.

2. Anonymous, "Specification of the Transmitted Loran-C Signal", Department of Transportation, United States Coast Guard, July 1981.

3. Roland, W.F., editor, "Radionavigation Journal 1978", Wild Goose Association, Inc., Acton, Massachusetts, 1978.

4. Scalise, T.E., Bolz, E.H., McConkey, E.D., "West Coast Loran-C Flight Test", Systems Control, Inc. (Vt.), Champlain Technology Industries Division for the Federal Aviation Administration Systems Research and Development Service, FAA-RD-80-28, March 1980.

5. King, L.D. and McConkey, E.D., "Alaska Loran-C Flight Test Evaluation", Draft Report, Prepared by Systems Control Technology, Inc., West Palm Beach, Florida, prepared for Department of Transportation, Federal Aviation Administration, Washington, D.C., January 1983.

APPENDIX A

AIRBORNE DATA LOGICAL RECORD FORMAT

AIRBORNE DATA LOGICAL RECORD FORMAT

OFFSET	BYTES	DESCRIPTION	SOURCE
0	6	Time code -- hundredths of seconds, seconds minutes, hours, days (2)	
6	4	Update flags: byte 1: bits 0-2 = # DME's, bit 3 = End of Data bit 6 = LORAN, bit 7 = OMEGA byte 2: bits 0-7 = packets 1-8 of OMEGA byte 3: bits 0-7 = packets 9-17 of OMEGA byte 4: bit 1 = packet 18 of OMEGA	
10	2	VOR bearing	VOR
12	2	DME distance	A/D
14	2	Distance to WP	A/D
16	2	A/C Heading	S/D
18	2	Airspeed	A/D
20	2	Altimeter reference	A/D
22	2	Altimeter signal	A/D
24	2	Omni-bearing selector	S/D
26	1	CDI #1 signal	A/D
27	1	CDI #1 flag	A/D
28	1	CDI #2 signal	A/D
29	1	CDI #2 flag	A/D
30	1	DME #1 time tag	
31	2	DME #1 frequency	DME
33	3	DME #1 distance	DME
36	1	DME #2 time tag	
37	2	DME #2 frequency	DME
39	3	DME #2 distance	DME
42	1	DME #3 time tag	
43	2	DME #3 frequency	DME
45	3	DME #3 distance	DME
48	1	DME #4 time tag	
49	2	DME #4 frequency	DME

OFFSET	BYTES	DESCRIPTION	SOURCE
51	3	DME #4 distance	DME
54	1	DME #5 time tag	
55	2	DME #5 frequency	DME
57	3	DME #5 distance	DME
60	1	DME #6 time tag	
61	2	DME #6 frequency	DME
63	3	DME #6 distance	DME
66	1	DME #7 time tag	
67	2	DME #7 frequency	DME
69	3	DME #7 distance	DME

LORAN SECTION

SOURCE = LORAN

OFFSET	BYTES	DESCRIPTION
72	2	LORAN time tag. 2's complement delta time relative to time code of record
74	1	CDU annunciators xxLRNSEW (1-off)
75	3	LH display to CDU (1st byte leftmost)
78	3	RH display to CDU (1st byte leftmost)
81	1	From/To display to CDU
82	1	Decimal points & lamps to CDU: bit 0 = hold 1 = legchange (0=off) 2 = offset 3 = all other dec. points 4 = RH display dec. pnt #5 5 = RH display dec. pnt #3 (0=on) 6 = LH display dec. pnt #5 7 = LH display dec. pnt #3
83	2	Distance in BCD. 4 digits as displayed on CDU. LSD = tenths of miles. (1st byte MSD)
85	2	Ground speed in decimal as displayed on CDU. LSD = knots. (1st byte MSD)
87	1	CDU switch status: bits 0-2 = octal selector: 0 = OFST/VAR 1 = TKE/TK 2 = XTK/DTK 3 = ETE/GS 4 = DIS/BRG 5 = PRES. POSN. 6 = WPT bit 3 = TD/LL (1=TD) bit 4 = area (1=area 2) bit 5 = test (1=test)
88	1	ETE (estimated time enroute) flag (OFFH = <300 mins)
89	1	Waypoints: MSD = 'from' waypoint number (OFH = blank), LSD = 'to' WP #
90	1	Hold flag: OFFH = hold
91	1	CDI scale factor (full scale deflection = 1.28/r nautical miles, for r = 00 to 07, where r = scale factor)
92	4	Binary time difference A. 16th bit = 5 microseconds

OFFSET	BYTES	DESCRIPTION	SOURCE = LORAN
96	4	Time difference B, same format	
100	4	Delta latitude. Two's complement binary difference between actual lat. & base lat. (actual = base + delta). 9th bit (MSB of 2nd byte) = 1 degree	
104	4	Delta longitude, same format	
108	4	Cross track error. 24th bit (LSB of 3rd byte) = 60 ft.	
112	4	Base latitude. 9th bit (MSB of 2nd byte) = 1 degree. Updated only every 10-20 seconds. South = negative (2's compl.)	
116	4	Base longitude, same format	
120	1	Track status. 0 = track, 1 = not track: bit 1 = secondary C bit 2 = secondary B bit 3 = secondary A bit 4 = master	
121	1	Master SNR. 0 - 070H	
122	1	Secondary A SNR	
123	1	Secondary B SNR	
124	1	Blink status. 1 = blink for bit positions as for track status	
125	1	Enveloping status bit 6 = master lost (1 = lost) 5 = master in search (1 = search) 4 = master in enveloping state (fine envelope, track or float) 3 = secondary A in enveloping state 2 = secondary B in enveloping state 1 = secondary C in enveloping state	
126	1	Secondary C SNR	
127	1	Envelope # for master	
128	1	Envelope # for secondary A	
129	1	Envelope # for secondary B	
130	1	Envelope # for secondary C	
131	5	"From" WP latitude in radians Floating point format, with 8-bit signed exponent with complemented sign bit, followed by a 32 bit signed 2's complement mantissa with an assumed binary point between the 2nd & 3rd most significant bits (MSB = sign bit)	

OFFSET	BYTES	DESCRIPTION	SOURCE = LORAN
		and hence a normalized value between 1 & 2 (e.g. unity is represented by 80 40 00 00 00 in hex). South negative.	
136	5	"From" WP longitude, same format, West = neg.	
141	5	"To" WP latitude, same format	
146	5	"To" WP longitude, same format	
151	4	Offset in BCD. 1st byte = OFFH for left, 00 for right. 2nd to 4th bytes BCD with OFH representing a blank	
155	4	Mag Var. same format, 1st byte = OFFH for west.	
159	1	Display blanking flag. Used to indicate blanking of invalid displays when no valid leg is inserted	
160	1	Triad in use: 00 = A, B, C 01 = M, B, C 02 = M, A, C 03 = M, A, B	
161	1	Track flag. OFFH = triad in track.	
162	1	Number of GRI's per CDU update. (see p. 13 of IDS programming manual)	

APPENDIX B

TDL-711 RDU DATA FORMATTING

RDU Data Formatting

FAA OUTPUT - SIGNIFICANCE AND SCALING OF WORDS

Note: Least significant bit (designated b0) is output first in all words.

WORD	QUANTITY
1	Identifier = AA
2	CDU annunicators (North, South, East, West) b0 (LSB) = W b1 = E b2 = S 1 = OFF b3 = N 0 = ON b4 = R b5 = L
3-5	LH display to CDU (wd3 = LEFT MOST DIGITS)
6-8	RH display to CDU (wd6 = LEFT MOST DIGITS)
9	From/To display to CDU
10	Decimal points and lamps to CDU b0 = Hold b1 = Legchange b2 = Offset b3 = All other decimal points (0=ON) b4 = RH display decimal point #5 (0=ON) b5 = RH display decimal point #3 (0=ON) b6 = LH display decimal point #5 (0=ON) b7 = LH display decimal point #3 (0=ON)
11-12	Distance in BCD. 4 digits as displayed on CDU. LSD = tenths of a n mile (WD11 = most significant digits)
13-14	Ground speed in decimal as displayed on CDU. LSD = knots. (WD13 = most significant digits)
15	Unused
16	CDU switch status b2, b1, b0 = octal selector switch position: 0 = OFST/VAR 1 = TKE/TK 2 = XTK/DTK 3 = ETE/GS 4 = DIS/BRG 5 = PRES. POSN. 6 = WPT b3 = TD/LL (1=TD) b4 = Area (1=Area 2) b5 = Test (1=Test)

WORD	QUANTITY
17	ETE Flag (FF = <300 mins) (ETE = Estimated Time Enroute)
18	Waypoints MSD = 'From' waypoint number (F = blank) LSD = 'To' waypoint number
19-20	No significance (Fast loop indirect address)
21	Hold flag. FF = Hold
22	CDI Scale Factor. (Full Scale deflection = 1.28/r nautical miles, for r = 00 to 07, where r = scale factor)
23-26	Binary Time difference A. Sixteenth bit (LSB of second byte) = 5 μ s. Total of 32 bits of 4 bytes.
27-30	Time difference B. Same format as TDA.
31-38	Base time differences A & B used in slow loop coordinate conversion. Format as for TDA.
39-46	Delta TDA & TDB. Difference between base TD and actual TD. (Scaling same as Wds 23-26)
47-50	Delta Latitude. Two's complement binary difference between actual Latitude and base latitude (Actual = Base + Delta). 32 bits or 4 bytes. 9th bit (MSB of second byte) is scaled as 1 degree.
51-54	Delta Longitude. As above, but for longitude.
55-58	Base cross track error. Slow loop output used in calculation of cross track error. Same format and scaling as words 67-70.
59-66	Cross track gradients with respect to altitude and longitude. 32 bits. Scaled as bit 17 (MSBA byte 3) = 60 ft/deg. Used in calculating of cross track error.
67-70	Cross track error. 32 bits. 24th bit (LSB of byte 3) Scaled as 60 ft.
71-74	Base Latitude. 32 bits. Ninth bit (MSB of byte 2) Scaled as 1 degree. Updated only every 10-20 secs. South = negative (2's complement)
75-78	Base Longitude. Format as Latitude. West = negative
79	Track Status. 0 = Track, 1 = not track (b0 = LSB) b4 = Master b3 = Secondary A b2 = Secondary B b1 = Secondary C
80	Master SNR. S bit binary number, HEX value = 0-70
81	Secondary A SNR
82	Secondary B SNR
83	Blink Status 1 = Blink, bit positions as for track status.

WORD	QUANTITY
84	Enveloping Status b6 = Master Lost (1=lost) b5 = Master in search (1=search) b4 = Master in enveloping state (Fine envelope, track or float) b3 = Secondary A in envelope state b2 = Secondary B in envelope state b1 = Secondary C in envelope state
85	Secondary C SNR
86	Unused
87	Track Status as for 79
88	Envelope number for master. Binary number with value from 00 to FF in hex.
89	Envelope number for secondary A
90	Envelope number for Secondary B
91	Blink status as 83
92	Enveloping status as 84
93	Envelope number for secondary C
94	Unused
95-99	"From" Waypoint Latitude in radians. This is in a 5 byte floating point format, having an 8 bit signed exponent with complemented sign bit, followed by a 32 bit signed 2'S complement mantissa with an assumed binary point between the 2nd and 3rd most significant bits (MSB=sign bit) and hence a normalized value between 1&2 (e.g. unity is represented by 80 40 00 00 00 in hex) as before South is negative.
100-104	"From" Waypoint Longitude in same 5 byte floating point format as Latitude. West is negative.
105-109	"To" Waypoint Latitude in floating point radians.
110-114	Sine of "To" Latitude in floating point format.
115-119	Cosine of "To" Latitude in floating point format.
120-124	"To" Waypoint Longitude (in floating point radians)
125-129	Bearing of leg between "To" and "From" waypoints (in floating point radians)
130-133	Waypoint 0 Latitude. 4 bytes, first byte = FF for South, 00 for North, bytes 2, 3 & 4 in BCD format with a blank represented by hex F.
134-137	Waypoint 0 Longitude - Format as above with FF in first byte for West Longitude.
138-141	Waypoint 0 time difference A - 4 bytes, first is unused (normally FF), bytes 2-4 in BCD format.

WORD	QUANTITY
142-145	Waypoint 0 time difference B in same format.
146-149	Offset in same BCD format as 130-133. Left is negative (FF).
150-153	Mag Var in same format. West is negative (FF).
154	Display blanking flag. Used to indicate banking of invalid displays when no valid leg is inserted.
155	Triad in Use (00=A, B, C. 01=M, B, C. 02=M, A, C. 03=M, A, B).
156	Track flag. FF=Triad in track.
157	Number of GRI's per CDI update. (see P13 of IDS programming manual).

APPENDIX C

DATA PROCESSING ALGORITHMS

This appendix contains data processing equations that were used to 1) determine the aircraft position from DME measurements, and 2) compute system accuracy parameters. The equations for the minimum mean square DME residual error and the DRMS position error estimate are developed in the appendix. Equations for great circle distance and bearing over a spherical earth are also included in the section. These equations were obtained from navigational text.

C.1 MINIMIZATION OF THE MEAN SQUARED RESIDUAL ERROR

Figure A.1 presents the geometric configuration of the residual error problem. Assume that the current estimate of the aircraft's position is at P_1. Also assume that after correction the estimated position of the aircraft is at P_2. The position P2 is east of P_1 by an amount ΔE and north of P_1 by an amount of ΔN. The computed distance from the current position is D_c and the measured distance from the DME is D_m. The DME error is then expressed as

$$\Delta D_i = D_m - D_c = \Delta E \sin \beta_i + \Delta N \cos \beta_i + \text{Residual}_i$$

where β_i is the azimuth from the i th DME station to the estimated aircraft position P_1 as measured at P_1, and Residual_i is any remaining error after the shift from P_1 to P_2 is made.

Solving for Residual_i

$$\text{Residual}_i = R_i = \Delta D_i - \Delta E \sin \beta_i - \Delta N \cos \beta_i$$

and squaring

$$\begin{aligned} R_i^2 = {} & \Delta D_i^2 + \Delta E^2 \sin^2 \beta_i + \Delta N^2 \cos^2 \beta_i \\ & - 2 \Delta D_i \Delta E \sin \beta_i - 2\Delta D_i \Delta N \cos \beta_i \\ & + 2 \Delta E \Delta N \sin \beta_i \cos \beta_i \end{aligned}$$

The mean value of the squared residual errors is

$$\begin{aligned} \Sigma R_i^2 = {} & \Sigma \Delta D_i^2 + \Delta E^2 \Sigma \sin \beta_i^2 + \Delta N^2 \Sigma \cos^2 \beta_i \\ & - 2\Delta E \Sigma \Delta D_i \sin \beta_i - 2\Delta N \Sigma \Delta D_i \cos \beta_i \\ & + 2 \Delta E \Delta N \Sigma \sin \beta_i \cos \beta_i \end{aligned}$$

where Σ represents the summation over the number of available DME stations.

The minimumization is performed by extracting the partial derivatives of the mean squared residual error with respect to the unknowns ΔE and ΔN and setting these derivatives to zero.

$$\frac{\partial \Sigma R_i^2}{\partial E} = 0 = 2 \Delta E \Sigma \sin \beta_i^2 - 2 \Sigma \Delta D_i \sin \beta_i + 2 \Delta N \Delta \sin \beta_i \cos \beta_i$$

$$\frac{\partial \Sigma R_i}{\partial N} = 0 = 2 \Delta N \Sigma \cos^2 \beta_i - 2 \Sigma \Delta D_i \cos \beta_i + 2 \Delta E \Sigma \sin \beta_i \cos \beta_i \cdot$$

Collecting terms

$$\begin{bmatrix} \Sigma \Delta D_i \sin \beta_i \\ \Sigma \Delta D_i \cos \beta_i \end{bmatrix} = \left[\begin{array}{c:c} \Sigma \sin^2 \beta_i & \Sigma \sin \beta_i \cos \beta_i \\ \Sigma \sin \beta_i \cos \beta_i & \Sigma \cos^2 \beta_i \end{array}\right] \begin{bmatrix} \Delta E \\ \Delta N \end{bmatrix} \qquad \text{(Equation A.1)}$$

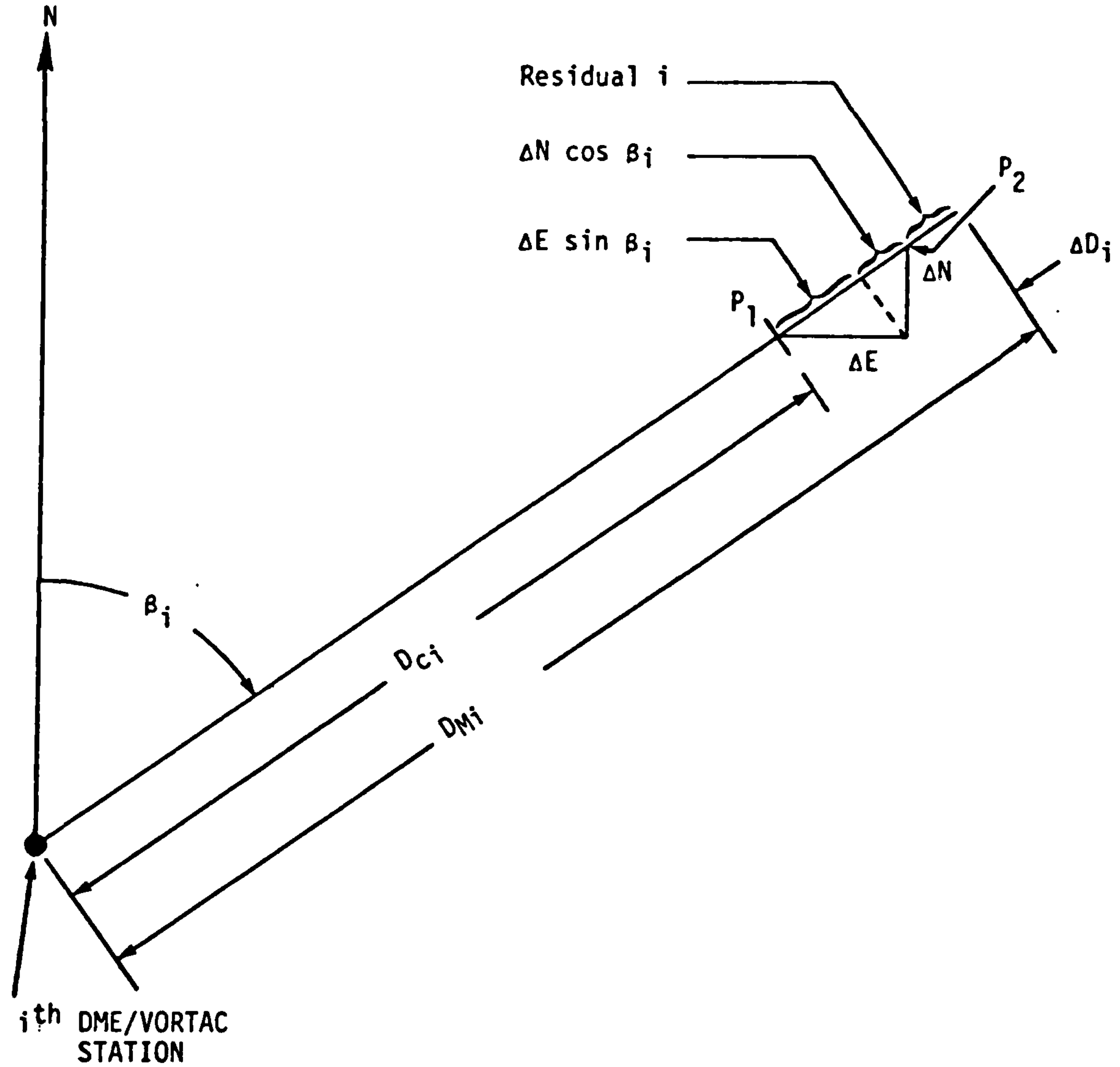


Figure C.1 Residual Error Geometry

Solving for ΔE and ΔN

$$\Delta E = \frac{(\Sigma \Delta D_i \sin \beta_i)(\Sigma \cos^2 \beta_i) - (\Delta \Sigma D_i \cos \beta_i)(\Sigma \sin \beta_i \cos \beta_i)}{(\Sigma \cos^2 \beta_i)(\Sigma \sin^2 \beta_i) - (\Sigma \sin \beta_i \cos \beta_i)^2}$$

$$\Delta N = \frac{(\Sigma D_i \cos \beta_i)(\Sigma \sin^2 \beta_i) - (\Sigma \Delta D_i \sin \beta_i)(\Sigma \sin \beta_i \cos \beta_i)}{(\Sigma \cos^2 \beta_i)(\Sigma \sin^2 \beta_i) - (\Sigma \sin \beta_i \cos \beta_i)^2}$$

C.2 EVALUATION OF THE ROOT MEAN SQUARE POSITION ERROR (D_{RMS})

Equation A.1 can be utilized to develop the root mean square position error value which is the familiar D_{RMS} statistic. Expressed in matrix form Equation A.1 can be written

$$[\Delta D] = [A][\Delta P]$$

where $[\Delta D] = \begin{bmatrix} \Sigma \Delta D_i \sin \beta_i \\ \Sigma \Delta D_i \cos \beta_i \end{bmatrix}$ a 2x1 matrix

$[A] = \left[\begin{array}{c:c} \Sigma \sin^2 \beta_i & \Sigma \sin \beta_i \cos \beta_i \\ \Sigma \sin \beta_i \Sigma \cos \beta_i & \Sigma \cos^2 \beta_i \end{array}\right]$ a 2x2 matrix

$[\Delta P] = \begin{bmatrix} \Delta E \\ \Delta N \end{bmatrix}$ a 2x1 matrix

The solution for $[\Delta P]$ can be written

$$[\Delta P] = [A^{-1}][\Sigma D]$$

where $[A^{-1}]$ is the inverse of A

The covarience matrix can be evaluated by multiplying $[\Delta P]$ by its transpose, $[\Delta P]^T$, and averaging the result.

$$[\Delta P]^T = [A^{-1}][\Delta D]^T = [\Delta D]^T [A^{-1}]^T = [\Delta D]^T [A^{-1}]$$

Since A is symmetrical $[A]^T = [A]$ and $[A^{-1}]^T = [A^{-1}]$.

$$[\text{cov } \Delta P] = E\left\{[\Delta P][\Delta P]^T\right\} = E\left\{[A^{-1}][\Delta D][\Delta D][A^{-1}]\right\}$$

where $E\{\ \}$ represents averaging.

Examining the right most term, the quantities in the A matrix are deterministic and can be brought outside the averaging process. This term then becomes

$$[\text{cov } \Delta P] = [A^{-1}]\left\{[\Delta D][\Delta D]^T\right\}[A^{-1}]$$

Expanding the averaging term

$$E\left\{[\Delta D][\Delta D]^T\right\} = \begin{bmatrix} E\left\{\Sigma \Delta D_i \sin \beta_i \Sigma \Delta D_j \sin \beta_j\right\} & E\left\{\Sigma \Delta D_i \sin \beta_i \Sigma \Delta D_j \cos \beta_i\right\} \\ E\left\{\Sigma \Delta D_i \cos \beta_i \Sigma \Delta D_j \sin \beta_j\right\} & E\left\{\Sigma \Delta D_i \cos \beta_i \Sigma \Delta D_j \cos \beta_j\right\} \end{bmatrix}$$

(Equation A.2)

The averaging process depends upon the statistical character of the random variables ΔD_i and ΔD_j which are the errors in the DME measurements. These errors are of two types, those associated with the station and those associated with the receiver. For this analysis it is assumed that station errors are much geater than receiver errors. Furthermore, it is assumed that the ensemble of station errors have zero mean error and a standard deviation of σ_D and the station errors are independant of each other, which implies that the correlation between stations, ρ_{ij} is zero for $i \neq j$. Under these assumptions, equation A.2 becomes

$$E \left\{ [\Delta D] [\Delta D]^T \right\} = \sigma_D^2 \left[\begin{array}{c:c} \Sigma \sin^2 \beta_i & \Sigma \sin \beta_i \cos \beta_i \\ \Sigma \sin \beta_i \Sigma \cos \beta_i & \Sigma \cos^2 \beta_i \end{array} \right]$$

$$= \sigma_D^2 [A]$$

The matrix on the right is the matrix [A]. Therefore, the convarience matrix becomes

$$[\text{cov } \Delta P] = \sigma_D^2 [A^{-1}] [A] [A^{-1}] = \sigma_D^2 [A^{-1}]$$

or expanding

$$\left[\begin{array}{c:c} \sigma_E^2 & \rho_{EN} \sigma_E \sigma_N \\ \rho_{EN} \sigma_E \sigma_N & \sigma_N^2 \end{array} \right] = \frac{\sigma_D^2 \left[\begin{array}{cc} \Sigma \cos^2 \beta_i & - \Sigma \sin \beta_i \Sigma \cos \beta_i \\ -\Delta \sin \beta_i \cos \beta_i & \Sigma \sin^2 \beta_i \end{array} \right]}{\Sigma \sin^2 \beta_i \ \Sigma \cos^2 \beta_i - (\Sigma \sin \beta_i \cos \beta_i)^2}$$

The trace of the matrix on the left is recognized as the square of the D_{RMS} statistic. Therefore,

$$D^2_{RMS} = \frac{\sigma_D^2 (\Sigma \cos^2 \beta_i + \Sigma \sin^2 \beta_i)}{\Sigma \sin^2 \beta_i \ \Sigma \cos^2 \beta i - (\Sigma \sin \beta_i \cos \beta_i)^2}$$

which, upon inspection, reduces to

$$D^2_{RMS} = \frac{M \sigma_D^2}{\sum_{i=1}^{M} \sum_{j=i+1}^{M} \sin^2 (\beta_i - \beta_j)}$$

where M is the number of DME stations.

C.3 GREAT CIRCLE DISTANCE AND COURSE EQUATIONS

The following equations were used to compute great circle distance (D) and course (ϕ) from an origin at P_1 and a destination at P_2 over a spherically shaped earth:

$$D = 60 * \frac{180}{\pi} * \theta$$

$$\theta = 2\sin^{-1}\sqrt{\sin^2\frac{(\beta_1 - \beta_2)}{2} + \cos\beta_1 \cos\beta_2 \sin^2\frac{\Delta\lambda}{2}}$$

where θ is the central angle at the center of the earth β_1, β_2 are the latitude coordinates of P_1 and P_2 and $\Delta\lambda$ is the difference in longitude $(\lambda_2 - \lambda_1)$

$$\psi = \tan^{-1}\left(\frac{\sin A}{\cos A}\right)$$

where $\sin A = \dfrac{\cos\beta_2 \sin\Delta\lambda}{\sin\theta}$

$$\cos A = \frac{\sin\beta_2 - \sin\beta_1 \cos\theta}{\cos\beta_1 \sin\theta}$$

where ψ is the course at P_1.

The sign convention for ψ is shown in Figure A.2

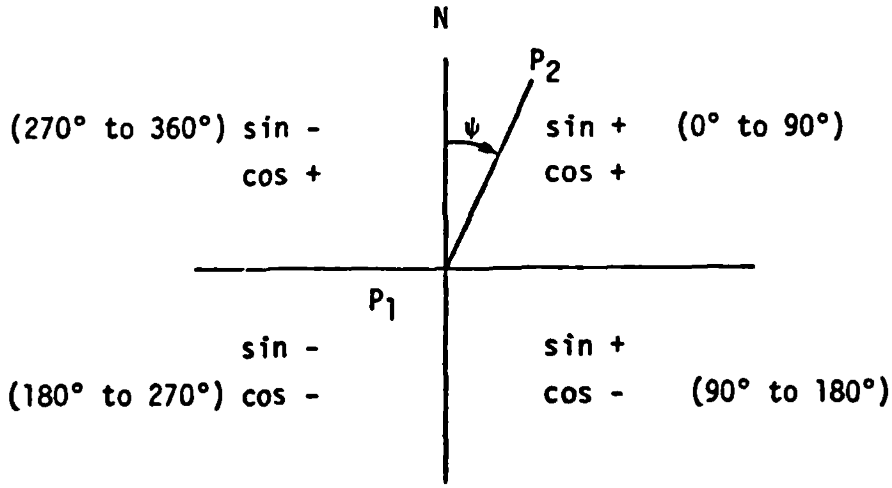
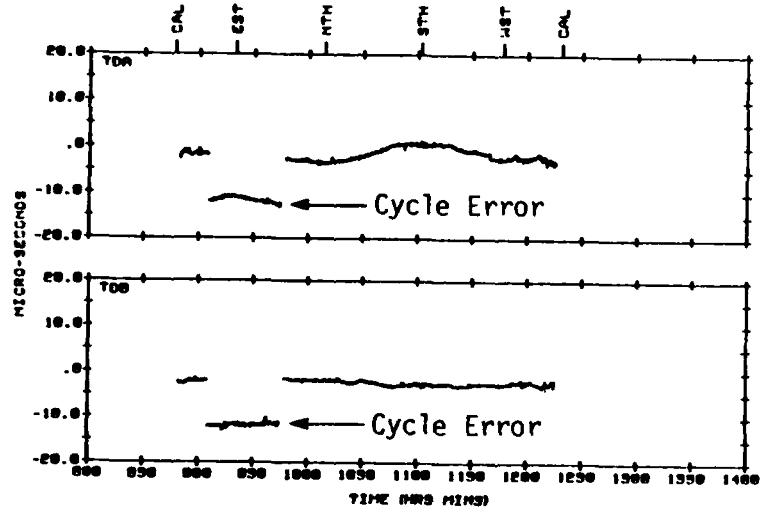


Figure C.2 Sign Convention for Course Computation

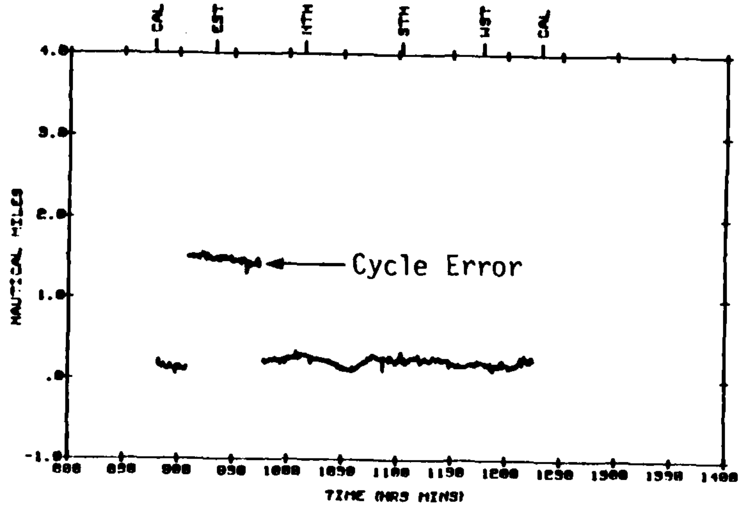
APPENDIX D

SYSTEM ERRORS FOR THE CALIBRATION FLIGHTS

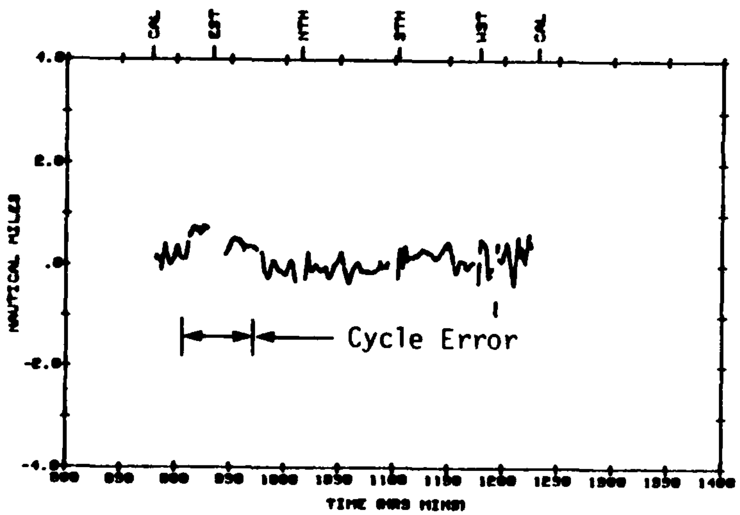
This Appendix contains plots of the system errors experienced at each of the area calibration locations. The errors are plotted as a function of time of day at the departure airport. The five plots on each page depict time difference errors, DRMS position error, total system crosstrack error and total system alongtrack error. The nominal flight pattern is depicted in Section 2.4.2.



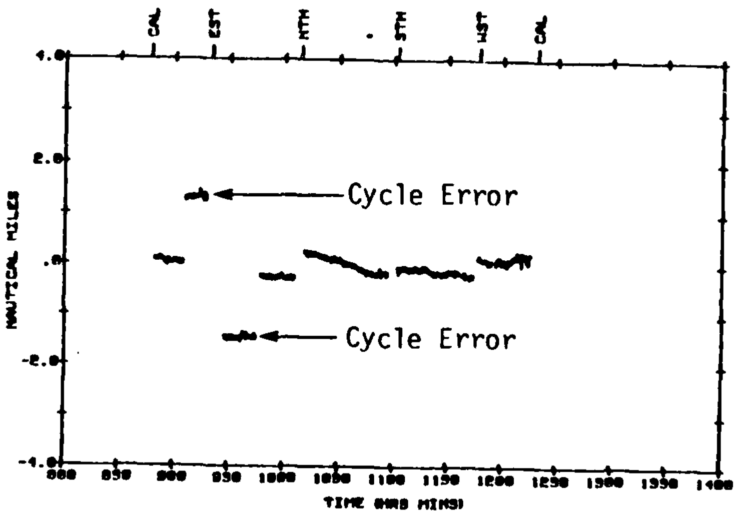
Time Difference Error



Position Error

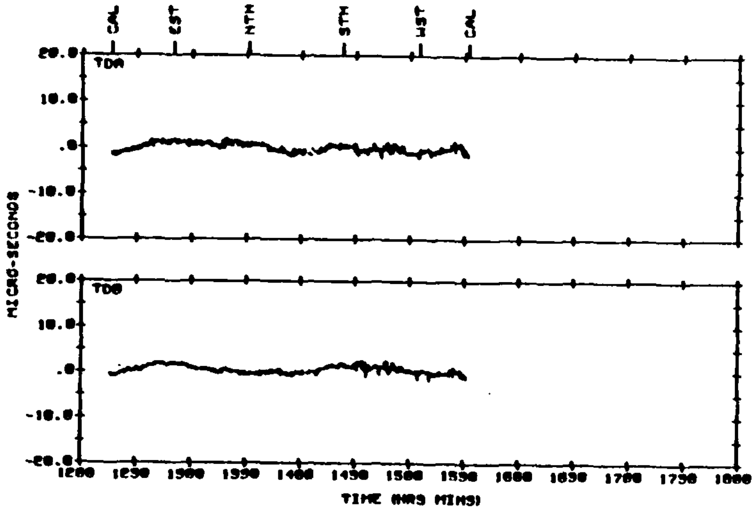


Total System Crosstrack Error

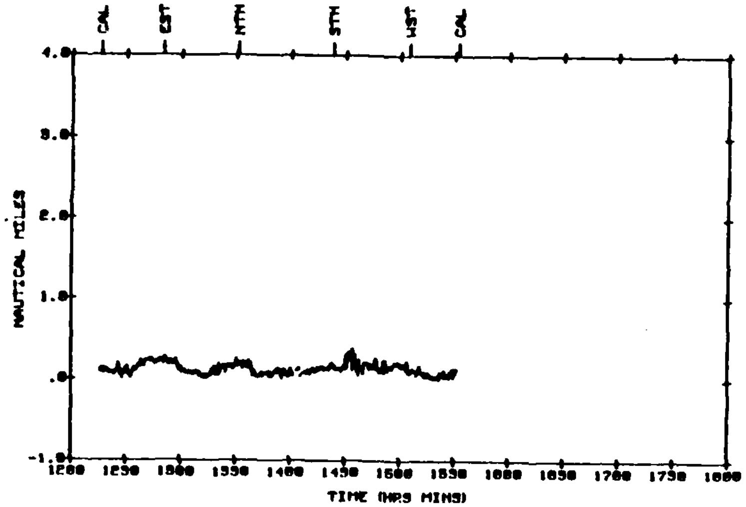


Total System Alongtrack Error

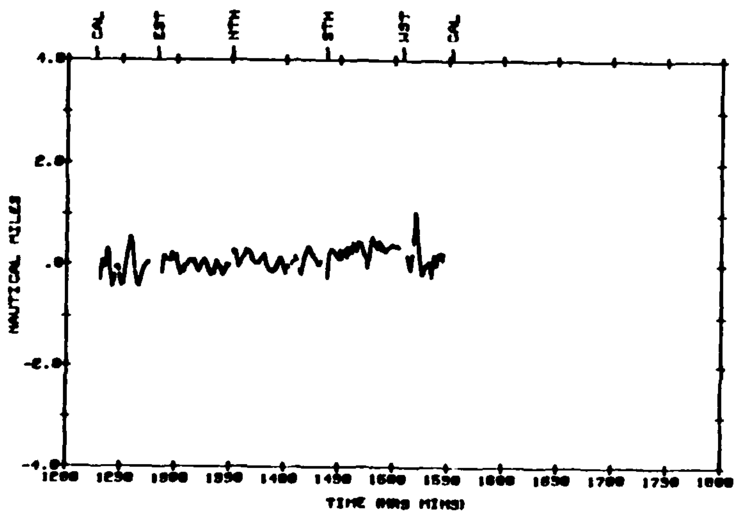
Figure D.1 Calibration System Errors, London, KY (July 6, 1983)



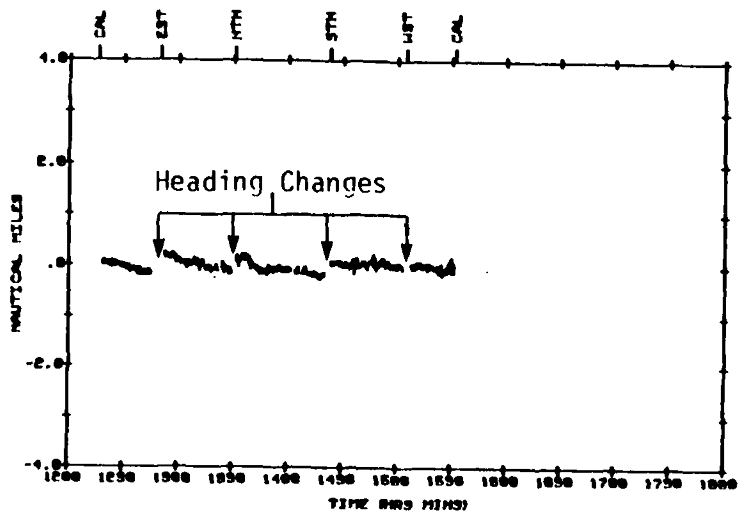
Time Difference Error



Position Error

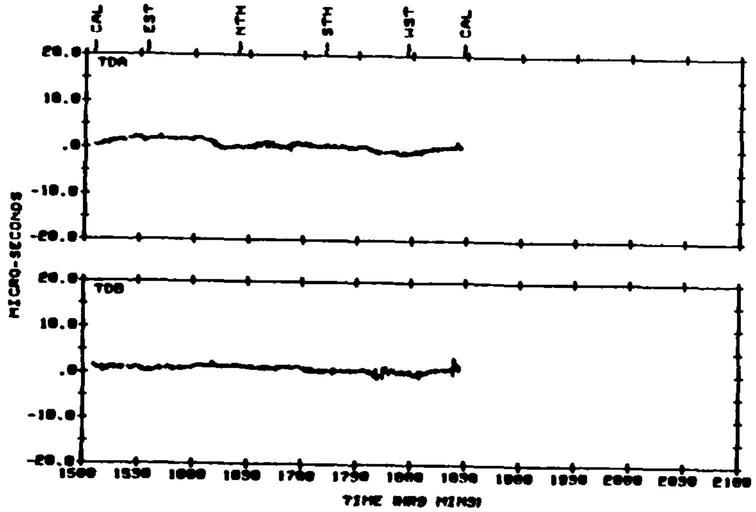


Total System Crosstrack Error

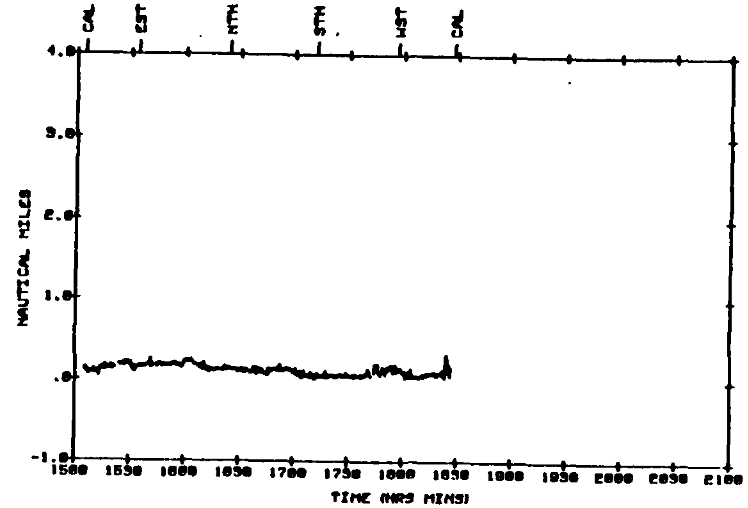


Total System Alongtrack Error

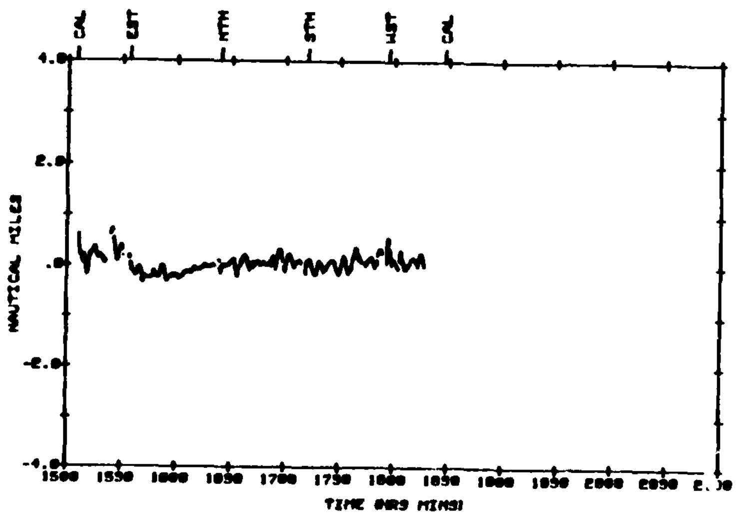
Figure D.2 Calibration System Errors, Burlington, VT (July 7, 1983)



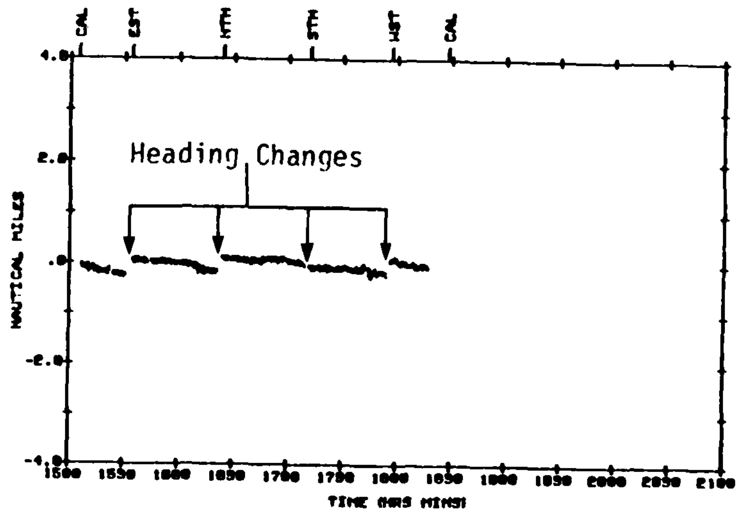
Time Difference Error



Position Error

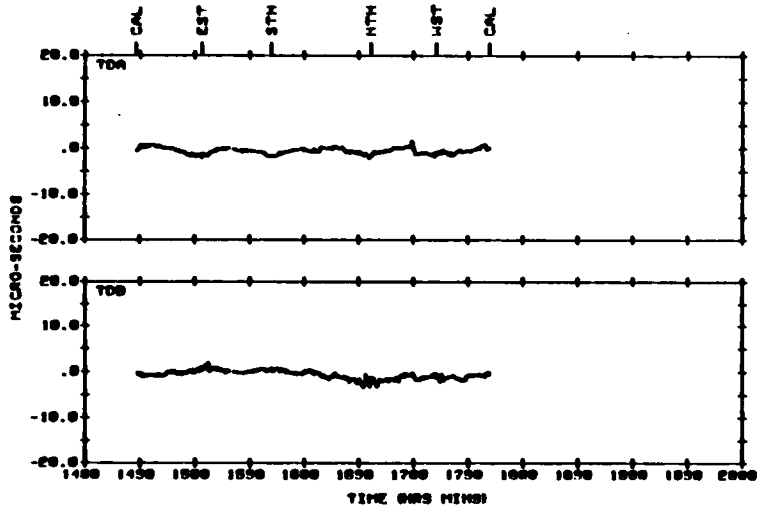


Total System Crosstrack Error

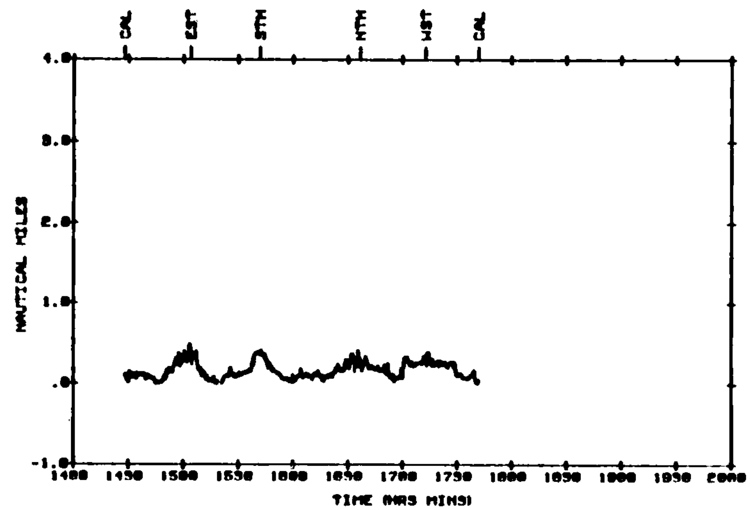


Total System Alongtrack Error

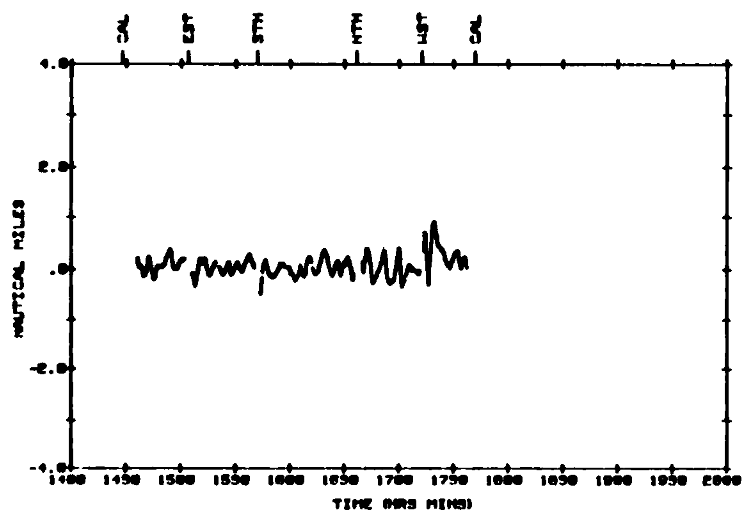
Figure D.3 Calibration System Errors, Muskegon, MI (July 8, 1983)



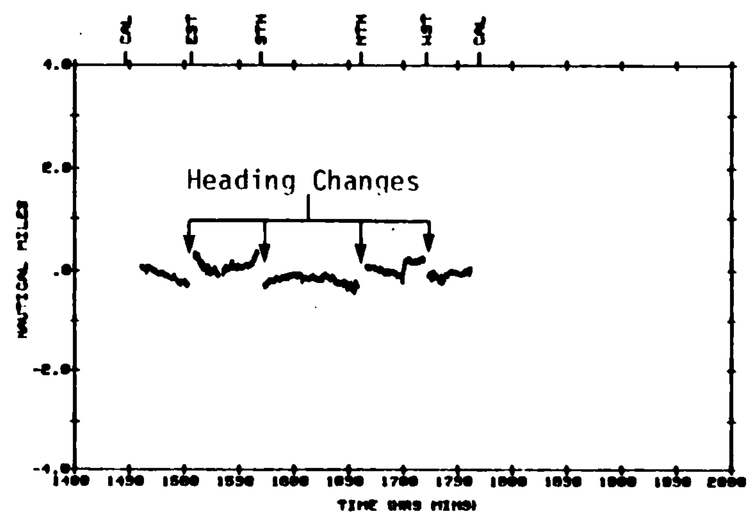
Time Difference Error



Position Error

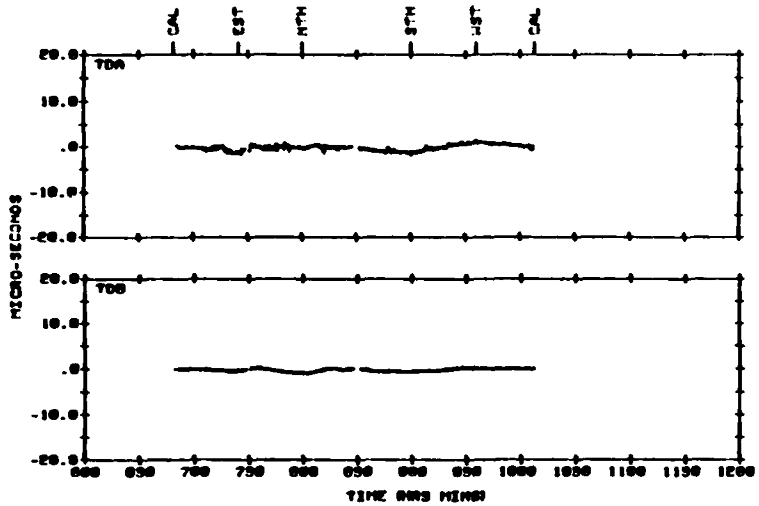


Total System Crosstrack Error

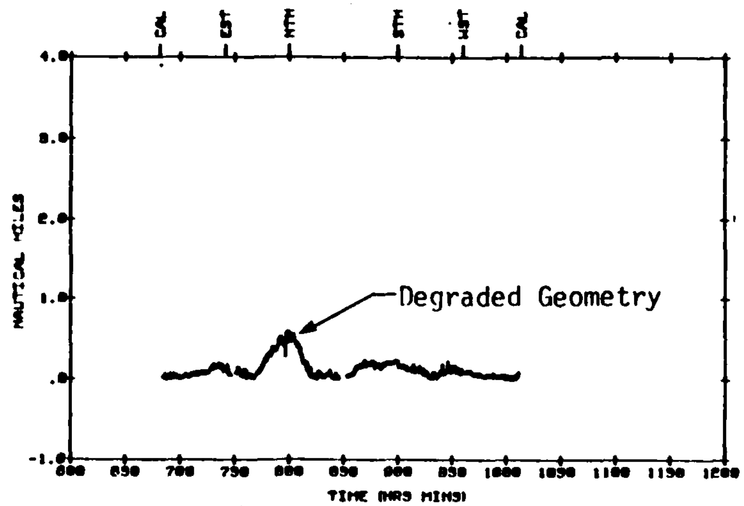


Total System Alongtrack Error

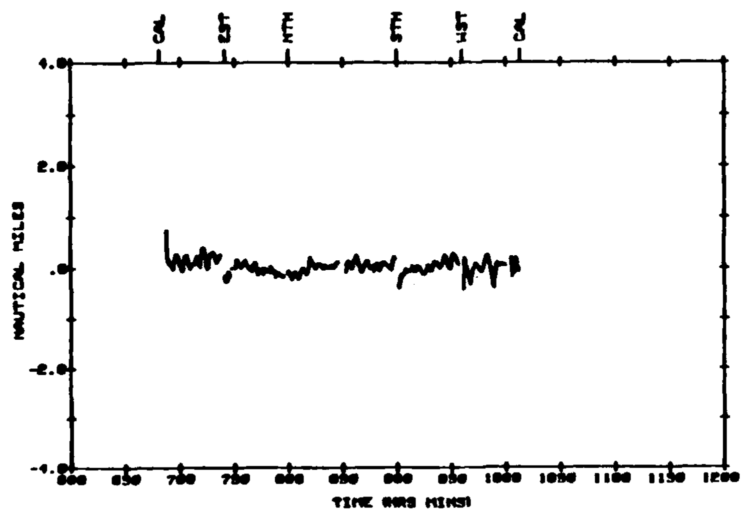
Figure D.4 Calibration System Errors, Fresno, CA (July 12, 1983)



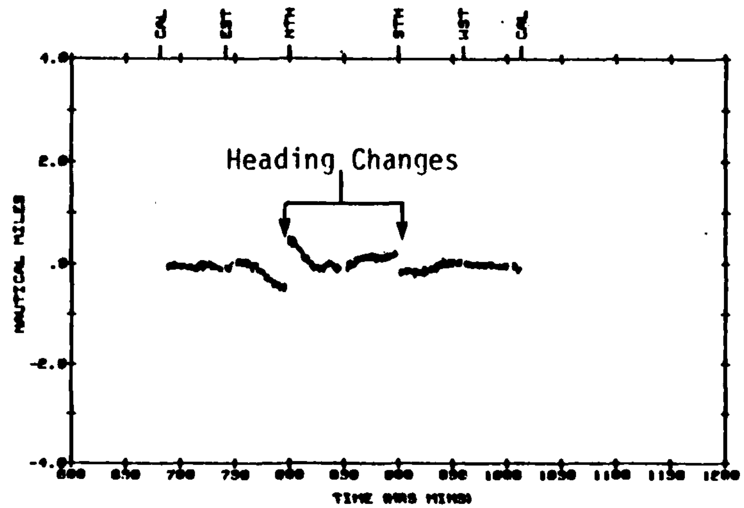
Time Difference Error



Position Error



Total System Crosstrack Error



Total System Alongtrack Error

Figure D.5 Calibration System Errors, Lafayette, LA (July 15, 1983)

END

FILMED

1-86

DTIC