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Loran C Nonprecision Approaches

Robert Erikson

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16. Abstract

This report describes flight tests conducted by the Federal Aviation Administration (FAA) Technical Center at six airports across the continental United States. The airports were chosen to evaluate Loran C for nonprecision approaches over a large geographic area. The effects of user/transmitter geometry, signal-to-noise ratio, and terrain were examined to develop minimum operational performance criteria for nonprecision approaches. Five state-of-the-art receivers are evaluated in the report.

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EXECUTIVE SUMMARY

The flight test evaluation described in this report is part of a study on the use of Loran C for nonprecision approaches conducted by the Federal Aviation Administration (FAA). The objective was to provide inputs for developing an Advisory Circular (AC), National Standard, and minimum operational performance criteria. Flight tests were conducted by the FAA Technical Center at six airports across the continental United States. The airports were chosen to evaluate Loran C for nonprecision approaches under various user/transmitter geometries, signal-to-noise ratios (SNR's), and transmitter to airport terrains. The evaluation included: comparison of Loran C equipment accuracies (with and without area calibration) and pilotage with respect to AC 90-45A, acquisition and track of the Loran C signals, and operator interaction with the various Loran C receivers with respect to human factors.

The six airports were London, Kentucky; Atlantic City, New Jesey; Saginaw, Michigan; Billings, Montana; Grand Junction, Colorado; and Gallup, New Mexico. Airports were chosen with good SNR and good geometry, with marginal SNR and marginal geometry, and at or very near the anticipated limit of coverage. In addition, airports were also chosen such that different chains and various terrains between the transmitter and airport should be used by the Loran C receiver. At each airport five test conditions were flown: wide open, primary triad without area calibration, primary triad with area calibration, alternate triad without area calibration, and alternate triad with area calibration. Five approaches were conducted for each condition and airport. For each condition one Loran C receiver was selected to be used for navigation guidance by the pilot. Flight technical error (FTE) and total system crosstrack error (TSCT) were measured for that receiver.

Six Loran C receivers from four manufacturers were operated simultaneously to collect navigation equipment errors. The receivers were the Advanced Navigation Inc. ONI-7000 (2), the Micrologic ML-4000, the Teledyne TDL-711 and TDL-711A, and the Texas Instruments TI-9100.

Pilots found Loran C guidance very easy to follow and could meet the accuracy requirements for FTE except for one receiver in a series of approaches. The particular receiver had an update rate of about 4 seconds. The guidance from the receiver was difficult for the pilots to follow because of large jumps on the course deviation indicator (CDI) needle and the slow update rate.

Results of the flight tests indicate navigation equipment error can meet the accuracies of AC 90-45A for nonprecision approaches provided area calibration is used and the receiver is operated within the proper coverage area. Use of area calibration reduced the mean navigation errors but not to zero. Area calibration did not help the receivers meet the accuracy requirements in areas of poor geometry. The measured accuracy for a particular airport was not the same for all receivers. In general, navigation equipment errors varied as a function of geometry. To establish limits of coverage, the results at each airport were analyzed. It was found that the receivers operated properly at an SNR of -10 decibel (dB) and envelope to cycle deviation (ECD) of 4.2 microseconds, as measured by the ONI-7000 receiver. These results were similar

to the manufacturers' published specifications. Navigation equipment errors were found to be related to two parameters: conversion of time differences (TD's) to latitude and longitude and user/transmitter geometry. The mean navigation errors were related to coordinate conversion while the standard deviation of the navigation errors were related to the geometry. A performance index was established which included two terms: one for propagation modeling used to convert the TD's to latitude and longitude and the other for geometry. The allowance for modeling error or the navigation error means, as determined from flight data, was estimated to be 1,000 feet after area calibration. The large value is due to the many Loran C receivers used. Some receivers were better than this limit. The geometry limit was then established for the remaining error allowed by AC 90-45A which is 823 feet. This is equivalent to a geometric dilution of precision (GDOP) of 2,939 feet per microsecond as defined in the MITRE Airport Screening Model.

TSCT error was computed, using measured FTE and crosstrack error (CTE) data, and compared to the measured TSCT. Measured TSCT, FTE, and CTE data had non-zero means. No mention is made of data means in AC 90-45A when combining FTE and CTE to obtain TSCT. It was found that TSCT measured directly and computed from CTE and FTE were similar provided: (1) the standard deviations were combined in a root-sum-square (rss) method, (2) the means were added, and (3) the equations and constants used by the Loran C receiver and data reduction software were similar.

Acquisition on the wrong cycle was only a problem for one Loran C receiver at Billings and Grand Junction. Once the receiver was manually forced to track the proper cycle it performed correctly for that series of tests. The SNR for the weakest station was around -10 dB at these airports. At Gallup, several of the Loran C receivers were unable to acquire the Loran C signals. The SNR for the weakest station was approximately -14 dB. Of the receivers that could acquire, one experienced an undetected cycle slip. SNR and geometry at Gallup would make it outside the coverage limit for nonprecision approaches; therefore, this cycle slip should not be unexpected.

With Loran C receivers from four manufacturers it was possible to observe several different implementations of receiver operation. Selection of the displayed function, entry of data, display update rate, display of data, calculation of area calibration data, entry of area calibration data, pushbutton size, and pushbutton feedback varied from receiver to receiver. In general, the calculation of area calibration by the operator was a source of error. The more digits required to be entered as area calibration data, the more errors were introduced. The smaller the button size and less feedback from depressing the button, the harder it was to make correct data entries. Annunciation of receiver status was either a flashing display, status number, or separate lights for warning and advise codes. Annunication of area calibration in use included a status number or separate lights. Some receivers provided no indication that area calibration was in use. All receivers indicated a warning condition by raising the CDI flag.

In summary, Loran C can meet the accuracy requirements stated in AC 90-45A provided the receivers use area calibration and are operated within a good coverage area.

INTRODUCTION

OBJECTIVE

The objective of this project was to provide inputs for developing an Advisory Circular (AC), a National Standard, and minimum operational performance criteria for Loran C nonprecision approaches. The following key issues were evaluated using current state of the art Loran C receivers while flying actual approaches:

1. Flight Technical Error (FTE). Can pilots follow Loran C derived guidance within the limits of AC 90-45A?

2. Navigation Equipment Error.

   a. Can Loran C meet the accuracy requirements in AC 90-45A with or without area calibration?

   b. Establish minimum operation criteria which can be used to identify areas for nonprecision approaches.

3. Total System Crosstrack (TSCT). Can FTE and crosstrack error (CTE) be combined according to the methods described in AC 90-45A?

4. Acquisition and Track. Do Loran C receivers have problems acquiring Loran C stations on the proper cycle? Do Loran C receivers experience cycle slip?

5. Human Factors. How well do the present technology Loran C receivers interact with the operator?

BACKGROUND.

Loran C is a pulsed low frequency (100 kilohertz (kHz)) navigation system. Range, accuracy, and groundwave operation make it very attractive for nonprecision approaches, especially in mountainous areas.

Within the last several years at least 10 manufacturers have produced new airborne Loran C receivers. Design of the receivers has taken many directions. Receiver front ends are divided into hard limited and linear, with the first being the most popular. Some are capable of only tracking a master and two secondaries (master dependent) on one chain, while others track and use up to five stations per chain on several chains (cross chain) for navigation.

Coordinate conversion, the process of converting Loran C time differences (TD's) to a geodetic position, has also seen a great deal of change. The process involves compensating for the various propagation velocities of the Loran C signal over a nonhomogenous earth. The propagation models generally include secondary phase delay and additional secondary phase delay terms. Secondary phase delay compensates for propagation delay due

to an assumed all seawater path between the transmitter and receiver. It is the difference between a free space propagation path and a seawater path. In reality, the path between the transmitter and receiver will contain various land and water segments, each having a different propagation velocity. It is the additional secondary phase delay which is intended to account for the differences between an all seawater path and a mixed path.

Early receivers could only convert a Loran position to a geodetic position using two time differences and a simple seawater propagation correction. Coordinate conversion on current production Loran C receivers vary in complexity from simple to very elaborate. Variations in the coordinate converters are in numbers of TD's used for the navigation solution and the complexity of the model used to correct for the propagation path. Most receivers still use the two best TD's from one chain in their navigation solution. At least one manufacturer has implemented a navigation solution which is able to use up to eight stations from various chains in its computations. However, the implementation is only for hyperbolic navigation, which requires at least two stations from one chain for that chain to be used. Time differences for the simpler receivers requires the master to be one of the three stations to form the hyperbolic lines of positions. Many of the receivers can now use any station in the chain as a pseudomaster.

Corrections necessary to compensate for the various propagation speeds of the transmitted signals are also implemented differently. The corrections are divided into two separate groups: fixed values and constants dependent upon propagation path. Fixed values assume all seawater paths or some optimized value which best describes the expected paths between the transmitters and receiver. For those units which calculate a propagation correction based on the signal path, the process is more complex. Each path between the various transmitters and the receiver must be analyzed in detail. The analysis involves computation of a correction which is obtained from dividing the path into various conductivities and combining the delay associated with the conductivity and distance.

Several Loran C receivers have been approved for instrument flight rules (IFR) operation in en route and terminal areas within certain geographic areas. Other manufacturers are currently preparing for approval in the terminal and en route areas. A request has been received by the Southwest Region to approve nonprecision approaches with Loran C. An FAA Loran C working group has been established to address the many questions involved with the approvals. AC 20-121, "Airworthiness Approval of Airborne Loran C Systems for Use in the U.S. National Airspace System" (Related Documents number 16), was published and released in August 1984. At present, Loran C is not approved for nonprecision approaches.

Technical issues affecting approval may be divided into two groups, safety related and positional accuracy. Safety related issues include backup modes of operation such as availability of other chains or triads, variation in local noise, and time to detect and annunciate a problem. Undetected station outages, skywave interference, and improper tracking point selection may cause large position errors not typical of "normal"

Loran C performance. Related Documents number 8, "World Distribution and Characteristics of Atmospheric Radio Noise," shows atmospheric noise varies over 30 decibels (dB) as a function of the seasons.

Each of the above issues may well require a signal-to-noise ratio (SNR) substantially higher than the value required to acquire and track. Factors affecting position accuracy are interrelated but manifest themselves as navigation errors in along-track, crosstrack, and TSCT. The sources of errors are TD bias caused by propagation modeling error, variation of TD standard deviation, time delays in computing and displaying navigation information, as well as the TD gradients and crossing angles associated with triad station geometry.

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EQUIPMENT

LORAN C RECEIVERS.

The following Loran C airborne receivers were used for this series of tests: Teledyne TDL-711A and TDL-711, Micrologic ML-4000, Texas Instruments TI-9100, and Advanced Navigation Inc. ONI-7000. All units were production aviation Loran C receivers available for public purchase. The TDL-711 and ML-4000 are being phased out and replaced by other units. Table 1 provides a summary of the Loran C receiver specifications.

AIRCRAFT TRACKING AND DATA SYSTEM.

The Aircraft Tracking and Data System (ATADS) was used as the aircraft position reference. The position is determined using multiple distance measuring equipment (DME) ranges from several DME ground stations. The DME ground station transmitter may be the normal International Civil Aviation Organization (ICAO) pulse or a fast rise time (precision) pulse. The airborne equipment consists of a modified airborne DME interrogator and a microprocessor unit. Station channeling, station acquisition, and

TABLE 1. LORAN C RECEIVER MANUFACTURE SPECIFICATIONS

Parameter	Manufacturer Model: Teledyne TDL-711A	Teledyne TDL-711	Micrologic ML-4000	Advanced Navigation Inc. ONI-7000	Texas Instruments TI-9100
Area of Operation	All Existing chains	16 triads	All existing chains	All existing chains	All existing chains
Receiver Type	Hard Limit	Hard Limit	Hard Limit	Linear	Hard Limit
No. of Chains Simultaneously Tracked	1	1	1	4	1
No. of Stations Simultaneously Tracked	5	3	6	8	5
Chain/Station Selection					
a. Auto/Manual	Auto Advise	Manual	Automatic	Automatic	Automatic
b. Method	Man. Select		Geometry	Largest Signal	Geometry
Acquisition	Automatic	Automatic	Automatic	Automatic	Automatic
Notch Filters					
a. Numbers	2	2	4	3	
b. Method Set	Manual	Manual	Manual	Automatic	Automatic
Minimum SNR for Operation					
a. Acquisition	---	-10 dB	---	-12 dB	---
b. Track	---	-16 dB	-17 dB	-18 dB	---
Maximum Signal Imbalance	---	60 dB	---	60 dB	---
Position Fix					
a. No. of chains (if > 1 cross-chain)	1	1	1	4 max	1
b. No. of stations	3	3	3	8 max	3

TABLE 1. LORAN C RECEIVER MANUFACTURE SPECIFICATIONS (CONTINUED)

Parameter	Manufacturer Model: Teledyne TDL-711A	Teledyne TDL-711	Micrologic ML-4000	Advanced Navigation Inc. ONI-7000	Texas Instruments TI-9100
Loran C GRID	Hyperbolic	Hyperbolic	Hyperbolic	Hyperbolic	Hyperbolic
Master Independence					
a. Acquisition	no	no	no	*	no
b. Track	yes	yes	no	yes	yes
North Reference (operator selectable)	Mag/True	Mag/True		Mag/True	Mag
Grid Reference					
a. Lat/Long	yes	yes	yes	yes	yes
b. TD	yes	yes	yes	yes	yes
Coordinate Conversion Model	**	Seawater	**	Based on Millington's Method	**
Area Calibration	yes	yes	yes	yes	yes
Dedicated TRIAD	yes	yes	yes	yes	yes
Maximum Velocity (unaided) Knots	950	950	1000	600	565
Software Version		12 x 1	A251	Nav 5.75 Rec 4.95	A371

Note:

* Requires peak energy of the master.
** Single optimized value which gives best results for both land and sea.

range tracking are controlled by the microprocessor. The normal sequencing rate of the cycler/tracker is 10 stations per second. Up to 10 stations may be tracked using any combination of normal or precision pulses. The system may be configured for free scan (auto search and acquisition) or preprogrammed (which uses only selected ground stations). Five portable precision DME ground systems are provided to obtain more precise position fixes or coverage in areas without adequate signal coverage from commissioned DME facilities.

For more information refer to Related Documents number 1, "Aircraft Tracking and Data Systems (ATADS), En route Accuracy."

AIRBORNE DATA COLLECTION SYSTEM.

A Norden PDP-11/34M mini-computer was used to collect and provide selected engineering data to the operator during flight. An aircraft systems coupler was used to interface the various equipment to the PDP-11/34M. Table 2 lists the various Loran C parameters that were recorded on 9-track magnetic tape, while table 3 lists additional parameters recorded. A line printer was used to print selected engineering data both in-flight and post-flight.

SURVEY EQUIPMENT.

In order for the ATADS to provide accurate aircraft positions, each of the precision portable beacons must be accurately located. To evaluate Loran C performance, all positions must be referenced to a common grid system, in this case the World Geodetic System of 1972 (WGS-72). Two different types of instruments were used to accurately determine the geodetic positon of each beacon: a JMR-4 satellite receiver and a Hewlett Packard (HP) 3810 "Total Station."

Two geodetic positions in WGS-72 coordinates were obtained with the JMR-4's and served as the reference points for the HP 3810. The HP 3810 was then used to determine the relative bearing and distance to all ATADS portable beacons, runway thresholds, and aircraft calibration points. As a check, the distance for the third side of each triangle was measured and compared to the calculated value obtained from the remaining measured sides and included angle. Distances obtained using the HP 3810 exhibit little error because of its electronic measurement capability, ease of operation, and digital display. Stated errors for the HP 3810 are less than 1 inch for distances up to 1 mile, with angular measurements less than 10 seconds of arc. Point positioning using the JMR-4 yields errors less than 5 meters.

DISCUSSION

The following six airports were selected to evaluate Loran C performance during actual nonprecision approaches. Aircraft positions were determined using ATADS. Appendix A contains approach plates used for each airport with waypoints. Figure 1 is a composite of the United States Coast Guard

TABLE 2. LORAN C DIGITAL OUTPUT DATA

	TDL-711	TDL-711A	ML-4000	ONI-7000	TI-9100
Present Position Lat/Long	x	x	x	x	x
Station Status			M + 5	8	
Station SNR's	M + 3	M + 4	M + 5	8	
Time Differences	2	4	2	8 TOA	
ECD's	M + 3	M + 4		8	
To Waypoint Lat/Long	x		x	x	x
From Waypoint Lat/Long	x		x		x
Crosstrack Error	x	x	x	x	x
Ground Speed			x	x	x
Distance to Go	x	x	x	x	x
Front Panel Switch Setting			x	x	
En Route/Approach				x	
Annunciator Lamps				x	
Receiver Status	x	x		x	x
Grid Reference				x	
Bearing to Waypoint				x	x
Desired Track				x	x
Estimated Time En Route				x	x
Heading				*	
True Airspeed				*	
Notch Filter Setting				x	
Secondary Phase Delay				x	
Triad in Use		x		x	

Note:

*Require TAS and Mag Heading into ONI-7000, but is not used for navigation.

x = Data present in digital output
M = Master
TOA = Time of Arrival

TABLE 3. REMAINING DIGITAL DATA RECORDED

TIME:	Hours Minutes Seconds Milliseconds
LTN-51 INS:	Present Position Heading Track Angle Ground Speed
ADC-80:	True Airspeed Altitude
ATADS:	Multi-DME Ranges With Time Tags
CDI:	Digitized analog course deviation information from the Loran C system that was displayed to the pilot and the digitized course guidance found in the receivers digital data stream.

INS = Inertial navigation system.

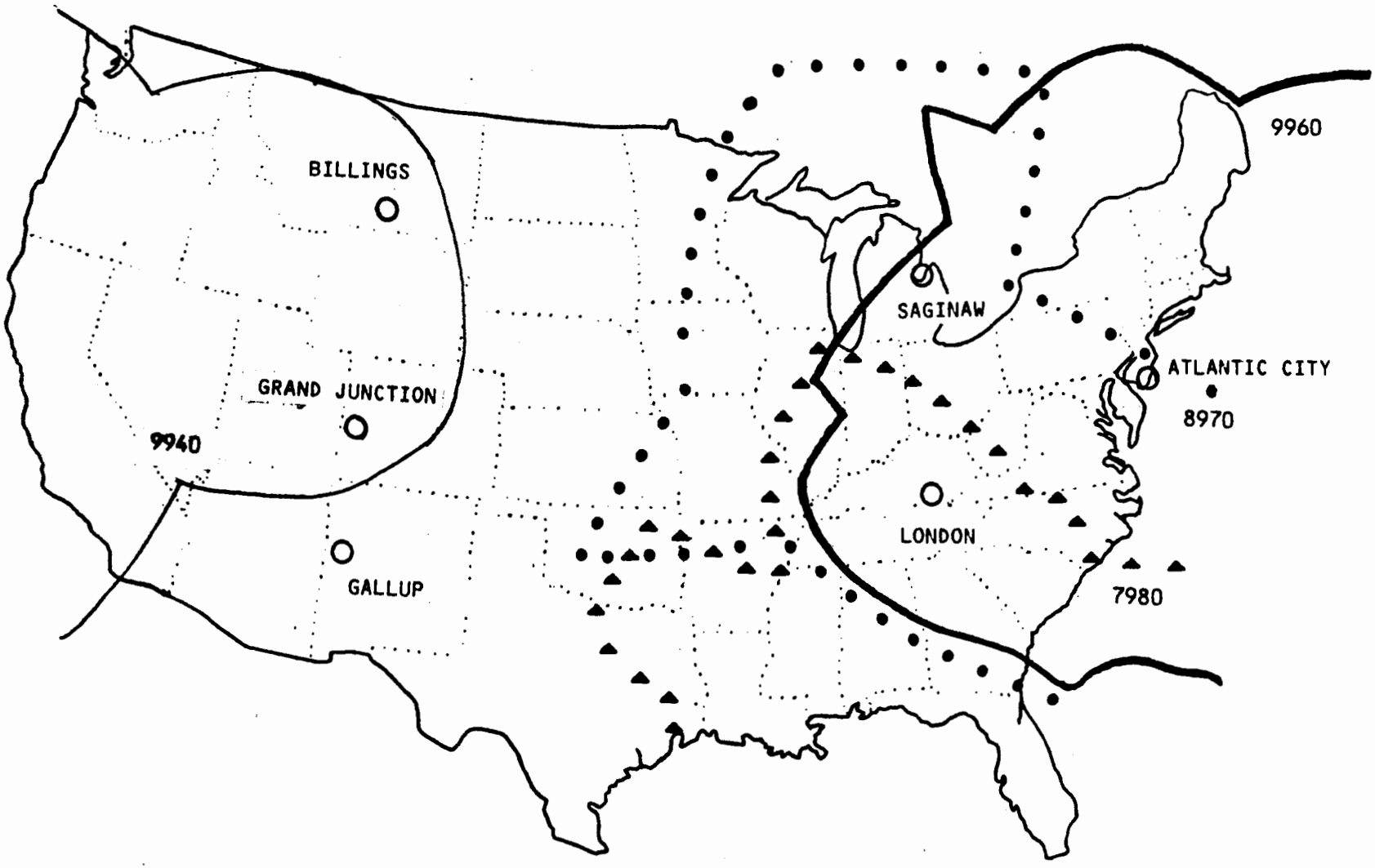


FIGURE 1. UNITED STATES COAST GUARD PREDICTED LORAN C COVERAGE

Loran C coverage charts for the continental United States, obtained from Related Documents number 3.

1. Atlantic City, New Jersey. Located within the 9960 chain with good geometric dilution of precision (GDOP) and adequate signal-to-noise ratio (SNR) while on the edge of the 8970 chain.

2. London, Kentucky. Located within the 9960 and 7980 chains. One year of seasonal ground Loran C stability data has already been collected on the 9960 chain. The terrain is mountainous with good GDOP and adequate SNR from both chains.

3. Saginaw, Michigan. Located within the 9960 and 8970 chains. Predictions indicate good GDOP and adequate SNR from both chains. Reports by users indicate poor signal reception and large positional errors.

4. Gallup, New Mexico. Located within 30° of the baseline extension from the master station Fallon and the secondary station Searchlight (Y) of the 9940 chain (poor GDOP). Predictions indicate marginal SNR conditions for the winter, but summer operation may not be possible due to the increased atmospheric noise.

5. Grand Junction, Colorado. Located within the 9940 chain with reasonable SNR and GDOP values. Due to the many mountainous transmission paths, envelope-to-cycle discrepancy (ECD) values are expected to be affected.

6. Billings, Montana. Located within the 9940 chain and at the expected limit of SNR and GDOP. Again, the transmission paths are mountainous.

Table 4 shows a summary of the nonprecision approach conditions flown. In general, five approaches were conducted in each of the following modes: the wide open mode (automatic station select), dedicated mode using the primary triad, dedicated mode using an alternate triad, and both dedicated modes using area calibration. Area calibration values were determined with the aircraft parked over a surveyed point on the airfield. Manufacturers published methodologies were used to obtain calibration values. The calibration values were obtained just prior to flying the approaches. Along-track errors (ATE's) and CTE's were computed for each receiver and condition. FTE's were obtained from the course guidance information flown by the pilot. Course guidance information was obtained from the course deviation indicator (CDI) and Loran C receiver's digital data stream. A different Loran C receiver was selected for CDI guidance for each series of five approaches. Due to large positional errors and special requests by air traffic control, not all receivers were flown for FTE at each site. However, with the selected FTE flights verification of the equation to combine FTE and CTE as a root sum square (rss) for TSCT error can be made. FTE was obtained using three high time instrument rated test pilots. The flights were all conducted under visual flight rules (VFR) conditions without the pilots using a hood to simulate instrument meterological conditions (IMC).

TABLE 4. SUMMARY OF NONPRECISION APPROACH CONDITIONS

Airport	Parameter	Flight Series 1 Wide Open	2 Without Area Cal.	3	4 With Area Calibration	5
Atlantic City, NJ	Chain/Triad	(A)	9960MXY	---	9960MXY	---
	FTE Receiver	---	ONI-7000		TDL-711A	
London, KY	Chain/Triad	(A)	9960MYZ	7980 MWZ	9960MYZ	7980 MWZ
	FTE Receiver	ONI-7000	ML-4000	---	TI-9100	TDL-711A
Gallup, NM	Chain/Triad	(A)	9940MWY	9940MXY	9940MWY	9940 MXY
	FTE Receiver	---	---	---	---	---
Saginaw, MI	Chain/Triad	(A)	8970MXY	9960MYZ	8970MXY	9960MYZ
	FTE Receiver	TDL-711A	TI-9100	ONI-7000	TDL-711A	ML-4000
Billings, MT	Chain/Triad	(A)	9940WXY	9940WXY	9940MWY	9940WXY
	FTE Receiver	ONI-7000	ONI-7000 ML-4000	TDL-711	TDL-711	TI-9100 ONI-7000
Grand Junction, CO	Chain/Triad	(A)	9940MWY	9940WXY	9940MWY	9940WXY
	FTE Receiver	ONI-7000	TDL-711A	TI-9100	TDL-711	ML-4000

Note:

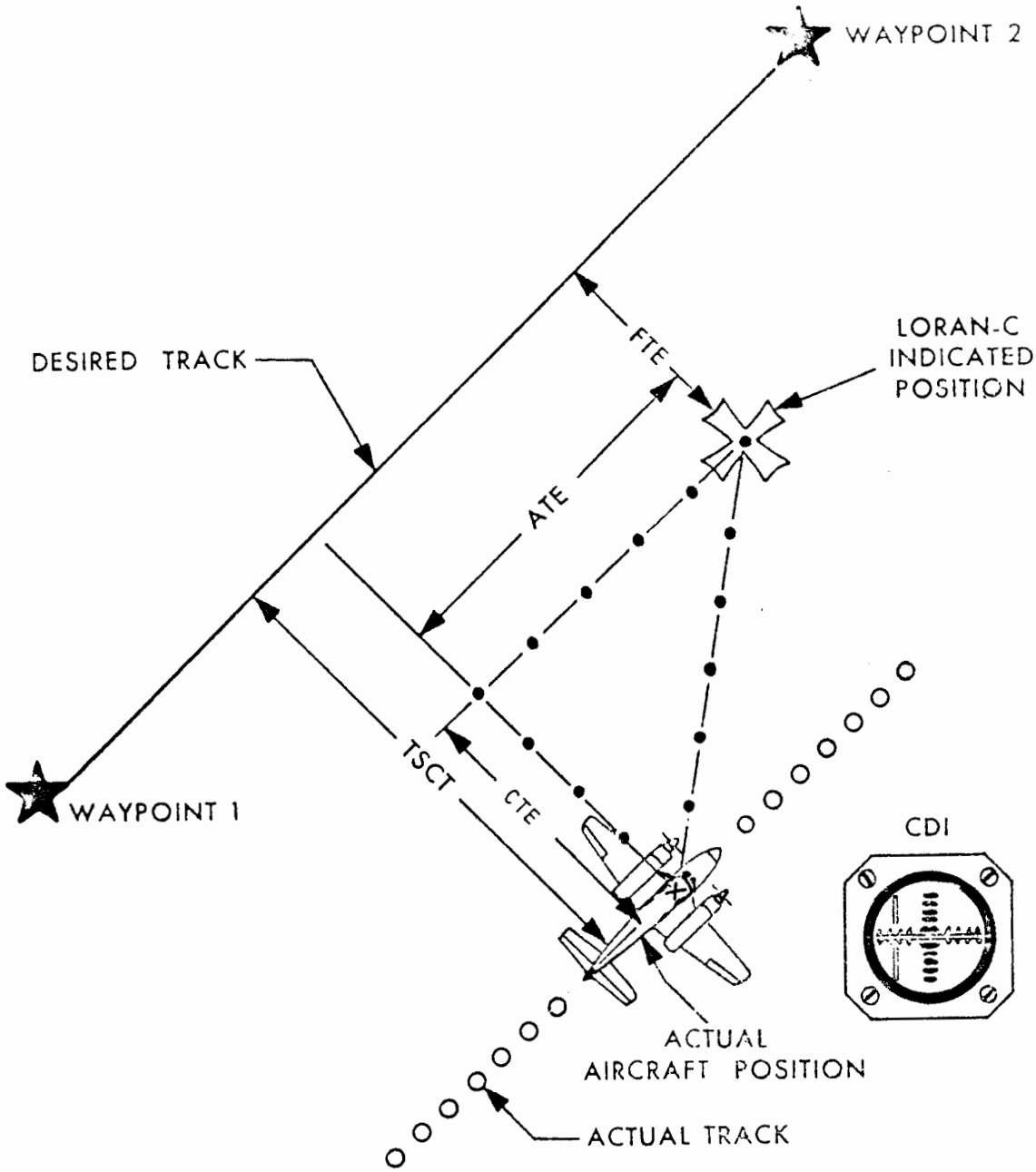
A = receiver allowed to pick chain and triad.

RESULTS

Tables 5 to 27 contain a summary of results for each airport. Each airport has four tables except Gallup. The first type of table (type 1), "Summary of Navigation Equipment Errors" (tables 5, 9, 13, 17, 21, and 24) show the statistical mean and standard deviations of the ATE's and CTE's for a number of runs. The errors represent navigation equipment errors and not pilotage errors. The errors are the difference between the present position of the aircraft as recorded from the Loran C receivers digital data output and the actual position of the aircraft. Error differences in latitude and longitude are rotated into ATE's and CTE's based on the direction of desired track.

Figure 2 shows a graphic representation of the errors while detailed equations may be found in appendix B. Column 1 of the navigation equipment error tables shows the Loran chain used, column 2 the Loran stations used, column 3 the mode of the receiver, column 4 the Loran receiver (ONI-1 = ONI-7000 receiver number 1, ONI-2 = ONI-7000 receiver number 2), column 5 the number of samples, column 6 the total number of runs for the sample size followed by the number of individual runs meeting AC 90-45A criteria in parenthesis, and columns 7 and 8 are the mean and standard deviations of the along-track receiver errors for each series of test conditions. Columns 9 and 10 are the mean and standard deviations of the crosstrack receiver errors for each series of test conditions. (The output rate of the ML-4000 was once every 4 seconds. Several runs had to be combined to obtain a sample size of 30 for meaningful statistics.) A line through the data table indicates that Loran C receiver did not acquire, or had problems which made the data invalid. At Billings and Grand Junction the alternate triads were master independent. The ML-4000, TDL-711, and TDL-711A were not used in the master independent mode. Special flights were conducted to investigate the effects of data latency. A description of special flight tests, data, and analysis of results may be found in appendix C. Data presented in this report were not adjusted for data latency.

The second type of table (type 2), "Summary of TD Bias" (tables 6, 10, 14, 18, 22, and 25), shows a summary of the TD bias for various triads used at each airport. TD bias was defined as the difference between the TD's as measured by the Loran C receiver and a calculated value based on the present position of the aircraft and the DMA seawater propagation model. The equations may be found in appendix B. Column 1 of the table lists the Loran receiver whose data are contained in the remaining columns. Column 2 lists the various parameters contained in the table. The maximum and minimum values are the largest and smallest mean or standard deviation obtained on an individual run. The average value is an average of the individual run means or standard deviations for all approaches using that TD. The number of runs shows how many approaches were included in the table. Columns 3, 5, 7, and 9 pertain to the standard deviations obtained on individual runs. No data are presented for the TI-9100 receiver because TD's were not available from the digital data stream. Results are presented for the two triads used for navigation.



TSCT = TOTAL SYSTEM CROSS TRACK ERROR
ATE = AIRBORNE EQUIPMENT ALONG TRACK ERROR
CTE = AIRBORNE EQUIPMENT CROSS TRACK ERROR
FTE = FLIGHT TECHNICAL ERROR

FIGURE 2. NAVIGATION SYSTEM ERROR TERMS

The third type of table (type 3), "Summary of Pilotage Parameters" (tables 7, 11, 15, 19, and 26), shows the results of parameters related to pilotage for various Loran C receivers. Included in the table is summary data by receiver which include TSCT, FTE, and CTE. Column 1 lists the various parameters in the table. The remaining columns each pertain to one Loran C receiver operated on a single chain, triad, and either with or without area calibration. The number of samples describe the number of individual data points used in computing the statistics.

TSCT error was defined as the perpendicular distance between the desired course and the actual position of the aircraft. FTE was measured by recording the course guidance information supplied to the pilot by the Loran C receiver used for navigation. Two sources of course guidance were available and recorded. The first method used the recorded analog voltage from the Loran C receiver to the CDI, the second method used the recorded digital course guidance information found in the digital data stream. The tables only include the analog data. FTE was collected using three high time instrument rated pilots. The flights were all conducted under VFR conditions and the pilots did not use a hood to simulate IMC. CTE was defined as the distance between the Loran C indicated position and actual position of the aircraft perpendicular to the desired track. CTE values found in these tables may vary from those found in the type 1 tables. CTE values in type 3 tables only include samples with valid FTE and TSCT samples. Runs where the wrong CDI information was selected for display to the pilots or with wrong waypoints have been deleted from the tables.

The fourth type of table (type 4), "Summary of ONI-7000 No. 1 SNR's and ECD's" (tables 8, 12, 16, 20, 23, and 27), is a summary of Loran C SNR and ECD values as measured by the Advanced Navigation, Inc., ONI-7000 receiver. The ONI-7000 was selected because it is a linear receiver able to measure ECD, field strength, and atmospheric noise directly. The values in the table are the maximum and minimum values of individual run averages. Also included in the table are the minimum and maximum atmospheric noise of individual runs.

TABLE 5. SUMMARY OF NAVIGATION EQUIPMENT ERRORS FOR SAGINAW, MICHIGAN

Chain	Stations In Use	Mode	Loran Receiver	# of Samples	Total Runs (Note A)	Along-Track Error (Feet)		Crosstrack Error (Feet)	
						Mean	Std. Dev.	Mean	Std. Dev.
		Auto	(D)ONI-1	212	4 (3)	-211	674	-322	390
		Auto	(D)ONI-2	217	4 (3)	-119	341	-386	502
8970	MXY	Auto	ML-4000	26	4 (3)	929	118	791	476
9960	MYZ	Auto	TI-9100	414	4 (0)	-1553	223	-3399	479
8970	MXY	Dedicated	TDL-711	409	4 (0)	698	91	1511	421
8970	MXY	Dedicated	TDL-711A	414	4 (0)	692	89	1531	422
8970	MXY	Dedicated	(D)ONI-1	260	5 (5)	140	352	72	480
		Triad	(D)ONI-2	260	5 (5)	272	277	91	472
		No	ML-4000	32	5 (5)	934	76	893	344
		Area	TI-9100	517	5 (5)	-185	249	522	417
		Cal	TDL-711	510	5 (0)	673	142	1602	339
			TDL-711A	517	5 (0)	679	143	1626	338
8970	MXY	Dedicated	(D)ONI-1	120	3 (3)	-161	276	-350	407
		Triad	(D)ONI-2	-	-	-	-	-	-
		Area	ML-4000	16	3 (3)	470	73	-326	245
		Cal	TI-9100	221	3 (3)	-195	227	-20	393
			(B)TDL-711	216	3 (0)	648	80	1642	330
			TDL-711A	221	3 (3)	-139	74	-553	332
9960	MYZ	Dedicated	(D)ONI-1	246	5 (1)	-266	521	-742	898
		Triad	(D)ONI-2	248	5 (2)	-213	404	-698	774
		No	ML-4000	32	5 (0)	-1362	96	-4888	430
		Area	TI-9100	486	5 (0)	-1587	221	-3301	457
		Cal	TDL-711	390	5 (0)	-3128	96	-8011	267
			TDL-711A	437	5 (0)	-3063	120	-7900	335
9960	MYZ	Dedicated	(D)ONI-1	251	5 (4)	116	595	-546	524
		Triad	(D)ONI-2	-	-	-	-	-	-
		Area	ML-4000	30	5 (5)	831	109	-41	432
		Cal	TI-9100	493	5 (5)	-149	232	-342	381
			TDL-711	-	-	-	-	-	-
			(C)TDL-711A	494	5 (0)	1327	100	-1902	378

Notes:

A. Value in parenthesis is number of individual runs meeting AC 90-45A criteria.
B. No area calibration
C. Incorrect area calibration inserted
D. Kalman filter not optimized for approaches! Refer to Analysis of Results, Navigation Equipment Errors for explanation.

TABLE 6. SUMMARY OF TD BIAS FOR SAGINAW

Loran Receiver	Parameter	Chain 8970				Chain 9960			
		TD	X	TD	Y	TD	Y	TD	Z
		Mean	Std Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
ONI-7000 #1	MAX	.16	.80	1.60	.88	3.13	.49	.39	.79
	AVG	-.06	.57	1.42	.52	2.87	.35	.19	.61
	MIN	-.31	.48	1.24	.29	2.30	.26	-.05	.47
	# of Runs	22	22	22	22	22	22	22	22
ONI-7000 #2	MAX	.28	.67	1.70	.71	3.00	.37	.35	.75
	AVG	.06	.51	1.48	.50	2.92	.28	.11	.55
	MIN	-.16	.43	1.30	.37	2.80	.11	-.15	.46
	# of Runs	14	14	14	14	14	14	14	14
ML-4000	MAX	.07	.46	1.53	.71	3.00	.18	.36	.41
	AVG	-.10	.32	1.35	.40	2.92	.12	.22	.31
	MIN	-.30	.16	1.21	.24	2.80	.06	-.01	.18
	# of Runs	12	12	12	12	10	10	10	12
TDL-711	MAX	.07	.48	1.62	.61	3.20	.13	.40	.34
	AVG	-.09	.30	1.49	.40	3.10	.10	.24	.26
	MIN	-.20	.15	1.32	.22	3.05	.09	.18	.16
	# of Runs	12	12	12	12	5	5	10	10
TDL-711A	MAX	.09	.56	1.66	.61	3.20	.15	.37	.34
	AVG	-.06	.33	1.49	.40	3.09	.12	.21	.26
	MIN	-.14	.15	1.30	.22	3.00	.08	.15	.16
	# of Runs	12	12	12	12	10	10	10	10

Note:

All values are in microseconds.

TABLE 7. SUMMARY OF PILOTAGE PARAMETERS FOR SAGINAW

	Loran C Receivers				
Parameter	TI-9100	ONI-1	TDL-711A	TDL-711A	ML-4000
Chain	8970	9960	9870	9870	9960
Triad	MXY	MYZ	MXY	MXY	MYZ
Mode	Ded. Triad	Ded.Triad	Ded. Triad	Area Cal.	Area Cal.
# of Samples	517	195	403	211	13
TSCT Mean.	13	-559	991	-516	-473
Std. Dev.	319	639	422	285	525
FTE Mean	-269	28	-164	-127	-415
Std. Dev.	377	984	158	472	504
CTE Mean	552	-655	1531	-553	-30
Std. Dev.	417	996	422	332	350

Note:

All values in feet.

TABLE 8. SUMMARY OF ONI-7000 NO. 1 SNR'S AND ECD'S FOR SAGINAW

Station	Chain	Sta.	SNR (dB)			ECD (microseconds)		
			Min	Max	# of Runs	Min.	Max.	# of Runs
Dana	8970	M	9.3	11.0	22	2.0	3.0	22
Malone		W	-16.2	-14.0	22	.1	1.2	22
Seneca		X	8.8	11.0	22	2.5	3.6	22
Baudette		Y	-8.2	-6.0	22	.9	2.0	22
Seneca	9960	M	8.8	11.0	22	2.5	3.7	23
Nantucket		X	-17.7	-15.6	22	-.9	1.4	22
Carolina Beach		Y	-11.2	-9.0	22	.3	1.9	23
Dana		Z	8.8	11.0	22	2.2	2.8	23
Atmos. Noise (A)			55.0	56.6	22	-	-	-

Note:

A = dB/Microvolt/Meter

TABLE 9. SUMMARY OF NAVIGATION EQUIPMENT ERRORS FOR ATLANTIC CITY, NEW JERSEY

Chain	Stations In Use	Mode	Loran Receiver	# of Samples	Total Runs (Note A)	Along-Track Error (Feet)		Crosstrack Error (Feet)	
						Mean	Std. Dev.	Mean	Std. Dev.
9960	MXY	Dedicated	(B)ONI-1	295	5(5)	-70	320	-829	280
		Triad	(B)ONI-2	-	-	-	-	-	-
		No	ML-4000	39	5(0)	1134	91	-1956	88
		Area	TI-9100	580	5(0)	306	212	-1960	183
		Cal	TDL-711	570	5(0)	655	76	-1899	97
			TDL-711A	580	5(0)	736	89	-1752	104
9960	MXY	Dedicated	(B)ONI-1	263	4(4)	-261	256	-536	146
		Triad	(B)ONI-2	195	3(3)	-240	281	-533	131
		Area	ML-4000	34	4(4)	232	70	-494	76
		Cal	TI-9100	515	4(4)	-658	212	-405	179
			(C)TDL-711	508	4(0)	626	87	-1874	82
			TDL-711A	512	4(4)	-95	98	-230	85

Notes:

A = Value in parenthesis is number of individual runs meeting AC 90-45A criteria.
B = Kalman filter not optimized for approaches! Refer to Analysis of Results, Navigation Equipment Errors for explanation.
C = No area calibration.

TABLE 10. SUMMARY OF TD BIAS FOR ATLANTIC CITY

Loran Receiver	Parameter	Chain 9960			
		TD X		TD Y	
		Mean	Std. Dev.	Mean	Std. Dev.
ONI-7000 #1	MAX	-2.73	.12	-.71	.55
	AVG	-2.80	.10	-.79	.47
	MIN	-2.83	.07	-.85	.38
	# of Runs	9	9	9	9
ONI-7000 #2	MAX	-2.73	.16	-.72	.48
	AVG	-2.76	.15	-.78	.41
	MIN	-2.79	.14	-.87	.37
	# of Runs	3	3	3	3
ML-4000	MAX	-2.70	.12	-.78	.17
	AVG	-2.74	.08	-.85	.12
	MIN	-2.81	.04	-.91	.06
	# of Runs	9	9	9	9
TDL-711	MAX	-2.68	.17	-.76	.17
	AVG	-2.72	.12	-.80	.14
	MIN	-2.79	.09	-.85	.11
	# of Runs	9	9	9	9
TDL-711A	MAX	-2.59	.19	-.73	.20
	AVG	-2.66	.13	-.78	.16
	MIN	-2.76	.10	-.84	.14
	# of Runs	9	9	9	9

Note:

All values are in microseconds.

TABLE 11. SUMMARY OF PILOTAGE PARAMETERS FOR ATLANTIC CITY

	Loran C Receivers				
Parameter	TDL-711A	ONI-1			
Chain	9960	9960			
Triad	MXY	MXY			
Mode	Area Cal.	Ded. Triad			
# of Samples	460	292			
TSCT Mean.	-71	-532			
Std. Dev.	118	364			
FTE Mean	115	225			
Std. Dev.	141	460			
CTE Mean	-239	-829			
Std. Dev.	77	280			

Note:

All values in feet.

TABLE 12. SUMMARY OF ONI-7000 NO.1 SNR'S AND ECD'S FOR ATLANTIC CITY

Station	Chain	Sta.	SNR (dB)			ECD (microseconds)		
			Min	Max	# of Runs	Min.	Max.	# of Runs
Seneca	9960	M	10.2	11.1	9	2.8	3.9	9
Caribou		W	-21.9	-20.9	9	-3.3	-1.9	9
Nantucket		X	7.0	7.5	9	1.8	2.5	9
Carolina Beach		Y	8.1	8.7	9	3.1	4.1	9
Dana		Z	-10.9	-10.3	9	0.6	1.5	9
Atmos. Noise (A)			58.3	59.5	9			

Note:

A = dB/Microvolt/Meter

TABLE 13. SUMMARY OF NAVIGATION EQUIPMENT ERRORS FOR BILLINGS, MONTANA

Chain	Stations In Use	Mode	Loran Receiver	# of Samples	Total Runs (Note A)	Along-Track Error (Feet)		Crosstrack Error (Feet)	
						Mean	Std. Dev.	Mean	Std. Dev.
		Auto	(C)ONI-1	222	3 (1)	1436	881	1484	657
		Auto	(C)ONI-2	294	4 (4)	-197	348	62	378
9940	MWY	Dedicated	ML-4000	36	4 (0)	-193	580	1150	491
9940		Auto	TI-9100	-	-	-	-	-	-
9940	MWY	Dedicated	TDL-711	424	3 (0)	-1380	452	1543	402
9940	MWY	Dedicated	TDL-711A	583	4 (0)	-823	348	1969	216
9940	MWY	Dedicated	(C)ONI-1	367	5 (4)	-922	693	-77	386
		Triad	(C)ONI-2	-	-	-	-	-	-
		No	ML-4000	49	5 (0)	-211	552	1284	406
		Area	TI-9100	733	5 (0)	-163	380	1457	282
		Cal.	TDL-711	727	5 (0)	-1351	444	1825	347
			TDL-711A	734	5 (0)	-1100	316	1842	253
9940	MWY	Dedicated	(C)ONI-1	276	4 (1)	894	853	647	440
		Triad	(C)ONI-2	278	4 (2)	608	950	454	509
		Area	ML-4000	38	4 (4)	362	296	-21	217
		Cal.	TI-9100	553	4 (4)	-458	336	308	225
			(B)TDL-711	545	4 (0)	-1032	426	1936	295
			TDL-711A	553	4 (4)	-647	282	-69	174
9940	WXY	Dedicated	(C)ONI-1	310	5 (0)	3961	587	4067	525
		Triad	(C)ONI-2	-	-	-	-	-	-
		No	ML-4000	-	-	-	-	-	-
		Area	TI-9100	615	5 (0)	4318	437	5521	323
		Cal.	TDL-711	-	-	-	-	-	-
			TDL-711A	-	-	-	-	-	-
9940	WXY	Dedicated	(C)ONI-1	324	5 (3)	776	992	503	564
		Triad	(C)ONI-2	-	-	-	-	-	-
		Area	ML-4000	-	-	-	-	-	-
		Cal.	TI-9000	520	4 (4)	183	339	109	267
			TDL-711	-	-	-	-	-	-
			TDL-711A	-	-	-	-	-	-

Notes:

A. Value in parenthesis is the number of individual runs meeting AC 90-45A criteria.
B. Area calibration not inserted.
C. Kalman filter not optimized for approaches! Refer to Analysis of Results, Navigation Equipment Errors for explanation.

TABLE 14. SUMMARY OF TD BIAS FOR BILLINGS

Loran Receiver	Parameter	Chain 9940 TD W		Chain 9940 TD X		Chain 9940 TD Y		TD	
		Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
ONI-7000 #1	MAX	-1.43	.43	1.75	.40	.65	.94		
	AVG	-1.68	.29	1.54	.26	.51	.30		
	MIN	-1.82	.15	1.31	.07	.34	.17		
	# of Runs	25	25	25	25	25	25		
ONI-7000 #2	MAX	-1.48	.56	1.61	.51	.66	.44		
	AVG	-1.69	.27	1.48	.18	.52	.20		
	MIN	-1.90	.16	1.29	.05	.29	.14		
	# of Runs	20	20	20	20	20	20		
ML-4000	MAX	-1.47	.23			.77	.31		
	AVG	-1.71	.13			.62	.16		
	MIN	-1.86	.08			.45	.06		
	# of Runs	25	25			25	25		
TDL-711	MAX	-1.47	.16			.71	.18		
	AVG	-1.78	.12			.55	.14		
	MIN	-1.91	.08			.42	.10		
	# of Runs	24	24			24	24		
TDL-711A	MAX	-1.69	.15			.69	.14		
	AVG	-1.86	.10			.50	.10		
	MIN	-1.97	.06			.34	.07		
	# of Runs	25	25			25	25		

Note:

All values are in microseconds.

TABLE 15. SUMMARY OF PILOTAGE PARAMETERS FOR BILLINGS

	Loran C Receivers					
Parameter	ONI-1	ONI-2	TDL-711	TDL-711A	ONI-2 Wide Open	TI-9100
Chain			9940	9940	9940	9940
Triad			MWY	MWY	MXZ	MXY
Mode	Wide Open	Wide Open	Ded. Triad	Area Cal.	Area Cal.	Area Cal.
# of Samples	220	144	607	553	128	393
TSCT Mean.	650	-45	1692	-116	-78	-13
Std. Dev.	544	263	376	385	180	142
FTE Mean	-957	-129	-993	-147	-391	-116
Std. Dev.	613	375	503	415	430	284
CTE Mean	1484	44	1627	-69	-296	92
Std. Dev.	657	414	232	174	439	262

Note:

All values in feet.

TABLE 16. SUMMARY OF ONI-7000 NO.1 SNR'S AND ECD'S FOR BILLINGS

Station	Chain	Sta.	SNR (dB)			ECD (microseconds)		
			Min	Max	# of Runs	Min.	Max.	# of Runs
Fallon	9940	M	-8.0	-2.0	25	-3.5	-.1	25
George		W	4.1	9.5	25	-1.2	1.36	25
Middletown		X	-13.4	-8.6	25	-1.6	4.2	25
Searchlight		Y	-9.2	-3.3	25	-2.3	2.6	25
Atmos. Noise (A)			45.6	50.4	25			

Note:

A = dB/Microvolt/Meter

TABLE 17. SUMMARY OF NAVIGATION EQUIPMENT ERRORS FOR GRAND JUNCTION, COLORADO

Chain	Stations In Use	Mode	Loran Receiver	# of Samples	Total Runs (A)	Along-Track Error (Feet)		Crosstrack Error (Feet)	
						Mean	Std. Dev.	Mean	Std. Dev.
		Auto	(B)ONI-1	242	5 (4)	-10	591	-27	219
		Auto	(B)ONI-2	242	5 (3)	-1285	2464	-1153	2168
9940	MWY	Dedicated	ML-4000	13	3 (0)	1435	315	-2491	201
9940		Auto	TI-9100	-	-	-	-	-	-
9940	MWY	Dedicated	TDL-711	481	5 (0)	-2215	212	-5130	195
9940	MWY	Dedicated	TDL-711A	487	5 (0)	-283	216	-2118	183
9940	MWY	Dedicated	(B)ONI-1	219	5 (2)	-1174	412	-752	415
		Triad	(B)ONI-2	-	-	-	-	-	-
		No	ML-4000	28	5 (2)	281	299	-1169	330
		Area	TI-9100	439	5 (5)	-161	292	-286	340
		Cal	TDL-711	433	5 (0)	-330	249	-1975	326
			TDL-711A	439	5 (0)	-623	247	-2488	329
9940	MWY	Dedicated	(B)ONI-1	-	-	-	-	-	-
		Triad	(B)ONI-2	238	5 (3)	930	368	841	364
		Area	ML-4000	33	5 (1)	1389	239	758	341
		Cal	TI-9100	472	5 (4)	180	291	1146	354
			TDL-711	465	5 (4)	359	211	1217	296
			TDL-711A	472	5 (5)	297	221	667	308
9940	WXY	Dedicated	(B)ONI-1	240	5 (3)	1078	550	173	240
		Triad	(B)ONI-2	-	-	-	-	-	-
		No	ML-4000	-	-	-	-	-	-
		Area	TI-9100	479	5 (0)	2790	323	1124	263
		Cal	TDL-711	-	-	-	-	-	-
			TDL-711A	-	-	-	-	-	-
9940	WXY	Dedicated	(B)ONI-1	242	5 (5)	739	405	516	242
		Triad	(B)ONI-2	240	5 (5)	571	340	320	208
		Area	ML-4000	-	-	-	-	-	-
		Cal	TI-9100	482	5 (0)	-1563	336	-1497	294
			TDL-711	-	-	-	-	-	-
			TDL-711A	-	-	-	-	-	-

Notes:

Wrong area calibration inserted.

(A) Value in parenthesis is number of individual runs meeting AC 90-45A Criteria.

(B) Kalman filter not optimized for approaches! Refer to Analysis of Results, Navigation Equpment Errors for explanation.

TABLE 18. SUMMARY TO TD BIAS FOR GRAND JUNCTION

Values in microseconds

Loran Receiver	Parameter	Chain 9940 TD W Mean	Chain 9940 TD W Std Dev.	Chain 9940 TD X Mean	Chain 9940 TD X Std. Dev.	Chain 9940 TD Y Mean	Chain 9940 TD Y Std. Dev.	TD Mean	TD Std. Dev.
ONI-7000 #1	MAX	1.19	.50	1.66	.45	-.43	.46		
	AVG	.95	.22	1.51	.23	-.53	.28		
	MIN	.77	.08	1.38	.04	-.61	.17		
	# of Runs	20	20	20	20	20	20		
ONI-7000 #2	MAX	1.14	.36	1.62	.22	-.41	.24		
	AVG	.88	.18	1.53	.11	-.49	.19		
	MIN	.74	.08	1.43	.02	-.58	.13		
	# of Runs	15	15	15	15	15	15		
ML-4000	MAX	1.15	.35			-.30	.18		
	AVG	.87	.17			-.37	.09		
	MIN	.60	.05			-.45	.04		
	# of Runs	22	22			25	25		
TDL-711	MAX	1.19	.29			-.45	.17		
	AVG	.78	.15			-.50	.07		
	MIN	.52	.08			-.56	.05		
	# of Runs	25	25			25	25		
TDL-711A	MAX	1.28	.30			-.41	.18		
	AVG	.92	.15			-.47	.07		
	MIN	.64	.09			-.61	.05		
	# of Runs	25	25			25	25		

Note:

All values are in microseconds.

TABLE 19. SUMMARY OF PILOTAGE PARAMETERS FOR GRAND JUNCTION

	Loran C Receivers				
Parameter	ONI-1	TDL-711A	TI-9100	TDL-711	ML-4000
Chain		9940	9940	9940	9940
Triad		MWY	WXY	MWY	MWY
Mode	Wide Open	Ded.Triad	Ded. Triad	Area Cal.	Area Cal.
# of Samples	242	439	479	465	31
TSCT Mean.	213	-2162	530	880	217
Std. Dev.	127	340	198	634	109
FTE Mean	183	128	-551	-379	-417
Std. Dev.	140	149	216	521	513
CTE Mean	-27	-2488	1123	1217	935
Std. Dev.	219	329	263	296	442

Note:

All values are in feet.

TABLE 20. SUMMARY OF ONI-7000 NO. 1 SNR'S AND ECD'S FOR GRAND JUNCTION

Station	Chain	Sta.	SNR (dB)			ECD (microseconds)		
			Min	Max	# of Runs	Min	Max	# of Runs
Fallon	9940	M	-.8	9.5	25	1.3	2.2	25
George		W	-11.7	-.4	25	.9	5.2	25
Middletown		X	12.7	-2.4	25	-.9	1.7	25
Searchlight		Y	3.3	14.0	25	1.4	1.9	25
Dana	8970	M	-22.4	-16.9	7	2.8	4.7	7
Baudette		Y	-14.4	-8.9	7	1.5	4.3	7
Atmos. Noise (A)		-	47.4	57.7	25	-	-	-

Note:

A = dB/Microvolt/Meter

TABLE 21. SUMMARY OF NAVIGATION EQUIPMENT ERRORS FOR GALLUP, NEW MEXICO

Chain	Stations In Use	Mode	Loran Receiver	# of Samples	Total Runs (A)	Along-Track Error (Feet)		Crosstrack Error (Feet)	
						Mean	Std. Dev.	Mean	Std. Dev.
		Auto	(C)ONI-1	202	5 (0)	2712	912	-3766	952
		Auto	(C)ONI-2	-	-	-	-	-	-
9940	MWY	Dedicated	ML-4000	25	5 (0)	3378	696	-5608	837
		Auto	TI-9100	-	-	-	-	-	-
9940	MWY	Dedicated	TDL-711	402	5 (0)	491	544	-6970	907
9940	MWY	Dedicated	TDL-711A	405	5 (0)	627	560	-7281	776
9940	MWY	Dedicated	(C)ONI-1	224	5 (0)	1780	574	-2849	751
		Triad	(C)ONI-2	-	-	-	-	-	-
		No	ML-4000	31	5 (0)	2726	1293	-4876	824
		Area	TI-9100	451	5 (0)	3931	483	-5132	480
		Cal	TDL-711	-	-	-	-	-	-
			TDL-711A	-	-	-	-	-	-
9940	MWY	Dedicated	(C)ONI-1	238	4 (1)	816	1159	-349	1262
		Triad	(C)ONI-2	238	4 (0)	595	1039	-165	1262
		Area	ML-4000	39	4 (1)	626	733	258	549
		Cal	TI-9100	469	4 (1)	191	653	-642	589
			(B)TDL-711	464	4 (0)	181	584	-6445	437
			TDL-711A	-	-	-	-	-	-
9940	MXY	Dedicated	(C)ONI-1	236	5 (0)	12223	5404	-9653	3182
		Triad	(C)ONI-2	235	5 (0)	15704	4837	-11680	2552
		No	ML-4000	21	4 (0)	25846	16410	-18933	9928
		Area	TI-9100	395	5 (0)	14663	11751	-11464	6849
		Cal	TDL-711	-	-	-	-	-	-
			TDL-711A	-	-	-	-	-	-
9940	MXY	Dedicated	(C)ONI-1	201	5 (0)	4891	7980	-3636	3583
		Triad	(C)ONI-2	201	5 (0)	4554	6513	-2766	3232
		Area	(B)ML-4000	27	5 (0)	31789	5075	-19081	3070
		Cal	TI-9100	402	5 (0)	4489	2236	-2415	1304
			TDL-711	-	-	-	-	-	-
			TDL-711A	-	-	-	-	-	-

Notes:

9940 MXY well outside USCG Geometry Limits.
(A) Value in parenthesis is number of individual runs meeting AC 90-45A Criteria
(B) No Area Calibration.
(C) Kalman filter not optimized for approaches! Refer to Analysis of Results, Navigation Equipment Errors for explanation.

TABLE 22. SUMMARY OF TD BIAS FOR GALLUP

Loran Receiver	Parameter	Chain 9940				Chain 9940			
		TD	W	TD	X	TD	Y	TD	
		Mean	Std Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
ONI-7000 #1	MAX	.67	.42	1.09	.65	-1.81	.74		
	AVG	.44	.24	.87	.29	-2.01	.42		
	MIN	.19	.14	.52	.11	-2.62	.17		
	# of Runs	24	24	25	25	25	25		
ONI-7000 #2	MAX	.65	.49	1.10	.38	-1.84	.45		
	AVG	.44	.24	.90	.25	-1.99	.31		
	MIN	.24	.12	.53	.14	-2.56	.20		
	# of Runs	25	25	25	25	25	25		
ML-4000	MAX	.53	.63	.90	.77	-1.69	.27		
	AVG	.38	.23	.78	.30	-1.82	.12		
	MIN	.27	.04	.52	.06	-2.24	.06		
	# of Runs	15	15	9	9	25	25		
TDL-711	MAX	.46	.36	-	-	-1.91	.21		
	AVG	.34	.15	-	-	-2.03	.11		
	MIN	.17	.09	-	-	-2.40	.07		
	# of Runs	15	15	-	-	15	15		

Note:

All values in microseconds.

TABLE 23. SUMMARY OF ONI-7000 NO. 1 SNR'S AND ECD'S FOR GALLUP

Station	Chain	Sta.	SNR (dB)			ECD (microseconds)		
			Min	Max	# of Runs	Min	Max	# of Runs
Fallon	9940	M	-3.4	4.6	25	-.3	1.8	25
George		W	-11.2	-2.0	25	-.8	1.9	25
Middletown		X	-13.7	-4.5	25	-2.2	.6	25
Searchlight		Y	11.3	18.6	25	.6	2.2	25
Atmos. Noise (A)		-	45.0	52.3	25	-	-	-

Note:

A = dB/Microvolt/Meter

TABLE 24. SUMMARY OF NAVIGATION EQUIPMENT ERRORS FOR LONDON, KENTUCKY

Chain	Stations In Use	Mode	Loran Receiver	# of Samples	Total Runs (Note A)	Along-Track Error (Feet)		Crosstrack Error (Feet)	
						Mean	Std. Dev.	Mean	Std. Dev.
		Auto	(C)ONI-1	181	4 (3)	778	448	392	165
		Auto	(C)ONI-2	-	-	-	-	-	-
8970	MWX	Dedicated	ML-4000	20	3 (0)	22	108	2038	120
	MYZ	Auto	TI-9100	359	4 (0)	-1840	277	424	207
9960	MYZ	Dedicated	TDL-711	354	4 (0)	-2962	91	456	107
9960	MYZ	Dedicated	TDL-711A	359	4 (0)	-2956	81	482	107
9960	MYZ	Dedicated	(C)ONI-1	236	5 (2)	-1154	1435	-499	1096
		Triad	(C)ONI-2	-	-	-	-	-	-
		No	ML-4000	29	5 (1)	-1448	531	161	288
		Area	TI-9100	467	5 (0)	-2024	384	307	320
		Cal.	TDL-711	466	5 (0)	-3077	129	470	69
			TDL-711A	466	5 (0)	-3018	123	478	63
9960	MYZ	Dedicated	(C)ONI-1	271	5 (4)	333	653	-46	220
		Triad	(C)ONI-2	253	5 (3)	318	658	-40	226
		Area	(B)ML-4000	35	5 (0)	-1916	256	2049	188
		Cal.	TI-9100	529	5 (5)	-359	258	360	234
			TDL-711	523	5 (5)	84	125	280	122
			TDL-711A		-	-	-	-	-
7980	MWZ	Dedicated	(C)ONI-1	225	5 (1)	-1037	1466	-850	795
		Triad	(C)ONI-2	-	-	-	-	-	-
		No	ML-4000	25	4 (0)	166	551	-1778	316
		Area	TI-9100	448	5 (5)	-30	330	-722	311
		Cal.	TDL-711	446	5 (0)	-218	119	-2858	286
			TDL-711A	448	5 (0)	-169	121	-2825	284
7980	MWZ	Dedicated	ONI-1	255	5 (3)	20	1090	294	465
		Triad	ONI-2	-	-	-	-	-	-
		Area	ML-4000	32	5 (5)	820	427	157	437
		Cal.	TI-9100	401	4 (4)	-405	289	300	474
			(D)TDL-711	501	5 (0)	-237	155	-2865	307
			(E)TDL-711A	505	5 (5)	58	145	1192	292

Notes:

A. Value in parenthesis is number of individual runs meeting AC 90-45A.
B. Wrong Area Calibration Value Used. Sense of Longitude Correction Reversed.
C. Kalman filter not optimized for approaches! Refer to Analysis of Results, Navigation Equipment Error for explanation.
D. No Area Calibration.
E. Wrong Value of Area Calibration Used.

TABLE 25. SUMMARY OF TD BIAS FOR LONDON

Loran Receiver	Parameter	Chain 7980				Chain 9960			
		TD	W	TD	Z	TD	Y	TD	Z
		Mean	Std Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
ONI-7000 #1	MAX	1.15	.59	-.20	.70	-.45	.31	-2.49	.54
	AVG	.94	.40	-.35	.49	-.79	.22	-2.71	.38
	MIN	.78	.19	-.48	.38	-1.03	.06	-2.91	.21
	# of Runs	10	10	10	10	14	14	14	14
ONI-7000 #2	MAX					-.59	.28	-2.50	.50
	AVG					-.70	.22	-2.57	.35
	MIN					-.79	.17	-2.62	.28
	# of Runs					5	5	5	5
ML-4000	MAX	.95	.24	-.34	.14	-.69	.24	-2.63	.21
	AVG	.91	.13	-.41	.10	-.76	.14	-2.69	.14
	MIN	85	.07	-.48	.07	-.85	.08	-2.80	.10
	# of Runs	10	10	10	10	9	9	9	9
TDL-711	MAX	1.04	.19	-.28	.18	-.61	.17	-2.66	.25
	AVG	.97	.13	-.35	.12	-.72	.11	-2.76	.14
	MIN	.93	.07	-.44	.09	-.79	.08	-2.84	.08
	# of Runs	10	10	10	10	14	14	14	14
TDL-711A	MAX	1.03	.28	-.31	.19	-.62	.17	-2.67	.18
	AVG	.97	.14	-.38	.13	-.74	.10	-2.76	.11
	MIN	.91	.08	-.48	.09	-.81	.07	-2.85	.07
	# of Runs	15	15	15	15	9	9	9	9

Note:

All values are in microseconds.

TABLE 26. SUMMARY OF PILOTAGE PARAMETERS FOR LONDON

	Loran C Receivers			
Parameter	ONI-1	ML-4000	TI-9100	TDL-711A
Chain		9960	9960	7980
Triad		MYZ	MYZ	MWZ
Mode	Wide Open	Ded.Triad	Area Cal.	Area Cal.
# of Samples	181	27	529	487
TSCT Mean.	47	241	91	518
Std. Dev.	172	291	171	564
FTE Mean	-713	555	-669	-445
Std. Dev.	109	1476	135	400
CTE Mean	392	161	360	1192
Std. Dev.	165	288	234	292

Note:

All values are in feet.

TABLE 27. SUMMARY OF ONI-7000 NO.1 SNR'S AND ECD'S FOR LONDON

Station	Chain	Sta.	SNR (dB)			ECD (microseconds)		
			Min	Max	# of Runs	Min.	Max.	# of Runs
Malone	7980	M	4.5	7.0	10	1.9	2.4	10
Grangeville		W	.5	2.9	10	2.4	2.9	10
Caroline Beach		Z	3.1	5.4	10	.9	1.6	10
Seneca	9960	M	6.2	8.8	14	3.0	3.6	14
Carolina Beach		Y	4.5	7.8	14	.9	1.6	14
Dana		Z	17.8	20.8	14	2.3	2.5	14
Atmos. Noise (A)		-	49.3	52.9	14	-	-	-

Note:

A = dB/Microvolt/Meter

ANALYSIS OF RESULTS

Data presented to this point showed the results of approaches to six airports under various Loran C conditions. The remainder of this section will attempt to establish the behavior of Loran C receivers as a family to answer the stated objectives. The data previously presented are summarized or plotted graphically for ease of understanding in this section.

FLIGHT TECHNICAL ERROR.

FTE is a measure of the pilots ability to follow course guidance. Course guidance is usually presented to the pilot on a CDI. Recording the CDI value is, therefore, a measure of the pilot's ability to follow the information. Two sources are available to obtain this information: an analog voltage to the CDI and the digital CDI data from the receiver digital data stream. To investigate possible differences between the two sources, data were collected and compared from each source. A mean and standard deviation was calculated for each of the 22 conditions flown.

A condition is defined as one to five approaches conducted with the same pilot following course guidance from a selected Loran C receiver operated in a single mode. A mode was defined as one of the following receiver configurations: primary dedicated triad uncalibrated, primary dedicated triad with area calibration, alternate dedicated triad uncalibrated, alternate dedicated triad with area calibration, and automatic or wide open mode. For the dedicated mode, a single chain and single triad were used for the approaches. When operating in the automatic mode, the receiver was allowed to select chains and triads per the manufacturers' algorithm. The average difference between the analog and digital CDI information for the condition means was 22 feet, while that for the condition standard deviations was 28 feet. The largest difference between analog and digital CDI values for a single condition was 394 feet for the means and 452 feet for the standard deviations.

The above observations indicate that analog and digital FTE are similar. Only FTE obtained from the analog CDI will be analyzed in the rest of this section. Data for this section were obtained from tables 7, 11, 15, 19, and 26. FTE data were not collected at Gallup due to poor receiver performance. As stated earlier, AC 90-45A assumes an FTE of 0.5 nmi (95 percent probability) for error budget purposes. The most accurate method to determine the 95 percent error probability of the data is to arrange the errors by magnitude and determine the value which includes 95 percent of the data points. The method becomes cumbersome with large amounts of data. From basic statistics it can be shown for normally distributed data, 95 percent of the data will be contained within a value equal to the mean minus 2 standard deviations and the mean plus 2 standard deviations. If the mean is zero, the magnitude of the value at each limit will be equal. For non-zero means the magnitude of the value at each limit will not be equal. AC 90-45A seeks the magnitude of the value where 95 percent of the data will be less than the specified value. The magnitude of the largest value at the limit is the absolute value of the data mean plus 2 standard deviations. Depending upon the values of the mean and standard deviations for the non-zero mean case, 95.45 to 97.23 percent of the data will be smaller than the above value. The result is a possible over estimate of the 95 percent probability value point.

It is possible that some runs/conditions that are just over the AC 90-45A limit meet the specification. Under no case will the value of the 95 percent point be less than the absolute value of the mean plus 1.63 standard deviation.

Statistics presented in this report will use the absolute value of the mean plus 2 standard deviations as the 95 percent point. A more detailed explanation can be found in Related Documents number 13.

Of the 22 FTE conditions flown, the largest 95 percent error probability value was 3,507 feet. The value exceeds the AC 90-45A limit for FTE of 3,038 feet (0.5 nmi). The largest values were measured from the same receiver operating under the same condition. Flight notes indicate that this receiver had jumps of the CDI needle that were substantially larger than the other receivers. The update of the displayed data was slower than all other receivers. Although the mean FTE value for this condition was around 500 feet, the standard deviation was 1,400 feet. It should be noted that only 27 samples were recorded. The standard deviation is three to four times greater than obtained from other receivers. Review of the CDI data for the receiver shows a stepped output with a low update rate not typical of other receivers. The mean TSCT for this condition was -241 feet with a standard deviation of 291 feet. The indication is that the pilot flew the approach smoothly but was unable to follow the CDI. If this condition is eliminated from the data as a typical of what can be implemented, the largest 95 percent FTE probability error value would be 2,183 feet, well within the AC 90-45A limit for FTE. This emphasizes the need to establish dynamic criteria for crosstrack guidance provided by Loran C receivers.

Table 28 shows the accumulative distribution of FTE obtained from the analog CDI. Column 1 defines the size of the errors in feet. Column 2 shows the number of condition means (unsigned) equal to or smaller than the value listed in column 1. Columns 3 and 4 show the same accumulated values but for the standard deviation and the 95 percent probability FTE. The average mean FTE for the 22 conditions was 452 feet. Standard deviations for the same data were 425 feet. Results for the digital FTE were similar and are not presented.

TABLE 28. ACCUMULATIVE DISTRIBUTION OF ANALOG FTE

Size of Error (ft)	Mean No. of Cond.	Standard Deviation No. of Cond.	FTE (95%) No. of Cond.
200	9	6	0
400	15	12	1
600	18	19	4
800	20	20	5
1000	22	21	10
1200		21	13
1400		21	16
1600		22	18
1800			18
2000			20
2200			21
2400			22
2600			22
3507			22

A significant difference exists between the CDI information from a Loran C receiver and that from a very high frequency omnidirectinal range (VOR) or localizer. The Loran C CDI has constant sensitivity while that of a VOR/localizer changes with distance from the transmitter. The result is a noise free Loran C CDI needle, much easier to fly. For a localizer approach with a course width of 6° and a localizer to threshold distance of 6,678 feet (700 feet tailored course width), a full scale CDI deflection at 5 nautical miles (nmi) from threshold would occur when the aircraft is 1,942 feet off course. As the aircraft moved to within 0.5 nmi of the threshold, the same full scale deflection of the CDI would occur only 509 feet off course. Full scale CDI deflection for the Loran C receivers was 1.25 nmi (0.3 nmi for 1 model) regardless of how far the aircraft was from the runway threshold. On a standard CDI with plus and minus 5 dots, each dot would represent 1,519 feet (0.25 nmi).

Although the difference between CDI's was known before flight testing the effect did not become obvious until the data were processed. During flight testing a course deviation of one-half dot from zero was deemed acceptable, but in retrospect this represented an unacceptable 760-foot shift from the desired course. Pilots are trained to keep the CDI at zero. Pilots are also trained to average out CDI deflection by slowly bringing the CDI to zero and not over correcting. The process may result in the CDI being other than zero as the aircraft moves back to centerline. With a localizer CDI, a one dot shift from center would continue to bring the aircraft closer to the desired track by the very nature of the system. A pilot following a Loran C CDI, one dot off center, would remain a fixed distance off course.

NAVIGATION EQUIPMENT ERRORS.

Navigation equipment errors are those errors pertaining only to the navigation equipment and do not include pilotage. The two terms associated with navigation errors are along-track and crosstrack. The first describes the errors in the direction of desired track while the second describes errors perpendicular to the desired track. AC 90-45A allows an ATE and CTE of 0.3 nmi (1,823 feet), 95 percent probability. As stated earlier, the 95 percent probability is defined in this report as the absolute value of the mean plus two times the standard deviation. Table 29 shows a summary of receiver performance at each of the airports flown. To show overall performance, data has been grouped by receiver-run. A receiver-run is described as all data collected from one receiver during one approach. Data were only processed from the final approach fix to the missed approach point, a distance of about 5 nmi. If all receivers (six) were operating properly and five approaches were made, a total of 30 receiver-runs would have been conducted. A receiver-run meets AC 90-45A if both ATE and CTE are less than 0.3 nmi, 95 percent probability.

Data are broken into two conditions: area calibrated and uncalibrated. The last column, GDOP, is an indication of Loran C geometry. As GDOP increases, errors due to geometry increase. The equation for GDOP can be found in Related Documents number 17 or appendix B. GDOP using these equations is known as Swanson's method. The values in parenthesis excludes data from the ONI-7000 receivers. Receivers with documented problems have been removed from the table. For the uncalibrated condition, no airport, regardless of GDOP value, had

100 percent of the receiver-runs meet AC 90-45A. In fact, some airports such as Atlantic City with a GDOP of 1.4 had only 20 percent of the runs meet the limit, while Grand Junction with a GDOP of 5.4 had 36 percent of the runs meet the Advisory Circular criteria. If area calibration is used, the number of receiver-runs meeting the limit increased at some airports, but not always to 100 percent. The results indicate that area calibration improves receiver accuracy but does not correct all error sources.

From table 29 two observations can be made about the effect of the ONI-7000 receivers on the data. First, it increased the percentage of runs meeting AC 90-45A in the uncalibrated mode and second, it decreased the percentage of runs meeting AC 90-45A in the area calibrated mode. Although the purpose of the project was to evaluate Loran C receivers in general, it is important to look at these observations. The ONI-7000 used a complex propagation model in the uncalibrated mode and had a position filter that was not optimized for the dynamics of an approach. Table 29 brings out both points. In the uncalibrated mode the position errors are largely a function of how well the individual Loran C receivers can predict the actual propagation delay of the Loran C signals. The propagation models currently in use vary from very simple to very complex. The ONI-7000 had the most complex propagation model of the receivers tested. The results indicate the ONI-7000 was better able to predict the real world than other receivers. In fact, at some airports the ONI-7000 was the only receiver to have any receiver-runs meeting AC 90-45A. The more complex propagation model did not improve performance at all airports. Because the ONI-7000 position filter was not optimized for the dynamics of an approach, the mean position errors, on occasion, were shifted and standard deviations of position errors increased. This could have reduced the number of runs meeting AC 90-45A. The effect of the filter is easier to see when reviewing the area calibrated data. In this mode the effects of the propagation model are removed by inserting a correction value. It appears the ONI-7000 filter problem caused the receiver to have higher errors than the other Loran C receivers tested. A more detailed explanation of the ONI-7000 filter problem appears later in this section. If airborne Loran C receivers perform according to theory, the errors should come from three sources: Loran C geometry, propagation modeling error, and Loran C receiver implementations.

No detailed analysis of the navigation-equipment errors for the wide open or automatic station select mode was conducted. Review of tables 5, 9, 13, 17, 21, and 24, "Summary of Navigation Equipment Errors," for the wide open mode point out two facts. First, different receivers operating under the same exact conditions chose different chains and triads for the navigation solution. Second, two identical receivers (ONI-7000) operating under the same conditions chose different stations to use in the navigation solution, resulting in different navigation errors. Billings and Grand Junction are good examples of these observations.

To investigate the error sources, the measured data have been processed in several ways. Review of tables 5, 9, 13, 17, 21, and 24 on navigation equipment errors show that area calibration reduces the mean errors but does not change the standard deviations when compared to uncalibrated values. Figure 3 shows the standard deviations for ATE and CTE without area calibration plotted against the

TABLE 29. REVIEW OF RECEIVER PERFORMANCE

Airport	Chain	Triad	UNCALIBRATED Total Rcvr Runs	UNCALIBRATED # Meeting AC-90-45A	UNCALIBRATED % Meeting AC-90-45A	AREA CALIBRATED Total Rcvr Runs	AREA CALIBRATED # Meeting AC-90-45A	AREA CALIBRATED % Meeting AC-90-45A	GDOP
Saginaw	8970	MXY	30 (20)	20 (10)	67 (50)	12 (9)	12 (9)	100 (100)	1.4
	9960	MYZ	30 (20)	3 (0)	10 (0)	15 (10)	14 (10)	93 (100)	3.8
Atlantic City	9960	MXY	25 (20)	5 (0)	20 (0)	19 (12)	19 (12)	100 (100)	1.4
Billings	9940	MWY	25 (20)	4 (0)	16 (0)	20 (12)	15 (12)	75 (100)	6.3
	9940	WXY	10 (20)	0 (0)	0 (0)	9 (4)	7 (4)	78 (100)	9.2
Grand Junction	9940	MWY	25 (20)	9 (7)	36 (35)	20 (15)	13 (10)	65 (67)	5.4
	9940	WXY	10 (5)	3 (0)	30 (0)	10 (5)	5 (0)	50 (0)	
Gallup	9940	MWY	15 (10)	0 (0)	0 (0)	16 (8)	3 (2)	19 (25)	9.8
	9940	MXY	19 (9)	0 (0)	0 (0)	15 (5)	0 (0)	0 (0)	56.6
London	7980	MWZ	24 (19)	6 (5)	25 (26)	19 (9)	12 (9)	89 (100)	3.8
	9960	MYZ	25 (20)	3 (1)	12 (5)	20 (10)	17 (10)	85 (100)	1.6

Notes:

1. Values in parenthesis do not include data from the ONI-7000 receivers.
2. Table does not include data with wrong area calibration values.

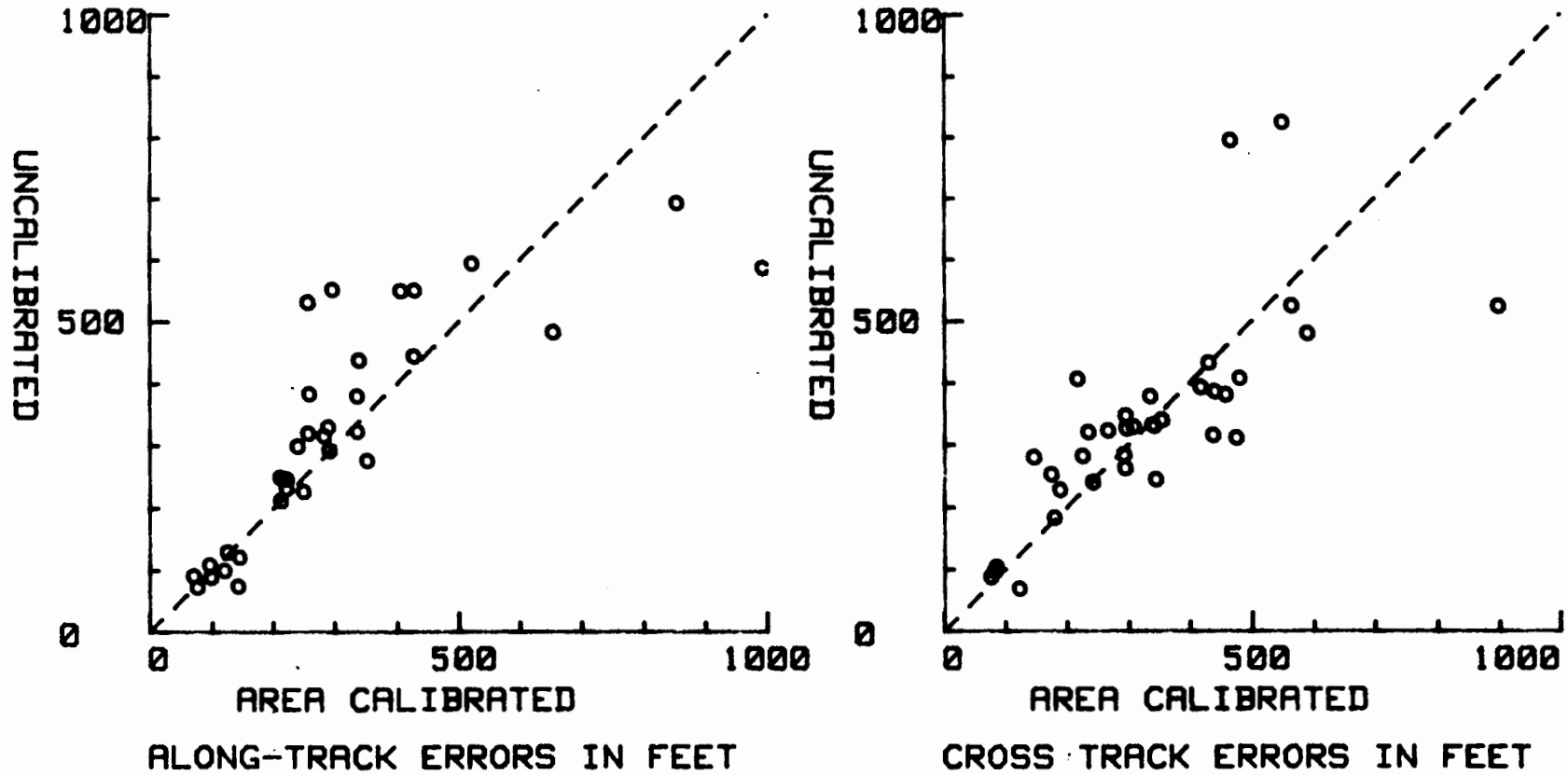
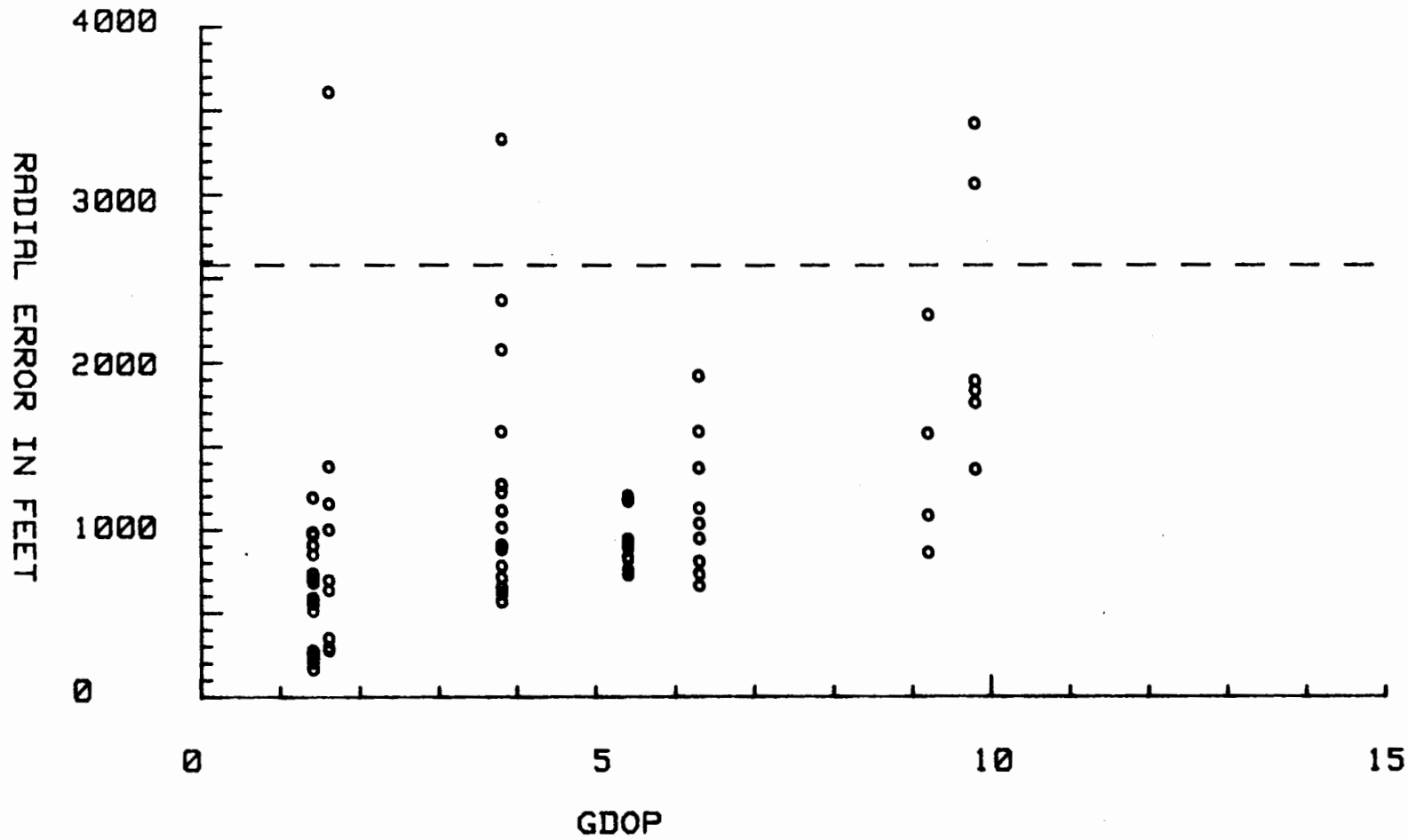


FIGURE 3. NAVIGATION EQUIPMENT ERRORS (STANDARD DEVIATIONS) AREA CALIBRATED VERSUS UNCALIBRATED

standard deviation using area calibration. Standard deviations were calculated for all approaches conducted using the same chain, triad, Loran C receiver, and airport. The data are a statistical combination of data points obtained on one to five approaches. Standard deviations were plotted with the area calibrated value on the horizontal axis and the uncalibrated value on the vertical axis. The dashed line indicates the point where the two values would be equal. From the plot it can be seen that the magnitude of the standard deviation varied, but the uncalibrated and area calibrated values were similar. Errors greater than 1,000 feet were not plotted. Data from all receivers have been included in the plot. The plot indicates the use of area calibration or correction value does not change the standard deviation of ATE and CTE.

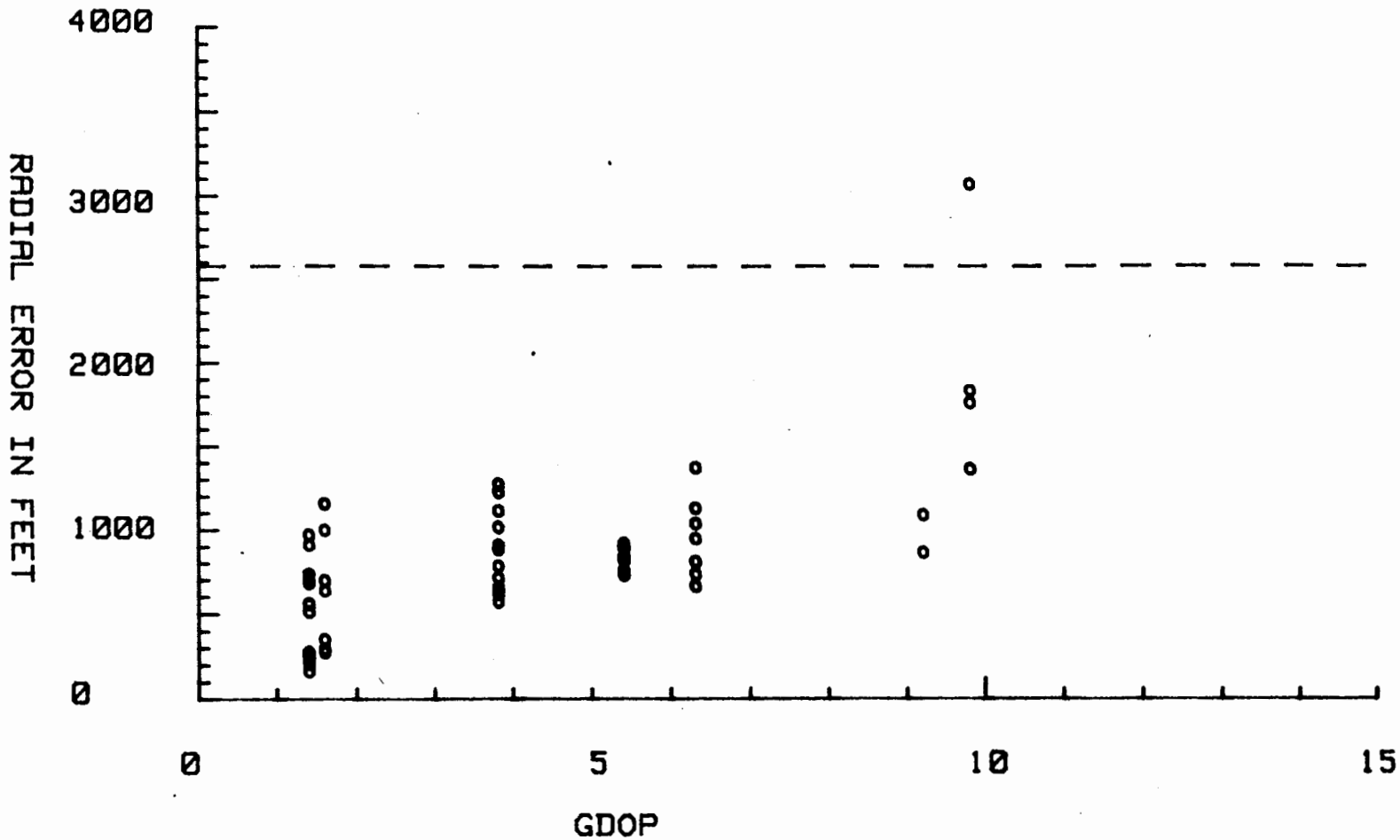
It is well known by the Loran C community that transmitter-receiver geometry affects Loran C position errors. In the previous paragraph it was shown that area calibration did not change the standard deviation of the position errors when compared to uncalibrated values. The magnitude of the standard deviations did vary from airport to airport. To investigate the effects of geometry on standard deviation, ATE and CTE were combined and plotted against GDOP. Two times the standard deviation for ATE and CTE were combined in an rss manner to obtain an indication of radial error. Figure 4 shows the results for all the Loran C receivers. A trend is observed between radial error and GDOP, but is difficult to see. If the ONI-7000 Loran C receiver data are removed from the plot, the trend is easier to see (figure 5). Data are grouped on the horizontal axis about the GDOP of the airports flown. The spread of the data vertically at a particular GDOP shows the variation between the receivers. As expected, the magnitude of the errors increases as a function of increasing GDOP. The ONI-7000 receiver data, which was deleted from the plot, acted differently than the other three manufacturers' receivers. From time to time it would perform just like the other receivers, but on occasion would exhibit a long term bend away from the other receivers. Although the track of position looked smooth, the long term bend greatly increased the standard deviation of the data.

Discussions about the results and subsequent analysis by ANI have determined the cause. The effect was caused by the Kalman filter used to smooth the geodetic position. The many turns encountered while conducting the approaches for this project caused the Kalman filter to wander. The wander for the en route environment was negligible with respect to the accuracy limits of AC 90-45A. The filter was optimized to smooth the position while flying en route and not for the maneuvering common to an approach. If the time difference data recorded during the flights were converted to a geodetic position using an algorithm similar to that used by the ONI-7000 receivers without Kalman filtering, the position closely follows the other Loran C receivers. A dynamic Loran C simulator was used by ANI to simulate the Federal Aviation Administration (FAA) flights. The simulated pattern was a racetrack 10 nmi long and 3 nmi wide. The results were similar to those found in flight. ANI has now changed the Kalman filter constants used to filter the present position during the approach mode. This points out that static testing or dynamic testing without maneuvers cannot detect these problems. Criteria must be established for dynamic performance of Loran C receivers.



RADIAL ERROR= SQRT((2*(STD. DEV. ATE))^2 +((2*STD. DEV. CTE))^2)

FIGURE 4. NAVIGATION EQUIPMENT ERROR (RADIAL STANDARD DEVIATION) VERSUS GDOP ALL RECEIVERS



RADIAL ERROR= SQRT((2*(STD. DEV. ATE))^2 +((2*STD. DEV. CTE))^2)

FIGURE 5. NAVIGATION EQUIPMENT ERROR (RADIAL STANDARD DEVIATION) VERSUS GDOP ONE RECEIVER REMOVED

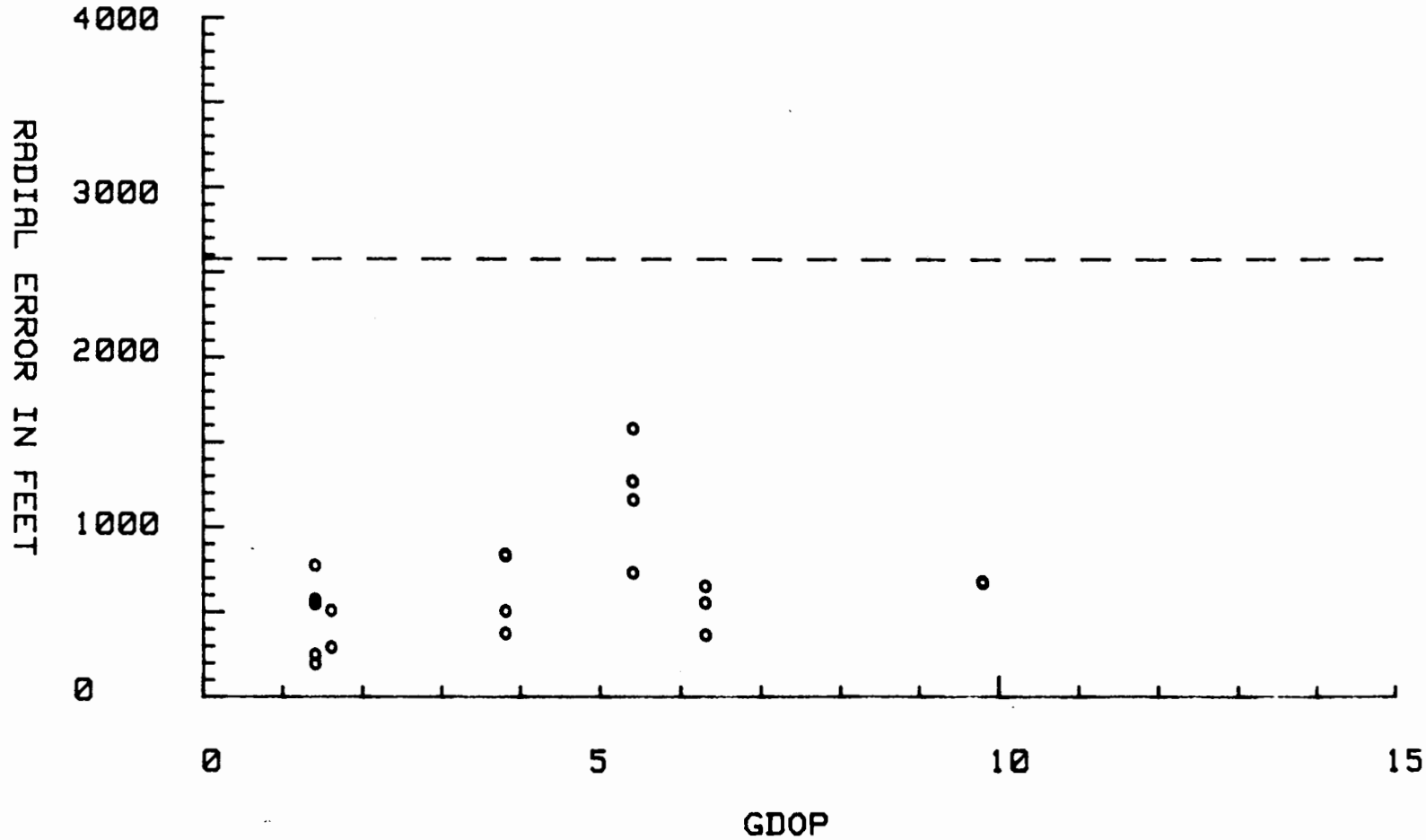
Area calibration, the process of removing propagation modeling error is intended to reduce ATE and CTE means. Theory indicates the means should be zero after calibration. Figure 6 shows the rss value of ATE and CTE mean values versus GDOP after area calibration. Data were grouped by receiver and airport. As before, data are grouped at the GDOP of the airport with the vertical spread showing the different receiver errors. Although the ONI-7000 data were similiar to the other receivers, it was not included in the plot.

Three things are obvious: errors are not zero, receivers at the same airport do not have the same error, and the errors at a GDOP of 5.4 do not fall in line with the other points. Post-flight analysis of the data at the airport where GDOP is 5.4 indicates the position of the ramp calibration used for area calibration was in error by 227 feet. This does not account totally for the larger shift shown on the plot at a GDOP of 5.4. Data indicate that the radial mean errors do vary to some extent with GDOP. As GDOP increases, the gradient increases and the crossing angles decrease. The effect is a larger radial position shift for smaller time difference errors.

Figures 7 and 8 show the effect of area calibration on navigation equipment errors. Each figure shows a scatter plot of navigation equipment errors with and without area calibration for the Teledyne TDL-711A receiver. Figure 7 is for Atlantic City and figure 8 is for Saginaw. The plots are scaled so that each tic mark is 1,000 feet. On each plot two separate clusters of data are present. The one closer to the center of the plot is with area calibration, the other is uncalibrated. From these figures it is clearly evident that area calibration only shifted the center of the data cluster but did not change the shape or distribution of errors. Results were similar for other airports and receivers.

So far in the report it has been shown that the mean ATE and CTE are reduced by area calibration, but that the standard deviation remains unaffected. From the same data it has been shown that ATE and CTE standard deviation of the errors increase with increasing GDOP. In short, the mean position errors are a function of the errors in the receiver propagation model, while the standard deviation of the position error is a function of the geometry between the user and the Loran C transmitters. If the test results are to be expanded to estimate the performance of Loran C at other airports, data must be compared to some model or performance index.

The data presented earlier versus GDOP can be misleading. Approaches were only conducted using one runway. Work done by Pierce and Slagle and Wenzel (Related Documents numbers 11 and 10, respectively) show that the distribution of position errors are a function of time difference variation, correlation coefficient between time differences, gradient, and crossing angles. The position errors are in the form of an ellipse, therefore, the direction of flight with respect to the ellipse will change the ATE and CTE errors measured. Studies by Slagle (Related Documents number 10) show error ellipses drawn using the standard deviation and correlation coefficient calculated from a population of TD data do, in fact, enclose the selected probability of individual points. Past studies using error ellipses have only dealt with position errors when in the time difference mode. Unlike many of the earlier marine receivers, which only report position in time differences, the airborne units convert this information into a latitude and



RADIAL ERROR= SQRT(((MEAN ATE))^2 +((MEAN CTE))^2)
AREA CALIBRATION RESOLUTION .1AND .01 MIN.

FIGURE 6. NAVIGATION EQUIPMENT ERROR RADIAL MEAN VERSUS GDOP WITH AREA CALIBRATION

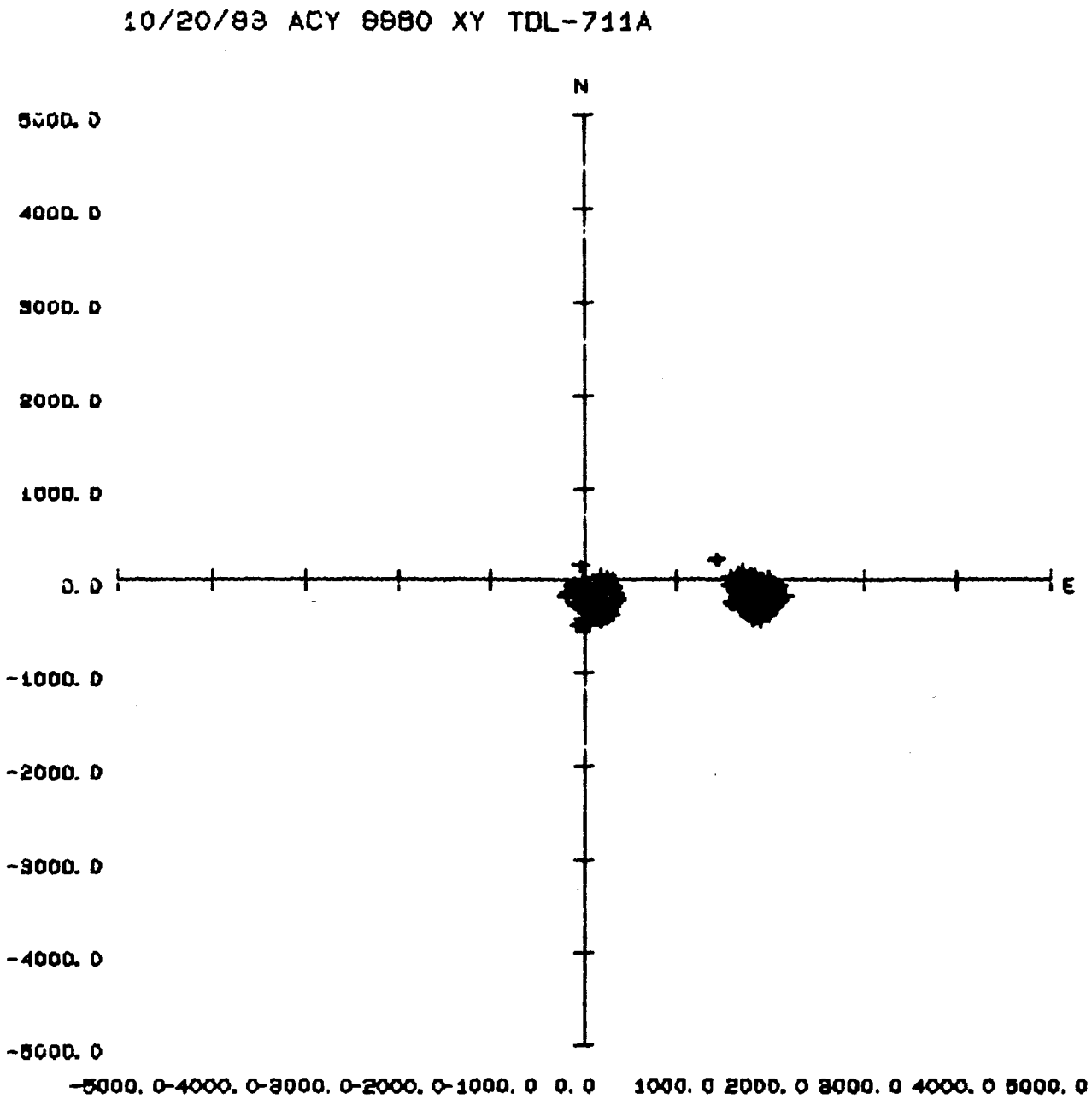


FIGURE 7. NAVIGATION EQUIPMENT ERRORS FOR ATLANTIC CITY USING TDL-711A

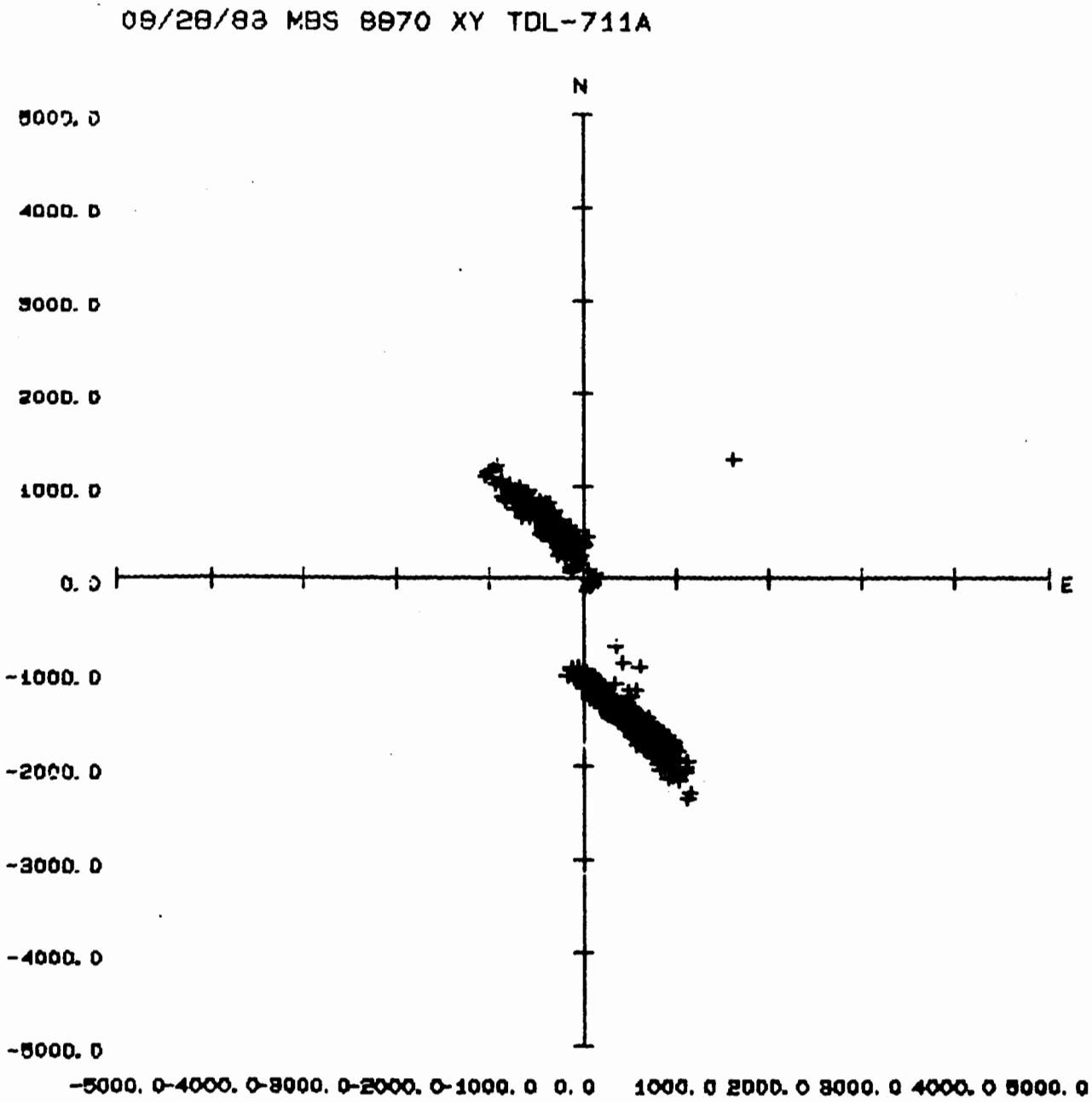


FIGURE 8. NAVIGATION EQUIPMENT ERRORS FOR SAGINAW USING TDL-711A

longitude. The conversion process may change the shape of errors due to resolution, conversion rate, and filtering.

It is very important to realize that the time difference variations and correlation coefficients calculated from seasonal data cannot be used to estimate position variation during an approach. An approach is only 5 to 15 minutes long, therefore, variation of the time differences due to the seasonal effect will be very small and look like a constant propagation modeling error. Time difference variation and correlation coefficients must reflect any changes due to modulation, control, and noise over a short period of time. Error ellipses calculated from seasonal data can only be used to estimate the errors due to modeling as a function of the seasons.

Time difference standard deviations and correlation coefficients were calculated for all Loran C receivers except the TI-9100. Both parameters were calculated from the TD bias term. The TD bias term is the difference between the measured TD and a calculated TD based on the DMA seawater propagation model and actual aircraft position. The TI-9100 did not output time differences in the digital data stream and, therefore, no data could be processed. Standard deviation of the time differences were similiar run to run and airport to airport. The value was 0.14 microseconds. The correlation coefficient term was not stable and varied from -1 to +1. The value was expected to be constant for an airport. The shape and orientation of the error ellipse is affected by the correlation coefficient. It was felt that the variation of the correlation coefficient term was due to the limited accuracy of the aircraft positioning system. Through trial and error it was determined that a standard deviation of 0.14 microseconds and a correlation coefficient of 0.3 produced ATE and CTE errors similiar to that measured. Therefore, error ellipses can be used to estimate the expected errors at an airport.

The error ellipse, although accurate, is cumbersome in use for predicting coverage areas. GDOP and 2drms are terms used to give an estimate of overall performance at a particular location. GDOP is generally unitless while 2drms is expressed as a distance. The 2drms values were compared to error ellipses drawn for 95 percent probability. The standard deviation and correlation coefficient were the same for both methods. In general, a circle with a radius equal to the 2drms value contains most of the error ellipse. As the error ellipse becomes long and narrow, more of the ellipse is outside the circle. Therefore, 2drms is a reasonable estimate of performance at a particular airport. Some runways may perform better than the 2drms value and others will be worse. A more detailed explanation of error ellipses, their comparison with 2drms errors, and ATE and CTE calculated from error ellipses compared to measured values may be found in appendix D.

A performance index should include one term for the errors due to propagation modeling and a 2drms term for position variation due to geometry, therefore, the only thing left is to establish the values. AC 90-45A sets a limit of 1,823 feet (0.3 nmi), 95 percent probability for ATE and CTE. From these tests the average errors due to propagation modeling errors were 1,000 feet. The value is larger than expected, but represents a value for all receivers tested, and should be used to estimate modeling error. Some receivers had mean error less than this value. With a modeling error of 1,000 feet, the 2drms value must be 823 feet. If at a

future date it can be shown that modeling errors are in fact smaller, the coverage area for nonprecision approaches can be increased or area calibration values would not have to change as often to compensate for seasonal change. To convert 2drms limits used in this report to the GDOP used in the MITRE Airport Screening Model (Related Documents number 15), divide the 2drms value by 0.28 microseconds. The value 0.28 is two times the standard deviation of the time differences (0.14 microseconds).

TOTAL SYSTEM CROSSTRACK ERROR.

TSCT is perhaps the most important error parameter because it describes how well the pilot and navigation equipment perform together. It measures how far the aircraft is off-course from the desired track. It tells airspace planners how much airspace must be protected to insure safe flight. Once protected airspace is established, it tells future navigation equipment manufacturers what accuracy must be obtained by their equipment. AC 90-45A specifies a TSCT of 0.6 nmi (95 percent probability). The most accurate method to determine TSCT for any system is to measure it directly by comparing the actual aircraft position to the desired track. This method has several disadvantages. TSCT is made up of two components, FTE and CTE. FTE will vary as a function of the on pilot and navigation guidance presented to him. AC 90-45A assumes an FTE of 0.5 nmi (95 percent probability) as a reasonable estimate. Some pilots will be better, but allowances must be made for the less proficient pilot.

In testing a Loran C receiver for compliance with AC 90-45A, recording only TSCT would require many pilots to fly each receiver at every airport, a long and expensive process. The authors of AC 90-45A recognized this and set forth a method to combine FTE and CTE to obtain TSCT. Since the Advisory Circular budgets an FTE of 0.5 nmi (95 percent probability), only CTE need be measured. In this section the methodology for combining FTE and CTE to obtain TSCT will be analyzed.

Questions have been raised about the calculation of TSCT, CTE, and FTE. TSCT and CTE are calculated during post-flight data reduction, while FTE is calculated from the Loran C receiver course guidance inflight. Differences in mathematical equations, waypoints, waypoint resolution, desired track, and constants between data reduction software and the Loran C receiver could produce significantly different results. Waypoint resolution for all receivers except the TDL-711 was 0.01 minute for latitude and longitude. The TDL-711 resolution was 0.1 minute. Therefore, the waypoint can only be defined in steps of 60 feet for latitude and 51 feet for longitude. For the TDL-711 the values are 10 times greater. By definition, the instantaneous TSCT is equal to the instantaneous FTE plus instantaneous CTE. If data collection and reduction software do not preserve this definition on an instantaneous level, it could affect the results when comparing the statistical results.

One way to guarantee the instantaneous values agree with the equation is to calculate two of the three components and make the third component dependent on the first two. Unfortunately, the third component could be contaminated. For this project TSCT, FTE, and CTE were calculated independently. TSCT and CTE were calculated post-flight while FTE was obtained inflight. The equations used by the post-flight data reduction software were designed to preserve the instantaneous equations. FTE was obtained from the Loran C receiver computed

course deviation information to guarantee it was the same course guidance being used by the pilot.

To verify the Loran C receiver was computing course deviation information correctly it was compared to a value calculated by the post-flight data reduction software). For the 22 conditions flown, with four different manufactures' mathematical implementations, the mean difference for course deviation between the Loran C receiver value and post-flight value was 17 feet. Differences between the two methods based on individual conditions included values up to 1,000 feet. The results seem to be receiver dependent. Data calculated using the information obtained from the analog voltages to the CDI varied more than information obtained from the CDI information in the digital data stream. Analog CDI information is not synchronized with the digital data stream (present position) as is the digital CDI information and, therefore, would be expected to exhibit more variations. The above results indicate the mathematics is similiar between the Loran C receiver and the data reduction software, but not identical. When comparing the methodology to combine FTE and CTE into TSCT, the results might not be identical but should certainly be similiar.

AC 90-45A discusses combining the standard deviations of the various error sources in an rss manner. No mention is made of error sources with non-zero means. CTE, FTE, and TSCT data collected for this project all had non-zero means. It was necessary to examine the equations for combining CTE and FTE. It can be shown (appendix B) that the following equations are valid.

$$\overline{TSCT} = \overline{CTE} + \overline{FTE} \tag{1}$$

$$\sigma\, TSCT^2 = \sigma\, CTE^2 + \sigma\, FTE^2 + 2\,\gamma\, FTE/CTE \sqrt{\sigma\, CTE^2 + \sigma\, FTE^2} \tag{2}$$

where: $\overline{TSCT}$ = mean TSCT

$\overline{CTE}$ = mean CTE

$\overline{FTE}$ = mean FTE

σ TSCT = standard deviation TSCT

σ CTE = standard deviation CTE

σ FTE = standard deviation FTE

γ FTE/CTE = correlation coefficient between FTE and CTE.

If CTE and FTE are uncorrelated and have zero means the equations reduce to that found in AC 90-45A.

$$\sigma\, TSCT = \sqrt{\sigma\, CTE^2 + \sigma\, FTE^2} \tag{3}$$

The assumptions are realistic. If large amounts of data were collected using many pilots and airports, it is expected that some runs would be right of course and others left. When all the data are averaged together the means should be close to zero, but the standard deviations would be larger than any individual run. As shown earlier, Loran C has a propagation modeling error which is constant for an airport and non-zero, therefore, repeat flights at that airport and the same runway produce a CTE with a non-zero mean and standard deviation that is very repeatable. A pilot following a CDI will try to minimize the deviation but will be unable to follow it exactly because of wind effects, pilot control lags, noise, and aircraft maneuver lags, therefore, FTE and CTE should not be correlated.

To verify the equations, measured and calculated TSCT were compared. Equations 1 and 2 were used to combine FTE and CTE into TSCT. FTE was obtained from the analog course guidance presented to the CDI and pilot. Correlation between FTE and CTE was assumed to be zero. The average difference between mean TSCT using calculated and measured values was 43 feet. The largest difference between the two methods for an individual condition was 1,066 feet. This value was measured on a receiver with 0.1 minute waypoint resolution. The next largest difference between the means for the two methods was 475 feet. Comparing standard deviations show an average difference between methods of 243 feet. In almost every case, the calculated standard deviation over-estimated the actual measured standard deviations.

Examining equations 1 to 3 suggests the need to add a term to compensate for the differences between data processing software and Loran C receiver software. If the mean error between calculated FTE and Loran C FTE was included in calculating the TSCT mean, the average difference was not changed significantly, but the individual condition differences were greatly reduced. To include a correction term in the TSCT standard deviation, the standard deviation of the correction term and cross-correlation between correction term, FTE, and CTE would be needed. Realistically, these terms would not be available unless the pilot was following course guidance, in which case TSCT could be measured directly, therefore, no correlation terms were calculated. Results using FTE obtained from the CDI information in the digital data stream were similiar to the analog FTE. The equations can be found in appendix B.

It has been shown that:

1. The mean FTE and CTE should be included to obtain a mean TSCT. If FTE is assumed to have a zero mean, as would be expected for many runs, then the mean CTE would be the mean TSCT.

2. Calculation of TSCT standard deviations from FTE and CTE standard deviations in an rss manner is conservative.

3. Calculation of FTE and CTE independently to obtain TSCT is valid.

CYCLE ACQUISITION AND TRACK ANOMALIES.

Of major concern to many people is the undetected tracking of the wrong cycle in the Loran C pulse. The effect is manifested as an incorrect present

position with no annunciation by the receiver. The problem may occur on acquisition or while in track. It is easy to check for a wrong cycle while at a known point, but the effect may go unnoticed during flight. The cycle acquisition and tracking process is affected by SNR and ECD. For most Loran C receivers acquisition requires a higher SNR than for normal track. It is possible to start a flight in good SNR using one Loran C TRIAD and operate the receiver to a destination airport where acquisition would not be possible. Atmospheric noise varies with the seasons, time of day, as well as with local noise sources such as lightning. A charge can build up on the airframe and antennas while flying in certain types of precipitation that might cause a Loran C receiver to lose track. This effect is known as precipitation static (P-STAT). Good bonding between metal parts on an aircraft and the use of the proper static dischargers should reduce this problem.

The effect of ECD is receiver dependent. Loran C receivers generally are mechanized to acquire on absolute or relative ECD. An absolute ECD receiver uses data from each Loran C station and analyzes it independently to determine the proper tracking point. As long as the ECD is within some range, it will acquire the signal regardless of what the other stations' pulses look like. A relative ECD receiver acquires the master or reference station on an absolute ECD, but requires the secondaries to be within some relative ECD value of the master or reference station.

Two basic methods are used to detect the tracking point, linear and hard-limited tracking. In a linear receiver, samples of the pulse envelope are measured directly. Because the slope of the envelope varies with time from the start of the pulse, a range of slopes can be found that will define the proper tracking point. Hard limited receivers do not measure the slope of the pulse directly. By delaying the pulse a fixed amount and then adding it back to the undelayed pulse with some gain factor, a phase reversal will occur at the proper tracking point. Once the tracking points are determined, it is no longer necessary to preserve the pulse envelope, therefore, the bandwidth can be narrowed so that the 100 kHz phase information will be less affected by interfering signals.

Receiver manufacturers use different enhancement techniques to detect and maintain the proper tracking point. Some receivers disable the check for proper tracking point once acquisition is complete, but others continually check except, perhaps, at a slower rate. Some manufacturers add additional checks such as verifying no 100 kHz energy is found before the expected start of the pulse.

During the testing for this project, cycle acquisition and/or tracking problems were encountered at Billings, Grand Junction, and Gallup. In general, acquisition at these airports took more time then at Saginaw, Atlantic City, and London. At Billings and Grand Junction, acquisition on the correct cycle was a problem for only one receiver. Once the receiver was manually forced to the correct cycle it performed correctly for that series of approaches. At Gallup, several of the receivers were unable to acquire at all. Two different manufacturers' receivers initially acquired properly, but had a cycle slip during flight. The receiver that had problems at Billings and Grand Junction performed well at Gallup. SNR and ECD values obtained from the ONI-7000 were used to analyze the results. As stated earlier, this is a linear receiver which measures parameters for each transmitter separately. It must be kept in mind that other receivers process signals differently.

SNR values for the weakest stations in the triad used for navigation were above 0 dB at Atlantic City and London, close to -10 dB at Saginaw, Billings, and Grand Junction and -14 dB at Gallup. The primary triad for Saginaw had higher SNR values than the alternate triad described above. Minimum SNR required for acquisition listed in manufacturers' specifications are typically -10 to -12 dB. It appears that the slightly lower SNR values found at Gallup were too low for some of the receivers to acquire. Absolute ECD values were consistent from run to run at all airports except Billings. The maximum absolute ECD for any one approach at all airports was 4.2 microseconds. Relative ECD values were calculated as worst case between the absolute master and secondary ECD values. For all airports except Billings the relative ECD was 3 microseconds. At Billings the relative ECD was 7 microseconds where the run to run absolute ECD values varied more than at the other airports.

Tables 8, 12, 16, 20, 23, and 27 show a summary of SNR and ECD values recorded at each airport from the ONI-7000 receiver. Flights were conducted during the months of October and November when the atmospheric noise is generally lower and during good weather. While flying en route to each of the airports, charge build-up on the aircraft was noticed while penetrating certain clouds. Charge build-up was noticed on a spectrum analyzer monitoring the Loran C band and SNR indicators on several Loran C receivers. Because the problem was first noticed while on travel and approaches were planned for good weather, no attempt was made to improve bonding or static discharges.

During approaches to Gallup, a localized noise source was noticed about 5 nmi west of the airport. Closer examination discovered a power line radiating signals at 108.7 and 111.9 kHz. Probe flights flown parallel to the power lines caused the receivers to unlock. Once the aircraft moved away from the power lines the receivers reacquired. Receivers did not unlock during approaches which were perpendicular to the power lines.

Results indicate once receivers have acquired properly or were corrected to track the proper cycle, the receivers properly tracked throughout approach maneuvers except at Gallup. Cycle slips at Gallup should be ignored because the accuracy needed for a nonprecision approach could not be met due to Loran C geometry (GDOP).

HUMAN FACTORS.

The ensemble of receivers used to collect Loran C performance data also provided a convenient method to review the various techniques used to operate the Loran C receivers. In this section, features which made the receivers easy or hard to operate will be addressed. In particular, five areas were considered: selection of desired function, entry and display of data, course deviation indicators, area calibration, and waypoint selection.

Selection of a desired function was accomplished using a rotary switch or multifunction pushbuttons. An advantage of the rotary switch was the ability to hold on to the knob in rough air and indication of function selected through the knob position. Multifunction pushbuttons required one or more buttons to be depressed in the proper sequence to display the desired function. Without a

clear indication of function selected, the operator was required to remember what the various displays represented.

Entry of data was accomplished using pushbuttons on all receivers. Size, spacing, number of functions per button, and feedback from the pushbuttons varied from receiver to receiver. In general, more errors were introduced as the size of the buttons and spacing between buttons became smaller. Entry errors also increased as the number of functions per button increased. Feedback from depressing a button was provided by one or more of the following methods: detent, beep, or character appearing in the display. A detent in the button proved to be the best method. The beep was often not heard in the high aircraft noise environment. All methods were acceptable as long as the character appeared in the display almost at the same time as pushing the button. One receiver had a relatively long delay between pushing the button and the character appearing in the display. This delay caused the operator to push the buttons more than once, requiring the entries to be corrected. Annunication of: area calibration in use, waypoint change required, loss of Loran C station, chain and triad in use, warn, and advise varied from receiver to receiver. A blinking decimal point or changing status number is not sufficient to attract the operator's attention.

It is the opinion of the project personnel who operated the Loran C receivers that: use of separate annunicators for area calibration in use, warn, and advise should be required. Each receiver did provide a flag signal to the CDI to indicate course guidance was not valid. Another source of error may be the way each manufacturer describes the triad in use. Only one manufacturer defined the secondaries by letter (W, X, Y, Z) as it appears in all U.S. Coast Guard documents. Other manufacturers number the transmitters in a chain from 1 to 5 or 0 to 4. Another method was to use the approximate time difference (27,000, 43,000). To avoid possible confusion, some standard notation should be implemented.

Signals provided to the CDI's by each receiver were similiar. In general, the course guidance was very smooth and easy to follow. The pilots were able to follow the course guidance from a receiver with a full scale deflection of 1.25 nmi as easy as one with 0.3 nmi. One receiver with a full scale deflection of 1.25 nmi provided a very noisy display. It appeared that the receiver only updated course guidance every 4 seconds without any filtering. The result was a stepped output which varied. The average value seemed to be correct but was difficult for the pilot to follow.

Use of area calibration also caused some problems. The problems were related to: the calculation of an area calibration value, the insertion of the area calibration values, and annunciation of area calibration in use. Receivers either automatically calculated an area calibration value once certain data was entered, or required the operator to manually calculate the values. The manual method often resulted in math errors or the correct value but the wrong sign. Loran C receivers required different parameters to describe area calibration values. The parameters were: two time differences plus geodetic position, two delta time differences, or delta geodetic position. Delta time difference required the entry of eight characters, while time differences plus geodetic

position required 30 characters. The entry of 30 characters was time consuming and increased the chance of errors.

Verification of the correct area calibration value while at a known geodetic position was a problem. Display of present position by the Loran C receiver in latitude and longitude was in degrees, minutes, tenths of minutes, and hundredths of minutes. The variation of the tenths of minutes digit in the display by one number represents a 600-foot shift in position, a third of the error budget in AC 90-45A for navigation equipment errors. Annunciation of area calibration in use was done with a light, status number, or not at all. A light appeared to be the best method to verify status for project personnel. Area calibration values were generally inserted only once and remained stored in the receiver until changed or chains and triad were reselected. When power was turned back on, most receivers required the operator to reselect their use in the navigation solution. This step often forced the operator to check the values stored before using them. One receiver automatically used the area calibration values in the solution when power was restored. This could lead to the use of wrong area calibration values. One receiver required area calibration values to be entered for each waypoint. The technique has merit for en route flights but unnecessarily increases the work for an approach. The method to initiate the use of area calibration in the navigation solution was difficult for the operator to select on some receivers.

The last area which caused problems was waypoint selection. Most receivers automatically sequenced the waypoints in the approach mode, but two did not. The tests defined the desired track using three waypoints, therefore, different waypoints had to be selected for navigation along the approach path. One receiver without automatic waypoint switching proved to be unacceptable for a three-waypoint approach. It was unacceptable because of the number of steps required to execute a change. The sequence was so long it took almost the entire distance between the final approach fix and missed approach point to change waypoints. The result does not mean manual waypoint sequencing is unacceptable, only that the selection sequence must be short and easy. Using the second receiver with manual waypoint sequencing was not a problem.

In summary, each area that had a human factors problem was only related to one or two receivers. The problems affecting individual receivers varied. It must be noted that each receiver was developed before standards were established. The technology does exist to produce a Loran C receiver which is easy to operate and minimize blunder errors as exhibited by some feature on every Loran C receiver.

SUMMARY OF RESULTS

FLIGHT TECHNICAL ERROR.

1. For the 22 conditions flown, 21 were in compliance with the limits set forth in AC 90-45A. A condition was defined as one to five approaches using one Loran C receiver operating on a single triad of a chain for guidance. The tests were conducted in good visibility with three test pilots.

2. The one condition not meeting the Advisory Circular requirements was from a receiver that had a CDI considerabily noiser than the rest and with a slower update rate. The standard deviation for this receiver was 1,400 feet, three to four times greater than the other receivers. The CDI from a typical receiver was very smooth and easy to follow.

3. The following 95 percent probability FTE's were determined:

Number of Conditions	Analog (ft)	Digital (ft)
22	3507	3118 (includes FTE described in item 2 above)
21	2183	2367

AC 90-45A limit 0.5 nmi or 3,038 feet

CDI information obtained from the digital data stream and the analog meter were similar.

4. A constant offset on the CDI needle from zero resulted in a constant position bias for the entire run. Loran C sensitivity is different than that used by VOR and instrument landing system (ILS) systems.

NAVIGATION EQUIPMENT ERRORS.

1. Table 30 shows a summary of receiver performance at all airports flown. A receiver stays within the limit if the statistical mean plus two times the standard deviation for all runs with that condition is less than 0.3 nmi or 1,823 feet.

2. Many receivers and airports did not meet AC 90-45A without area calibration.

3. Good GDOP does not guarantee AC 90-45A can be met without area calibration as shown at Atlantic City.

4. The use of area calibration increases the number of receiver runs meeting the Advisory Circular criteria but did not increase it to 100 percent at all airports.

5. Three sources were determined to affect position errors: receiver mechanization, GDOP, and modeling error. GDOP affects the variation in the position errors while modeling affects the mean value. Receiver mechanization can change the effect of GDOP and modeling error.

6. Use of area calibration reduced the mean position errors but not to zero as expected.

TABLE 30. SUMMARY OF RECEIVER PERFORMANCE WITH DEDICATED TRIAD

Airport and Configuration	Receivers				
	ONI-7000	ML-4000	TI-9100	TDL-711A	GDOP
Atlantic City, NJ					
9960 MXY TRIAD	Y	N	N	N	1.4
9960 MXY TRIAD*	Y	Y	Y	Y	1.4
Saginaw, MI					
8970 MXY TRIAD	Y	Y	Y	N	1.4
8970 MXY TRIAD*	Y	Y	Y	Y	1.4
9960 MYZ TRIAD	N	N	N	N	3.8
9960 MYZ TRIAD*	Y	Y	Y	*2	3.8
Grand Junction, CO					
9940 MWY TRIAD	N	N	Y	N	5.4
9940 MWY TRIAD*	Y	N	*2	Y	5.4
Billings, MT					
9940 MWY TRIAD	N	N	N	N	6.3
9940 MWY TRIAD*	N	Y	Y	Y	6.3
Gallup, NM					
9940 MWY	N	N	N	*1	9.8
9940 MWY*	N	N	Y	*1	9.8
London, KY					
9960 MYZ TRIAD	N	N	N	N	1.6
9960 MYZ TRIAD*	Y	*2	Y	*1	1.6
7980 MWZ TRIAD	N	N	Y	N	3.8
7980 MWZ TRIAD*	N	Y	Y	Y	3.8

Notes:

Y - Satisfied AC 90-45A ATE and CTE criteia
N - Did not satisfy AC 90-45A ATE and CTE criteia
* - Area calibration
*1 - Data not available
*2 - Incorrect area calibration value used

7. Mean position errors were different for each receiver even after area calibration.

8. Mean position errors after area calibration increased with increasing GDOP.

9. The standard deviation of the position errors were similar for four out of the six receivers tested.

10. Standard deviations of position errors increased with increasing GDOP.

11. The standard deviations of navigation errors were similiar with and without area calibration.

12. Error ellipses computed using a time difference standard deviation of 0.14 microseconds and a correlation coefficient of 0.3 can be used to predict the standard deviation of along-track and crosstrack position errors for any selected heading.

13. Along-track and crosstrack errors measured at an airport will vary as a function of heading as shown by error ellipses.

14. When establishing a performance index it should indicate the performance expected during all phases of flight. An error ellipse describes the expected errors at an airport due to geometry. A 2drms circle is a reasonable approximation of the maximum excursion of the error ellipse from zero for any heading.

15. To convert 2drms to GDOP as used in the MITRE Airport Screening Program (Related Documents number 15), 2drms must be divided by 2 times the time difference standard deviation in microseconds or 0.28 microseconds.

16. The performance index must account for modeling error and geometry. From the flight test data a conservative estimate for allowances after area calibration for modeling error and receiver variations is 1,000 feet. AC 90-45A specifies an along-track and crosstrack error of 0.3 nmi or 1,823 feet, 95 percent probability. If allowances for modeling error requires 1,000 feet, then the effect due to geometry can only be 823 feet. In terms of the MITRE Airport Screening Model, this is a GDOP of 2,939 feet/microsecond.

TOTAL SYSTEM CROSSTRACK ERROR.

1. TSCT errors did not have a zero mean at a particular airport.

2. Navigation errors at any particular airport did not have a zero mean even after area calibration. Variation of the navigation errors are a function of GDOP at an airport. TSCT must, therefore, account for a non-zero mean.

3. Combining the standard deviations of CTE and FTE in an rss manner to obtain a standard deviation for TSCT is a reasonable method.

4. Adding the mean CTE to the mean FTE to obtain the mean TSCT is a reasonable method.

5. FTE, CTE, and TSCT can be calculated independently.

CYCLE ACQUISITION AND TRACK ANOMALIES.

1. Cycle acquisition and track was not a problem at London, Kentucky; Atlantic City, New Jersey; and Saginaw, Michigan.

2. Acquisition on the proper cycle was a problem for one receiver at Billings, Montana; and Grand Junction, Colorado.

3. A cycle slip occured at Gallup, New Mexico, on one receiver. Several receivers were unable to acquire at all. Gallup is in a marginal signal strength area and the GDOP is such that the accuracy could not meet AC 90-45A. Therefore, approaches would not normaly be conducted in this area.

4. Proper acquisition was accomplished at SNR's down to -10 dB with ECD's of 4.2 microseconds. Results were consistent with published receiver specifications. The above limits for SNR and ECD are for the receivers studied and may not reflect a minimum performance receiver. SNR's required to meet time constraints for annunciation of faults were not studied.

HUMAN FACTORS.

1. Use of operator calculated area calibration values caused incorrect values to be used several times. The errors were due to mathematics or the correct value for area calibration but wrong sign.

2. Function selection using a rotary switch was the easiest to use, but multifunction push buttons were acceptable provided the selection of the function was annunciated.

3. The smaller the size of the push buttons and the smaller the spacing between buttons, the more difficult it was to ensure the correct values were being inserted.

4. Feedback from depressing a button was provided by tactile response, audio tone, and appearance of the character in the display. Tactile response in the button was the easiest to use, but all methods were acceptable provided the character appeared in the display almost immediately following button depression. One receiver had a long delay between depression of the button and appearance of the selected character in the display. This method caused the button to be depressed several times which required correcting the data entry.

5. Current methods to calculate, insert, and annunciate the use of area calibration varied from receiver to receiver.

6. The parameters required to be entered for area calibration varied from receiver to receiver. Parameters required for entry were: time differences measured at some point and the geodetic position, difference between measured and calculated time differences, or the difference between the displayed position and the actual geodetic position. The various methods required from 6 to 30 characters to be inserted. The more characters required to be entered increased the time to insert data and the number of errors.

7. Several receivers currently require the operator to initiate the use of area calibrtion data in the navigation solution. The method to initiate the use of area calibration data varies from receiver to receiver, but generally included a sequence of button depressions. At times, the sequence was very long.

8. Receivers requiring area calibration values to be entered for each waypoint used, significantly increased the workload over receivers requiring only one set of calibration values regardless of waypoints used.

9. Most of the receivers automatically sequenced through waypoints while in the approach mode as the flight progressed. The flight profile flown at each airport used three waypoints which required changing the waypoints selected for navigation. One receiver did not automatically sequence through waypoints while in the approach mode. The method used by that receiver to change the selected waypoints was so complicated that it took the entire distance between the final approach fix and the missed approach point, a distance of 5 nmi, to manually change the waypoints selected for navigation. Manual waypoint changing may be acceptable if the sequence is made easy and fast.

CONCLUSIONS

FLIGHT TECHNICAL ERROR.

The pilots could follow Loran C derived guidance within the limits of Advisory Circular (AC) 90-45A for four of the five model receivers used in the test.

NAVIGATION EQUIPMENT ERRORS.

1. Results of the flight tests indicate navigation equipment errors can meet the accuracies of AC 90-45A for nonprecision approaches provided area calibration is used and the receiver is operated within the proper signal coverage area. In addition:

a. Many receivers did not meet AC 90-45A without area calibration.

b. Use of area calibration reduced but did not eliminate mean navigation errors.

c. Mean navigation errors after area calibration were measured as large as 1,000 feet. Many of the Loran C receivers had smaller mean errors.

d. Use of area calibration in areas of bad geometry did not guarantee compliance with AC 90-45A.

e. Navigation errors for Loran C are approach-path dependent at an airport.

f. The standard deviation of the navigation errors were similiar with and without area calibration.

2. Minimum operational criteria for navigation equipment errors must include an allowance for propagation modeling error and for user/transmitter geometry. In addition:

a. Error ellipses using a time difference (TD) standard deviation of 0.14 microseconds and a correlation coefficient of 0.3 produced errors similiar to the standard deviations measured inflight at an airport.

b. Two distance root mean squared (drms) is a reasonable estimate of the maximum errors obtained from an ellipse.

c. From these tests, data suggest a value of 1,000 feet should be allowed for modeling error. AC 90-45A requires an error less than 0.3 nmi or 1,823 feet (95 percent probability), therefore, the error due to geometry must not be greater than 823 feet.

d. The error due to geometry is equivalent to a Geometric Dilution of Precision (GDOP) of 2,939 feet/ microsecond as found in MITRE's Airport Screening Model.

TOTAL SYSTEM CROSSTRACK ERROR.

Crosstrack error (CTE) and flight technical error (FTE) can be combined to obtain total system crosstrack (TSCT) provided:

1. The mathematics used by the Loran C receiver and data reduction software are similiar.

2. The FTE and CTE means can be added to obtain a TSCT mean.

3. The FTE and CTE standard deviations can be combined in a root sum squared (rss) manner to obtain a TSCT standard deviation.

CYCLE ACQUISITION AND TRACK ANOMALIES.

1. Signal-to-noise ratios (SNR's) down to -10 decibels (dB) and envelope-to-cycle discrepancies (ECD's) of 4.2 microseconds with relative values (difference between the master and secondary) of 3 microseconds did not create an acquisition or track problem.

2. A cycle slip occurred on one receiver at Gallup, New Mexico. Gallup had low SNR and bad geometry, which should put it outside the normal service area for Loran C nonprecision approaches.

HUMAN FACTORS.

1. Use of shorter predetermined area calibration values obtained from a chart would have reduced the number of incorrect values entered. The incorrect values caused the navigation errors to exceed AC 90-45A limits.

2. Insertion of area calibration values, such as time difference bias, must require minimum operator input.

3. Selection of area calibration for use in the navigation solution and waypoint sequencing must be easy to use.

4. A receiver should be cross-checked for proper cycle selection before an approach. Flight tests indicate once the receiver is on the proper cycle, it tracks properly provided minimum SNR, ECD, and GDOP requirements are satisified as specified in this report.

5. A standard method to describe the stations in a chain should be used.

6. Criteria must be established for Loran C receiver dynamic performance as experienced in turning maneuvers.

APPENDIX A

APPROACH PLATES

APPENDIX A

Appendix A contains all the nonprecision approaches flown on this project. Waypoints used are indicated by asterisks on the approach plates. At London-Corbin Airport, the standard published random area navigation system (RNAV) approach for runway 5 was used. At the remaining airports no RNAV approaches were published for the desired runways. At these airports, waypoints were superimposed on the published localizer/instrument landing system (ILS) approaches; the missed approach point (MAP) was defined as the runway threshold, the final approach fix (FAF) was defined as the outer marker and the initial approach fix (IAF) was defined as a point 10 nautical miles (nmi) from the runway threshold. The FAF was approximately 5 nmi from the runway threshold. The IAF was on the same bearing as the FAF to MAP segment and approximately 10 nmi from the runway threshold. Latitudes and longitudes used for each waypoint appear on the approach plates. At Atlantic City the only published approach for runway 4 used a very high frequency omni-directional radio range (VOR). The VOR approach came in at an angle to the runway, so it was not used. A new approach was set up that would bring the aircraft straight in and lined up with the runway. The approaches were set up by project personnel and are not approved Loran C approaches.

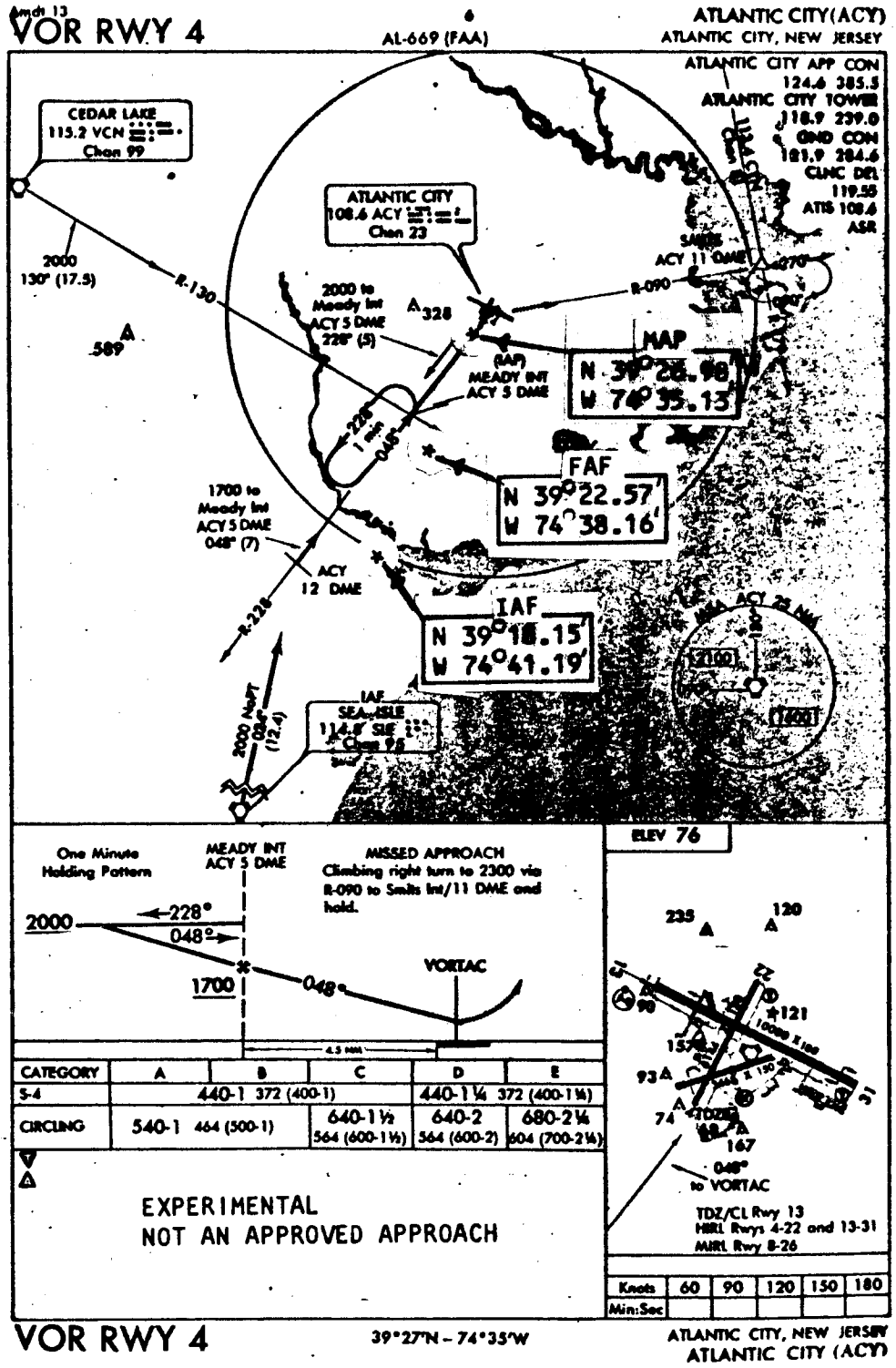


FIGURE A-1 LORAN NONPRECISION APPROACH USED FOR ATLANTIC CITY, NJ

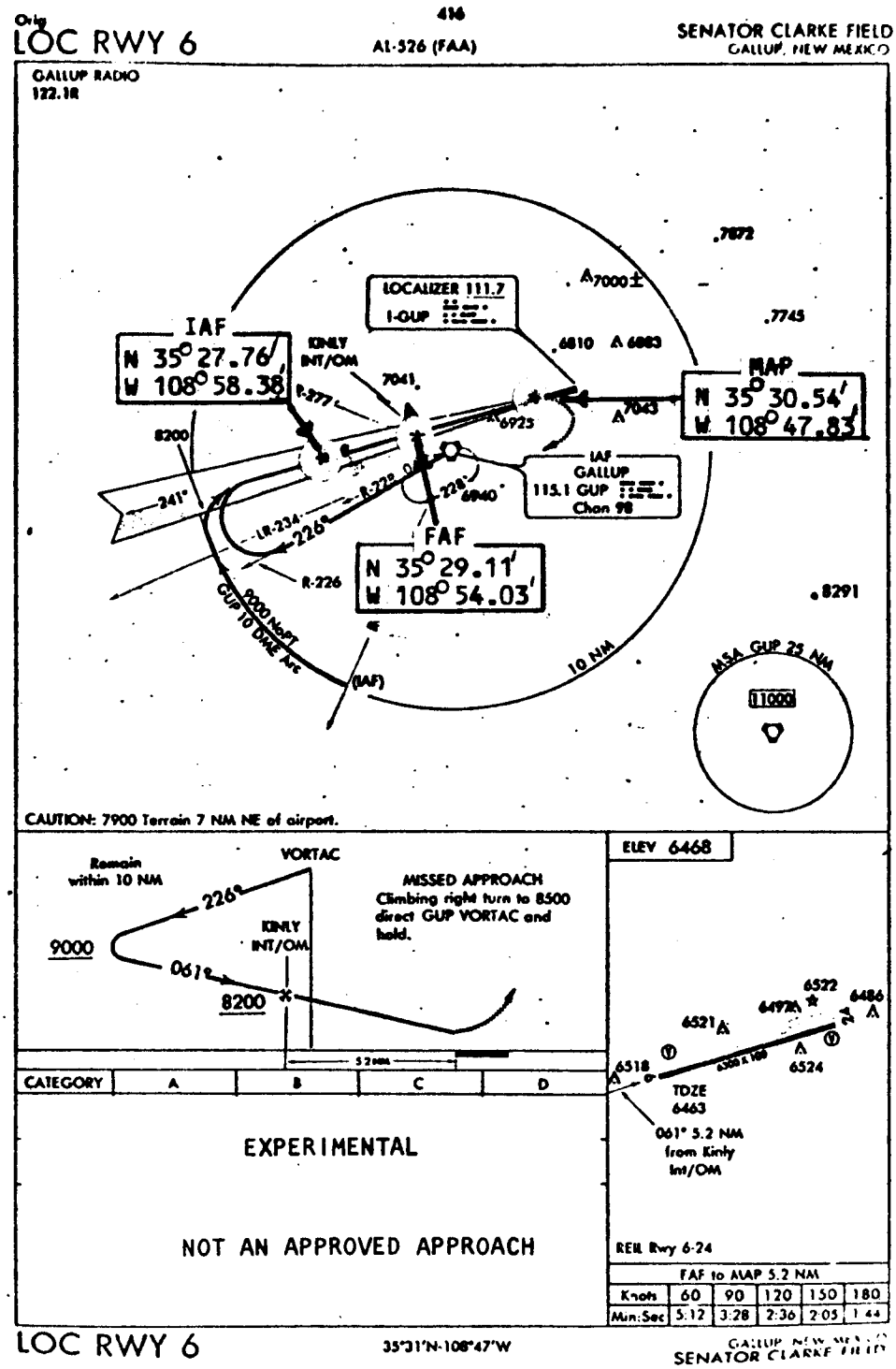


FIGURE A-2 LORAN NONPRECISION APPROACH USED FOR GALLUP, NM SENATOR CLARKE FIELD

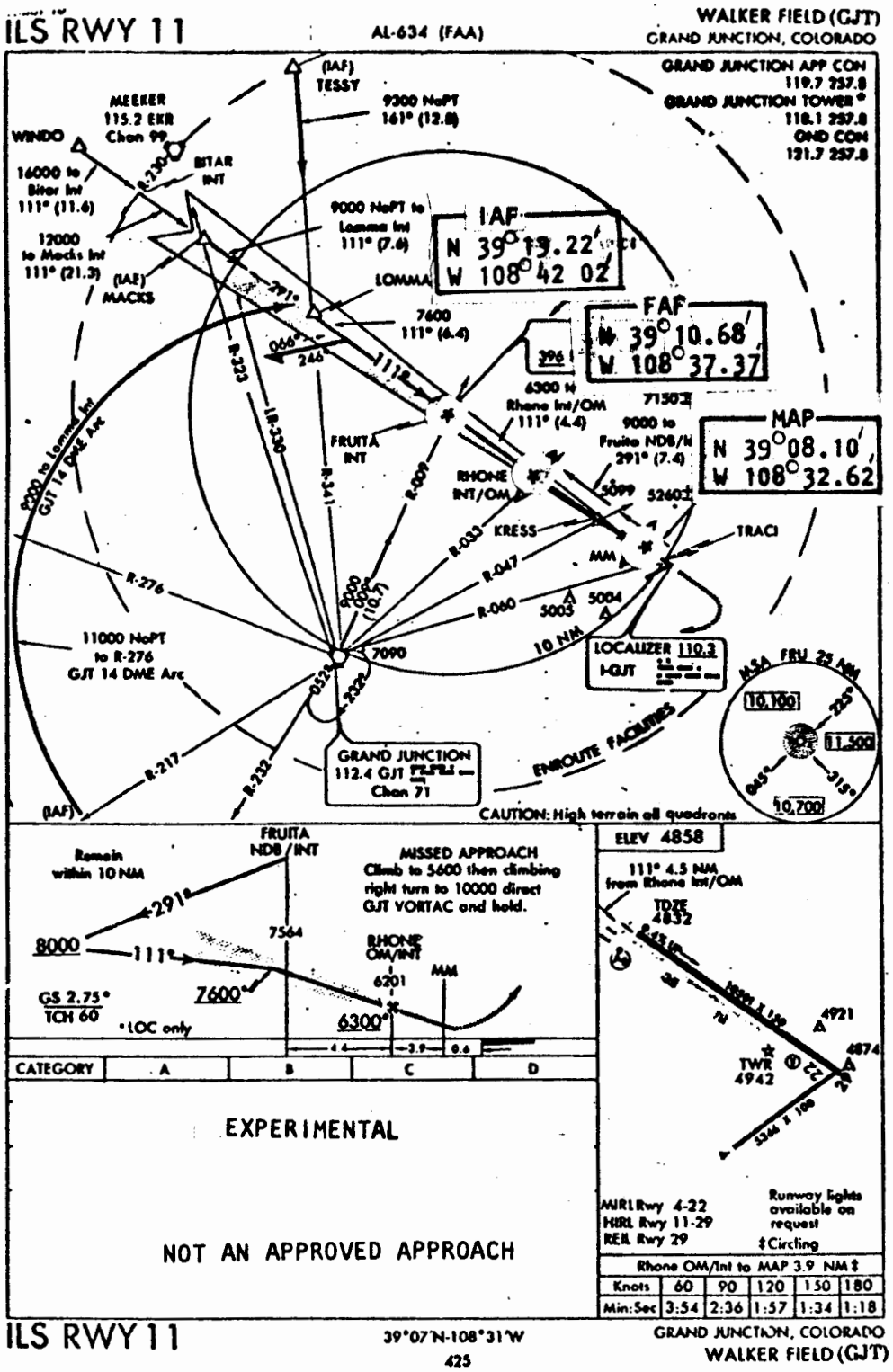


FIGURE A-3 LORAN NONPRECISION APPROACH USED FOR GRAND JUCTION, CO, WALKER FIELD

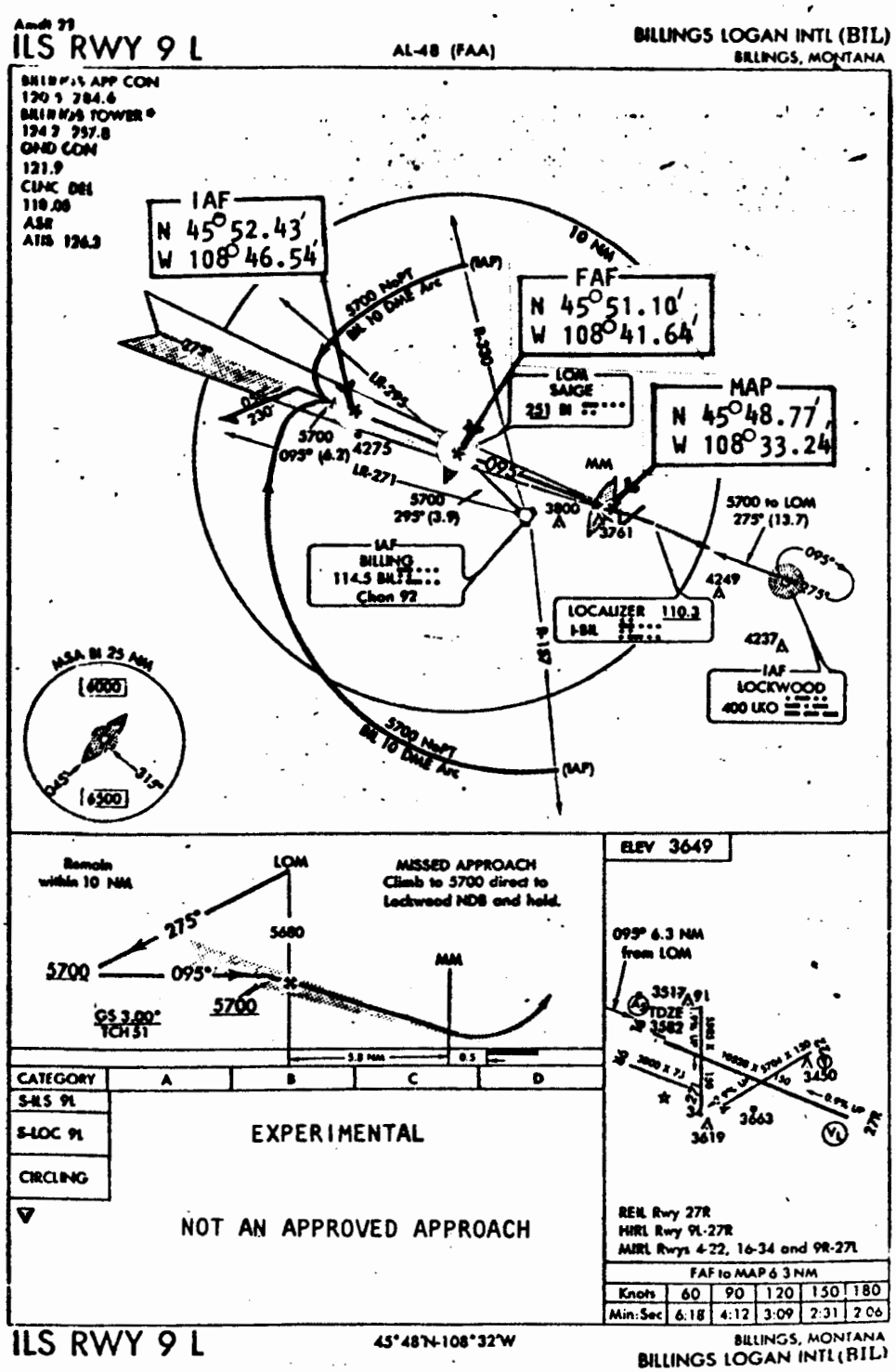


FIGURE A-4 LORAN NONPRECISION APPROACH USED FOR BILLINGS, MT, LOGAN INTL.

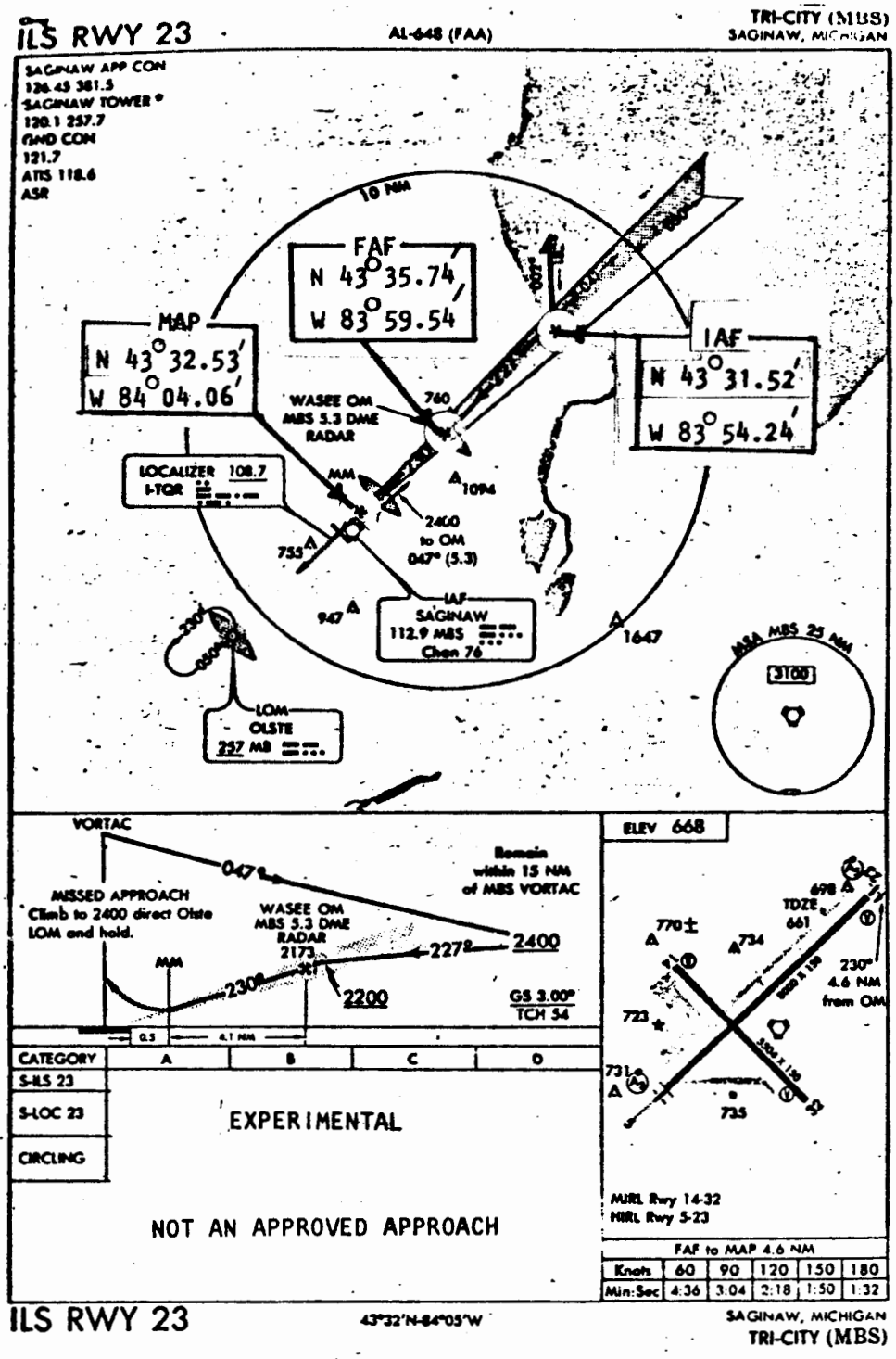


FIGURE A-5 LORAN NONPRECISION APPROACH USED FOR SAGINAW, MI, TRI-CITY

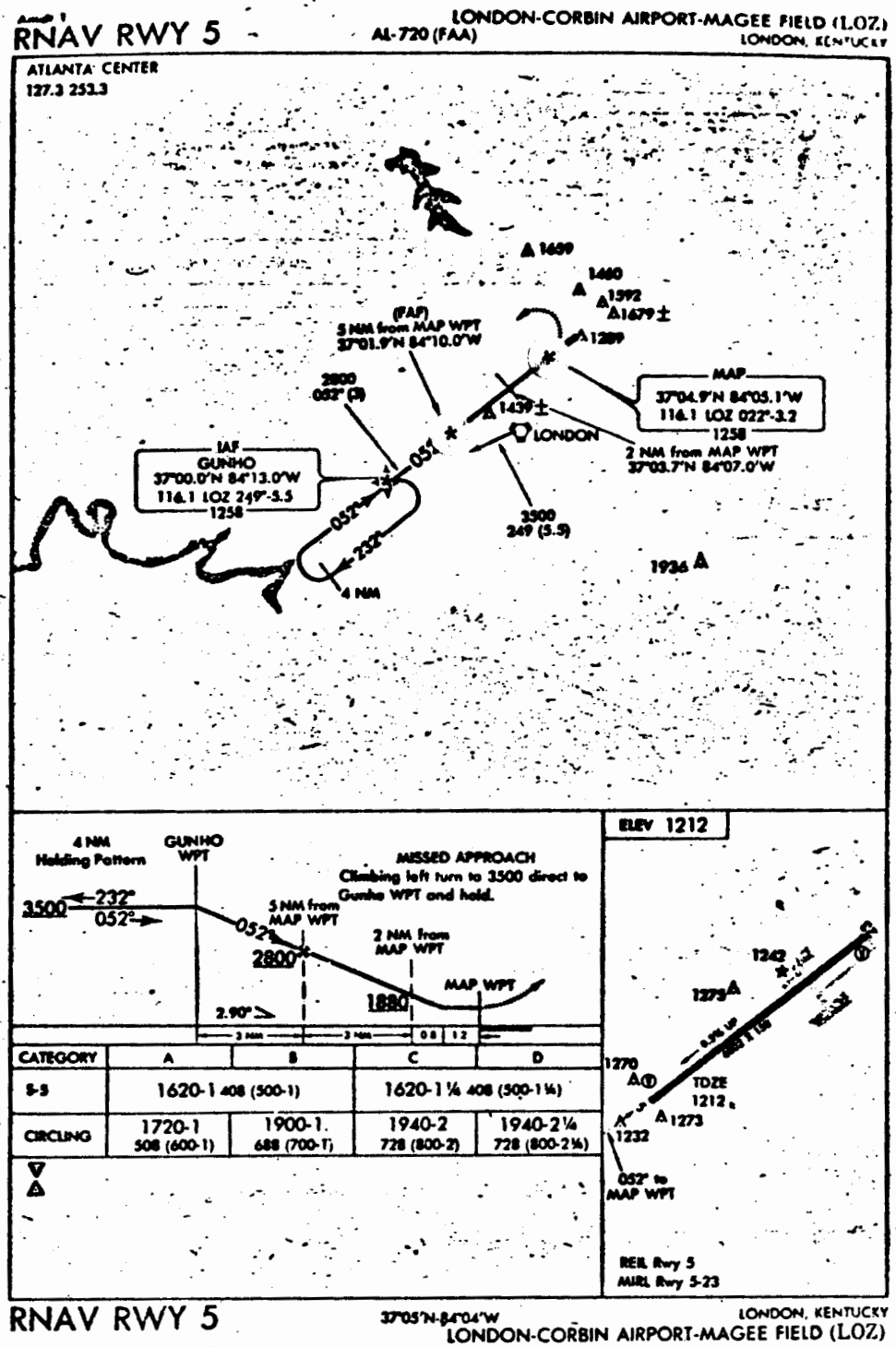


FIGURE A-6 LORAN NONPRECISION APPROACH USED FOR LONDON, KY, MAGEE FIELD

APPENDIX B

EQUATIONS AND CONSTANTS

GREAT CIRCLE DISTANCES

The calculation of great circle distances was needed in the time difference equations. Equations can be found in Advisory Circular (AC) 90-45-A Appendix J (Related Documents number 4). These mathematical formulas are known as Sodano's method. The following constants representing the World Geodetic System 1972 (WGS-72) were used for the reference ellipsoid instead of those for the North American Datum 1927 (NAD-27). WGS-72 constants are used by the Loran C community to calculate Loran C receiver positions. All Loran C transmitters are defined in WGS-72 coordinates.

Earth flattening	= F = 1/298.26
Semimajor axis of the earth	= Ao = 6378135 meters = 3443.91049 nmi
1 meter	= 3.280840 feet
1 nmi	= 6076.1155 feet

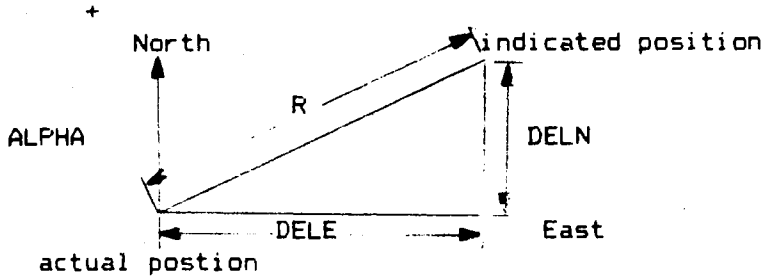
CONVERSION OF NAD-27 COORDINATES TO WGS-72 COORDINATES

The abridged Molodensky equations were used to convert latitude and longitude coordinates from NAD-27 to WGS-72. The equations can be found in the The Department Of Defense World Geodetic System 1972 (Related Documents number 19). The following constants were used to convert NAD-27 to WGS-72:

Ao = 6378206.4 meters
f = 1/294.9786982
del a = -71.4 meters
del x = -22 meters
del y = +157 meters
del z = +176 meters
del f = -3.7295850*E-5

COMPUTATION OF ATE AND CTE FOR SPECIAL ATLANTIC CITY FLIGHTS

The following equations were used to compute along-track (ATE) and crosstrack (CTE) for the special flights. These equations are different than the equations used for calculating ATE and CTE for comparation with AC 90-45-A.



ALPHA is defined as the angle between True North and a line connecting the actual position of the aircraft and the Loran C indicated position.

ALPHA = inverse tan(DELE/DELN)

DELN is defined as the difference between the latitude of the actual position of the aircraft and the Loran C indicated position expressed in feet.

DELN = (LAA - LAI) * 60.0 nmi/degree

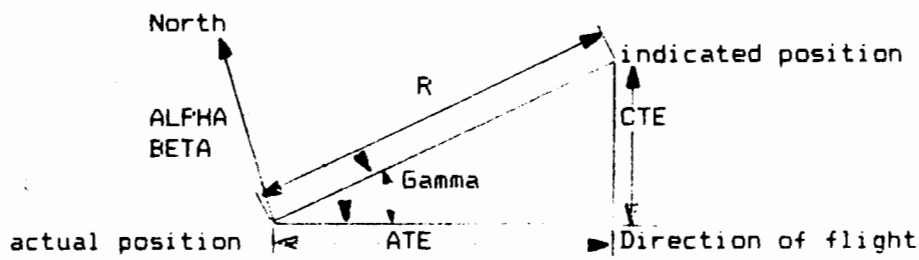
DELE is defined as the difference between the longitude of the actual position of the aircraft and the Loran C indicated position expressed in feet.

DELE = (LOA - LOI) * 46.3359 nmi/degree

R is defined as the slant range between the actual position of the aircraft and the Loran C indicated position.

R = square root of (DELN^2 + DELE^2)

where:
LAA = latitude of actual aircraft position in degrees
LAI = latitude of Loran C indicated position in degrees
LOA = longitude of actual aircraft position in degrees
LOI = longitude of Loran C indicated position in degrees



where:
BETA is the aircraft ground track obtained from the intertial navigation system (INS). Bearing is from true North.

GAMMA = ALPHA - BETA

ATE is defined as the difference between the actual postion of the aircraft and the Loran C indicated position along the direction of flight.

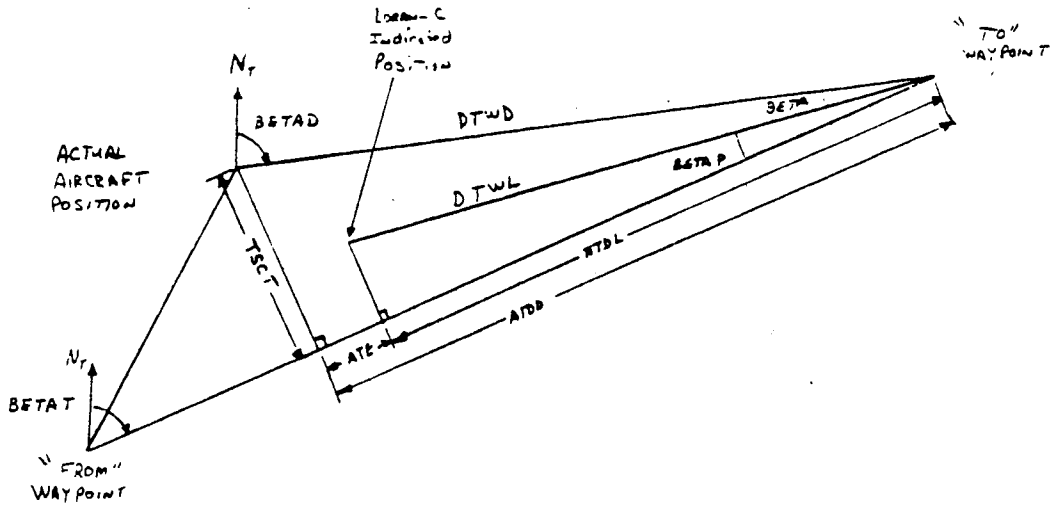
ATE = R * cos(GAMMA)

CTE is defined as the difference between the actual position of the aircraft and the Loran C indicated position perpendicular to the direction of flight.

CTE = R * sin(GAMMA)

ATE, CTE, AND TSCT USED FOR NONPRECISION APPROACHES

The following equations were obtained from An Accuracy Algorithm To Evaluate Loran C Performance During Nonprecision Approaches (Related Documents number 12).



Total system crosstrack (TSCT) is defined as the perpendicular distance between the desired course and the actual position of the aircraft. In the MITRE document it is defined as ACTD.

TSCT = DTWD * sin(BETA)

where:

BETA is the difference between the desired track angle (BETAT) and the actual track angle from the aircraft to the "TO" waypoint (BETAD).

BETA = BETAD - BETAT

BETAT = inverse tan{[(LOF - LOT)/(LAF - LAT)] * cos(LAT)}

BETAD = inverse tan{[(LOA - LOT)/(LAA - LAT)] * cos(LAT)}

LOF = longitude of the FROM waypoint

LOT = longitude of the TO waypoint

LOA = longitude of the aircraft

LAF = latitude of the FROM waypoint

LAT = latitude of the TO waypoint

LAA = latitude of the aircraft

DTWD = GR * square root{(LOA - LOT)^2 * [cos(LAT)]^2 + (LAA - LAT)^2}

GR = Gaussian radius of curvature of the earth
= [ER * square root(1 - ES)]/{1-[ES * (sin(LAT))^2]}

ER = Equatorial radius of the earth = 3443.9174 mni

ES = Eccentricity of the earth squared = 0.006694317778

The following constants were used:

Airport	GR	BETAT (FAF-MAP)	BETAT (IAF-MAP)
Saginaw	2500.5085	225.5	225.6
Atlantic City	2663.0718	27.8	27.9
Billings	2404.7249	111.7	111.6
Grand Junction	2675.0144	125.0	125.1
Gallup	2806.7209	74.1	72.0
London	2750.9521	52.5	52.1

ATE = ATDD - ATDL

ATDD = DTWD * cos(BETA)

ATDL = DTWL * cos(BETAP)

DTWL uses the same equations as DTWD except the Loran C indicated position is substituted for the aircraft position.

BETAP is the difference between the desired track BETAT and the indicated track angle from the measured position to the TO waypoint. The value is computed using the same equations as for BETA except the latitude and longitude for the Loran C indicated position is substituted for the latitude and longitude of the aircraft position.

CTE is defined as the difference between the actual position of the aircraft and the Loran C indicated position perpendicular to the desired track.

CTE = TSCT - CTD

FLIGHT TECHNICAL ERROR

FTE(D) is equal to course deviation indicator (CDI) information found in the digitial data stream of the appropriate Loran C receiver.

FTE(A) is equal to the measured voltage from the CDI being flown by the pilot. Voltages were measured for different CDI deflections and fit to the following curve:

$Y = A + B * X$

where:

X = analog voltage measured at CDI in volts

Y = CDI reading in nmi

Receiver	A	B
ONI-7000#1	.00925	.14459
ONI-7000#2	.01405	.1451
ML-4000	.03968	.16560
TI-9100	.01364	.14502
TDL-711A	.00252	.04186
TDL-711	.00208	.15438

Calculated CDI is defined as the CDI value obtained post-flight using the desired waypoints and the Loran C indicated position. It is the same term appearing in Related Documents number 15 as CTD.

CTD = DTWL * sin(BETAP)

DCDI(A) is defined as the difference between the analog CDI information from the analog CDI and the post-flight calculated CDI value.

DCDI(A) = FTE(A)-CTD

DCDI(D) is defined as the difference between the digitial CDI information from the Loran C receiver's digitial data stream and the post-flight calculated CDI value.

DCDI(D) = FTE(D)-CTD

TIME DIFFERENCES

The following equations were used to compute time differences at a given geodetic position. The method uses the same constants as the DMA seawater model but the secondary phase delay has been converted to use distances in nmi instead of in microseconds.

TD =(TS + DELTS)- (TM + DELTM) + ED

where:

TD = time difference at a given geodetic point P

TS = distance in microseconds from point P to the secondary

TM = distance in microseconds from point P to the master

DELTS = secondary phase delay in microseconds from point P to the secondary

DELTM = secondary phase delay in microseconds from point P to the master

ED = Nominal emmission delay in microseconds as published by the USCG. In reality, ED of a secondary is changed to maintain a control TD at the SAM. Early equations used baseline length and coding delay in the equations but is equivalent to emmission delay.

TM or TS = D * v/c

where:

D = great circle distance between the Loran C transmitter and point P
v = index of refraction = 1.000338
c = free space velocity = .299792458 km/microseconds
v/c = 3.336768 microseonds/km = 6.179707 microseconds/nmi

DELTM or DELTS :

1. for great circle distances greater than 86.9 nmi
   = Co/D + C1 + C2 * D
   Co = 20.8820
   C1 = -0.40758
   C2 = 0.0039906

2. for great circles distances less than 86.9 nmi
   = Do/D + D1 + D2 * D
   Do = 0.443597
   D1 = -0.011402
   D2 = 0.002025

TIME DIFFERENCES BIAS

Time difference bias is defined as the difference between the measured TD at a location and the TD calculated using the above equations.

TIME DIFFERENCE GRADIENT

Gradient = K / sin(T)

where:

K = 491.62 feet/microsecond
T = one half the angle formed by the master -point of observation -secondary

CROSSING ANGLE

XANG = ALPHA/2 + BETA/2

where:

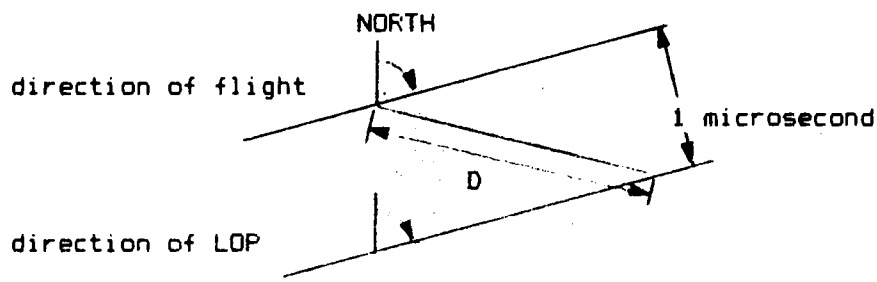
ALPHA = one-half the angle formed by the master -point of observation -secondary A

BETA = one-half the angle formed by the master -point of observation -secondary B

If the secondaries both lie on the same side of the master to observation point the two values must be subtracted instead of added.

TD DATA LATENCY

In the evaluation of the data latency it was necessary to compute the distance the aircraft would traverse for a given TD variation. The following equations were used:



Direction of line of position (LOP) with respect to True North = Alpha plus the bearing from the master to observation point

D = distance aircraft will traverse for a one microsecond TD change = gradient * sin (direction of flight - direction of LOP)

GDOP BY SWANSON (Related Documents number 17)

$$GDOP = \frac{1}{2 * \sin(P)} \left(\frac{1}{\sin\ (A/2))^2} + \frac{1}{(\sin(B/2))^2} + \frac{2 * \cos(P)}{\sin(A/2)\sin(B/2)} \right)^{1/2}$$

where:

A = the angle formed by the master ,observation point, and secondary 1

B = the angle formed by the master, observation point, and secondary 2

P = crossing angle of lop1 and lop2

= A/2 + B/2

If both secondaries lie on the same side of the master-observation point subtract instead of add.

GDOP BY MITRE (Related Documents number 15)

$$GDOP = \frac{C}{2 * \sin(P)} \left(\frac{1}{\sin\ (A/2))^2} + \frac{1}{(\sin(B/2))^2} + \frac{2 * RHO * \cos(P)}{\sin(A/2)\sin(B/2)} \right)^{1/2}$$

where:
C = speed of light = 983.5710564 feet/ microsecond
A = angle formed by the master-observation point-secondary A
B = angle formed by the master-observation point-secondary B
P = crossing angle between the two LOP's
RHO = correlation coefficient between the two LOP's

2dRMS (Related Documents number 18)

$$2dRMS = \left(\frac{C}{\sin(P)} \quad \frac{S1^2}{\sin\ (A/2))^2} + \frac{S2^2}{(\sin(B/2))^2} + \frac{2\ S1\ S2\ RHO\ \cos(P)}{\sin(A/2)\sin(B/2)} \right)^{1/2}$$

where:
A, B, C, RHO, and P are the same as in GDOP by MITRE
S1 = standard deviation of TD's for master-secondary1
S2 = standard deviation of TD's for master-secondary2

ERROR ELLIPSES

A full explaination of the equations can be found in Loran C Signal Stability Study: St. Lawerence Seaway report (Related Documents number 10). The basic equations were:

Covariance Matrix

$$\underline{K} = \begin{bmatrix} S1^2 & RHO * S1 * S2 \\ RHO * S1 * S2 & S2^2 \end{bmatrix}$$

where:
S1 = standard deviation of TD1
S2 = standard deviation of TD2
RHO = correlation coefficient between TD1 and TD2

$$\underline{B} = -V \begin{bmatrix} \sin(B1)-\sin(BM) & \cos(B1)-\cos(BM) \\ \sin(B1)-\sin(BM) & \cos(B2)-\cos(BM) \end{bmatrix}^{-1}$$

where:
V = propagation of the signal = 983.2 feet/microsecond
BM = true bearing from observation point to the master
B1 = true bearing from observation point to secondary 1
B2 = true bearing from observation point to secondary 2

$$\underline{H} = (\underline{B}^{-1})^T\ \underline{K}^{-1}\ \underline{B}^{-1}$$

let $\underline{F} = \underline{H}^{-1}$

$$\underline{H}^{-1} = \underline{F} = \begin{bmatrix} F11 & F12 \\ F21 & F22 \end{bmatrix}$$

Definiation of ellipse:

$$C^2 = F11 * X^2 + (F12 + F21) * X * Y + F22 * Y^2$$

where: C defines size of ellipse based on the desired probability

$$C^2 = -2 \, LN(1-P)$$

for 95% $C^2 = 5.9914$

STATISTICAL METHODS

MEAN

$$X = \Sigma Xi / N$$

where:
X = mean
Xi = individual value
N = number of samples

STANDARD DEVIATION

$$S = \left(\frac{N \quad Xi^2 - (\quad Xi)^2}{N(N - 1)} \right)^{1/2}$$

where:

S = standard deviation
Xi = individual value
N = number of samples

CORRELATION COEFFICIENT

$$R = \frac{N \ \Sigma Xi * Yi - \Sigma Xi * \Sigma Yi}{\text{square root}\{[N \ \Sigma Xi^2 - (\ \Sigma Xi)^2] \ [N \Sigma Yi^2 - (\Sigma \ Yi)^2]\}}$$

where:

N = number of samples
Xi = individual samples of X
Yi = individual samples of Y

APPENDIX C

DATA LATENCY

DISCUSSION

Special flights were conducted at Atlantic City, New Jersey, to estimate/verify aircraft positon errors due to time lags in the Loran C receivers and data collection system. The flights were straight and level runs inbound starting 10 nautical miles (nmi) from the airport continuing over the center of the airfield and then outbound 10 nmi. Each run was tracked by the Nike radar. The following conditions were flown:

Runway 22 - 150 Knots ground speed.

Runway 22 - 250 Knots ground speed.

Runway 4 - 150 Knots ground speed.

Runway 4 - 250 knots ground speed.

RESULTS

Along-track and crosstrack errors for the special Atlantic City flights are shown in table C-1. Errors are the difference between the Nike tracking system (truth system) and the appropriate Loran C receiver positions rotated into along-track error (ATE) and crosstrack error (CTE) components. Inertial navigation system (INS) ground track was used as the aircraft track angle. ATE and CTE errors for runs 2, 4, 6, and 8 have the signs reversed to compensate for the reversed direction of flight.

Table C-2 shows a summary of the time difference (TD) bias (means and standard deviations). TD bias is the difference between the Loran C receiver measured value and a calculated value based on the aircraft position and the IMA seawater model. Equations and constants used may be found in appendix B. Values in tables C-1 and C-2 are the statistical results of the entire 20 nmi level run. The odd numbered runs were flown on runway 4 and the even numbered runs on runway 22. Runs 1 to 4 were flown at 150 knots, runs 5 to 8 at 250 knots.

ANALYSIS OF RESULTS

The special flights were designed to determine the amount of time delay introduced into the position errors and TD measurements by the Loran C receivers and data collection system. It was assumed that for the short duration of the test, the Loran C environment was stable, therefore, data collected on runway 4 should be the same as runway 22 (180° from runway 4) except for any time delays. If the position errors are rotated into their ATE and CTE components and Loran C is stable, only ATE should vary as a function of time delay. It is important that the rotation be done on actual track heading and not desired track. INS track angle was used to determine the direction of flight. The actual time delay will be half the difference

TABLE C-1. ALONG-TRACK AND CROSSTRACK ERRORS FOR SPECIAL ATLANTIC CITY FLIGHTS

		Run							
		1	2	3	4	5	6	7	8
	Runway	4	22	4	22	4	22	4	22
	Ground Speed(kts)	150	150	150	150	250	250	250	250
Loran Receiver	Parameter								
ONI-7000 #1	ATE mean	-388	-38	-301	-188	-431	-65	-657	-335
	std. dev.	247	153	273	199	476	241	591	413
	CTE mean	-454	-798	-90	-874	2	-1271	-79	-919
	std. dev.	159	123	277	164	259	253	493	170
ONI-7000 #2	ATE mean	-320	+11	-35	-37	-322	-371	-175	+133
	std. dev.	168	173	246	262	507	259	371	501
	CTE mean	-411	-826	-234	-477	-224	-555	-120	-786
	std. dev.	111	137	219	170	283	295	368	268
ML-4000	ATE mean	1280	+99	1184	+101	1625	-208	1545	-186
	std. dev.	166	109	234	112	181	139	360	164
	CTE mean	-1831	-1867	-1883	-1825	-1931	-1889	-1766	-1855
	std. dev.	99	60	232	96	141	123	240	84
TI-9100	ATE mean	116	817	32	878	-189	1062	-163	+1112
	std. dev.	293	235	299	232	332	298	291	292
	CTE mean	-1939	-2002	-1967	-1970	-1986	-2004	-1963	-1983
	std. dev.	207	170	222	174	186	214	352	191
TDL-711	ATE mean	774	1131	641	1143	580	1251	595	+1288
	std. dev.	176	113	210	99	160	162	544	128
	CTE mean	-1772	-1778	-1815	-1716	-1828	-1737	-1710	-1705
	std. dev.	110	86	178	77	79	71	360	70
TDL-711A	ATE mean	820	+1127	691	+1147	659	+3384	679	+1286
	std. dev.	172	113	199	95	166	350	205	132
	CTE mean	-1593	-1703	-1679	-1658	-1749	-5959	-1678	-1645
	std. dev.	100	85	179	77	81	180	133	72

Note: All values in feet.
Runs 2, 4, 6, and 8: ATE and CTE signs have been reversed.

TABLE C-2. TIME DIFFERENCE BIAS FOR SPECIAL ATLANTIC CITY FLIGHTS

		Run							
		1	2	3	4	5	6	7	8
	Runway	4	22	4	22	4	22	4	22
	Ground Speed(kts)	150	150	150	150	250	250	250	250
ONI-7000 #1	TD mean X	-2.70	-2.79	-2.70	-2.76	-2.67	-2.82	-2.66	-2.82
	std. dev.	.18	.13	.19	.16	.30	.34	.28	.32
	TD mean Y	-.47	-.26	-.60	-.19	-.87	-.17	-.92	-.06
	std. dev.	.40	.42	.54	.55	.94	.93	1.05	.82
ONI-7000 #2	TD mean X	-2.79	-2.78	-2.72	-2.77	-2.70	-2.81	-2.71	-2.83
	std. dev.	.13	.19	.15	.25	.42	.27	.23	.38
	TD mean Y	-.49	-.41	-.53	-.33	-.62	-.23	-.60	-.22
	std. dev.	.43	.43	.47	.40	.81	.59	.73	.58
ML-4000	TD mean X	-2.64	-2.79	-2.69	-2.72	-2.66	-2.83	-2.58	-2.79
	std. dev.	.13	.08	.10	.14	.09	.09	.14	.11
	TD mean Y	-.63	-.12	-.73	-.12	-.84	+.08	-.82	.13
	std. dev.	.13	.12	.13	.16	.24	.21	.19	.20
TDL-711	TD mean X	-2.69	-2.78	-2.67	-2.71	-2.66	-2.76	-2.43	-2.73
	std. dev.	.16	.13	.19	.12	.09	.07	.92	.11
	TD mean Y	-.66	-.24	-.68	-.22	-.83	-.05	-.85	+.02
	std. dev.	.16	.16	.23	.14	.21	.21	.24	.20
TDL-711A	TD mean X	-2.51	-2.74	-2.55	-2.70	-2.64	7.26	-2.57	-2.71
	std. dev.	.13	.14	.17	.12	.09	.07	.13	.11
	TD mean Y	-.55	-.18	-.62	-.16	-.81	9.99	-.82	+.08
	std. dev.	.17	.17	.21	.15	.21	.20	.24	.20

Note: All values in microseconds.

between the ATE on runway 4 and ATE on runway 22 divided by the speed of the aircraft.

Table C-3 shows a summary of the one direction time delays in feet and seconds, for 150 and 250 knots, for each receiver. Delta crosstrack error (DCTE) was defined as one-half the difference between the crosstrack errors from runway 4 and runway 22. Delta along-track error (DATE) was defined as one-half the differences between the along-track errors for runway 4 and runway 22. Results are calculated from data presented in table C-1. The following significant conclusions can be made from this table.

1. DCTE for the ML-4000, TI-9100, TDL-711, and TDL-711A receivers was less than 25 feet, indicating Loran was stable and the direction of flight was correct.

2. The time delay in seconds for the ML-4000, TI-9100, TDL-711, and TDL-711A receivers was approximately the same at 150 and 250 knots.

3. The TI-9100, TDL-711, and TDL-711A receivers had time lags of 1.5, 0.8, and 0.7 seconds, respectively.

4. The ML-4000 receiver had a 2-second time lead. Conversations with Micrologic indicate this is valid. With a position update every 4 seconds, the company has decided to predict a position 2 seconds ahead so that position errors will have a zero mean. The post-processing software compared the Loran present position with the reference system based on time of reception of the digital data stream. Therefore, ATE means will be contaminated with a bias of 338 feet at a ground speed of 100 knots.

5. DCTE's for the ONI-7000 receivers were 164 feet which was seven times greater than the largest value for the other four receivers. Investigation of the above result showed the receiver was operating in the wide open mode which used lines of position formed by the 9960 chain, M,W,X,Y, and Z stations, and the 8970 chain, stations M and X. During wide open operation the receiver is allowed to update secondary phase factors and change selection of Loran stations for navigation. Review of these parameters in the digital data stream showed station selection did not change and the variations of the secondary phase factors were too small to cause this change. It appears the problem must be in the present position computation.

Discussions with Advanced Navigation Inc. (ANI) about the results and subsequent analysis by ANI has determined the cause. The effect was caused by the Kalman filter used to smooth the geodetic position. The many turns encountered while conducting the approaches for this project caused the Kalman filter to wander. The wander for the en route environment was negligible with respect to the accuracy limits of Advisory Circular (AC) 90-45A. The filter was optimized to smooth the position while flying en route and not for the maneuvering common to an approach. If the time difference data recorded during the flights were converted to a geodetic position (using an algorithm similar to that used by the ONI-7000 receivers without Kalman filtering), the position closely follows the other Loran C receivers. A dynamic Loran C simulator was used by ANI to simulate the Federal Aviation Administration (FAA) flights.

TABLE C-3. LORAN C PRESENT POSITION DATA LATENCY

Parameter	Loran C Receivers					
	ONI-7000 #1	ONI-7000 #2	ML-4000	TI-9100	TDL-711	TDL-711A
150 kt Ground Speed						
DCTE (feet)	282	164.5	-5.5	16.5	-23.5	22.5
DATE (feet)	-116	-82.5	566	-387	-215	-191
DATE (seconds)	-.46	-.33	2.24	-1.53	-.85	-.75
250 kt Ground Speed						
DCTE (feet)	528.5	249.5	12	9.5	-24	-17
DATE (feet)	-172	-65	891	-631.5	-341	-308.5
DATE (seconds)	-.41	-.15	2.11	-1.50	-.81	-.73

The simulated pattern was a racetrack 10 nmi long and 3 nmi wide. The results were similar to those found in flight. The position errors previously encountered were reduced when the Kalman filter constants were changed and the simulation rerun. ANI will change the Kalman filter constants used for the present position during the approach mode when new software in development is released.

Table C-4 shows data latency for Loran TD's. One direction average TD delay is obtained by subtracting the average TD bias for runway 4 from runway 22 and dividing by two. These TD variations must be converted to feet before a data latency time can be calculated. At first, it might seem correct to simply multiply the TD variation by the TD gradient. The direction of flight crossed the two TD lines of position at an angle, therefore, a 1 microsecond TD variation would cover a distance greater than the gradient. The distance would be equal to the TD gradient divided by the sine of the angle between the line of position and the direction of flight. At Atlantic City, with a direction of flight of 28°, the conversion value is 3,805 feet/microsecond for TDX and 623 feet/microsecond for TDY. In table C-4, the data latency is presented for each Loran C receiver. The following data for each receiver and indicated TD is included in the table: one direction average TD delay, TD delay converted to feet, and TD delay converted to seconds for a ground speed of 150 knots followed by the same columns for 250 knots ground speed.

It can be shown from table C-4 that all TD measurements were between 0.2 and 0.9 seconds old. This means the TD measurement might be 152 to 345 feet in error for a 100 knot approach due to data latency.

TABLE C-4. LORAN C TD DATA LATENCY

		150 knots Ground Speed			250 knots Ground Speed		
Loran Receiver	TD	One Dir. Average TD Delay (1)	TD Delay in Feet	TD Delay in Sec.	One Dir. Average TD Delay (1)	TD Delay in Feet	TD Delay in Sec.
ONI-1	X	.02	76	.3	.08	304	.7
	Y	-.16	97	.4	-.39	243	.6
ONI-2	X	.01	38	.2	.06	228	.5
	Y	-.07	44	.2	-.19	118	.3
ML-4000	X	.05	190	.8	.10	381	.9
	Y	-.28	174	.7	-.47	293	.7
TDL-711	X	.03	114	.5	.1	381	.9
	Y	-.22	137	.5	-.41	255	.6
TDL-711A	X	-.01	38	.2	-.05	190	.5
	Y	-.21	131	.5	-.45	280	.7

Note:

1. Units are TD microseconds.

APPENDIX D

ERROR ELLIPSES

DISCUSSION

In the main body of this report it was shown that Loran C navigation equipment errors were mostly caused by propagation modeling and geometry. The first affects the mean errors while the second affects the standard deviation. If one is to predict areas of acceptable Loran C accuracies, the underlying causes of the errors must be understood. In this appendix the effects of geometry will be analyzed. Work done by Pierce and Slagle and Wenzle (Related Documents numbers 11 and 10, respectively) show that the variation of the position errors (standard deviation) are a function of the time difference variations, correlation coefficient, gradient, and crossing angles. The position errors are in the form of ellipse. The above work was done on the time difference level.

Unlike many of the earlier marine Loran C receivers which only reported present position in time differences (TD's), present airborne Loran C receivers convert this information into a latitude and longitude. The conversion process may change the shape of the errors due to resolution, conversion rate, and filtering. If the position errors for Loran C receivers are in the form of an ellipse, than data presented earlier for a single runway heading at an airport versus Geometric dilution of precision (GDOP) could be misleading. GDOP describes how the root mean square (rms) errors will be affected but cannot break the errors into along-track error (ATE) and crosstrack error (CTE). In the remainder of this appendix the error ellipse will be validated for airborne receivers and then used to develop a performance index. The validation process will compare measured ATE and CTE with error ellipse calculated data.

Studies by Pierce and Slagle and Wenzel have proven that error ellipses generated from the TD standard deviation and correlation coefficient of the data do enclose the desired probability. The studies conducted by Slagle and Wenzel deal with the seasonal effect and were done on a TD level. Data collected for the nonprecision approach tests in this report were collected and analyzed by specific triad and condition. Each approach was about 15 minutes long with a total time for all approaches under one condition of about 2 hours. Variation of the TD's due to the seasonal effect for such a short period should be very small and appear as a propagation modeling error. TD's variation and correlation coefficients must reflect any changes due to modulation, control, and noise over a short period of time. Work done by Slagle and Wenzel only addressed the long term effects and did not consider errors due to receiver mechanization of area calibration values or the effect of infrequent area calibration updates. Literature currently uses a TD standard deviation of 0.1 microseconds when calculating the effects of geometry on position fixes for short periods of time (no seasonal effect).

RESULTS

Standard deviations and correlation coefficients were calculated for each receiver, airport, and condition for all measured TD's. No TD's were available

from the digital data stream of the TI-9100. The statistics were calculated on the TD biases for each receiver. TD bias was defined as the difference between the measured TD at a point and a calculated TD, based on the aircraft position and a DMA seawater propagation model. Data were grouped by test conditions and contained one to five approaches. Measured correlation coefficients varied from run to run at the same airport. Individual run values varied from -1 to 1. Correlation coefficients were expected to be approximately 0.3 and consistent from run to run. The test results indicate the aircraft position reference may not be accurate enough to properly calculate the correlation coefficient or the correlation coefficient is not as expected.

Figure D-1 shows the measured standard deviation of the TD bias as a function of the gradient for the ML-4000, TDL-711, and TDL-711A. Once the gradient is over 600 feet per microsecond, the standard deviations are grouped within a band from 0.1 to 0.2 microseconds, with an eyeball average of 0.14. Standard deviations of points below a gradient of 600 feet per microsecond are as large as 0.4 microseconds. Again, the inaccuracies of the aircraft position reference and data latency may be masking the true value. With a gradient of 550 feet per microsecond the effect of a 200-foot reference position error perpendicular to the line of position would shift the time difference by 0.36 microseconds. As the gradient gets bigger, the effect of the same size position reference error on the TD measurement error will be smaller. Ignoring the measured standard deviations of points with a gradient of less than 700 feet per microsecond show the data to be fairly consistant.

Before an error ellipse can be drawn, a value for the correlation coefficient must be determined. As mentioned earlier, the attempt to measure this value failed. To determine what effect the correlation coefficient has on the error ellipses, several error ellipses were drawn for geometry found at Saginaw, Michigan, using nine different correlation coefficients. The TD standard deviations were held constant at 0.2 microseconds, while the correlation coefficient was varied from 0.8 to -0.8 in 0.2 steps. The results can be found in figure D-2. Listed on the figure is the maximum value of the ellipse in the along-track and crosstrack directions for an approach heading of 225° (dashed line). All error ellipses, regardless of correlation coefficient, fall within a band of 2.5 TD standard deviations (solid straight lines). As shown in the plot, the correlation coefficient changes the direction of the major axis of the ellipse as well as the shape. For example, a correlation coefficient of 0.8 has the major axis of the ellipse pointing toward the short corners of the parrallelogram, while a -0.8 value causes the ellipse to point toward the long corners with a narrower ellipse. Maximum ATE and CTE obtained from an error ellipse, drawn for 95 percent probability, will include more than 95 percent of the data because theory expects some data to be outside of the ellipse in all directions.

To validate the error ellipse, measured ATE and CTE were compared with values calculated from the ellipse. Use of a standard deviation of 0.14 microseconds and a correlation coefficient of 0.3 produced results similar to that measured. Figure D-3 shows the actual measured ATE and CTE standard deviations compared to a value obtained from the error ellipse calculated value. The ONI-7000 data are not included in the plot. The dashed line shows the point where measured

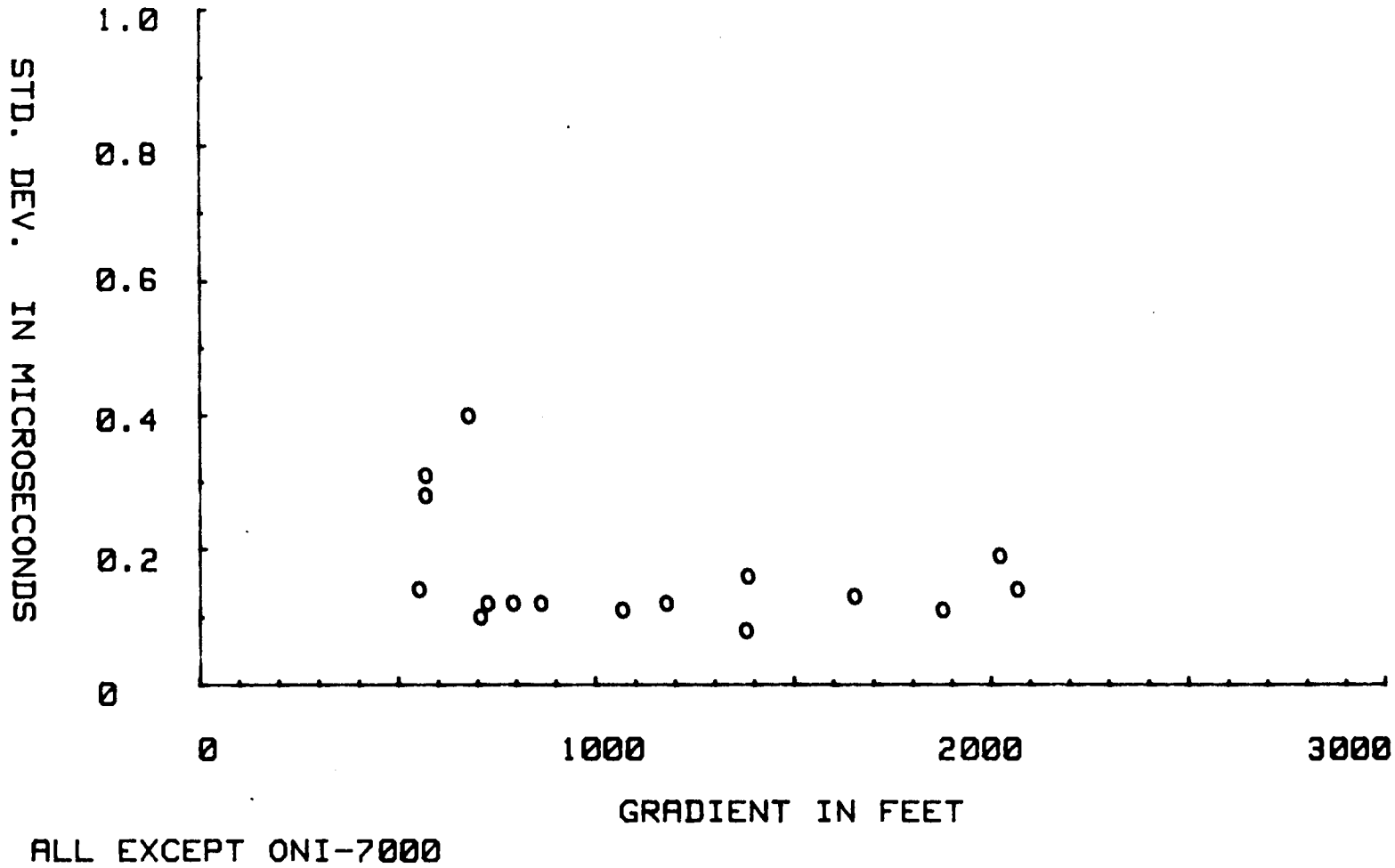


FIGURE D-1. TIME DIFFERENCE STANDARD DEVIATION VS GRADIENT

APPROACH HEADING: 225.0000
ELLIPSE PROBABILITY: .9500
STD. DEV. US TD1: .200
STD. DEV. US TD2: .200
LAT OF SITE (dd.mmss) 43.3200
LON OF SITE (dd.mmss): 84.0500
CHAIN & TRIAD: 9960 MYZ
GRADIENT TD1 FEET/MICROSEC: 1068
GRADIENT TD2 FEET/MICROSEC: 569
CROSSING ANGLE DEGS: 32
NUM OF TD STD DEVS PLOTTED +- 2.50

RHO	MAX ATE(FT)	MAX CTE(FT)
-.80	+147	+1352
-.60	+207	+1285
-.40	+254	+1210
-.20	+293	+1130
+.00	+328	+1045
+.20	+359	+952
+.40	+387	+849
+.60	+413	+731
+.80	+436	+590

TIC SPACING 100 FEET

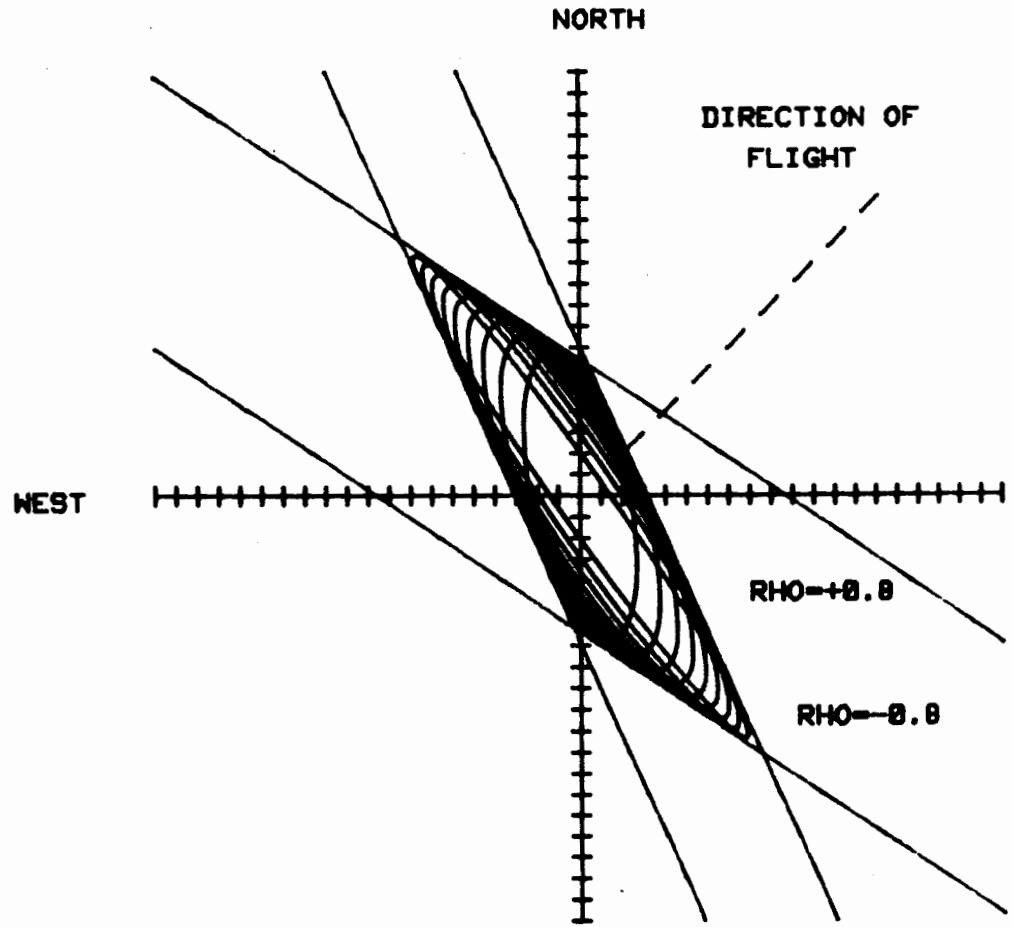
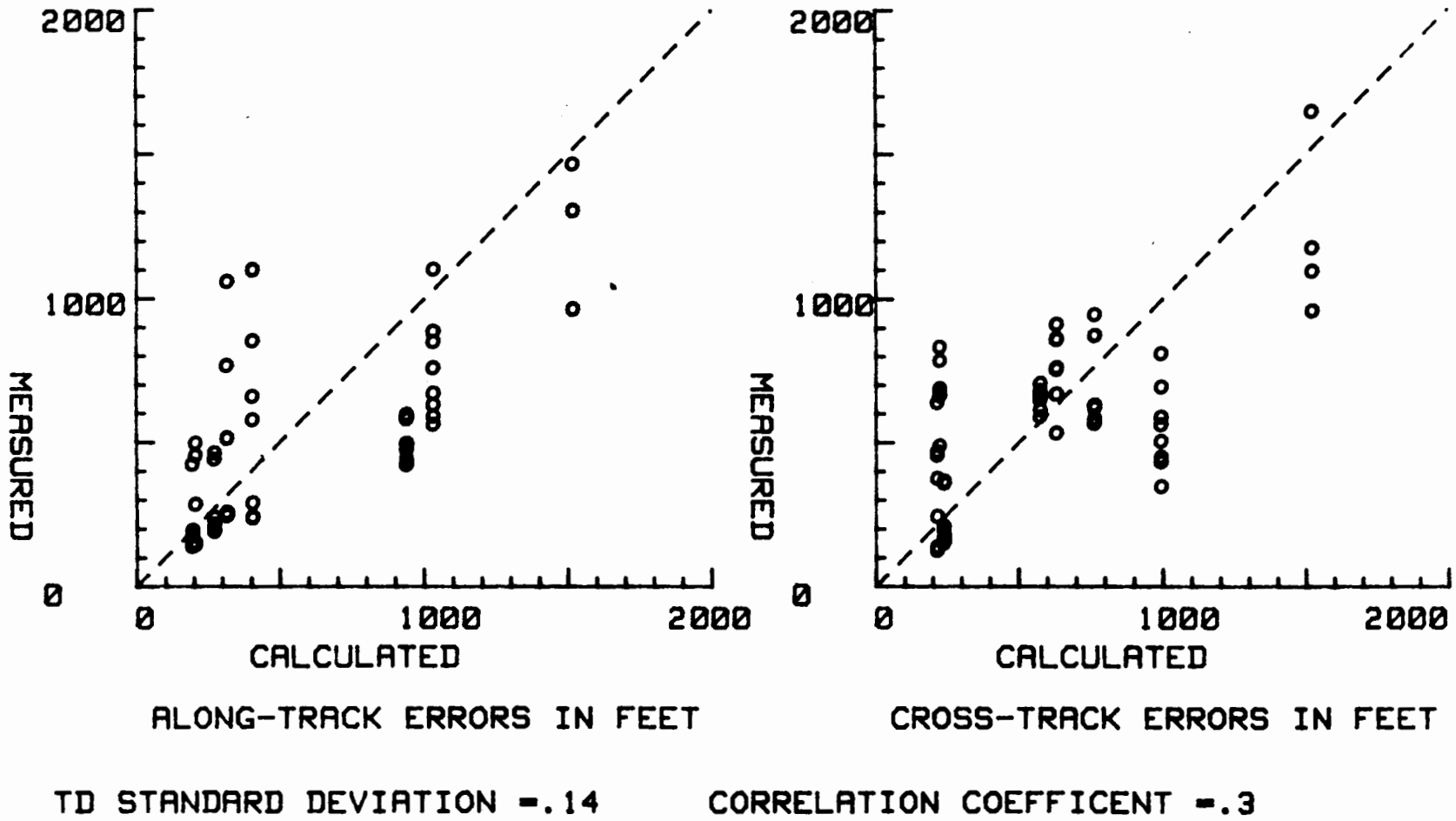


FIGURE D-2. ERROR ELLIPSES FOR SAGINAW, MICHIGAN



TD STANDARD DEVIATION =.14 CORRELATION COEFFICENT =.3

FIGURE D-3. VARIATION OF NAVIGATION EQUIPMENT ERRORS (95%) MEASURED VERSUS CALCULATED FROM ELLIPSE

and calculated data are equal. The dispersion of the data points vertically are due to the difference in receivers.

Now that is has been shown that an error ellipse drawn using a standard deviation of 0.14 microseconds and a correlation coefficient of 0.3 do produce results similiar to that measured, it can be used as a baseline model to look at other performance indexes. A performance index should be independent of heading and worst case. It is possible to determine the radius of a circle that just passes through the extremes of the ellipse. The value calculated would be worst case and include more than 95 percent of the data. The method would be computationally burdensome when calculating a contour for possible nonprecision approach certification. Two other performance indicators, GDOP and distance root mean square (drms), would be easier to compute. GDOP and drms can be converted back and forth by multiplying by the proper scaler. Because drms is calculated in feet it will be compared to the error ellipses. Figures D-4 and D-5 show a comparision of 2 times drms with the 95 percent probability error ellipse. In each plot the tic spacing is 100 feet. Both the ellipse and 2drms used a TD standard deviation of 0.14 microseconds and a correlation coefficient of 0.3. The gradients and crossing angle are those found at each airport for the triad in use. The dashed line represents the direction of flight into the airport that was flown. Notice that 2drms does give a reasonable estimate of performance. From the figure it can be seen that the flight tests did not include data from the worst direction, therefore, comparing the performance index back to measured data on one heading could be invalid. Presently, the Federal Aviation Administration (FAA) has a computer program known as the MITRE Airport Screening Model which will be available to the various regions. The program predicts Loran C performance at operator entered positions. The parameters included are SNR and GDOP. The GDOP term is also known sometimes as GDOPth. While GDOP is unitless, GDOPth is expressed in unit of feet per microsecond. To covert 2drms to GDOPth, divide 2 drms by two times the standard deviation of the time difference. For the studies in this report the time differences were 0.14 microseconds.

CONCLUSIONS

In conclusion, it has been shown that error ellipses calculated for 95 percent probability using a time difference (TD) standard deviation of 0.14 microseconds and a correlation coefficient of 0.3 can be used to predict the expected along-track error (ATE) and crosstrack error (CTE) at an airport for a specific heading. It was shown that 2 distance root mean square (drms) gives a reasonable estimate of overall performance at an airport provided the above values for standard deviation and correlation coefficient are used. Two drms can be coverted to the GDOP term used by the MITRE Airport Screening Model.

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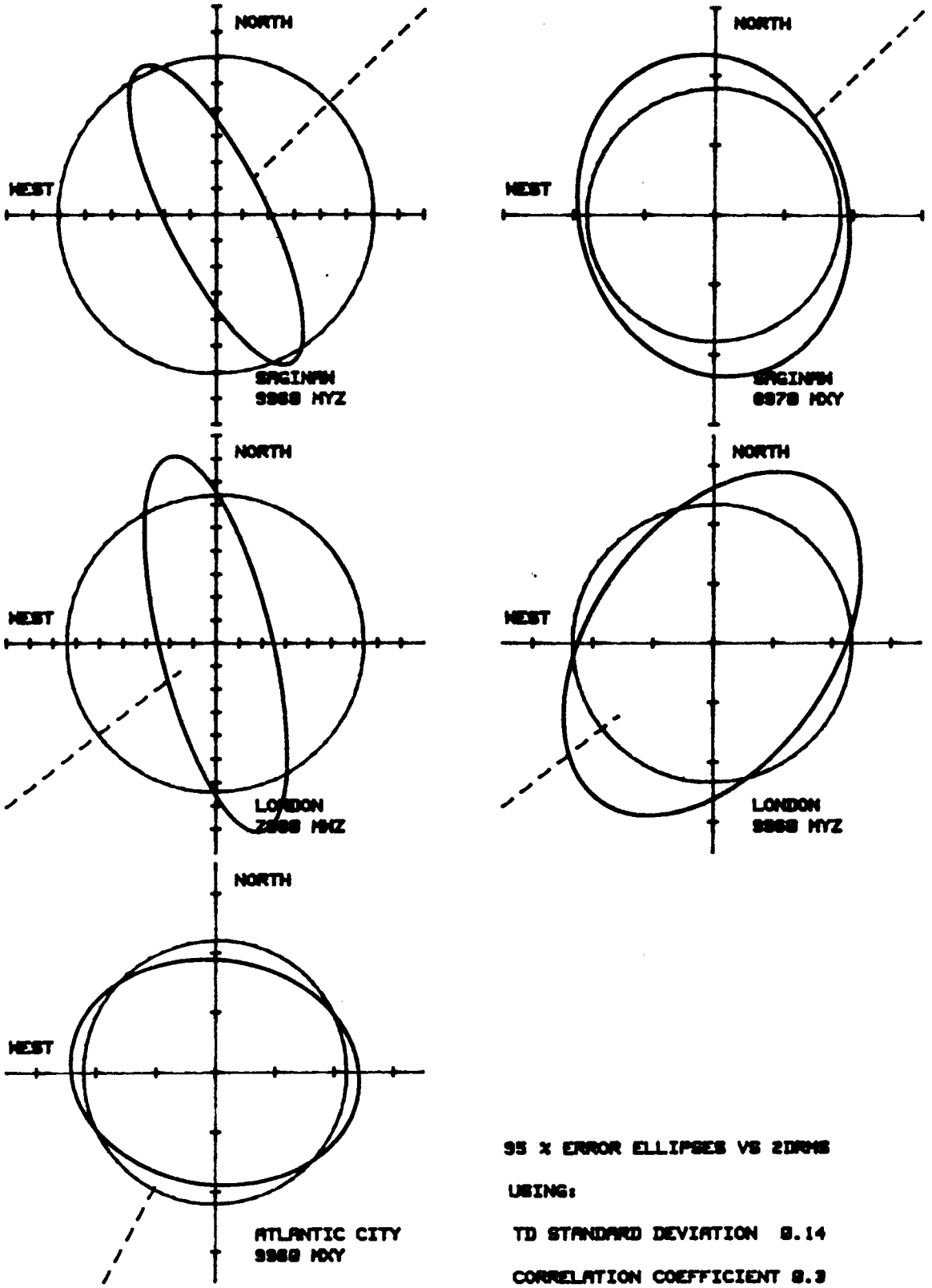

95 % ERROR ELLIPSES VS 2DRMS

USING:

TD STANDARD DEVIATION 0.14

CORRELATION COEFFICIENT 0.3

TIC SPACING 100 FEET

FIGURE D-4. 95 PERCENT ERROR ELLIPSES VS 2 DRMS

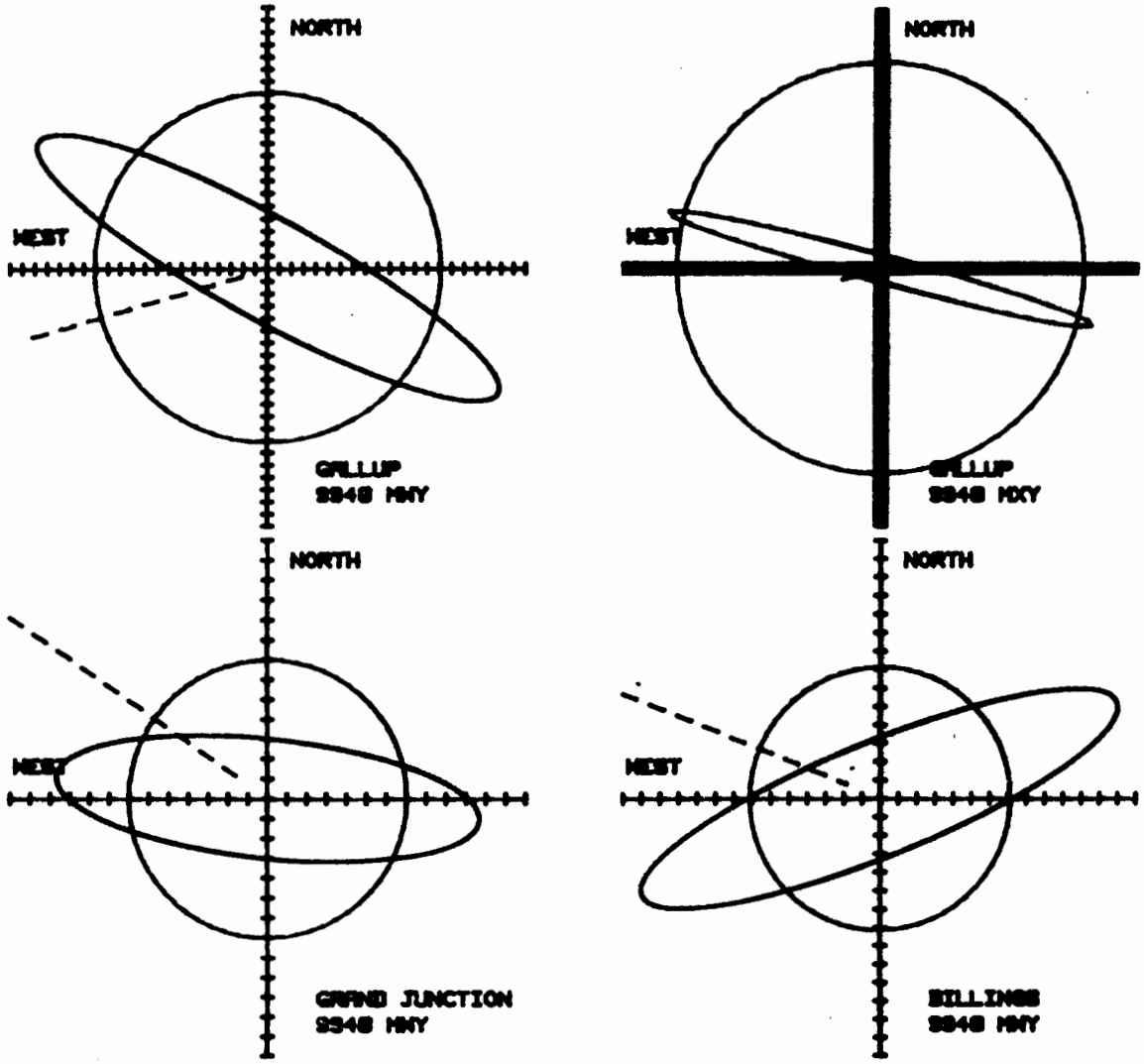

FIGURE D-5. 95 PERCENT ERROR ELLIPSES VS 2 DRMS

95 % ERROR ELLIPSES VS 2DRMS

USING:

TD STANDARD DEVIATION 0.14

CORRELATION COEFFICIENT 0.9

TIC SPACING 100 FEET