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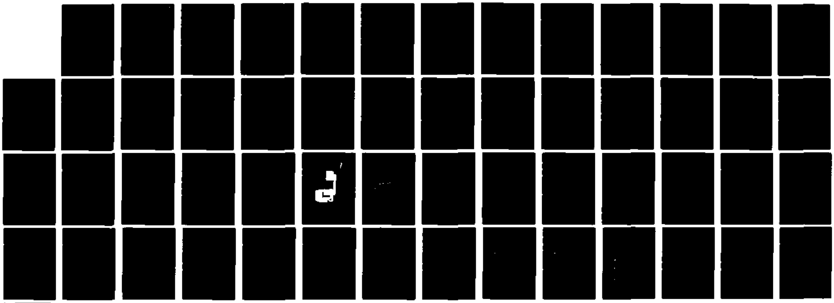

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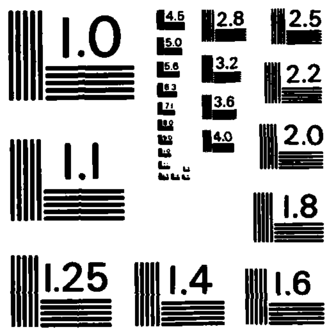
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DOT/FAA/RD-82/7
DOT/FAA/CT-81/72

Flight Test Investigation of Area Calibrated Loran-C for En Route Navigation in the Gulf of Mexico

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September 1982

Final Report

This document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161.

U.S. Department of Transportation
Federal Aviation Administration
Systems Research & Development Service
Washington, D.C. 20590

NOTICE

Technical Report Documentation Page

1. Report No.
DOT/FAA/RD-82/7

2. Government Accession No.
AD-A121 169

3. Recipient's Catalog No.

4. Title and Subtitle
FLIGHT TEST INVESTIGATION OF AREA CALIBRATED LORAN-C FOR EN ROUTE NAVIGATION IN THE GULF OF MEXICO

5. Report Date
September 1982

6. Performing Organization Code
ACT-100

7. Author(s)
John G. Morrow

8. Performing Organization Report No.
DOT/FAA/CT-81/72

9. Performing Organization Name and Address
Federal Aviation Administration
Technical Center
Atlantic City Airport, New Jersey 08405

10. Work Unit No. (TRAIS)

11. Contract or Grant No.
045-390-130

12. Sponsoring Agency Name and Address
U.S. Department of Transportation
Federal Aviation Administration
Systems Research and Development Service
Washington, D.C. 20590

13. Type of Report and Period Covered
Final Report
July 8-9, 1980

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

Flight tests of two Loran-C airborne navigators were conducted in the Gulf of Mexico oil/gas exploration and production area. Two systems were installed in a Federal Aviation Administration (FAA) CV-580 aircraft to examine simultaneously the performance of a Loran-C receiver operated in an area-calibrated mode and one operated in an uncalibrated model. Two separate test routes were flown over a period of 2 days. These routes covered the central and western test areas of the Gulf of Mexico and an overland route from Palacios, Texas, to Lafayette, Louisiana. An Inertial Navigation System (INS) was used as a position reference standard. The INS data were updated to correct for drift. Accuracy of the position reference from the corrected INS data was ±0.3 nautical mile.

The flight tests indicated that the use of area calibration greatly increased the area of compliance with Advisory Circular 90-45A en route accuracy requirements in the flight test.

This report is a followup of report No. FAA-RD-80-47 (FAA-CT-80-18), "Flight Test Investigation of Loran-C for En Route Navigation in the Gulf of Mexico."

17. Key Words
Loran-C
En Route Navigation
Area Navigation
RNAV

18. Distribution Statement
This document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	50	

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

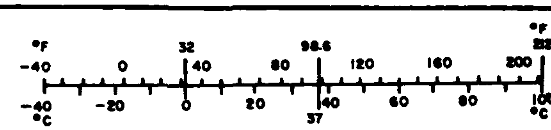

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (CONTINUED)

LIST OF ILLUSTRATIONS (CONTINUED)

LIST OF TABLES

LIST OF TABLES (CONTINUED)

INTRODUCTION

PURPOSE.

The purpose of these flights was to:

1. Examine the difference in performance between a Loran-C receiver operated in the area calibrated mode versus one operated in the nonarea calibrated mode in the Gulf of Mexico oil exploration area.

2. Obtain data on group repetition interval (GRI) 7980 Loran-C performance in the baseline extension region west of Grangeville, Louisiana.

4. Develop a contour defining the boundary of Federal Aviation Administration (FAA) Advisory Circular (AC) 90-45A, "Approval of Area Navigation Systems for Use in the U.S. National Airspace System," compliance of the 7980 Loran-C chain in the Gulf of Mexico oil exploration area.

5. Document signal-to-noise ratios (SNR) of Loran-C stations in the flight test area.

BACKGROUND.

The Gulf of Mexico is an area of intense oil exploration and development which, in turn, requires heavy helicopter traffic in support of these operations. The nature of these operations require low level flights as far as 100 miles or more offshore. Conventional very high frequency (VHF) omnidirectional radiorange (VOR)/distance measuring equipment (DME) coverage is limited to line-of-sight constraints and, therefore, only provides useful navigation information near the shore, but cannot meet the needs of helicopters farther out in the Gulf.

Loran-C offers a useful alternative to VOR/DME navigation and is not subject to the line-of-sight constraints as is VOR/DME. Loran-C is presently approved for en route instrument flight rules (IFR) operations in the Gulf and is being used by operators in this area. There are, however, certain restrictions applied to its use in the area west of longitude 93°00'. These restrictions were applied as a result of a flight test investigation conducted by the Technical Center and reported on in report FAA-RD-80-47 (FAA-CT-80-18) "Flight Test Investigation of Loran-C for En Route Navigation in the Gulf of Mexico." Based on these tests, additional tests were recommended to examine the area west of longitude 93°00' more thoroughly.

EQUIPMENT DESCRIPTION

INERTIAL NAVIGATION SYSTEM.

A Litton LTN-51 Inertial Navigation System (INS) was used for primary course guidance and position reference during the two test flights.

LORAN-C.

The Loran-C equipment used during these tests was the Teledyne Systems TDL-711 Loran Micro-Navigator (figure 1) with version No. 12X1 software incoporated. The system consists of three units: a control display unit (CDU), a receiver computer unit (RCU), and an antenna with an integral coupler (ACU). The CDU provides the operator interface with the system and displays all navigation and self-test functions. The RCU processes the Loran-C signals and computes all navigation data using great circle computations. The RCU incorporated two adjustable notch filters, which can be adjusted to remove two interfering frequencies. Both notch filters on each receiver were adjusted so as to be effectively removed from the circuit for these flight tests. The antenna is a whip antenna with an integral antenna coupler in the base. The ACU provides impedance matching and bandpass amplication for the Loran-C signals. Two of these systems were installed in the CV-580 aircraft.

DATA COLLECTION SYSTEM AND EQUIPMENT.

An FAA Technical Center designed and fabricated digital data collection system was utilized to collect aircraft, Loran-C, and INS parameters. The data system is based on a NORDEN PDP 11/34M Digital Processor with 32K memory, floating point processor, and input/output (I/O) as necessary to support system peripherals. This is a militarized version of the Digital Equipment Corporation PDP 11/34 Digital Computer. A Miltope Corporation militarized dual floppy disk drive is used for data storage.

An aircraft system's coupler interfaces the various aircraft sensor signals to the computer's internal UNIBUS™ structure. The aircraft system coupler outputs 16-bit parallel words compatible with the PDP 11/34M. Table 1 lists the parameters that were recorded at a 1 hertz (Hz) rate for this flight test.

ROUTE STRUCTURE.

Two separate routes were flown, one on July 8, 1980, and the other on July 9, 1980. The routes were so constructed to cover gas and oil producing areas in the western Gulf of Mexico where problems had been identified in previous flight tests. The test areas were flown as follows:

1. First flight: between 27°30' and 29°45' latitude, 94°00' and 96°30' longitude, 1435 to 1915 hours, July 9, 1980, as listed in tables 2 and 3.

2. Second flight: between 28°30' and 30°15' latitude, 92°00' and 94°00' longitude, 1030 to 1400 hours, July 9, 1980, as listed in tables 2 and 3.

These routes duplicate existing offshore helicopter routes whenever possible while still providing maximum coverage of the given area.

AREA CALIBRATION MODE.

Because of radio propagation phenomena, the position of a given point as computed and displayed by the Loran-C receiver/processor may be different from the surveyed geographic position. The TDL-711 used in these tests has a feature which will allow the computation and application of a correction factor to bring the computed position into correspondence with the surveyed position. The process, called area calibration, is accomplished by parking at or overflying a point of known latitude and longitude, and activating the area calibration sequence. The receiver records measured time differences (TD's) at that point and the operator enters the known position. The receiver calculates the delta difference between recorded TD's and the TD's that correspond to the entered position. This delta is then added to successive measured time differences and the result used to calculate position.

Area calibration assumes that propagation effects are uniform throughout a given area, and this uniformity determines the region over which the calibration is valid. These tests were flown to examine the effects of area calibration in the western Gulf of Mexico.

FLIGHT TEST PROCEDURE.

Flight tests were conducted in an FAA owned, fixed-wing CV-580 aircraft, designated N-49, based out of the FAA's Technical Center in New Jersey. The aircraft was flown on July 7, 1980, to Jefferson County Airport, Port Arthur, Texas, and based there for the project flights.

Prior to taxi for takeoff the INS was aligned, placed in the navigation mode, and data recording was initiated. The aircraft was then taxied to a surveyed spot on the airport where one Loran-C receiver was corrected, as described in the "Area Calibration Mode" section. The other Loran-C receiver was operated in the uncalibrated mode.

Each flight proceeded along the coast to intercept one of the defined lanes to an oil rig. Certain rigs were overflown in a criss-cross pattern, up to 85 miles offshore. An altitude was maintained at 500 feet for overwater sections and 1,000 feet overland, with a ground speed of approximately 180 knots.

LORAN-C STATIONS USED.

A group of Loran-C stations with a unique operating characteristic is called a chain. A Loran-C chain consists of a master transmitting station designated M, and two or more secondary stations designated W, X, Y, or Z. The unique operating characteristic which defines a chain is the time interval between the beginning of any two consecutive master pulse groups, known as the GRI. Coverage within an area is provided when signals from the master and at least two secondaries can be received, and station geometry is such that accurate position fixes can be obtained.

Coverage of the operating area is provided by the Southeast United States chain with a GRI of 79,800 microseconds (μs). The following stations make up the 7980 chain:

Malone, Florida	Master
Grangeville, Louisiana	W Secondary
Raymondville, Texas	X Secondary
Jupiter, Florida	Y Secondary
Carolina Beach, North Carolina	Z Secondary

The flight test area and the baselines between the master and the secondaries are shown in figure 2. Three stations within a chain are required for navigation.

These three stations (a master and two secondaries) form a triad. The selection of two secondaries to form the triad must be done so that the intersection of the two lines of position in the general operating area is as close to 90° as possible. This geometry will provide the best accuracy of a position fix. When the lines of position cross at close to 90°, the area of uncertainty defined by the intersection of the lines is nearly square, as shown in figure 3.

When crossing angles decrease, the area of uncertainty becomes trapezoidol, as shown in figures 4 and 5. In the case of figure 4 with the aircraft flightpath as shown, one would expect larger along-track errors than crosstrack errors. The situation would be reversed if the aircraft flightpath was changed by 90°, as shown in figure 5. The accuracy of a position fix will degrade as the crossing angle goes from 90° to 0°. Operation of Loran-C should be avoided in areas where the crossing angle is less than approximately 30°. The TDL-711 systems used in these tests track four Loran-C stations, but only use three (the triad) for navigation. If one of the three selected for navigation purposes should become unusable, the system will go into a backup mode of navigation called master independent. In this mode the two remaining stations of the prime triad are combined with the fourth station in track to form a new triad. Since the original prime triad is selected to give the most accurate position fix for the general operating area, use of the fourth station to form a new triad may result in decreased accuracy. In these tests both receivers were configured to use Malone, Grangeville, and Raymondville with Jupiter selected as the backup station.

BASELINE EXTENSION.

Another area of operation that will result in decreased accuracy is the baseline extension area. The baseline is a straight line drawn between the master and a secondary. Figure 2 illustrates the baselines between the master and all of the available secondaries for the 7980 chain. Operations near or along baseline extensions should be avoided when using that master-secondary pair as part of the triad because of the resultant decrease in position accuracy. The TDL-711 will continue to operate in this baseline extension area without warnings or indications of degraded position accuracy.

INERTIAL NAVIGATION SYSTEM UPDATE.

The LTN-51 INS was used as the position standard for post-flight determination of Loran-C sensor errors. However, the INS is subject to drift rates which can approach 1 nautical mile (nmi)/hour. Obviously, if the INS was used without position updates for a 4-hour flight, the errors in the position measurement would be much greater than those expected for Loran-C. For this reason, the routes were established with a system of waypoints which were visually identifiable and which had known latitudes and longitudes. By visually identifying these waypoints (flying directly over them and having the copilot use an event marker connected to the data acquisition system) the position of the aircraft at that given time could be accurately determined. This procedure was repeated at each waypoint on the route. Times between these waypoints varied from about 5 to 27 minutes.

INS error can be computed by comparing the measured INS position at the waypoint with the known position of the waypoint. By computing these errors at successive waypoints, drift was approximated. Since relatively short periods of time elasped between waypoints, INS drift was approximated as a linear function. Correction factors for both latitude and longitude were computed and applied to the measured INS values at 1-Hz rate. These correction factors were applied to the data during post-flight data processing and reduction. Based on the observed values at the waypoints, the magnitude of the measured INS values at those points and the frequency of update, it is believed that the INS position standard was accurate to within ±0.3 nmi. This must be considered when interpreting the quantitative data.

LORAN-C PERFORMANCE AND AC 90-45A REQUIREMENTS.

Presently, approvals for the use of Loran-C will be based on criteria contained in AC 90-45A, which are directed primarily at approval of VOR-DME area navigation (RNAV) systems, but contain criteria for RNAV systems not using VOR/DME for continuous navigation information. Table 4 contains the specific AC 90-45A limits for non-VOR/DME RNAV in the various airspaces. AC 90-45A requires that the total of the error contributions of the airborne equipment (including update, aircraft position, and computational errors), when combined with appropriate flight technical errors (listed in table 5), should not exceed the values listed in table 4 within a 95 percent confidence interval.

The 2.5 nmi maximum crosstrack error for en route airspace is the root sum square (rss) of the 2.0 nmi flight technical error (FTE) and a 1.5 nmi airborne equipment crosstrack error allowance, or $2.5 = [FTE^2 + (Air\ Equip)^2]^{1/2} = [(2)^2 + (1.5)^2]^{1/2}$.

Since the data presented in this report are airborne equipment errors only, and does not include FTE, the maximum allowable airborne system error from Loran-C on a 95 percent probability basis, assuming a ±2 nmi value for FTE, would be ±1.5 nmi on a 2-sigma basis for the en route case. No FTE is used in determining along-track accuracy. Therefore, maximum allowable airborne system error for the along-track case in en route airspace is taken directly from table 4 and is 1.5 nmi.

TEST RESULTS

DATA ANALYSIS.

Comparative data were analyzed from both Loran-C receivers; accuracy of each was determined with respect to position information derived from corrected INS data.

Crosstrack and along-track errors were calculated for each Loran-C receiver and aggregated over each leg straight line flight from one waypoint to another. Errors were characterized as a mean and two standard deviations for each leg.

Loran-C errors were also sorted into latitude and longitude errors for sectors of the flight test area. Each sector extends for 0.5° of latitude and 0.5° of longitude. Latitude and longitude errors were characterized by a mean and standard deviation in nautical miles for each sector. These values were combined to determine the total Loran-C northing and easting errors for each sector for the Loran-C chain being investigated. Total Loran-C error is defined as the mean plus two standard deviations for an error range within a 95 percent confidence interval.

LORAN-C SYSTEM EN ROUTE ERRORS.

The errors presented in this section are Loran-C system en route errors. These include errors that may exist in the airborne receiving and processing equipment, as well as errors that could occur in the transmission of the signal to the aircraft. The comparable error element analyzed in AC 90-45A is the total of the error contributions of the airborne equipment (including update, aircraft position, and computational errors). The errors are computed by taking the difference between the actual position as measured by the INS and the position computed by the Loran-C. The difference in the latitudes yields the northing error, while the difference in the longitudes yields the easting error. By rotating these errors to the aircraft desired track, along-track and crosstrack errors result.

The resulting errors for each individual segment are presented in tables 6 through 23, inclusive. Each table presents the mean and two standard deviations of the along-track, crosstrack, northing, and easting errors for the triad used on a particular segment of the route flown. Tables 6, 7, 8, and 23 cover overland routes; tables 9 through 22, inclusive, cover overwater routes. Figures 6 through 23 are graphical presentations of the data in tables 6 through 23. A problem in the software for the microprocessor interface receiving INS data resulted in some INS data being unusable. These data were edited out before data analysis.

Several data trends can be seen from these tables. For the uncalibrated receiver, easting error is always negative (+ = east). Northing error is always positive (+ = north). Northing error is larger than easting error for most of the segments flown. For the area calibrated receiver, northing error is predominately negative. Easting error is always positive and is larger than northing error for most of the segments flown. Magnitudes of the errors from the areas calibrated receiver are much smaller than those from the nonarea calibrated receiver.

When comparing the area calibrated receiver data with the data from the nonarea calibrated receiver, it can be seen that the application of the area calibration factor in the Gulf test area reversed the signs of the northing and easting errors, changed the direction of the predominant error from north to east and reduced the error magnitude in all cases.

All of the figures (6 through 23) except one show the reduction of errors in the area calibrated receiver when compared to the uncalibrated receiver. The single exception appears in table 18 where a difference of 0.03 nmi exists between mean along-track errors of the separate receivers. Another effect of the area calibration is the reduction of the two standard deviation values. This is particularly evident in tables 9, 10, 12, 14, 15, 17, 19, 22, and 23. The reason for this can be seen from the corresponding figures. The mean errors for the uncalibrated receiver changes along the route flown. When the standard deviation is calculated, it is inflated by the changing mean error values along the route. The area calibrated receiver does not exhibit this changing mean tendency.

INTERPRETATION OF STATISTICAL ANALYSIS OF LORAN-C DATA.

The Loran-C errors associated with the flight of the test aircraft were characterized as a mean and two standard deviations for each leg of the flight. These values were computed for crosstrack, along-track, northing, and easting parameters. The calculation of values along each leg of the route could cause some misinterpretation of the data, particularly when the error values change as a function of geographic position (typified by the data presented in figure 9 for the uncalibrated Loran-C receiver. If the mean and two standard deviation values calculated and presented in table 9 were applied to the graphical data (using northing error as an example), a two standard deviation envelope would result (as in figure 24). This envelope can be characterized as the amount of protected airspace required to assure that the indicated Loran-C position would be within the confines of the envelope on a 95 percent probability basis when navigating anywhere along the track defined by waypoints 4 and 5.

The two standard deviation value presented may be viewed as uncharacteristically high for Loran-C, but is caused by the method of computing the standard deviation along the entire leg in the presence of a changing bias error. The corresponding two standard deviation value for the area calibrated receiver northing error in table 9 is only one-third of the value of that for the uncalibrated receiver with both receivers using the same triad.

Static measurements taken at p ints along the entire leg would result in a plot such as that shown in figure 25. This would define an envelope where there was a uniform variance about a changing bias error and would probably be a much more accurate characterization of the Loran-C error, but would not define the amount of protected airspace relative to the desired course.

DATA COMPOSITE.

The data from both flights were then aggregated in blocks of 0.5° of latitude by 0.5° longitude. The numbers in each block of figure 26 represent the mean ± two standard deviations of the northing and easting errors of the area calibrated and the uncalibrated Loran-C receivers with the quantity given the sign of the mean. These numbers clearly show the reduction in northing and easting errors when using area calibration. In both flights the calibration was done at Jefferson County Airport. Straightline distances from Port Arthur, Texas, to the furthest point in the test area were 205 nmi in a southeasterly direction and 236 nmi in a southwesterly direction.

The data (± two standard deviation with the sign of the mean) for northing and easting errors presented in figure 26 were then combined in an rss manner to obtain the values presented in figure 27. These values represent the maximum crosstrack or along-track error that can be expected on a 95 percent probability basis. These data indicated that a TDL-711 receiver operated in the area calibrated mode meets AC 90-45A requirements for en route navigation in all of the test area except the block directly south of Galveston, Texas.

Figure 28 was generated from figures 6 through 23 using the data for the uncalibrated receiver. The 1.5 nmi crosstrack error point was identified on each of the route segments flown. A contour was then drawn through these points. All areas to the north of the dotted contour lines are areas of noncompliance with the en route accuracy requirements of AC 90-45A when using the Malone-Raymondville-Grangeville triad and operating the TDL-711 in the uncalibrated mode of operation.

Table 24 presents a summary of maximum mean errors encountered in the flight test area for the area calibrated receiver, while table 25 presents the same type of data for the uncalibrated receiver. Table 26 presents the maximum rss value of northing and easting errors found in any block for both calibrated and uncalibrated receivers.

LORAN-C SIGNAL STRENGTH MEASUREMENTS.

The TDL-711 Loran-C receiver measures the SNR of the four Loran-C stations that it is setup to receive. This information is part of the data recorded during the Gulf Coast Loran-C test flights.

Typical plots are shown in figures 29 through 32. Figures 29 and 30 are plots for the receiver operating in the area calibrated mode and the receiver operating in the uncalibrated mode, respectively, for a portion of the test route. Figures 31 and 32 are for the same receivers but a different portion of the test route.

An analysis of these plots shows the following results: the signals from Grangeville and Raymondville show at least +5 decibels (dB) SNR for both receivers throughout the entire area covered by the test flights. The TDL-711 will not compute an SNR if it is better than +5 dB. SNR for Malone varied +4 to +5 dB for both receivers.

An analysis of the Jupiter station shows an SNR of about -2 to +4 dB for both receivers for the flight test area. There were no signal dropouts or out-of-track conditions for any stations for either receiver during the flight test.

When the SNR results of this flight test are compared to the results of the previous flight tests (report FAA-CT-80-18), two differences are noted. First, the numerous out-of-track conditions seen in the data of the previous flights, which used software version No. 11X3, were not evident in the data from these flight tests using software version No. 12X1. This is due to improvements which were made in the receiver/processor software. Second, Jupiter provided a usable signal and was in track 100 percent of the time during these flights. This contrasts with the previous flights when Jupiter was not received during some portions of the flights, particularly in the western test area. No explanation can be offered for this except that Jupiter provides a marginal signal in the western test area.

SUMMARY OF RESULTS

1. En route mean error data were aggregated into blocks of 0.5° latitude by 0.5° longitude covering the test area as shown in figure 26. The range of values seen in these blocks for calibrated and uncalibrated Loran-C receivers when using the Malone, Raymondville, Grangeville triad are as follows:

a. The calibrated Loran-C receiver had a range of -1.21 to 0.76 nmi for a mean northing error (+ = north) and from 0.33 to 1.10 nmi for mean easting error (+ = east) (shown in figure 26).

b. The uncalibrated Loran-C receiver had a range of 0.32 to 4.8 nmi for mean northing error (+ = north) and from -0.47 to -4.09 nmi for mean easting error (+ = east) (shown in figure 26). Out of the 32 sectors flown, only 12 met the AC 90-45A requirements.

The data show that the area calibrated receiver meets AC 90-45A en route accuracy requirements in all but one section directly south of Galveston, Texas (SHS), while the uncalibrated receiver met AC 90-45A en route accuracy requirements in only 12 of the 31 sections. The uncalibrated receiver shows increasing errors as one proceeds west and north in the flight test area. This is possibly due to the varing proportion of overland and overwater segments of the master signal propagation path.

2. SNR's measured by the TDL-711 Loran-C system for Raymondville and Grangeville showed +5 dB, the maximum the system is capable of measuring. SNR for Malone varied from +4 to +5 dB and Jupiter from -2 to +4 dB throughout the test area.

CONCLUSIONS

1. In the flight test area a TDL-711 Loran-C receiver using area calibration (calibration point at Port Arthur, Texas) provides greatly improved accuracy when compared to a TDL-711 operated in the uncalibrated mode. Compliance with Advisory Circular (AC) 90-45A en route accuracy requirements is obtained in almost the entire area when using area calibration.

2. The uncalibrated TDL-711 Loran-C receiver only meets AC 90-45A en route accuracy requirements in certain offshore areas. A contour of AC 90-45A non-compliance for uncalibrated operation is shown in figure 28.

3. When using the Malone, Raymondville, Grangeville triad, errors in the flight test area increase as one proceeds west and north.

4. The Malone, Raymondville, and Grangeville Loran-C stations provide high signal-to-noise ratios throughout the test area. Jupiter provides usable, but marginal coverage of the area with lower signal-to-noise ratios. Previous flight tests (report FAA-RD-80-47/FAA-CT-80-18) showed Jupiter signal strength to be very marginal in this test area.

TABLE 1. LIST OF AIRBORNE PARAMETERS COLLECTED

Inertial Navigation System

- Latitude
- Longitude
- Ground Speed
- True Heading
- Track Angle
- Wind Direction

Loran-C (Both Systems)

Present Position Latitude	Signal-to-Noise Ratios
Present Position Longitude	Envelope Numbers
Delta Latitude	Crosstrack Distance
Delta Longitude	Distance to Waypoint
Time Difference A	"From" Latitude
Time Difference B	"From" Longitude
Track Status	"To" Latitude
Loran Flags	"To" Longitude

Aircraft

- Pitch Attitude
- Roll Attitude
- Magnetic Heading
- Radar Altitude

Time

- Hours
- Minutes
- Seconds
- Milliseconds

TABLE 2. LIST OF WAYPOINTS FOR FLIGHT TEST ROUTES

WP No.	Station Ident	Lat "N"	Long "W"	VOR/RBN Frequency	Waypoint Description
1	SB1	29°41'12"	94°02'18"	115.4 MHz	Sabine Pass (VTAC) Port Arthur, Tex.
2	SHS	29°19'54"	94°59'30"	112.8 MHz	Scholes (VTAC) Galveston, Tex.
3	BYY	28°58'18"	95°51'36"	344.0 MHz	Radio Beacon Bay City, Tex.
4	PSX	28°45"48"	96°18"18"	117.3 MHz	Palacios (VTAC) Palacios, Tex.
5	BR76A	27°58'18"	95°55'12"		Cities Service Block 76A BRAZOS Area
6	BR76A +20 nmi	27°39'30"	95°47'30"		Corpus Christi Area Point in Space
7	BR538A	28°18'54"	95°37'12"	354.0 KHz	TRANCO 116-1 Block 538A BRAZOS Area
8	Hi Isle A480	29°17'12"	94°28'42"		Marathon 108 Block A480 High Island Area
9	116-3	28°22'36"	93°29'30"		Kerr McGee, West Cameron Block 22A High Island Area Fast
10	UT	29°47'42"	93°20'36"	323.0 KHz	Radio Beacon Calacieu, Tex.
11	171-1	28°28'36"	92°44'30"		East Cameron Area Block 257A Mobil
12	LLA	29°39'48"	92°22'06"	111.4 MHz	White Lake (VTAC) Tex.
13	134-2	28°37'06	92°04'12"		South Marsh Island Area Block 69B Exxon
14	LFT	30°08'42"	91°58'54"	110.8 MHz	Lafayette, La. (VTAC)
15	LCH	30°08'30"	93°06'18"	113.4 MHz	Lake Charles, La. (VTAC)

Refer to figure 28 for diagram of flight segments.

MHz = megahertz
KHz = kilohertz

TABLE 3. FLIGHT TEST ROUTES AS FLOWN

Date	WP to WP	Station Identification	Distance Between Waypoints (nmi)
7/8/80	1 - 2	SB1 - SHS	54
	2 - 3	SHS - BYY	52
	3 - 4	BYY - PSX	27
	4 - 5	PSX - BR-76A	57
	5 - 6	BR-76A - BR-76A +20 nmi	20
	6 - 5	BR-76A +20 nmi - BR-76A	20
	5 - 3	BR-76A - BYY	60
	3 - 7	BYY - BR-538A	42
	7 - 2	BR-538A - SHS	69
		(Aircraft Landed at Galveston for Fuel)	
	2 - 8	SHS - A-480A	68
	8 - 1	A-480A - SB1	88
7/9/80	1 - 9	SB1 - 116-3	85
	9 -10	116-3 - UT	85
	10 -11	UT - 171-1	85
	11 -12	171-1 - LLA	75
	12 -13	LLA - 134-2	67
	13 -14	134-2 - LFT	92
	14 -15	LFT - LCH	60

TABLE 4. AC 90-45A TOTAL SYSTEM ERROR CRITERIA

Airspace	FTE (nmi)	Total System Crosstrack (nmi)	Airborne Equipment Crosstrack (nmi)	Airborne Equipment Along-Track (nmi)
En Route	±2.0	2.5	1.5	1.5
Terminal	±1.0	1.5	1.1	1.1
Approach	±0.5	0.6	0.3	0.3

TABLE 5. AC 90-45A FTE CRITERIA

Airspace	FTE (nmi)
En Route	2.0
Terminal	1.0
Approach	0.5

TABLE 6. ERROR TERMS SABINE PASS (WP1) TO SCHOLES (WP2), OVERLAND FLIGHT

Error	Mean (nmi)	Two Std Dev's (nmi)	Samples
Area Calibrated Loran Receiver			
Along-Track	0.49	0.12	1,039
Crosstrack	0.10	0.16	1,039
Northing	0.29	0.16	1,039
Easting	0.41	0.09	1,039
Uncalibrated Loran Receiver			
Along-Track	-0.42	0.24	1,039
Crosstrack	3.67	0.15	1,039
Northing	3.21	0.11	1,039
Easting	-1.83	0.26	1,039

TABLE 7. ERROR TERMS SCHOLES (WP2) TO BAY CITY (WP3), OVERLAND FLIGHT

Error	Mean (nmi)	Two Std Dev's (nmi)	Samples
Area Calibrated Loran Receiver			
Along-Track	0.45	0.15	962
Crosstrack	0.11	0.15	962
Northing	-0.10	0.15	962
Easting	0.45	0.15	962
Uncalibrated Loran Receiver			
Along-Track	-0.62	0.21	962
Crosstrack	3.80	0.13	962
Northing	3.17	0.13	962
Easting	-2.19	0.21	962

TABLE 8. ERROR TERMS BAY CITY (WP3) TO PALACIOS (WP4), OVERLAND FLIGHT

Error	Mean (nmi)	Two Std Dev's (nmi)	Samples
Area Calibrated Loran Receiver			
Along-Track	0.50	0.14	525
Crosstrack	-0.29	0.13	525
Northing	-0.02	0.10	525
Easting	0.57	0.16	525
Uncalibrated Loran Receiver			
Along-Track	-0.64	0.10	525
Crosstrack	3.81	0.13	525
Northing	3.05	0.13	525
Easting	-2.36	0.11	525

TABLE 9. ERROR TERMS PALACIOS (WP4) TO BR-76A (WP5)

Error	Mean (nmi)	Two Std Dev's (nmi)	Samples
Area Calibrated Loran Receiver			
Along-Track	-0.35	0.24	1,300
Crosstrack	-0.34	0.16	1,300
Northing	-0.19	0.19	1,300
Easting	0.45	0.22	1,300
Uncalibrated Loran Receiver			
Along-Track	2.56	0.82	1,300
Crosstrack	0.77	0.34	1,300
Northing	2.06	0.62	1,300
Easting	-1.71	0.62	1,300

TABLE 10. ERROR TERMS BR-76A (WP5) TO BR-76A +20 NMI (WP6)

Error	Mean (nmi)	Two Std Dev's (nmi)	Samples
Area Calibrated Loran Receiver			
Along-Track	-0.46	0.23	380
Crosstrack	-0.25	0.07	380
Northing	-0.35	0.22	380
Easting	0.39	0.10	380
Uncalibrated Loran Receiver			
Along-Track	1.76	0.45	380
Crosstrack	0.65	0.14	380
Northing	1.43	0.38	380
Easting	-1.20	0.27	380

TABLE 11. ERROR TERMS BR-76A +20 NMI (WP6) TO BR-76A (WP5)

Error	Mean (nmi)	Two Std Dev's (nmi)	Samples
Area Calibrated Loran Receiver			
Along-Track	0.49	0.11	369
Crosstrack	0.26	0.08	369
Northing	-0.37	0.11	369
Easting	0.41	0.09	369
Uncalibrated Loran Receiver			
Along-Track	-1.71	0.17	369
Crosstrack	-0.63	0.11	369
Northing	1.39	0.14	369
Easting	-1.18	0.14	369

TABLE 12. ERROR TERMS BR-76A (WP5) TO BAY CITY (WP3)

Area Calibrated Loran Receiver

Error	Mean (nmi)	Two Std Dev's (nmi)	Samples
Along-Track	0.32	0.13	1,209
Crosstrack	0.59	0.14	1,209
Northing	-0.35	0.13	1,209
Easting	0.57	0.14	1,209

Uncalibrated Loran Receiver

Error	Mean (nmi)	Two Std Dev's (nmi)	Samples
Along-Track	-1.81	0.69	1,209
Crosstrack	-1.58	0.55	1,209
Northing	1.89	0.62	1,209
Easting	-1.49	0.51	1,209

TABLE 13. ERROR TERMS BAY CITY (WP3) TO BR-538A (WP7)

Area Calibrated Loran Receiver

Error	Mean (nmi)	Two Std Dev's (nmi)	Samples
Along-Track	-0.36	0.13	860
Crosstrack	-0.38	0.16	860
Northing	-0.23	0.13	860
Easting	0.47	0.16	860

Uncalibrated Loran Receiver

Error	Mean (nmi)	Two Std Dev's (nmi)	Samples
Along-Track	2.61	0.81	860
Crosstrack	1.00	0.23	860
Northing	2.18	0.71	860
Easting	-1.75	0.46	860

TABLE 14. ERROR TERMS BR-538A (WP7) TO SCHOLES (WP2)

Error	Mean (nmi)	Two Std Dev's (nmi)	Samples
	Area Calibrated Loran Receiver		
Along-Track	-0.04	0.22	1,298
Crosstrack	0.63	0.32	1,298
Northing	-0.26	0.33	1,298
Easting	0.58	0.20	1,298
	Uncalibrated Loran Receiver		
Along-Track	-1.12	0.55	1,298
Crosstrack	-2.23	0.90	1,298
Northing	2.05	0.91	1,298
Easting	-1.43	0.53	1,298

TABLE 15. ERROR TERMS SCHOLES (WP2) TO HI ISLE A-480A (WP8)

Error	Mean (nmi)	Two Std Dev's (nmi)	Samples
	Area Calibrated Loran Receiver		
Along-Track	-0.28	0.19	1,385
Crosstrack	-0.39	0.09	1,385
Northing	-0.10	0.17	1,385
Easting	0.47	0.12	1,385
	Uncalibrated Loran Receiver		
Along-Track	2.13	1.26	1,385
Crosstrack	0.37	0.23	1,385
Northing	1.81	1.06	1,385
Easting	-1.19	0.70	1,385

TABLE 16. ERROR TERMS HI ISLE A-480A (WP8) TO SABINE PASS (WP1)

Area Calibrated Loran Receiver

Error	Mean (nmi)	Two Std Dev's (nmi)	Samples
Along-Track	0.10	0.11	647
Crosstrack	0.42	0.09	647
Northing	-0.21	0.12	647
Easting	0.38	0.07	647
	Uncalibrated Loran Receiver		
Along-Track	-0.91	0.19	647
Crosstrack	-1.18	0.17	647
Northing	1.19	0.22	647
Easting	-0.90	0.13	647

TABLE 17. ERROR TERMS SABINE PASS (WP1) TO WEST CAMERON (WP9)

Area Calibrated Loran Receiver

Error	Mean (nmi)	Two Std Dev's (nmi)	Samples
Along-Track	-0.40	0.49	1,617
Crosstrack	-0.57	0.15	1,617
Northing	-0.18	0.41	1,617
Easting	0.67	0.29	1,617
	Uncalibrated Loran Receiver		
Along-Track	1.41	1.68	1,617
Crosstrack	0.21	0.35	1,617
Northing	1.25	1.46	1,617
Easting	-0.68	0.89	1,617

TABLE 18. ERROR TERMS WEST CAMERON (WP9) TO CALCASIEU (WP10)

Error	Mean (nmi)	Two Std Dev's (nmi)	Samples
Area Calibrated Loran Receiver			
Along-Track	0.55	0.72	1,646
Crosstrack	0.56	0.10	1,646
Northing	-0.61	0.71	1,646
Easting	0.51	0.13	1,646
Uncalibrated Loran Receiver			
Along-Track	-0.52	0.29	1,646
Crosstrack	-0.74	0.44	1,646
Northing	0.59	0.29	1,646
Easting	-0.69	0.45	1,646

TABLE 19. ERROR TERMS CALCASIEU (WP10) TO EAST CAMERON (WP11)

Error	Mean (nmi)	Two Std Dev's (nmi)	Samples
Area Calibrated Loran Receiver			
Along-Track	-0.65	0.50	1,597
Crosstrack	-0.24	0.18	1,597
Northing	-0.51	0.52	1,597
Easting	0.46	0.11	1,597
Uncalibrated Loran Receiver			
Along-Track	0.69	0.59	1,597
Crosstrack	0.41	0.25	1,597
Northing	0.49	0.48	1,597
Easting	-0.64	0.43	1,597

TABLE 20. ERROR TERMS EAST CAMERON (WP11) TO WHITE LAKE (WP12)

Area Calibrated Loran Receiver

Error	Mean (nmi)	Two Std Dev's (nmi)	Samples
Along-Track	-0.18	0.15	1,442
Crosstrack	0.22	0.10	1,442
Northing	0.12	0.14	1,442
Easting	0.26	0.11	1,442

Uncalibrated Loran Receiver

Error	Mean (nmi)	Two Std Dev's (nmi)	Samples
Along-Track	-0.55	0.11	1,279
Crosstrack	-0.83	0.21	1,279
Northing	0.75	0.13	1,279
Easting	-0.66	0.20	1,279

TABLE 21. ERROR TERMS WHITE LAKE (WP12) TO SOUTH MARSH ISLE (WP13)

Area Calibrated Loran Receiver

Error	Mean (nmi)	Two Std Dev's (nmi)	Samples
Along-Track	0.05	0.28	1,282
Crosstrack	-0.30	0.09	1,282
Northing	0.13	0.27	1,282
Easting	0.28	0.14	1,282

Uncalibrated Loran Receiver

Error	Mean (nmi)	Two Std Dev's (nmi)	Samples
Along-Track	0.78	0.48	1,140
Crosstrack	0.41	0.13	1,140
Northing	0.65	0.47	1,140
Easting	-0.59	0.23	1,140

TABLE 22. ERROR TERMS SOUTH MARSH ISLE (WP13) TO LAFAYETTE (WP14)

Error	Mean (nmi)	Two Std Dev's (nmi)	Samples
	Area Calibrated Loran Receiver		
Along-Track	-0.05	0.15	1,615
Crosstrack	0.30	0.12	1,615
Northing	0.03	0.16	1,615
Easting	0.30	0.12	1,615
	Uncalibrated Loran Receiver		
Along-Track	-0.57	0.53	1,577
Crosstrack	-0.62	0.31	1,577
Northing	0.60	0.54	1,577
Easting	-0.59	0.29	1,577

TABLE 23. ERROR TERMS LAFAYETTE (WP14) TO LAKE CHARLES (WP15), OVERLAND FLIGHT

Error	Mean (nmi)	Two Std Dev's (nmi)	Samples
	Area Calibrated Loran Receiver		
Along-Track	0.34	0.12	1,115
Crosstrack	0.43	0.17	1,115
Northing	0.43	0.17	1,115
Easting	0.34	0.12	1,115
	Uncalibrated Loran Receiver		
Along-Track	-1.24	0.73	1,080
Crosstrack	2.58	1.49	1,080
Northing	2.57	1.50	1,080
Easting	-1.25	0.74	1,080

TABLE 24. MAXIMUM MEAN ERRORS IN FLIGHT TEST AREA CALIBRATED LORAN-C RECEIVER

Area Calibrated Loran-C Receiver	Malone, Grangeville, and Raymondville
Maximum mean along-track error (nmi) in any segment	-0.65
Maximum mean crosstrack error (nmi) in any segment	0.63
Maximum mean northing error (nmi) in any segment	-0.61
Maximum mean easting error (nmi) in any segment	0.67

TABLE 25. MAXIMUM MEAN ERRORS IN FLIGHT TEST AREA UNCALIBRATED LORAN-C RECEIVER

Area Calibrated Loran-C Receiver	Malone, Grangeville, and Raymondville
Maximum mean along-track (nmi) in any segment	2.61
Maximum mean crosstrack (nmi) in any segment	3.81
Maximum mean northing error (nmi) in any segment	3.21
Maximum mean easting error (nmi) in any segment	-2.36

TABLE 26. MAXIMUM RSS VALUES, NORTHING AND EASTING ERRORS IN FLIGHT TEST AREA

Malone, Raymondville, and Grangeville	
Area calibrated Loran-C receiver	1.63
Uncalibrated Loran-C receiver	6.29

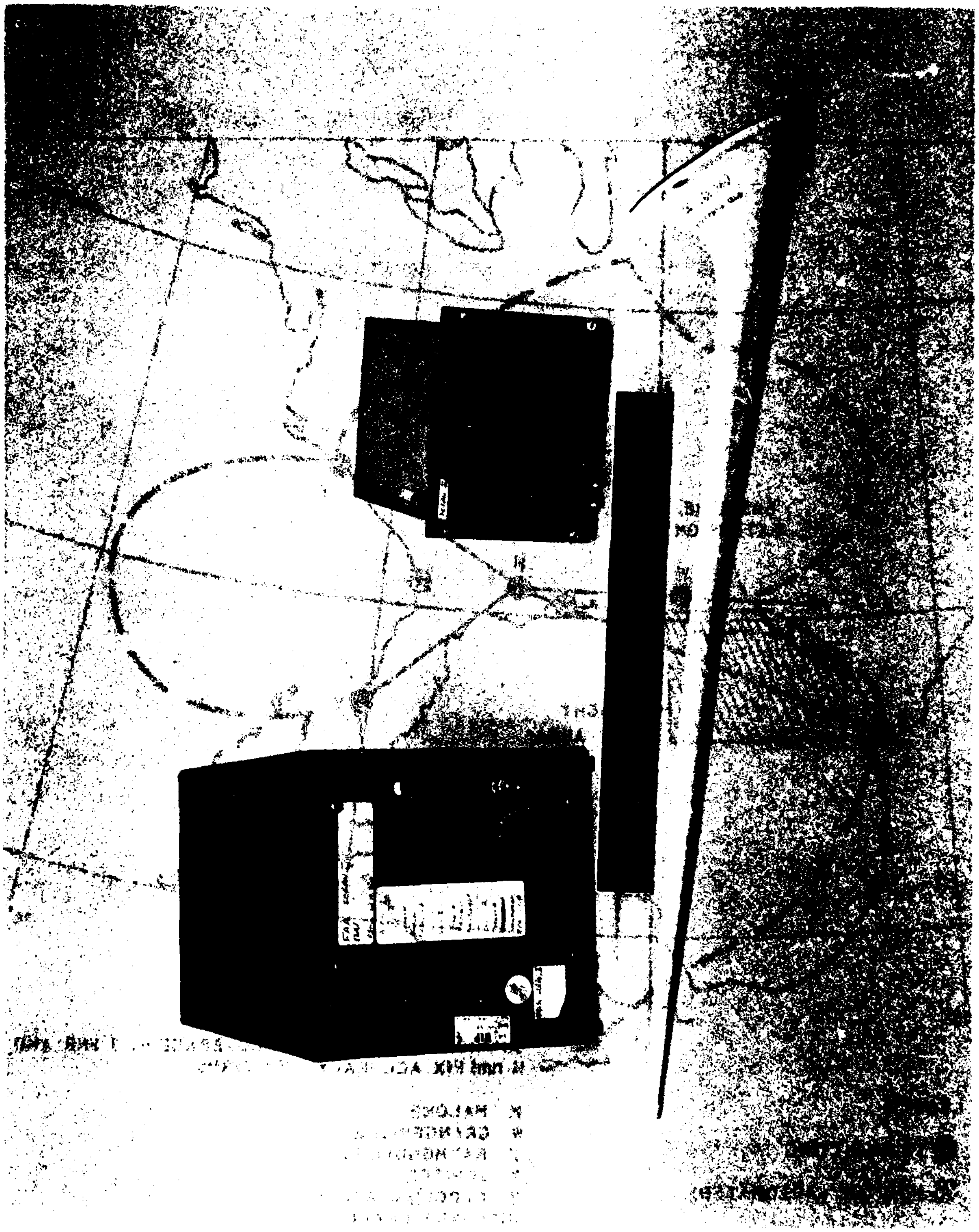

FIGURE 1. TDL-711 LORAN-C SYSTEM

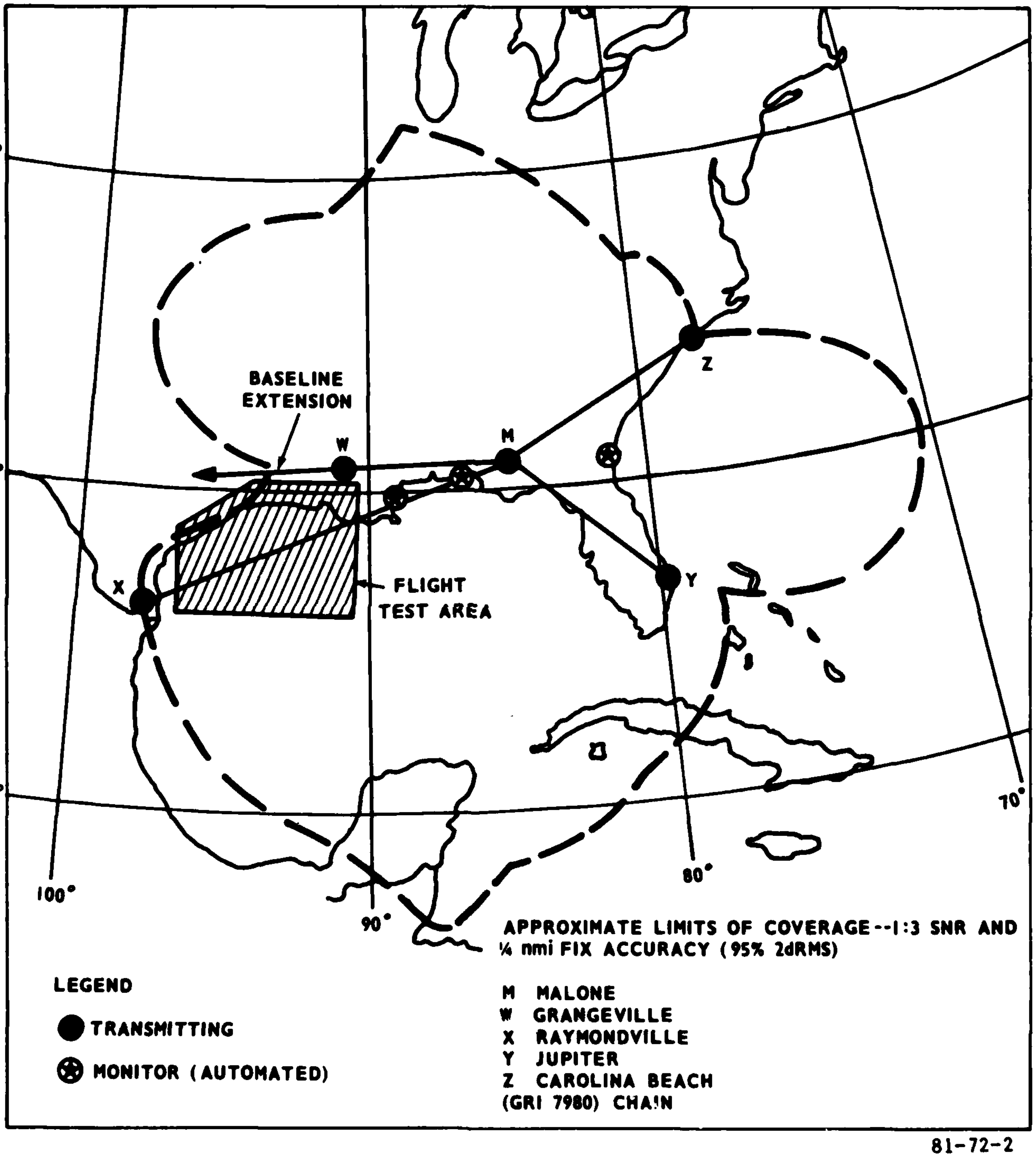

FIGURE 2. U.S. SOUTHEAST LORAN-C CHAIN GEOMETRY AND FLIGHT TEST AREA

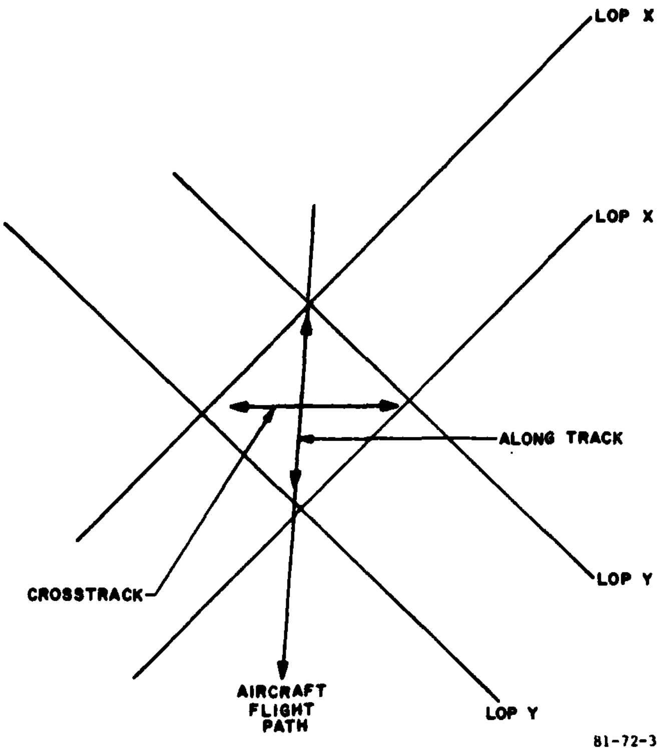

FIGURE 3. LORAN-C CROSSTRACK AND ALONG-TRACK GEOMETRY CONSIDERATIONS, ALONG-TRACK AND CROSSTRACK ERRORS EQUAL

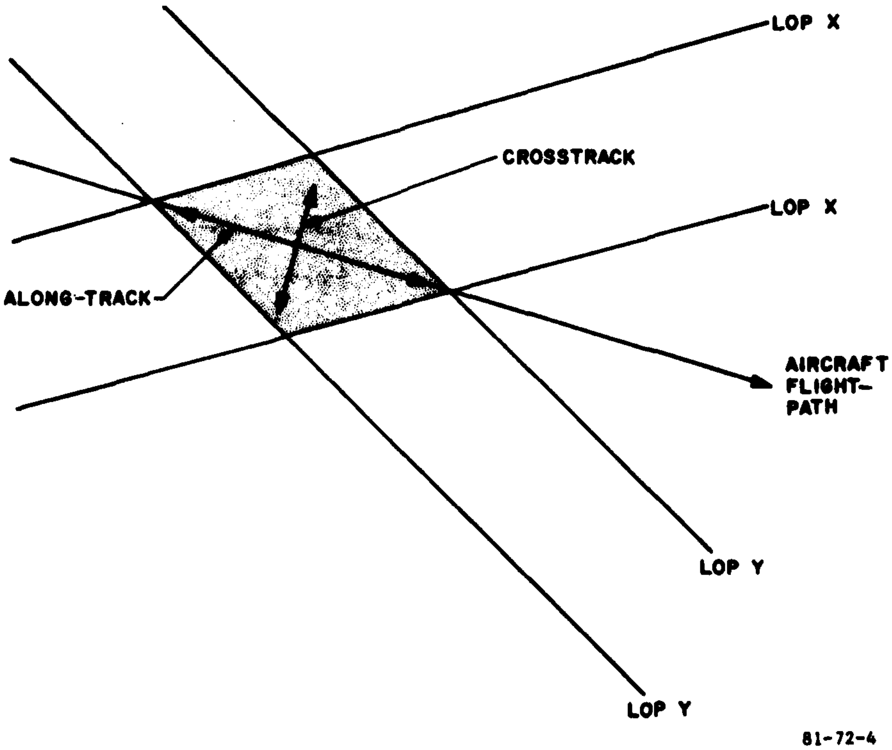

FIGURE 4. LORAN-C CROSSTRACK AND ALONG-TRACK GEOMETRY CONSIDERATIONS, ALONG-TRACK ERROR PREDOMINANT

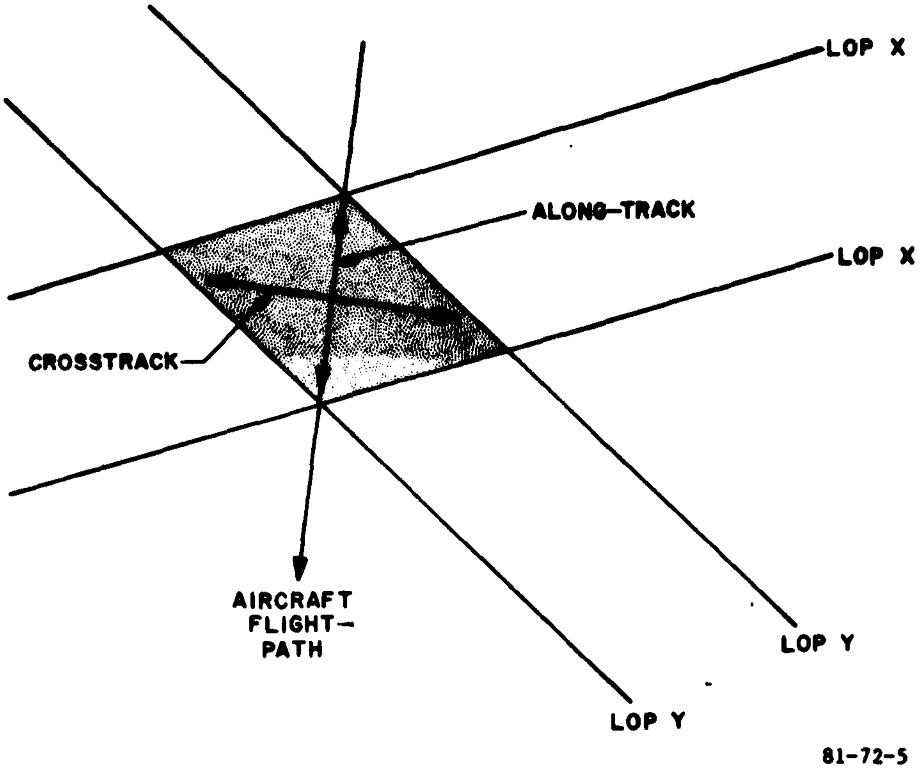

FIGURE 5. LORAN-C CROSSTRACK AND ALONG-TRACK GEOMETRY CONSIDERATIONS, CROSSTRACK ERROR PREDOMINANT

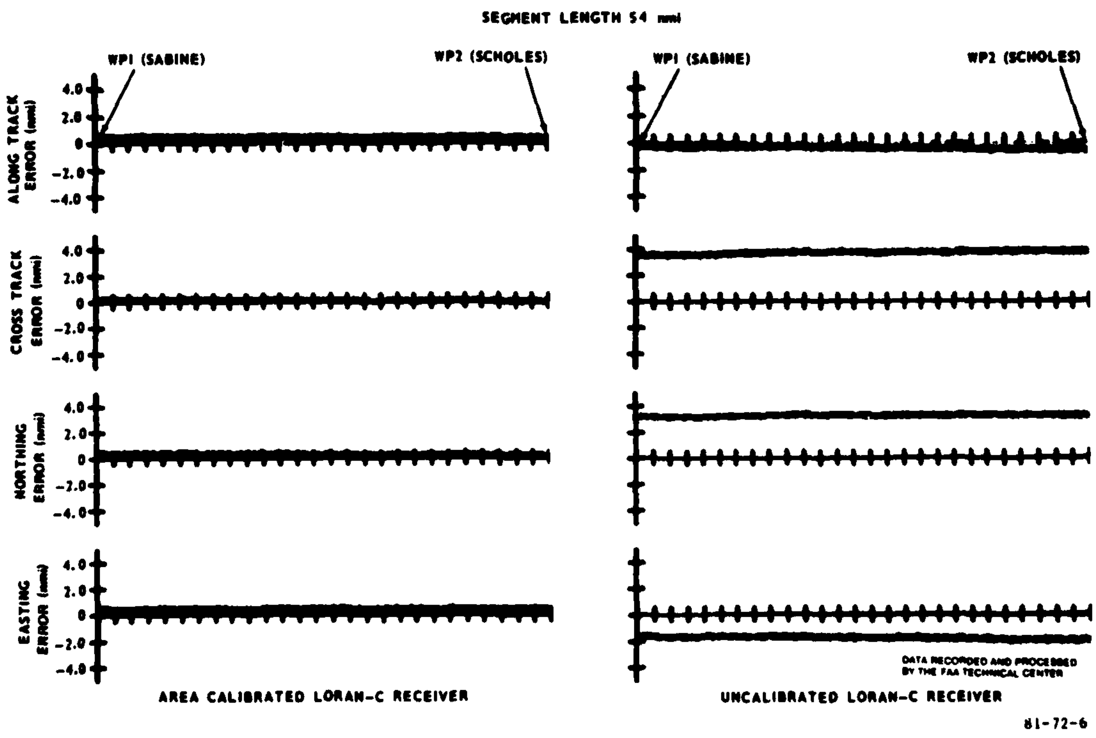

FIGURE 6. ERROR PLOTS FOR SABINE (WP1) TO SCHOLES (WP2) OVERLAND ROUTE, MALONE, GRANGEVILLE, RAYMONDVILLE TRIAD, CALIBRATED AND UNCALIBRATED LORAN-C RECEIVERS

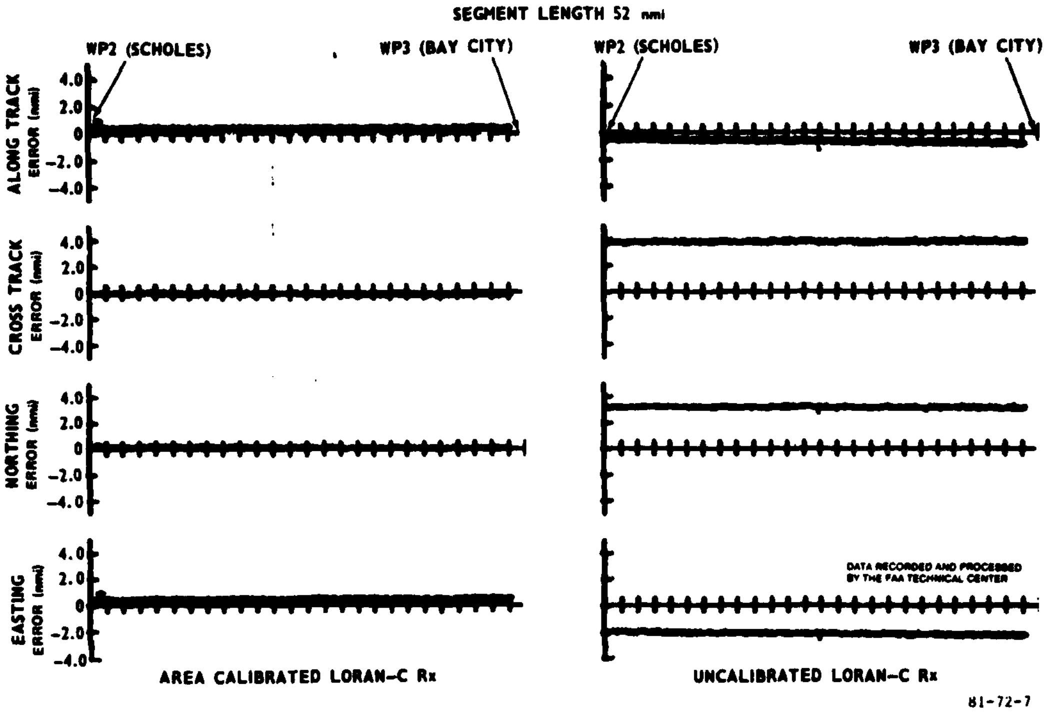

FIGURE 7. ERROR PLOTS FOR SCHOLES (WP2) TO BAY CITY (WP3) OVERLAND ROUTE, MALONE, GRANGEVILLE, RAYMONDVILLE TRIAD, CALIBRATED AND UNCALIBRATED LORAN-C RECEIVERS

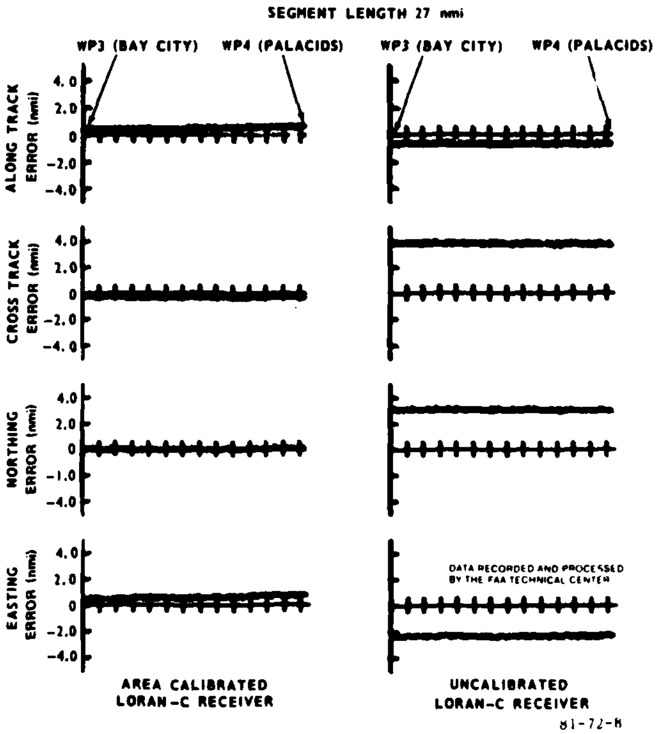

FIGURE 8. ERROR PLOTS FOR BAY CITY (WP3) TO PALACIOS (WP4), OVERLAND ROUTE MALONE, GRANGEVILLE, RAYMONDVILLE TRIAD, CALIBRATED AND UNCALIBRATED LORAN-C RECEIVERS

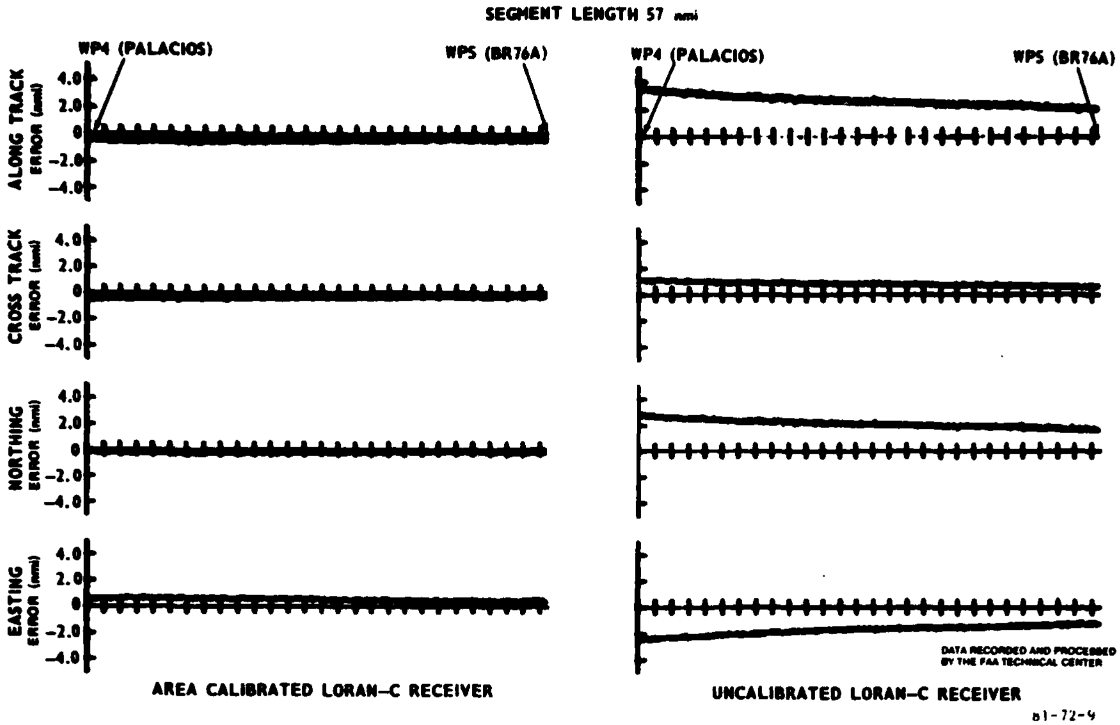

FIGURE 9. ERROR PLOTS FOR PALACIOS (WP4) TO BR-76A (WP5), OVERWATER, MALONE, GRANGEVILLE, RAYMONDVILLE TRIAD, CALIBRATED AND UNCALIBRATED LORAN-C RECEIVERS

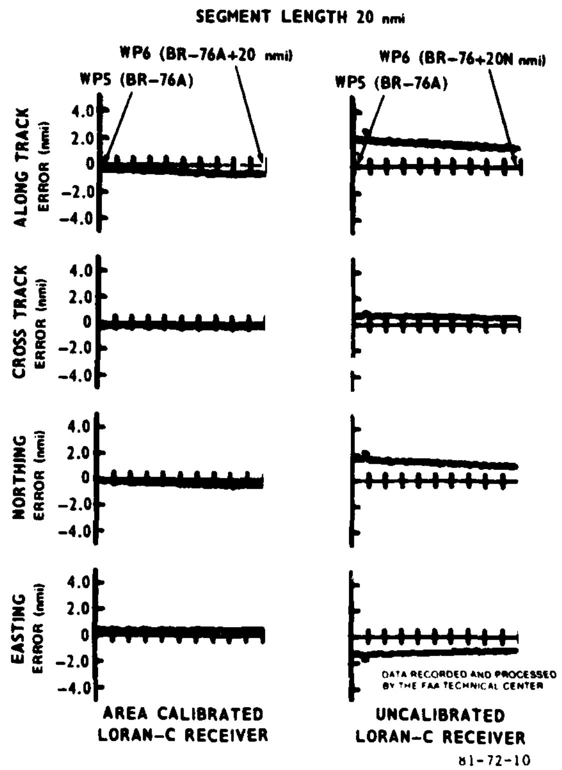

FIGURE 10. ERROR PLOTS FOR BR-76A (WP5) TO BR-76A +20 NMI (WP6) OVERWATER, MALONE, GRANGEVILLE, RAYMONDVILLE TRIAD, CALIBRATED AND UNCALIBRATED LORAN-C RECEIVERS

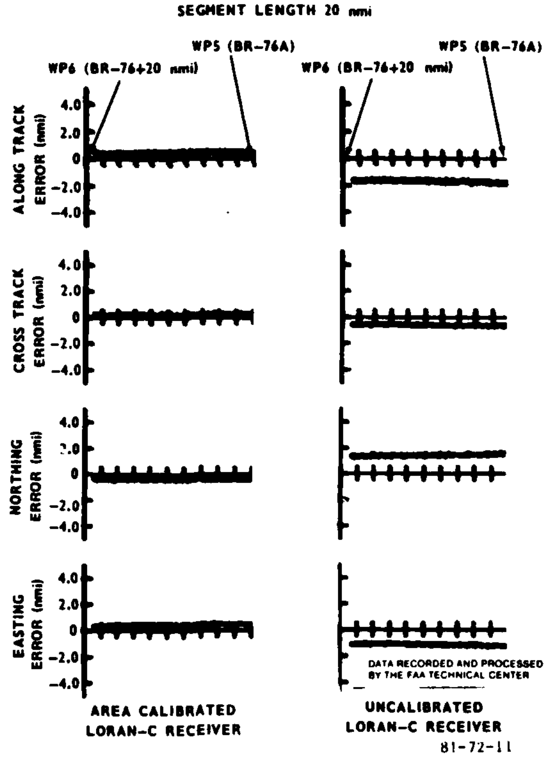

FIGURE 11. ERROR PLOTS FOR BR-76A +20 NMI (WP6) TO BR-76A (WP5), OVERWATER, MALONE, GRANGEVILLE, RAYMONDVILLE TRIAD, CALIBRATED AND UNCALIBRATED LORAN-C RECEIVERS

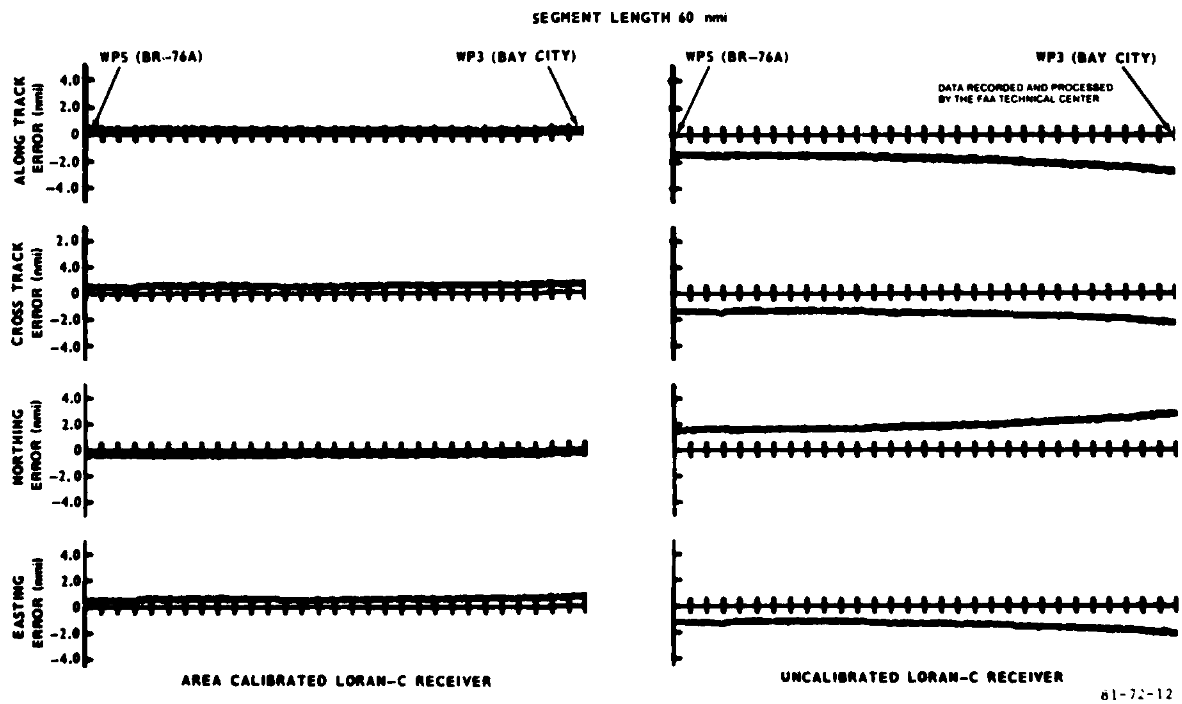

FIGURE 12. ERROR PLOTS FOR BR-76A (WP5) TO BAY CITY (WP3), OVERWATER, MALONE, GRANGEVILLE, RAYMONDVILLE TRIAD, CALIBRATED AND UNCALIBRATED LORAN-C RECEIVERS

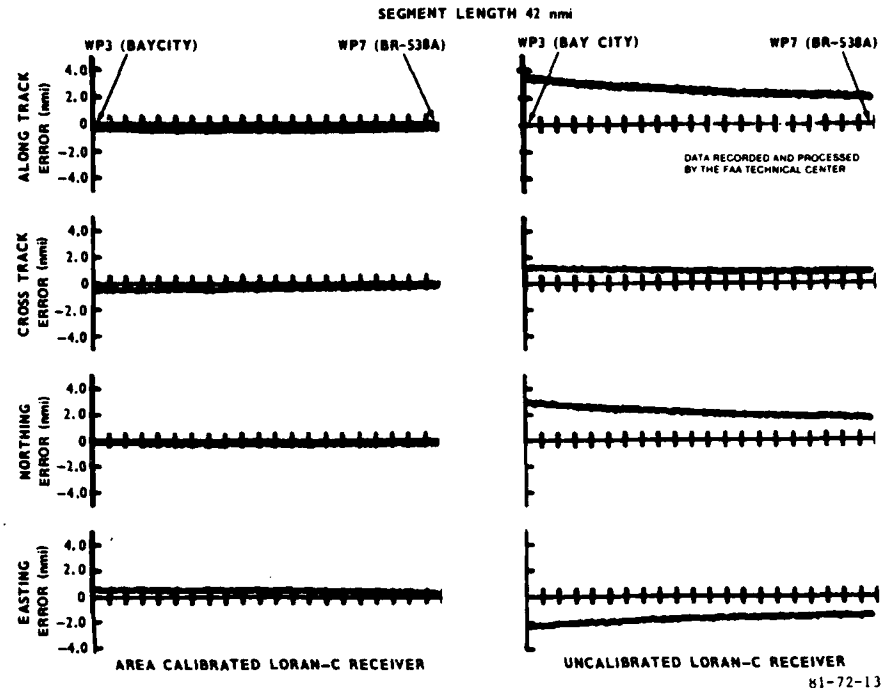

FIGURE 13. ERROR PLOTS FOR BAY CITY (WP3) TO BR-538A (WP7), OVERWATER, MALONE, GRANGEVILLE, RAYMONDVILLE TRIAD, CALIBRATED AND UNCALIBRATED LORAN-C RECEIVERS

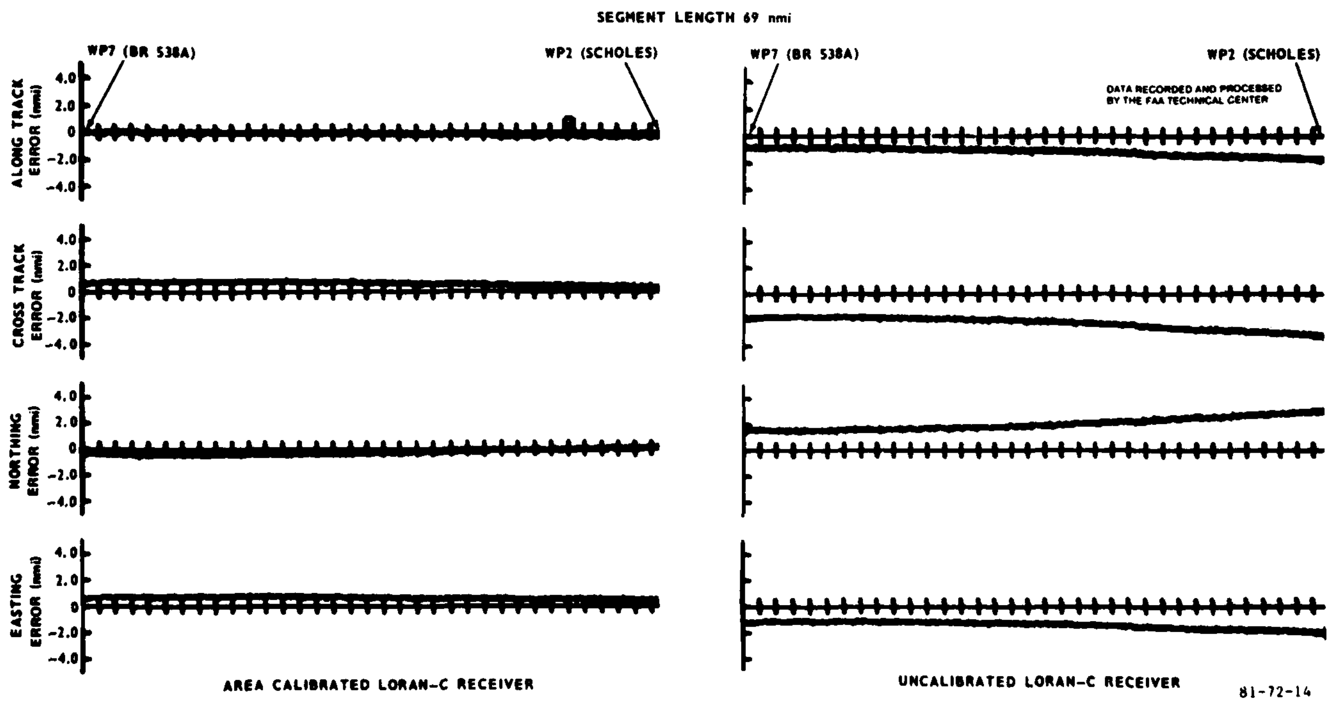

FIGURE 14. ERROR PLOTS FOR BR-538A (WP7) TO SCHOLES (WP2), OVERWATER, MALONE, GRANGEVILLE, RAYMONDVILLE TRIAD, CALIBRATED AND UNCALIBRATED LORAN-C RECEIVERS

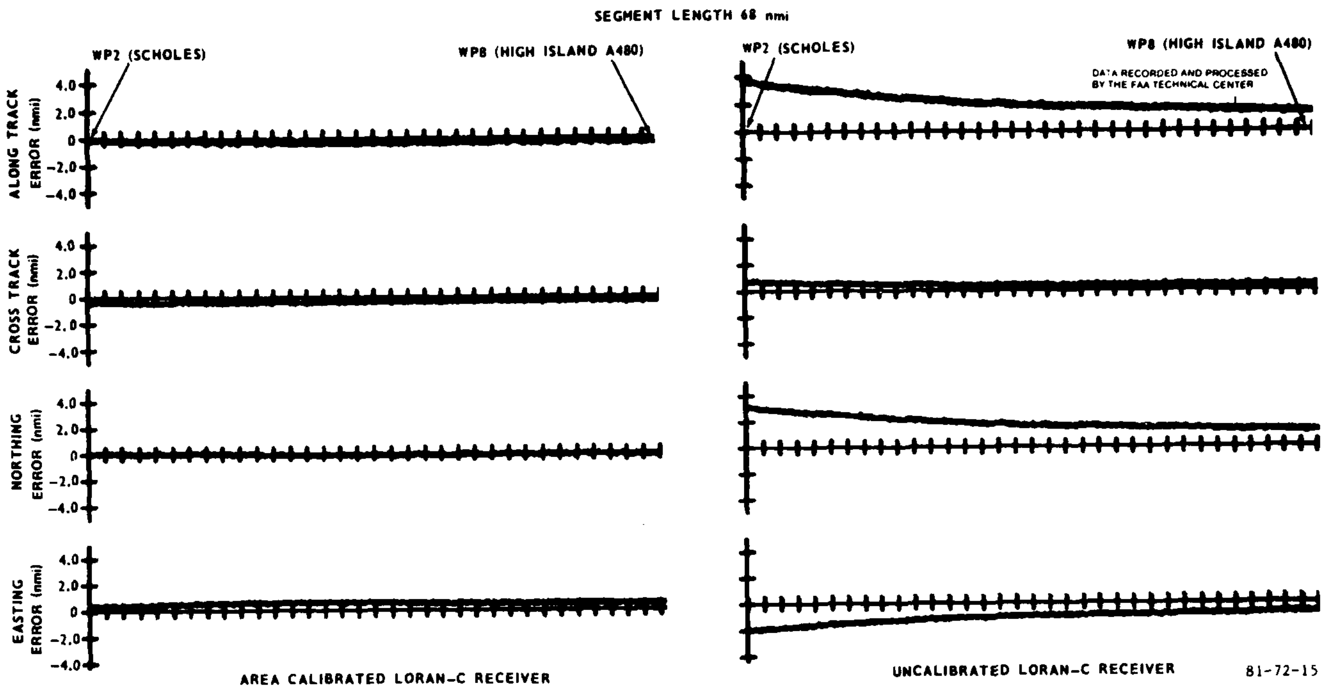

FIGURE 15. ERROR PLOTS FOR SCHOLES (WP2) TO HI ISLE A-480 (WP8), OVERWATER, MALONE, GRANGEVILLE, RAYMONDVILLE TRIAD, CALIBRATED AND UNCALIBRATED LORAN-C RECEIVERS

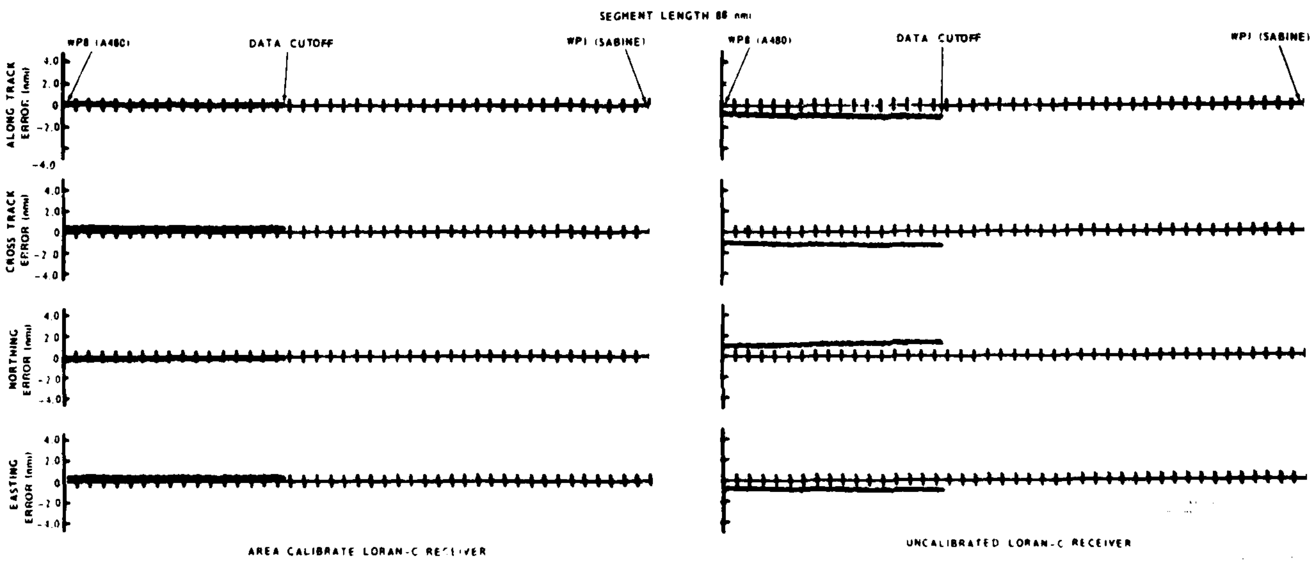

FIGURE 16. ERROR PLOTS FOR HI ISLE A-480 (WP8) TO SABINE (WP1), OVERWATER, MALONE, GRANGEVILLE, RAYMONDVILLE TRIAD, CALIBRATED AND UNCALIBRATED LORAN-C RECEIVERS

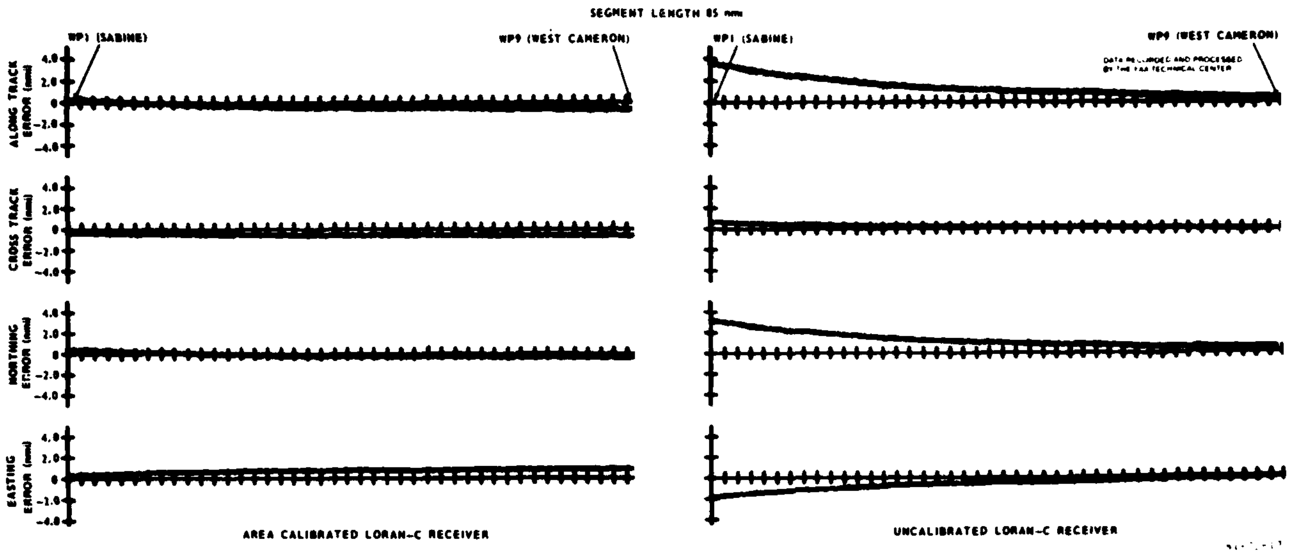

FIGURE 17. ERROR PLOTS FOR SABINE (WP1) TO WEST CAMERON (WP9), OVERWATER, MALONE, GRANGEVILLE, RAYMONDVILLE TRIAD, CALIBRATED AND UNCALIBRATED LORAN-C RECEIVERS

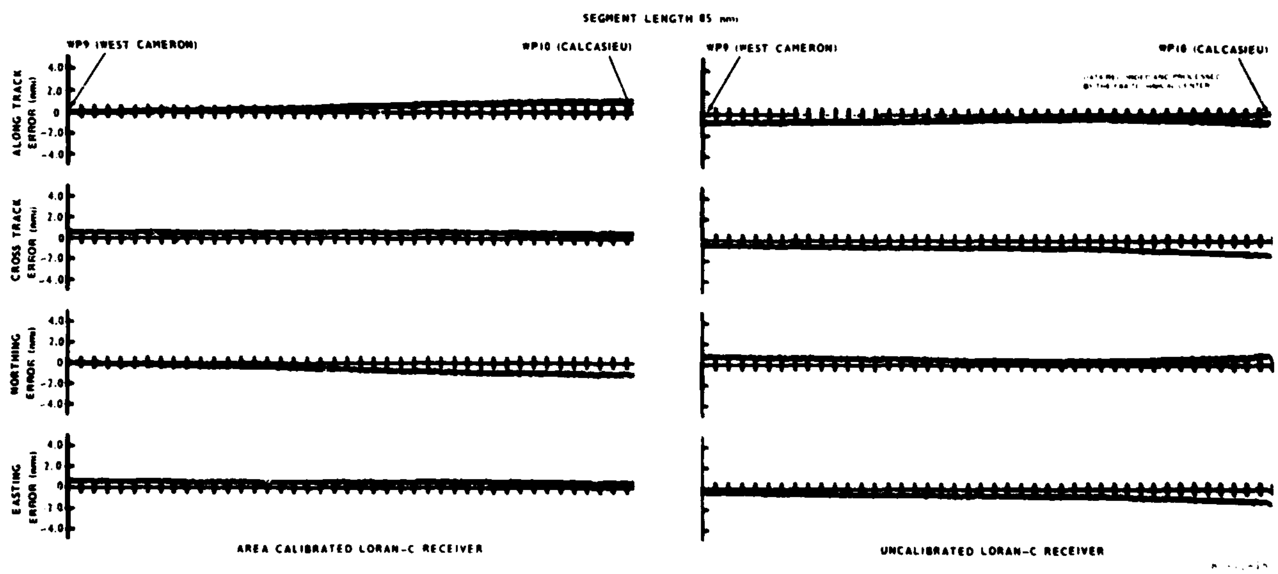

FIGURE 18. ERROR PLOTS FOR WEST CAMERON (WP9) TO CALCASIEU (WP10), OVERWATER, MALONE, GRANGEVILLE, RAYMONDVILLE TRIAD, CALIBRATED AND UNCALIBRATED LORAN-C RECEIVERS

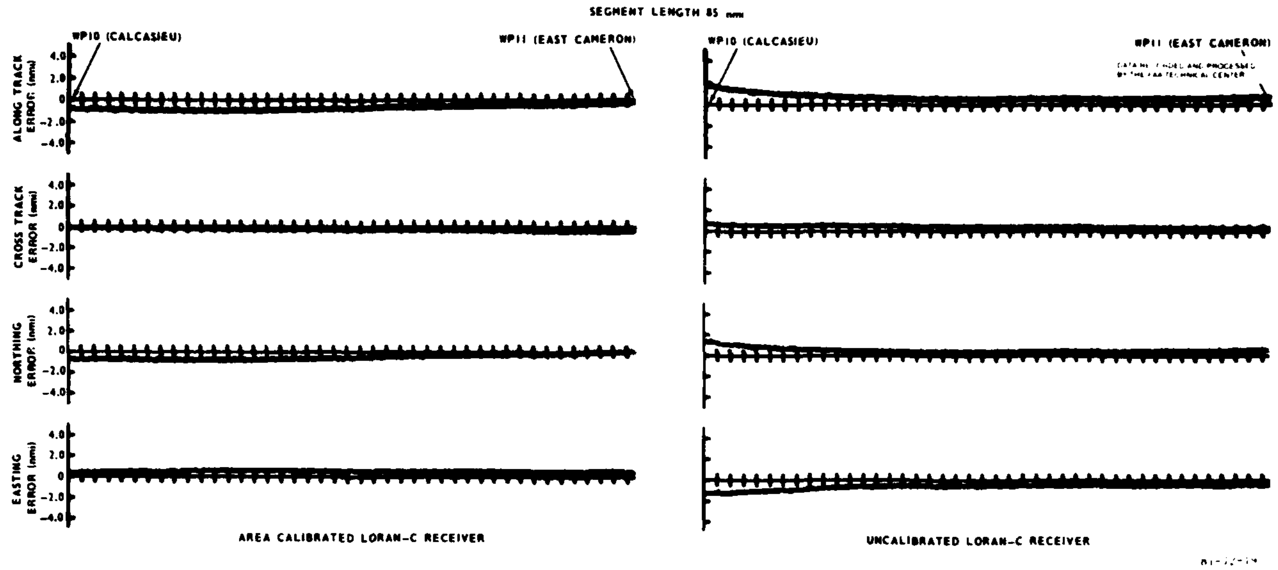

FIGURE 19. ERROR PLOTS FOR CALCASIEU (WP10) TO EAST CAMERON (WP11), OVERWATER, MALONE, GRANGEVILLE, RAYMONDVILLE TRIAD, CALIBRATED AND UNCALIBRATED LORAN-C RECEIVERS

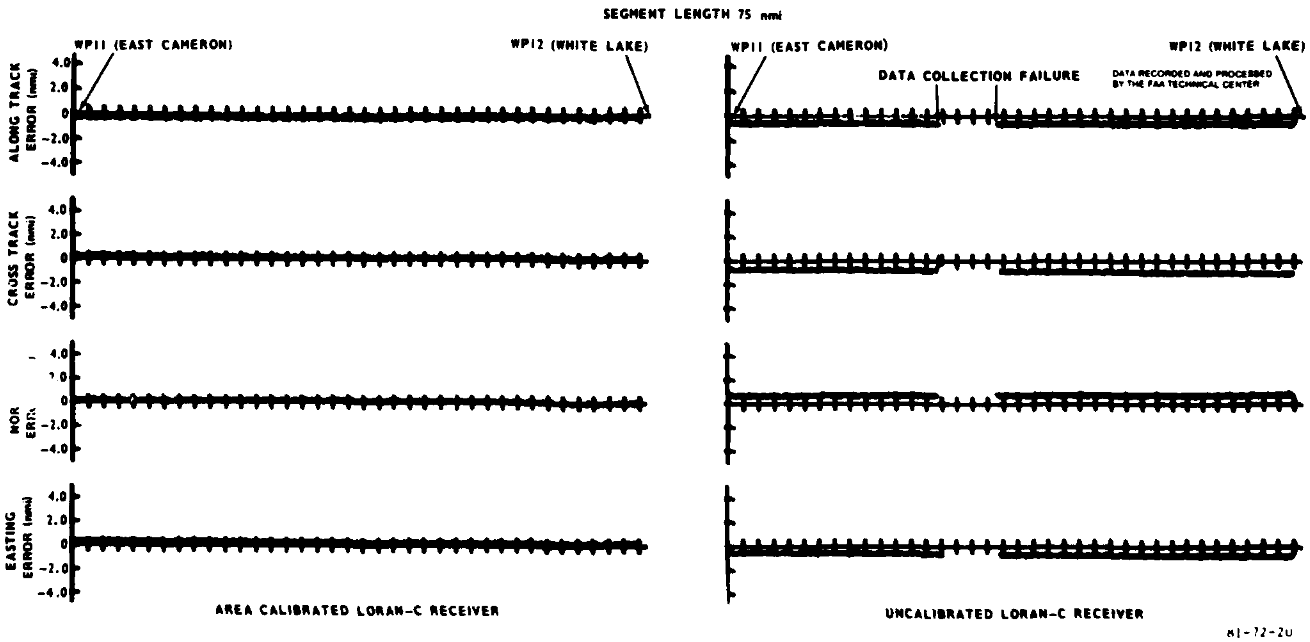

FIGURE 20. ERROR PLOTS FOR EAST CAMERON (WP11) TO WHITE LAKE (WP12), OVERWATER, MALONE, GRANGEVILLE, RAYMONDVILLE TRIAD, CALIBRATED AND UNCALIBRATED LORAN-C RECEIVERS

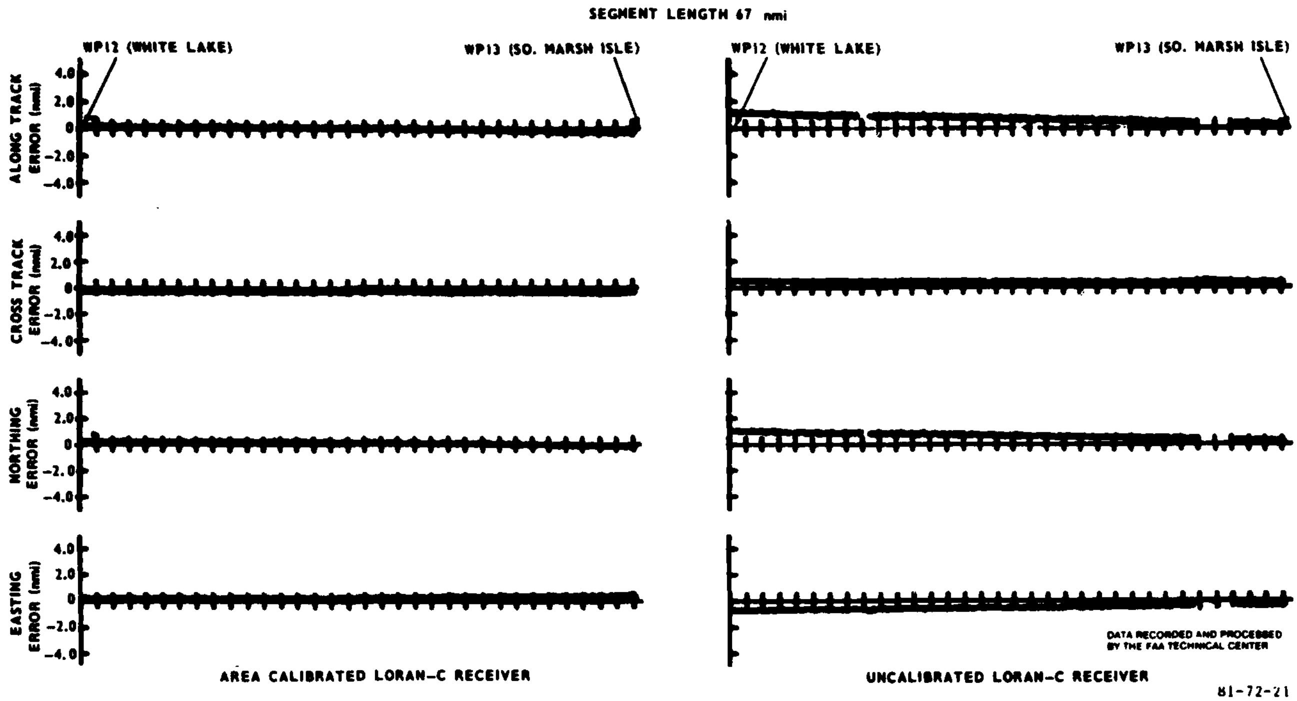

FIGURE 21. ERROR PLOTS FOR WHITE LAKE (WP12) TO SOUTH MARSH ISLE (WP13), OVER-WATER, MALONE, GRANGEVILLE, RAYMONDVILLE TRIAD, CALIBRATED AND UNCALIBRATED LORAN-C RECEIVERS

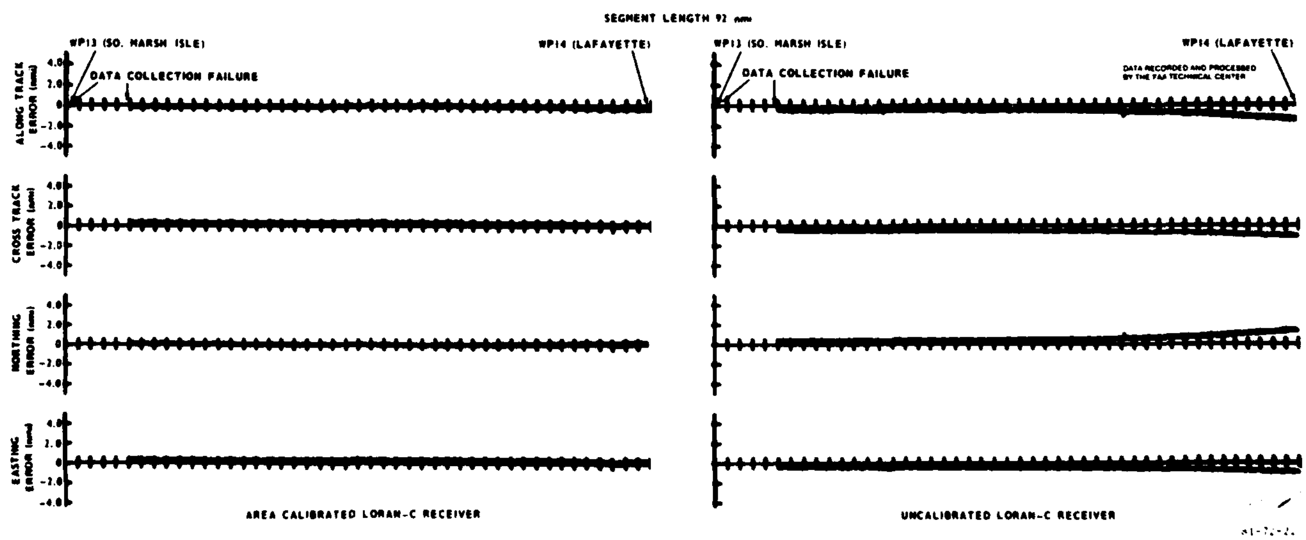

FIGURE 22. ERROR PLOTS FOR SOUTH MARSH ISLE (WP13) TO LAFAYETTE (WP14), OVER-WATER/LAND, MALONE, GRANGEVILLE, RAYMONDVILLE TRIAD, CALIBRATED AND UNCALIBRATED LORAN-C RECEIVERS

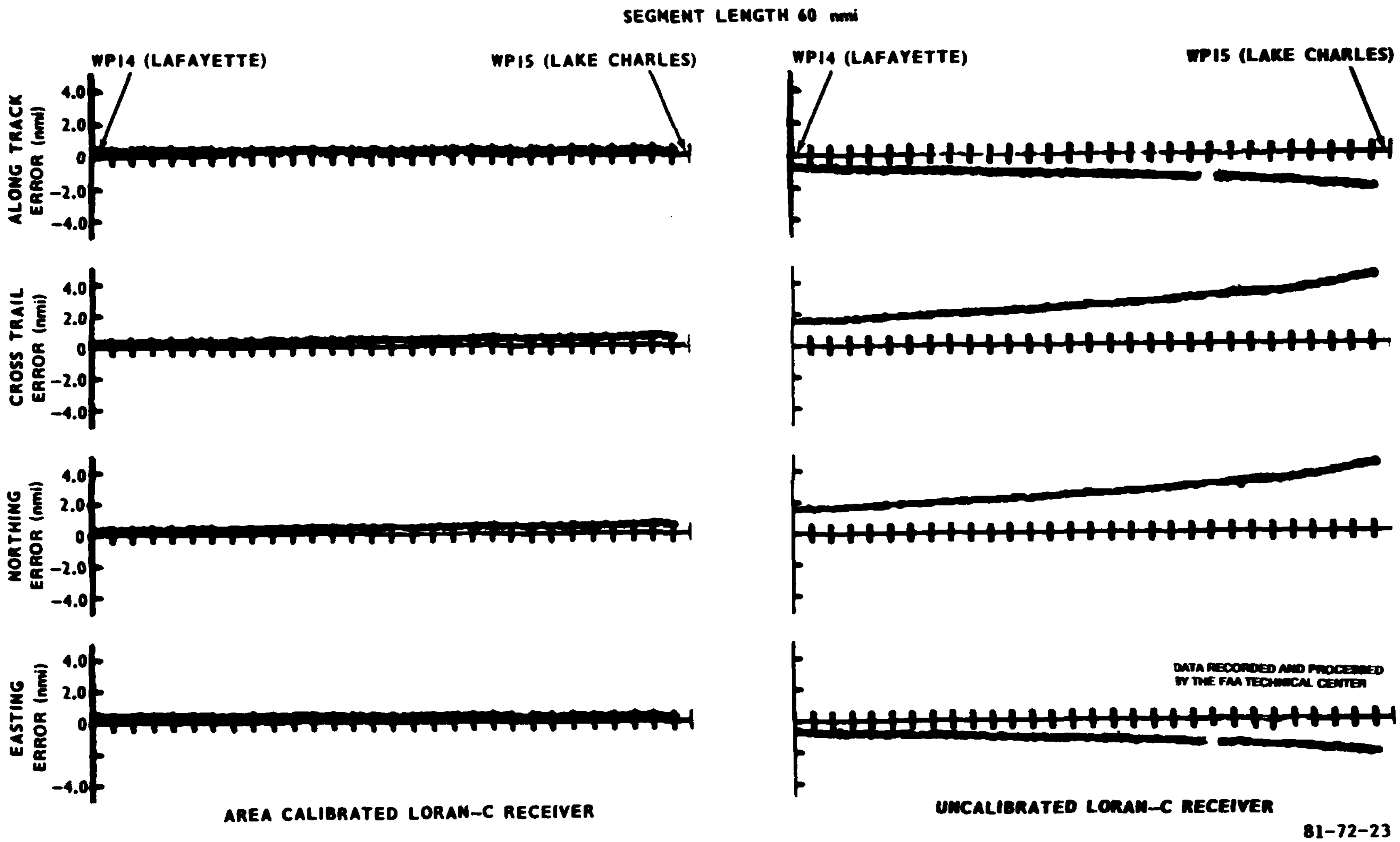

FIGURE 23. ERROR PLOTS FOR LAFAYETTE (WP14) TO LAKE CHARLES (WP15), OVERLAND, MALONE, GRANGEVILLE, RAYMONDVILLE TRIAD, CALIBRATED AND UNCALIBRATED LORAN-C RECEIVERS

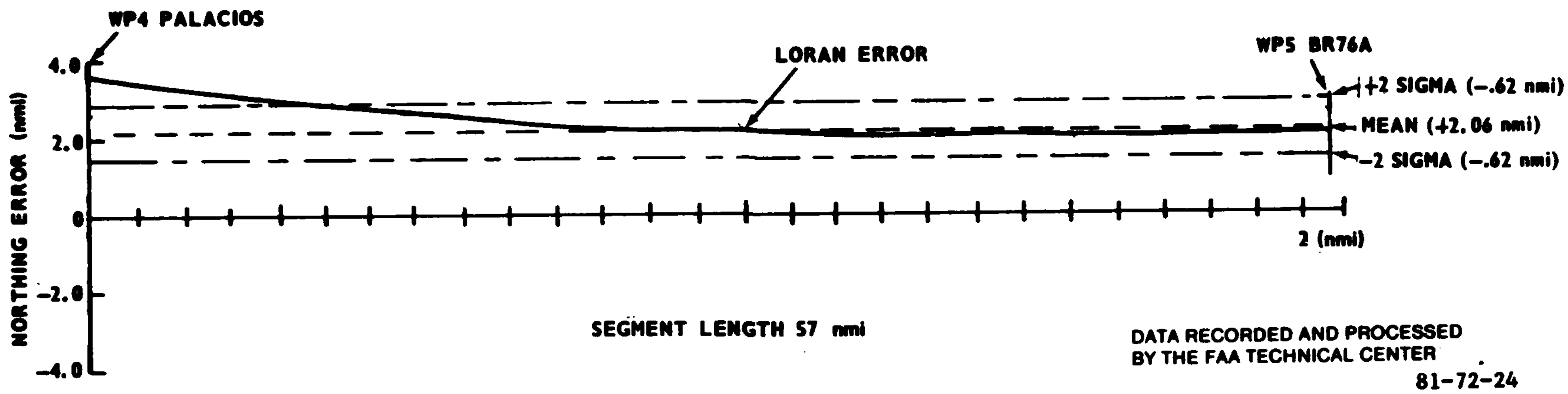

FIGURE 24. CHARACTERIZATION OF PROTECTED AIRSPACE REQUIRED

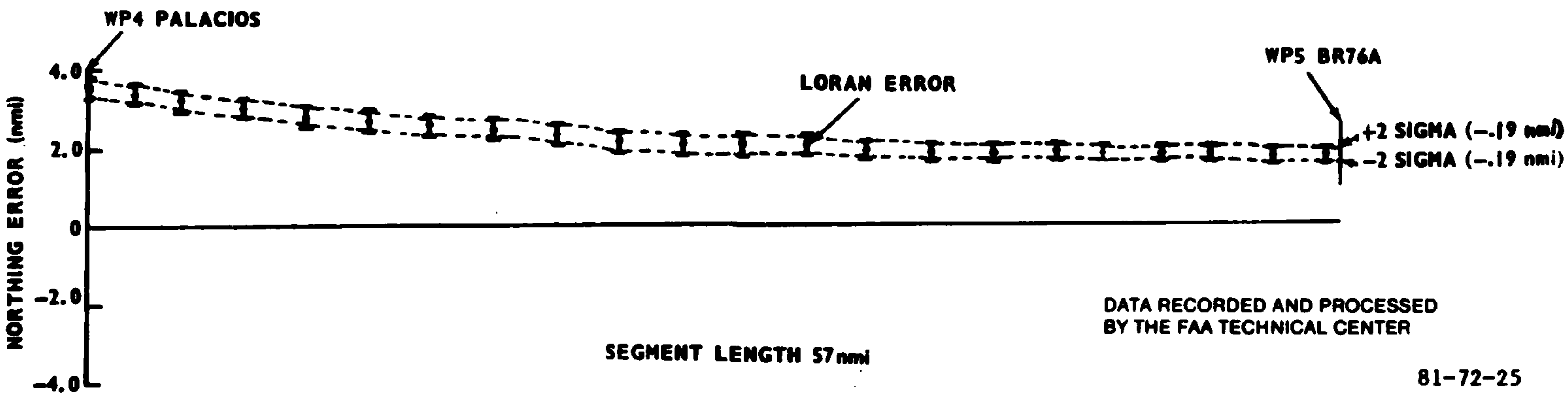

FIGURE 25. CHARACTERIZATION OF LORAN-C SIGNAL ERROR

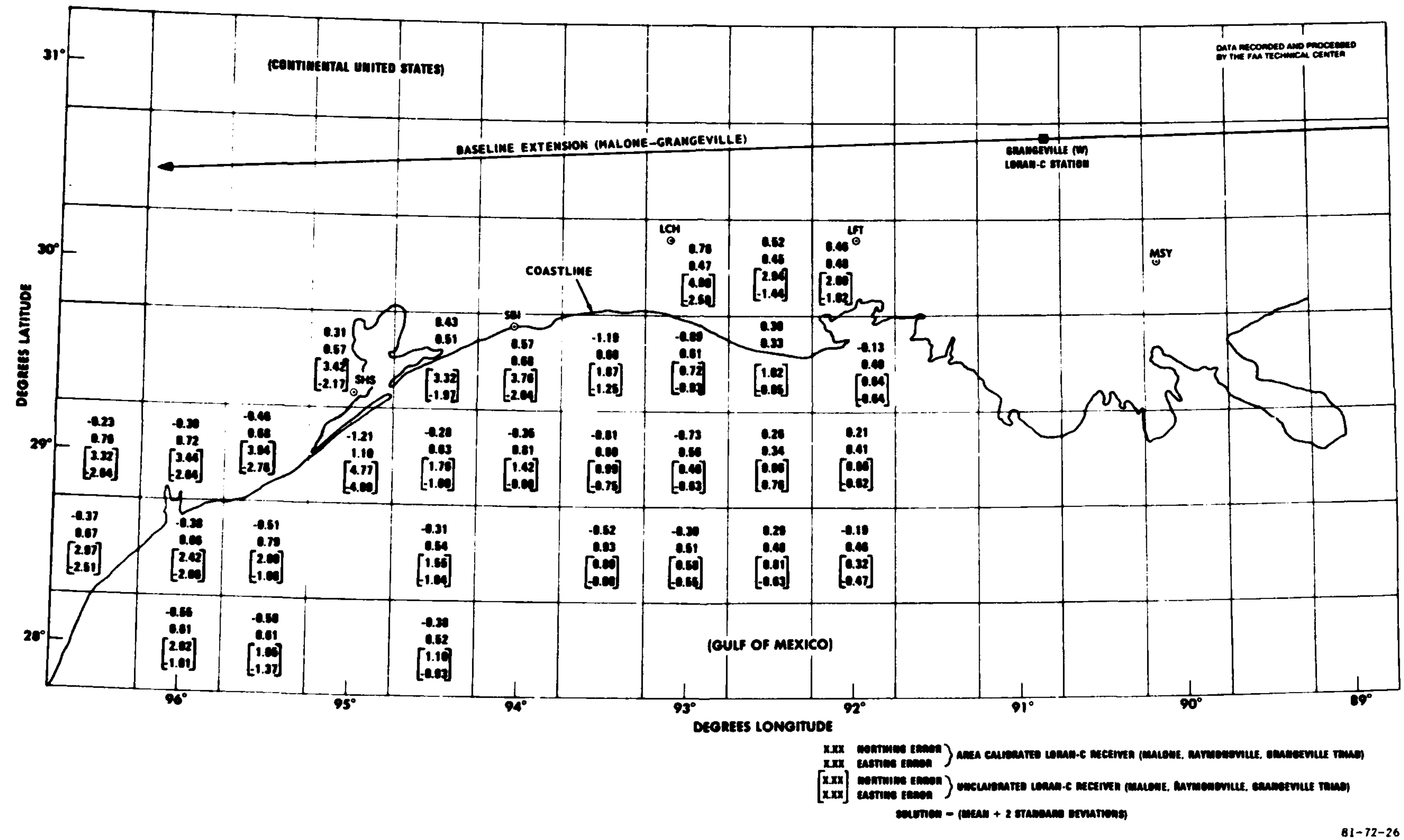

FIGURE 26. COMPOSITE NORTHING AND EASTING ERRORS FOR AREA CALIBRATED AND UNCALIBRATED RECEIVERS

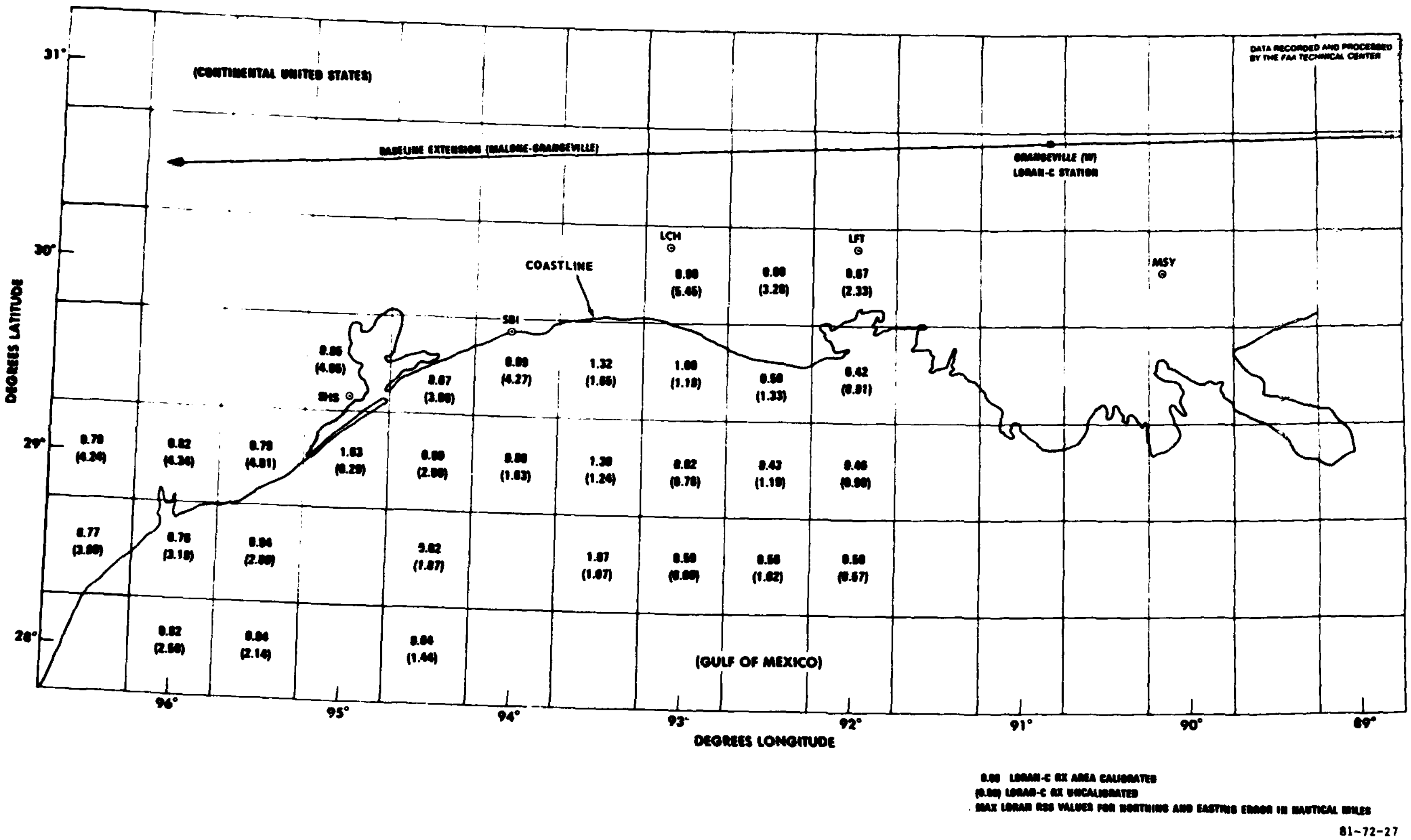

FIGURE 27. MAXIMUM RSS VALUES OF NORTHING AND EASTING ERRORS FOR CALIBRATED AND UNCALIBRATED RECEIVERS

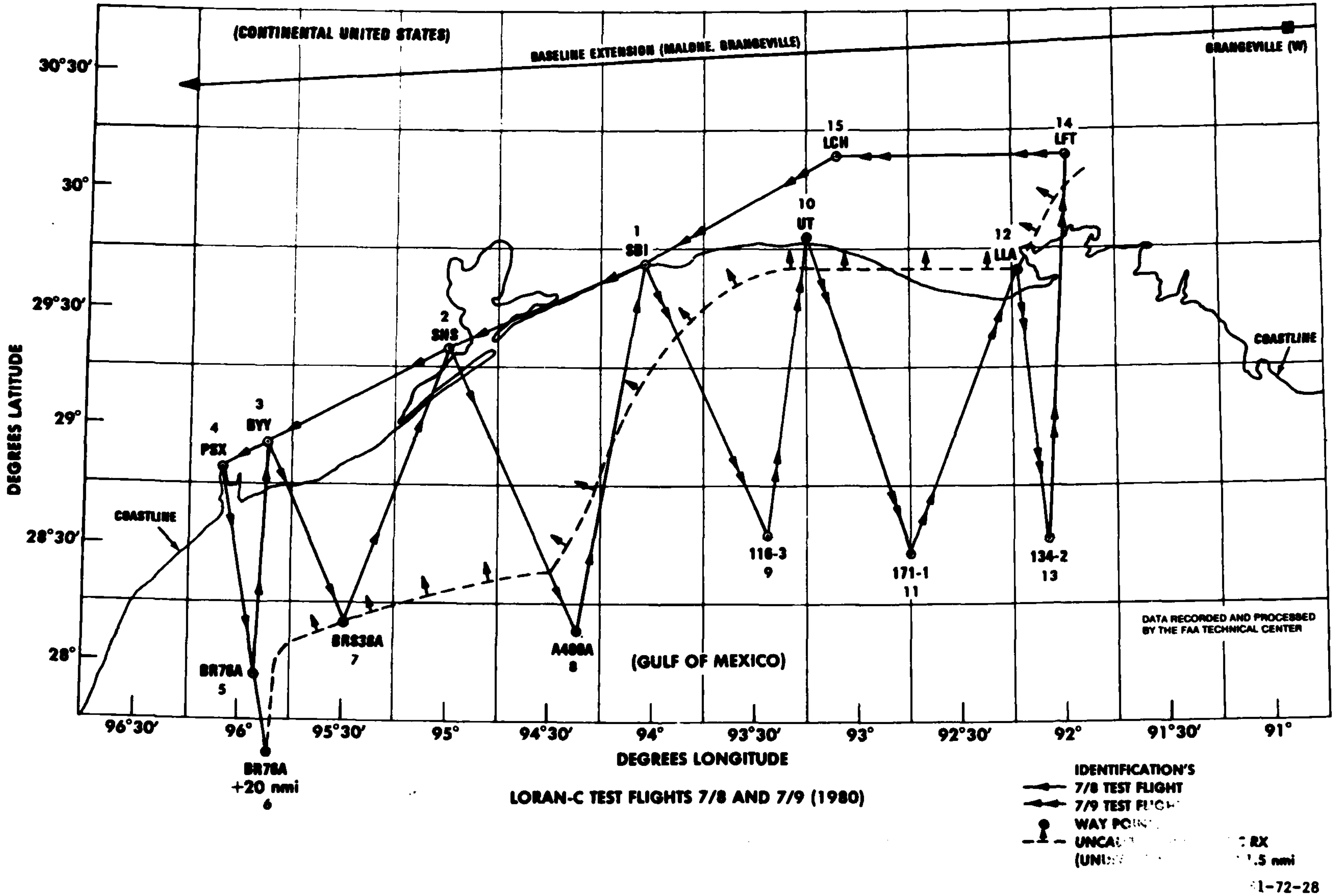

FIGURE 28. CONTOUR OF AC 90-45A EN ROUTE ACCURACY COMPLIANCE FOR UNCALIBRATED RECEIVER

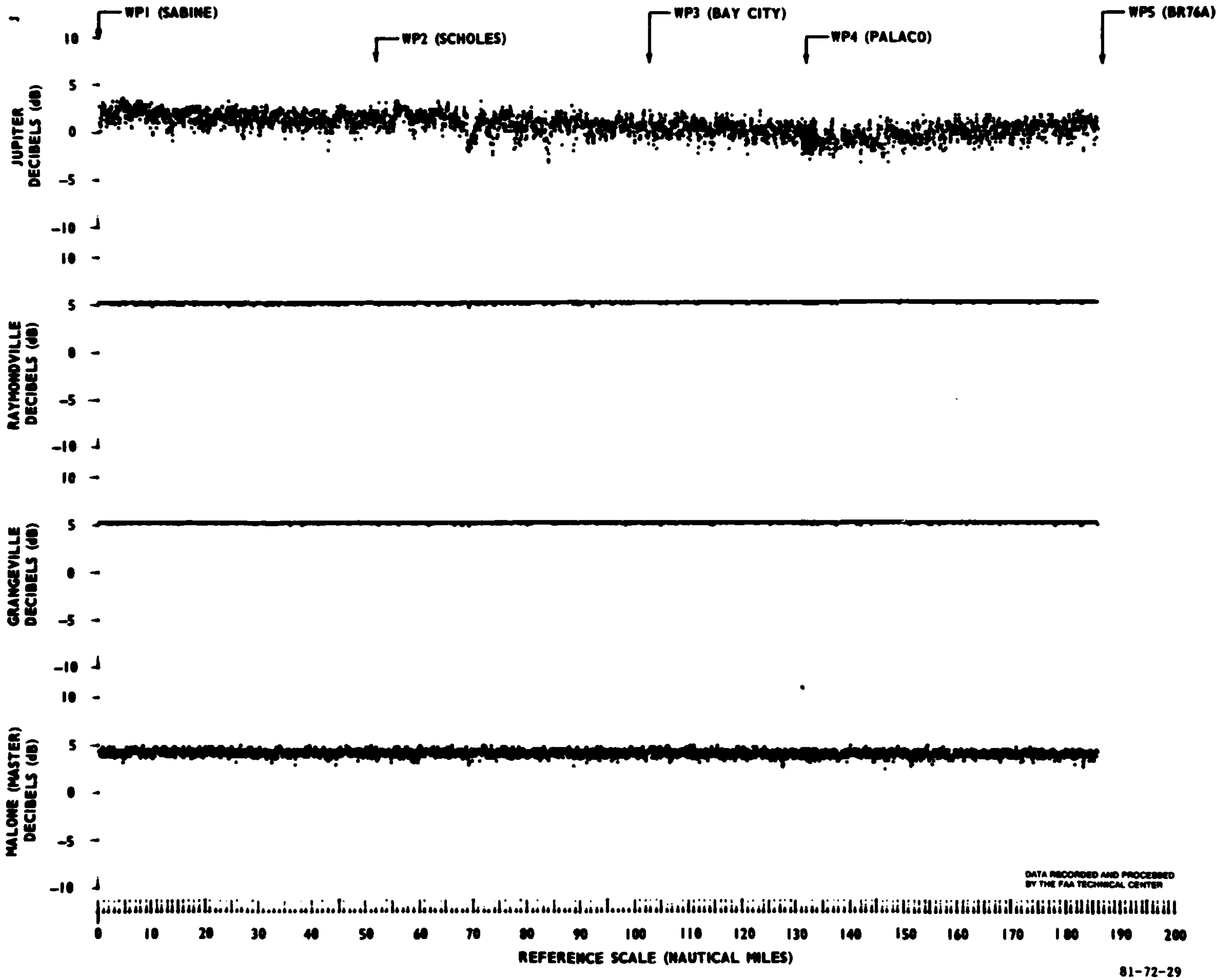

FIGURE 29. SIGNAL-TO-NOISE PLOT, WP1 TO WP5 LORAN-C RX CALIBRATED

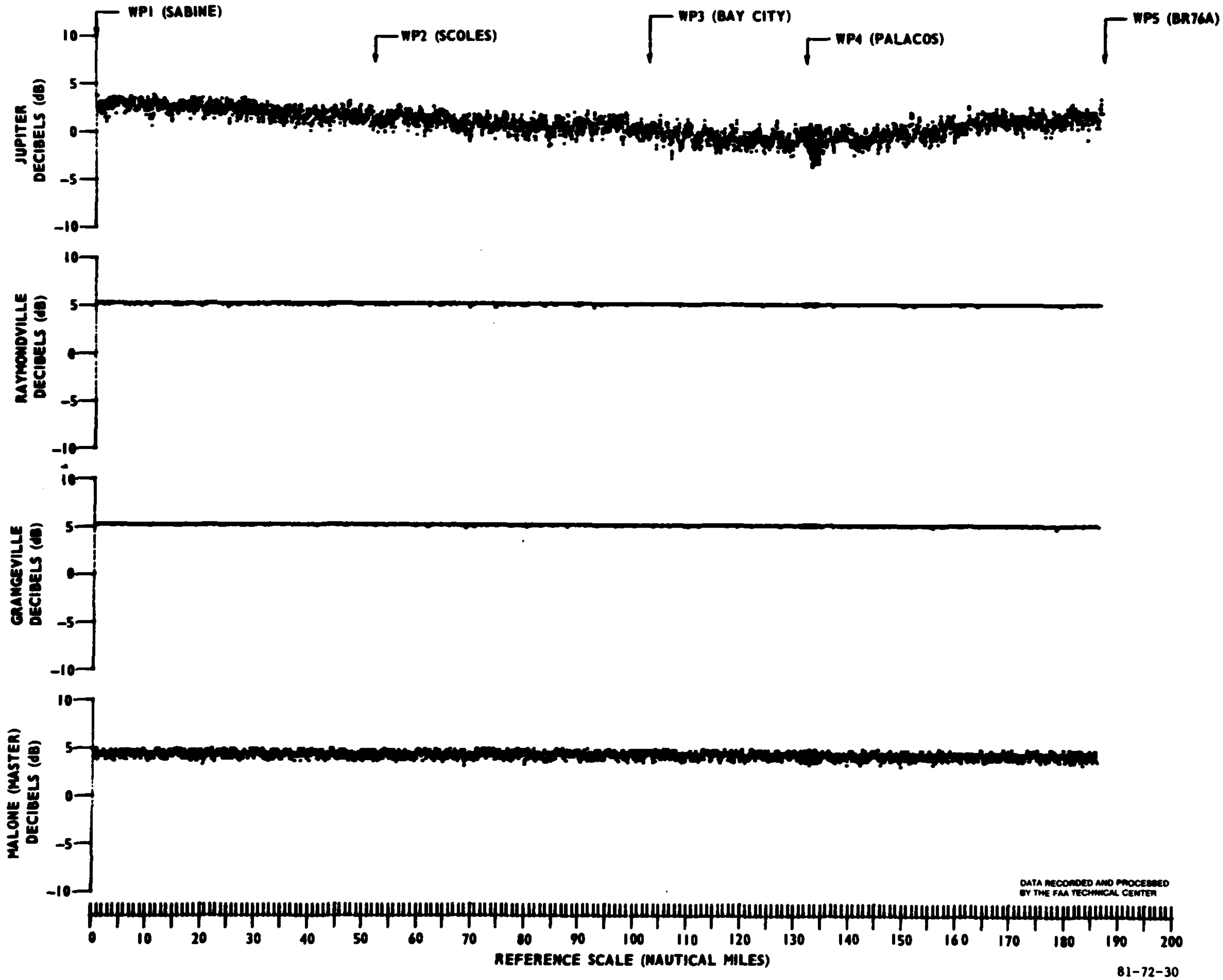

FIGURE 30. SIGNAL-TO-NOISE PLOT, WP1 TO WP5 LORAN-C RX UNCALIBRATED

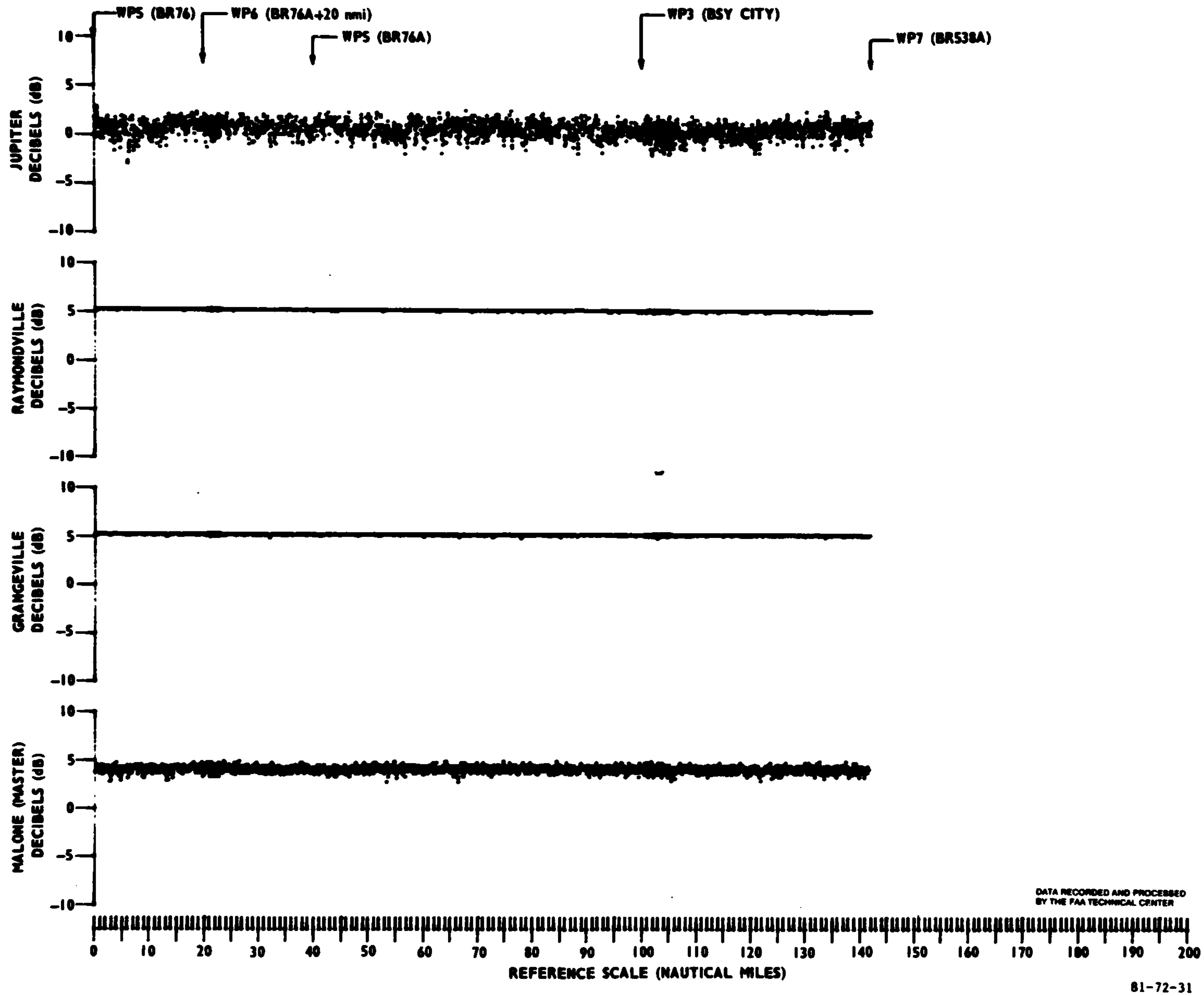

FIGURE 31. SIGNAL-TO-NOISE PLOTS, WP5 TO WP7 LORAN-C RX CALIBRATED

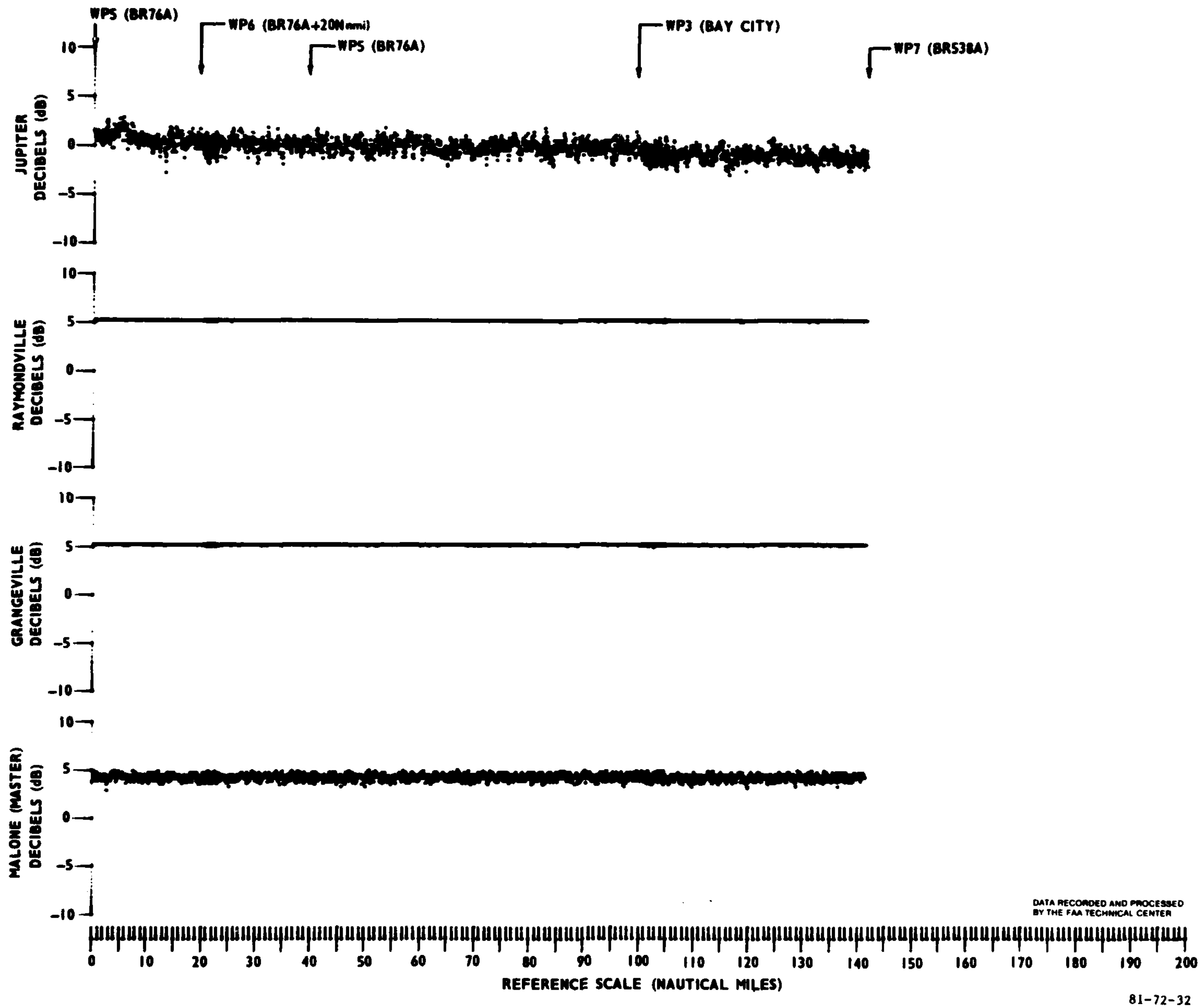

FIGURE 32. SIGNAL-TO-NOISE PLOT, WP5 TO WP7 LORAN-C RX UNCALIBRATED

APPENDIX A

CORRECTED INS POSITION ACCURACY

LTN-51 INS position errors are comprised of both linear and cyclic variation, which can combine to produce drift errors at a rate of up to 1 nautical mile (nmi) per hour. Variations due to mass imbalances, friction, and timing errors in the unit produce constant velocity and acceleration errors that degrade position accuracy. Nonlinear error terms are introduced by several sources of Schuler variations, sinusoids with a period of 84 minutes. The source of greatest Schuler error causes an amplitude of 0.1 nmi, while other lesser sources contribute a total of 0.1 nmi.

Linear drift compensation is achieved by computing the difference between INS and actual position over succeeding references, and determining the per second correction to be applied over intervening time segment. References were chosen for high visibility from the air and because they were at known latitude and longitude. Oil rigs were chosen for most of the reference points required.

Use of visual references causes some small errors in computation of the correction factor. The operational method employed was to have the copilot activate a switch when he believed he was directly over the reference. Switch position was recorded once every second with rest of the airborne parameters. The INS position recorded at that time was used to compute the correction factor. At speeds of approximately 180 knots, used for the entire flight test, an aircraft travels approximately 350 feet (0.06 nmi) per second. This is the uncertainty due to the recording method. The ability to judge position over the reference was estimated to be approximately 150 feet (0.025 nmi).

The sum of the errors discussed is 0.285 nmi in the worse case, with maximum Schuler effect. Also, each of the errors may occur in a positive or negative direction, and the possible error is actually +0.285 nmi, rounded off to +0.3 nmi for data analysis.

Data presented in table A-1 show the INS drift on the July 10, 1980, flight. They show a maximum drift of 0.171 nmi between INS position updates. In a perfectly linear system, the correction factor applied will eliminate all the error terms. However, the Schuler variations cause a remaining position uncertainty that may be as great as the total Schuler amplitude. Data show that, in most cases, the magnitude differences in latitude and longitude used to make the linear correction are much less than the corresponding drift magnitude which shows the cyclic variation. In all cases, the difference between these two is less than 0.2 nmi. It should be emphasized that these data are raw differences before INS correction is applied. After correction, there is no difference between the INS computed position and the actual position at the update point.

TABLE A-1. INS DRIFT ON JULY 10, 1980 FLIGHT

	Difference Values Actual Position Minus INS Position (nmi)		Computed INS Drift (nmi)		
Update Number	Northing	Easting	Northing	Easting	Drift Magnitude
1	-0.0048	-0.0011	-0.0048	-0.0011	0.0049
2	-0.023	0.022	-0.0182	0.0231	0.029
3	0.013	0.026	0.036	-0.048	0.06
4	-0.014	-0.0029	-0.027	0.0231	0.035
5	0.015	0.015	0.029	0.0179	0.171
6	-0.0065	0.0005	-0.0215	-0.0145	0.026
7	-0.0083	-0.0042	-0.0018	-0.0047	0.005
8	-0.011	-0.0051	-0.0027	-0.0009	0.003
9	-0.0014	0.011	0.0096	-0.0051	0.01
10	-0.011	0.0089	-0.0096	-0.0021	0.009