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DESIGN STUDY REPORT FOR GENERAL AVIATION LORAN-C RECEIVER.(U)

MAY 81 H L WALKER, R ELLERBE

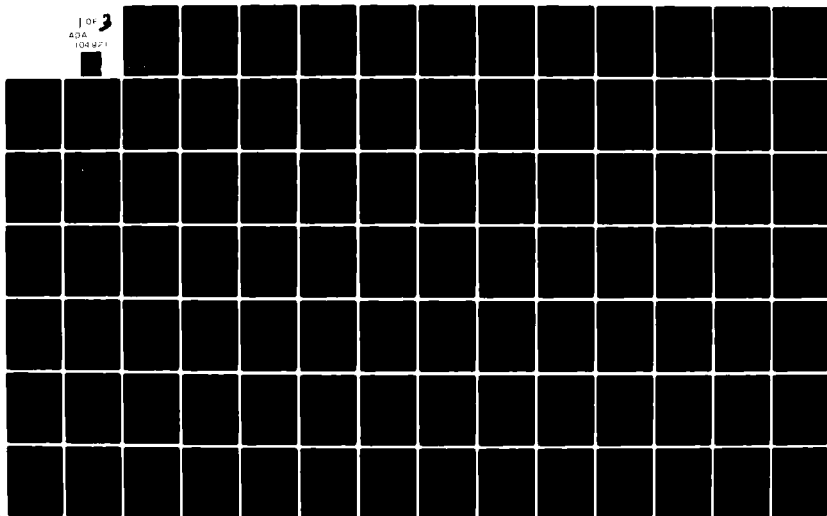
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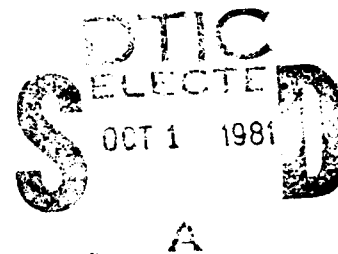


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Design Study Report for General Aviation LORAN-C Receiver



May 1981

Final Report

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16. Abstract This document summarizes the results of studies and trade-off analysis conducted for a low cost Loran-C Receiver. The Loran-C Receiver is intended to meet the Minimum Operational Performance Standards for Area Navigation (RNAV) equipment for General Aviation Aircraft operating in the National Aerospace System. The studies and analysis examined the required receiver performance, design approaches and design criteria, and cost to the user of the receiver. The study concludes that a low cost receiver meeting the General Aviation RNAV requirements is practical. A design approach for the receiver is described.			
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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

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

* 1 in = 2.54 cm (exact). For other exact conversions and more detailed tables, see NIST Special Publ. 400-1, Units of Measurement and Measures, Price \$2.25, SD Catalog No. C1116-700.

Approximate Conversions from Metric Measures

When You Know	Multiply by	To Find	Symbol	
LENGTH				
millimeters	0.04	inches	in	
centimeters	0.4	inches	in	
meters	3.3	feet	ft	
meters	1.1	yards	yd	
kilometers	0.6	miles	mi	
AREA				
square centimeters	0.16	square inches	in ²	
square meters	1.2	square yards	yd ²	
square kilometers	0.4	square miles	mi ²	
hectares (10,000 m ²)	2.5	acres	ac	
MASS (weight)				
grams	0.035	ounces	oz	
kilograms	2.2	pounds	lb	
tonnes (1000 kg)	1.1	short tons	sh	
VOLUME				
milliliters	0.03	fluid ounces	fl oz	
liters	2.1	pints	pt	
liters	1.06	quarts	qt	
liters	0.76	gallons	gal	
cubic meters	35	cubic feet	cu ft	
cubic meters	1.3	cubic yards	cu yd	
TEMPERATURE (exact)				
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

°F



PREFACE

This report describes the results of trade-off analysis performance evaluations, and cost studies for a General Aviation Loran-C Receiver conforming to the Minimum Operational Performance Standards for Area Navigation (RNAV) equipment intended to operate in the National Airspace System. This work was sponsored by the Federal Aviation Administration under Contract No. DTFA01-80-C-10108. This report summarizes the results of the first phase of a four phase program.

The objective of the first phase of this program was to determine if a low cost Loran-C Receiver can be developed which meets all the required minimum performance standards for General Aviation RNAV equipment. The following three major tasks were accomplished to determine if the program objective was achievable:

- Conduct trade-off analyses to define minimum system performance requirements and the best method of achieving the required levels of performance.
- Define the receiver performance criteria and design requirements.
- Determine cost to the user of the Loran-C Receiver.

Subsequent phases of the program are intended to continue the receiver development and tests in the following three specific program phases:

Phase 2 - Development and evaluation of a laboratory model of the receiver.

Phase 3 - Fabrication of three flight test models of the low cost Loran-C Receiver.

Phase 4 - Flight test evaluation of the Loran-C Receiver.

TABLE OF CONTENTS

<u>Section</u>	<u>Page</u>
1 EXECUTIVE SUMMARY	1-1
1.1 Objectives	1-1
1.2 System Requirements	1-2
1.3 Trade-Off Analysis	1-4
1.4 Receiver Performance Criteria and Design Approach	1-14
2 DEFINITION OF SYSTEM REQUIREMENTS	2-1
2.1 Benefits of Loran RNAV	2-1
2.2 Requirements for Loran-C Signal Coverage	2-3
2.3 Performance Requirements for Low Cost Loran-C RNAV ...	2-3
3 TRADE-OFF ANALYSIS	3-1
3.1 Position Determination Methods	3-1
3.1.1 Background	3-1
3.1.2 Requirements	3-2
3.1.3 Analysis of Position Determination Methods	3-3
3.1.4 Selection Summary	3-10
3.1.5 Conclusion	3-11
3.2 Loran Signals Required for Navigation	3-12
3.2.1 Background	3-12
3.2.2 Requirements	3-12
3.2.3 Analysis of Signals Required for Navigation	3-13
3.2.4 Selection Summary	3-15
3.2.5 Conclusion	3-15
3.3 Single and Dual Chain Operation	3-16
3.3.1 Background	3-16
3.3.2 Analysis	3-16
3.3.3 Selection Summary and Conclusion	3-19
3.4 Propagation Anomaly Compensation	3-19
3.4.1 Background	3-19
3.4.2 Requirements	3-21
3.4.3 Secondary Phase Model Candidates	3-21
3.4.4 Summary and Conclusion	3-23

TABLE OF CONTENTS (Continued)

<u>Section</u>		<u>Page</u>
3.5	Waypoint Designation Methods	3-24
3.5.1	Purpose	3-24
3.5.2	Candidate Waypoint Designation Methods	3-25
3.5.3	Requirements	3-27
3.5.4	Analysis of Waypoint Designation Methods	3-27
3.5.5	Selection Summary and Conclusion	3-33
3.6	Number of Waypoints Stored	3-34
3.6.1	Background	3-34
3.6.2	Requirements	3-35
3.6.3	Waypoint Storage Analysis	3-35
3.6.4	Summary and Conclusion	3-41
3.7	Antenna/Antenna Coupler Tradeoff Analysis	3-42
3.7.1	Introduction	3-42
3.7.2	Requirements	3-42
3.7.3	Method	3-45
3.7.4	Analysis	3-52
3.7.5	Trade-Off Evaluations	3-58
3.7.6	Selection Summary	3-58
3.7.7	Conclusion	3-59
3.8	Linear vs Hard-Limited Receiver	3-59
3.8.1	Linear Receiver Design	3-61
3.8.2	Hard-Limited Receiver Design	3-63
3.8.3	Cost/Performance Trade-Off	3-65
3.9	Interference Filters	3-66
3.9.1	Requirements	3-66
3.9.2	Design Concepts	3-66
3.9.3	Summary	3-67
3.10	Processor Selection	3-68
3.10.1	Requirements	3-68
3.10.2	Processor Comparison	3-68
3.10.3	Summary	3-70

TABLE OF CONTENTS (Continued)

<u>Section</u>	<u>Page</u>
4 RECEIVER PERFORMANCE CRITERIA	4-1
4.1 Signal Reception	4-1
4.1.1 Receiver Sensitivity	4-1
4.1.2 Dynamic Range	4-1
4.1.3 Signal Acquisition Time and Cross Chain Transition	4-2
4.1.4 Interference Rejection	4-3
4.2 Signal Processing	4-4
4.2.1 Phase Tracking	4-4
4.2.2 Cycle Identification	4-5
4.3 Navigation	4-5
4.3.1 Signal Propagation Correction Method	4-6
4.3.2 Position Determination Accuracy	4-6
4.3.3 Receiver Performance After Signal Loss	4-32
4.3.4 Information Update Rates	4-42
4.3.5 Navigation Parameter Accuracy and Resolution	4-46
4.3.6 Recognition and Warning of Unacceptable Conditions or Performance	4-52
4.3.7 Capability to Use Differential Corrections	4-57
4.4 Operation and Displays	4-60
4.4.1 Initialization Parameters	4-60
4.4.2 Data Entry Procedure	4-64
4.4.3 Cross Track Deviation Indication	4-66
4.4.4 Display of Pilot Entered and Computed Navigation Values	4-70
4.4.5 Procedure for Transition Between Loran-C Chains	4-72
4.4.6 Non-Precision Approach Display Requirements ...	4-75
4.4.7 Display of Receiver Operational Status	4-76
4.4.8 Low Cost Loran-C CDU Design	4-79

TABLE OF CONTENTS (Continued)

<u>Section</u>	<u>Page</u>
4.5 Self Test Capability	4-89
4.5.1 Basic Display Verification Tests	4-90
4.5.2 Basic Functional Tests	4-90
4.5.3 Built-In-Test Equipment (BITE) Tests	4-91
4.6 Data Input/Output	4-95
4.6.1 Requirements	4-95
4.6.2 Mechanization	4-99
4.7 Mechanical Characteristics	4-99
5 RECEIVER DESIGN APPROACH	5-1
5.1 Antenna/Antenna Coupler	5-1
5.2 Notch and Bandpass Filters	5-3
5.3 RF Unit	5-3
5.4 Loran Signal Processing	5-4
5.4.1 Strobe Patterns and Timing	5-4
5.4.2 Signal Processing Modes	5-6
5.4.3 Phase Tracking	5-7
5.5 Data Processor	5-7
5.6 Input/Output	5-7
5.7 Control Display Unit	5-10
5.8 Housing Assembly/Modules	5-11
5.9 Power Supply	5-15
5.10 Software	5-15
6 COST TO THE USER	6-1
Appendix A WORKLOAD ANALYSIS TECHNIQUE	

LIST OF ILLUSTRATIONS

<u>Figure</u>		<u>Page</u>
1-1	Hardware Breakdown for Loran Navigation System	1-15
1-2	Loran Navigation System Block Diagram	1-15
1-3	One of Two E-Field Antennas with Internally Mounted Antenna Coupler	1-16
1-4	Receiver Computer Unit	1-16
1-5	Control Display Panel	1-17
1-6	Control Display Unit Construction Method	1-17
3-1	Basic Hyperbolic Coverage	3-4
3-2	Composite Hyperbolic Coverage	3-5
3-3	Basic Range-Range Coverage	3-5
3-4	Composite Range-Range Coverage (Master Dependent)	3-6
3-5	Composite Range-Range Coverage (Master Independent)	3-6
3-6	Comparison of Hyperbolic and Range-Range Composite Coverage (Master Independent)	3-7
3-7	Composite Hyperbolic Coverage with One Secondary Outage	3-7
3-8	Composite Hyperbolic Coverage with a Master Outage	3-8
3-9	Range-Range Coverage with a Secondary Outage	3-9
3-10	Range-Range Coverage with a Master Outage	3-9
3-11	Cross Chain Coverage with a Hyperbolic System	3-17
3-12	Antenna/Antenna Coupler: Alternative A (Single E-Field Dipole)	3-50
3-13	Antenna/Antenna Coupler: Alternate B (Two Element Balance E-Field)	3-51
3-14	Antenna/Antenna Coupler: Alternative C (H-Field Antenna)	3-51
3-15	Linear Receiver Block Diagram	3-62
3-16	Linear Receiver Design Strokes	3-62
3-17	Hard-Limited Receiver Block Diagram	3-64
4-1	US West Coast 1	4-18
4-2	US West Coast 2	4-20
4-3	US West Coast 3	4-21
4-4	US West Coast 4	4-22

LIST OF ILLUSTRATIONS

<u>Figure</u>		<u>Page</u>
4-5	US Great Lakes 5	4-23
4-6	US Great Lakes 6	4-24
4-7	US Great Lakes 7	4-25
4-8	US North East 8	4-26
4-9	US North East 9	4-27
4-10	US North East 10	4-28
4-11	US South East 11	4-29
4-12	US South East 12	4-30
4-13	US South East 13	4-31
4-14	US West coast M, W, Y Stations 14	4-33
4-15	US West Coast M, W, Y Stations 15	4-34
4-16	US West Coast M, W, Y Stations 16	4-35
4-17	Enroute Scenario	4-38
4-18	Terminal Area Scenario	4-40
4-19	Low Cost Loran-C "TO-TO" System	4-81
4-20	Low Cost Loran-C "TO-FROM" System	4-82
4-21	Alternate BITE Signal Injection Points	4-92
4-22	BITE Signal Generator, Alternate A	4-94
4-23	BITE Signal Generator, Alternate B	4-96
4-24	I/O to CPU	4-97
4-25	Data Stream from Loran Receiver to CPU (per Channel)	4-98
4-26	Candidate No. 1 Mechanical Configuration	4-100
4-27	Candidate No. 2 Mechanical Configuration	4-100
4-28	Candidate No. 3 Mechanical Configuration	4-100
5-1	One of Two E-Field Antennas with Internally Mounted Antenna Coupler	5-2
5-2	Linear Receiver Block Diagram	5-5
5-3	Data Processor	5-8
5-4	Input/Output Module	5-9
5-5	Control Display Unit Front Panel	5-10
5-6	Control Display Unit Assembly	5-12
5-7	Receiver/Computer Housing Assembly	5-13
5-8	Software Organization	5-16

SECTION 1

EXECUTIVE SUMMARY

1.1 OBJECTIVES

The primary objective of this study effort has been to determine if it is practical to develop a Loran-C Receiver that can meet both technical requirements and cost goals. The technical requirements are loosely defined as performance of all functions required for General Aviation users to perform area navigation (RNAV) within the U.S. National Airspace System (NAS). The cost goals are for costs to be competitive with other available area navigation equipment or to meet a cost to the user of \$3000.

Implementation of the program objective required accomplishment of the following tasks:

- Definition of the system requirements in terms of the functions which must be performed, the accuracy with which the functions must be performed, and the manner in which the system would interact with the user.
- Conduct trade-off analysis of the concepts and methods for achieving the required levels of performance to determine the best or most cost effective approach.
- Define the performance criteria for each system function so that the system and subsystem design parameters can be established.
- Describe a specific design approach for each functional area. Definition of a specific design approach is necessary to permit confirmation of system performance and to provide a factual basis for establishing the cost of the system.

As will be described in detail in later sections, all study objectives have been achieved in that the Loran Navigation System will meet all RNAV performance requirements for operating in the NAS and will be available to the user for \$2885 which is within the cost goal.

It should be noted that this study report deals primarily with the user equipment and does not specifically address the Loran transmitters or signal coverage requirements. However, a certain level of transmitter performance and signal coverage is assumed to exist during the period of time when the user equipment would be operational. The Loran signal conditions which have been assumed to exist (and which the study is based upon) are as follows:

- Loran-C signal coverage will be available throughout the U.S.A.
- Sufficient signal redundancy will be provided that the user may continue navigation after failure of a Loran transmitter.

While the study does not address the Loran-C transmitter siting requirements, some additional stations would be required (for the mid-continent) but fewer than stated in some analysis.* There is a definite relationship between the cost of the receiver and the characteristics of the Loran signal coverage. The assumption that has been made for this study is that the signal coverage will be tailored to minimize the cost of the user equipments. However, since the low cost receiver will have the capability for multiple station (five per chain) and dual chain tracking, the number of Loran transmitters required to provide full coverage and redundancy are actually fewer than initially estimated based upon less capable user equipment.

1.2 SYSTEM REQUIREMENTS

While the general requirements are to accurately and reliably provide area navigation with a system that is low cost, the following provides a more detailed listing of the system requirements and desirable features as identified in this study:

* "Evaluation of Loran-C for Domestic Air Navigation," Mitre Technical Report MTR-7180, October 1976.

- Meet the area navigation requirements defined in Advisory Circular 90-45. (± 2.0 nm enroute, ± 0.3 nm landing).
- Meet the Loran performance parameters defined in RTCA document DO-159.
- Provide reliable navigation anywhere within the U.S., for any flight condition, and under any weather condition.
- Continue to provide accurate navigation (both acquisition and track) following a Loran transmitter failure, even if the failed transmitter is the master.
- Store all basic Loran information for automatic selection and use by the system. The fact that navigation is based upon Loran signals should be transparent to the operator.
- Track all receivable stations within the chain in order to continue navigation following a station failure and to provide accurate navigation in areas of poor geometry, weak signals or high noise.
- Track stations from two chains simultaneously with the ability to automatically transition from chain to chain as the flight path progress from one coverage area to the next.
- Correct all received signals for propagation anomalies caused by variations in earth conductivity along the signal propagation path.
- Automatically compute and apply propagation anomaly corrections to relieve the operator of the data entry tasks and to guard against operator data entry errors which would cause excessive navigation errors.

- Provide an easy and convenient method for waypoint entry, designation, and display. Provide storage for a sufficient number of waypoints to enable full usage of the system without requiring the pilot to enter new waypoint data during time critical periods.
- Bandpass and notch filter designs must reject the near band signals which will otherwise interfere with the receiver performance. In-band interferences are assumed to be of low level when present in the USA.
- The advantages realizable with state-of-the-art microprocessors should be used to improve system performance, reduce costs, and automate all functions which can best be performed by the equipment rather than the operator.

1.3 TRADE-OFF ANALYSIS

Ten different trade-off analyses were conducted to select the best design approach, performance requirements, or characteristics for the low cost Loran-C receivers. The trade-off candidates, requirements, and selections are summarized in Tables 1-1 through 1-9. The selections from the trade-off analysis are summarized as follows:

- Conventional, rather than two station range-range, position determination methods were selected.
- The system will operate in the master independent mode if the master station signal is lost. The system will track all receivable stations within a chain.
- Dual chain operation will be provided.
- Propagation anomaly compensation will be completely automatic and will cover the entire United States.

- All waypoints will be designated by bearing and distance to a navigation reference point (usually a VOR station).
- A minimum capability for storage of four waypoints is required. (since there is no cost impact, nine waypoint storage will be provided).
- Dual (top and bottom mounted) antennas will be provided to improve reception during periods of high P-static.
- Either a linear or hard limited receiver can meet both performance and cost requirements.
- Two fixed frequency notch filters are needed for rejection of near-band interferences.
- A single microprocessor, the Intel 8088, is recommended.

Table 1-1. Trade-Off Analysis of Position Determination Methods

Trade-Off

Position determination methods:

- Hyperbolic time difference line-of-position, versus
- Range-range circular lines-of-position, versus
- Hyperbolic with a change to range-range operation when station failure occurs.

<u>Candidates</u>	<u>Advantages</u>	<u>Disadvantages</u>
Hyperbolic	• Simple implementation • Low quality, low cost, oscillator.	• Covers smaller area • Provides less backup
Range-Range	• Covers larger area • Backup (2 station) navigation	• Requires expensive oscillator • Oscillator calibration needed • Navigation possible for only short time.
Hyperbolic with change to range-range	• Provides advantages of range-range	• Requires expensive oscillator • Mode not available if calibration incomplete • Navigation available for only short time.

Selection: Hyperbolic

Reasons: Disadvantages can be overcome by tracking additional stations and/or second chain.

Table 1-2. Trade-Off Analysis of Loran Signal Required for Navigation

Trade-Off

Station's signals required for navigation:

- Master dependent, versus
- Master independent versus
- Change to master independent operation from master dependent operation when the signal from the master is lost.

<u>Candidate</u>	<u>Advantages</u>	<u>Disadvantages</u>
Master Dependent	• Simple mechanization	• Cannot acquire or track chain after master is lost.
Master Independent	• Allows acquisition and track after master is lost.	• Complex mechanization • In certain cases, the position solution is ambiguous.
Master Dependent with change to master independent	• Mechanization simpler for station acquisition • Avoids test for ambiguous solution.	

Selection: Master dependent with change to master independent

Reason: Mechanization is simpler, yet it retains all the advantages of the master independent. Master dependent cannot meet navigation reliability requirements.

Table 1-3. Trade-Off Analysis of Single and Dual Chain Operation

Trade-Off

Single and dual chain operation

- Operation within one chain at a time, versus
- Simultaneous use of signals from two chains for navigation.

<u>Candidate</u>	<u>Advantages</u>	<u>Disadvantages</u>
Single Chain Operation	• Simple mechanization • Requires less hardware and/or software	• Cannot provide navigation during acquisition of second chain • May be unable to return to first chain if acquisition of second chain unsuccessful.
Dual Chain Operation	• Can fly from one chain area to another without loss of navigation data • Improved navigation accuracy • Extends coverage area.	• Hardware/Software more complex

Selection: Dual chain operation

Reason: Single chain operation will not meet navigation requirements.

Table 1-4. Trade-Off Analysis of Propagation Anomaly Compensation

Trade-Off

Propagation Anomaly compensation method

- Encoded conductivity table
- Fitted conductivity table
- Directly fitted phase
- Fitted phase velocity

<u>Candidates</u>	<u>Advantages</u>	<u>Disadvantages</u>
Encoded conductivity Table	• Minimizes storage • Station independent	
Fitted conductivity Table	• Station independent	• Computationally complex
Directly fitted phase	• Computationally simple	• Station dependent
Fitted phase velocity	• Computationally simple	• Station dependent • Large data storage
Stored Correction Table	• Computationally simple • Data base easily acquired	• Station dependent

Selection: Stored correction table

Reasons: Provides good accuracy. Data for correction values easiest to obtain.

Table 1-5. Trade-Off Analysis of Waypoint Designation Method

Trade-Off

Waypoint designation method

- Latitude/Longitude
- Coded identifier (5 letter unique designation)
- Radial and distance from a designated point

<u>Candidates</u>	<u>Advantages</u>	<u>Disadvantages</u>
Latitude/Longitude	• Coordinates are the same as used for position computations. • Coordinates of positions shown on charts have lat/lon values.	• ATC requests usually in range and bearing • Number of keystrokes for data entry.
Coded Identifier	• Route intersection and terminal area fixes being assigned 5 letter identifier for ATC	• Requires prestorage of 5 letters vs lat/lon • Solution/entry of letters • Requires large memory storage
Radial & Distance	• Same procedure as used for VOR • Compatible with existing ATC structure	• Requires storage of all VOR station locations and designations • Frequent changes in stored data • Requires large memory storage.

Selection: Radial & Distance

Reasons: Least complex and most familiar pilot interface.

Table 1-6. Trade-Off Analysis of Number of Waypoints Stored

<u>Trade-Off</u>		
Number of waypoints stored		
• Two • Four • Nine		
<u>Candidates</u>	<u>Advantages</u>	<u>Disadvantages</u>
Two	• Minimum storage requirements	• Increases pilot workload
Four	• Low storage requirements • Acceptable pilot workload	
Nine	• Lowest pilot workload	• Increased storage requirements
Selection: Four waypoints stored (as a minimum)		
Reason: Meets minimum requirements with lower storage requirement		

Table 1-7. Trade-Off Analysis of Antenna/Antenna Coupler

Trade-Off

Select antenna type and antenna coupler characteristics

Antenna: Single E - field
Dual E - field
H - field

Coupler: Broadband
Tuned

<u>Candidates</u>	<u>Advantages</u>	<u>Disadvantages</u>
Single E-field antenna	• Low cost	• Poor P-Static noise rejection
Dual E-field antenna	• Good P-static noise rejection	• Cost twice as much as a single antenna • Aircraft installation difficult
H-field antenna	• Best P-static noise rejection	• High cost • Aircraft installation difficult • Requires heading input
Broadband Coupler	• Requires no tuning on aircraft	
Tuned Coupler		• Requires tuning on aircraft

Selection: Dual E-field antenna and broadband coupler

Reason: Antenna selection represents best performance available at an affordable cost.
Antenna coupler provides acceptable performance and is easier to install.

Table 1-8. Trade-Off Analysis of Linear Vs. Hard Limited Receiver

Trade-Off

R. F. Amplification

- Linear
- Hard Limited

<u>Candidates</u>	<u>Advantages</u>	<u>Disadvantages</u>
Linear	• Best Performance • Low Cost	
Hard Limited	• Good Performance • Low Cost	

Selection: None. Either design approach is acceptable.

Reason: Both units provide acceptable performance at approximately the same cost.

Table 1-9. Trade-Off Analysis of Interference Filters

Trade-Off

Interference filters

- Manual, preset filters
- Automatic signal searching
- Software methods for reducing the effects of interference

<u>Candidates</u>	<u>Advantages</u>	<u>Disadvantages</u>
Manual	• Simple • Low Cost • Good interference rejection	• If interference source changes frequency, or a new source appears, notch will not reject interference
Automatic	• Will reject largest interfering signal regardless of frequency changes.	• Complexity • High Cost
Software	• Low hardware cost	• Limited effectiveness

Selection: Manual, preset filters

Reason: Since all interfering frequencies within the United States are known, the manual filter can be designed to reject them. It also provides the greatest interference rejection of any of the filter designs.

1.4

RECEIVER PERFORMANCE CRITERIA AND DESIGN APPROACH

The selected design approach and the expected receiver performance are briefly described below. A three box system has been selected as representing the best compromise between the various installation, performance and cost constraints. The hardware breakdown for the system is illustrated in Figure 1-1, while a simplified block diagram is shown in Figure 1-2.

The Antenna/Antenna Coupler Unit, shown in Figure 1-3, is installed as a dual antenna configuration with one unit mounted on top of the aircraft and another mounted on the bottom of the aircraft. This configuration was chosen to provide improved performance during periods of severe P-static interference. (The system can also be operated with a single antenna.) The antenna coupler electronic module is mounted in the base of the antenna. The antenna coupler provides impedance matching to the antenna, one stage of bandpass filtering and amplification, and a 50 Ω output to the RF module.

The Receiver Computer Unit (RCU) is shown in Figure 1-4. The unit contains a Radio Frequency Module, a Computer/Memory Module, an Interface Module, and Power Supply. Except for the power supply, all modules are approximately 6 in. x 8 in. two-sided printed wiring boards. The RCU housing is made of sheet metal. It is designed to be bolted directly to the aircraft structure, although it can easily be adapted to other attachment methods. The unit does not require cooling air.

The front face and construction features of the Control Display Unit (CDU) are shown in Figures 1-5 and 1-6, respectively. The CDU panel reflects a design approach aimed at simplifying the tasks of entering and displaying data. Data are entered by slewing the numbers to their correct values. This eliminates the need for a keyboard and its cost, complexity, and difficulty of operation in an aircraft subject to turbulent flight. The small size of the CDU also simplifies installation, particularly when the CDU is installed on the pilot's instrument panel.

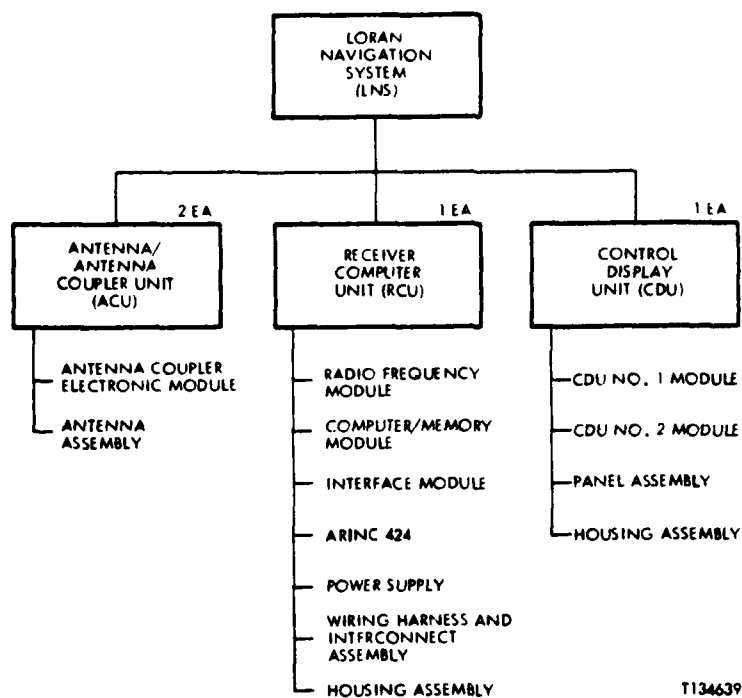


Figure 1-1. Hardware Breakdown for Loran Navigation System

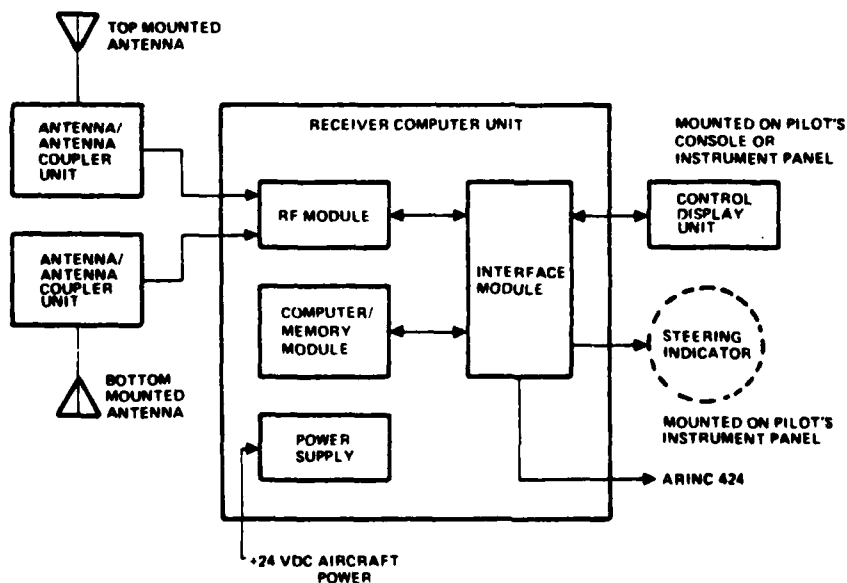


Figure 1-2. Loran Navigation System Block Diagram

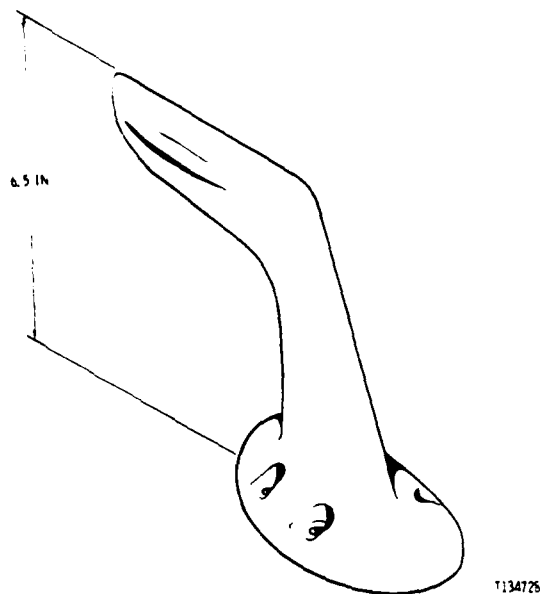


Figure 1-3. One of Two E-Field Antennas with Internally Mounted Antenna Coupler

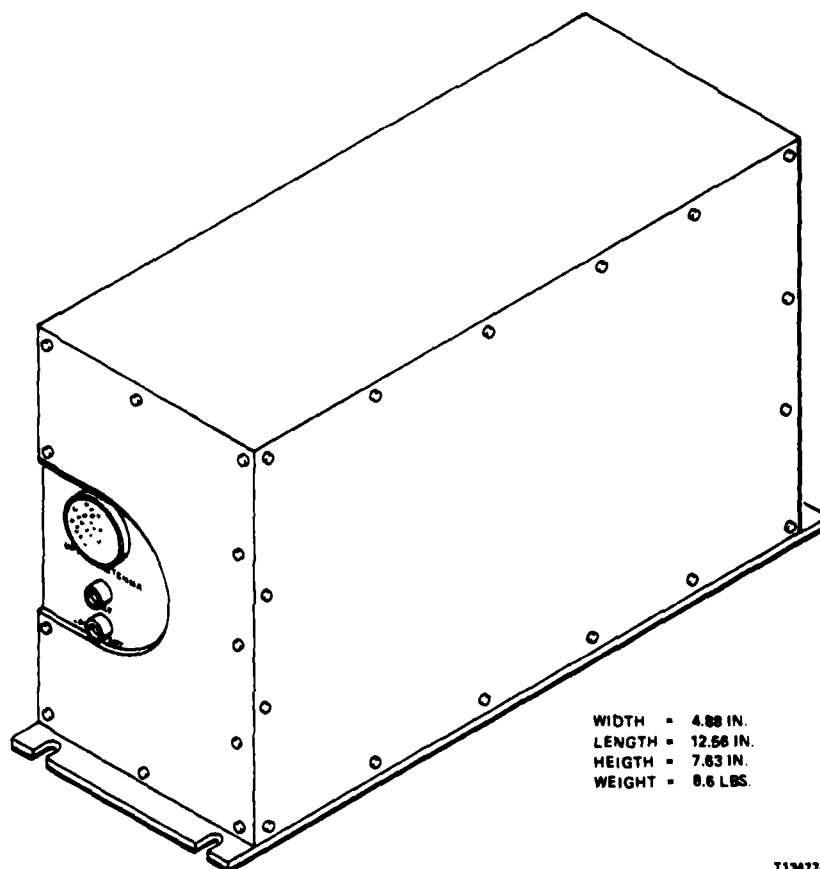


Figure 1-4. Receiver Computer Unit

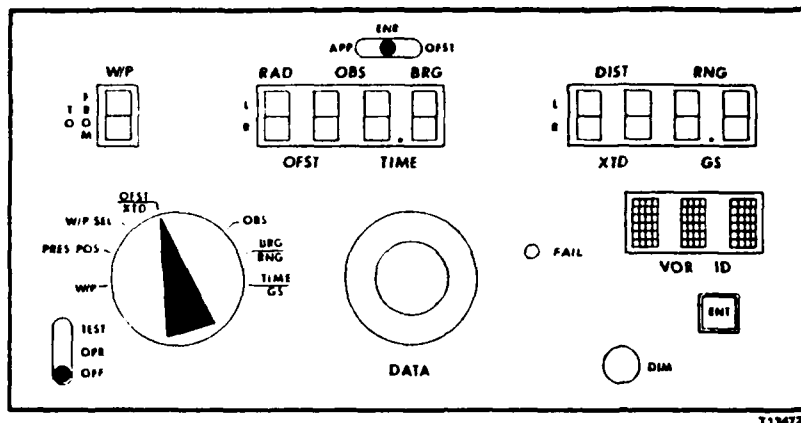


Figure 1-5. Control Display Panel

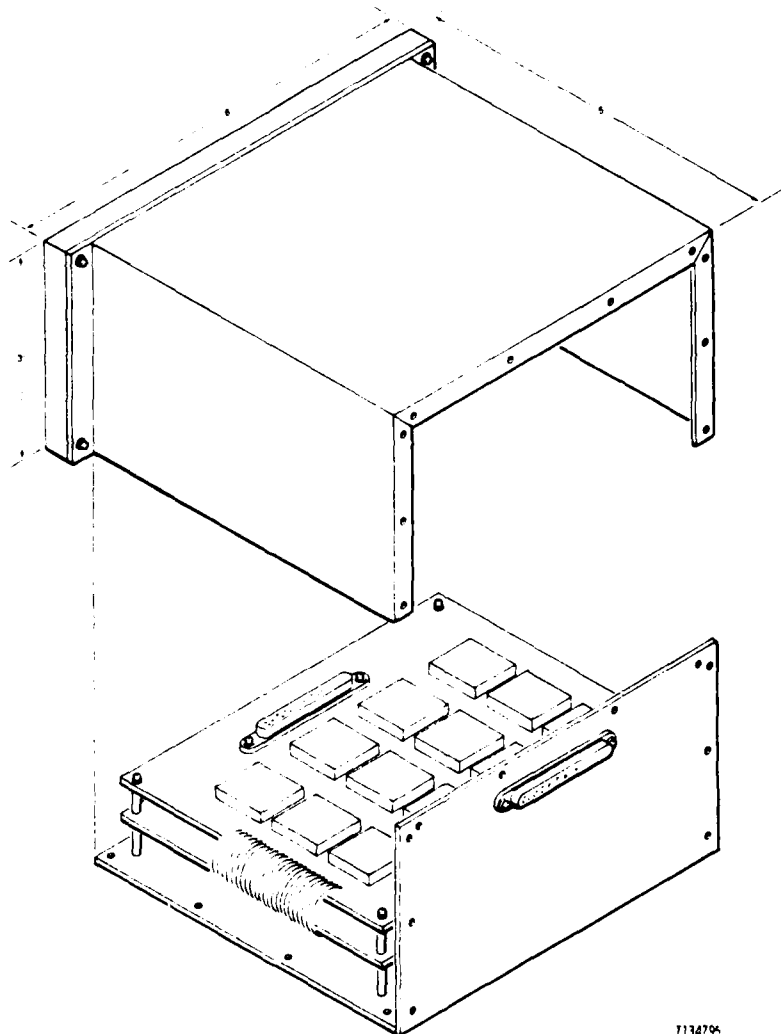


Figure 1-6. Control Display Unit Construction Method

Performance capabilities of the Loran Navigation Systems have been directed toward meeting all the minimum performance requirements identified for operating in the National Airspace System. In some cases, performance in excess of the minimum can be achieved without adding to the cost of the unit.

The major performance and design parameters are listed in Table 1-10.

Table 1-10. Summary of Receiver Performance

Parameter	Value
Receiver Sensitivity	< 10 μ v
Signal-to-noise threshold-acquisition	-10 dB
-track	-14 dB
Number of stations tracked simultaneously	10
Number of chain tracked simultaneously	2
Minimum signal level	100 μ v/m
Antenna - Type	Dual E-field
- Effective height (total)	8 in
Dynamic range	80 dB
Notch Filters - Numbers and type	2, fixed
- Frequency	88 KHz, 115.3 KHz
- Rejection	>40 dB
Front end bandwidth at 3 dB	20 KHz
Front end bandwidth at 40 dB	26 KHz
Secondary Phase Correction - Model	Conductivity map of CONUS
- Accuracy	250 ft (RMS)

SECTION 2

DEFINITION OF SYSTEM REQUIREMENTS

2.1 BENEFITS OF LORAN RNAV

There are benefits to be derived from a Loran-C based area navigation system that cannot now be provided by any other equipments at comparable costs. Loran-C is capable of providing high accuracy, especially repeatable accuracy, over a wide geographic area. Since it is a low frequency system, it is not dependent upon maintaining line of sight to the transmitters.

In 1974, Loran-C was designed as the navigational system for the U.S. coastal confluence zone. Since that time, Loran-C coverage has been expanded to cover the coastal and Great Lakes area. During the same period of time Loran-C has been widely accepted within the marine user community. Today, Loran-C navigation systems are available from a variety of manufacturers at low cost.

Civil aviation users of Loran-C have also been growing in spite of the fact that users are generally restricted to the coastal and limited inland areas. Clearly, if the coverage area was expanded inland the number of civil aviation users would increase more rapidly. The question now becomes: Are there enough potential users of Loran-C and are the benefits to be derived from the use of Loran-C sufficient to justify expanding the coverage throughout the U.S.A.? The number of users of Loran depends upon:

- the performance of the Loran-C receiver
- the cost of the receiver
- the quality and reliability of the signal coverage
- the ability of the users to obtain certification of the equipment.

The performance and cost of the receiver are related and are addressed in this report. The cost and performance are also affected by the signal coverage. Since an analysis of the signal coverage requirements were not included as part of this study, assumptions were made regarding the availability of Loran-C signal coverage. The study does point out, however, that the signal coverage may not have to be as extensive as earlier supposed because of the dual chain, multiple station tracking, and master independent operational capabilities of the low cost receiver.

The benefits of Loran stem from its performance, economic, and safety related features.

The performance benefits of Loran include the following:

- Navigational services will be available to all users within the USA regardless of their location.
- There will be no restrictions due to low altitude or other "line of sight" limitations.
- There will be no "holes" in navigational coverage.
- Improved navigational accuracy will mean better control of aircraft within assigned airspace, particularly important in the terminal areas.
- Improved navigational accuracy will permit reductions in minimums which will promote greater airport utilization and improve schedule reliability.
- Reductions in number of missed approaches, overflights, and cancellations.
- Increase in the terminal area capacity without a decrease in safety.
- Increase in enroute airspace capacity.

Some of the economic benefits of Loran include:

- Reduction in air miles flown because of improved route planning and "direct to" operations.
- The reduction in air miles will also reduce fuel consumption and lower operating and support costs.
- Reduction in the number of denied landings.
- Use of all runways, as contrasted with the single ILS installation characteristic of many airports, will improve airport capacity and provide accommodations for aircraft of substantially different characteristics.
- Cost of government operations, i.e., search and rescue, can be reduced.

The safety benefits of Loran are:

- Reduction in traffic densities, particularly around navigation aids.
- Reduction in uncertainty of position will reduce the cockpit workload and increase the time available for visual scanning.
- With all runways at an airport available for instrument approach, aircraft separations can be increased and conflicts reduced.

2.2 REQUIREMENTS FOR LORAN-C SIGNAL COVERAGE

In order for the Loran-C receiver to provide acceptable RNAV performance throughout the USA, adequate signal coverage must be available. Acceptable RNAV performance (and reliability) requires the following signal conditions throughout the coverage area (the entire USA):

- Signals from four stations normally be available. This assures continued navigation after a station failure.
- Acceptable signal geometry (Refer to Section 4.3).
- Acceptable signal to noise ratio (normally -10 dB, or better, which provides a sufficient margin for reliable signal acquisition and navigation).

This study does not address how the coverage can be achieved or the number of additional Loran-C transmitters required to establish the coverage.

2.3 PERFORMANCE REQUIREMENTS FOR LOW COST LORAN-C RNAV

The performance requirements for a Loran-C based RNAV system are generally the same as for any other RNAV system. The performance requirements are:

- Meet Advisory Circular 90-45 for all locations and for all conditions of flight likely to be encountered by General Aviation aircraft.
- Simplify operation and control of the RNAV system to the extent that it is unlikely the operator's attention will be required during critical times or that he would make a blunder that might compromise system performance, accuracy, or safety.

Although it is not a performance requirement, as a practical requirement, the cost of the system to the user must be affordable. A cost to the user of \$3,000 has been established.

There are a number of performance related areas that have been problems or concerns for the operation of Loran-C based navigation systems. Each of these concerns are addressed below along with the approach which will be taken to correct it in the low cost Loran-C receiver:

- Operation of the Loran-C receiver requires that the operator be familiar with the peculiarities of Loran. (For example, some sets when initialized may indicate an ambiguous solution.)

SOLUTION: Eliminate the peculiarities of Loran so that the system operation is similar to any other type of navigation system. The fact that the navigation solution is based upon Loran-C signals should be transparent to the operator.

- To achieve good performance in areas of poor geometry, i.e., baseline extensions, the operator must recognize the problem and select a different triad to restore navigational accuracy.

SOLUTION: The system should track all stations in the chain (and those of an adjacent chain if available) and automatically utilize the data according to the quality of the data considering geometry, signal to noise, etc.

- Good receiver performance requires frequent calibration or alignment of the receiver and adjustment of notch filters.

SOLUTION: Eliminate manual receiver adjustments. If calibration is required, perform it automatically as part of the self test process. Since the sources of CWI are known within the USA, factory set the notch filters to reduce these interferences.

- P-static noise restricts operation of the receivers, particularly during IFR conditions or sometimes when only flying through clouds.

SOLUTION: Design the antenna and front-end for operation in conditions likely to produce severe P-static noise. Select antenna design based primarily upon its ability to reject P-static noise.

NOTE: Reduction of P-static noise to satisfactory levels will also require minimization of other aircraft noise sources.

- Good absolute accuracy from Loran requires that the operator insert exact values of propagation anomaly correction for each station being tracked at the location of interest.

SOLUTION: Install a propagation anomaly compensation model that covers the entire USA, that will provide corrections for any station being tracked, and will provide corrections accurate enough to achieve absolute position accuracy requirements. The model must be completely automatic since the operator cannot determine which corrections are necessary or provide the control needed to make the proper corrections.

- Control of software is difficult where data insertion or software modifications are required for different regions of operation.

SOLUTION: One software program for the entire USA. Software updates are accomplished by replacement of the memory devices.

SECTION 3

TRADE-OFF ANALYSIS

3.1 POSITION DETERMINATION METHODS3.1.1 Background

The purpose of this trade-off analysis was to select the best position determination method for use in the low cost Loran Navigation System. Three position determination methods were considered:

- Hyperbolic time difference lines of position, versus
- Range-Range circular line of position, versus
- Hyperbolic with reversion to range-range upon loss of signal from a station.

The hyperbolic position determination method uses the differences in arrival times of the Loran signals from three or more stations to determine the position of the receiver. Usually, the time differences are measured as the difference in times of arrival of the signals from the master station and the signals from each of the slave stations. Each measurement of time difference represents a hyperbolic line of position (LOP) with the intersection of the line of position representing the measured position of the receiver. For the low cost Loran Navigation System the hyperbolic position determination method, if selected, will incorporate the following features:

- If the master signal is not available, the time differences LOP will be based upon the differences in time of arrival of the slave signals. (Refer to Section 3.2)
- All receivable signals from the chain will be tracked so that redundant position determinations are usually available. The redundant data will be used in the navigation solution.

The range-range position determination method is based upon measuring the time of arrival of each Loran signal using a very accurate time base within the receiver. Thus, each Loran signal received will yield a circular line of position which is a constant

value of range to the station transmitting the signal. The range-range mechanization also implies the ability to determine position using signals from two Loran stations plus the accurate receiver time base. (It does not infer a particular time difference to latitude/longitude mechanization).

The absolute accuracy requirements of the oscillator, from which the receiver time base is derived, can be relaxed if it is assumed that redundant position measurements can be used to calibrate the oscillator. This consideration forms the third position determination method listed above.

The analysis of the position determination methods made use of a theoretical chain with four stations located in a symmetrical star pattern. The master was located at the center of the star and the three secondaries were spaced 120° apart. The baselines were assumed to be 400 nm long and the effective range of each station was assumed to be 800 nm.

The methodology used was to develop coverage patterns for the theoretical chain with specific station ranges and measurement accuracies. This method permitted analysis of the fundamental limits of each configuration independent of outside influences such as station power, noise, interference, etc. The accuracy of the hyperbolic measurement (time difference) was assumed to be $0.15 \mu s$ (1σ) and the range measurement (propagation time) was $0.1 \mu s$ (1σ). The required position accuracy was 0.25 nm (2 drms).

For the range-range configuration it was assumed that measurements of propagation time would be received from all available stations and that the receiver had a capability to measure and adjust clock bias and drift rate.

3.1.2 Requirements

Accurate position information is required for both enroute and approach to landing. Since the approach to landing requires the most accurate navigation its requirements will be used for evaluation of the position determination methods.

The existing accuracy requirement for approach to landing in FAA Advisory Circular 90-45A is 0.3 nm along track error and 0.6 nm cross track error (which includes 0.5 nm flight technical error on an RSS basis). Removing the flight technical error from cross track error leaves 0.33 nm for navigation system error in cross track.

Analysis of the position determination methods will consider clock accuracy, coverage, and the effects of station outage.

3.1.3 Analysis of Position Determination Methods

For the hyperbolic concept the clock need only be accurate over the duration of one GRI. For an accuracy of $0.1 \mu\text{s}$ over the longest GRI (0.1s) the minimum accuracy would have to be about 1 part of 10^6 .

An uncompensated clock in a range-range system would have to be accurate to 1 part in 10^{11} for a six-hour flight to hold drift to less than $0.2 \mu\text{s}$. Such a clock would be very expensive and not within the cost goals of the low cost Loran-C Receiver.

By utilizing redundant range measurements in the range-range system, estimates of clock bias and clock drift can be determined. These estimates can in turn be used to compensate for the clock inaccuracies. In this manner a clock with accuracy characteristics in between the two extremes can be utilized. Typically a clock with 10^{-7} to 10^{-8} stability can be used. However, clocks of this accuracy require temperature controlled environments, are relatively expensive, and must be carefully evaluated for use on the low cost Loran-C Receiver.

Obviously if only two stations are received for a long period of time in the range-range mode, the clock compensation terms cannot be estimated. Under these conditions system accuracy is dependent upon clock accuracy and clock drift will cause position errors to build up until navigation accuracy will be outside of the required values. This situation must be indicated to the pilot through one of the system warning annunciators.

Coverage diagrams for both hyperbolic and range-range position determination methods were developed to illustrate the differences in coverage area for the two position determination methods. The basic coverage for a master and two secondaries is shown in Figure 3-1. The pattern shows the primary coverage area in between the two baselines. Coverage is obtained in the area of the baselines and extends to the region behind the baseline. A lobe of coverage behind the master is also shown in the figure.

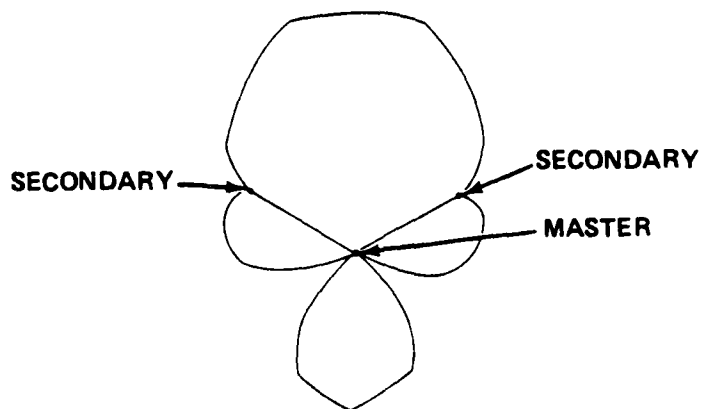


Figure 3-1. Basic Hyperbolic Coverage

A composite coverage diagram for the three master-secondary combinations is shown in Figure 3-2. The single chain coverage is shown in dashed lines in the figure. The primary holes in the coverage can be seen on the baseline extension areas beyond the secondary stations.

The coverage diagram for the range-range position determination method is shown in Figure 3-3. Coverage gaps in the baseline and baseline extension area can be seen in the figure. In spite of these gaps the range-range coverage from two stations exceeds the hyperbolic coverage from three stations. Composite range-range coverage is shown in Figure 3-4.

A slight increase in coverage areas can be achieved by utilizing range-range measurements from two secondary stations. The composite coverage of all possible range-range measurements is shown in Figure 3-5.

A comparison of the composite hyperbolic coverage and the composite range-range coverage is shown in Figure 3-6. It is apparent that the range-range coverage capability exceeds that of the hyperbolic coverage for the assumed conditions.

An analysis of station outages for the hypothetical chain was performed. Coverage diagrams for the hyperbolic and range-range methods with one station out were prepared. Two cases were considered; master out and secondary out.

Secondary out coverage for hyperbolic position determination is shown in Figure 3-7. Obviously for this chain configuration the secondary outage produces significant coverage loss in the vicinity of the baseline extensions of the operating stations.

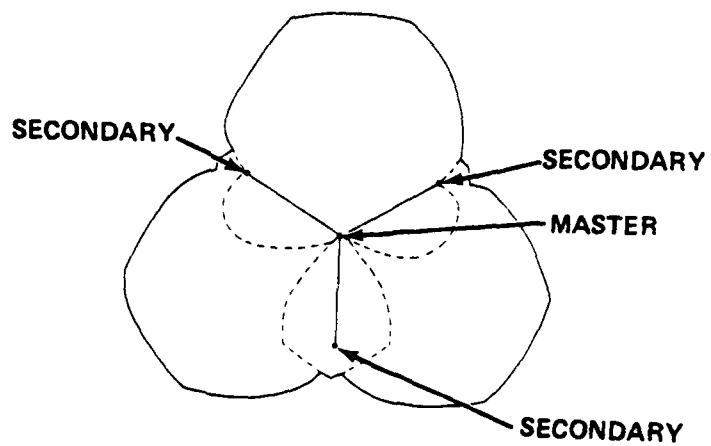


Figure 3-2. Composite Hyperbolic Coverage

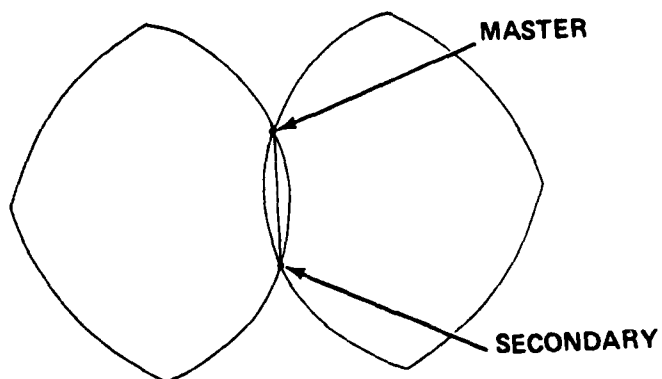


Figure 3-3. Basic Range-Range Coverage

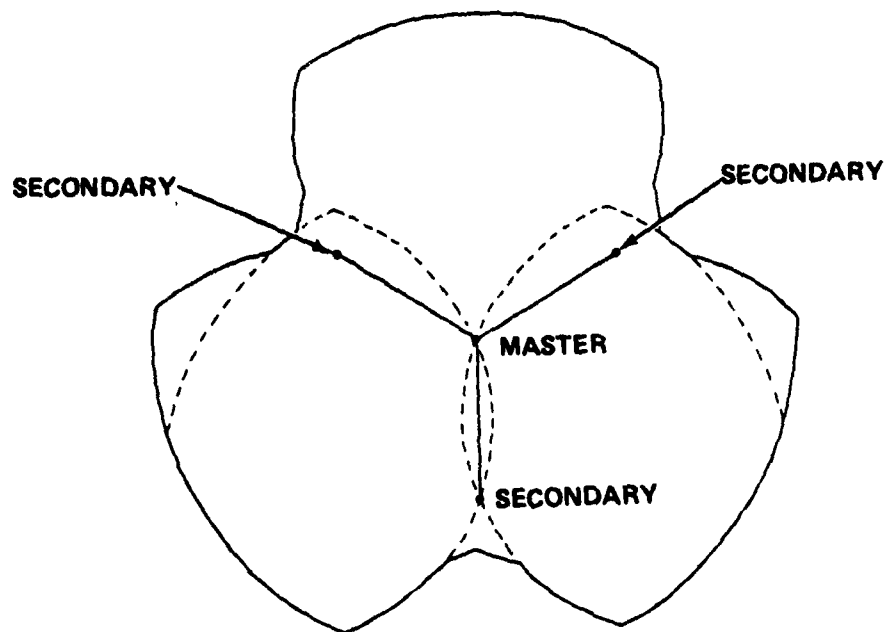


Figure 3-4. Composite Range-Range Coverage (Master Dependent)

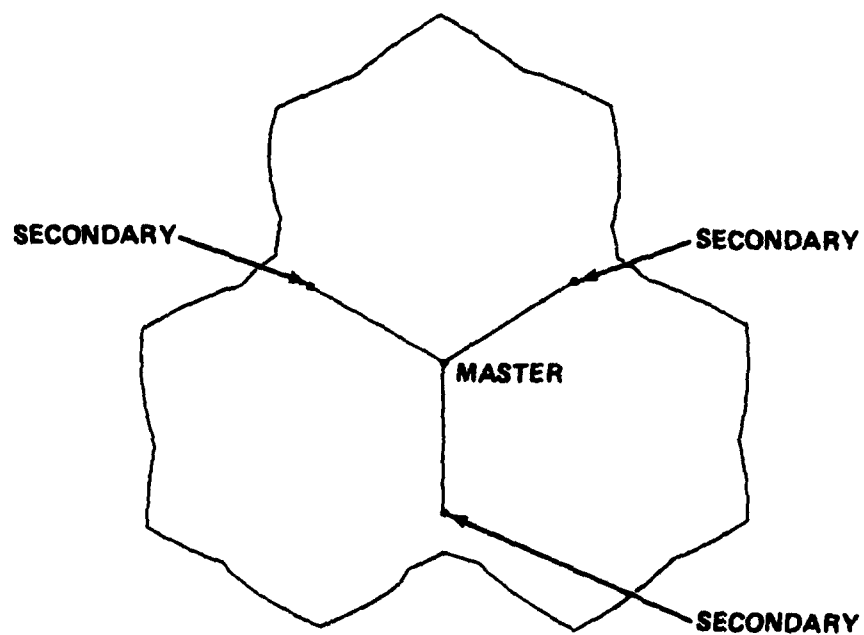


Figure 3-5. Composite Range-Range Coverage (Master Independent)

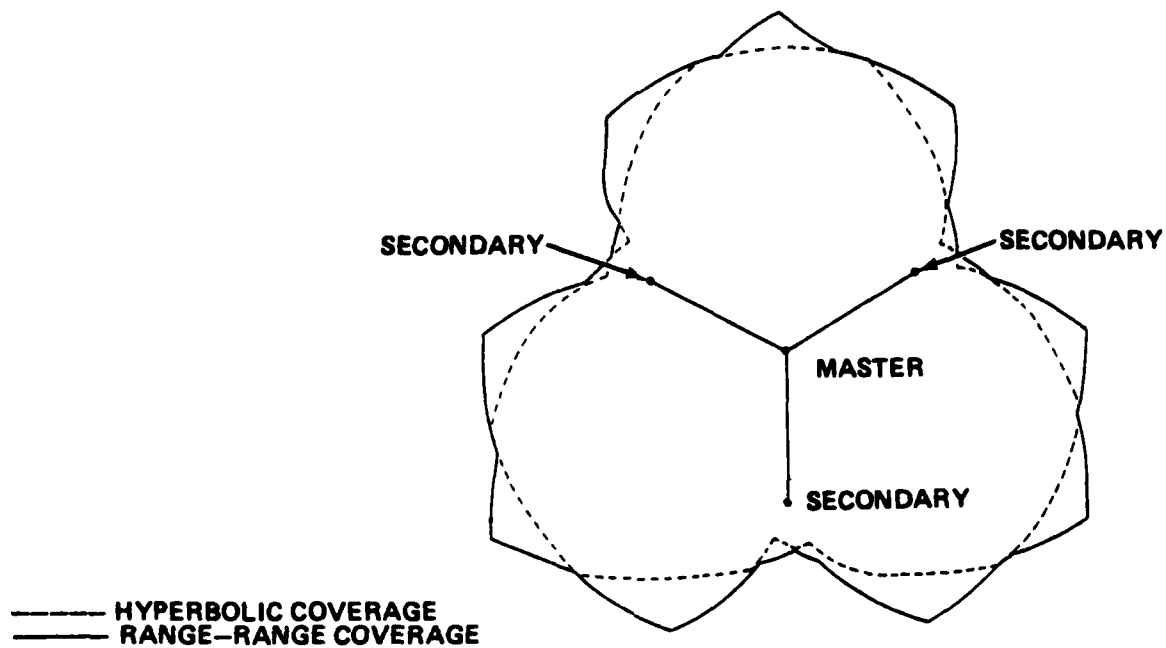


Figure 3-6. Comparison of Hyperbolic and Range-Range Composite Coverage (Master Independent)

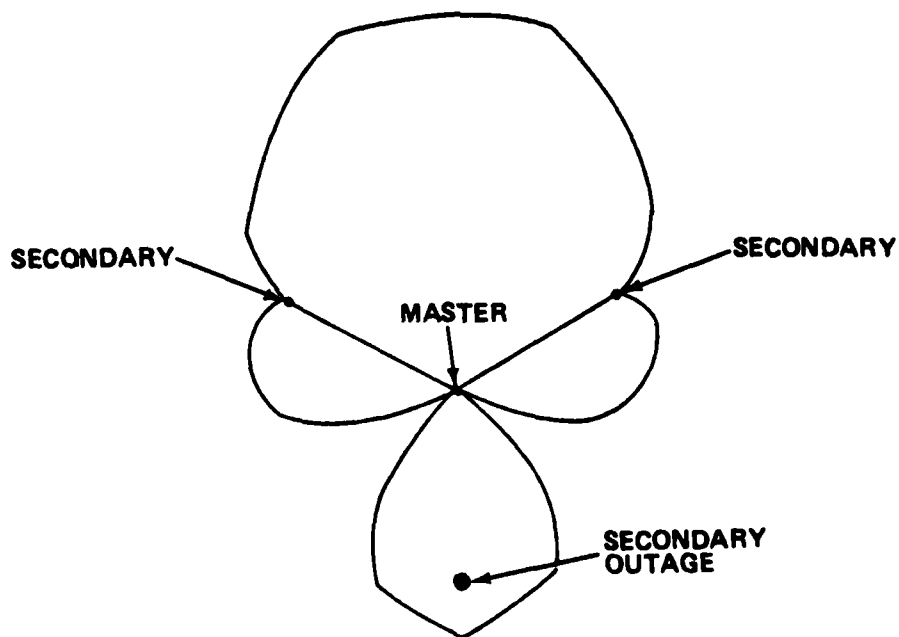


Figure 3-7. Composite Hyperbolic Coverage with One Secondary Outage

Master out coverage for a hyperbolic system is shown in Figure 3-8. Obviously, this configuration assumes master independent capability. There is no coverage for a master dependent system when the master is out. As shown in Figure 3-8, there is a significant loss of coverage area with a master outage.

Secondary out coverage for a range-range position determination system is shown in Figure 3-9. The outside boundary of the diagram is the composite coverage with all stations operating. Coverage loss with the outage is shown by the dashed lines. Moderate losses of coverage are observed in the edges of coverage in the vicinity of the non-operating station. Small losses in coverage can be observed in the baseline extension areas near the operating secondaries. The coverage is considerably less than that loss with the hyperbolic system.

Similar results are shown in Figure 3-10 which depicts the coverage loss caused by a master outage. Again master independent position determination is assumed. Coverage is lost in six areas near the edge of the composite coverage diagram.

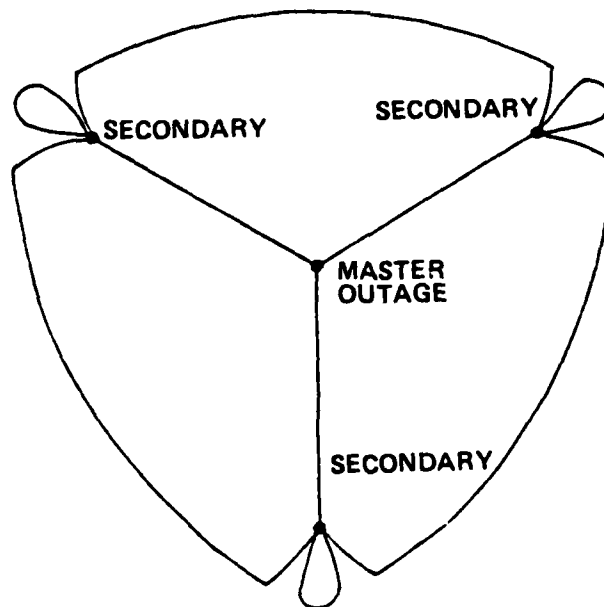


Figure 3-8. Composite Hyperbolic Coverage with a Master Outage

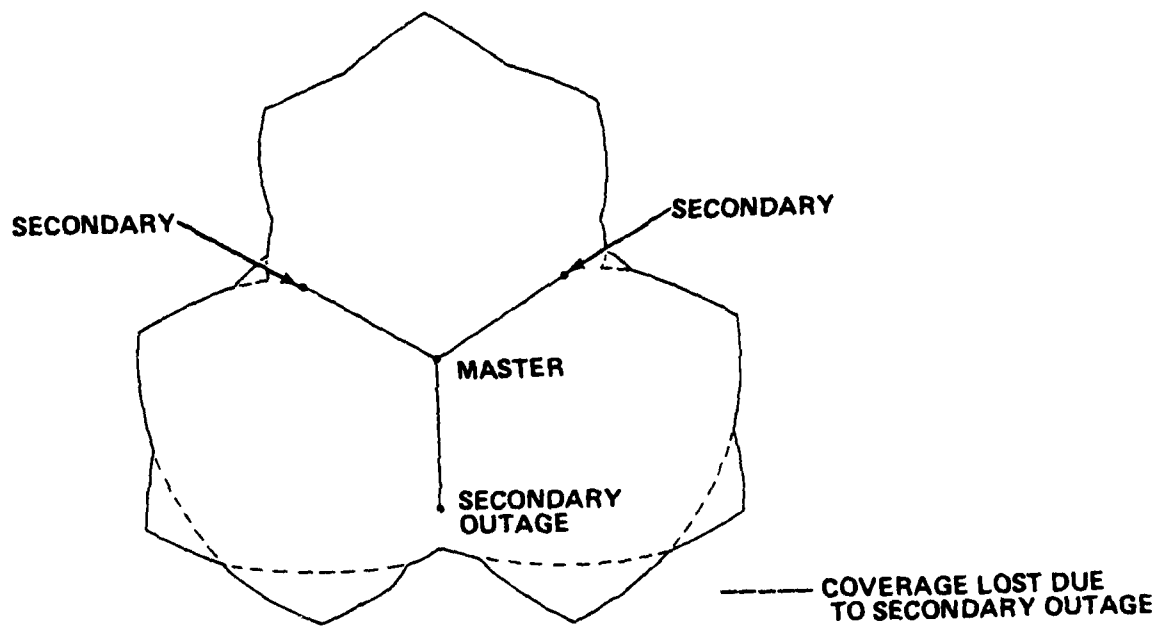


Figure 3-9. Range-Range Coverage with a Secondary Outage

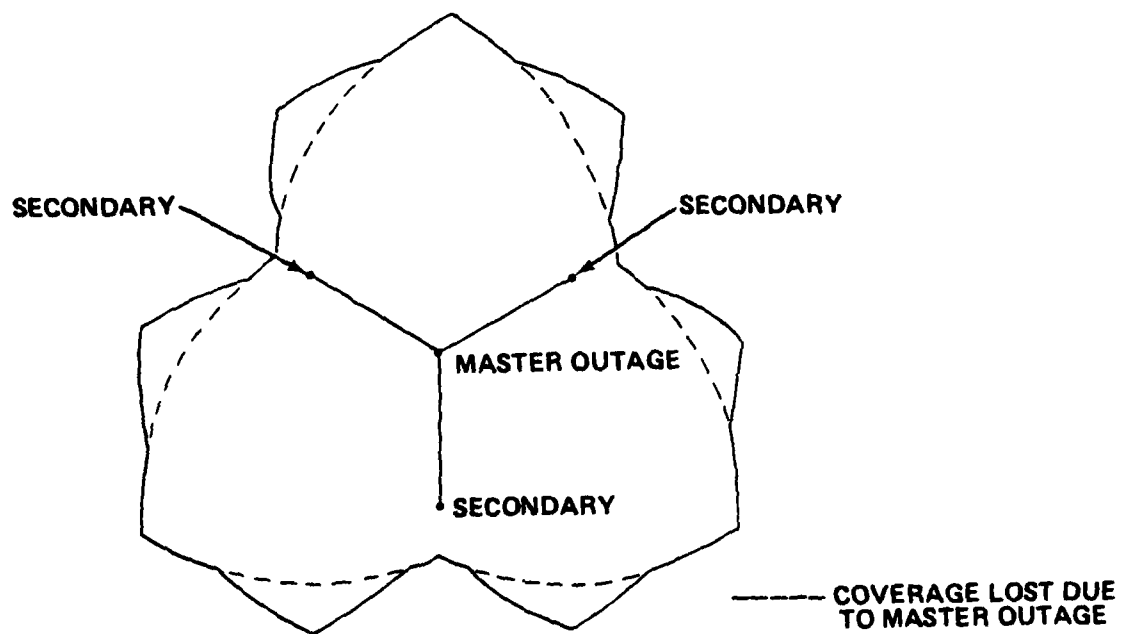


Figure 3-10. Range-Range Coverage with a Master Outage

3.1.4 Selection Summary

Based upon the analysis presented above, it can be seen that the range-range mechanization provides two operational advantages. Namely:

- Range-Range provides greater coverage than hyperbolic.
- Range-Range will permit navigation to continue for a while on two stations (following loss of one station) provided the required oscillator accuracy is available. This capability would be sufficient to enable the system to continue navigating during brief periods of third station outage but would generally not be adequate for sustained backup mode navigation.

A range-range position determination method based upon use of a less accurate (lower cost) oscillator would yield accurate navigation for a short period of time if it can be assumed that the system has calibrated the oscillator using redundant (three or more stations) information prior to reverting to the two station operation. From an operational standpoint this invokes several important questions critical to system performance.

- How long does it take to calibrate the oscillator considering the possible variation in temperature as well as position measurement errors caused by low signal to noise and poor geometry?
- Can the operator be confident that the calibration has been accurately accomplished and that navigation errors are within allowable limits?
- How long should the system be permitted to operate on two stations before a navigation failure is declared?

The major disadvantage of the range-range mechanization is that it requires a precise, and therefore a more costly, oscillator than is needed for the hyperbolic mechanization.

The selection of hyperbolic versus range-range must be considered on the following basis: Does the improved coverage and limited backup navigation capability justify the higher cost for the oscillator? To resolve this question the effects of adjacent chain coverages and the ability of the system to implement chain to chain operations must be considered.

If the coverage from an adjacent chain provides some overlap, then the greater coverage provided by the range-range mechanization is of less importance provided the system has the capability to acquire and use the navigational data from the adjacent chain. During periods of station outage the system should acquire and track stations of an adjacent chain rather than rely on the two-station range-range capability due to the increase in position error that would otherwise occur.

3.1.5 Conclusion

For the following position determination methods:

- Hyperbolic time difference lines-of-position, versus
- Range-Range (rho-rho) circular lines-of-position, versus
- Hyperbolic with a change to range-range operation when station failure occurs.

It is concluded that the hyperbolic time difference position determination method is the best choice. This choice is based on:

- The hyperbolic methods provide adequate coverage based upon the postulated conditions of complete station coverage with redundant capabilities to account for station outages.
- A chain-to-chain capability is provided (refer to Section 3.3). This enables the system to utilize stations in adjacent chains to extend the coverage area and to provide continued operation in the event of station outage.
- The range-range capability results in higher system cost because of its need for a more precise oscillator incorporating temperature control capabilities.

- The navigation data provided by the range-range capability cannot be relied upon by the operator to maintain the aircraft in its assigned airspace during periods of two station operation. This is because the navigation error is a function of the oscillator error and is dependent upon the extent to which the oscillator was calibrated prior to its use for range-range navigation. The primary use of the range-range capability would be to provide backup navigation and data to aid in system reacquisition of the Loran signals.

3.2 LORAN SIGNALS REQUIRED FOR NAVIGATION

3.2.1 Background

The purpose of this trade-off analysis task is to determine the Loran-C signals required to perform the position determination and navigation functions of the Loran Navigation System.

In this analysis the following types of station selection methods were considered:

- Master Dependent, versus
- Master Independent
- Change to Master Independent from Master Dependent operation when the signal from the master station is lost.

3.2.2 Requirements

There are currently no requirements for specific station selection criteris in either FAA Advisory Circular 90-45A or RTCA DO-159. Therefore, the requirements are dictated by the user needs to:

- Select stations that provide the most accurate navigation
- Avoid ambiguous position solutions
- Minimize other systems constraints, i.e., cost, complexity, etc.

3.2.3 Analysis of Signals Required for Navigation

The analysis of station selection criteria and the analysis of position determination methods (see 3.1) used the same methodology. Coverage patterns for master dependent versus master independent station selection methods and signal acquisition were performed. The analysis considered the unique pulse and phase coding of the master signal and methods for identifying secondary signals when the master is unavailable.

In addition a comparison of manual vs automatic station selection was performed by observing regions of changing coverage in the various coverage areas.

Many of the results of the master dependent versus master independent study are contained in the position determination analysis in Section 3.1. Station selection and position determination are interrelated topics, therefore, the analyses were performed concurrently.

The major impact of master independent versus master dependent coverage is observed in station outage situations. With both hyperbolic and range-range positioning methods a master dependent receiver cannot operate with a master outage. An examination of the position determination algorithms for navigation indicated that the master independent procedure is no more difficult to solve nor does it require additional hardware for implementation. Therefore from a coverage standpoint, master independent operation is superior to master dependent operation.

In master dependent operation the signal from the master station is easily identified by its ninth pulse and unique phase code. When the master signal is unavailable for any reason, identification of the secondary station is not possible unless the time base in the receiver has been (or can be) synchronized with the chain time base. This synchronization must be achieved for each chain being tracked by the receiver. It can be accomplished by having an accurate knowledge of present position, station identification, station location and coding delay. Without knowing the source of a single secondary signal, it is not possible to establish the chain time base.

If two secondaries in the chain are being received, their time difference can be used to identify the secondary stations if present position is known. There may be ambiguous solutions to the secondary time difference solutions in some cases. In a moving

aircraft the ambiguity will be resolved in a short period of time. Therefore, the station identification solution should be checked over a sufficient period of time to assume that the ambiguity has been resolved.

If during flight the master station is lost, the system is capable of continuing to navigate if three or more slave stations are being tracked. Even if after the master is lost a new slave station is acquired, it can easily be identified since the other stations are known and it has a unique time slot.

During flight the system may be operating on one chain and trying to acquire the second chain. If only a single slave station from the second chain is received, it is impossible to accurately identify it unless the Loran receiver has established an absolute time base from which the time of transmission of any signal can be predicted. (For the low-cost receiver such a time base would add significantly to cost, therefore, it is not practical for a \$3,000 receiver.) Receipt of two slave signals from the second chain may allow identification of the signals as described above.

Another method that the system may use to identify the signals is by the amplitude of the received signal. Since the station locations and radiated power levels are known, the amplitude of the signal can be computed and compared against the received signal for use as an initial estimate by the computer in establishing slave station identity.

Since acquisition of chains is an easier task when the master is being received, it is recommended that master dependent acquisition be attempted initially. If this is not effective in producing station identification and synchronization, then other methods may be attempted such as the time difference method outlined in the previous paragraph.

Examination of the coverage patterns in Section 3.1, reveals many situations in which the aircraft could be passing through areas where the station coverages change very rapidly. This occurs in the range-range system as the aircraft crosses a baseline or baseline extension area. In such instances in a manual system the stations would have to be changed as the aircraft entered the non-coverage area. These areas can occur suddenly in a fast moving aircraft. Coverage patterns also change rapidly in station outage situations. In these instances the station that would provide coverage in the aircraft's operating area would need to be rapidly identified and entered into the computer. This procedure could cause a significant workload burden on the pilot at critical times in the flight.

Receivers which have the capability to receive and track all stations within range of the aircraft can track alternate position solutions and be prepared to continue to provide navigation in the event of a station outage. The coverage of multistation navigation systems is a complex analytical problem that the pilot cannot possibly solve in the cockpit without maps or charts which cover all situations of coverage and station outage. The navigation computer on the other hand is capable of solving complex problems and can have the solution available as non-coverage areas occur or as station outage situations occur. Therefore, it is recommended that automatic station selection procedures be used in the low cost receiver.

3.2.4 Selection Summary

Master independent position determination methods have superior coverage characteristics as compared to master dependent methods. Master dependent receivers cannot operate when the master station is out in either hyperbolic or range-range systems.

Identification of the station and synchronization of the computer clock with the chain timing are simplified if the master is being received and tracked. Station identification and synchronization are possible if two secondaries are being received.

Automatic selection of the stations-to-be-used in the position determination algorithms produces lower pilot workloads than manual station selection and reduces confusion on the part of the pilot.

3.2.5 Conclusion

The receiver should operate in the master dependent mode when the master signal is available and revert to the master independent mode of operation when the master is unavailable. Therefore, the slave station identification process need be employed only for the master independent mode.

The receiver should track all available stations in a chain. This will provide more accurate navigation and will enable the system to continue navigation during periods of station outage (if four or more stations were being tracked prior to the station outage).

Station selection should be automatic because the computer can perform the task better than the operator.

Note that the above tasks are performed within software and do not add greatly to system costs.

3.3 SINGLE AND DUAL CHAIN OPERATION

3.3.1 Background

The purpose of this analysis is to determine the need for the Loran Navigation System to operate using one or two chains simultaneously. The analysis considered operations in the National Airspace System using both single and dual chain receivers.

For the single chain receiver it was assumed that the chain being tracked would be dropped before acquisition of the second chain can begin.

There are no specific requirements in the Federal Air Regulations or in FAA Advisory Circulars pertaining to the requirement for a Loran-C receiver to track one or more chains at one time.

3.3.2 Analysis

The primary advantage of a single chain receiver is the reduced amount of hardware and software complexity that results from tracking only one chain at a time. Typically, a single chain receiver will have to track no more than five stations at any one time. Only one time base need be established and the possibility of having to measure two signals simultaneously does not occur with a single chain receiver.

On the disadvantageous side, the single chain receiver will have a significant navigation loss during the time after the first chain has been dropped and before the second chain is acquired. Also the pilot has no positive indication that the second chain can be acquired. Furthermore, it may be impossible to reacquire the first chain if the second chain cannot be received. Receivers typically are able to track at a lower signal to noise level than they are able to acquire. In such a situation the pilot would be left with no navigational information until one of the chains can be acquired.

Single chain operation also eliminates the capability to expand coverage of the ground system by utilizing cross chain operation. In cross chain operation propagation times or time differences from stations in the two chains are used for position determination.

The dual chain receiver is more complex in terms of hardware and software requirements in the receiver front end. The amount of additional complexity in hardware will affect the low cost goal of the receiver.

The dual chain receiver does have the capability to provide cross chain coverage. This capability can increase the coverage of sparsely spaced ground stations such as those that exist in the middle of the U.S. at the current time. One cautionary note should be brought up concerning cross chain position determination. Cross chain hyperbolic time difference receivers can have insidious coverage gaps that are not apparent when first looking at the station configuration. This problem is caused by the lines of position being parallel or nearly parallel. One such situation is depicted in Figure 3-11, showing a large coverage gap in the north central U.S. when the West Coast and Great Lakes chains are used to provide hyperbolic time difference coverage.

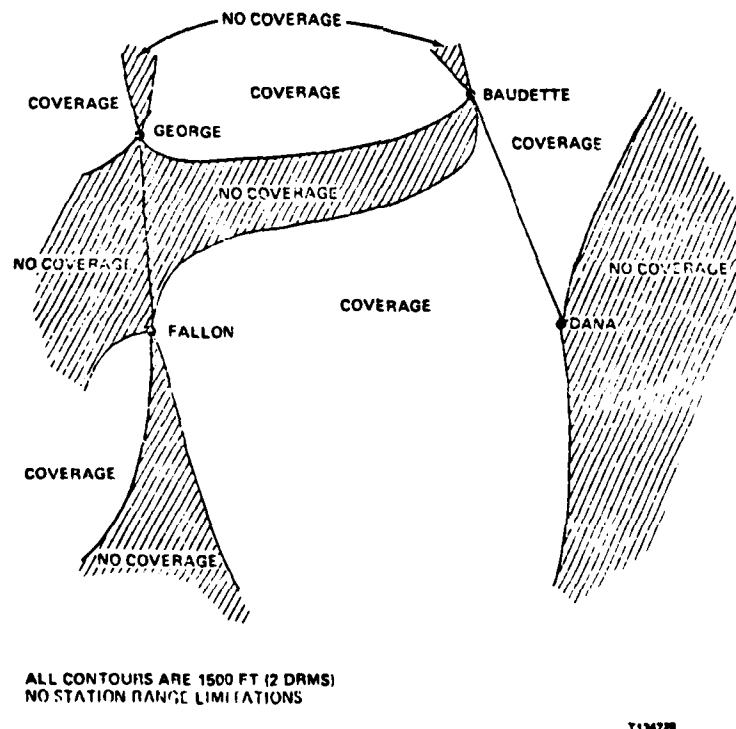


Figure 3-11. Cross Chain Coverage with a Hyperbolic System

One of the major benefits of using a dual chain receiver is the removal of gaps in navigation capability that was discussed in the single chain section. Continuous operation using automatic chain and station selection produces a system whose signal source is basically transparent to the type of signals in space being used. Such a system would undoubtedly instill a significantly higher level of pilot confidence than a system that had gaps.

Provisions for a dual chain capability raises several questions relative to operation of the system. For example,

- What will be the criteria for selection of the Loran primary and alternate chains?
- What will be the criteria for transition from the primary to the alternate chain?
- What provisions must be made to prevent jumps from occurring in the position and steering displays?

The receiver will contain in memory the location of all Loran chains and stations within CONUS. Based upon the initial position of the receiver, the primary chain will be chosen which provides the best geometry and signal strength (based upon transmitter power and range to station). The secondary chain will be the adjacent chain that provides the next best geometry and signal strength. All receivable stations in each chain will be tracked, however, the navigation algorithm will process to data to achieve the most accurate position fix.

The receiver will periodically reevaluate the chain and stations selected to determine if a better choice is available. If so, the secondary channel will be used to acquire the new chain while the primary continues to provide navigation data. If at any time the secondary chain is capable of providing more accurate navigation, then the computer will interchange the primary and secondary chain.

During periods when two chains are being tracked it is possible to use the data from both chains in the navigation solution. While this data processing method may yield improved navigation accuracy it cannot be considered a requirement for the minimum system because the required navigation accuracy can be met by processing the data from only one chain at a time.

When chain switching occurs there is the possibility of jumps in the position and steering displays. Any jumps should be relatively small (less than 1/4 mile) since the Loran signals from both chains will be corrected for propagation anomalies. If tests or experience indicates that this is distracting to the operator the data can be blended so that a smooth transition occurs. Chain switching while in the approach mode should be avoided unless necessary to maintain accurate navigation.

3.3.3 Selection Summary and Conclusion

Single chain receivers are less complex from a hardware and software viewpoint. However, these receivers produce gaps in navigation capability as they transition from one chain to another. Coverage area is less for a single chain receiver than for a dual chain receiver because cross chain operations are not able to be used. Also in areas of weak signals the pilot may be left without navigation for some time because any attempt to reacquire the previous chain may be unsuccessful due to the higher signal levels required to acquire as opposed to those needed for tracking.

Dual chain receiver can overcome many of the deficiencies of single chain receivers. However, dual chain receivers will be more complex and therefore more costly.

A dual chain receiver is considered necessary for the low cost Loran-C receiver to avoid the loss of navigation information which would occur with a single chain receiver when it transitioned from the first to the second chain.

3.4 PROPAGATION ANOMALY COMPENSATION

3.4.1 Background

In order to achieve the navigational accuracy required for operation in the National Airspace System, the Loran receiver must correct all signals for propagation anomalies. The propagation anomaly, also called additional secondary phase factor, results because of the varied terrain conductivities along the signal propagation path. While the value of the propagation anomaly changes with variation in earth conductivity resulting from precipitation or seasonal changes, the changes in propagation anomaly are small enough that the Loran receiver can meet the required navigational accuracies by using a constant value.

Two areas must be examined in order to determine the best method for propagation anomaly compensation in the low cost receiver. They are:

- What algorithm and data storage can best fit within the processor and memory capabilities of the receiver?
- How will the propagation anomaly correction values for the data storage table be obtained?

Clearly one method that could be used for the low cost receiver that would have minimum cost impact would be to require the operator to manually enter the propagation anomaly corrections for the waypoint that he is steering to.

Such an approach is unsatisfactory for the General Aviation Loran-C receiver for the following reasons:

- The correction data is valid for only one location and may not be accurate enough for other nearby locations that could be used for waypoints or landing.
- Insertion of the correction data into the system by the pilot may impose too great a work load. Pre-storage of the correction data for the waypoints is not considered practical unless it covers the entire operational areas.
- Since the data will be required for some navigation modes, particularly for the approach to landing mode, it is not clear to either the pilot or the ground controller that the correct data have been entered and is being used such that everyone is confident the aircraft will remain in its assigned airspace.

In order for a propagation anomaly compensation technique to be satisfactory for General Aviation, it must satisfy the following requirements:

- It must provide sufficient correction to enable the system to meet the position accuracy requirements throughout the Loran-C coverage area.
- The corrections must be automatic. The operator error rate in inserting propagation anomaly corrections is unacceptable considering that the system may be tracking multiple stations, more than one chain, and may be periodically adding and deleting stations.

For the reasons stated above, the propagation anomaly compensation trade-off analysis will consider only those methods that are automatic, covers all of CONUS, and uses prestored data.

3.4.2 Requirements

The navigation system must provide position in an absolute, or ground based, reference frame. While the radio grid established by the Loran signals are relatively fixed and repeatable, they must be corrected for the propagation anomalies (grid warpage) to establish absolute accuracy. The accuracy of the propagation anomaly correction must be approximately 250 feet (rms) in order to meet the navigational accuracy requirements for the approach to landing mode.

Since the Loran station selection is automatic, the propagation anomaly data base must provide for tracking and signal correction for all Loran signals that are usable in a given location. Because the task of inserting this amount of data into the system exceeds the operator's capability during flight, the data base must be prestored and automatically selected by the receiver.

3.4.3 Secondary Phase Model Candidates

The first candidate is Millington's method in which a conductivity map of the contiguous 48 states is stored in the system. The map is encoded with a differential technique. The cell size is 5 nm square. A raw map of 120,000 items is reduced to approximately 15,000 items with coding. Each item is 8 bits. The model decodes the map to derive a string of conductivity values for the path between transmitter and receiver. The conductivity values are used in Millington's equations to compute an estimate of secondary phase. Each 8-bit conductivity item is a best fit to the cell properties and is itself a coded representation of conductivity. The model is computationally modest in complexity and some post-decode processing of the string of conductivity values may be necessary. The model ignores altitude effects as do the other candidates. Altitude effects are not expected to appear in approach mode and will not defeat the error budget at significant altitudes when less precise modes are in use. The accuracy of the model will be strained over very rugged terrain. The model is station independent; i.e., the same formulation and map will support all station locations.

The second candidate is an alteration of the first in which the encoded map is replaced by a sectorized fit of the conductivity surface with 7th order, two dimension polynomials. The sector size is 75 nm square. There are 36 coefficients, each 8 bits, for each of 520 sectors. The coefficients are prescaled for the order of term in the fit. The total storage is then 18.7 kilobytes. The model evaluates conductivity at discrete points along the signal path by tracing the path through the sector structure, computing offsets with respect to the origin of each sector found and evaluating polynomials. This model appears to be computationally more difficult than the other candidates. A rectangular coordinate system is used in the surface fit. Some storage economies are possible by allowing the order of fit to vary.

The third candidate does not involve conductivity maps or the solution of the propagation equations. This model is a direct surface fit of the secondary phase for each transmitter. The secondary phase surface, derived by integral equation prediction or by measurement, is split into eight polar sectors and fitted with a polar polynomial expansion of tenth order. Each expansion has 66 terms for each sector and each term is one prescaled byte. Total storage for 31 stations is 16.4 kilobytes. The fit extends to the maximum groundwave range of the planned coverage for each station.

The fourth candidate is an alteration of the third. Phase velocity is fitted instead of phase. The fit is sectorized into 25 nm annular rings about each transmitter out to 1200 nm. The total number of rings is 48 per station. The innermost pair of rings are fitted to first order and the next pair to second order, rising linearly to a maximum of fifth order. Each coefficient is a prescaled byte and a total of 908 coefficients fit each station. Total storage for 31 stations is 28.1 kilobytes. The model evaluates phase velocity at discrete points along a radial by expansion of each polynomial out to the position of the receiver. Integration of the string of phase velocity values along the signal path yield a phase prediction. Both the third and fourth candidates are computationally simple.

The fifth model takes advantage of the fact that aircraft position is expressed as a range and bearing from a designated point (refer to Section 3.5). Generally, the designated point will be a VOR station. Storage of all VOR station for use as navigational reference points is being provided. The propagation model is based upon storage of the propagation anomaly corrections for all Loran signals receivable at the

navigation reference point. Thus, when the navigation reference point is being used for navigation (range and bearing) the corresponding propagation anomaly values for the Loran signal being tracked will be used. This method should yield most accurate results for approach to landing mode when the navigation reference is the nearby VOR station as is now operational procedure with current VOR based navigation systems. Storage for this propagation anomaly method will require five to eight thousand words of memory based upon approximately 1000 reference points (VOR station) times five to eight Loran stations per location.

3.4.4 Summary and Conclusion

The first four candidates embody a substantial compression of an exact solution of the wave equations for groundwave propagation over inhomogeneous surfaces. The first two candidates use a simplification of the exact equations and compress the characterization of the surface in a special way. The next two candidates involve a compression of the response of the groundwave to the surface. The first two candidates are stationed independent whereas the other three are not, implying that a proliferation of transmitters as part of a coverage densification policy will penalize the latter three candidates. Table 3-1, illustrates the properties of the five candidates. Given the very low rates at which the model will run, e.g., once each two minutes per transmitter of interest, and the prospects for coverage, the encoded conductivity map model is the best choice. Storage devices for any of the model data bases may be the most economical form of ROM, 8K or 16K byte mask programmed ROM.

One problem in implementing the propagation anomaly correction methods is obtaining the data base from which the corrections are made. While some data exists for each method, there is insufficient data to completely describe the entire coverage area for any of the methods. In fact, as stated earlier, not all areas now have Loran signal coverage. Most of the data that are currently available, and the data easiest to obtain supports selection of the fifth or stored correction table method.

It is therefore concluded that the propagation anomaly correction method initially used in the low cost receiver should be the stored table of correction values. This conclusion is based upon

- Compatibility with the navigation (range and bearing) mechanization
- Availability of correction data for existing Loran coverage areas
- Ease of obtaining correction data for new coverage areas as Loran coverage is expanded.

Table 3-1. Secondary Phase Model Comparison

	<i>Storage, K Bytes</i>	<i>Computational Complexity</i>	<i>Station Dependent</i>	<i>Surface Fit</i>	<i>Propagation Equations</i>	<i>Sectorization</i>
Encoded conductivity Table & Millington's Method	15.0	Medium	No	Yes	No	No
Fitted conductivity Table & Millington's method	18.7	High	No	Rect.	Yes	Yes
Directly Fitted Phase	16.4	Very Low	Yes	Polar.	No	Yes
Fitted Phase	28.1	Low	Yes	Annul.	No	Yes
Stored Correction Values	8	Low	Yes	No	No	NA

The encoded conductivity model listed first in Table 3-1 is considered to best method to use and should be reconsidered when the Loran coverage has been expanded and additional data obtained to fully describe the conductivity throughout the coverage areas.

3.5 WAYPOINT DESIGNATION METHODS

3.5.1 Purpose

The waypoint designation task was performed to determine the waypoint entry method or methods that are most suitable for a low cost Loran-C receiver.

3.5.2 Candidate Waypoint Designation Methods

Three waypoint designation methods were selected for detailed analysis. The methods are:

- Latitude - Longitude
- Coded Identifier
- Radial and Distance from a designated point

3.5.2.1 Latitude - Longitude - The latitude/longitude (lat/lon) method is obviously the most direct waypoint entry method. The coordinates of the waypoints that form the route of flight are entered into the computer through the Control Display Unit (CDU). Because of the nature of the computational concept of the proposed receiver, the lat/lon reference system is the most compatible with the airborne computer requirements. Internal navigation functions will be accomplished in lat/lon after conversion from the signal input reference. If pilot inputs are couched in the lat/lon reference system, computer conversion algorithms and memory requirements would be minimized. From the pilot's viewpoint, however, lat/lon is probably the most difficult of the methods with which to work. The National Airspace System (NAS) is currently based on VOR system navigation and ATC requests are usually referenced to the VOR. Route intersections and reporting points are generally defined in radials and distances from associated VORs. In short, today's pilots have adapted to the VOR system and find it a very natural environment in which to operate. Transition to a straight lat/lon navigation reference would require considerable change on the part of both pilots and controllers. Additionally, analysis will show that definition of a waypoint using lat/lon requires selection of up to fourteen characters on the CDU in order to obtain the desired accuracy. The entry of this number of characters produces the distinct possibility of a data input error by the pilot which, if uncorrected, could cause the aircraft to deviate from its intended flight path. In summary, while a lat/lon reference ranks highly in terms of computer compatibility, it is not entirely compatible with minimum pilot workload levels.

3.5.2.2 Coded Identifier - Computerization of the ATC system has allowed mechanization of many of the tasks which required controller interpretation. To accommodate this mechanization, most route intersections and terminal area fixes have been allocated five letter unique designations. Those fixes which haven't been converted will be as the computerization process proceeds. The incorporation of these computer adopted identifiers into the ATC structure, creates the potential

for using them as an onboard navigation reference system. Waypoint definition would be relatively easy from the standpoint of pilot workload factors, but the definition of waypoints other than published intersections or fixes could be difficult to handle. Several problems arise from the aspect of onboard computerization, however. First, additional conversion algorithms would have to be included in the software to go from five letter identification to lat/lon position coordinates. Second, a relatively large memory capability would have to be included in the computer design to accommodate a universal set of fixes and their coordinates. This memory would also have to be accessible for modification since these navigation fixes are sometimes moved to streamline the ATC structure. Although the use of five letter identifiers for the definition of waypoints appears to be feasible superficially, adaptation of this particular reference may produce more problems than it solves, particularly during any kind of long term transition period.

3.5.2.3 Range and Bearing from a Designated Point - The third navigation reference system to be discussed has the potential for allowing Loran-C navigation operations to function in the same manner that VOR operations are conducted. By storage (in computer memory) of VOR identifiers (three letter) and position data, pilot/computer interface can be accomplished in that reference system with which the pilot is most familiar. Additionally, this system is most compatible with the current ATC structure reducing the requirement to change charting and controlling procedures. Pilot inputs would be radial/distance entries related to specific VOR station locations, thus enabling the pilot to continue to navigate with reference to the system in which he has traditionally become accustomed. Computer computational software requirements would be greater than that needed for the other two systems discussed. On the other hand, memory capacity requirements would be less than those needed for a five letter intersection/fix reference system since there are far fewer VOR stations than intersections and fixes. Additionally, the location of a VOR station remains as a system constant except in rare instances. This will reduce the requirement for remote access to navigator memory on a frequent basis. Although a synthetic VOR based reference system is most compatible with current ATC structure and the pilot's traditional thought processes, incorporation of this concept in the proposed receiver unit will entail additional conversion algorithms in computer software and memory capacity to store associated position data for all VOR stations to be used.

3.5.3 Requirements

The waypoint designation method to be used by the low cost Loran-C receiver must be compatible with existing NAS route structures and procedures. This means that the airborne system must be capable of operating on the following routes:

- VOR Airways
- RNAV Airways
- Terminal Area STAR and SID Routes
- Non-Precision Approach Routes

In addition the low cost Loran-C receiver must be capable of interfacing with current required ATC procedures including holding patterns and radar vectors. The unit should also be capable of performing RNAV control procedures which include the direct to waypoint procedure and the parallel offset feature.

3.5.4 Analysis of Waypoint Designation Methods

The three waypoint designation methods were subjected to an analysis of their suitability for use in the low cost Loran-C receiver. These studies investigated the following areas:

- Manual Data Input
- Waypoint Data Storage
- Chart Compatibility
- Pilot Workload

The analyses performed for each waypoint designation method task assumed that the normal computational process in the navigation computer section of the receiver would be in the lat/lon reference system. Therefore, whichever method is employed, it requires translation to latitude-longitude for use by the computer algorithms.

3.5.4.1 Manual Data Input - Analysis of the manual data input procedure consisted of counting the number of characters required for complete definition of the waypoint. This analysis assumed that the computer had no large data base storage for VOR facility locations or five letter intersection/fix locations. The computer storage capability was assumed adequate to store all of the manual input data.

Lat/Lon - The input of latitude and longitude waypoints directly into the computer requires the selection of five latitude digits and up to six longitude digits. In addition a control/display unit designed for universal application would require setting the north or south letter for latitude and the east or west letter for longitude. This plus the waypoint number, assumed to be a single digit, produces a total of 14 alphanumeric characters required to define the waypoint.

Coded Identifier - The manual input of five letter, coded identifier waypoints imposes the necessity of entering latitude/longitude data plus five letter characters which can range from A to Z. A total of nineteen alphanumeric characters must be entered with this configuration. This imposes a considerable workload burden on the pilot with little apparent operational benefit. Therefore, manual data entry of five letter waypoints was considered unacceptable. Use of the five letter identifier was considered acceptable only if the identifier and lat/lon data associated with the waypoint were prestored in read only memory (ROM).

Radial and Distance from VOR Facility - The use of the radial and distance specification from a designated point such as a VOR requires fourteen digits to define the VOR location and waypoint number plus up to four digits to define waypoint radial and four digits to determine waypoint distance. This produces a total of twenty-two alphanumeric digits required for waypoint entry of the radial and distance concept. It should be mentioned that often it is possible to specify several waypoints from a given VOR facility, particularly in the terminal area. This would lessen the number of characters required from twenty-two to nine for a VOR facility that had already been entered (four for radial, four for distance and one for waypoint number). However, this improvement was considered as marginal at best. Therefore, manual data entry of the VOR lat/lon followed by manual entry of the radial and distance was considered as unacceptable workload burden on the pilot. Therefore, the radial-distance concept was determined to be acceptable only if the designated points, such as VOR locations, were stored in ROM.

3.5.4.2 Waypoint Data Storage - This analysis was performed to estimate the amount of storage required to hold a data base for the VOR facility locations and the five letter intersection/fix locations. The VOR estimate was based on the approximately 1000 VOR facilities in the CONUS. The intersection/fix location analysis assumed that there are approximately five intersections or fixes associated with each VOR facility.

Lat/Lon - The lat/lon system requires only storage for the input lat/lon values. Access of the waypoint data through reference to another point or through a coded identifier is not required. Therefore lat/lon storage requirements are minimal. For CONUS coverage it can be assumed that waypoints will lie between 15°N and 55°N latitude and between 50°W and 140°W longitude. For a resolution of 0.1 minutes of arc, the following data storage requirements in terms of bits are needed:

Latitude

55°N - 15°N = 40° range

40° X 60 minutes/degree X 10 tenth of minutes = 24,000 parts

$$\log_2 24,000 = 14.6$$

Therefore, the requirement is 15 bits.

Longitude

140°W - 50°W = 90° range

90° X 60 minutes/degree X 10 tenths of minutes = 54,000 parts

$$\log_2 54,000 = 15.7$$

Therefore, the requirement is 16 bits.

Thus, for CONUS coverage two sixteen bit words are required for each lat/lon point.

For a full worldwide range of lat/lon, seventeen bits of latitude and eighteen bits of longitude are necessary. This would require three 16 bit words per lat/lon pair.

The lat/lon storage requirement in words is two times the number of waypoints provided for a CONUS receiver and three times the number of waypoints for a worldwide receiver. Thus for a ten waypoint system, no more than 20 to 30 memory words are necessary.

Coded Identifier - The coded identifier system requires a five letter identifier to be associated with each intersection or fix in the NAS. Using a conservative number of five intersections/fixes per VOR facility produces about 5000 locations to be named. Each letter requires five bits of storage for a total of twenty-five bits for the five letter name. Therefore, four 16-bit words are needed for each fix or intersection. A full CONUS system would require at least 20,000 words of memory for the waypoint data storage.

In addition to the large data storage requirement, the fixes and intersections would require updating at the normal 56 day chart cycle established by the FAA. Management of this data base plus the large data storage requirement is not considered compatible with the low cost goal of the receiver. Therefore the five letter coded identifier system was not considered feasible for a low cost system at this time.

Radial and Distance from VOR Facility - Storage of the VOR facility locations and three letter identifiers was also analyzed. There are about 1000 VOR facilities in CONUS. The three letter identifier would require 15 bits of storage. Therefore, the VOR identifier and the lat/lon of the facility would require three words of memory. For CONUS application about three thousand words of memory would be needed. This data would need to be updated occasionally as new facilities are installed by the FAA.

The radial and distance concept was considered acceptable from a word storage and data management viewpoint if the cost of the storage media and its periodic update could be offset by reduction in control/display panel hardware or significant savings in pilot workload.

3.5.4.3 Chart Compatibility - The chart compatibility analysis consisted of analyzing the data presentation contained on current navigation charts and determining if this data is adequate to define the waypoint in the low cost Loran-C receiver. Current series charts from the U.S. Government, National Ocean Survey (NOS) and from the Jeppesen Company of Denver, Colorado, were studied. The analysis included the following IFR chart series:

- High altitude enroute (Jet routes)
- Low altitude enroute (Victor routes)
- Area charts
- Instrument approach procedures
- Standard instrument departures (SIDs)
- Standard terminal arrival routes (STARs)

Lat/Lon - Historically, lat/lon coordinates are not found on conventional IFR navigation charts. Recently, the increased use of inertial and Omega/VLF navigation systems has produced a trend toward increased use of lat/lon coordinates on charts. Currently, lat/lon coordinates are found on many SID and STAR charts produced by the Jeppessen Company of Denver, Colorado. These coordinates are also found on all series of RNAV charts. They are not, however, found on current high and low altitude airway charts. Therefore, in the near term it is quite possible that special charting would be necessary for the lat/lon waypoint designation method.

Coded Identifier and Radial-Distance Methods - These waypoint designation methods are entirely compatible with current charting practices. However, there are potential problems involved when the airborne data base and that used by the controller are of a different vintage. The radial-distance method could overcome these problems with alternate coordinate inputs from the controller. The five letter method with no alternate waypoint entry method could not be used for points that were not in the data base inventory.

3.5.4.4 Pilot Workload - The analysis of pilot workload was performed by setting up three typical general aviation flight scenarios and determining an estimate of the amount of time required to perform the data input functions for each scenario. The scenarios are described by the following characteristics:

- Corporation route - a fairly structured set of routes typical of those which might be used by a corporation with several facilities at different locations.
- Sales route - an unstructured set of routes which would change from day-to-day. These routes would typically be used by a salesman-pilot who uses his aircraft to visit clients.
- Terminal area route - a pair of routes in a high density terminal area with SIDs and STARs.

Details of the route structures and the pilot workload analysis are contained in Appendix A.

Pilot workload studies were carried out for the lat/lon system and the radial-distance method. The detailed analyses are contained in Appendix A. The results are summarized in the following paragraphs.

Table 3-2, is a tabulation of the results obtained in this analysis. Four operations were considered:

- Waypoint loading (or definition)
- Waypoint change (active waypoint selection)
- Course change (for the TO-FROM system)
- Parallel Offset Selection

Table 3-2. Estimated Navigation Workload (seconds)

Scenario	System	Waypoint Load	Waypoint Change	Course Change	Total Airborne	Total Ground
Corporate	Lat/Lon	561 (23)	42 (36)	—	59	544
Corporate	Radial-Dist	132 (108)	32 (32)	42 (32)	88	118
Salesman	Lat/Lon	698 (181)	90 (90)	—	271	517
Salesman	Radial-Dist	296 (227)	64 (64)	47 (42)	333	74
Terminal	Lat/Lon	585 (60)	36 (36)	—	102*	525
Terminal	Radial-Dist	140 (96)	24 (24)	47 (43)	169*	48

() Indicates airborne workload

* Includes 6s for parallel offset maneuver

These results are relatively self-explanatory. A reduction in airborne workload is considered to be intrinsically valuable than a reduction in ground workload. The large value obtained for waypoint definition in the lat/lon system will be significantly reduced by the incorporation of non-volatile memory for pilot entered data. As can be seen, the large waypoint load values are a result of the long data switch drive times incurred during waypoing definition immediately following system turn-on under the assumption that no waypoint locations had been previously stored. These drive times will normally be much smaller since non-volatile memory storage is available.

Therefore, for most waypoint entries the operator will need make only small changes in the degrees values of lat/lon resulting in considerably shorter load times. However, for this analysis a worst case condition was considered.

3.5.5 Selection Summary and Conclusion

The lat/lon method and the radial-distance method with stored VOR facility locations both survive as candidate waypoint designation methods. Five letter designation was dropped because of the excessive number of characters required for manual data entry and the large amount of ROM storage and 56 day base update requirements.

The lat/lon method requires only 20 to 30 words of non-volatile memory for ten waypoint data storage. The radial-distance method requires three thousand words of ROM for storing the three letter VOR identifier and the VOR lat/lon. Therefore, the lat/lon method has the advantage over the radial-distance method in terms of ROM storage.

The radial-distance method is completely compatible with current charting practices. The lat/lon system would require all charts used with the low cost Loran-C system to designate waypoints, intersections and other fixes with lat/lon values. Therefore, the radial-distance method has the advantage in terms of chart compatibility.

Because of the slightly higher airborne workload levels for the rho/theta system and the possibility that the high waypoint load workload levels will not be incurred by the lat/lon system, this assessments tends to favor the lat/lon system design over the rho/theta design. The differences are not of a large enough magnitude to constitute a major design consideration. Both designs are equally acceptable from a physical workload assessment point of view, therefore the selection should be based upon other considerations.

Examination of the cost (of the Control Display Unit) for both the lat/lon and range and bearing methods indicated that there was no significant cost differences in the two methods.

Review of the designation methods, using the candidate Control Display Panel designs described in Section 4.4, by experienced pilots indicated a definite preference for the range and bearing waypoint designation method because it is most compatible with the pilot's current navigational procedures and equipment. Since neither the

analysis nor costs data yielded a definite preference, the range and bearing method was chosen based upon its user acceptability.

3.6 NUMBER OF WAYPOINTS STORED

3.6.1 Background

The purpose of the waypoint storage task is to determine minimum waypoint storage requirements for the low cost Loran-C receiver. Initially three waypoint storage capabilities were to be considered in this task. They were:

- one
- three
- more than three

After an initial literature survey, it was found that emerging industry minimum waypoint storage requirements are being developed around four waypoints for TO-TO navigator sets (i.e. navigation receivers that fly to a waypoint only, rather than to the waypoint, then from the waypoint) and two waypoints for TO-FROM sets. Consequently, the analysis was changed to consider the following waypoint storage capabilities:

- two
- four
- nine

Two types of waypoint designation methods were considered in the waypoint storage analysis, the lat/lon method and the radial/distance method. The lat/lon method was assumed to use the TO-TO waypoint sequence technique while the radial/distance configuration was assumed to use a TO-FROM waypoint sequence technique. This convention is consistent with many current navigation computers available for use on civil aircraft.

Four documents were used in the investigation of waypoint storage. These documents are:

- a. Advisory Circular 90-45A, "Approval of Area Navigation Systems For Use in the U.S. National Airspace System".
- b. "Preliminary RNAV Avionics Standards (2D and 3D Area Navigation Systems)"; Adams, R.J., Systems Control, Inc. (Vt.); Report Number FAA-RD-75-178; July 1974.
- c. "An Operational Evaluation of Flight Technical Error"; Adams, R.J.; Systems Control, Inc. (Vt.); Report Number FAA-RD-76-33; July 1975.
- d. "Minimum Operational Performance Standards (MOPS) For Optional Equipment Which Displays Non-Radar Derived Data on Weather and Ground Mapping Radar Indicators (Proposed Final Draft)"; SC-133/Radio Technical Commission For Aeronautics: RTCA Paper No. 252-80/SC133-128; October 1980.

3.6.2 Requirements

Current requirements for waypoint storage are contained in Advisory Circular 90-45A, which states that one waypoint is required for enroute and two are necessary for non-precision approach applications. Emerging requirements being developed by RTCA are discussed below.

3.6.3 Waypoint Storage Analysis

Two methods of approach were used in analyzing the waypoint storage requirements. First, a literature survey of studies, simulator tests, and flight test results on the subject was performed. The four documents listed above were reviewed. The second part of the study effort was performed through the use of pilot workload analyses. The detailed methodology is contained in Appendix A.

Most of the empirical research work waypoint storage was completed in conjunction with the extensive area navigation effort expended by the FAA in the 1973 to 1976 time frame. During the course of this effort, the FAA Area Navigation Task Force formulated minimum recommended standards for waypoint storage capacities based upon the 2D or 3D characteristics of the system being described. A minimum of six waypoint storage capacity was recommended for 2D systems while ten was recommended for 3D systems. Quantitative results from flight and simulated test programs, presented by System Control, Inc. (Vt.), indicated that these recommended minimums may have been set too high initially. In "Preliminary RNAV Avionics Standards" (1), the report recommends:

"A minimum storage capability for more than one waypoint is required for 2D area navigation terminal area operations. Single waypoint systems are acceptable for enroute operations only".

These recommendations were based on the analysis of preliminary data obtained in conjunction with the FAA area navigation effort. In a subsequent report, "An Operational Evaluation of Flight Technical Error" (2), the following recommendation is presented:

".....both the current cockpit simulator study and the preliminary avionics standards document support the fact that from an accuracy (FTE and TSCT)* and a functional viewpoint, no reliable differences can be measured for one, two or three waypoint storage capability. However, both the flight tests performed to date and the workload/blunder data from the simulator tests performed indicate that terminal area workload is too high for a single waypoint system to be acceptable. In fact, the simulator workload/blunder results indicate that two waypoint system is preferable to a one or three waypoint system for terminal area operations."

*Two sigma cross track

Initially, this conclusion might appear to be surprising, but it should be realized that some of the collected data may have been reflecting other design aspects of the total display system tested. It does appear significant, however, that all available quantitative data point to the unacceptability of a single waypoint storage system in a terminal area environment.

Recently, the Radio Technical Commission for Aeronautics (RTCA) established a Special Committee 137(SC-137) chartered to determine the Minimum Operational Performance Standards (MOPS) for area navigation systems. As a part of this charter, minimum waypoint storage capacity was examined. Area navigation systems were defined in terms of two generic types, TO-FROM systems (desired path determined by waypoint and course TO or FROM it) and TO-TO systems (desired path internally computed connecting two waypoints). Based upon these system definitions, minimum waypoint storage capacities recommendations are shown in Table 3-3.

Table 3-3. Proposed Waypoint Storage Minimums

Phase of Flight	Type of System	
	To-From	To-To
Enroute	1	2
Terminal & Approach	2	4

It should be emphasized that these values constitute the absolute minimum system capabilities recommended. Additional capability would be desirable in any future system design.

Based upon the literature search discussed in Section 3.6.7.1 an area navigation system being used in the terminal area must have a waypoint storage capacity of at least two if it qualifies as a TO-FROM system. A TO-TO system is required to have a four waypoint storage capacity. Thus, these two values become natural selections for evaluation in a storage capacity workload analysis. The third value to be evaluated, nine waypoints, has

been chosen because it is the largest, single-digit value available. From it evaluation of multiple waypoint systems can be accomplished while not exceeding the physical constraint of one display window for waypoint number identification on the CDU.

The scenario to be used will be scenario number three, the terminal area scenario. This scenario originates from John F. Kennedy International (N.Y.) with a takeoff from runway 04R, transits the Belle One Departure with a Pawling Transition, flies direct to the Kingston VOR, and makes a Kingston One Arrival to an ILS Approach to runway 13L. For the purposes of this analysis the route will terminate at Ellis Intersection and the ILS approach will not be evaluated. The waypoints required to be entered will be the departure end of runway 04R, Belle Intersection, Bridgeport VOR, Pawling 151/31, Pawling VOR, Kingston VOR, and Ellis Intersection. An unexpected controller-initiated parallel offset maneuver will be accomplished between Kingston and Ellis Intersection. Rho/theta waypoint definition will be based on that depicted on standard STD and STAR charts used for terminal area navigation.

Because this route is based on terminal area operations a two waypoint storage capacity is only practical in a TO-FROM system. For this reason the entire analysis will be based on the TO-FROM system described in this report. The analysis methodology is dealt with in detail in Appendix A and reference should be made to this source if any questions should arise during the course of this discussion. The results are presented in terms of seconds of work. These values are conservative estimates of the amount of time to perform the indicated functions.

Tables 3-4 through 3-6 present the results of the workload analysis for the nine, four, and two waypoint storage system using the terminal area scenario described above.

Table 3-4. Nine Waypoint Storage System (Distance-Bearing Method)

W/P Name	W/P Loading	W/P Change	Course Change	Offset
RW 04R	*14s	4s	5s	
MAD 244/26	*25	4	8	
BDR	*9	4	4	
PWL 151/31	*29	4	7	
PWL	*11	4	11	
IGN	*9	4	8	
JFK 318/15	*15	4	43s	6
TOTAL	*112s	24s		6s

*ground loaded inputs

Table 3-5. Four Waypoint Storage System (Distance-Bearing Method)

W/P Name	W/P Loading	W/P Change	Course Change	Offset
RW 04R	*14s	4s	5s	
MAD 244/26	*25	4	8	
BDR	*9	4	4	
PWL 151/31	*29	4	7	
PWL	14	4	11	
IGN	12	4	8	6
JFK 318/15	18		43s	6s
TOTAL	*77/44s	24s		
121				
4 Waypoint Storage System				

*ground loaded inputs

Table 3-6. Two Waypoint Storage System (Distance-Bearing Method)

W/P Name	W/P Loading	W/P Change	Course Change	Offset
RW 04R	*14s	4s	5s	
MAD 244/26	*25	4	8	
BDR	13	4	4	
PWL 151/31	23	4	7	
PWL	13	4	11	
IGN	16	4	8	6
JFK 318/15	19			
	*39/84	24s	43s	6s
TOTAL	123s			

*ground loaded inputs

Although these results are relatively self explanatory in nature, there are several aspects which should be expanded by discussion. It should be noted that no initialization has been included in these analyses. It was felt that initialization would be the same for all three cases and since the workload involved was low-stress ground workload this aspect was not included. The workload associated with ground loaded waypoint definition was included, however, since this was directly associated with the parameter being analyzed. It would also be noted that although course changes occur at the time of waypoint passage, waypoint changes, in a TO-FROM system actually occur between waypoints. For this reason these parameters are presented separately.

The workload results have been divided into two types, ground input associated and airborne input associated. Workload associated with ground inputs is significantly less stressful than that associated with airborne inputs. Neither time nor concurrent requirements are adding to operator stress levels. Operator workload reduction is greatly facilitated by enabling accomplishment

of as much data insertion as possible while on the ground. As was expected, airborne related workload is significantly higher for low waypoint capacity systems. Interestingly, however, overall workload also increases slightly for the low capacity systems. This increase was due primary to the switching of the data selector switch from an enroute monitor mode to an entry mode each time waypoint definition occurred in flight.

Another interesting facet of these results is the high percentage of overall navigation workload which is directly attributed to waypoint definition activity. If the capability of ground loading all necessary waypoint definition data is incorporated into the system design, airborne workload requirements could be cut by as much as sixty percent. Assuming that airborne workload reduction is desirable, there does exist an upper limit in waypoint storage capacity, above which no further workload benefits are accrued. As an example, in the case of this limited analysis, if the nine waypoint system had been only a seven waypoint system the results would have been the same as depicted here. Thus, in a sense, the last two waypoint storage positions were unnecessary for this particular application. Determination of this upper limit of utility for a general case is impractical, however, as its determination is totally dependent on the specific application being considered. Thus it is reasonable from a strictly workload point of view to have as large a waypoint storage capacity as possible. Cost constraints indicate that single digit waypoint numbers are more practical than multi-digit designators. These factors indicate that the most ideal system would be a nine waypoint storage capacity system.

3.6.4 Summary and Conclusion

Research results to date indicate that a single waypoint storage system in today's ATC environment would be unacceptable in all but the most basic enroute applications. A two waypoint system would be marginally acceptable in the terminal area environment as long as the basic system structure was designed to be a TO-FROM type of system.

From a pilot workload standpoint the greater the number of waypoints the less the workload, although on shorter routes a practical upper limit may be about nine waypoints.

For efficient operation in the ATC system a storage capacity of four waypoints is considered to be a minimum acceptable number. Increase storage capacity will reduce pilot workload and should be considered if additional costs are negligible.

Note: In the receiver design approach described in Section 5, no additional costs are attributable to nine waypoints (as opposed to four); therefore, the system will contain a nine waypoint storage capability.

3.7 ANTENNA/ANTENNA COUPLER TRADEOFF ANALYSIS

3.7.1 Introduction

The objective of this analysis is to select the most cost efficient Antenna and Antenna Coupler (ACU) design for the reception of Loran-C navigation signals on general aviation aircraft.

The Antenna/ACU subsystem is comprised of the functional blocks that performs the functions of signal interception, amplification, bandpass filtering, input circuit protection and output signal impedance matching. The Antenna/ACU consists of a single mechanical assembly, and is limited to include only those circuits that partially or completely perform the foregoing functions within its mechanical envelope.

It is assumed that adaptive signal processing, such as bandpass modification, AGC, or antenna selection and commutation, will be performed in the navigation receiver.

3.7.2 Requirements

Operational Requirements

Operating Environment:	Temperature:	-20°C to +55°C
	Altitude:	0 to 15,000 meters
	Relative Humidity:	up to 100%
	Airspeed:	0 to 250 Kts

Weight:	10 lbs max.
Maintenance:	No scheduled maintenance required.
Installation:	The Antenna/ACU may be installed at a distance up to 30 meters from the navigation receiver. The Antenna may be installed on either metal or fabric skin aircraft.

Technical and Functional Requirements

The Antenna/ACU must maintain the Loran signal envelope shape in the region about the standard sampling point such that the standard sampling point can be identified within ± 1.0 microseconds over a 80 dB dynamic range. Note: the 80 dB dynamic range reflects the expected range of signal field strength levels from 100 microvolts/meter to 1.0 volt/meter.

The Antenna/ACU must provide adequate precipitation static immunity to enable the Loran receiver to acquire and track Loran signals at minimum signal strength levels of 100 microvolts/meter under 99% of the flight conditions encountered in the U.S.

The Antenna/ACU shall be designed for lightning immunity such that the Antenna and ACU remain functional and sustain no damage after the aircraft is exposed to severe lightning conditions.

The Antenna/ACU must be provided with a low impedance signal output interface to the Navigation Receiver for interface cables up to 30 meters long.

The Antenna/ACU must be designed for a 3 dB bandwidth of 40 KHz or greater so that the bandpass characteristics of the Antenna/ACU have a negligible effect on the overall bandwidth requirements of the Navigation Receiver.

The Antenna/ACU must be provided with the smallest voltage gain required (up to a 20 dB maximum) to maintain a minimum Signal to Set Noise Ratio of 0 dB for a 100 microvolt/meter input signal field strength level.

Tradeoff Objectives

The tradeoff objectives of these analyses are to:

- Develop realistic Antenna and ACU alternatives
- Identify pertinent criteria for evaluating these alternatives
- Evaluate the alternatives in terms of the criteria
- Select the most cost effective Antenna/ACU alternative.

Problem Elements

In order to avoid loss of Loran navigation data when flying under heavy precipitation static conditions, a P-static immune antenna design is virtually mandatory. Unfortunately, these performance constraints must be traded off against the significantly higher cost of P-static immune antennas.

The following constraints are imposed on the alternatives considered:

- The maximum cost of the Antenna/ACU shall not exceed one fifth of the total system cost (i.e., \$600).
- Research and development manpower and schedule requirements shall not exceed 4 man months and 4 months, respectively.
- The physical size, weight and installation requirements shall not interfere with the normal operation of general aviation aircraft.
- The antenna pattern must be essentially omidirectional in the horizontal plane.

The following assumptions are made for this tradeoff analysis:

- The Loran-C groundwave coverage within the national airspace will consist of signal strength levels from 100μ volts/meter to 1.0 volt/meter for at least 3 stations in all operational areas considered.

- Effective P-static and streamer generated noise reduction techniques, such as the installation of orthodecoupled dischargers and the application of conductive coatings to insulated aircraft skin surfaces, are implemented. A minimum noise field reduction of 40 dB is assumed.
- The Loran receiver considered in these analyses can acquire and track Loran signals at a minimum SNR of -10 dB (SNR = 1.3).
- The general aviation aircraft, for which this Loran receiver is intended, will not sustain roll attitudes greater than 45° and pitch attitudes greater than 30° for more than 5 seconds in any 1 minute period.

The minimum performance characteristics are the same as the technical and functional requirements listed above.

3.7.3 Method

Establishment of Criteria for Evaluation

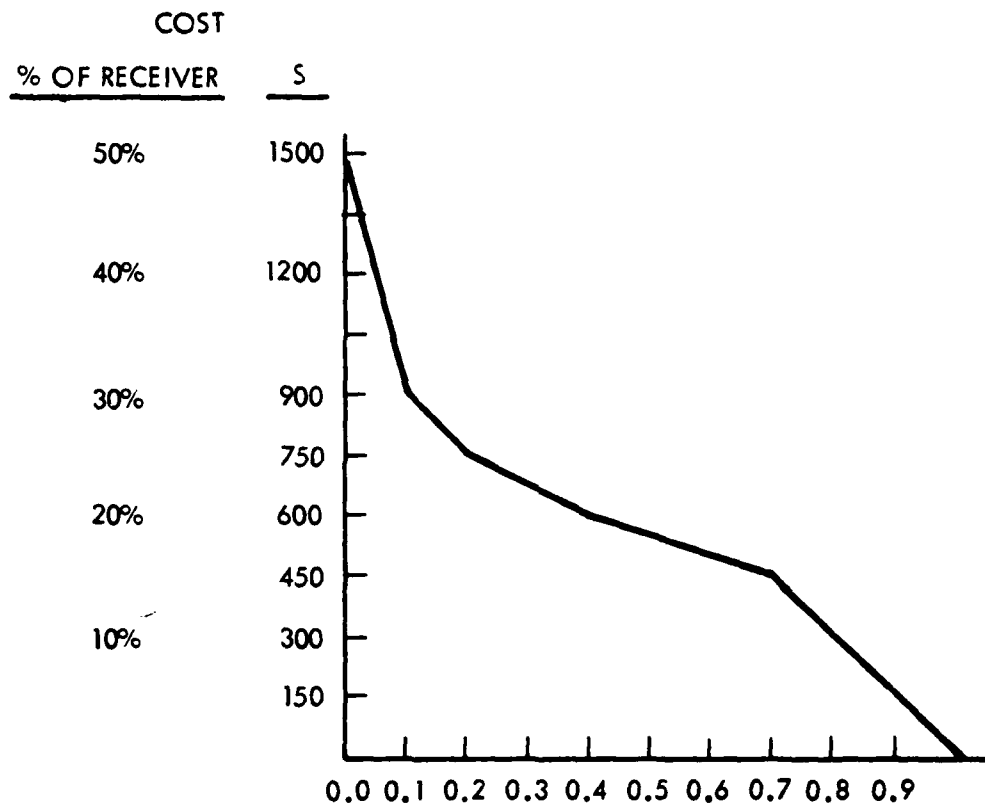
In general, all Antenna/ACU alternatives will be screened to eliminate alternatives that clearly do not fall within the constraints of Paragraph 3.7.2 or do not meet the minimum performance requirements of Paragraph 3.7.2. The remaining candidates will be evaluated based on an assigned figure of merit for a number of different criteria.

The criteria established to evaluate this tradeoff are:

- Cost
- Performance
- Development and Technology Risk
- Functional Dependence on Other Systems

The weighing of evaluation criteria is naturally somewhat subjective, therefore, the reasons for selecting a given figure of merit will be explained where appropriate. The figure of merit selected will range from 0.0 to 0.9 where a higher value represents a more desirable characteristic.

Cost - The cost of the Antenna/ACU should not exceed 20% of the total Loran receiver cost. For this reason a weighing function was selected such that costs above 20% are heavily penalized and costs below 10% are favored. A graph of the selection weighing function is given below:



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Performance - In addition to meeting the performance requirements in Section 3.7.2, the Antenna/ACU must remain functional when operated in a precipitation static environment. In rare instances extremely severe P-static conditions can render any radio receiver system unusable. It becomes necessary therefore to evaluate antenna performance primarily in terms of probabilities of encountering severe operating environments. The table below gives the criteria for evaluating Antenna alternatives based on cumulative probabilities of successfully acquiring and tracking Loran signals at the minimum signal strength level ($100 \mu\text{v/m}$).

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<u>Cumulative Probability</u>	<u>Performance Figure of Merit</u>
0 to 80%	0
0 to 90%	.1
0 to 95%	.3
0 to 99%	.7
0 to 99.9%	.9

The performance figure of merit is very heavily weighed in favor of the antenna alternative that provides maximum performance.

Development and Technology Risk - The development and technology risk is weighed according to the following complexity classifications:

<u>Complexity</u>	<u>Risk Figure of Merit</u>
New design, new technology, complex	.2
New design, new technology, simple	.4
New design, existing technology, complex	.5
New design, existing technology, simple	.6
Existing design and technology	.9

Reliability and Maintainability - The following matrix gives the reliability and maintainability figures of merit selected for this analysis. Reliability and maintainability are weighed approximately the same for a given level of complexity.

<u>Required Maintenance Level</u>			
<u>Hardware Complexity</u>	<u>Minimum</u>	<u>Moderate</u>	<u>High</u>
High	.4	.2	.1
Moderate	.7	.5	.2
Simple	.9	.7	.4

Functional Dependence on Other Systems - Some antenna systems require inputs from other aircraft systems to maintain required signal relationships based on alignment of the antenna pattern. Such functional dependence is penalized according to the following merit rating:

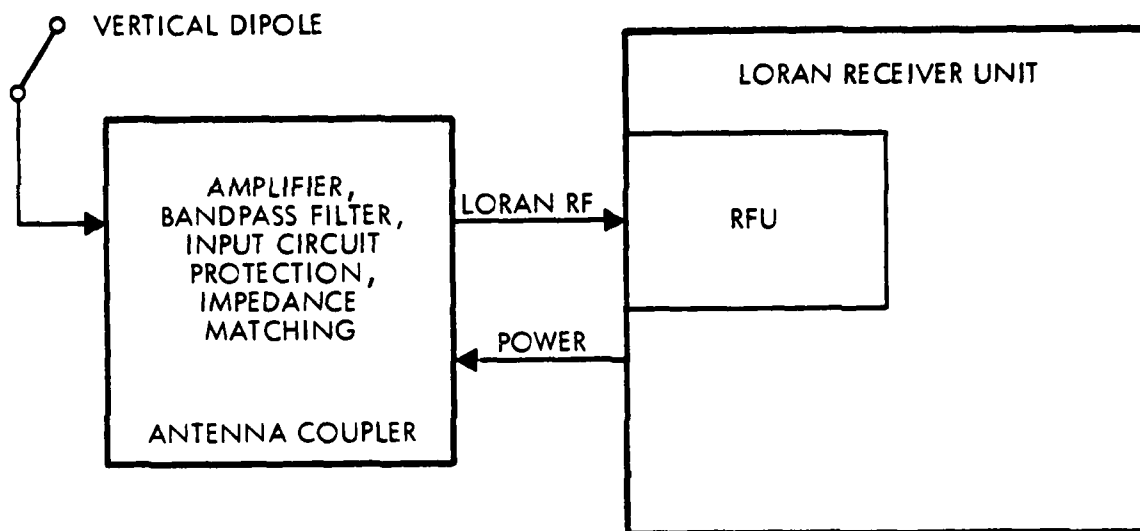
	<u>Figure of Merit</u>
● Antenna performance does not depend on other systems	.9
● Antenna performance depends on other systems already installed in most general aviation aircraft	.6
● Antenna performance depends on low cost systems not installed in most general aviation aircraft	.3
● Antenna performance depends on inertial grade instrument not installed in most general aviation aircraft	.1

Alternative Antenna/Antenna Coupler Configuration Considered

The Antenna/ACU alternatives considered in these tradeoff analyses are described below:

Alternate A: - Single E-field vertical dipole housed in a blade or fin type fiberglass shell. The Antenna Coupler circuits are made an integral part of the Antenna. The Antenna/ACU interfaces with the Loran Receiver as shown in Figure 3-12. The preferred mounting position of the antenna is on top of the aircraft's forward half of the fuselage.

Alternate B: - Dual balanced E-field dipoles of the same construction as Alternate A. One element is mounted above the fuselage while the other is mounted below it. Received Loran signals are combined additively as shown in the diagram of Figure 3-13.



T134683

Figure 3-12. Antenna/Antenna Coupler: Alternative A (Single E-Field Dipole)

Alternate C: - Two-axis H-field antenna. This antenna consists of two crossed loopstick elements that are aligned with the roll and pitch axes of the aircraft. Loop selection and commutation circuits as well as the front end signal processing functions are implemented in the Loran receiver. This Antenna/ACU configuration requires the selection and commutation of the appropriate loop elements so that the correct signal phase is maintained in real time for each Loran pulse group. An externally supplied aircraft heading reference is required to provide the basis on which loop selection and commutation must be accomplished. A block diagram of the Antenna to Loran receiver interface is given in Figure 3-14.

Alternate D: - Three-axis H-field antenna. This configuration is similar to Alternate C except that three orthogonally positioned loopstick elements are used to provide all-attitude signal reception capability. Externally supplied aircraft roll, pitch and heading inputs are required.

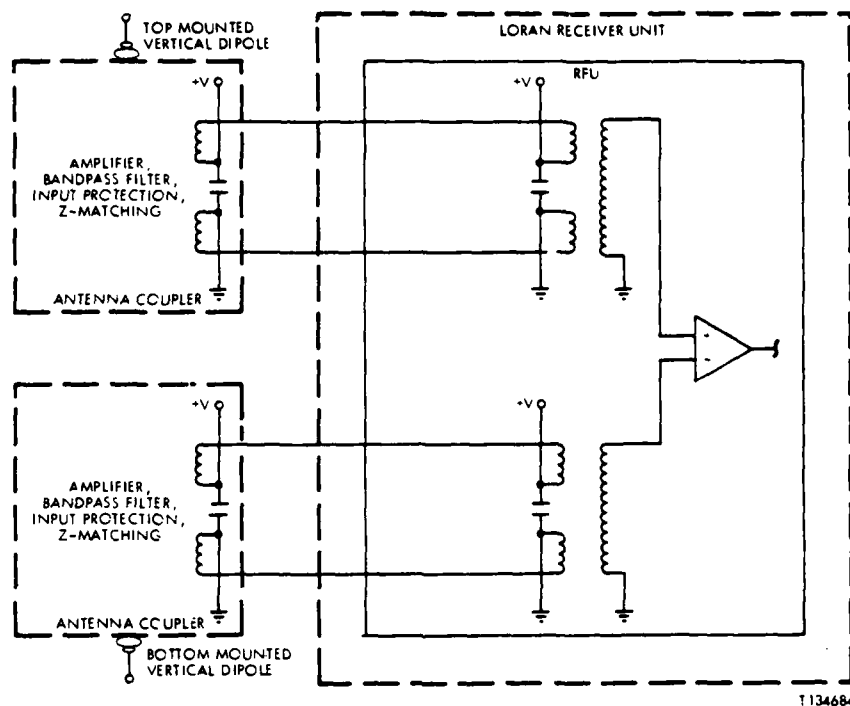


Figure 3-13. Antenna/Antenna Coupler: Alternate B
(Two Element Balanced E-Field)

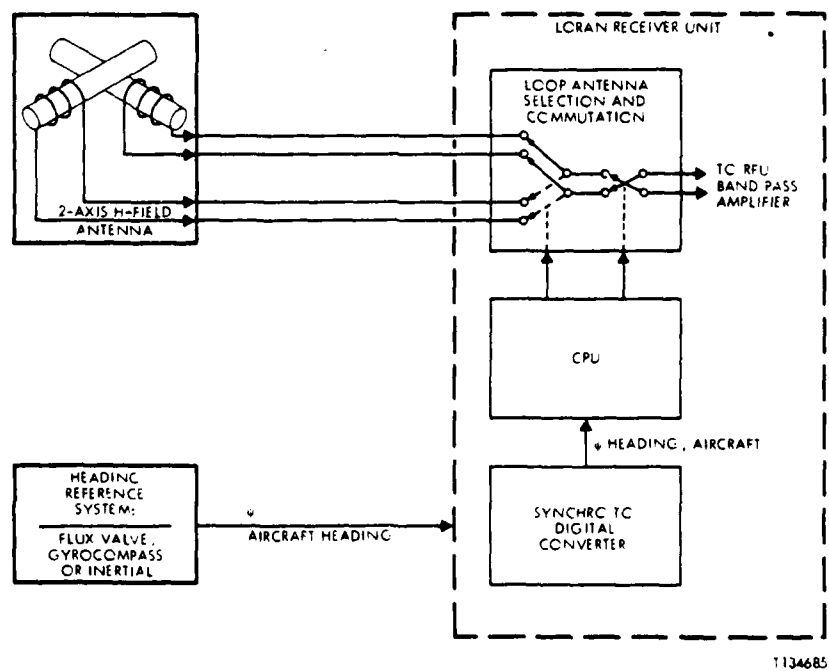


Figure 3-14. Antenna/Antenna Coupler: Alternative C
(H-Field Antenna)

Alternate E: - Longwire E-field Antenna. This antenna consists of a single wire element installed between two or more convenient locations on the aircraft's vertical stabilizer and the fuselage. A lead-in wire connects the antenna to the antenna coupler via an insulated feedthrough.

3.7.4 Analysis

Screening of Alternatives to eliminate those that fail to meet minimum requirements.

Alternative E, the Longwire Antenna, is rejected because it does not provide an essentially omnidirectional antenna pattern. The antenna pattern is highly dependent on the installation which varies from aircraft to aircraft. In addition, longwire antennas perform poorly under P-static conditions, are difficult to protect from lightning strikes and do not offer performance advantages over other low cost antennas such as Alternative A.

Detailed Analysis of Alternative A: - The single E-field dipole.

Cost Analysis - The mechanical and electrical design of the Antenna/ACU will be very similar to the TDL-418 antenna (P/N 8015263) in production at Teledyne. The mechanical housing will be improved to provide lightning protection and a low resistivity coating for the purpose of leaking off triboelectric charges. The detailed cost breakdown for this Antenna/ACU and yields a total cost of \$25.00 each. This cost translates into a figure of merit of .9.

Performance Analysis - The single E-field dipole antenna meets all the performance requirements of Paragraph 3.7.2 except that of P-static immunity.

The worst-case corona noise field calculated for general aviation aircraft, based on charging experiments performed on KC135 aircraft¹, is approximately 400 millivolts/meter. The following worst case assumptions are made to arrive at this solution:

- | | |
|--------------------|---------------------------|
| a. Aircraft Speed: | 250 kts max |
| b. Altitude: | 15,000 meters (50,000 ft) |

¹ R. L. Tanner and J. E. Nanevich, "Precipitation Charging and Corona Generated Interference in Aircraft," Technical Report 73, SRI Project 2494, Contract AF19(604)-3458, Stanford Research Institute, Menlo Park, California (April 1961).

- c. Aircraft frontal area scale 0.36 max.
factor relative to KC135:
- d. Noise field coupling scale 1.0
factor relative to KC135:
- e. Environment: Worst Case Stratocumulus
- f. Probability of $P \leq .0001$
encountering worst
case weather conditions:
- 7. Corona discharge None
control techniques
applied to aircraft:

A general aviation aircraft, which has been outfitted with effective P-static and streamer reduction devices as specified in Paragraph 3.7.2, will provide a minimum noise field attenuation of -40 dB. This still yields a worst case noise field of 4 millivolts/meter at the antenna. In order for the receiver to remain functional (assuming a -10 dB minimum SNR search capability), an 1300 μV /meter signal strength level is required. This value places an excessive restriction on the size of the feasible operating area.

Since acceptable operation under worst case conditions is not feasible, a less severe environment must be considered. Aircraft changing experiments show that changing rates one tenth of worst case occur with a probability of about 1% and are less than one thousandth of worst case 95% of the time. Since noise fields are proportional to the square root of the changing current ratios, the noise fields for these probabilities can be calculated as follows:

- a. Worst case reference = 4 MV/meter @ $P \leq .0001$
- b. For $P \leq .01$: $\sqrt{.1} (4 \text{ MV/meter}) = 1.26 \text{ MV/meter}$
- c. For $P \leq .05$: $\sqrt{.001} (4 \text{ MV/meter}) = 126 \mu\text{V/meter}$

The corresponding minimum signal strength levels required for signal acquisition at -10 dB SNR are:

- | | |
|--------------------------------------|--------------------|
| a. Acquire up to 99.99% of the time: | 1300 μ V/meter |
| b. Acquire up to 99% of the time: | 400 μ V/meter |
| c. Acquire up to 95% of the time: | 40 μ V/meter |

From this analysis it is clear that the single E-field dipole antenna provides acceptable performance only about 95% of the time for the minimum field strength level of 160 μ V/meter. The corresponding figure of merit for this performance category therefore is 0.3.

Development and Technology Risk - The E-field dipole antenna and ACU present virtually no development or technology risk because units with very similar characteristics to this requirement have been in production for several years. Improvements can be made to the mechanical design to provide a better aerodynamic shape, lightning strike immunity and a low conductivity surface. These improvements involve minimal risk and require only the application of well known principles and technology. The appropriate risk figure of merit for this Antenna/ACU is therefore 0.9.

Reliability and Maintainability - The simple hardware complexity of this dipole Antenna/ACU, combined with minimal maintenance requirements, justify the assignment of a 0.9 figure of merit in this category.

Functional Dependence on Other Systems - Vertically mounted E-field dipole antennas have an essentially omnidirectional pattern in the horizontal plane within the specified attitude constraints of the aircraft. No external system inputs are therefore required, and the appropriate figure of merit is 0.9.

Detailed Analysis of Alternative B: - Dual Balanced E-field dipoles.

Cost Analysis - This Antenna/ACU configuration consists of two each Alternative A antennas plus a relatively simple signal mixing circuit in the receiver. The total cost of Alternative B is therefore \$58.00 each (factory cost) as presented in Section 6. The figure of merit for this cost is 0.8.

Performance Analysis - The principle behind the balanced antenna scheme is to provide signal cancelling for noise generated from point sources in the vicinity of the aircraft. The antenna elements are installed on the fuselage top and bottom so that noise fields emanating from the orthodecoupled discharges are equa-distant from each antenna element. Nearly equal noise coupling to each element is readily achieved and provides at least -20 dB of corona noise reduction with respect to a single element dipole.²

The minimum signal strength levels calculated in Paragraph 3.7.2 for the single dipole can be reduced by 20 dB to provide the following signal acquisition probabilities:

- a. Acquire up to 99.99% of the time: .25 $\mu\text{v}/\text{Meter}$
- b. Acquire up to 99% of the time: .40 $\mu\text{v}/\text{Meter}$

At the 100 $\mu\text{v}/\text{meter}$ minimum field strength level specified, Alternative B allows normal signal acquisition approximately 99% of the time. The corresponding performance figure of merit is 0.7.

Development and Technology Risk - Since each of the dual balanced dipoles is identical to the single dipole evaluated previously, the development and technology risk is the same as for Alternative A. The appropriate low risk figure of merit is 0.9.

Reliability and Maintainability - The simple hardware complexity and minimal maintenance requirement result in selecting a 0.9 figure of merit.

Functional Dependence on Other Systems - This alternative requires no external system inputs for the same reason given for Alternative A. The figure of merit here is also 0.9.

Detailed Analysis of Alternative C: The two-axis H-field antenna.

² J. E. Nanevics and E. F. Vance, "Precipitation Static Noise in the Loran Antennas of the GBU-15" Stanford Research Institute, Menlo Park, CA., Final Report, SRI Project 7368; July 1978.

Cost Analysis - Alternative C includes the antenna housing containing the crossed loop elements as a separate assembly and the following hardware in the Loran receiver:

- Antenna selection and commutation circuits
- Bandpass amplifier
- Input circuit protection
- Heading reference data converter
- Microprocessor interface circuits.

A detailed cost breakdown yields a total cost of \$600.00 each and results in a cost figure of merit of 0.4.

Performance Analysis - This H-field antenna meets all performance requirements in Section 3.7.2, including immunity to P-static. The P-static performance superiority of H-field antennas over E-field antennas is well known and has been demonstrated with the operational military AN/ARN-101 Loran Navigation System. Standard corona discharge control techniques applied to the aircraft will allow the H-field antenna equipped Loran receiver to successfully acquire and track minimum level signals for all but the worst case P-static conditions. Such worst case weather conditions occur with a probability of less than 0.0001. The highest performance figure of merit is selected for this antenna.

Development and Technology Risk - Since Loran-C H-field antennas are currently used very successfully in military applications, the new development effort consists primarily of transferring this technology to this commercial application. A complete development cycle from design through prototype testing will nevertheless be required, and will present some risk with respect to the manpower and schedule constraints given in Paragraph 3.7.2. A figure of merit of 0.6 is assigned to this risk.

Reliability and Maintainability - A 0.9 figure of merit is appropriate for this configuration because the hardware is simple and requires very little maintenance.

Functional Dependence on Other Systems - The crossed loop H-field antenna requires an external heading reference input to 1) select the best loop for optimum signal reception and 2) to select the desired phase of a given Loran signal. A low cost heading reference, such as a flux valve, will suffice providing that the antenna is constrained to operate within the specified 45° roll and 30° pitch attitude limits. Because most general aviation aircraft are not provided with heading reference systems that have a suitable electrical output, the low figure of merit of 0.3 is assigned to this criterion.

Detailed Analysis of Alternative D: The three-axis H-field antenna.

This alternative provides little advantage over Alternative D so long as aircraft attitudes are restricted to 45° in roll and 30° in pitch as assumed in Paragraph 3.7.2. Alternative D is included in this analysis primarily for the purpose of comparing an all-attitude H-field antenna with other alternatives. Such comparison is valuable because the cost and functional dependence evaluations for Alternative D also apply to sometimes proposed H-field antenna systems that employ signal delay and add techniques to eliminate loop selection and commutation functions at the expense of requiring precision attitude inputs.

Cost Analysis - Alternative D is similar to Alternative C except that the Antenna housing contains three orthogonally positioned loops and roll and pitch inputs are required. A detailed cost breakdown yields a total cost of \$750.00 each. The corresponding cost figure of merit is 0.2.

Performance Analysis - The performance analysis is the same as for Alternative C. The performance figure of merit is 0.9.

Development and Technology Risk - This risk is the same as for Alternative C. The risk figure of merit is 0.6.

Reliability and Maintainability - Alternative D falls in the simple hardware category and requires minimal maintenance. The figure of merit is 0.9.

Functional Dependence on Other Systems - For an all-attitude loop antenna system the Loran receiver requires antenna roll, pitch and heading inputs from

an external source in order to perform optimum loop selection and signal commutation. Attitude reference systems that provide electrical outputs are not generally standard equipment in most general aviation aircraft. The cost of installing an appropriate attitude reference system is likely to be prohibitive for general aviation. The lowest figure of merit is therefore assigned to this alternative.

3.7.5 Trade-off Evaluations

Table 3-7 summarizes the results of the tradeoff evaluations for each alternative considered. The alternative with the highest average figure of merit is considered to be the most cost effective - that is Alternative B, the dual balanced E-field dipoles.

Table 3-7. Figure of Unit Summary for All Antenna/ACU Alternatives Evaluate

Alternative: Criteria	A	B	C	D
(1) Cost	.9	.8	.4	.2
(2) Performance	.3	.7	.9	.9
(3) Risk	.9	.9	.6	.6
(4) Reliability & Maintainability	.9	.9	.9	.9
(5) Functional Independence	.9	.9	.3	.1
	3.9	4.2	3.1	2.7
Mean Figure of Merit	.78	.84	.62	.54

3.7.6 Selection Summary

Both H-field antennas are clearly superior to E-field alternatives in terms of performance under high precipitation static conditions. This advantage however is more than offset by their higher cost, higher risk and dependence on external system inputs.

Although the dual element balanced E-field Antenna/ACU is approximately twice as costly as the single element alternative, its superior performance in severe weather conditions outweighed this cost disadvantage. The dual element balanced E-field Antenna/ACU therefore emerges as the recommended alternative.

(NOTE: The system design will enable operation from a single antenna, however, the system susceptibility to noise would be increased.)

3.7.7 Conclusion

Cost and performance under precipitation static conditions were the primary trade-off parameters in choosing between E and H-field alternatives. Both H-field antennas were eliminated on the basis of high cost and functional dependence on other systems. The dual element balanced E-field antenna was selected as the best alternative principally because it strikes the most reasonable balance between cost and performance.

3.8 LINEAR vs HARD-LIMITED RECEIVER

In a hard-limited receiver, the Loran pulse, after some analog pre-processing, is amplified and clipped to the point where only the instantaneous polarity of the RF waveform is preserved. Hard-limiting in the presence of strong noise gives an output from which information about the original signal amplitude can be inferred from a large number of samples.

Since all information about the envelope is lost after the RF channel is hard-limited, receivers of this type employ a second channel in which the processed pulse envelope has a null at a certain point. When this channel is hard-limited, the carrier peak having the minimum value averaged over a period of time, is used to identify the desired point on the envelope.

For a linear receiver, by contrast, amplification of the received pulse is used to bring it up to useable levels with minimum distortion. The complete pulse, envelope and carrier is preserved as much as possible and is available to the subsequent function which detect time of arrival.

Hard-limiting was applied to Loran receivers as a means of reducing component count and thus achieving cost, reliability, size and weight benefits. No performance gain over a linear receiver has ever been claimed, although hard-limited

receivers have come close under certain conditions. Performance compromises of hard-limited receivers have occurred in two areas:

- a. When synchronous CWI exceeds the Loran pulse in amplitude, an effect known as "dead-banding" occurs. This happens because the polarity of the signal plus interference is determined by the interference, not the signal. Attempts to detect this condition and drop certain pulses in the group have been only partially successful.
- b. Determination of the tracking pointing using the envelope channel is subject to errors caused by envelope-to-cycle discrepancy and requires an excessive integration time with signal-to-noise ratios which are more than adequate for phase tracking.

For the present application, the first of these is not considered to be a major weakness. It is assumed that if Loran-C is to be used for civil aviation, the receiver will be operating in a controlled environment having a controlled spectrum. Synchronous CWI (falling on one of the in-band Loran-C spectral lines) is simply assumed not to be permitted. Unintentional synchronous CWI would, however, constitute a hazard.

The second is a definite consideration since it is a critical item in determining the required signal environment; and therefore, station placement and transmitting power.

Historically, hard limiting provided measureable economies when receivers were constructed principally from analog and discrete logic components. Since amplitude information did not have to be preserved, the front end could accommodate very large dynamic ranges without elaborate automatic gain control. Further, the hard-limiting process inherently adjusts the tracking loop gain for changes in signal-to-noise ratio. Although not theoretically optimal, the gain changes were in the proper direction and eliminated the need for a computer algorithm to accomplish the same result.

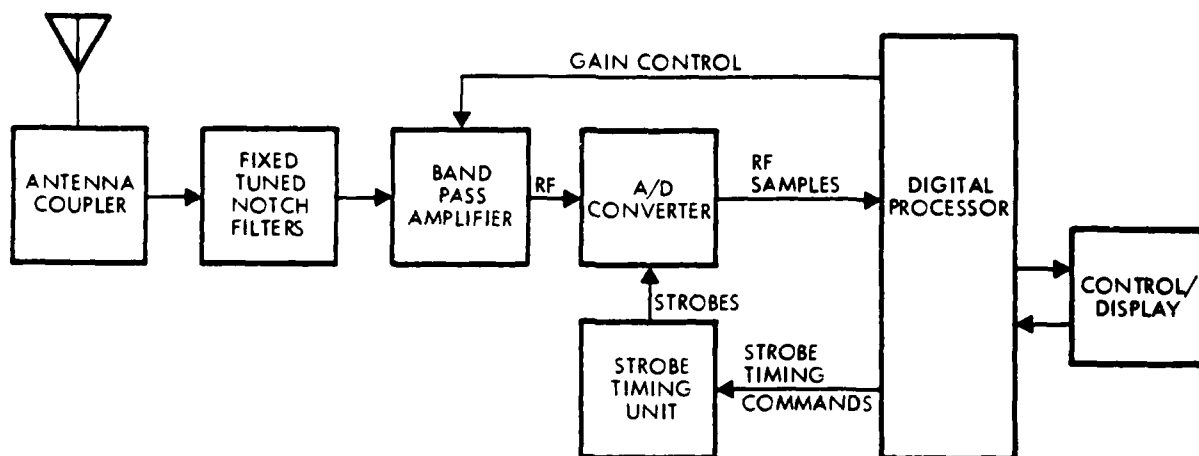
It will be shown, however, that previous relative economies are no longer applicable with current technology. The advent of microprocessors has significantly oriented trade-off decisions such as hard limited vs linear. The power of these devices is such that processes which were previously performed in external hardware (e.g., AGC) can now be handled in the computer with a modest increment of program memory and I/O capability.

3.8.1 Linear Receiver Design

While there are a multitude of approaches to the design of a linear receiver, a fair representative would be one which makes use of a powerful digital processor and minimizes the use of external analog and discrete logic units. Such an approach is shown in Figure 3-15, which attempts to detail those areas where the two types of receivers differ. Thus, for example, Control/Display is lumped into one box since it would not enter into the trade-off decision.

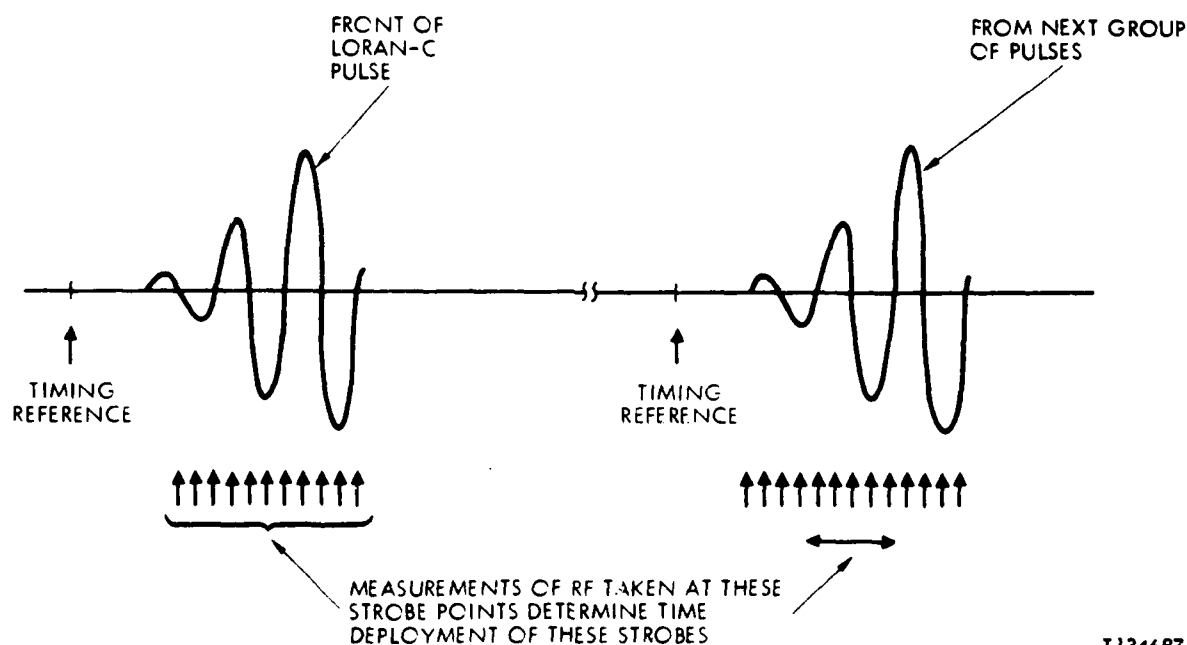
The basic operational philosophy of this design is that the digital processor commands a series of strobes to be generated relative to a fixed periodic reference. The commands to the strobe timing unit determine the pattern and overall timing which is adjustable to some increment. The strobes cause amplified samples of the received waveform to be converted to digital form and entered into the processor. As a result of an algorithm executed by the processor, new commands are issued for the next group of Loran pulses, which will reflect the timing adjustments based on this and previous measurements. Note, therefore, that this hardware configuration is applicable to all modes of the receiver (track, envelope, etc.); the particular mode being executed is determined solely by which software routine is called to adjust the deployment of this next group of strobes. Figure 3-16 illustrates this in more detail.

The Digital Processor block includes a microprocessor of the latest generation (16 bit, hardware multiply/divide) along with auxiliary LSI devices such as I/O ports, memory, interrupt control and DMA. The A/D converter is assumed to have a conversion time of 2.5 μ sec or less and 10 bits of resolution. The Strobe Timing Unit is a TTL random logic device which includes a timing source (~ 10 MHz) and is responsible for making the strobe timing adjustments



T134696

Figure 3-15. Linear Receiver Block Diagram



T134687

Figure 3-16. Linear Receiver Design. Strokes

AD-A104 921

TELEDYNE SYSTEMS CO NORTHridge CALIF F/6 17/7
DESIGN STUDY REPORT FOR GENERAL AVIATION LORAN-C RECEIVER.(U)
MAY 81 H L WALKER, R ELLERBE DT-FAU1-80-C-10108

UNCLASSIFIED

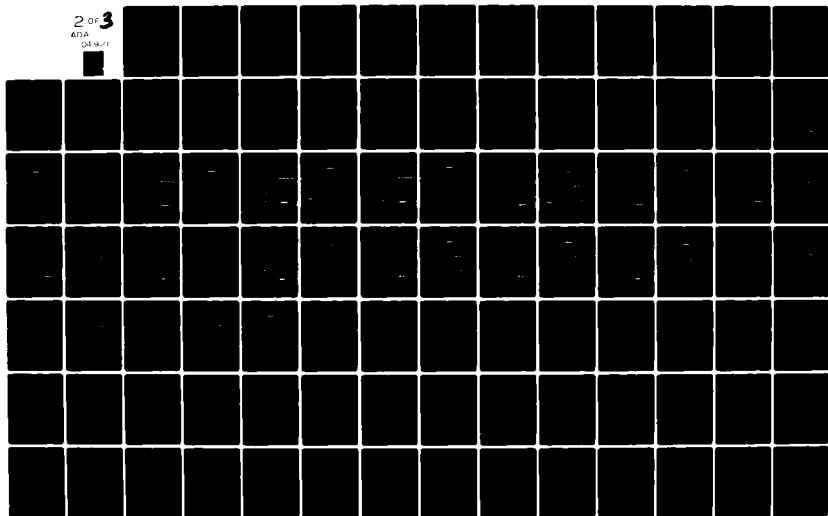
FAA/RD-81/36

NL

2 of 3

411A

019-71



commanded by the processor. The Band Pass Amplifier has adjustable gain to accommodate dynamic range, with the gain being set by the processor. It has a fixed bandwidth of 20 KHz.

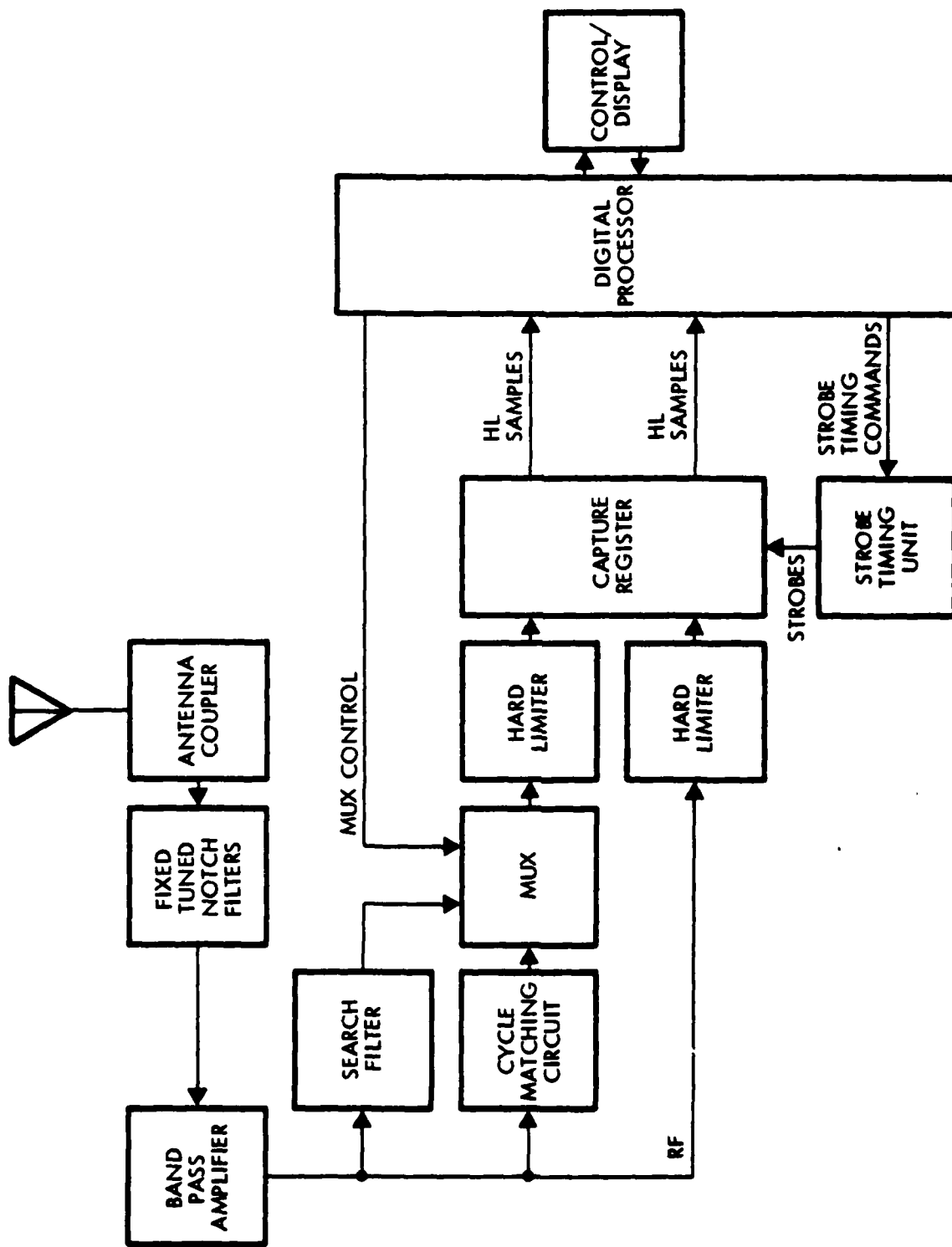
Absent from the diagram is the traditional search filter of typically 4 KHz bandwidth. Its functions are performed in software by digitally filtering samples taken from the 20 KHz filter during the search mode.

3.8.2 Hard-Limited Receiver Design

While again there are numerous designs of hard-limited receivers, a fair comparison requires that the representative approach perform all functions possible in a digital processor with minimal use of special purpose hardware. It will be seen that this is possible but to a lesser extent than in the linear case because the hard-limiter loses some of the signal content before it gets to the processor.

Figure 3-17 shows a typical hard-limited design oriented around the digital processor. The basic philosophy is the same as for the linear receiver in that the processor will command strobes to be deployed, input measured values taken at the strobe point, and determine timing adjustment for the next group of strobes. Several differences are apparent, however, in the hardware configuration of the two receivers:

- a. The hard-limited design does not employ an A/D converter. Instead, the strobes enable a capture register which latches the one-bit measurements.
- b. Because amplitude information is lost, the search filter must be mechanized as an analog device before the hard limiter. An analog multiplexer is used to select 20 Kc or 4 Kc data.
- c. Again, because the amplitude is not quantized, envelope detection must be performed in analog circuits prior to the hard limiter.
- d. No automatic gain control is required in the processor.



T134688

Figure 3-17. Hard-Limited Receiver Block Diagram

3.8.3 Cost/Performance Trade-off

Cost estimates for the two receiver designs have been made for comparative purposes. The basis for these estimates is as follows:

- a. Individual blocks have an estimated parts cost including pro-rated printed circuit card area.
- b. The receivers being estimated are for use in general aviation and business aircraft. It is assumed that these units are purchased through a dealer network. Special interface requirements, special reliability demonstrations, and special warranty provisions are not included.

The cost analysis is given in Section 6. It is seen that the cost comparison is very close. Items which have the same function in each receiver but differ in cost are explained as follows:

Bandpass Amplifier:	Lower cost in hard-limited receiver because gain control not required.
Power Supply	Higher cost in hard-limited receiver due to higher component count.
Housing	
Labor	

Other items of cost difference were impossible to resolve. For example, it might be argued that the processing of hard-limited data is mathematically simpler than that for linear data, and therefore a less expensive processor could be employed. On the other hand, the computational load on a processor is more affected by data rates and the number of tasks to be performed than by mathematical complexity. Further, the cost difference in microprocessors presently available is relatively small.

A performance trade-off between the two types of receiver is not necessary since the linear receiver will necessarily have performance at least equal to that of the hard limited receiver. If the reverse were true, the linear receiver could be programmed to look only at the sign bits of the strobed measurements, and it would

in effect become a hard-limiter receiver. Therefore, the result is inconclusive; the linear receiver costs virtually the same as its hard limited counterpart and they are equally capable of meeting the performance requirements.

3.9 INTERFERENCE FILTERS

3.9.1 Requirements

Within the U.S. the Loran band is free of interference; however, there are many adjacent band communication and navigation services both above and below 100 KHz. In some parts of the country, the field strength of some of these broadcasts can approach and surpass that of the meaningful Loran-C coverage. Since the sought navigation system performance is national in breadth, the receiver needs interference rejection means which will be effective everywhere in the NAS and not just in specific locales.

3.9.2 Design Concepts

Since the interferences are all in adjacent bands and there are only a few of significant power, a set of fixed tuned notches coupled with a steep skirt bandpass response is a simple and effective candidate. In particular, one notch on 88 KHz to reject the Naval Communication Station at Annapolis, MD and another at 115.3 KHz to reject the broadcast from Nova Scotia will suffice in concert with bandpass roll off which rejects all the stronger signals farther out. The bandpass would need to be narrower than the standard 23 to 25 KHz; i.e., 20-22 KHz. The narrower bandpass means that the close-in skywave rejection of the receiver is slightly degraded. Specifically, skywave appearing before the fifth cycle of the groundwave may be a problem. Such close-in skywave will not arise with the anticipated coverage diversification over the NAS and is only seen over sea water paths extending well over 1000 NM. The fixed-tuned approach has obvious cost advantages.

Automatic notch filters are another candidate and there are many ways to design such filters. None of these design methods yield a product as inexpensive as a fixed tuned notch. Automatic placement of notches as needed by the observed interference environment does permit a wider bandpass response. A generous

battery of such notches permits the bandpass roll off to be slow, thereby, maximizing the close-in skywave rejection performance of the receiver. Cost is reduced monotonically as the number of notches is decreased; i.e., steep bandpass response is comparatively cheap. The typical production parts cost of an automatic notch filter is \$80 not counting the interference detection function. A steep skirt bandpass filter costs less than \$20. Since there is no real benefit derived from being conservative in shaping the Loran spectrum, automatic notch filters of any kind are not attractive.

Linear phase detection does afford an opportunity to cancel or suppress interfering carriers after detection. Given that the sample conversion width is enough to resolve the Loran-C carrier buried in interference and that the Phase lock loop (PLL) bandwidth can be made very small, a linear receiver can reject coherent interference without losing signal power. The major drawbacks are the cost of the conversion device and the sluggish tracking performance. With a 10 bit converter and realistic PLL bandwidths in the absence of velocity aid, post-detection suppression can handle interferers only up to 6-8 dB stronger than the Loran carrier at the sample point. There is no such suppression in search mode. Annapolis and Nova Scotia will routinely exceed that limit in some areas of the Eastern seaboard; consequently, hardware filters are still required. The linear receiver does permit a slower roll off than its hard limited counterpart since it can better tolerate low level interference. There is potential then for better close-in skywave rejection in the linear set but little benefit in terms of real operational capability.

3.9.3 Summary

Automatic notch filters are both too costly and not necessary. It is concluded that the rejection of close-in skywave is not operationally critical and that a fixed tuned front end is workable and very economical. The receiver will have one notch on either side of band center to reject prominent fixed communications services and a steep skirt bandpass response. Linear detection will provide moderate but inconsequential rejection of interference not attainable with hard limiting.

3.10 PROCESSOR SELECTION

3.10.1 Requirements

The processing requirements for both linear and hard limited receivers have been analyzed in the light of the results of several other trade studies. The secondary phase prediction task, dual chain operation, flight guidance techniques and interference control have been accounted for in the processing requirements. Table 3-8 summarizes the instruction load and memory size demanded by both the linear and hard limited receiver versions of the navigation system. The instruction mix is not exact in that register to memory operations are accounted for by combinations of load/store instructions and arithmetic/logical instructions. The mix is representative of the machine load for a wide variety of candidate devices. Only centralized, 16 bit processor configurations are considered since it is clear from the mix that 8 bit systems in any form are not as promising as some of the 16 bit candidates.

3.10.2 Processor Comparison

Five machines have been compared against the instruction mix using each manufacturer's performance specifications. A comparison matrix is shown in Table 3-9. There are wide variations in architecture across the field. The features of each have been extensively presented and analyzed in the trade journals. An important common property of all five is the ability to do 16 bit arithmetic in hardware. The TMS 9900 does not do signed multiply in hardware. The Motorola 68000 is alone in having 32 bit registers. Of special note is the Intel 8088 which has 16 bit internal data paths but external data paths that are 8 bits wide, making it easier to interface than the other four. Otherwise the Intel 8088 is identical to the Intel 8086, its all-16 bit sister.

The comparison matrix shows the TI part not meeting the throughput requirements for either receiver but the other four candidates meeting both linear and hard limited receiver version throughput requirements. It appears that the Motorola part is an overkill. Based on the throughput analysis and the price, the Intel 8088 is an excellent choice for either receiver. The prices of Intel and Zilog parts will approach that of the TMS 9900 as production increases in the next 2-3 years. The TI part has already reached production maturity. It is expected

**Table 3-8. Minimum 16 Bit Machine Performance Instruction Mix,
And Memory Size**

Operation	Linear Receiver	Hard Limited Receiver
16 bit add RR	25 Kops	17 Kops
32 bit add RR	2.5	2.5
16 bit signal mult. RR	15	9
32 bit signal mult. RR	0.75	.75
16 bit logical R	8	5
1 bit shift R	8	7.5
4 bit shift R	3.3	5
16 bit load/store	58	46
Test and Branch R	45	38
Memory Size		
ROM	27K Bytes	25K Bytes
RAM	4.5	4
RR = Reg. to Reg. R = Reg.		

Table 3-9. Performance Comparison Matrix

		Throughput Margin		
Candidate CPU		Linear Receiver	Hard Limited Receiver	Price For 100 Units
TI	TMS 9900 3 MHz	-48%	-13%	\$ 26.00 ea.
Zilog	Z8002 4 MHz	39%	54%	105.00 ea.
Intel	8086 5 MHz	42%	53%	70.00 ea.
Intel	8088 5 MHz	29%	42%	31.00 ea.
Motorola	68000 8 MHz	61%	69%	250.00 ea.

that when the Intel 8088 reaches optimum production, its price will be competitive with the prevailing crop of 8 bit devices. The rapid advances being made in semiconductor device processing definitely are making 16 bit devices attractive from a "throughput per dollar" point of view. All candidates can handle the memory size without memory expansion devices.

3.10.3 Summary

The processing requirements have been analyzed and reduced to the form of an instruction mix. Systems with linear and hard limited receivers were treated separately. The most popular 16 bit processors were surveyed and the Intel 8088 was selected. This device looks like an 8 bit device to the other parts of the system but enjoys the advanced architecture and performance of a 16 bit machine. This part was the least expensive processor which was found to have adequate throughput. It was noted that the device was recently introduced and will drop in price in the next 2-3 years to become nearly as inexpensive as most 8 bit parts.

SECTION 4

RECEIVER PERFORMANCE CRITERIA

4.1 SIGNAL RECEPTION

4.1.1 Receiver Sensitivity

The receiver sensitivity requirement may be inferred by examining the lowest noise environment which can reasonably be expected. At this low noise level, a signal of sufficient strength to meet the SNR requirements must be detectable by the front end.

In general, the total noise environment would consist of atmospheric noise, thermal noise, and receiver noise. However, at the frequency of interest, atmospheric noise is dominant and the others will be neglected. This is a conservative decision in that it tends toward over design rather than under design. If, for example, thermal noise power approached that of atmospheric noise, then the receiver would be capable of detecting a signal which would actually be buried in this noise level.

Atmospheric noise in the LF band varies with geographic location, season, time of day, and weather conditions. In general, it tends to be highest in the tropical zones, highest during the months having tropical storms, and greater during the day than at night. Available data concerning atmospheric noise in terms useful for Loran analysis have been described in the literature. A choice of 50 dB(1 μ V/m) is a reasonable lower limit to the noise level which can be expected. This limit excludes rare quiet night conditions. Tracking is accomplished at a minimum SNR of -10 dB, so the receiver must detect a minimum field strength of 40 dB (1 μ V/m). Assuming use of a dual E-field antenna having 8 inch (= .22 meter) effective height, the minimum detectable signal level should be

$$(.22) (100 \mu V) = 22 \mu V$$

4.1.2 Dynamic Range

Dynamic range is the ratio of the largest signal which the receiver is required to accept (and process correctly) to the smallest signal which it is required to detect.

Conventionally, dynamic range is given as a relative value without reference to a particular signal level. It is more useful however, to specify the maximum and minimum levels directly in absolute field strength; dynamic range then becomes a computable parameter rather than a specified quantity.

The minimum distinguishable signal level is simply the receiver sensitivity, which for the antenna being used gives a field strength of 40 dB ($1\mu\text{v/m}$) as described in the previous section. Maximum signal level will be encountered in the immediate vicinity of a transmitter where several factors make it necessary to assume a minimum operating distance. These include grid warpage due to near field effects and rapid changes of the vehicle velocity vector relative to the transmitter. It will be assumed therefore that the receiver will never operate within 10 nm of a transmitter.

Much data has been published giving the Loran-C field strength as a function of distance from the transmitter. For all the terrains considered, with 100 KW radiated power (at the sampling point) the field strength at 10 NM is 105 dB ($1\mu\text{v/m}$). This value can then be adjusted for the power levels of typical transmitters which might be employed in an air navigation grid. The largest dynamic range (80 dB) is required if the transmitter has a peak power output of 3.0 MW. This is the ratio of the largest signal encountered (120 dB ($1\mu\text{v/m}$)) to the receiver sensitivity level (40 dB ($1\mu\text{v/m}$)).

4.1.3 Signal Acquisition Time and Cross Chain Transition

After turn on, a Loran-C receiver proceeds through several phases of signal acquisition before it can present valid position data to the operator or navigation system. The exact nature of these processes varies with the receiver design, but for present purposes signal acquisition time will be taken as the time from power on to the point at which the receiver is operating in its highest mode. This means that all stations intended for tracking are being tracked, and all cycle matching or envelope processing is complete. Tracked stations may include members of different chains operating on different rates.

The value adopted for the signal acquisition time requirement is that specified in RTCM DO-159, namely 450 sec. This time would not be acceptable for cross chain switchover; however, in view of the dual tracking capability recommended for cross chain operation, this acquisition time is a pre-flight, rather than in-flight procedure.

Cross chain transition should be invisible to the operator; in this sense, the transition time is zero. This is in keeping with the broader philosophy that the system should automatically provide the best navigational data possible at all times. Barring malfunction of equipment, the operator should not have the responsibility of selecting the data source, determining which processing algorithm is to be used, etc.

4.1.4 Interference Rejection

Interference consists of those elements of the signal environment other than noise which detract from receiver performance. Common sources of interference are crossing rate signals, near or in-band CW signals and long delayed skywaves.

CW interference has been a historic problem in certain areas of the world where very strong, very narrowband transmissions are permitted in the Loran band. Non-synchronous CWI does not introduce bias effects but appears as a large noise source. It has been large enough to cause saturation in receivers which otherwise have sufficient dynamic range to handle the largest expected Loran signal. Synchronous CWI also introduces a bias into the phase measurement. Attempts have been made to detect this phenomenon by sampling the dead time when no signal should be present. If synchronous CWI is found, some receivers will discard measurements made on certain pulses which essentially drops certain of the spectral lines to which the receiver is sensitive. The result is operation with degraded performance.

If Loran-C is to be used for civil aviation, it is assumed that in band CWI will not be present and that none of these measures need be taken. There is, however, the possibility that certain CW signals just outside the band may cause problems in parts of the service area. For this reason, 2 fixed tuned notch filters having 40 dB or more CW rejection should be employed in the front end. These filters will be fixed to the specific frequencies in question, and will not be swept across the band.

Long delayed skywave is again a dynamic range problem. For a linear receiver, the Loran phase code is designed such that extension of one pulse into the next will cancel out over a period of time. It is assumed that the maximum operating distances from the transmitters will be such that skywave amplitude will not reach saturation levels.

4.2

SIGNAL PROCESSING

Signal Processing refers to the digital algorithms which are performed on the RF Waveform samples of the received pulse. The ultimate objective of such processing is to measure pulse time of arrival, either with respect to a common time reference (rho-rho), or with respect to a pulse transmittal from another station (hyperbolic).

4.2.1

Phase Tracking

The phase lock loop of classical receivers provided the high resolution measurement of time of arrival, after it was placed on the proper cycle of the pulse. This type of processing can now be performed in software and should yield the identical accuracy characteristics, being subject to the same mathematical equations. Resolution, however, is now determined only by processor word length, not the clock period of high speed timing circuits.

The classical second order loop used in Loran-C will show a zero steady-state error under constant velocity (ramp input) and a constant steady-state lag for constant acceleration. In the latter case, the acceleration must not exceed the point of which the loop is pulled out of its linear operating region. Phase tracking always involves a trade-off between the ability to follow aircraft dynamics (high g) and the ability to smooth measurement noise (phase jitter). Because excessive jitter can cause cycle slippage even in a stationary vehicle, it has become customary to specify it at the 3σ level.

An acceptable level of phase jitter is one which: a) enables the receiver to meet stated accuracy criteria, and b) presents a sufficiently small probability of cycle slippage during maximum acceleration. A typical value for maximum phase jitter would be 250 nsec. (= 9 degrees at 100 kc.). This coupled with a maximum of 250 nsec acceleration lag at 2g would set a reasonable criterion for receiver performance in this area.

The above conditions do not assume velocity aiding from an external source. It has become common in more recent receivers to track the peak of the total pulse (groundwave and skywave) in addition to the sampling point; velocity from the second loop is then used to rate aid the first. While this feature has certain attractions (velocity aid is already in the proper coordinate frame), it cannot be counted upon to universally provide the results which have sometimes been attainable.

This is because a large skywave component (which can be over 30 dB above the groundwave), is not always present. The second loop would then track at the peak of the groundwave giving on a 3 dB improvement in SNR.

4.2.2 Cycle Identification

Cycle Identification is the process which tells the phase lock loop which cycle to track. It has historically been a more difficult process than phase tracking and has been less reliable.

The criterion for cycle identification is generally stated as the probability of choosing the correct cycle after a specified integration time. For typical receiver specifications, this would be 99% over a ten minute interval.

Recent receivers have performed cycle identification digitally, and, while showing some improvement over analog methods, have not solved problems of pulse shape variation, envelope to cycle, discrepancy, and susceptibility to interference without self alignment provisions. There is no reason to assume that the state-of-the-art can be greatly advanced in this area. A more fruitful approach would be to track more than three Loran stations and require consistency among derived positions as an aid to cycle identification. The receiver performance criterion, then, is not cycle identification per se, but is overall positional accuracy based on all available data.

4.3 NAVIGATION

The navigation performance required of the Loran Navigation System and the methods to be employed to achieve the required levels of performance are discussed in this section. The following topics are discussed:

- Signal Propagation Correction Method
- Position Determination Accuracy
- Receiver Performance after Signal Loss
- Information Update Rates
- Navigation Parameter Accuracy and Resolution
- Recognition and Warning of Unacceptable Condition or Performance
- Capability to Use Differential Corrections

All navigation information is derived from the processed Loran signals and the previously stored data defining Loran transmitter locations, signal propagation effects, waypoints, and desired flight conditions. Only Loran signal data are used for navigation in that no other velocity, position, or heading data are required by the system.

4.3.1 Signal Propagation Correction Method

In many areas of Loran coverage the signal propagation anomalies are large enough to prevent the system from achieving the required navigational accuracy unless a correction is applied for the propagation anomalies. Therefore, it is not a question of whether or not to apply the corrections but one of selecting the best method to use in applying the corrections. The trade-off analysis of section 3.4 examined several candidate methods and concluded one based upon a prestored correction map of waypoints distributed throughout CONUS offered the best solution.

The essential features of the selected correction method are:

- A table of correction values for all of CONUS is stored in the computer.
- Correction values are for the same locations used for navigational reference.
- Corrections are based upon previously collected time difference measurements and correct for the differences between measured time of arrival of the signal compared to theoretical values.
- Propagation anomaly corrections are applied to all received signals.

4.3.2 Position Determination Accuracy

The expected position determination accuracy of the Loran Navigation System has been evaluated based upon the various conditions under which the system is expected to operate. Since there are many factors effecting position accuracy, a single accuracy number cannot be stated for the system. Teledyne has developed a Loran

Coverage Program which analyzes the position accuracy of the system and displays the results in the form of an accuracy plot that shows position accuracy as a function of location within the Loran coverage area.

The Loran Coverage Program has been used to compute the position accuracy of the system under various signal, noise, geometry, and receiver conditions. In all cases, the computations are based upon use of existing CONUS Loran chains rather than the presumed signal coverage conditions which would be available in the future. This was done for the following two reasons:

- First, the position determination accuracy of the Loran Navigation System can be established using existing signal coverage conditions.
- Second, the exact Loran station placements that would be used to provide redundant signal coverage throughout the USA have not been established.

4.3.2.1 General - The position accuracy is determined by the following factors:

a. Loran Transmitter "Chain" Characteristics

- Transmitter Locations
- Transmitter Power
- Transmitter Timing Stability

b. Receiver Characteristic

- Noise induced time of arrival (TOA) variance
- Quantization
- Resolution
- Differential amplitude error
- Clock Error
- Mechanization (see geometry considerations)

c. Geometry Considerations

- Receiver position relative to the transmitters
- Mechanizations (single triad, multitriad, master independent, cross chain, direct ranging)

d. Terrain

- Conductivity along the signal path and its effect on signal to noise ratio (SNR)
- Secondary Propagation error as effected by signal path
- Range errors due to aircraft elevation

e. Interferences

- Cross chain interference
- Skywave interference

The following is a short discussion concerning the above factors.

- a. Loran Transmitter "Chain" Characteristics - Transmitter Location affects the navigation accuracy via the signal level propagating to the receiver and the geometry produced by the three relevant transmitters and the receiver. Both of these factors are treated quantitatively via the Teledyne Loran Coverage Program.

Transmitter power effects the SNR at the receiver site and therefore the TOA variance in the receiver. This effect is treated quantitatively via the Coverage Program.

Transmitter timing stability is on the order of several tens of nano-second, maximum. This effect may be incorporated into the Coverage Program by simply adding the variance of the transmitter instability to the noise induced variance of the TOA. This factor will have but a very minor effect on the accuracy or the area covered for the stated accuracies. In any event, this factor is negligible compared to secondary propagation problems.

- b. Receiver Characteristics - The main error source associated with receiver operation is the TOA jitter induced by atmospheric noise. For a typical receiver this source is on the order of 50 nsec (1σ) for an SNR of 0 dB and is approximately an inverse function of the SNR when the SNR is expressed in ratios. For a signal to noise ratio of -10 dB (SNR = 0.316) the TOA jitter is

$$\frac{50 \text{ nsec}}{0.316} = 158 \text{ nsec } (1\sigma)$$

These figures may change upwards or downwards by a factor of two (2) depending on the receiver design (PLL bandwidth, sampling point, etc.). This error source is fully treated by the Coverage Program.

The combined effect of quantization, resolution, differential amplitude caused error and clock error amounts typically to several tens of nanoseconds for hyperbolic mechanization. This error source is represented in the Coverage Program. (For Direct Ranging mechanization the clock stability has a much more significant role. The effect of clock stability for direct ranging Loran is accounted for by the Direct Ranging Coverage Program.)

- c. Geometry Considerations - It is well known that the position of the receiver relative to the relevant stations has a very significant effect on the position accuracy. This effect is referred to as a GDOP (geometric dilution of precision).

In hyperbolic mechanization the position accuracy deteriorates as we get closer to one of the baseline extensions. When the receiver is on (or very near) the baseline extension, the position cannot be determined. Such areas must be covered by a different triad of either the same chain or the adjacent chain.

The receiver may be mechanized to operate in a Master Independent Mode so that it can navigate on triads that do not necessarily include the master. As indicated by the coverage charts (to be presented later), master independent operation does not buy much in terms of accuracy, assuming typical chain configurations with the master in the center of the chain and operational. If the master becomes non-operational the master independent receiver may navigate as long as it receives three secondaries with adequate geometry and SNR.

Hyperbolic coverage may be improved by cross-chain operation whereby TOA's or TD's may be picked from two different chains.

An additional scheme which effects accuracy and coverage is the Direct Ranging (or range-range) mechanization. This scheme uses three (3) stations to minimize effects of clock errors. Here the Lines of Position are circles around the stations rather than Hyperbolas. The accuracy and coverage is considerably improved in comparison to that of the hyperbolic mechanization. The position now may be determined on the baseline extensions with an accuracy which is a function of the clock stability. With an extremely bad clock the direct range solution will be equivalent to that of the hyperbolic.

The effect of geometry is accurately treated by the Coverage Program for the different mechanizations.

- d. Terrain - The variation of field strength is strongly effected by the conductance of the terrain along the propagation path. The Coverage Program accounts for this effect.

Secondary Propagation is a major error source when absolute navigation is required. The spatial component of the secondary phase error is a function of the propagation path (conductivity, etc.). This component will be compensated for in the receiver. The temporal variation and the uncompensated component of the spatial variations are still a source of error. The effect of the secondary propagation error may be readily evaluated by the Coverage Program.

An additional error source is that caused by the elongated signal path due to aircraft elevation. This effect is significant only for high altitude aircrafts flying near one of the tracked stations. This effect may be compensated for by the same techniques used regarding secondary phase. Actually, this altitude effect may be viewed as part of the general problem of spatial secondary phase propagation problem. But this time the compensation algorithm must be worked out in three dimensions to include the varying aircraft altitude.

In any case, the chain configurations should be such that the relevant transmitters are not in the vicinity of the areas where the more stringent accuracy of Approach Mode is applicable.

- e. Interferences - Cross chain interference is negligible for the environment of the existing U.S. chains. With proper design and selection of GRI's for the additional chains required, the cross rate interference should not affect the system error budget. This problem is not addressed by the Coverage Program.

Short delay ($40 \mu s$) skywave interference is avoided by proper selection of sampling point on the pulse. Long delay (1 ms) skywave is reduced due to the phase coding employed. This area is not addressed by the Coverage Program.

4.3.2.2 Coverage Requirements - The requirements are stated as follows:

- a. The SNR resulting from any of the three relevant stations must be no less than -10 dB.
- b. The per axis position accuracy must be no less than:

Enroute	1.5 N.M. = 9000 ft	(2σ)
Terminal Area	1.1 N.M. = 6600 ft	(2σ)
Approach Mode	0.3 N.M. = 1800 ft	(2σ)

4.3.2.3 The Teledyne Loran Coverage Program - The following is a short description of the Teledyne Loran Coverage Program as utilized for this report. The coverage program accepts as input the various relevant parameters of the Loran system and provides plots showing accuracy contours and the SNR limit contour over a specified area.

Map Projection

The projection used by the program is the Mercator Projection. The lat/lon lines of this map are straight lines. The area of interest is specified by the left and right longitude lines and top and bottom latitude lines. For this report the borders were defined as follows:

For the western half of the continental U.S.:

Left border	-125° longitude
Right border	- 96° longitude
Top border	50° latitude
Bottom border	25° latitude

For the eastern half of the continental U.S.:

Left border	- 96° longitude
Right border	- 67° longitude
Top border	50° latitude
Bottom border	25° latitude

Chain Designation

Each plot is run for one of the designated chains. The position of the stations are defined and the designation used by the Coast Guard¹ (M, W, X, Y, Z) is shown on the plot at the station location. Various plots were run for the existing four U.S. chains, namely:

- US WEST COAST chain
- US GREAT LAKES chain
- US NORTH EAST chain
- US SOUTH EAST chain

The power level used are those indicated by the Coast Guard manual (Ref. 1). Any one of the stations may be removed by simply setting the power level of the particular station to zero. In this mode the effect of failure of one of the stations may be evaluated.

We should emphasize that for the purpose of this report, there was no intention either to show coverage of the entire US mainland or design additional chains or use any nonexistent chains to show full U.S. coverage. The intention was to use the existing U.S. chains as practical examples for analyzing typical Loran coverages.

¹Loran-C User Handbook, Department of Transportation, Coast Guard, COMDTINST M16562.3, May 1980.

Noise Level

The basis for the noise level used is the summertime 95 percentile RMS value for 20 KHz bandwidth, averaged over 24 hours.²

These values are:

North East Region of US	53.43 dB/1 μ v/m = 469 μ v/m
South East Region of US	64.86 dB/1 μ v/m = 1751 μ v/m
North West Region of US	56.81 dB/1 μ v/m = 693 μ v/m
South West Region of US	57.37 dB/1 μ v/m = 739 μ v/m

In view of those figures the following noise levels are used:

West Coast Chain	739 μ v/m
Great Lakes Chain	469 μ v/m
North East Chain	469 μ v/m
South East Chain	739 μ v/m

NOTE: The noise level used for the South East chain is that of the South West region or 7.5 dB lower than that of the South East region. This may be justified by the improved process gain attained for higher atmospheric (nongaussian) burst noise. For the same reason the daily average of summertime noise has been used rather than the highest noise timeframe (afternoon).

Receiver Measurement Error

The combined measurement error of the receiver, including the noise related jitter and other instrumentation errors, is modeled by a function with SNR as a variable. The values for various SNR's are:

<u>SNR</u>	<u>σ TOA</u>
-10 dB	136.4 nsec
0 dB	101.1 nsec
≥ 10 dB	58.7 nsec

²"Evaluation of Loran-C Domestic Air Navigation," Mitre Technical Report, MTR-7180, Oct. 76.

The SNR is the actual value as calculated for each geographical area. The signal level at the sampling point is derived for each point on the plot for the three relevant stations using a function describing the signal attenuation at 100 KHz.

The conductivity used for the various chains are:

West Coast Chain	0.003 mho/m
Great Lakes Chain	0.005 mho/m
North East Chain	0.005 mho/m
South East Chain	0.005 mho/m

These values are typical for the region of interest and are the same as those used in Reference 2.

The noise levels used for the SNR calculation are those previously indicated.

Secondary Propagation Effect

Residual uncompensated secondary propagation effects including transmitter timing stability, are illustrated by adding a variance of $(250)^2 \text{ nsec}^2$ (250 nsec standard deviation) to the TOA variance. For comparison, runs were also made with zero propagation error.

The actual value of residual secondary phase error will depend upon the accuracy of mathematical compensation and mapping techniques utilized.

Mechanizations

The coverage program may be run simulating the following mechanizations.

- a. Hyperbolic, Master Dependent
- b. Hyperbolic, Master Independent
- c. Direct Ranging (3 stations)

Accuracy Contour Plots

- a. Hyperbolic, Master Dependent - The 2σ error is calculated exactly, based on actual TOA variances from each of the triads and the geometry.

When the chain contains more than three stations the program calculates the error for each of the possible triads and plots the lowest error. This process is repeated for each point on the plot. The plot therefore indicates the accuracy if the best possible triad were used.

Each digit on the plot is to be multiplied by 1000 to get 2σ error in feet.

The tolerance is ± 0.25 meaning that:

0 represents	0 to 250 ft (2σ)
1 represents	750 to 1250 ft (2σ)
2 represents	1750 to 2250 ft (2σ)
3 represents	2750 to 3250 ft (2σ)
4 represents	3750 to 4250 ft (2σ)
5 represents	4750 to 5250 ft (2σ)
6 represents	5750 to 6250 ft (2σ)
7 represents	6750 to 7250 ft (2σ)
8 represents	7750 to 8250 ft (2σ)
9 represents	8750 to 9250 ft (2σ)

Between the above limits and beyond 9250 ft the plot is "blanked."
The "Enroute" accuracy of 9000 ft is represented by the digit "9".

The Terminal Area accuracy of 6600 ft is represented by the "blank" between "6" and "7".

The Approach Mode accuracy of 1800 ft is represented by the digit "2".

The SNR limit of -10 dB is indicated by "start"(*).

The following algorithm is employed regarding SNR.

- i. For each point on the plot the SNR is tested for each of the stations.
If the SNR for a particular station is less than -10 dB, this station is not used (for that particular point on the plot).
- ii. If there are at least three (3) stations with $\text{SNR} \geq -10\text{dB}$ (for the particular point on the plot), the accuracy is indicated.

- iii. If three (3) stations with $\text{SNR} \geq -10$ dB cannot be found, a "star" (*) is indicated.

For master dependent operation, the master must be on and SNR greater than -10 dB for any solution to be calculated.

- b. Hyperbolic, Master Independent - Plots for this mode of operation are made in the same manner as for the Master Dependent mode, except the Master need not be received.
- c. Direct Ranging - The algorithm for the Direct Ranging plots are similar to those of the Hyperbolic with the following exceptions:
- The presently used Direct Ranging Program works with three (3) stations only. The accuracy is therefore not minimized between various triads that may be configured for a chain consisting of four or five (or more) stations.
 - Digit "10" is designated by X.
 - The stations are tested for -18 dB rather than -10 dB and the plot is "blanked" rather than "starred".
 - Digit "1" represents 250 ft (2σ) error rather than 1000 ft (2σ).

4.3.2.4 Loran Coverage Plots -

Hyperbolic Coverage

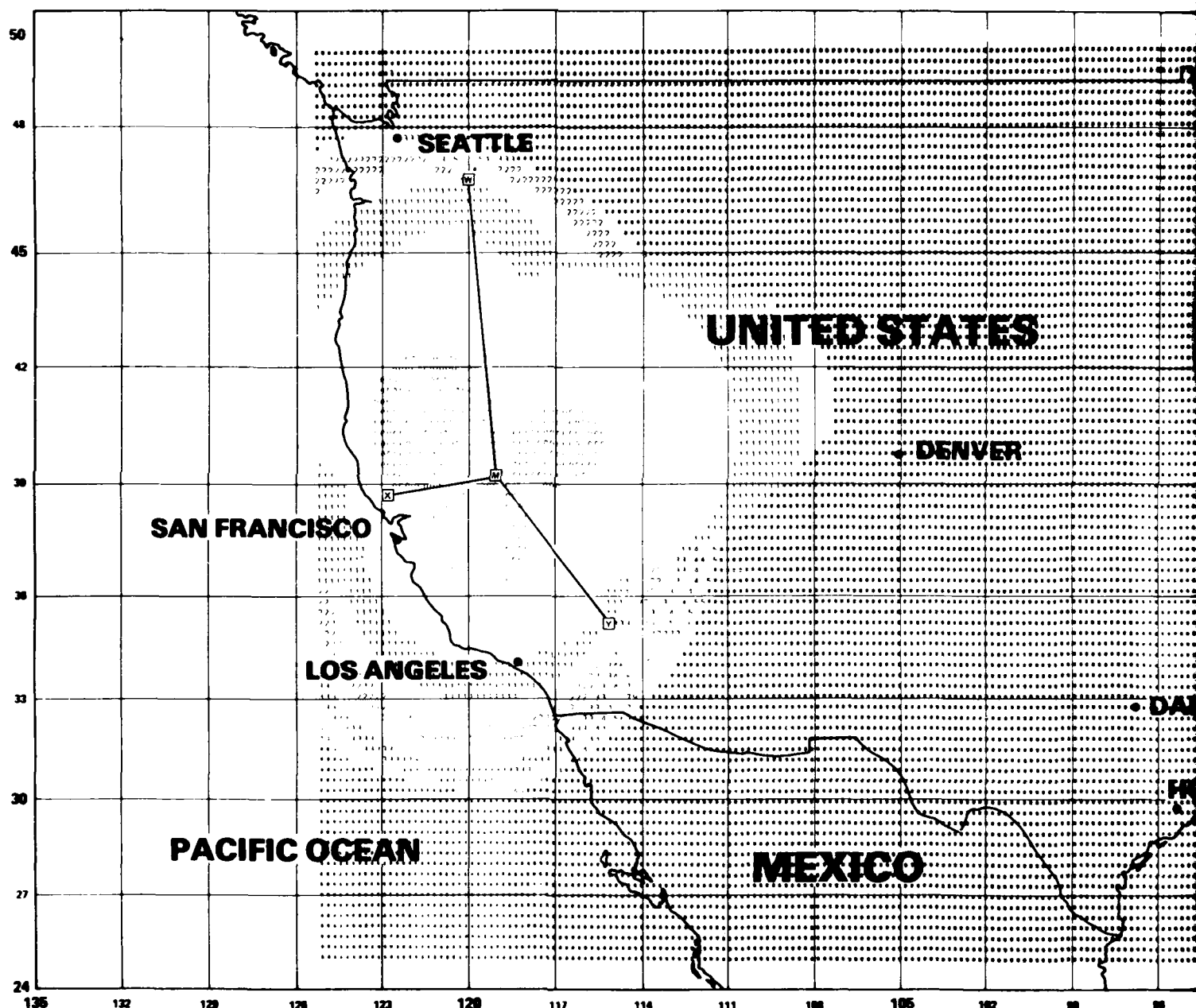
(See Table 4-1 and maps in Figures 4-1 through 4-16.)

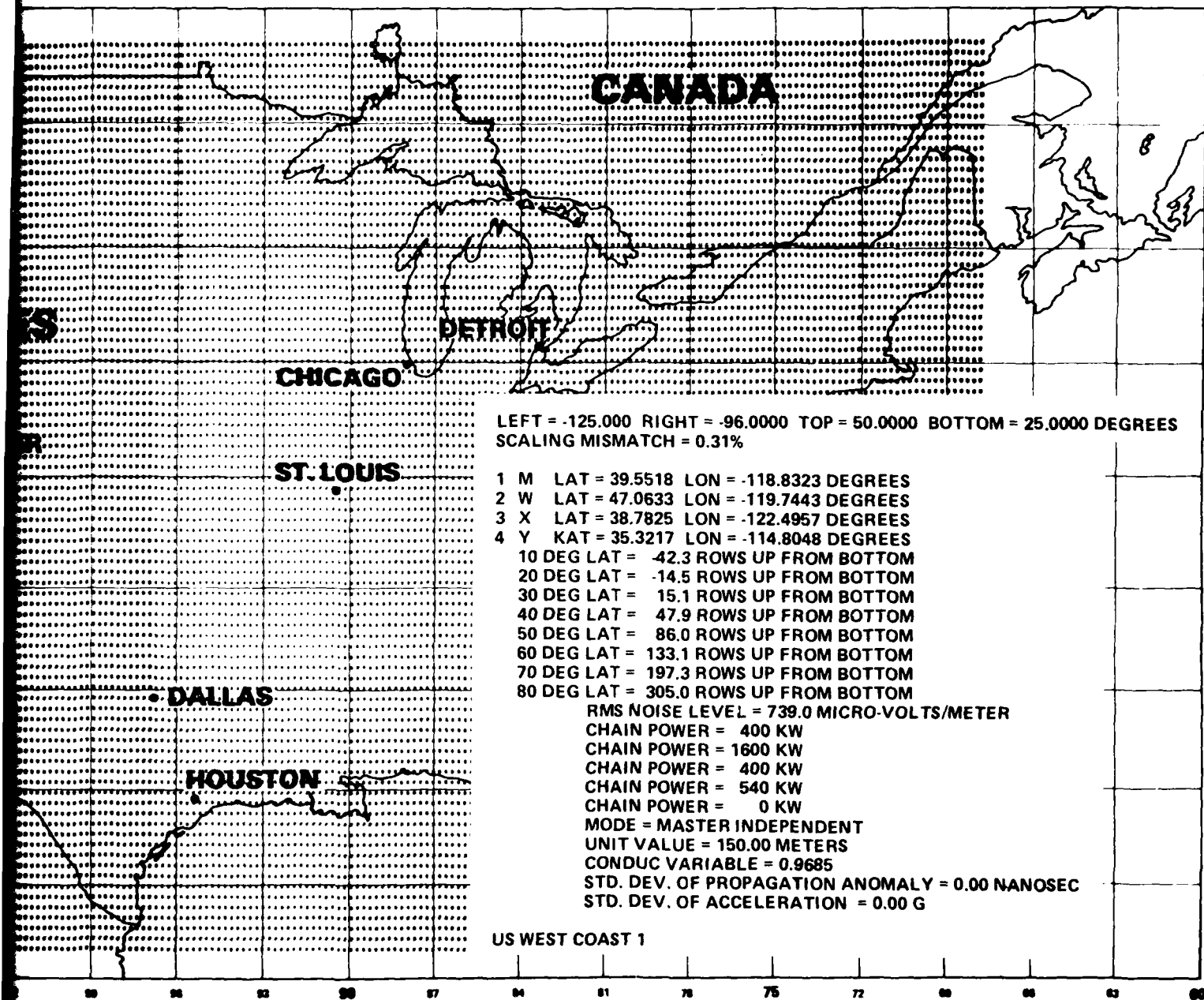
West Coast Chain

The basic coverage of the West Coast chain is shown on Figure 4-1 (master dependent). Notice that the coverage is primarily limited by the SNR ("start"). The limit for "Enroute" coverage is "9". Therefore, the entire area where the $\text{SNR} \geq -10$ dB is suitable for "Enroute" nav, except for small areas behind stations W and Y. The situation is very similar for "Terminal Area" navigation ("6" to "7"). The area covered for "Approach Mode" ("2") is somewhat limited in the North and South.

Table 4-1. Coverage Plots

Map	Chain	Mechanization	Special Conditions
1	West Coast	Hyperbolic, Master Dependent	Master Inoperative Prop anomaly 250 nsec
2	West Coast	Hyperbolic, Master Independent	
3	West Coast	Hyperbolic, Master Independent	
4	West Coast	Hyperbolic, Master Independent	
5	Great Lakes	Hyperbolic, Master Dependent	Prop anomaly 250 nsec
6	Great Lakes	Hyperbolic, Master Independent	
7	Great Lakes	Hyperbolic, Master Independent	
8	North East	Hyperbolic, Master Dependent	
9	North East	Hyperbolic, Master Independent	Prop anomaly 250 nsec
10	North East	Hyperbolic, Master Independent	
11	South East	Hyperbolic, Master Dependent	
12	South East	Hyperbolic, Master Independent	
13	South East	Hyperbolic, Master Independent	Prop anomaly 250 nsec
14	West Coast (M,W,Y Triad)	Hyperbolic	Clock var 10^4 (nsec) ² Clock var 10^6 (nsec) ²
15	West Coast	Direct Ranging	
16	West Coast	Direct Ranging	





T134896-1

Figure 4-1. US West Coast 1

Figure 4-2 indicates the coverage for a master independent mechanization. There is no significant improvement when compared to the previous master dependent plot (Figure 4-1). The major feature of the master independent mechanization is that the receiver can navigate when the master fails (Figure 4-3) on a limited area.

The effect of residual uncompensated propagation anomaly and chain instability is indicated on Figure 4-4 where the propagation anomaly was set to 250 nanoseconds (1σ). When compared to Figure 4-2 we notice that the accuracy contours have considerably retreated.

Great Lakes Chain

The basic master dependent plot is shown on Figure 4-5, the master independent plot on Figure 4-6, and the effect of propagation anomaly on Figure 4-7.

Here we meet the Approach Mode requirement ("2") for the entire area where $\text{SNR} \geq -10 \text{ dB}$, with the exception of very small areas on Figure 4-7.

North East Chain

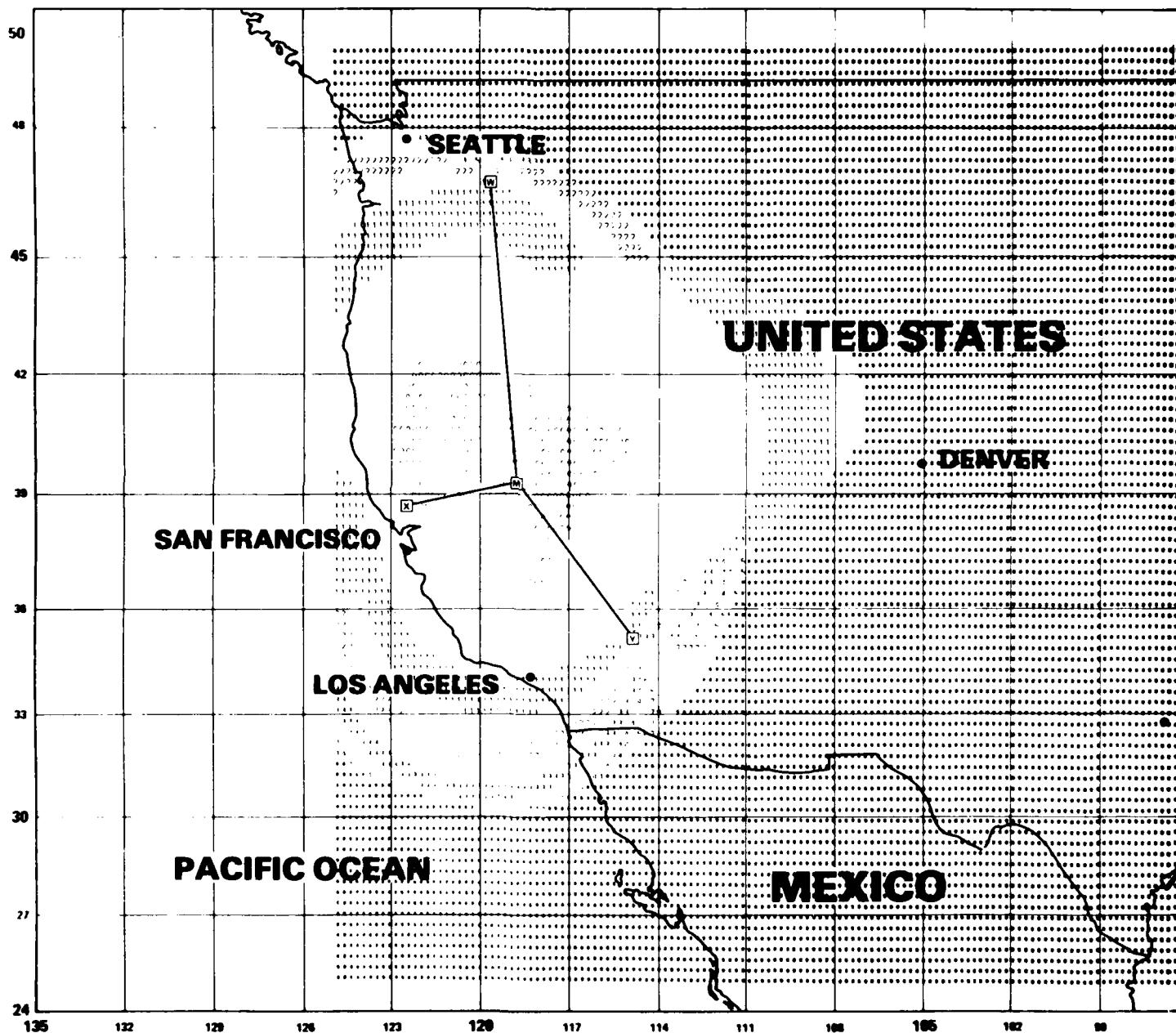
The basic master dependent plot is shown on Figure 4-8, the master independent on Figure 4-9, and the effect of propagation anomaly on Figure 4-10. The situation here is quite similar to that on the West Coast area.

Notice that the North East Chain and the Great Lakes Chain overlap and essentially cover the entire Northeast US (see Figures 4-6 and 4-9).

South East Chain

The basic master dependent plot is shown on Figure 4-11, the master independent plot on Figure 4-12, and the effect of propagation anomaly on Figure 4-13. The coverage situation is again basically similar to that described for the West Coast chain. Figures 4-6, 4-9 and 4-12 indicate that the three eastern chains essentially cover the entire eastern half of the U.S.

A word of caution: The South East Chain was run with $739 \mu\text{V/m}$ noise level instead of $1751 \mu\text{V/m}$ (as indicated above). The results on Figures 4-11, 4-12, and 4-13 might, therefore, be somewhat optimistic.



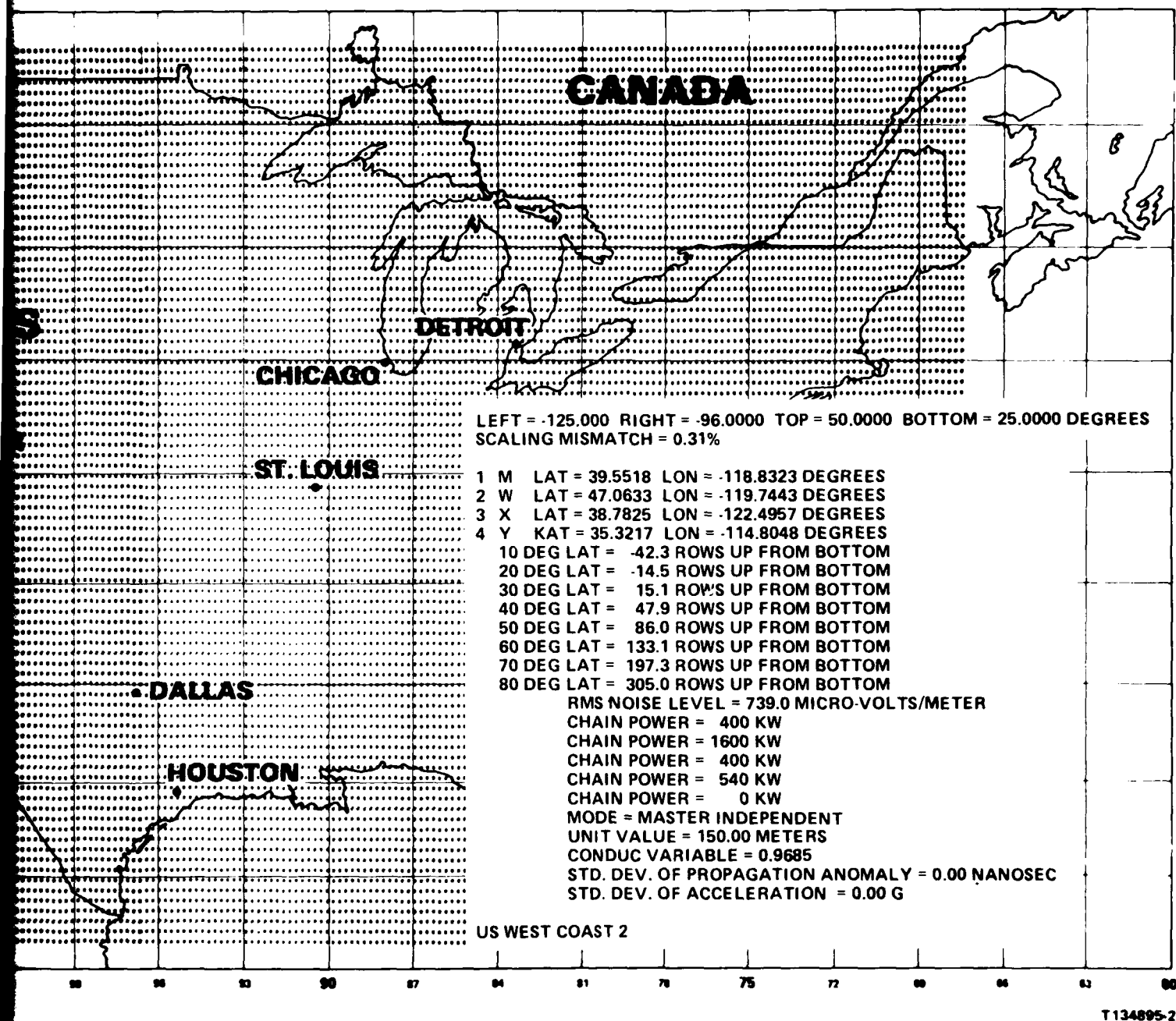
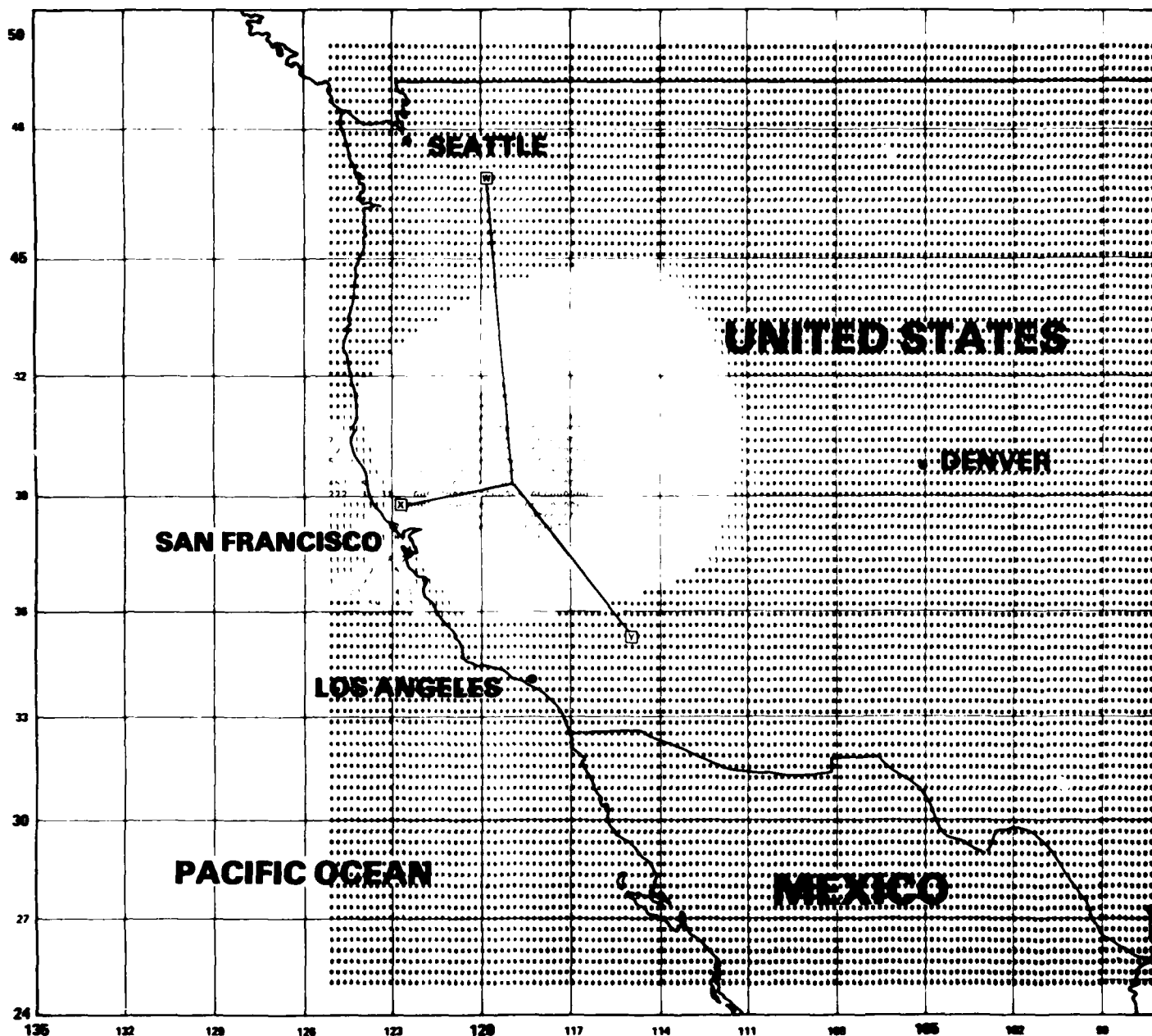


Figure 4-2. US West Coast 2



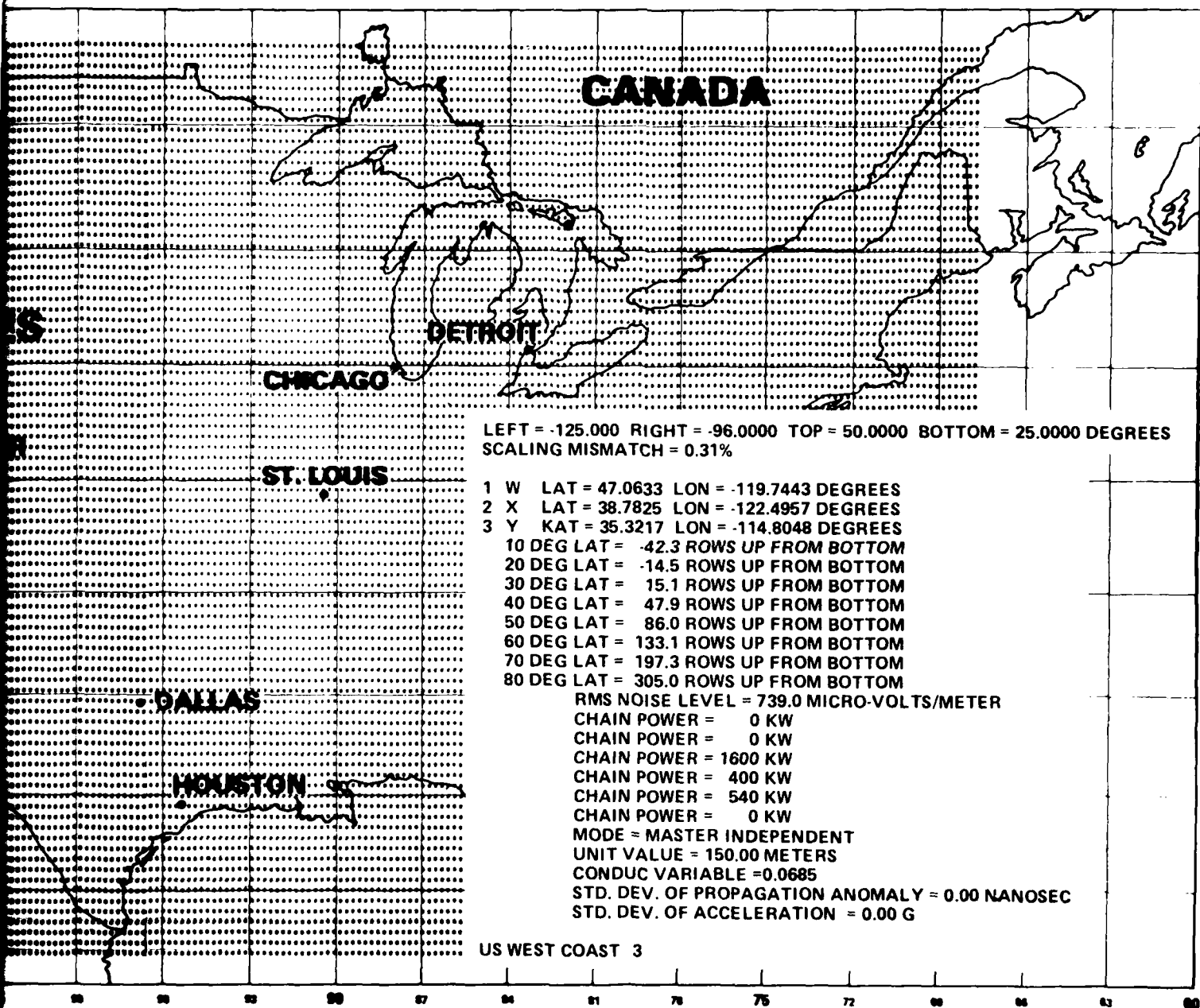
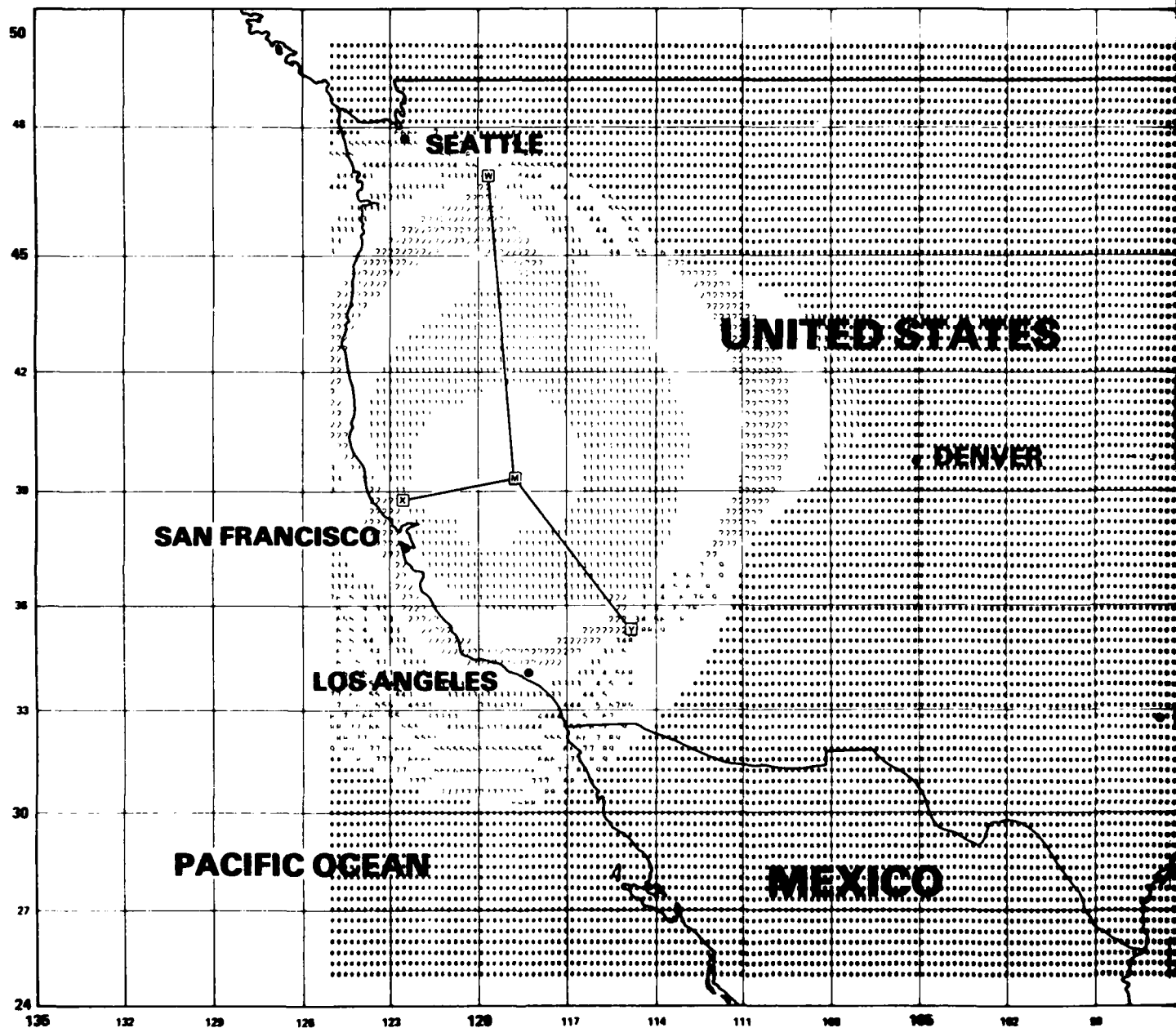
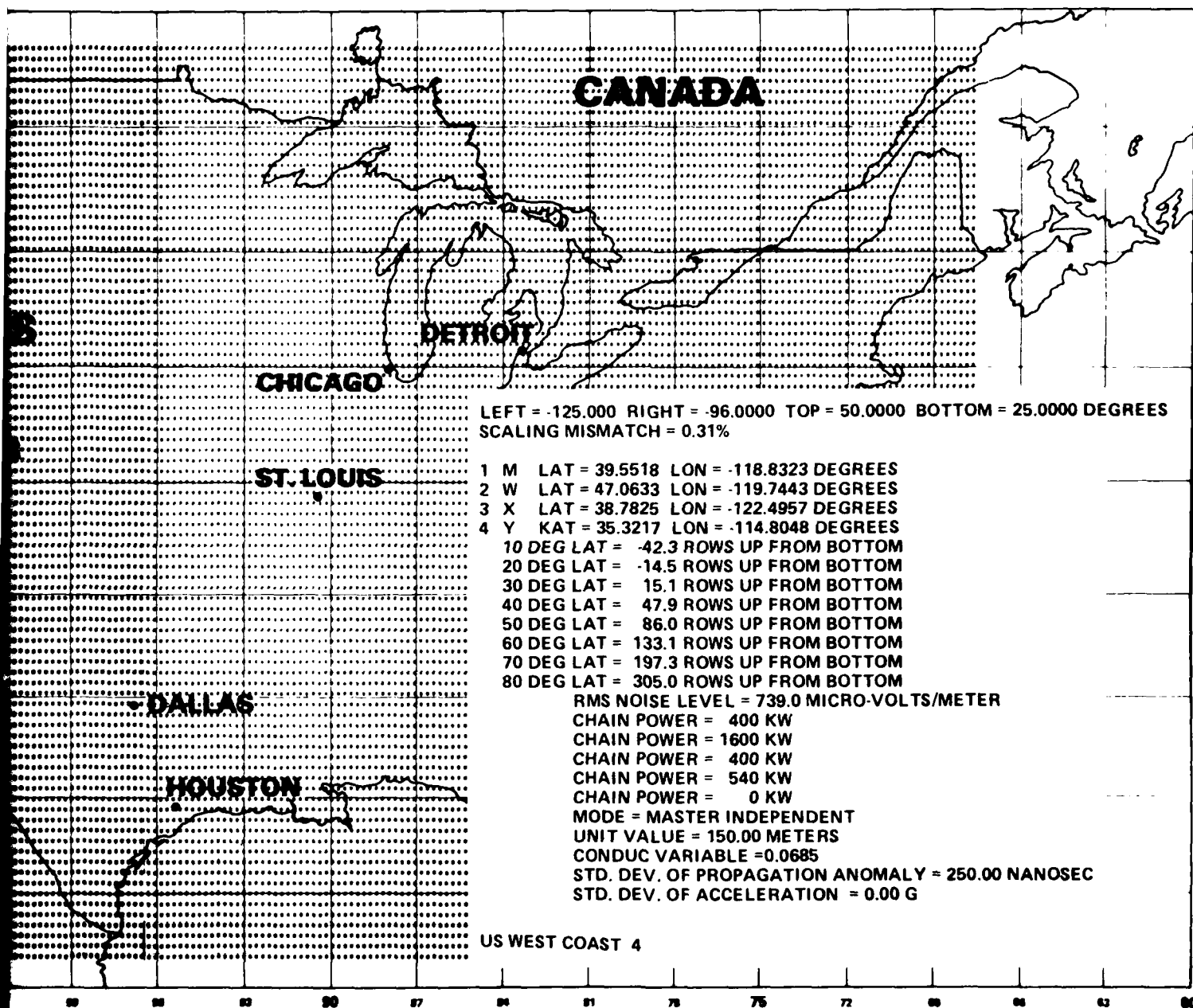


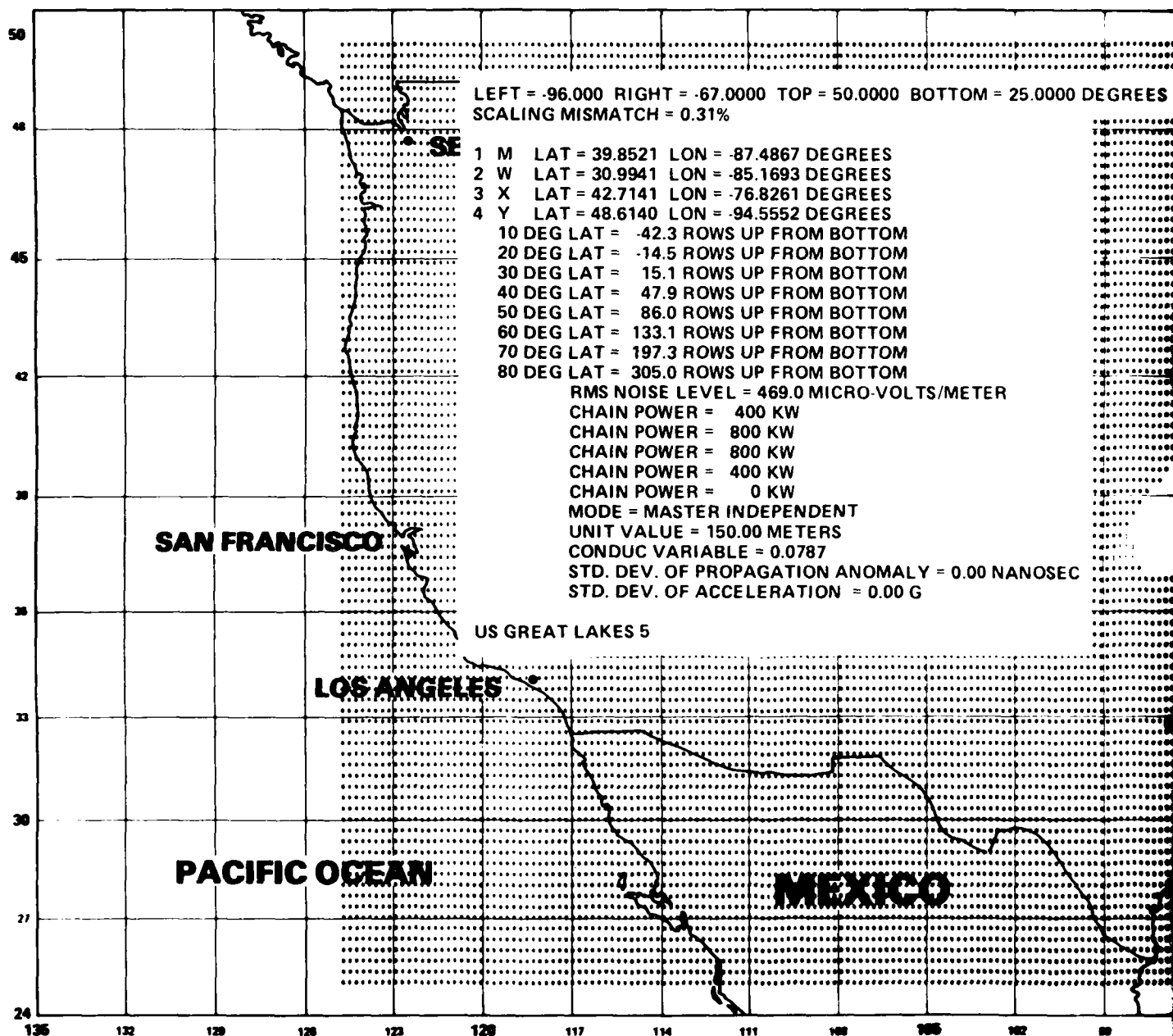
Figure 4-3. US West Coast 3

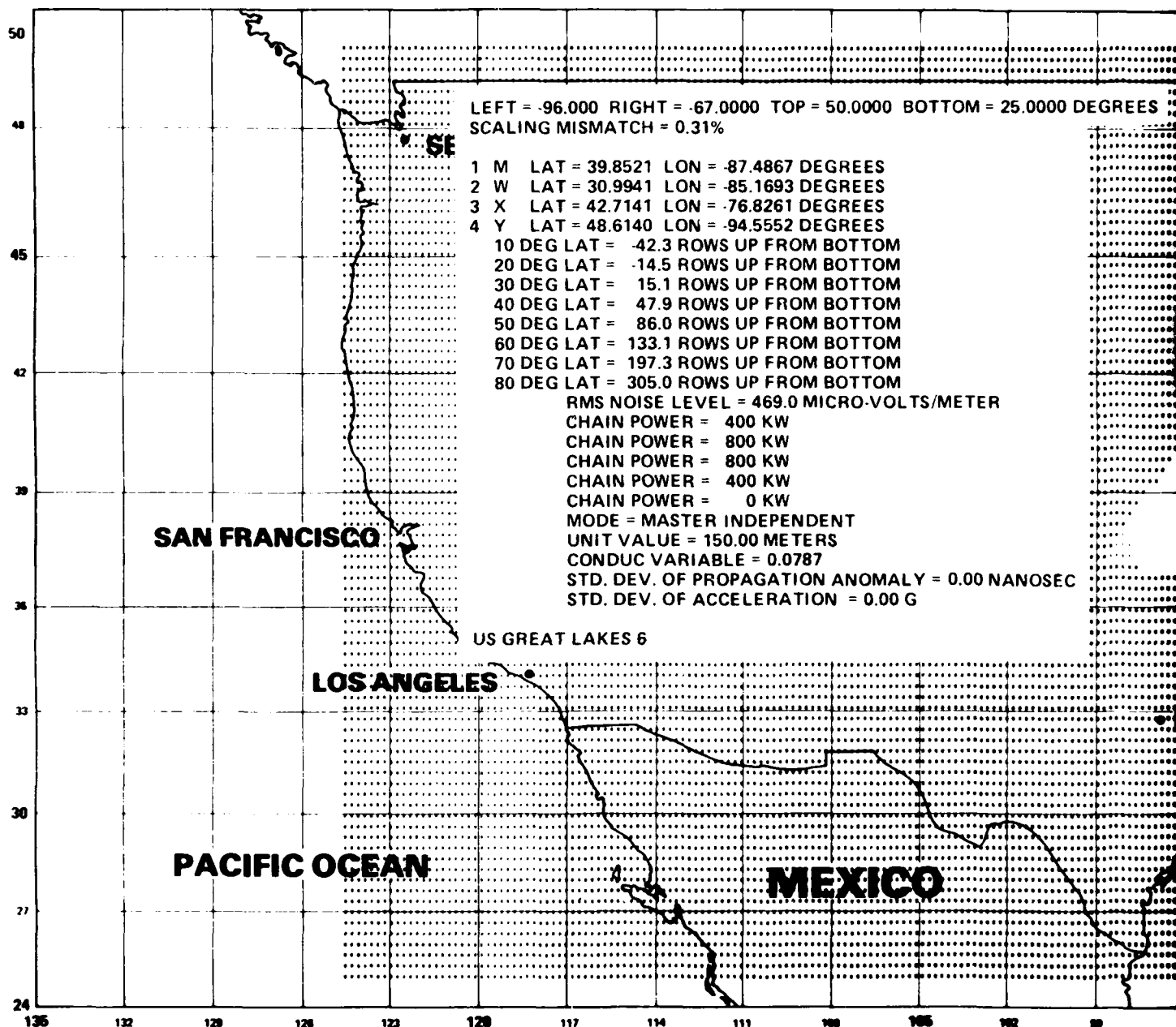


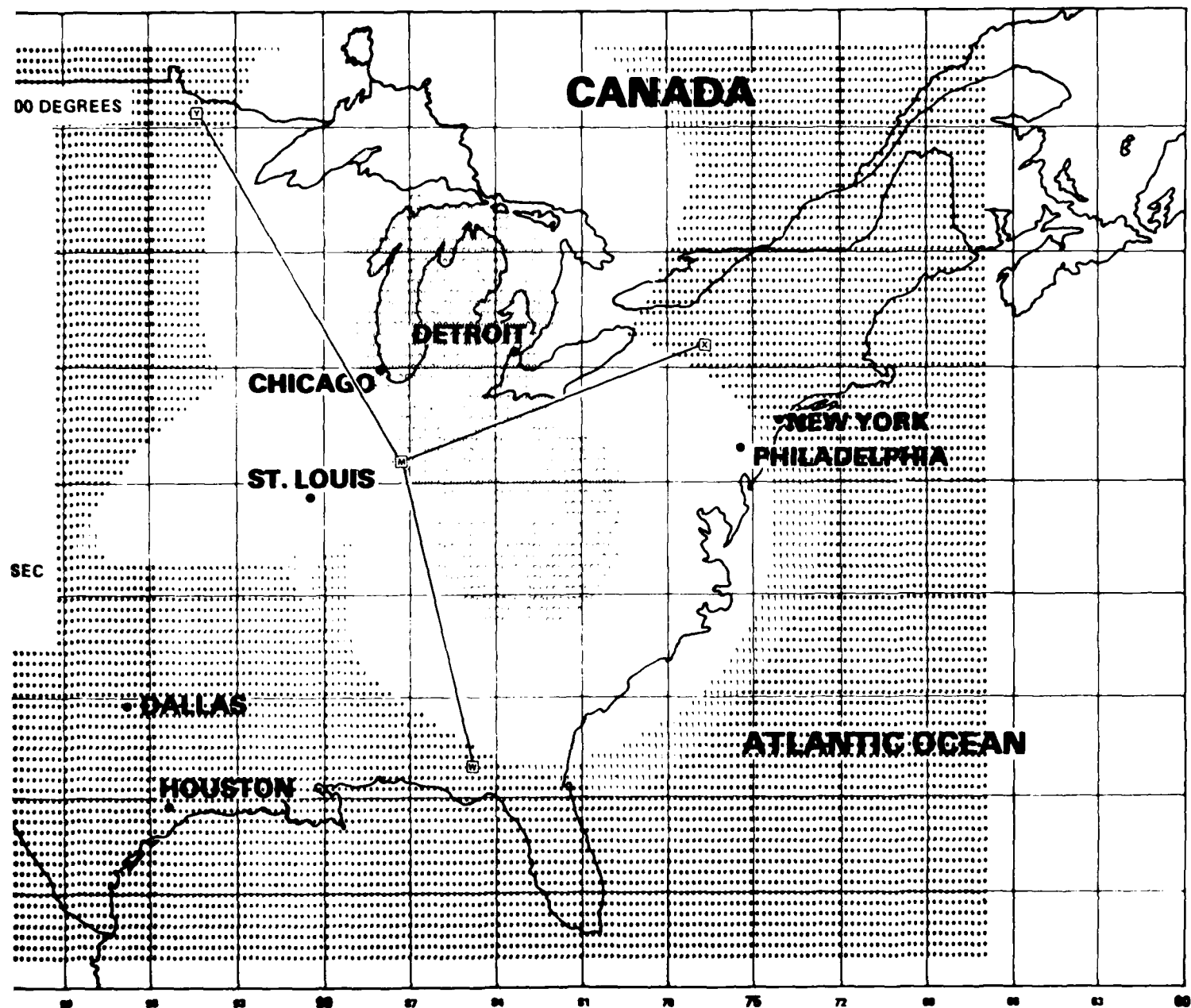


T134895-4

Figure 4-4. US West Coast 4

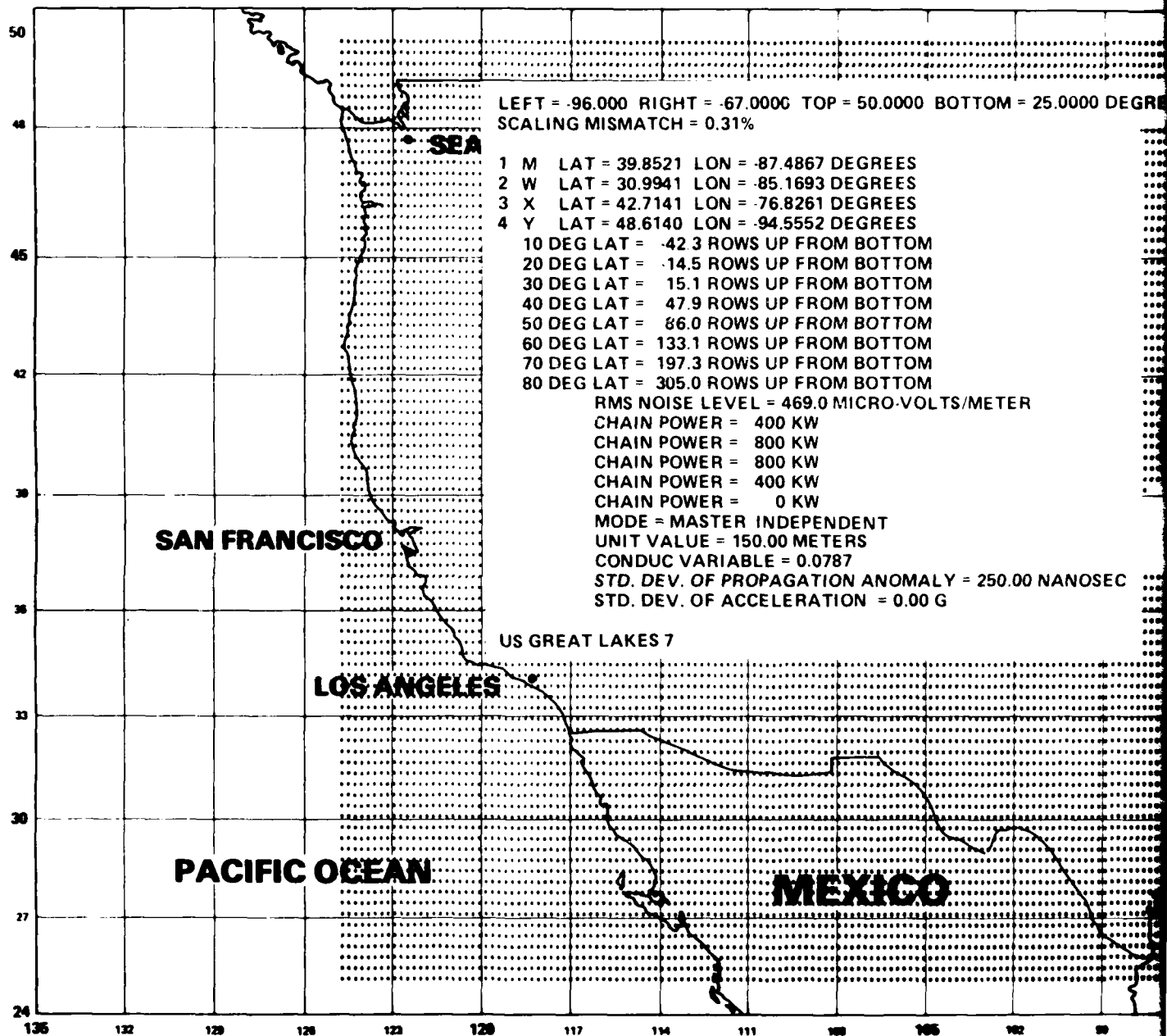


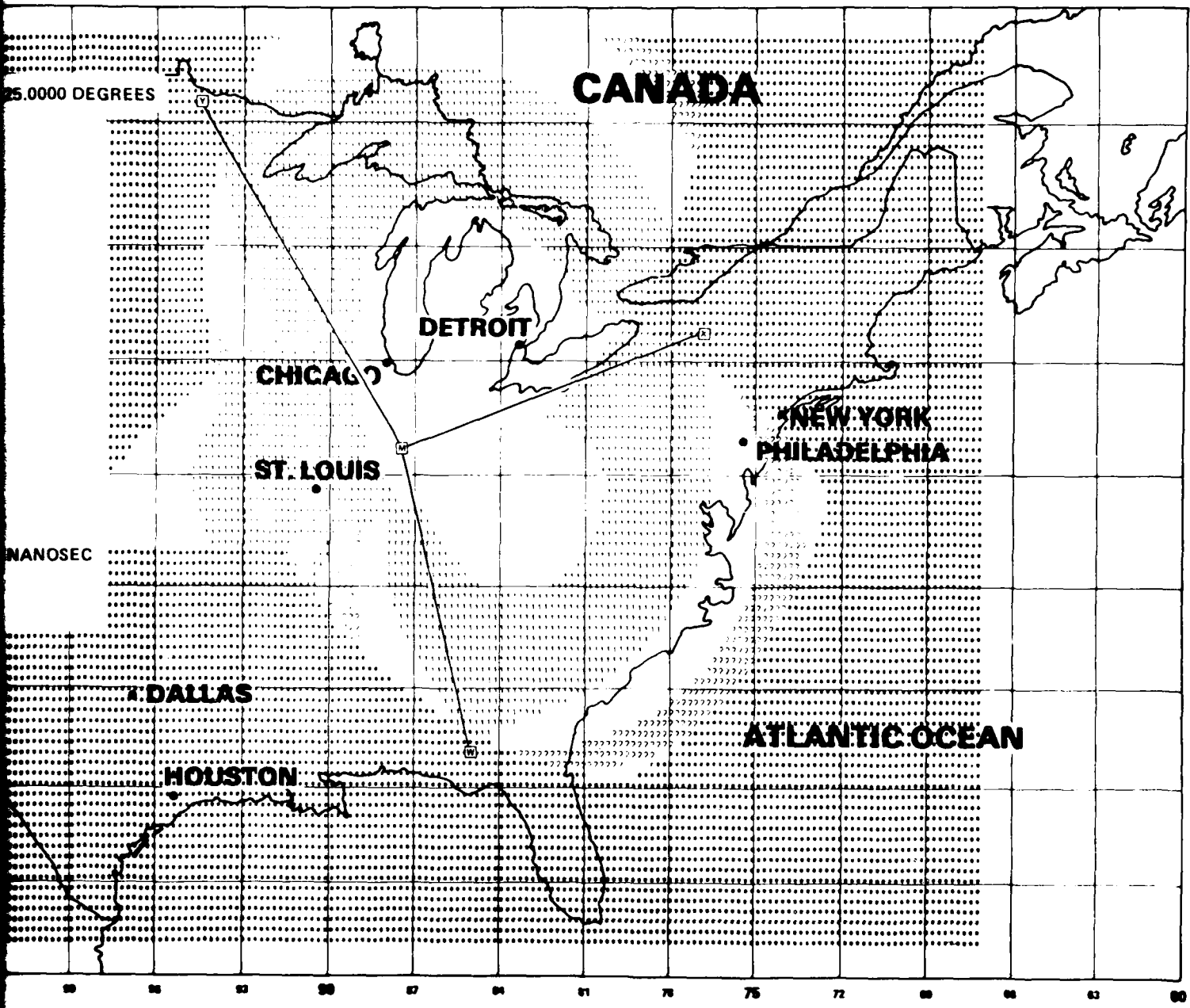




T134895-6

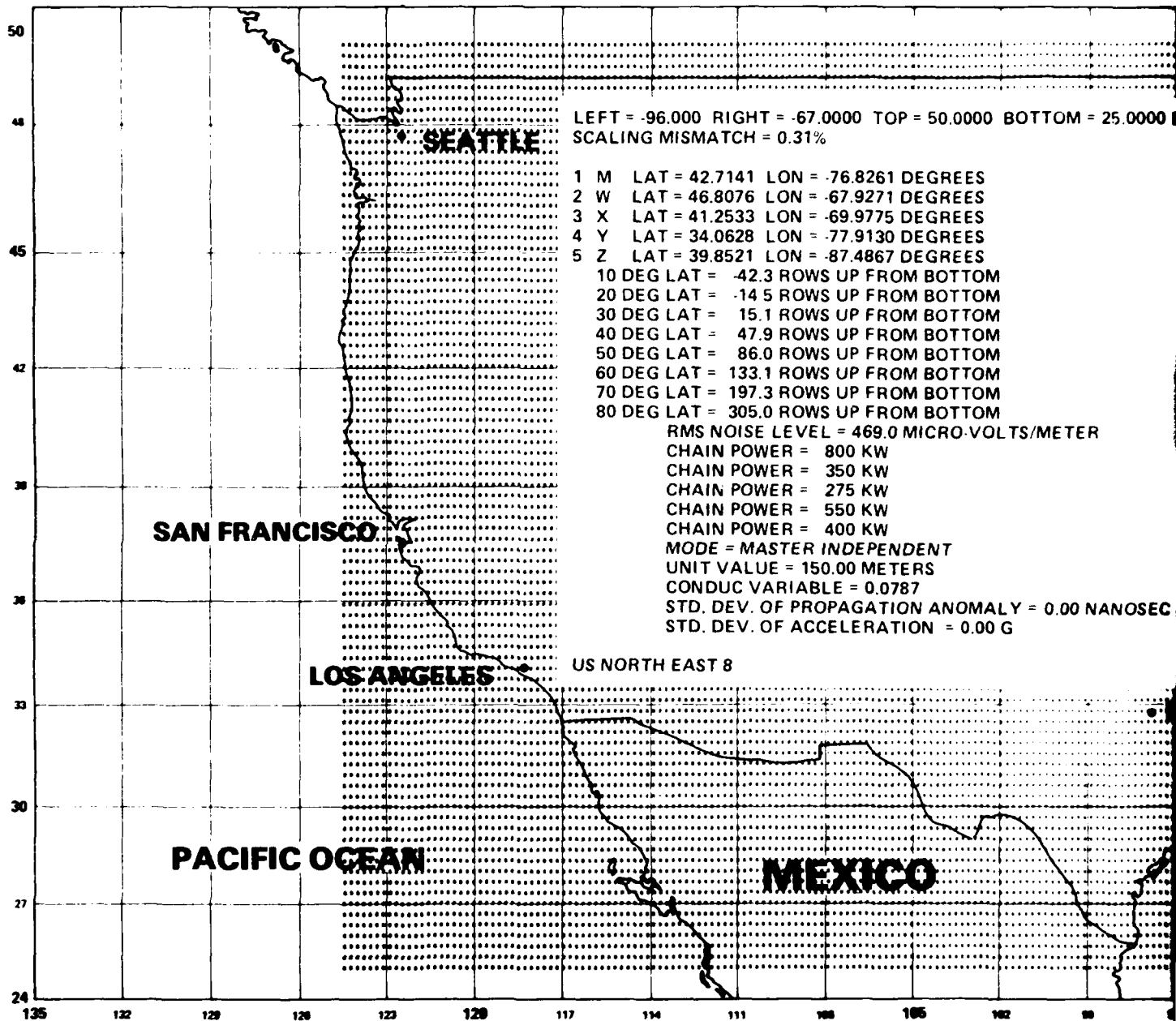
Figure 4-6. US Great Lakes 6



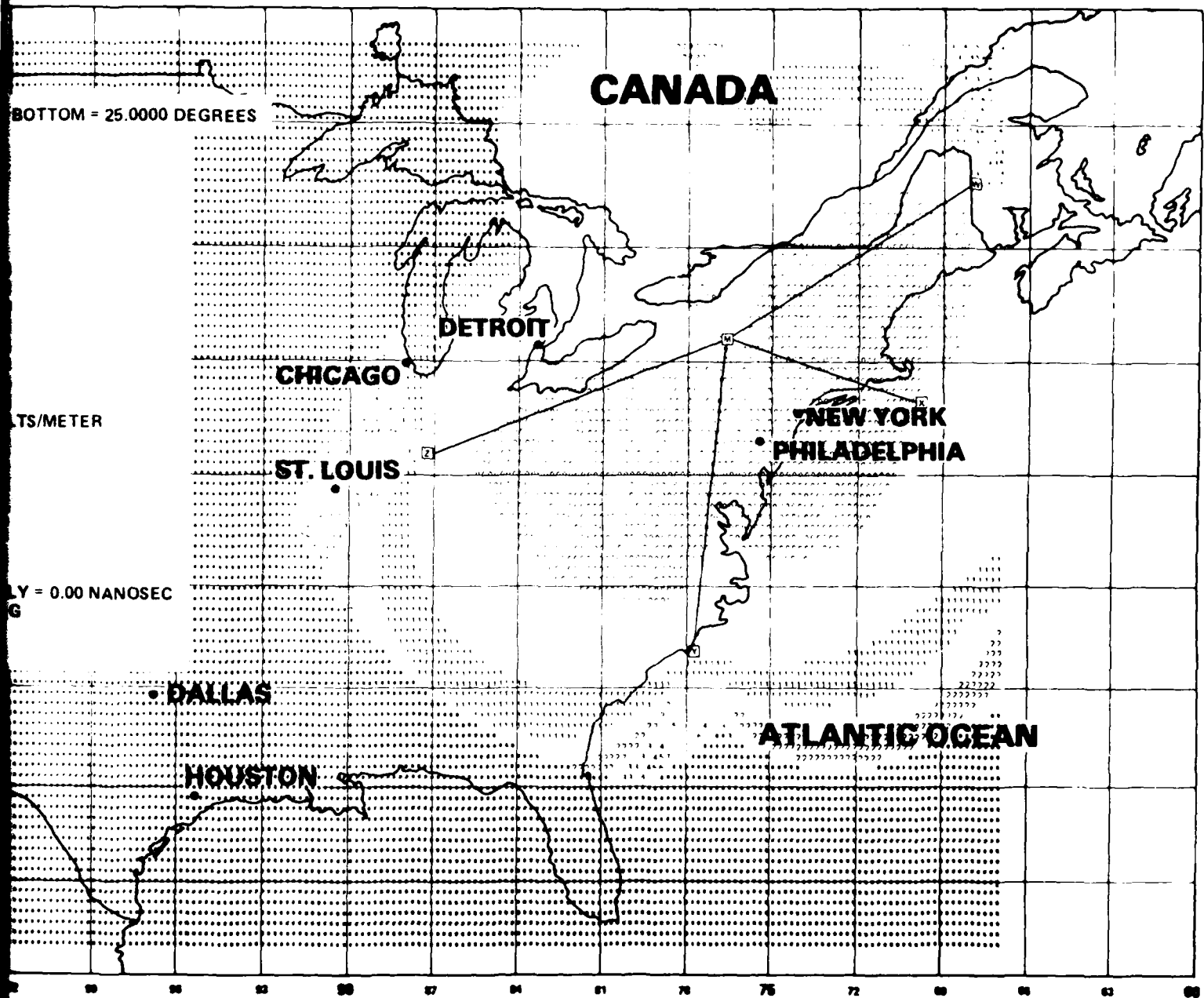


T134895-7

Figure 4-7. US Great Lakes 7

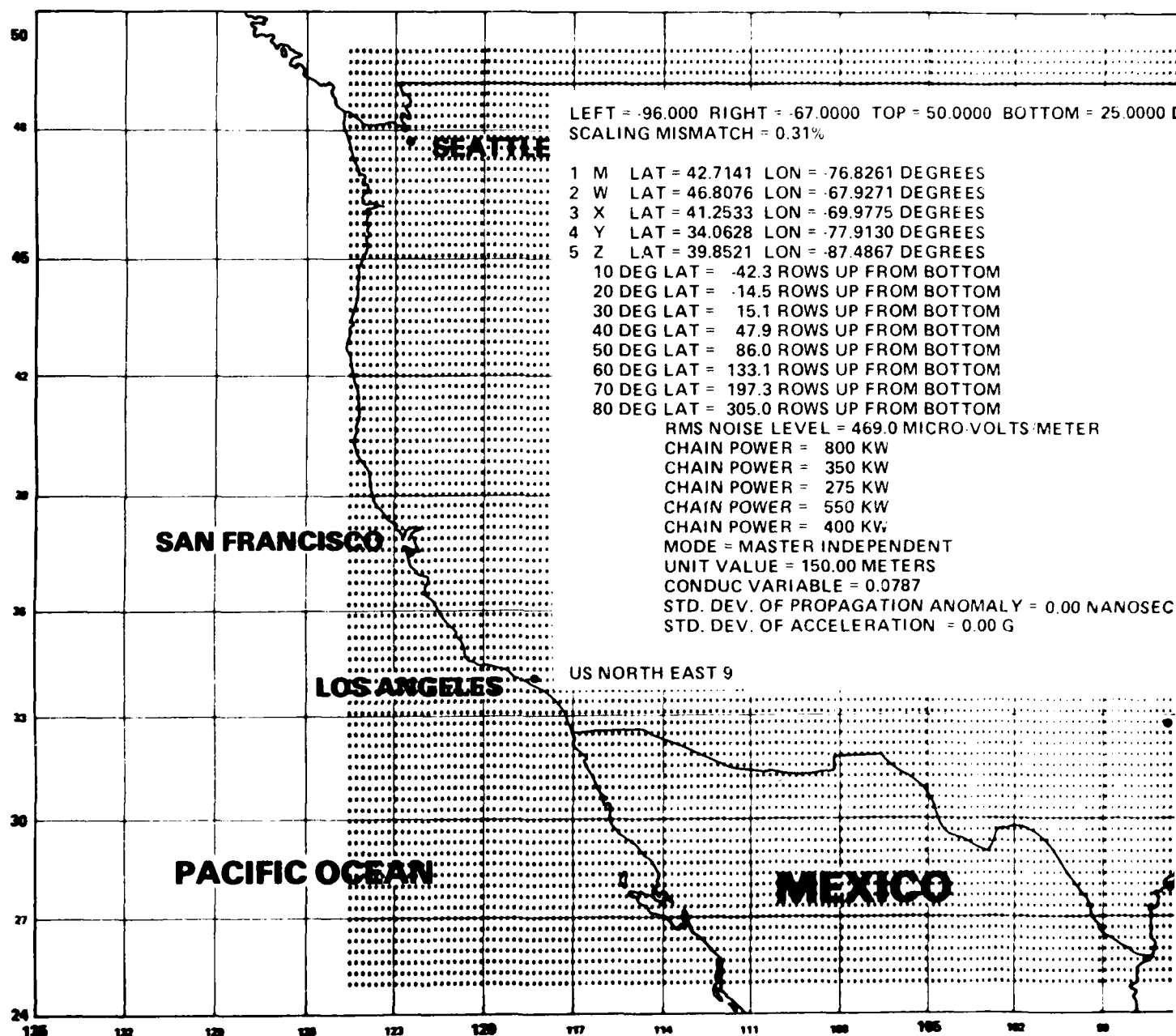


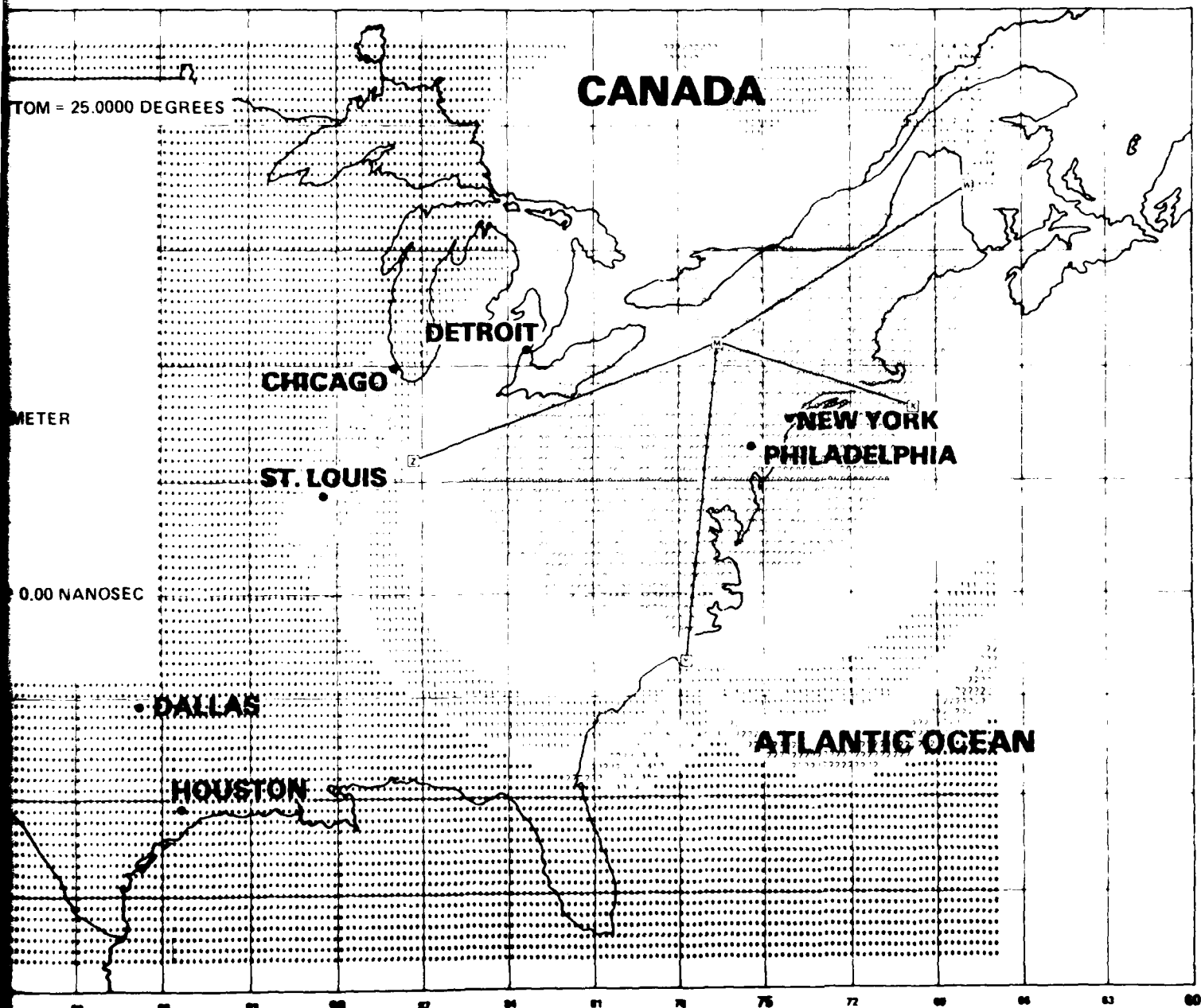
2



T134895-8

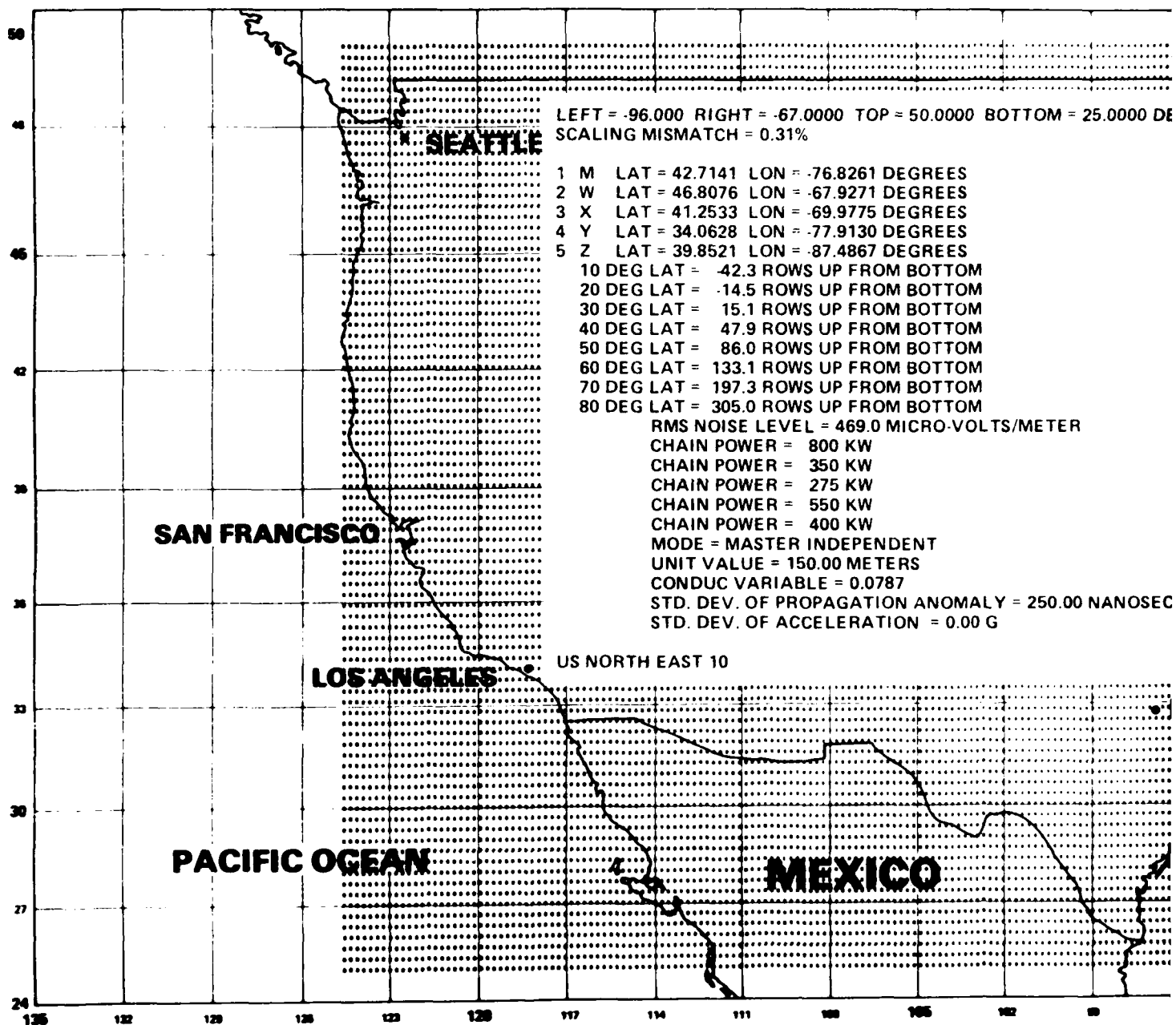
Figure 4-8. US North East 8

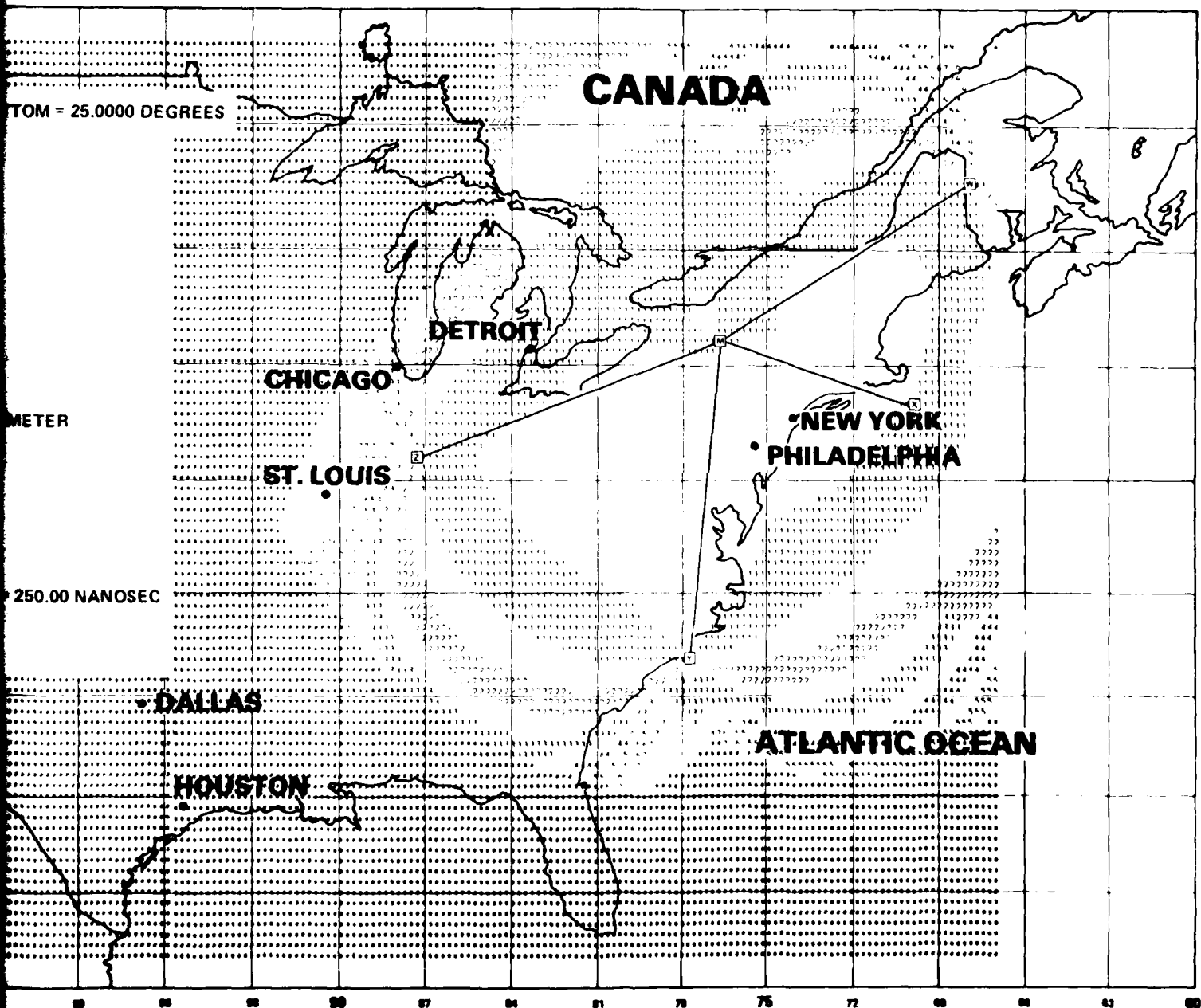




T134895-9

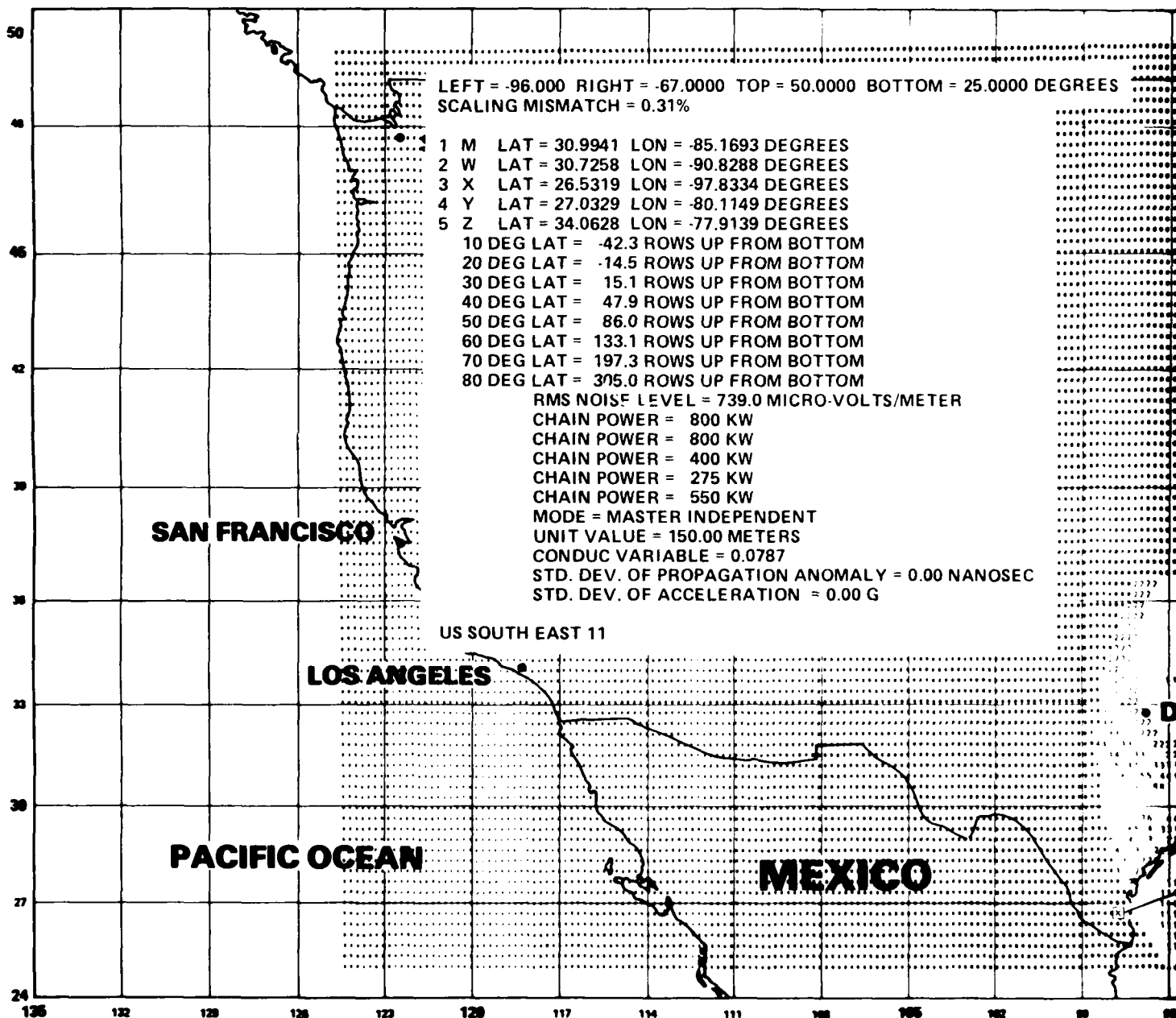
Figure 4-9. US North East 9

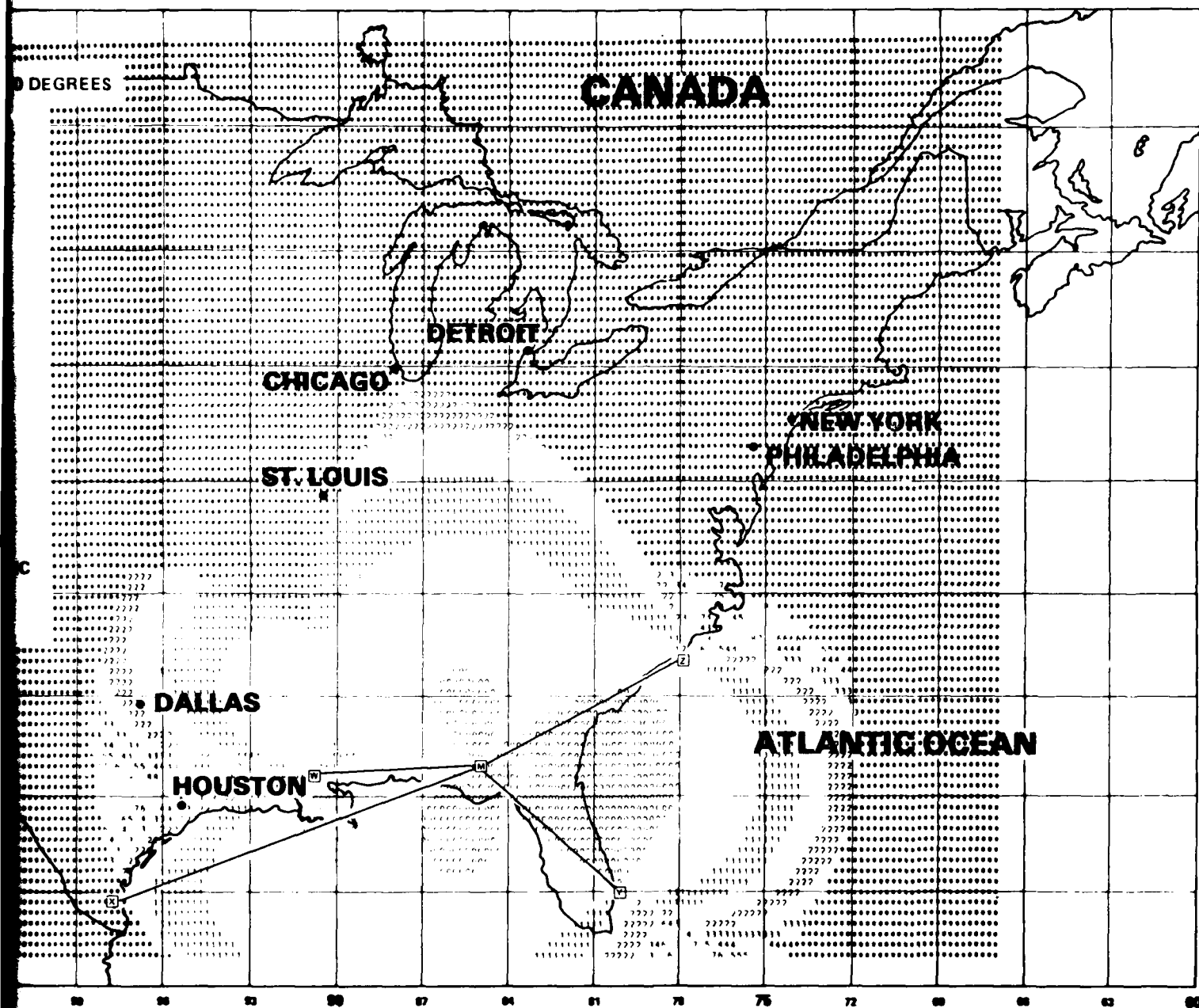




T134895-10

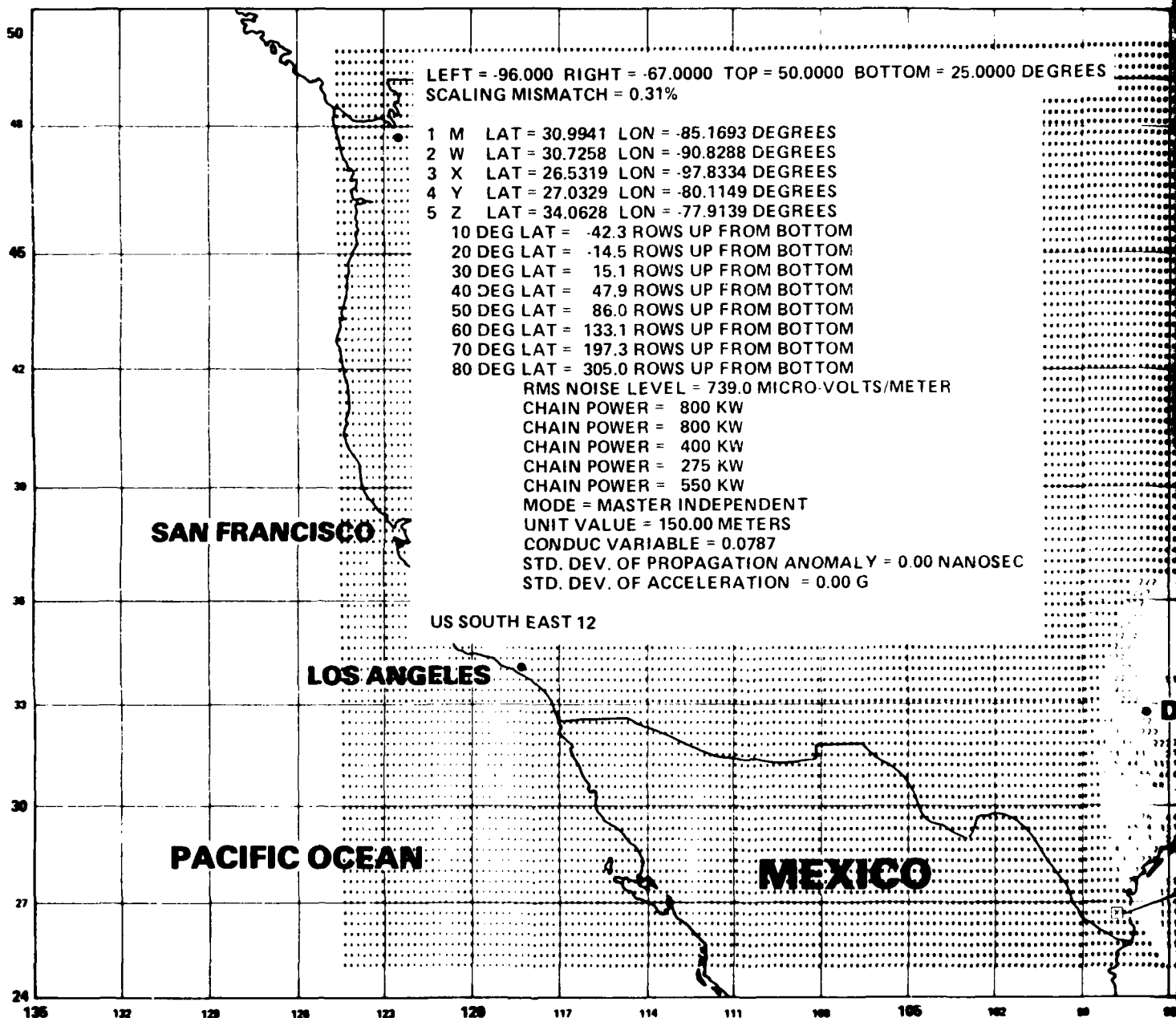
Figure 4-10. US North East 10

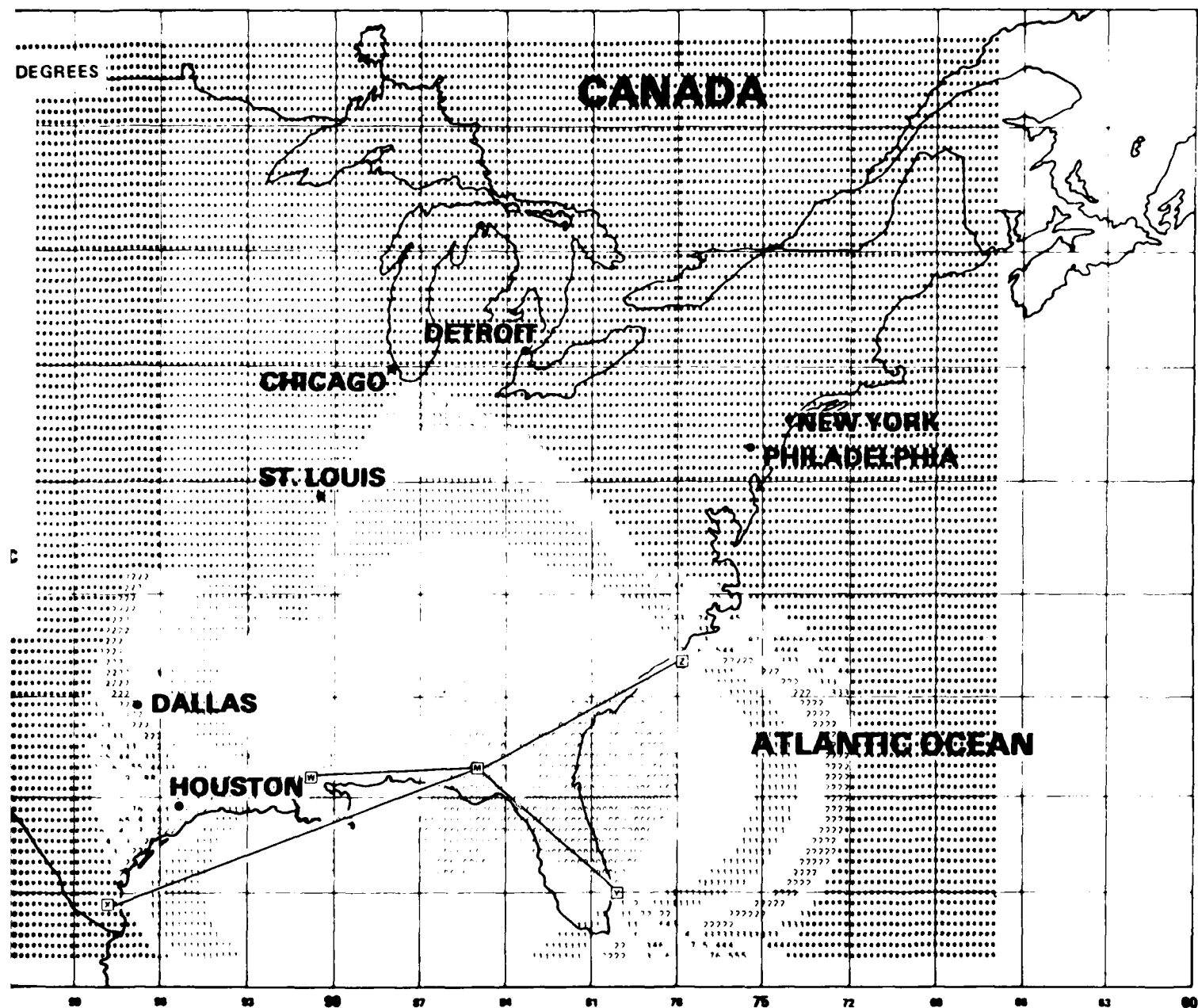




T134895-11

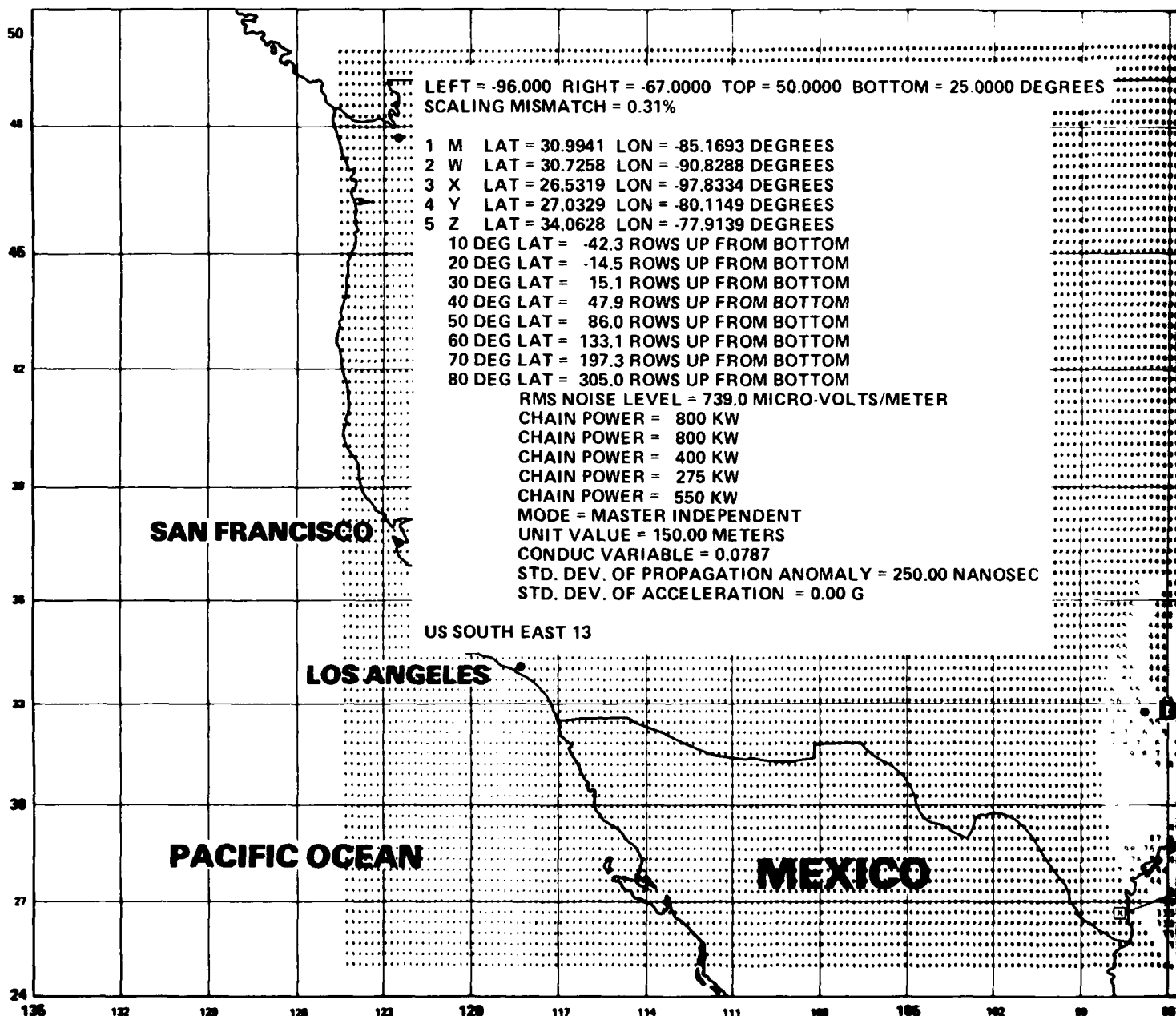
Figure 4-11. US South East 11

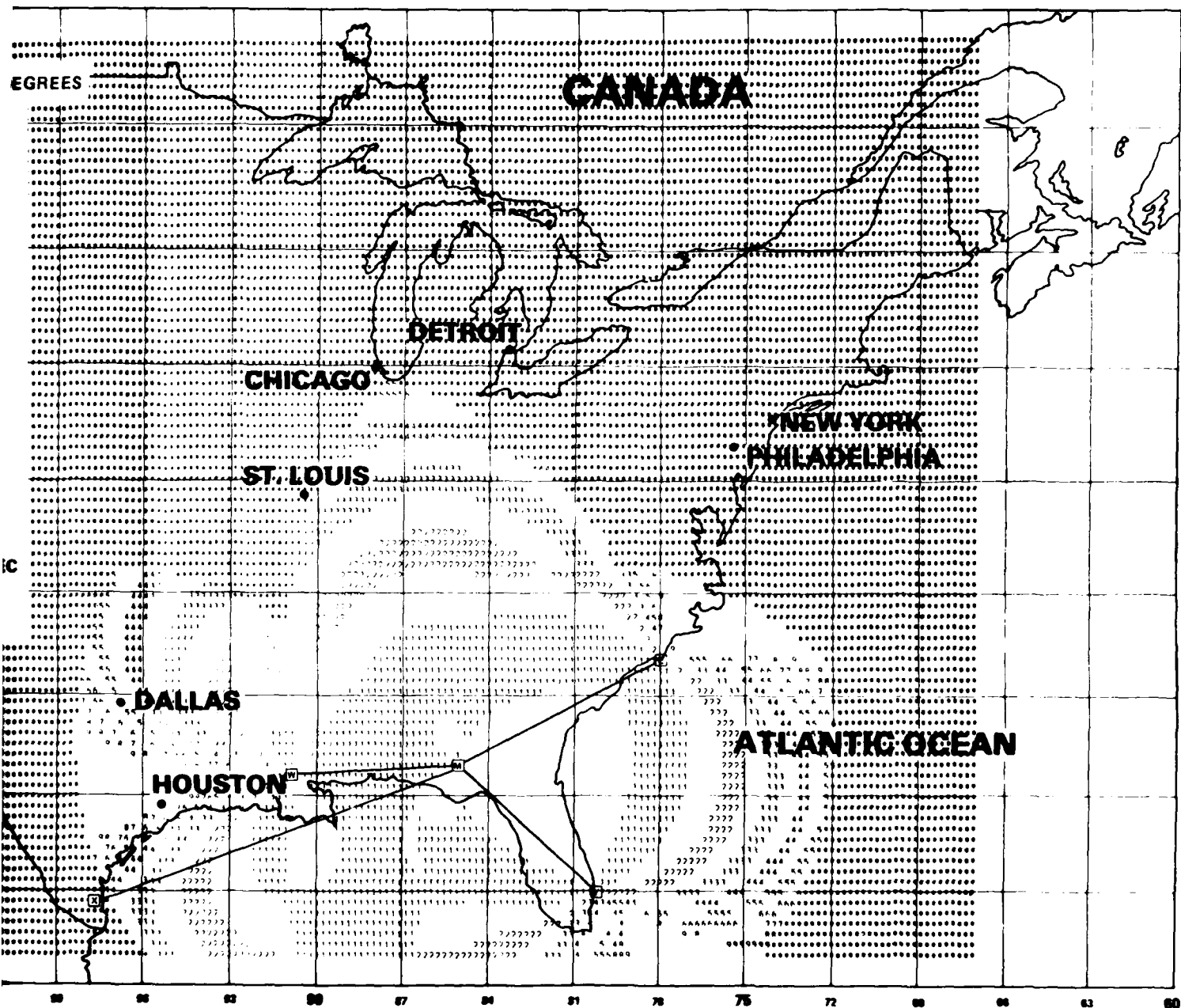




T134895-12

Figure 4-12. US South East 12





T134895-13

Figure 4-13. US South East 13

Direct Ranging Coverage

The merits of Direct Ranging are indicated on Figures 4-14, 4-15, and 4-16. These maps show coverage due to a single triad (M, W, Y) of the West Coast Chain.

On these maps the unit values have been changed from 1000 ft (2σ) to 250 ft (2σ) in order to more clearly demonstrate the advantage gained by Direct Ranging. For the same reason the "stars" were removed and the plot is blanked for SNR -18 dB. (The letter X on these plots indicate "10.")

Figure 4-14 is a hyperbolic plot for comparison. Figures 4-15 and 4-16 are direct ranging plots with clock phase variance of 10^4 and 10^6 (nsec)² respectively. Figure 4-15 with relatively low clock variance shows major improvement over the hyperbolic plot. The most easterly contour is "2" versus "X" (=10) on the hyperbolic plot. In addition, the baseline extensions are covered fairly well. When the clock variance is raised to 10^6 (nsec)² (Figure 4-16) the coverage characteristics approach those of the hyperbolic mechanization, although the advantage of the direct ranging is still retained to some extent. It is quite obvious that the direct ranging mechanization offers significant improvements.

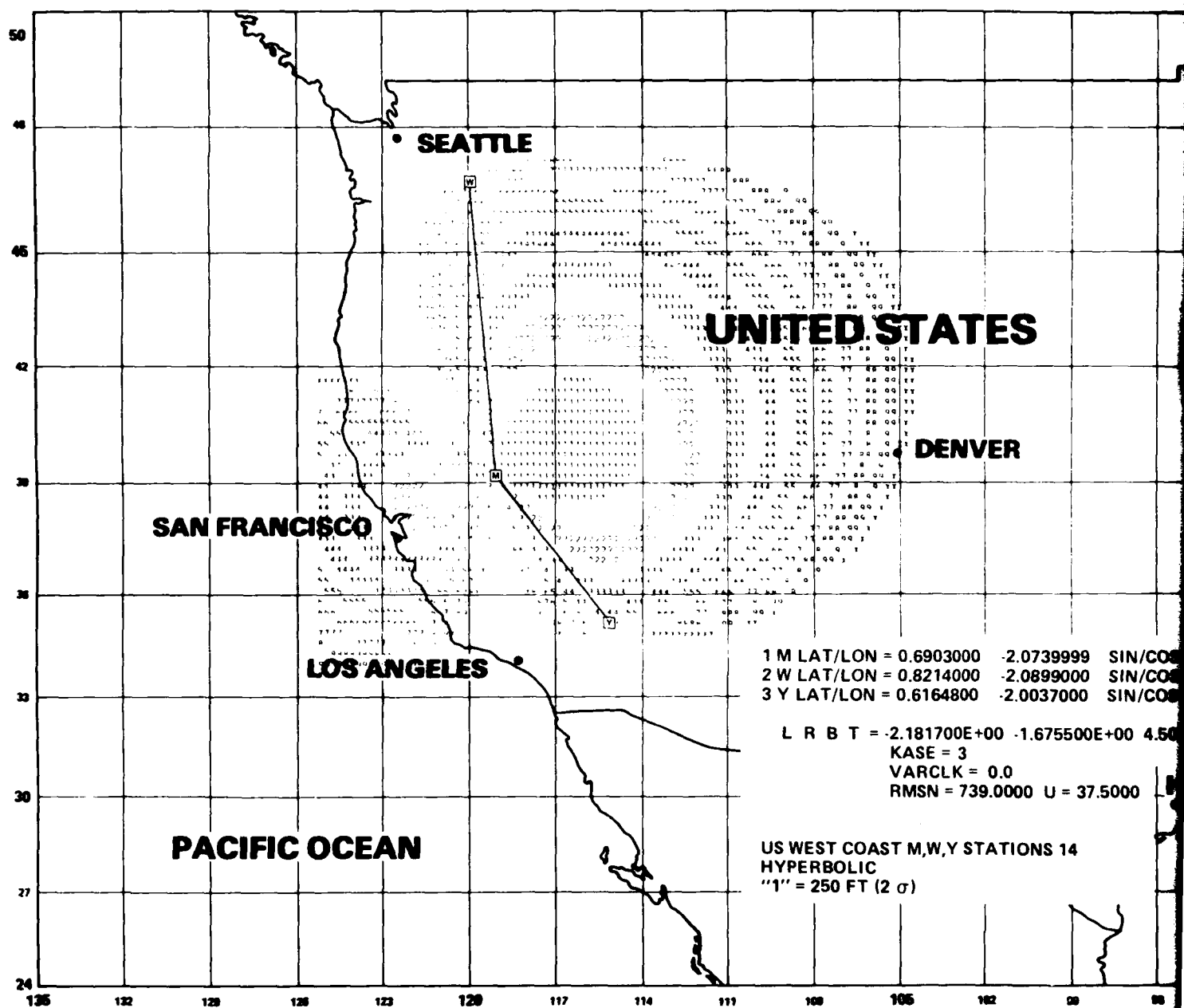
It should be emphasized, again, that the direct ranging advocated here is mechanized with three (3) stations. This mechanization is not absolutely dependent on the receiver clock and the worst case solution is that of the hyperbolic.

4.3.2.5 Conclusions - It can be seen from the plots presented that existing Loran chains do not cover the entire USA and that coverage within some areas is not sufficient to permit the desired position accuracy to be achieved. On the other hand, the coverage densities suggested in reference 2 are not required.

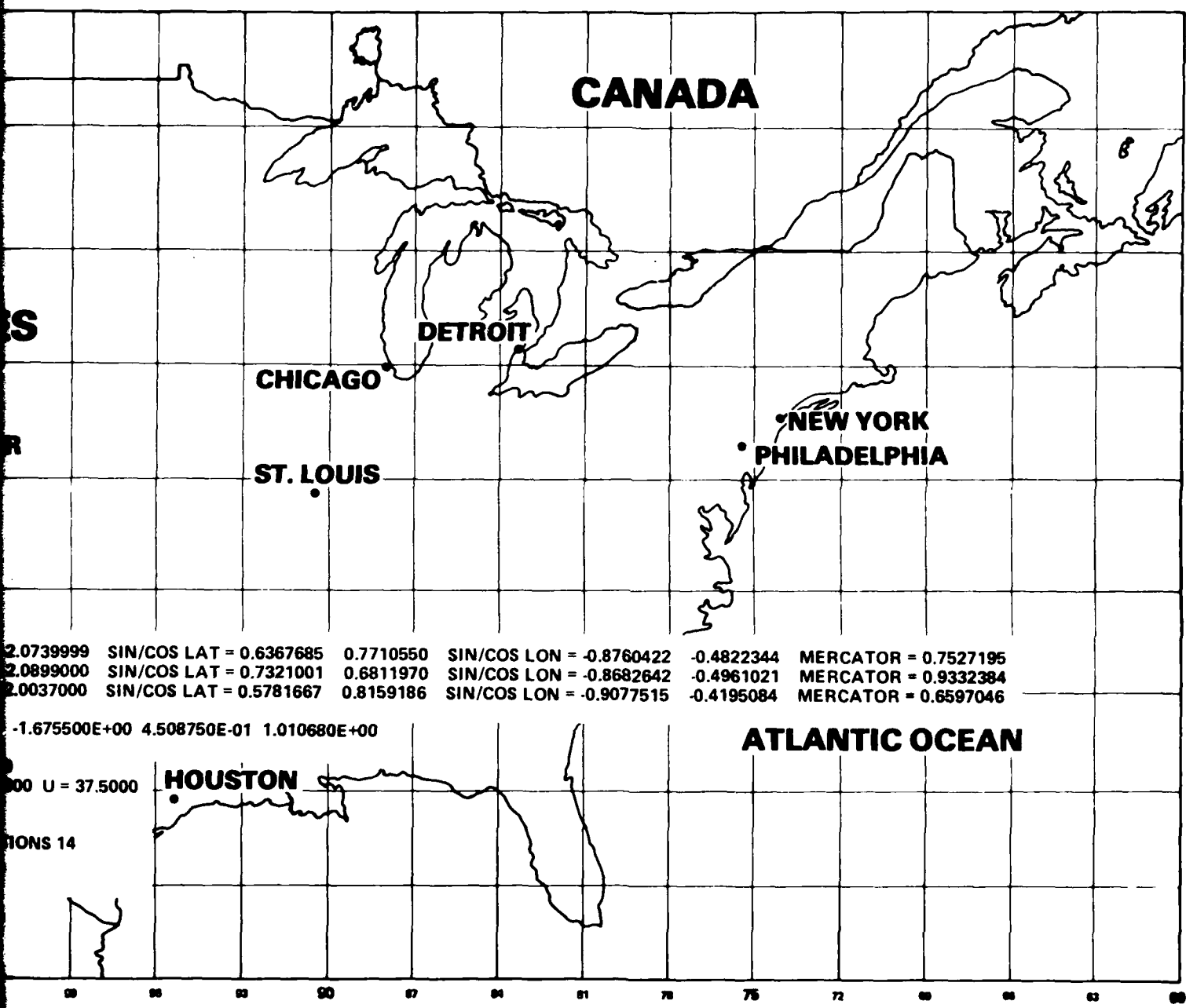
The analysis presented in this section shows that the Loran Navigation System will meet the required levels of position accuracy if sufficient signal coverage is provided.

4.3.3 Receiver Performance After Signal Loss

4.3.3.1 Purpose - The purpose of this task is to develop performance criteria for the receiver which permit the unit to remain operable with up to a seven minute signal loss.

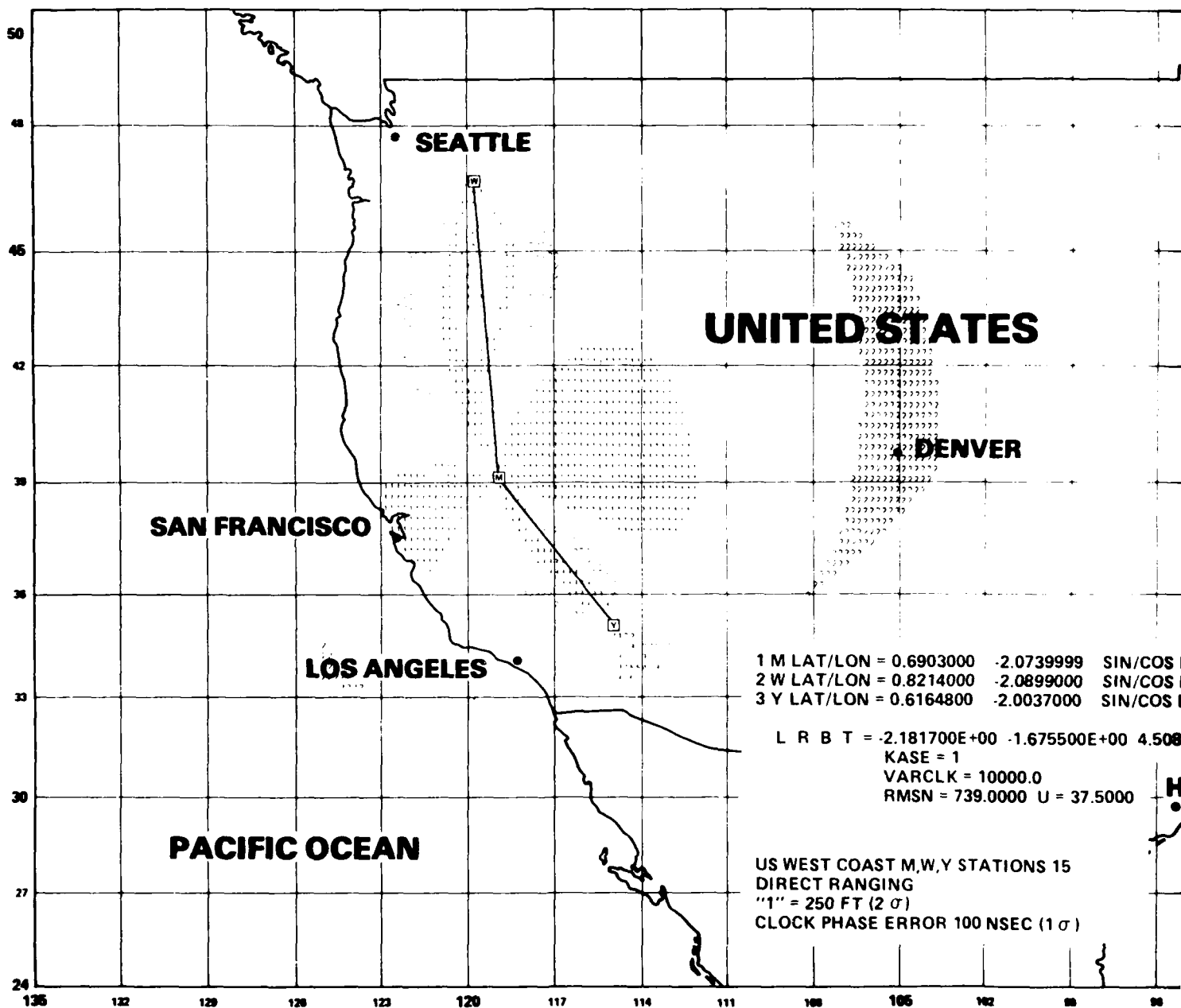


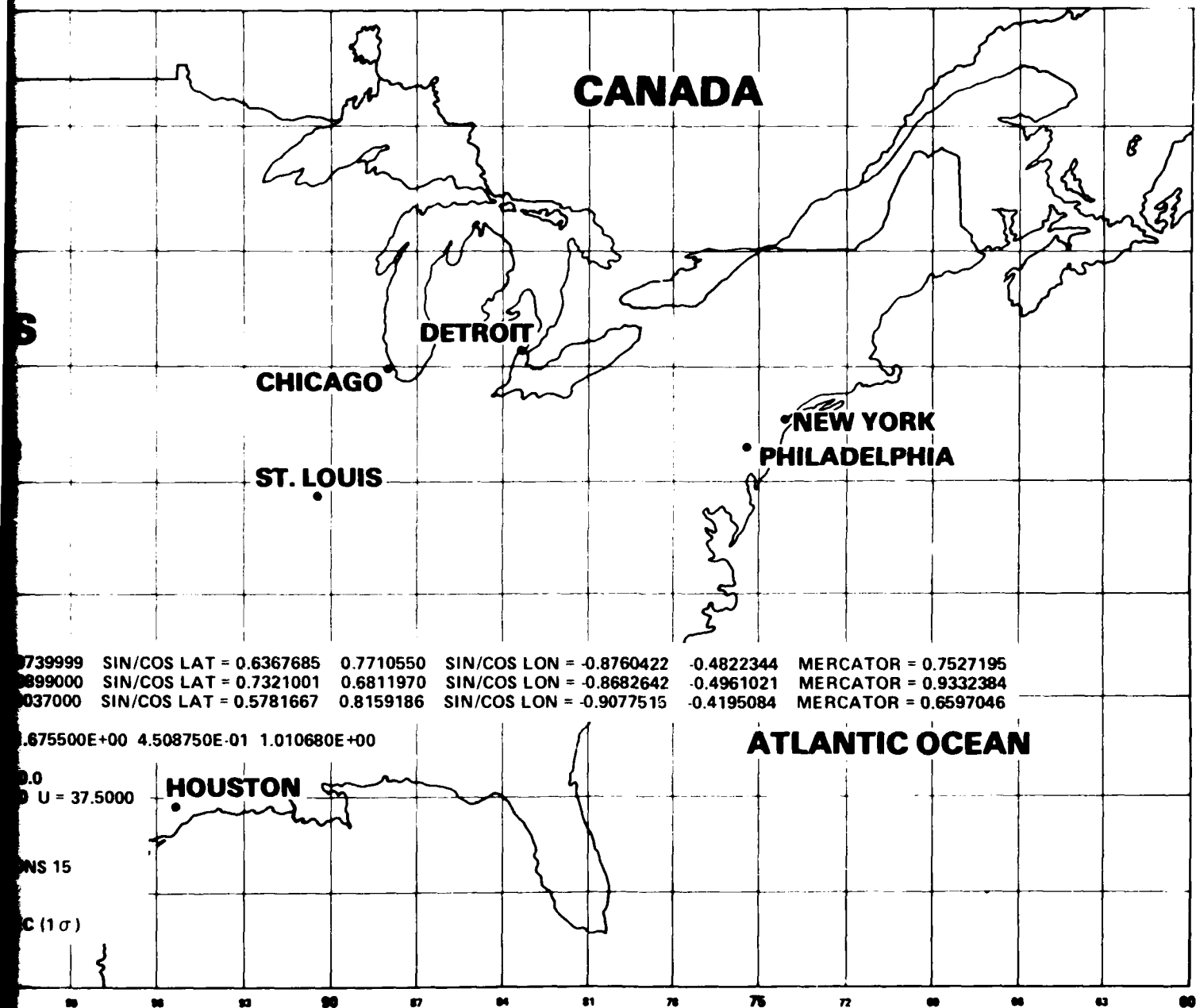
2



T134896-14

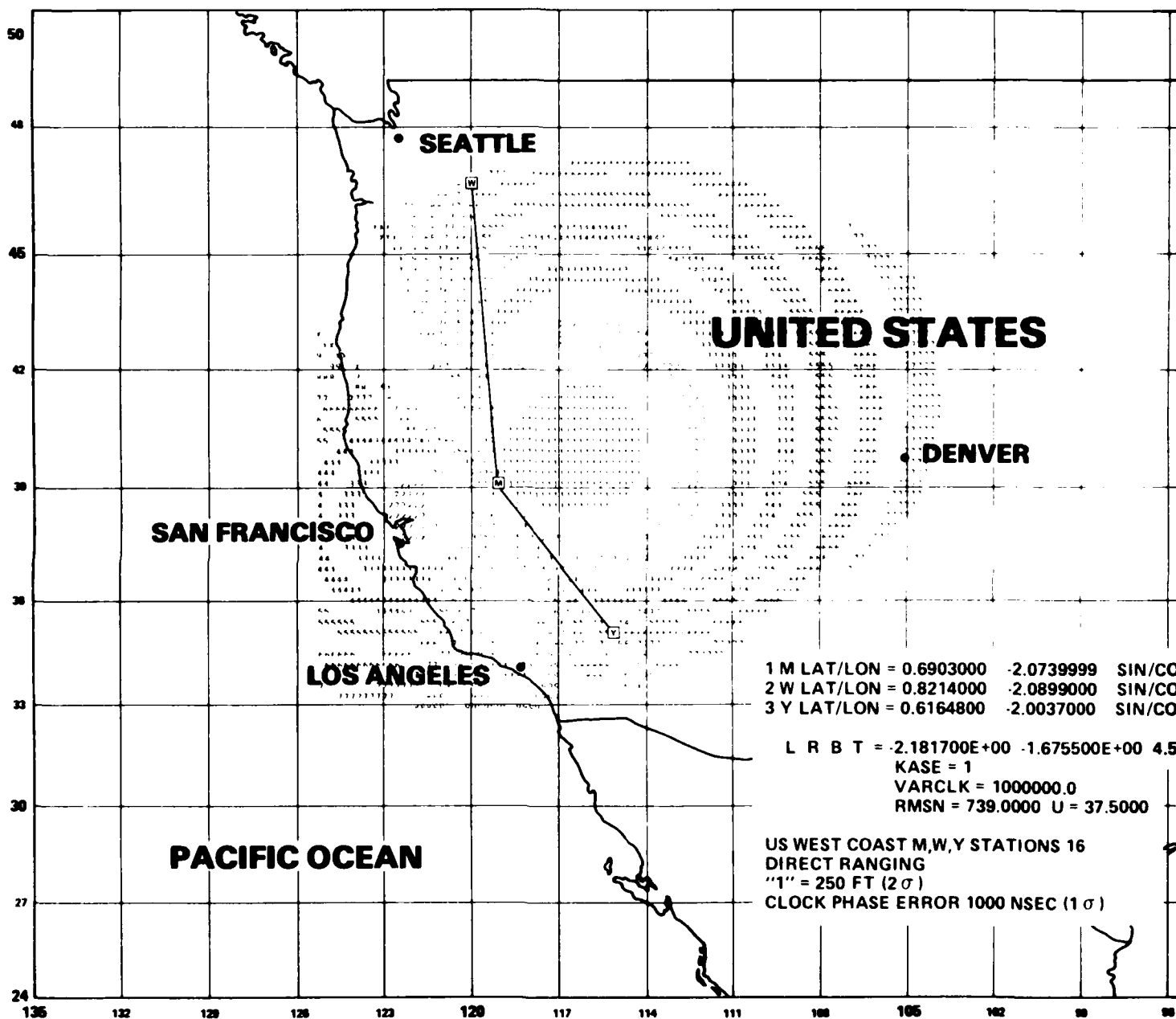
Figure 4-14. US West Coast M,W,Y Stations 14





T134885-15

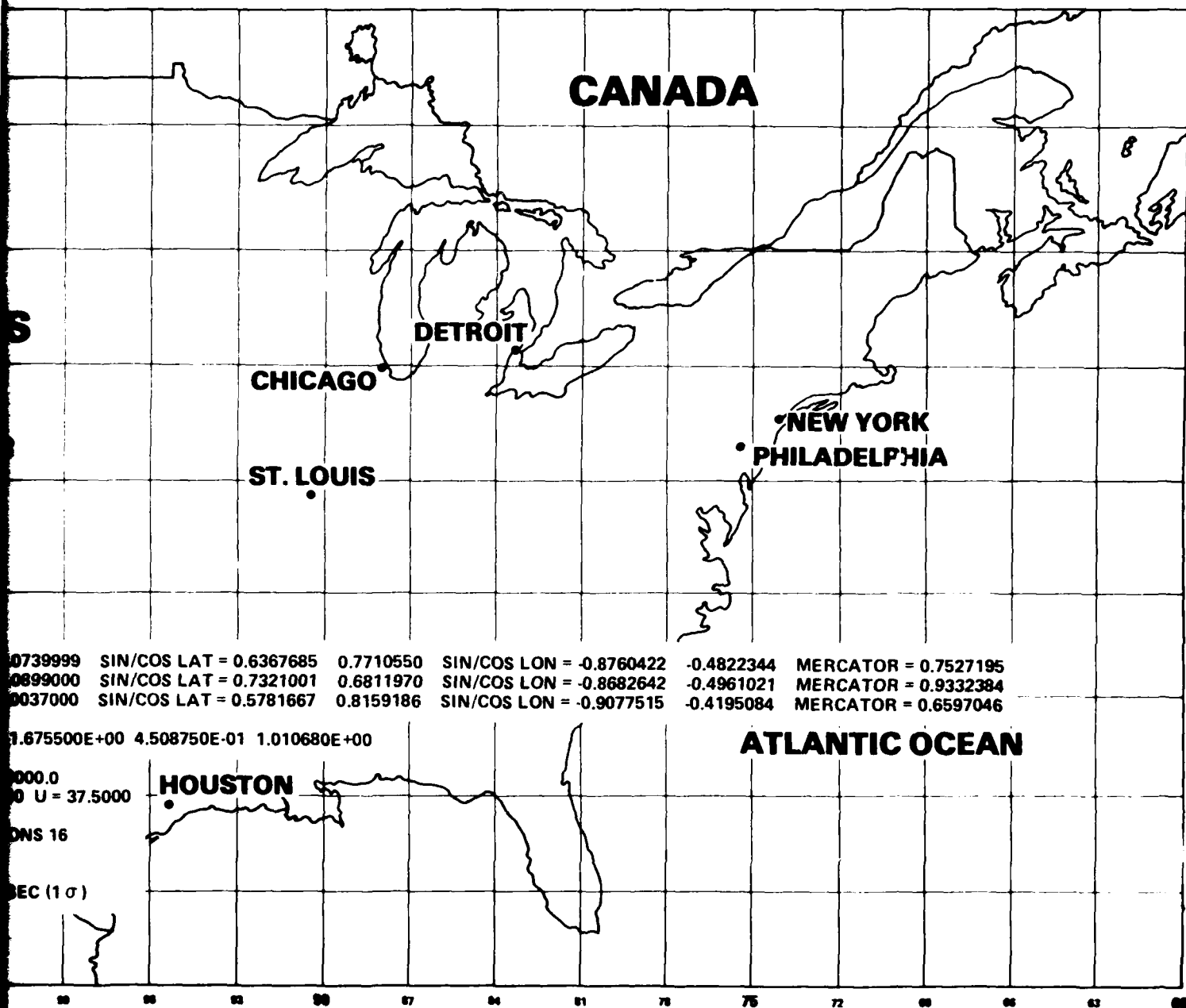
Figure 4-15. US West Coast M,W,Y Stations 15



1 M LAT/LON = 0.6903000 -2.0739999 SIN/CO
 2 W LAT/LON = 0.8214000 -2.0899000 SIN/CO
 3 Y LAT/LON = 0.6164800 -2.0037000 SIN/CO

L R B T = -2.181700E+00 -1.675500E+00 4.5
 KASE = 1
 VARCLK = 1000000.0
 RMSN = 739.0000 U = 37.5000

US WEST COAST M,W,Y STATIONS 16
 DIRECT RANGING
 "1" = 250 FT (2 σ)
 CLOCK PHASE ERROR 1000 NSEC (1 σ)



T134895-16

Figure 4-16. US West Coast M,W,Y Stations 16

4.3.3.2 Scope - The signal loss performance criteria study considered operations in the enroute, terminal area and non-precision approach operations in the NAS. The position determination study results from Section 3.1 were used in the development of the design constraints.

4.3.3.3 Assumptions - The analyses considered only the loss of a single station. Multiple station outages were considered to be a rare event (less than five minutes/year assuming 99.7% station reliability) which should not be used to impose additional constraints upon the receiver.

4.3.3.4 Requirements - Advisory Circular Number 90-45A provides guidelines for implementation of two-dimensional area navigation (2D RNAV) within the U.S. National Airspace System (NAS). This Advisory Circular provides for both VOR/DME dependent systems and self-contained systems such as Inertial Navigation Systems (INS) and even long range navigation system such as Loran-C. In developing these performance criteria it was necessary to establish route width requirements. Advisory Circular No. 90-45A provides these route width requirements based on a 95% (2σ) confidence level. These route width requirements are (note that these are assigned route widths and are not navigation accuracy requirements):

Enroute	4.0 nm
Terminal	2.5 nm
Approach	*1.9 - 0.6 nm

4.3.3.5 Method - In order to effectively evaluate the impact of the proposed Loran-C system certain worst case scenarios were developed to show the impact of a signal loss in the present day Air Traffic Control (ATC) system. These operational scenarios were developed to provide a realistic look at the limitations of the Loran-C system during a seven (7) minute signal loss. Scenarios were developed for three distinct airspace environments. They are: enroute, terminal and approach.

The receiver used in the analysis is assumed to lose its nominal navigation capabilities with the loss of signal and revert to a prediction method of navigation solution. The analysis determines whether this navigation method is or is not acceptable in the three airspace environments.

*Route width requirements change depending on the aircraft position along the approach path.

4.3.3.6 Analysis - The aircraft category chosen to be representative was a cabin class turboprop aircraft used in a variety of business applications. In all cases, aircraft operations are assumed to be single pilot, IFR flight plan operations using Loran-C equipment as the primary means of navigation with other radio navigation aids available as appropriate. The reason for selecting this type of aircraft is because of its high performance characteristics. That is, high altitude operations and high ground speeds. After sampling the speed ranges of many aircraft types and taking into account altitude effects and wind velocity, it was determined that a maximum ground speed of 400 knots would be encountered. Of course, in the terminal area and in the approach area lower ground speeds will be utilized for this analysis.

Enroute Scenario

This scenario assumes a pilot flying single pilot IFR in a Loran-C airspace environment. In this particular scenario the pilot is in level flight at an altitude of 20,000' when the Loran-C navigator becomes inoperative for a period of seven (7) minutes due to a total loss of signal. The pilot is assumed to be on the centerline of an airspace route width of ± 4.0 nm, when the signal is lost. The purpose of this scenario is to determine what the pilot must do during this seven minute signal dropout to remain within the established airspace requirements.

Figure 4-17 presents in graphical form the enroute flight situation. If the pilot is flying under perfect conditions, that is, no wind, good weather and a well trimmed aircraft then holding the desired course by dead reckoning offers no immediate problem. The only thing the pilot is required to do is to hold the last course on the aircraft's directional gyro. On the other hand though, ideal conditions are rare because of constantly changing aircraft and weather conditions. Since the pilot is assumed to be flying in IFR, wind factors can be assumed. As shown in Figure 4-17, assuming a ground speed of 400 kts, the aircraft will cover a distance along the ground of approximately 47 nm in a seven minute time period. If the pilot is to remain within the specified route width of ± 4.0 nm then the aircraft's drift angle (DA) is restricted to 4.9° . If this value is exceeded then the pilot could be in violation of another aircraft's airspace.

To remain within these airspace requirements two solutions are available until normal Loran-C navigation can be resumed. First, the pilot can fly by means of dead reckoning. For this procedure to be effective the pilot must have a knowledge of the

aircraft heading and the current winds and direction. Second, the pilot can fly by navigational inputs to the CDI, supplied by prediction navigational routines based on velocity from the Loran-C navigation computer. These navigational routines will provide guidance inputs to the CDI based on previous position fixes. The navigation computer could simply, based on previous aircraft position, predict where the aircraft should be a short time later. Although not as accurate, for the short period of time these special navigation routines could be utilized, navigation should be accurate enough to keep the aircraft within the specified airspace requirements.

Terminal Area Scenario

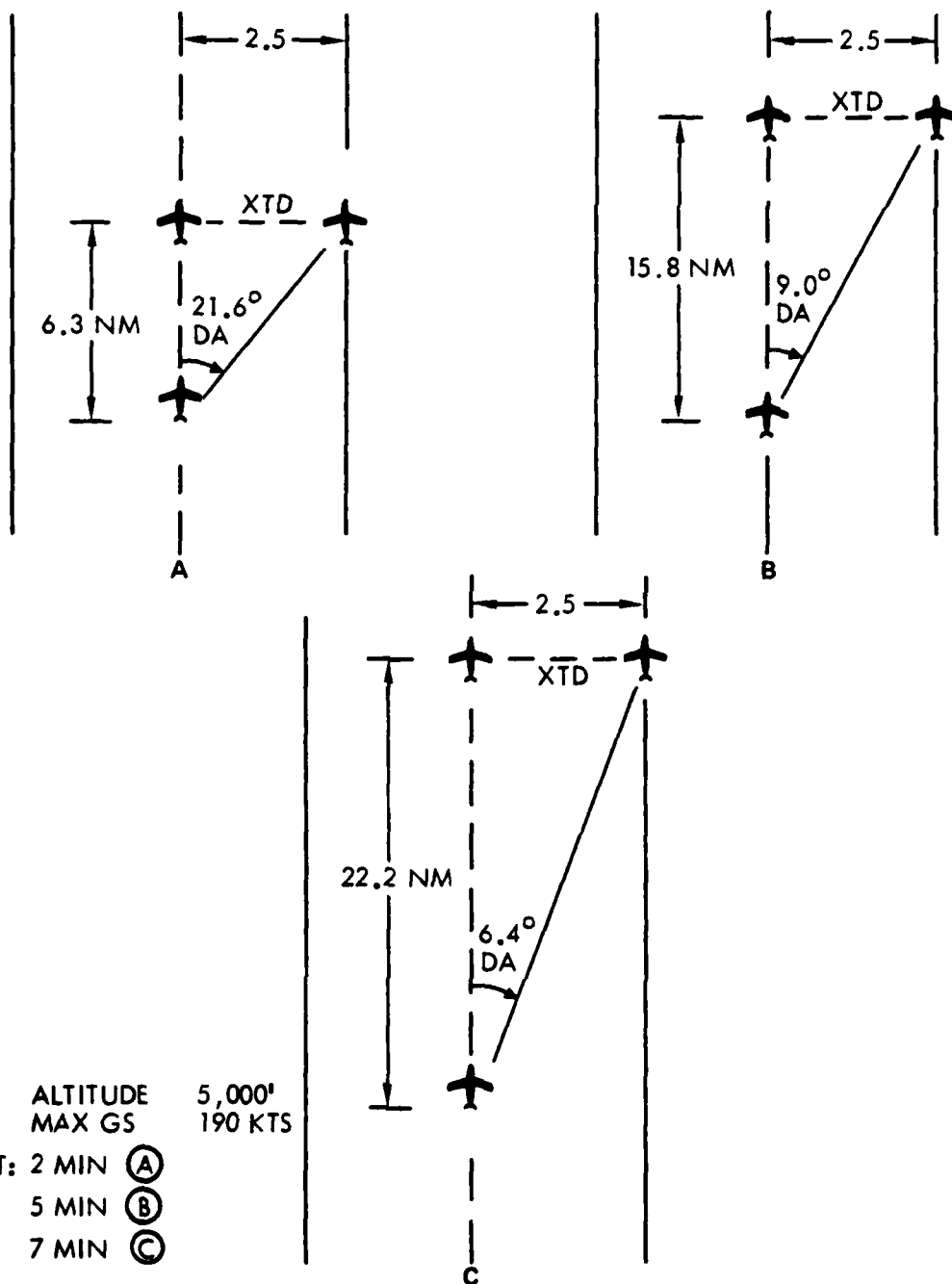
In the terminal area the route width is smaller than in the enroute phase of flight. Advisory Circular No. 90-45A has established a maximum terminal area route width of ± 2.5 nm. The terminal area is an environment which involves numerous aircraft, flying many different procedures. The question is, what accuracy must be maintained if the signal is lost for a certain period of time and if a station is out what procedures will be permitted? If some procedures are denied what should the pilot do?

To answer these questions several assumptions have been made concerning things such as altitude, ground speed and signal dropout duration. It is assumed that the aircraft is flying at an altitude of 5,000' with a maximum ground speed of 190 kts. In addition three signal dropout durations have been selected, 2 minutes, 5 minutes and 7 minutes. It is assumed that the pilot is flying into a congested terminal area and he is expected to transition for a Loran-C nonprecision approach.

Considering a signal dropout of 2 minutes and a 2.5 nautical mile route width, the pilot can be dead reckoning to effectively stay within the allotted route width. In this time period the aircraft has only travelled 6.3 nm along the ground and the pilot can fly as much as a 21.6° (Figure 4-18) drift angle and still be safe. Of course, as the signal dropout duration becomes longer the ground distance covered becomes larger and the allowable drift angle becomes smaller. For example, at five minutes the distance covered is 15.8 nm with an allowable drift angle of 9.0° , and with a signal dropout of seven minutes the distance covered becomes 22.2 nm with an allowable drift angle of only 6.4° . Trying to keep the aircraft within the allowable airspace limits, utilizing dead reckoning, with large signal dropout times would be difficult. Without dead reckoning there are only two alternatives left for the pilot to choose. They are to either navigate by radar vectors given by ATC or to use the prediction navigation routines described previously in the enroute area discussion.

ROUTE WIDTH: ± 2.5 NM

DISTANCE COVERED: 6.3 NM
15.8 NM
22.2 NM



TERMINAL AREA: ALTITUDE 5,000'
MAX GS 190 KTS
SIGNAL DROPOUT: 2 MIN (A)
5 MIN (B)
7 MIN (C)

Figure 4-18. Terminal Area Scenario

T134690

As mentioned, this type of navigation is not difficult in the enroute phase of flight because the aircraft is typically flying in a straight line. But in the terminal area where the aircraft is constantly changing heading, navigation based on previous position fixes is difficult or even impossible.

With this in mind it is recommended that certain procedures not be flown when there is a signal dropout. They are as follows:

- Holding Patterns
- Approach Transition*
- Procedure Turns

Without some type of positive position fix the procedures listed above cannot be flown safely and effectively. All of these procedures require the pilot's knowledge of some sort of predetermined, ground oriented, position fix. The only real solution to the problem, assuming that Loran-C is the only source of navigation, is to fly via radar vectors supplied by ATC.

Non-Precision Approach Scenario

The approach phase of the flight is probably the most critical phase of flight. Typically most non-precision approaches are flown using only altitude, along track and cross track indications. In addition time is an important factor if no along track information is available. A normal non-precision approach will only take approximately 6 minutes from the Final Approach Fix (FAF) to the threshold at a moderate ground speed. If for some reason the Loran signal was lost for a period of seven minutes obviously the approach would be impossible to execute. For this reason, and because of the relatively short distance covered at low altitudes, only a one minute signal dropout can be tolerated on approach. Without course guidance certain procedures are impossible to fly such as procedure turns, etc. The only alternative, if there is a large signal dropout period, is to abort the approach and fly the approach only when the signal is required.

4.3.3.7 Results - The results of the operational analysis indicate that satisfactory navigation performance is not possible in the terminal and approach phases of flight if a station loss produces a loss of normal position determination and navigation

*Approach transition could include transitioning to an ILS or some other type of approach.

functions. When this occurs, the receiver in question is no longer capable of supporting many necessary navigation support functions. This type of receiver is therefore, considered unacceptable for operation in the NAS.

4.3.3.8 Performance Criteria - The analysis has shown that the receiver that loses navigation capability when a single station is lost is unacceptable in many NAS operations. The antithesis of the receiver described in the analysis is one that continues to remain operable when one station is lost. This capability implies that the receiver be able to track more stations than are necessary for basic position determination.

In practical terms this performance criteria implies the capability to track and use, if required, all stations in a chain that are within reception range. It also implies that some form of master independent operation be utilized in case the non-functioning station is a master.

4.3.4 Information Update Rates

4.3.4.1 Background - The purpose of this effort is to determine optimum information and display update rates for the low cost Loran-C receiver.

The scope task encompassed analog displays, digital displays and autopilot interface signals.

The following documents were used in the analysis of the information update rates:

- a. "Minimum Operational Performance Standards (MOPS) For Optional Equipment Which Displays Non-Radar Derived Data on Weather and Ground Mapping Radar Indicators-Proposed Final Draft"; SC-133/Radio Technical Commission For Aeronautics; RTCA Paper No. 252-80/SC 133-128, October 1980.
- b. "Draft 3 of Supplement 4 to ARINC Specification 429, Mark 33 Digital Information Transfer System (DITS)", Aeronautical Radio, Inc., April 23, 1980.

4.3.4.2 Requirements - There are no specific requirements concerning information and display update rates for avionics at this time. RTCA has discussed this topic in Document #1 and ARINC/AEEC has described maximum and minimum rates for signals on their Specification 429 bus. These rates are discussed in the analysis.

4.3.4.3 Analysis - An increasing important aspect of aircraft instrumentation design is the determination of optimum display update rates. This realignment of priorities has occurred as the result of the introduction of digital avionics into the aircraft instrumentation market. Analog displays generally work on a continuum concept facilitating the need for rapid updating of source information in order to increase smoothing of the display presentation. Digital display presentations, on the other hand, utilize a discrete concept for information transfer. Displays of this type must remain unchanged for a sufficient period of time to enable pilot/operator assimilation of the data presented. Specific time intervals required depend on a variety of factors, including the data length of the display itself. Current cockpit configurations commonly employ both analog and digital displays, with a common data source supplying basic information to both types of displays. An example of this is a navigation computer unit supplying basic information to both a CDU digital display and a standard CDI display.

RTCA-SC 133 Radar Update Rates

Rather than attempting to formulate a single update rate which is marginally acceptable to both analog and digital displays, it would be desirable to employ two different update rates. For the purposes of this discussion these rates will be termed information update (analog related) and display update (digital related). Although information update rates approach an optimum as speed increases, little has been published recently about optimum display update rates.

Information update generally occurs no slower than about five times per second in most computer navigation systems in common use today. Although no specific time related minimum standards have been established for area navigation system certification, the subject has been addressed by Radio Technical Commission for Aeronautics (RTCA) Special Committee 133 (SC133) in regards to display of auxiliary information on cockpit radar displays [1].

"For data that is affected by aircraft motion, the equipment must provide new data for display at least two times per second. If the availability rates of other data are lower than that, the equipment need only supply data at the lower rate".

Indications are that this rate may in the long term become a minimum standard for information update rates relating to aircraft movement. It should be emphasized that this rate would require some artificial smoothing to accommodate an analog display and faster rates should be adapted in avionics design if possible.

Little recent empirical research has been accomplished in the area of determining optimum display update rates. As was mentioned above, this value is dependent on complexity of the information being presented and the "readability" of the presentation. Display update must be slow enough to allow the operator to assimilate the information presented but fast enough to not incur a significant information lag. In the case of a six digit longitude position, display update rates should be approximately one per second. Although less complex information, such as miles to go might be accommodated by a faster rate, the system should be designed to accommodate the most complex data being presented. In the interest of design simplicity it is also recommended that the display update rate be an even multiple of the information update rate.

ARINC/AEEC Recommended Update Rates

The establishment of navigation related update rates has been specifically addressed by the Airlines Electronic Engineering Committee (AEEC) of Aeronautical Radio, Inc. (ARINC) in Supplement 4 to ARINC Specification 429 [2]. Although the standards presented in this document apply specifically to airline quality systems, they can often indicate optimum parameter values to be applied to the design of general aviation equipment.

Attachment 2 of this document [2] establishes minimum and maximum transmit intervals to be used in the design of ARINC standard Mark 33 Digital Information Transfer Systems (DITS). As is pointed out in a commentary in Section 2.4.2:

"The time intervals between successive transmissions of a given BCD word specified in Table 1 of Attachment 2 to this document are, in general, too short for the signal to be of use in driving

a display device directly. If the signal was so used, the least significant character of display would change too rapidly for human perception. Considerations other than human factors demand the time intervals specified. Thus display designers should incorporate into their devices means for selecting those words to be used for updating the display from the greater quantity delivered".^[2]

Maximum transmit intervals (MTI) are directly comparable to minimum acceptable update rates (MAUR), (i.e., and MTI of 500 ms equates to an MAUR of 2 times/sec). These values are considered to be the minimum design standards required for functional operation. Minimum transmit intervals (or maximum update rates), on the other hand are specified to control bus loading and to improve bus efficiency. In all cases, minimum transmit interval values are exactly one half of the maximum transmit interval values.

Specific transmit intervals are listed for each parameter addressed in Attachment 2 of the above mentioned document^[2]. Reference to this document should be made for the specific parameter of design interest. Generally, the largest value recommended for navigation related parameters is 500 ms for maximum transit interval (present position, set latitude, set longitude, set magnetic heading, true heading, track angle-magnetic, estimated time of arrival, wind direction-magnetic, and true airspeed). This indicates that information update rate of two times per second should be adequate to meet the minimum specifications as recommended in ARINC Specification 429. If the Low Cost Loran-C Receiver is to be built to ARINC Specifications attention should be directed to other navigation related parameters in Attachment 2^[2].

Effect of Update Rates on Aircraft Control

Digital update rates have a definite influence on the smoothness of aircraft control, regardless of whether the digital output interfaces with an autopilot or a standard course deviation indicator. Additionally, display update rates will have an effect on total system along track errors in general and could influence cross track errors in the immediate vicinity of turnpoints. These factors will have a minimal amount of effect under the current design recommendations of update rates of at least two times per second.

Control smoothing in an automatic or autopilot mode could be critical in a highly responsive autopilot system. Aircraft autopilots, however, are designed to smooth erratic inputs and are not generally adversely affected by a two Hertz signal input. Course deviation indications on the pilot's instrument panel may be more sensitive to a smooth input. Because of the stability of the basic Loran-C signal, CDI movement should not be effected by unsmoothed update rates on the order of two Hertz except in a changing deviation situation. This specific situation will produce consistent but discrete CDI movement. If update rates are too slow this discrete movement will be observed by the pilot, leading to distraction and possibly distrust of his instrumentation. Aircraft control instrumentation should reproduce actual aircraft movement as faithfully as possible. This can be accomplished through either faster update rates or signal smoothing software algorithms.

Theoretically update rates can influence the amount of along track error which is operating on the aircraft/ATC system at any one time. Practically this influence is minimal at the recommended two Hertz display update rate. This rate will incur a .018 nautical mile along track error for each 100 knots of aircraft ground speed. This figure is insignificant in the along track direction in today's ATC system.

4.3.4.4 Summary - In summary the minimum information update rate currently found in the industry is two Hertz. This figure should be considered an absolute minimum and rates on the order of 5 to 10 Hertz are to be preferred.

Display updates on the other hand should be no faster than 2 Hertz and no slower than 1 Hertz. These rates represent an accommodation of information assimilation by the pilot and minimization of information lag for accuracy purposes.

4.3.5 Navigation Parameter Accuracy and Resolution

4.3.5.1 Purpose - The purpose of this task is to identify navigation and operational parameters that must be computed and displayed, and to determine the resolution and accuracy of these parameters.

The parameter specification task was limited to operations within CONUS and the offshore areas bordering CONUS. With slight modifications to the position parameters (latitude/longitude) the specifications could apply on a world-wide basis.

The parameters identified in this section are limited to general aviation aircraft whose groundspeed would not normally exceed 400 knots and whose range between legs would not exceed 1000 nautical miles.

Reference Documents -

- a. ARINC Characteristic #582, "Mark 2 Air Transport Area Navigation System"
- b. Assorted brochures from general aviation navigation equipment manufacturers

4.3.5.2 Requirements - Current RNAV accuracy standards are contained in FAA Advisory Circular 90-45A, "Approval of Area Navigation Systems for Use in the U.S. National Airspace System." These standards are stated in terms of along track and cross track accuracy for enroute, terminal and approach phases of flight. These standards are:

<u>Airspace</u>	<u>Total System Accuracy</u>	
	<u>Along Track</u>	<u>Cross Track*</u>
Enroute	±1.5 nm	±2.5 nm
Terminal	±1.1	±1.5
Approach	±0.3	±0.6

*Includes Flight Technical Error

This study was performed by surveying current airline standards for RNAV systems as developed by ARINC/AEEC and currently available RNAV systems. The standard current practices were then reviewed and modified as necessary to be consistent with the general aviation operational environment.

4.3.5.3 Analysis -

ARINC Navigation Parameter's Accuracy and Resolution Figures

This subsection will describe the accuracy and resolution of certain computed navigation parameters required by the low cost Loran receiver. These signal characteristics were obtained from the Airlines Electronic Engineering Committee, ARINC Characteristic 582 ("Mark 2 Air Transport Area Navigation System"). The signal characteristics are provided in two different formats: digital and analog.

Digital Outputs

- Distance-to-Go
 - Range 0 to 3999.9 nm
 - Resolution 0.1 nm
 - Signal Format BCD
- Time to Go
 - Range 0 to 399.9 minutes
 - Resolution 0.1 minute
 - Signal Format BCD
- Ground Speed
 - Range 0-2000 Kts
 - Resolution 1.0 Kt
 - Signal Format BCD & BNR
- Present Position
 - Range Lat 0° - 90° N, 0° - 90° S
 - Long 0° - 180° E, 0° - 180° W
 - Resolution 0.1 Arc Minute
 - Signal Format BCD & BNR
- Cross Track Distance
 - Range 0 - 299.9 nm Left or Right
 - Resolution 0.1 nm
 - Signal Format BCN & BNR
- Desired Track
 - Range 0° to 360°
 - Resolution 0.1°
 - Signal Format BCD
- Track Angle
 - Range 0° to 360°
 - Resolution 0.1°
 - Signal Format BCD & BNR
- Drift Angle (DA)
 - Signal Format BCD
- Track Angle Error (TKE)
 - Signal Format BCD

Analog Outputs

- **Desired Track**
 - Range 0° to 360°
 - Resolution 0.1°
 - Accuracy ±0.5°
 - Type 3 wire synchro
- **Track Angle**
 - Range 0° to 360°
 - Resolution 0.1°
 - Accuracy 0.5°
 - Type Synchro
- **Drift Angle**
 - Range 0° to ±39.9°
 - Resolution 0.1°
 - Accuracy 0.5°
 - Type Synchro
- **Track Angle Error**
 - Track Angle Error 0 to 180°
 - Resolution 0.1°
 - Accuracy 0.5°
 - Source Synchro
- **Cross Track Deviation**
 - Type DC Voltage
 - Sensitivities (HSI) Adjustable
 - Enroute 1 to 3 nm/DOT
 - Terminal 1/2 to 1 nm/DOT
 - Final App 300 to 1500 ft/DOT

Output 1

- Range 0 to ±3V
- Resolution 5 MV
- Accuracy ±1%

Output 2

- Range 0 to ± 200 microamperes
- Resolution 0 to microamp into 100Ω load
- Accuracy 10 microamperes

Output 3

- Range 0 to 6 volts
- Resolution 6 MV
- Centering Accuracy 12 MV

General Aviation RNAV Resolutions and Accuracies

The low cost Loran receiver will probably display and compute navigation parameters to resolutions and accuracies comparable to existing RNAV systems. A survey of some general aviation RNAV systems has yielded the following display accuracy and resolution figures. These figures are based solely on existing equipment and are only offered as a guideline for the low cost Loran receiver accuracy figures.

Bendix

BX 2000

- Bearing Display Accuracy $\pm 1^\circ$
- Distance Display Accuracy ± 0.3 nm $\pm 1\%$ of Distance
- GS Display Accuracy ± 10 kts (100-600 kts)
- Time to Station Display Accuracy ± 1 min $\pm 4\%$ (0-100 nm)
- Left/Right Deviation Output $\pm 2^\circ$ w/course centered

Foster Air Data

AD611

- Range to Waypoint Accuracy $\pm (2\% \text{ of Range } + 0.3 \text{ nm})$
- Bearing (BRG) to Waypoint Accuracy $\pm 1^\circ$
- Range Resolution 0.1 nm
- Bearing Resolution 0.1°

RNAV 511

- Waypoint Setting Resolution $0.1^\circ / 0.1$ nm
- DTW Accuracy ± 0.2 nm

4.3.5.4 Performance Criteria - In the development of any type of navigation system it is necessary to develop a set of accuracy and resolution specifications for the selected parameters. The parameters selected were based on current designs and ARINC specifications. In addition, certain new parameters have been introduced based on the low cost Loran-C design. Namely the acquisition status group repetition interval (GRI), and TRIAD parameters. The parameters are used for selecting one or more chains and selecting sets of stations within a chain. The following list presents the selected navigation parameters with their associated range, resolution and accuracy specifications.

- **Waypoint**
 - Range Lat 0° - 90° N, 0° - 90° S*
 - Long 0° - 180° E, 0° - 180° W*
 - Resolution 0.1 ARC Minute
 - Accuracy 0.1 ARC Minute
- **Present Position**
 - Range Lat 0° - 90° N, 0° - 90° S*
 - Long 0° - 180° E, 0° - 180° W*
 - Resolution 0.1 ARC Minute
 - Accuracy 0.1 ARC Minute
- **Cross Track Distance**
 - Range 0 - 399.9 nm Left or Right
 - Resolution 0.1 nm
 - Accuracy 0.1 nm
- **Parallel Offset Distance**
 - Range 0 - 20.0 nm Left or Right
 - Resolution 0.1 nm
 - Accuracy 0.1 nm
- **Group Repetition Interval (GRI) or Chain No. (If required)**
 - Range 4000 - 9999 1 - 20
 - Resolution N/A
 - Accuracy N/A
- **TRIAD (If required)**
 - Range Combination of any three station numbers or codes
 - Resolution N/A
 - Accuracy N/A

- **Distance Between Waypoints**
 - Range 0 to 999.9 nm
 - Resolution 0.1 nm
 - Accuracy 0.1 nm
- **Distance-To-Go (Range)**
 - Range 0 to 999.9 nm
 - Resolution 0.1 nm
 - Accuracy 0.1 nm
- **Bearing**
 - Range 0° to 360°
 - Resolution 0.1°
 - Accuracy 0.1°
- **Estimated Time Enroute (ETE)**
 - Range 0 to 399.9 Minutes
 - Resolution 0.1 Minute
 - Accuracy 0.1 Minute
- **Ground Speed (GS)**
 - Range 0 - 999 kts
 - Resolution 1.0 kt
 - Accuracy 1.0 kt
- **Acquisition Status**
 - Range 0.9
 - Resolution N/A
 - Accuracy N/A

4.3.6 Recognition and Warning of Unacceptable Conditions or Performance

4.3.6.1 Purpose - This study effort was aimed at determining under what conditions the low cost Loran-C receiver should provide warnings of unacceptable navigation performance or unsuitable conditions.

The survey of unacceptable performance conditions includes the transmission of the Loran-C pulse, external noise and interference factors, monitoring of the signal by Coast Guard facilities, and the reception and processing of the signal by the airborne system.

It was assumed that the Loran-C stations and chains, both those in existence and those new chains required for CONUS coverage, would be operated in accordance with current U.S. Coast Guard practices including pulse shapes, formats, timing control and blink.

Applicable Documents - "Minimum Performance Standards-Airborne Loran-A and Loran-C Receiving Equipment", RTCA DO-159, October 17, 1975.

4.3.6.2 Requirements - The only current requirement concerning warning signals for RNAV systems is contained in Advisory Circular 90-45A. This document states:

"Failure Warning. Provision should be made to alert the crew upon occurrence of any probable failure of major system functions or loss of inputs, including those that would affect aircraft position, heading, command course, command heading, altitude, or vertical guidance indications."

A survey of the various elements of the Loran-C system from the transmitter through the receiver navigation output and display was performed. These areas that could be used for problem recognition were identified.

4.3.6.3 Analysis - The conditions for unacceptable navigation are divided into five categories; signal level, signal contamination, signal format, geometry, and continuity.

Signal Level

When the received signal level from a station used for position determination drops below a predetermined detection threshold for a period of 2 seconds or longer the receiver must detect this condition and provide a status signal that can be used by other sections of the receiver to take appropriate corrective action or to warn the pilot that position determination and navigation are not available. Examples of corrective action include reversion to rho-rho navigation or switching to other acceptable stations.

A received signal which exceeds the upper threshold of the receiver must also be detected and flagged by the receiver. Strong signals which occur when passing close to a transmitting station can damage electronic components, drive some circuits beyond their specified range, or contain unwanted near field components of the signal and produce errors in the measurement of the time difference value.

Signals which exhibit an excessive variation must be signaled by the receiver as being invalid. Typically these signals have a fractional percentage of successful detections, that is, the signal level is sufficiently high on some pulses to permit a successful third cycle detection and not high enough on other pulses to permit successful detection.

Signal Contamination

The Loran-C signal may be contaminated by noise or interference. This contamination may be from within the band or outside the band. The interference can be self-generated by cross rate signals from other Loran-C chains or from a double-rated station. Band limiting and notch filtering may be effective for some types of noise and interference. However, in some instances these means of noise and interference rejection may not be totally effective and an unsuccessful detection of the third cycle zero crossing will occur. In these instances a status signal should be provided by the receiver detection circuitry to alert other sections of the navigator system or the pilot of improper signal processing. The status signal can be used to take corrective action as described in the signal level section, or to alert the pilot that the navigation information is unavailable.

Signal Format

The acquisition section of the receiver must provide a status signal when the receiver is unable to acquire Loran-C signals. In addition the tracking section of the receiver must detect missing pulses so that a station on blink status can be recognized. The receiver should also be able to detect situations when envelope-cycle discrepancy exceeds specified limits. Such situations indicate severe pulse distortion which may be caused by multipath or synchronous interference.

Geometry

Two geometrical situations must be recognized by the position determination portion of the receiver. The first is proximity to a Loran-C transmitting station used in the

positioning algorithm. Station distances of less than a specified distance should be detected by the receiver and a status signal should be set.

The second geometrical condition to be detected is unfavorable line of position geometry. This situation occurs on baseline extension regions and at locations in the coverage area where the lines of position, hyperbolic or circular, diverge. Recognition of this situation logically should take place in the position determination sections of the receiver. A status signal should be provided for this purpose if navigation is based upon a signal with poor geometry.

Continuity

Because the aircraft moves through the Loran-C coverage at a speed which is less than some estimated upper speed limit, it is possible and desirable to test the time difference and position information for continuity. Changes in these parameters which exceed some specified upper bound should be detected by the receiver and a status signal should be activated. Parameters which could be tested for continuity include time of arrival (for rho-rho operation), time difference (for hyperbolic operation), latitude/longitude position, cross track deviation and distance to go to the waypoint.

4.3.6.4 Performance Criteria - Performance criteria for the low cost Loran-C receiver shall be as follows:

Signal Level, Signal Contamination, and Signal Format

The receiver shall produce a warning signal when it has lost sufficient signals so that it is incapable of determining a position fix whose estimated fix error is less than 0.3 nm.

Geometry

The receiver shall produce a warning signal when the estimated fix error exceeds 0.3 nm due to poor line of position geometry.

The receiver shall disable, from the position determination process, any station within 6 nm of the receiver or whose signal level exceeds the dynamic range of the receiver front end.

Continuity

The receiver shall produce a warning signal when the change in indicated position of the aircraft shows that the aircraft ground speed exceeds 1000 knots in a time period not to exceed five seconds.

Warning Indicators

Currently there are a total of five warning lights which are being considered for incorporation.

- Failure - indicates that the receiver is unable to provide satisfactory navigation information with the stations being tracked.
- Triad - indicates that a selected station has been lost or that station geometry is poor and another triad or chain should be selected (this warning is not required for automatic station selection mechanizations).
- No Approach - indicates that for some reason (blink, signal degradation, poor geometry, etc.) navigation is only recommended in the enroute (ENR) mode and not in the approach (APP) mode.
- Seq W/P (TO-TO type of system) - indicates that the next way-point pair should be selected.

Each of these warning lights is associated with specific recommended pilot action design to adjust to or alleviate the indicated malfunction. These actions are as follows:

- Failure - The action associated with this light will depend on the current navigation situation. If at all possible reference to alternate means of supplying navigation information to the pilot should be made. Enroute this light probably indicates system failure but re-evaluation of selected chain and triad should be accomplished as well as an attempt at inflight reinitialization. It should be emphasized that navigation data obtained from the computer should not be trusted when this light is illuminated.

- Triad - This would indicate that a change in triad station selection should be made as soon as possible. Computed present position should be considered to be degraded in accuracy but reasonable (not required for receivers with automatic station selection).
- No Approach - With this light illuminated, the system should not be relied upon for approach navigation computations. If it is illuminated in conjunction with another warning light the corrective action associated with the other light will generally extinguish the no approach warning light. If the light cannot be extinguished, the system should not be used to provide primary navigation data for an instrument approach.
- Seq W/P - When this light illuminates the pilot should select the next waypoint pair needed for navigation.

While each of the above described warning indicators provides valuable information to the pilot, it was finally concluded that all non-essential indicators should be deleted and each of the warnings handled in the following manner:

- Failure - Incorporate this light on CDU. Also display Failed (or OFF) flag on steering indicator.
- Triad - Unnecessary due to automatic station and triad selection.
- No Approach - If when the approach mode is selected the system is not accurate enough to support the approach to landing mode then the failure warning will be displayed.
- Seq W/P - Eliminate the light on the CDU. Flash the TO-FROM flag on the steering indicator.

4.3.7 Capability to Use Differential Corrections

4.3.7.1 Purpose - The purpose of this study task is to determine if differential corrections are necessary in the low cost Loran-C receiver and, if so, what method should be used to enter the differential corrections.

The analysis included considerations of differential corrections as opposed to improve propagation modeling. Manual input of differential corrections are also considered.

4.3.7.2 Requirements - There are no specific requirements for or against the use of differential corrections in airborne navigation systems. However the use of correction data input by the pilot is generally looked upon with disfavor by both pilots and certifying authorities.

This analysis made use of available studies on the propagation of Loran-C signals and propagation anomalies.

4.3.7.3 Analysis -

Differential Correction Methods

Several methods of including differential corrections in the position determination equations are possible. These include:

- propagation time or time difference corrections
- latitude/longitude or east-north corrections
- displaced latitude and longitude
- operational methods
- improved propagation modeling

The propagation time or time difference, depending upon whether range-range or hyperbolic navigation is used, utilizes an adjustment to the measured propagation time used in the position determination algorithm. Application of this technique is quite straightforward as the receiver makes the time measurement. The measurement is adjusted and then the adjusted value is used by the positioning equations.

This method requires that a correction value be available for each time or time difference signal being used in the position determination algorithm. For manual chain and station selection receivers this concept is operationally feasible. For receivers that automatically select and deselect stations, there must be correction values for all possible stations that could be used.

The latitude/longitude correction method is conceptually similar to the propagation time correction. The corrections are stated in terms of a latitude or north correction and a longitude or east correction. This is basically a change of coordinate systems for the correction.

As with the propagation time correction, the latitude/longitude corrections are station specific. The corrections apply to only one specific set of stations used in the positioning equations. Other station selections would require different correction values. Automatic station selection is not feasible utilizing this correction technique.

The displaced latitude and longitude is essentially the latitude/longitude correction method with the corrections already applied. This method suffers from the same deficiencies as the latitude/longitude correction with the added problem that Loran-C charts which contain the displaced values would be incompatible with other NAS charts.

Operational methods for differential corrections require that measurements be taken at known locations. The known coordinate locations are entered into the navigator computer and the system then determines the correction value. This technique suffers from the same drawbacks as the latitude/longitude correction method and adds additional workload on the pilot.

The final method of applying differential corrections is through the use of improved propagation modeling. Propagation times are affected by surface conductivity, surface terrain features, and atmospheric lapse rates. The major contributor to the variation in propagation time is surface conductivity. Improvements in propagation modeling would require compensation for conductivity. These methods would necessarily be internal functions within the computer and would require storage of a conductivity related, propagation correction data base. The use of the method would be transparent to the pilot and would produce no increase in pilot workload nor be susceptible to pilot induced data entry errors.

Manual vs. Automatic Correction Methods

Manual entry of differential correction data creates additional workload on the pilot and is prone to data entry errors on his part. Data entry errors would produce erroneous position determination and produce navigation errors. This implies that the only way for accuracy standards to be assured is to develop a foolproof method for checking the accuracy of the entered data which implies some sort of parity check technique.

Automatic correction methods imply that a data base be stored in the computer.

4.3.7.7 Performance Criteria - The recommendation concerning the design of the low cost Loran-C receiver is for automatic propagation time correction methods. The type of correction method employed should be either improved propagation modeling or differential corrections stored for specific locations.

NOTE: As described in Section 3.4, an automatic propagation correction method will be used.

4.4 OPERATION AND DISPLAYS

Seven study and analysis tasks were performed to develop the control/display unit configuration and the course deviation indicator characteristics. The seven tasks areas are:

- receiver turn-on and initialization procedures
- data entry procedure
- cross track deviation indication
- display of pilot entered and navigation values
- chain transition procedure
- approach display requirements
- display of receiver operational status

Completion of these seven tasks produced two candidate control/display configurations, one utilizing a latitude/longitude waypoint designation method, and the second utilizing a radial-distance designation from stored VOR locations. These two CDU concepts are both capable of operation in the NAS on single-pilot, general aviation aircraft. The lat/lon system is compatible with minimum computer data storage while the radial distance concept is most compatible with the current NAS airway structure. Final selection of the CDU design for the low cost Loran-C receiver should be based on the cost comparisons of the two units.

4.4.1 Initialization Parameters

4.4.1.1 Purpose - The purpose of this study effort is to determine the receiver turn-on and initialization procedures.

Loran-C initialization procedures must, because of the nature of the signals involved, be more complex than VOR/DME initialization, but these procedures should be kept as simple as possible for the general aviation user. The following items are considered to be the minimum required for initialization and positive location identification in the National Airspace System as it has been established.

- GRI
- Station Selection
- Position Initialization
- Station Locations
- Coding Delay
- Magnetic Variation

Additional items which should be considered depending on future regulatory requirements and final navigator configuration include:

- CDU Light Test
- System Logic Test (Self Test)
- Synchronization of On Board Clock (for rho-rho navigation)

Initial analyses were carried out for a receiver that had the capability for manual Loran-C station selection. Completion of the position determination study (Section 3.1) indicated automatic station selection is superior for the low cost receiver. The final CDU configurations reflect this change in design.

4.4.1.2 Requirements - There are no specific control/display unit requirements for system start-up on initialization at this time contained in either Advisory Circular 90-45A or RTCA DO-159.

The method selected for analyzing initialization procedures consisted of identifying candidate initialization parameters and procedures and subjecting these parameters to a pilot workload analysis.

4.4.1.3 Analysis - The input of initialization parameters into the navigator/computer can be categorized into three classes according to method of entry. GRI selection, station selection and position initialization should be manually input with

the pilot selecting those values which correspond to his estimation of his position and desired signal source. A position determination technique which provides for computer selection of chains and stations would cause the chain and station selection parameters to be dropped from the list of required initialization parameters. In this type of mechanization and with computer storage of constants, magnetic variation and CDU light tests the only required input parameter for initialization is present position. With non-volatile memory even this parameter would be needed only on an infrequent basis. Consequently, automation of the station selection process and use of non-volatile memory would considerably simplify the pilot input requirements for initializing the unit. Coding delays, station location, clock synchronization and system self tests (if any) should be stored in memory for automatic call up during initialization or whenever needed. Magnetic variation and CDU light tests can be either manual or automatic functions depending on software and memory constraints. Workload impacts should be minimal especially if a non-volatile memory is used to store computed values at system shut down. Generally speaking however, initialization procedures should be kept as uncomplicated as system constraints allow in order to instill a high level of inherent pilot confidence in the system.

Workload Analysis for Initialization Procedures

The task analysis technique of workload analysis is dependent on finalized design concepts for accurate quantitative results which are statistically definitive. Because the low cost Loran-C receiver project is currently in the early design phases, this analysis and all other workload analyses included in this report will be based upon numerous estimations and assumptions. The final results will thus be basically qualitative in nature although they will be presented in a quantitative format. Because of this constraint, all conclusions based on these results should be comparative in nature. In this particular analysis, evaluation of initialization procedures, a comparison will be made between a basic lat/lon design concept and a basic rho/theta design concept. In order to enable valid comparisons between the systems, as many parameters as possible will be maintained equivalent. Because of the nature of the intrinsic capabilities of each of the systems being evaluated, an exception to this experimental concept will be made in the designation of the lat/lon system as a TO-TO system and the rho/theta system as a TO-FROM system. This is in keeping with the expected operational application of each system concept. Aside from this exception, the two system interfaces will be kept as similar as possible.

In most operational situations the initialization process will be accomplished in a ground environment. Because of this, workload levels associated with it will be relatively non-stressful. The operator will generally have no time constraints and will be able to devote his full attention to the initialization process. On the other hand, any appreciable reduction in workload levels, ground or airborne, is an important consideration in development of a design concept for the operator interface.

Details of the task analysis technique used are presented in Appendix A of this report. This technique was applied to the CDU design concepts developed for both the lat/lon (TO-TO) system and the radial-distance (TO-FROM) system in this report. The following is a tabular listing of those results.

<u>Initialization Procedure</u>	<u>Lat/Lon System</u>	<u>Radial-Distance</u>
Turn-on and self test	4 Seconds	4 Seconds
Present Position Insertion	132 (4*)	37 (7*)
Station Acquisition	4	4
Waypoint Selection	6	4
	146 (18*) Seconds	49 (19*) Seconds

*Indicates workload associated with a system containing non-volatile present position memory at time of system shutdown

Examination of these results indicate that there is little difference between the systems if a present position memory capability is included in the system. Without this capability (i.e., present position goes to zero value at shutdown), workload levels are significantly higher for the lat/lon system. This is primarily because of a larger range of values involved in setting present position in latitude and longitude. Not shown on the above table is one aspect of the radial-distance system which could be considered either as a part of the initialization process or as a part of the inflight routine operation. This aspect is the input of the initial course to be flown in conjunction with initial waypoint selection. Workload for this aspect is minimal (approximately six units) and effects the overall workload insignificantly, particularly in the case of no present position storage capacity. For the purposes of this report initial course selection is not considered to be a part of the initialization process and will be included in the section evaluating total system input requirements.

4.4.1.4 Performance Criteria - Performance criteria in the form of candidate initialization display and control mechanizations are contained in Section 4.4.8.

4.4.2 Data Entry Procedure

4.4.2.1 Purpose - The purpose of this effort was to define the data entry procedure. This analysis is closely related to the tradeoff analysis of waypoint designation methods described in Section 3.5.

Data entry procedures were developed for both the lat/lon and radial-distance waypoint entry methods.

The chain constants (station locations and coding delays) were assumed to be resident in computer memory. Also non-volatile memory was assumed with the capability to retain the aircraft position and waypoints when the computer is shut down.

4.4.2.2 Requirements - There are no specific requirements for data entry procedures in FAA Advisory Circular 90-45A or RTCA DO-159.

4.4.2.3 Analysis - This analysis was performed by identifying parameters that are required to define waypoints, select legs, select stations and chains and to otherwise operate the receiver in the NAS. Candidate CDU configurations were developed and scenarios were developed in which the data input functions were performed in a pilot workload analysis.

Pilot Entered Data

Results of the workload analysis for the low-cost Loran-C receiver set will be heavily dependent on the number of data items which must be manually input, data complexity and the number of repetitions the pilot must make during a typical flight. One of the first tasks in the design of a computer control system is to determine what type of data will have to be input. At this point in the design, two navigator configuration concepts are seriously considered for the low-cost Loran-C receiver, a latitude/longitude (Lat/Lon) configuration and a rho/theta configuration. Both

concepts will utilize the same basic navigation software with the primary difference being in data entry and display format. The lat/lon concept has the advantage of being more compatible with the operation of the navigator itself, thus reducing required memory capacity and software algorithms. On the other hand, the rho/theta concept is more compatible with traditional VOR based concepts and the National Airspace System as it is currently organized.

Each of the configuration concepts has its own unique set of data input requirements. Since a lat/lon system is naturally configured to be a "TO-TO" navigation system, and a rho/theta system is more functionally equivalent to a "TO-FROM" navigation system, the following data requirement elements will reflect these relationships. The following elements are considered to be the minimum required for function operation of a Loran-C based lat/lon (TO-TO) area navigation system:

- Waypoint definition (WP#/lat/lon)
- Present position (lat/lon)
- Active leg definition (WP#/WP#)
- Desired offset (direction/nm)
- Chain selection (GRI or GRI#)*
- Station selection (triad code)*
- Approach mode (toggle switch)
- Magnetic variation (degrees variation)**
- * Can be selected by position determination procedure
- ** Can reside in memory for automatic computer entry

A rho/theta system, which is designed to resemble a VOR system, has a different set of input requirements, many of which are similar to the lat/lon system:

- Waypoint definition (WP#/VOR ID/bearing/distance)
- Present position (VOR ID/bearing/distance)
- Active waypoint selection (WP)
- Desired offset (direction/nm)
- Chain selection (GRI or GRI#)*
- Station selection (triad code)*
- Approach mode (toggle switch)
- Magnetic variation (degrees variation)**

- Reference VOR (VOR ID)
- Desired Course (degrees)
- * Can be selected by position determination procedure
- ** Can reside in memory for automatic computer entry

These two lists comprise the minimum data entry requirements for the two navigation systems described. Additional features or different display concepts will change these requirements but these lists can be used as a functional baseline for most navigators.

Workload Analysis

The detailed workload analyses indicated that all data can be readily entered through the CDU in both the lat/lon and radial-distance conceptual panel designs. With the assumption of non-volatile memory both CDU configurations produce about the same amount of total workload time. The most significant difference occurs in the breakdown of workload into airborne and ground bases (preflight) entry. The lat/lon concept shows a definite benefit in this area as no airborne course selection is required. Additional results are described in Section 3.5 and Appendix A.

4.4.2.4 Performance Criteria - The performance criteria in terms of the control/display unit candidate configuration and operational procedures are discussed in Section 4.4.8.

4.4.3 Cross Track Deviation Indication

4.4.3.1 Purpose - The purpose of this task was to define the characteristics of the course deviation indicator (CDI) display for the low cost Loran-C receiver.

The study effort considered the following areas:

- Remote vs. Integral CDI display
- Use of a course selector (OBS) vs. Computer definition of course
- CDI sensitivity (nautical miles or degrees for full scale deflection)
- Amount of deviation signal filtering required
- Other CDI functional requirements

The analyses assumed that a deviation type of display of course position error was required. Some current VOR/DME RNAV units have been designed around use of waypoint distance to go and bearing to waypoint for course guidance. This type of design was considered to be too unconventional for the low cost Loran-C receiver.

4.4.3.2 Requirements - There are no specific requirements for cross track deviation indication in Advisory Circular 90-45A or RTCA DO-159.

4.4.3.3 Analysis - This study method used in this task consisted of examining current CDI configurations in use in general aviation aircraft. Implied in this method is an analysis of the "typical" general aviation cockpit layout.

Remote vs. Integral CDI Display

As in any type of course navigation system the Low Cost Loran-C system must incorporate some type of CDI display. The question that arises from this need is whether or not to utilize a remote CDI or to provide a CDI as an integral part of the Low Cost Loran-C system. The integral CDI display offers two disadvantages. First, the overall unit size is increased, therefore, increasing the amount of panel space required to install the system. Second, because more single area panel space is required the unit will probably be mounted in the center of the panel, this makes flying difficult for the pilot because he constantly must look away from his main instrument panel to fly the CDI.

The remote CDI, on the other hand, offers certain advantages over the integral CDI display. First, the unit can be considerably smaller than the integral CDI system, possibly a standard 3 x 6 inch NAV/COM size. Second, the CDI could be positioned on the panel so that the pilot could fly the system with a minimum amount of workload. Third, the Loran system could drive a pair of CDI's for dual panel installations. This could be very important in the larger cabin class aircraft.

OBS vs. Lat/Lon Course Input

Most Loran systems are called "TO-TO" systems because they provide range and bearing to the next waypoint. Many VOR/DME-RNAV's are "TO-FROM" systems using both bearing to the next waypoint and bearing from the last waypoint through

the CDI/HSI course selector (OBS). You can, for instance, fly some selected course outbound from a waypoint, then fly a different course inbound to the next waypoint. Loran-based systems generally allow direct flight only to the next waypoint from either the last waypoint or from the aircraft present position, at the pilot's option. Often these "TO-TO" systems will permit the pilot to fly past the "TO" waypoint and a "FROM" indication will be displayed on the CDI. But the pilot cannot select his outbound course; he can track only the course defined by the "FROM" and "TO" waypoints.

Often times it is more practical to utilize an OBS course line as an input rather than Lat/Lon positions. For example consider a holding pattern. Many holding patterns, especially missed approach holding patterns, are located some distance from approach or enroute courses. Often times these courses are oriented to NAVAIDS other than those defining the approach course.

Usually the holding fix is defined in terms of a radial and distance from a facility. With a totally dedicated Lat/Lon navigator, the pilot must know the coordinates of both the holding fix and the facility in order to define the holding course. This method could become cumbersome and impractical from the pilot's standpoint since this requires additional navigator inputs and it also makes the holding course difficult to visualize. A more practical solution is to utilize an OBS course line defined from the holding fix. This method allows the pilot to select the holding pattern course he desires while only inputting one set of Lat/Lon coordinates.

Another important issue is the ATC integration issue. For Loran-C to be used effectively in the ATC terminal and enroute environment it must be compatible with area navigation equipped users and ATC procedures. The utilization of the OBS for course input would certainly simplify the ATC integration issue since the present ATC system operates mainly in the distance/bearing mode from a particular station or fix.

CDI Sensitivities

Presently, existing VOR and RNAV CDI designs and sensitivities seem to be quite adequate. Typically VOR sensitivities are angular in nature and become more sensitive as the aircraft approaches the VOR. RNAV deviations, on the other hand, are generally linear and the sensitivity is independent of distance to the waypoint. The linear type display is recommended for the low cost Loran-C receiver.

A typical RNAV CDI utilizes a sensitivity of ± 5.0 nm full scale in the enroute mode and ± 1.25 nm full scale in the approach. For a VOR type CDI in the approach mode a full scale needle deflection would indicate a course deviation of $2-1/2^\circ$ from centerline and in the enroute mode a full scale needle deflection would indicate a 10° deviation from centerline. These design sensitivities are more than adequate for the Loran navigator output.

CDI Signal Filtering

The pilot likes to see a responsive CDI needle movement but it is also important that high frequency variations in cross track error be effectively filtered so that the needle does not continually oscillate at a rapid rate. Generally time constants on the order of 2 to 3 seconds are considered to be in the satisfactory range for cross track deviation.

Other CDI Functional Requirements

In addition to providing deviation information the display should contain a flag annunciator and a "TO-FROM" indicator. The flag indicator is pulled into view by the navigation unit to indicate that for some reason navigation data is unreliable. This cues the pilot to examine the CDU panel for further information concerning the status of the receiver. The "TO-FROM" indicator tells the pilot that the "TO" waypoint is being approached and that it is time to perform a waypoint sequencing procedure. The navigation processor must provide electrical signals to drive the CDI, flag, and the "TO-FROM" indicator.

4.4.3.4 Performance Criteria - The low cost Loran-C receiver should be capable of operating up to three CDI displays. The signals should have the following characteristics:

Sensitivity:	
enroute	± 5.0 nm full scale ($\pm 10\%$)
approach	± 1.25 nm full scale ($\pm 10\%$)
Time constant:	2 seconds ($\pm 50\%$)
Flag annunciator:	binary
"TO-FROM" indicator:	binary

4.4.4 Display of Pilot Entered and Computed Navigation Values

4.4.4.1 Purpose - The purpose of this task is to define the pilot entered data and computer navigation parameters that must be displayed on demand on the CDU.

The study considered the following areas:

- display parameter requirements
 - lat/lon configuration
 - radial-distance configuration
- pilot procedures for operating the CDU

4.4.4.2 Requirements - There are currently no specific requirements pertaining to the display of pilot-entered and computed navigation values.

4.4.4.3 Analysis - The analysis considered both lat/lon and radial-distance types of waypoint designation methods. In addition the analyses assumed that manual chain and station selection was possible. For design configurations that use automatic chain selection, chain and station parameter display functions can be deleted.

Method - A survey of the data-entry and navigation parameter display features of comparable RNAV and Omega/VLF systems was performed. The utility of each function used in these systems and its applicability to the low cost Loran-C receiver was made.

Display Parameter Requirements

In addition to serving as a computer input device, a CDU serves as the primary display device for both computer output values and input data verification. This section will identify those parameters which should be capable of being displayed on the low cost Loran-C computer display. Actual system display requirements will depend on system configuration design decision. The following items serve as a baseline set of display requirements. As in the section identifying pilot input requirements, this section will identify the requirements for two basic navigator concepts, the lat/lon "TO-TO" concept and the rho/theta "TO-FROM" system.

Although there are many similarities between the requirements for both of these systems, there are also significant differences. As can be determined by examination of the following lists, these differences are primarily a product of the navigation reference system being used.

The display requirements for a baseline lat/lon "TO-TO" navigation system include the following parameters:

- Waypoint definition (WP#/lat/lon)
- Present position (lat/lon)
- Active leg definition (WP#/WP#)
- Desired offset (direction/nm)
- Chain identification (GRI or GRI#)
- Station identification (pair or triad code)
- Acquisition status
- Bearing and range to waypoint (degrees/nm)
- Crosstrack deviation (direction/nm)*
- Course and distance between waypoints (degrees/nm)*
- Time to waypoint (minutes)*
- Ground speed (knots)*
- Station deselect**

* Although it is not absolutely necessary to display these parameters, they make an extremely valuable contribution to the understanding of the overall navigation situation.

** For systems using automatic station selection.

Many of these parameters correspond with similar parameters identified under input parameter requirements. These parameters can be combined under a single input/display mode if required. Although those parameters marked with (*) are technically optional, their inclusion reduces workload levels to such an extent that they should be considered requirements.

The display requirements for a rho-theta "TO-FROM" system are as follows:

- Waypoint definition (WP#/VOR ID/bearing/distance)
- Present position (VOR ID/bearing/distance)
- Active waypoint (WP#)
- Desired offset (direction/nm)

- Chain identification (GRI or GRI#)
 - Station identification (pair or triad code)
 - Acquisition status
 - Bearing and range to waypoint (degrees/nm)
 - Desired course (degrees)
 - Crosstrack deviation (direction/nm)*
 - Time to waypoint (minutes)*
 - Ground speed (knots)*
 - Station deselect**
- * Although it is not absolutely necessary to display these parameters, they make an extremely valuable contribution to the understanding of the overall navigation situation.

** For system using automatic station selection.

As was the case with the parameters identified with the lat/lon concept described above, many of these parameters correspond to input parameter requirements. In the interest of space conservation, input and display parameters should be combined in a single mode selection position whenever feasible.

Pilot Procedures for CDU Operation

The pilot procedures for operating the CDU are described in detail in Section 4.4.8.

4.4.4.4 Performance Criteria - The performance criteria are presented in Section 4.4.8 in terms of candidate CDU configurations and pilot operational procedures.

4.4.5 Procedure for Transition Between Loran-C Chains

4.4.5.1 Purpose - The purpose of this task is to define the procedures that are necessary to transition from one Loran-C chain to another.

The analysis of chain transition considered two transition methods, automatic and manual. In addition, for the manual method both single chain and dual/multiple chain receiver capability was considered.

It was assumed in these analyses that all station and chain constants, such as GRI, locations, and coding delays, were contained in ROM and could be readily available if required. It is also assumed that the acquisition process will take some amount of time in excess of one or two minutes (or longer in some cases).

4.4.5.2 Requirements - The only requirements pertaining to some type of constraint on the chain transition and signal acquisition are contained in FAA Advisory Circular 90-45A which states:

"...Installations intended for final approach should use position information that is essentially continuous with interruptions no longer than would result from switching from one preprogrammed waypoint to another. The system should give no operationally significant misleading information."

and in RTCA DO-159 which states:

"Received signal acquisition may be manual or automatic. If the receiving equipment has an automatic signal acquisition feature, a positive indication that the time difference(s) is valid shall be provided to the operator. The maximum time for indication of valid time difference(s) to be displayed from turn on, or on changing Loran stations shall be 450 sec.

This test assures that with Type III (auto acquisition) receivers, which provide automatic signal acquisition the process will provide valid time difference information in less than 450 sec..."

4.4.5.3 Method - The method used to analyze the chain transition problem was to identify the information elements that were required by the receiver to acquire a new chain. For manual acquisition these information elements must be entered by the pilot and be available to the receiver when the chain acquisition process begins. For automatic acquisition these elements must be available to the receiver so that the acquisition process can begin when the appropriate signal is received from the navigation section of the receiver.

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DESIGN STUDY REPORT FOR GENERAL AVIATION LORAN-C RECEIVER.(U)

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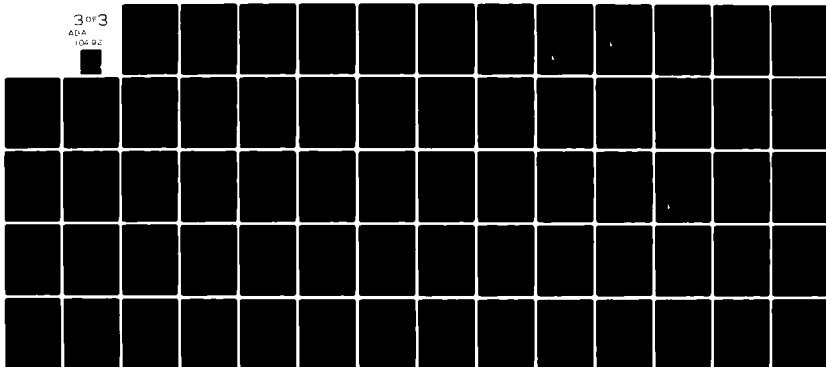
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4.4.5.4 Analysis -

Automatic Chain Selection

In a receiver with automatic selection logic, the capability to receive dual or multiple chains is required. This conclusion can be reached by considering operations in the NAS with a single chain, automatic-selection receiver. With this type of equipment the pilot can never be sure that the equipment will not try to acquire a new chain just when he needs it for some procedure. The delay in navigation information availability caused by the acquisition process would be unacceptable for IFR operations in the NAS.

The automatic chain selection process could be triggered by several methods. One method is to continually track distance to the stations from present position in a computer background area. When the station is within some range threshold, the acquisition process would be initiated. For automatic chain selection an acquisition status function has been added to the CDU panel. This indicator would produce a coded status value that would indicate to the pilot how the acquisition procedure was progressing.

Manual Selection-Single Chain

The manual selection procedure for a single chain receiver would require a deselection of the current chain being tracked and reselection of the GRI or (coded chain designator) for the new chain. Navigation would be unavailable during the acquisition of the new chain and dead reckoning or other alternate navigation procedures would be necessary during this time. This situation is undesirable because the pilot is left without navigation capability for some period of time. Typically this would occur in the enroute phase of flight when it would be of minimal significance. However, undoubtedly there will be occasions when accurate navigation is needed during a chain transition. Therefore, the manual selection-single chain concept is considered unacceptable for the low cost Loran-C receiver.

Manual Selection-Dual/Multiple Chains

The manual selection of two or more chains requires a means to enter and store the chain selection values in the computer. This could be accomplished in much the same manner that waypoint numbers are assigned, only now these values would become chain numbers. This chain selection and numbering capability is thought

to be a workable method of multiple chain operation. However, it is believed that there is little to be gained in the way of operational benefit or hardware simplification in using this procedure over the automatic selection process. Therefore, the automatic chain selection with the capability to acquire and track stations on two or more chains is considered the most desirable chain to chain transition procedure.

4.4.5.5 Performance Criteria - The low cost Loran-C receiver shall be capable of transitioning from one chain to another without the need for operator intervention.

4.4.6 Non-Precision Approach Display Requirements

4.4.6.1 Purpose - The purpose of this analysis is to determine the accuracy and resolution of the displayed parameters required for non-precision approach applications.

The display parameter analysis for non-precision approach considered the distance to waypoint and the cross track distance parameters.

For non-precision approach operations the pilot was assumed to be guiding the aircraft through use of the CDI display while monitoring his along track progress by watching the distance to waypoint display on the low cost Loran-C display panel.

4.4.6.2 Requirements - There are no specific requirements for displayed accuracy or resolution. However system accuracy in cross track must be better than 0.6 nm and in along track must be better than 0.3 nm according to FAA Advisory Circular 90-45A. These values imply resolution greater than the specification values.

4.4.6.3 Method - The display parameters requirements for non-precision approach were determined from a review of current user RNAV systems that are approved for RNAV approach operations. These systems included those which meet ARINC/AEEC specifications.

4.4.6.4 Analysis -

Non-Precision Approach Parameters

The low cost Loran-C navigator must compute and display certain navigation parameters accurately so that non-precision approaches may be executed. Operationally, two parameters from the navigation set are used for non-precision approach, they are as follows: along track distance (ATD) information and cross track distance information. The along track distance information is typically obtained through the distance to waypoint (DTW) display. Typically for the type of aircraft in which the low cost Loran-C will be installed, one-tenth of a nautical mile is the required display accuracy in the along track direction. The reason for this accuracy is so that step-down fixes can be identified accurately, therefore, allowing the pilot to make accurate and timely altitude changes. Increasing resolution to 0.01 nm causes the DTW display to change at a rate of about 3 digits per second for an aircraft traveling at 100 knots on approach. This increased resolution does not substantially improve the along track accuracy of the system and may, in fact, be a distraction to the pilot.

4.4.6.5 Performance Criteria - The performance criteria stated in Section 4.3.3.8 is adequate for non-precision approach applications.

4.4.7 Display of Receiver Operational Status

4.4.7.1 Purpose - The purpose of this task is to define the display annunciators and display parameters that are necessary to determine the receiver operational status.

The analysis utilized the results of Section 4.3.4 concerning the recognition and warning of unacceptable system conditions or performance. In addition methods of route definition and leg change operations were considered.

Waypoint sequence methods were developed for both the lat/lon and radial-distance waypoint designation methods. The lat/lon concept was assumed to be a "TO-TO" type navigator while the radial-distance concept was assumed to be a "TO-FROM" type navigator.

It was further assumed that the position determination section of the receiver produces a position error estimator which is sensitive to poor signal quality and/or poor fix geometry.

4.4.7.2 Requirements - The current requirement for displaying the RNAV failure warning signal is contained in FAA Advisory Circular 90-45A. This document states:

"Failure Warning. Provision should be made to alert the crew upon occurrence of any probable failure of major system functions or loss of inputs, including those that would affect aircraft position, heading command course, command heading, altitude, or vertical guidance indications".

There are no specific requirements for displaying the operational status of waypoints, route legs, and other necessary operational status parameters.

4.4.7.3 Analysis -

The performance criteria presented in Section 4.3.6.4 were used to define the operational status requirements for warning signals on the CDU panel.

An analysis of route definition parameters was performed for the lat/lon and radial-distance waypoint designation methods.

An indication of the acquisition status of the receiver during turn-on and reinitialization procedures. An analysis of the necessary characteristics of this parameter was performed to determine the minimum necessary information required by the pilot.

Warning Annunciators

From the performance criteria contained in Section 4.3.6.4 the following warning condition should activate the failure warning annunciator:

- Insufficient signal levels, signal contamination and signal format;
poor geometry -

If the position error estimator from the position determination section of the receiver indicates an error exceeding 0.3 nm, the failure annunciator should illuminate if in the approach mode.

If the position error estimator excess 1.1 nm, the failure annunciator should illuminate for any selected mode.

- Continuity test -

If the continuity test should fail, indicating a large change in position over a short period of time, the failure annunciator should be illuminated.

Route Segment Indicators

Since the lat/lon waypoint designation method is assumed to be a "TO-TO" type navigator both a FROM and TO waypoint must be specified to define a route segment or leg. This has been achieved through the use of a leg define (LEG DEF) position on the data selector switch.

Also in the lat/lon system, a flashing TO-FROM flag on the steering indicator will be used to indicate to the pilot that the aircraft is approaching the waypoint and a new leg should be defined. The TO-FROM indicator on the steering indicator will change from TO to FROM as the waypoint is passed.

In the radial distance system only one waypoint is used for guidance. This is selected by the W/P SEL position on the data switch. The course into or out of the waypoint is selected through the OBS position on the data selector switch. No waypoint sequence annunciator is needed because the system is designed to fly from the waypoint as well as to the waypoint.

Mode Selector

The mode selector is used to set the sensitivity of the course deviation signal... approach or enroute. This switch is also used to select the parallel offset mode. The value of the offset is entered with the data selector switch in the OFST position.

On-Off-Test

The on and off positions are self-explanatory. The test position illuminates all of the panel lights and display segments to identify any burned out indicators. This position also initiates self-test procedures (if provided).

4.4.7.4 Performance Criteria - The performance characteristics described in the previous section are incorporated in the CDU panel design presented in Section 4.4.8.

4.4.8 Low Cost Loran-C CDU Design

4.4.8.1 General - Functional and operational design of CDU for the low cost Loran-C receiver system is of major importance to the success of this project, both in terms of certification and in terms of marketing considerations. This section will deal with general considerations for the determination of CDU functional recommendations. Many of these aspects are discussed elsewhere in this report while others will be introduced in this section. In any event, this section will assemble these functional components into a operationally oriented entity.

Two of the most important constraints which should be considered are the physical size and layout of the cockpit itself. Instrument panel space is at a premium in a well instrumented single engine aircraft. Often times, the only method of installing a new navigation system is by replacing on old one. Replacement is considerably more attractive if the new unit is the same physical size as the old one. For this reason it is recommended that the low cost Loran-C CDU face conform to the standard nav/comm tuner component face size of 3 inches by 6 inches* if at all possible. The

*Rack size is 2.625 inches by 5.75 inches

CDU described below conforms to these size constraints. In addition to the limitation in space availability, the GA instrumentation panel is different in general configuration. Most commercially operated and business aircraft have a center console panel upon which area navigation CDU's are typically mounted (horizontally). Smaller single pilot aircraft typically do not have this console and this area navigation computer must be mounted on the main instrument panel (vertically). Keyboard operation is well suited to the center console, horizontally mounted position, but is less than ideal for the main instrument panel, vertically mounted position. This is particularly true in the high workload, turbulent flight conditions often traversed by general aviation aircraft. For this reason, it is recommended that the keyboard typically associated with digitally based navigation systems be replaced by rotary knobs and toggle switches. The configuration described below complies with this recommendation.

The primary display function of the recommended CDU will be accomplished through the use of seven segment display elements for numerical data and dot matrix display elements for alpha characters (if required). In addition to the primary data display, back lighted annunciator lights should be used to identify the data being presented and system status warning lights should be incorporated to identify system degradation situations. In the following recommended design every effort has been made to make all annunciation and warning lights meaningful with a minimum amount of reference to the pilots manual required for interpretation. At the same time, warning lights are designed to present solutions to the navigation discrepancy rather than just presenting the problem whenever feasible. These concepts should make display interpretation a relatively simple task, reducing the level of operator attention required for data assimilation.

Design discussions uncovered several data elements which it was felt should be continuously displayed in an Loran-C system design. These elements include:

- Active waypoint(s)
- Approach/Enroute mode (sensitivity) status
- System failure status

In the proposed design, these elements are continuously displayed, either by visual reference to switch position or through the activation or critical element dedicated display or warning lights.

Because of the low cost nature of this system, unnecessary navigation routines, such as automatic waypoint sequencing, have not been included in this design, even though they might add to market desirability. If cost constraints enable, these features should be considered again as possible added features to the current design.

4.4.8.2 System Description (TO-TO System) - This particular Loran system operates as a standard Loran-C "TO-TO" navigation system. It is referred to as a "TO-TO" system because it provides range and bearing to the next waypoint. As in other Loran systems the primary position and waypoint input is in Lat/Lon coordinates. Figure 4-19 presents the Control Display Unit (CDU) front panel. The CDU provides complete operator interface with the system and displays all navigation and self test functions.

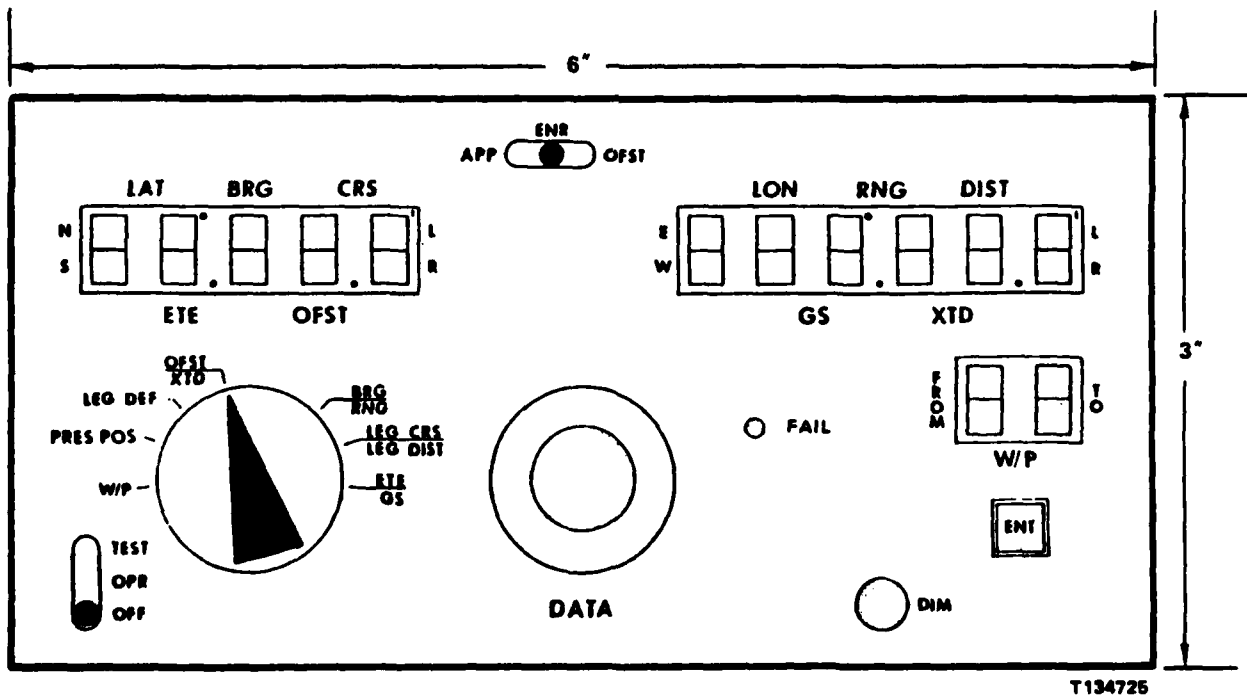
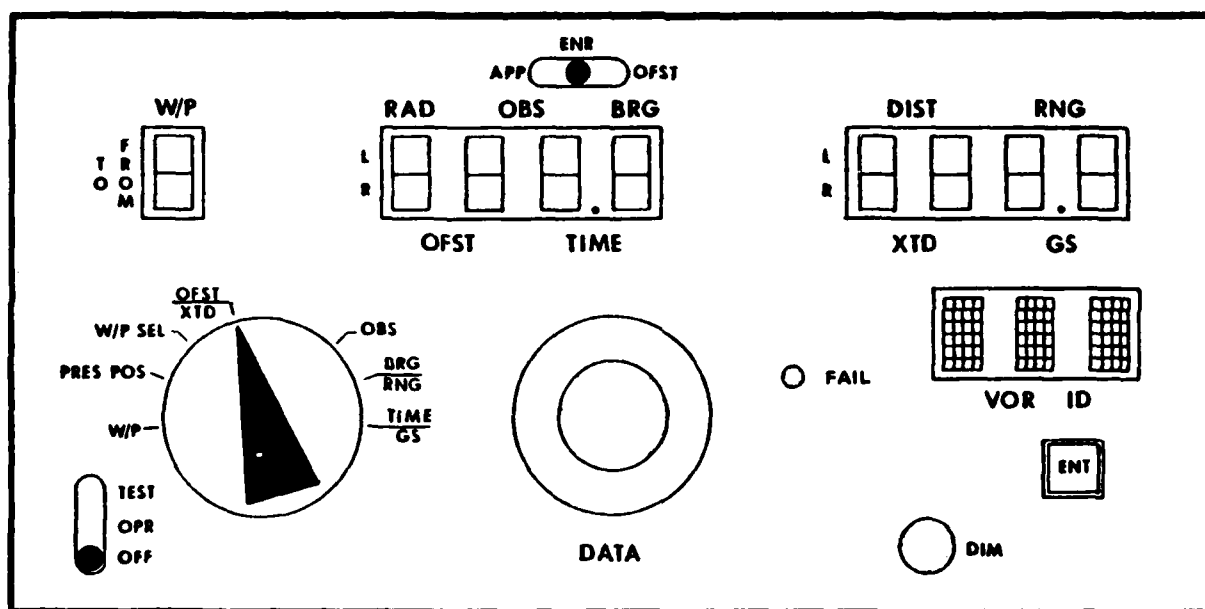


Figure 4-19. Low Cost Loran-C "TO-TO" System

4.4.8.3 System Description (TO-FROM System) - This particular Loran system operates as a "TO-FROM" navigation system utilizing the standard Loran-C signal. Many VOR/DME-RNAV's are "TO-FROM" systems using both bearing to the next waypoint and bearing from the last waypoint through the CDI/HSI course selector (OBS). This system operates much in the same manner because the pilot can fly a selected course outbound from a waypoint, then fly a different course inbound to the next waypoint. This particular system also allows ease of operation in the present ATC system since most position fixes are defined as a radial and a distance from a particular facility. Figure 4-20 presents the Control Display Unit (CDU) front panel.



T134728

Figure 4-20. Low Cost Loran-C "TO-FROM" System

The reference coordinate system for the "TO-FROM" system is relatively straightforward. Waypoint definition is through the use of radial and distance coordinates from a particular pseudo VOR station. These pseudo VOR stations are pre-stored in memory with their associated Lat/Lon's and other data and correction factors necessary for navigation. These pseudo VOR stations are identified by their unique three letter alpha code. After the waypoint has been defined the navigation computer

then computes what the Lat/Lon of the waypoint is by utilizing the Lat/Lon of the pseudo VOR station and the associated radial and distance from the station to the waypoint. After this process, navigation is conducted as in any conventional "TO-FROM" system. The purpose of this system is to reduce pilot data input workload and to allow a long-range navigation system that is compatible with the present ATC system.

4.4.8.4 Controls, Indicators and Display Functions (TO-TO System)

Data Selector Switch

W/P	Allows you to display or enter coordinates of selected waypoints.
PRES POS	Allows you to display or enter present position.
LEG DEF	Allows you to display or define the FROM and/or TO waypoints.
OFST/XTD	OFST lets you display or select a parallel offset course on the left display, and XTD displays cross track distance (NM) on the right display.
BRG/RNG	Lets you see bearing from your present position of the selected TO waypoint in the left display. Range from your present position, in nautical miles, of the selected TO waypoint appears in the right display.
LEG CRS/LEG DIST	Lets you see computer course between selected FROM-TO waypoint pairs in the left display and computed distance, in nautical miles, between selected FROM-TO waypoint pairs in the right display.
ETE/GS	Lets you see time to go to any selected TO waypoint in the left display and ground speed in the right display.

Mode Selector Switch

Selects mode of operation (three position pull-to-set switch).

OFF - Removes power from the system.

OPR - Places system in normal operation mode.

TEST - Initiates self test of all display lights.

Left Display

Five digit, seven segment, displays showing various data under control of the data selector switch. Degree marks, minute marks and decimal points are engraved above and below each display.

North and South Indicators

N - Designates north latitude

S - Designates south latitude

Left and Right Indicators

L - Designates left of course

R - Designates right of course

Left Display Annunciators

LAT - Indicates latitude is being displayed or ready to be selected.

BRG - Indicates bearing to the waypoint from present position is being displayed.

CRS - Indicates the course between waypoint pairs is being displayed.

ETE - Indicates estimated time enroute is being displayed.

OFST - Indicates that the parallel offset course distance is being displayed or ready to be selected.

Right Display

Six digit, seven segment, displays showing various data under control of the data selector switch. Degree marks, minute marks and decimal points are engraved above and below each display.

East and West Indicators	E	-	Designates East longitude
	W	-	Designates West longitude
Left and Right Indicators	L	-	Designates left of course
	R	-	Designates right of course
Right Display Annunciators	LON	-	Indicates longitude is being displayed or ready to be selected
	RNG	-	Indicates range to the waypoint from present position is being displayed.
	DIST	-	Indicates the distance between waypoint pairs is being displayed.
	GS	-	Indicates ground speed is being displayed.
	XTD	-	Indicates that the cross track distance is being displayed.

Waypoint Display

Two digit, seven segment, display showing the appropriate FROM and TO waypoints selected by the data selector switch (LEG DEF).

W/P Annunciator

Indicates that the waypoint display is ready for data input.

ENT

ENTER: Used at the end of entry sequences to insert the data control knob entry.

DIM

DIM Control: Regulates intensity of left, right displays and all back lighted annunciators.

DATA

Data Control Knob used to enter information into the navigator. This knob is actually a combination of two concentric knobs. Both knobs are rate switches with the outside knob controlling the degrees portion of the LAT/LON display and the inside knob controlling the decimal minutes portion of the same display.

Navigation Mode Selector

Selects the type of navigation mode desired.

APP - Approach mode offers the pilot increased CDI sensitivity (1/4 nm per dot).

ENR - Enroute mode: Normal navigation mode (1 nm per dot CDI sensitivity).

OFST - Parallel offset mode: Used to fly the already selected parallel offset track. When removed from this mode normal navigation is resumed either in the Enroute or Approach modes.

FAIL

Failure: Indicates that the receiver is unable to provide satisfactory navigation information.

4.4.8.5 Controls, Indicators and Display Functions (TO-FROM System)

Data Selector Switch

W/P

Allows you to display or enter coordinates (in bearing and distance from a selected VOR) and the appropriate pseudo VOR station of selected waypoints.

PRES POS

Allows you to display or enter present position relative to a pseudo VOR station.

W/P SEL

Allows you to display or define the selected waypoint in the extreme left-hand display.

OFST/XTD

OFST lets you display or define a parallel offset course on the left display, and XTD displays cross track distance, in nautical miles, on the right display.

OBS

OBS lets you display or define the desired inbound course relative to the waypoint.

BRG/RNG	Lets you display bearing from your present position of the selected waypoint in the left display. Range from your present position, in nautical miles, of the selected waypoint appears in the right display.
TIME/GS	Lets you display time TO or FROM any selected waypoint in the left display and ground speed in the right display.
Mode Selector Switch	Selects mode of operation. (Three position pull-to-set switch). OFF - Removes power from the system. OPR - Places system in normal operating mode. TEST - Initiates self test of all display lights.
Waypoint Display	One digit, seven segment, display showing the selected waypoint in use under control of the data selector switch.
Left and Right Display	Four digit, seven segment, display showing various data under control of the data selector switch. Decimal points are engraved below each display.
Left and Right Indicator	L - Designates left of course R - Designates right of course (In the XTK mode)
Waypoint Display Annunciators	W/P - Indicates Waypoint number is being displayed or ready to be selected. TO - Indicates flying TO the selected waypoint. FROM - Indicates flying FROM the selected waypoint.

Left Display Annunciators

RAD - Indicates that the pseudo VOR radial is being displayed or ready to be selected.

OBS - Indicates OBS is being displayed or ready to be selected.

BRG - Indicates bearing TO the waypoint from present position is being displayed.

OFST - Indicates that the parallel offset course distance is being displayed or ready to be selected.

TIME - Indicates that the time TO or FROM the waypoint is being displayed.

Right Display Annunciators

DIST - Indicates that the pseudo VOR distance is being displayed or ready to be selected.

RNG - Indicates range to the waypoint from present position is being displayed.

GS - Indicates ground speed is being displayed.

XTD - Indicates that the cross track distance is being displayed.

Navigation Mode Selector

Selects the type of navigation mode desired.

APP - Approach mode offers the pilot increased CDI sensitivity (1/4 nm per dot).

ENR - Enroute mode: Normal navigation mode (1 nm per dot CDI sensitivity).

OFST - Parallel offset mode: Used to fly the already selected parallel offset track. When removed from this mode normal navigation is resumed either in the Enroute or Approach modes.

VOR Display	Three digit, 5 x 7 dot matrix, display showing the appropriate three letter alpha pseudo VOR code.
VOR ID Annunciator	Indicates that the VOR display is ready for data input.
ENT	ENTER: Used at the end of entry sequences to insert the data control knob entry.
DIM	Dim Control: Regulates intensity of left, right, waypoint and VOR displays. It also regulates the intensity of all the back lighted annunciators.
DATA	Data Control Knob: Used to enter information into the navigator. This knob is actually a combination of two concentric knobs. Both knobs are rate switches with the outside knob controlling the thousandth portion of the display and the inside knob controlling the hundredth portion of the same display.
FAIL	Failure: Indicates that the receiver is unable to provide satisfactory navigation information.

4.5 SELF TEST CAPABILITY

The self test features of the General Aviation receiver must be sufficiently comprehensive to establish a high confidence level in the reliability and accuracy of the navigation output parameters. In addition, fail-safe features must be designed in to ensure that no critical failures can go undetected in the receiver. A warning indicator must positively alert the operator whenever navigation data becomes unreliable. The required high level of confidence in receiver performance will be established by (1) basic display verification tests, (2) basic functional tests, and (3) Built-In-Test Equipment (BITE) tests. Each of these classifications will be described in detail.

The basic hardware and functional tests are considered minimum requirements for a navigation receiver, and fortunately are implemented at very low cost so that further tradeoff analyses are not required. The BITE tests, however, can be designed to establish increasing levels of confidence at the expense of greater hardware complexity. The BITE test concept becomes subject to diminishing returns as the complexity of BITE circuits increases. BITE tradeoffs will be examined to determine the most cost-effective approach for a General Aviation receiver.

4.5.1 Basic Display Verification Tests

These tests consist of the sequential activation of all displays, annunciators and course indicator functions. The NAV steering needle will be slewed to an arbitrary course indicator reference mark for the 4 to 6 second duration of this test. Normal functioning of each display device is verified by the operator. This test is automatically initiated immediately after power is applied to the receiver and can also be initiated manually by the operator. The manually initiated test can be performed at any time and will not interfere with the navigation functions of the receiver except, of course, that navigation data are not displayed for the short duration of this test.

4.5.2 Basic Functional Tests

These tests provide the principal basis on which the reliability of the receiver and of the received Loran signals are continuously evaluated. The reliability status of the system is conveyed to the operator via the failure indicator on the receiver's front panel and also via the NAV warning flag on the course indicator. The failure indicator will be activated under the following conditions:

- a. Selected Loran channels lost lock
- b. Receiver fails BITE mode
- c. Selected Loran signal BLINK (when signal with BLINK required for navigation)
- d. Nav output parameters fail "reasonableness" test
- e. Microprocessor diagnostic test failure
- f. Microprocessor halted
- g. Memory checksum failure

The NAV warning flag on the course indicator will drop into view for any of the above conditions including the following:

- a. Power failure to Loran receiver
- b. Steering data invalid or not available

The steering needle will not be powered whenever the NAV warning flag is displayed.

4.5.3 Built-In-Test Equipment (BITE) Tests

Very comprehensive end-to-end tests can be performed on the navigation receiver by injecting a simulated Loran signal into the RF section and applying GO/NO-GO criteria to expected receiver output parameters. Teledyne has applied this concept to the production TDL-711 and TDL-424 Loran navigators with great success.

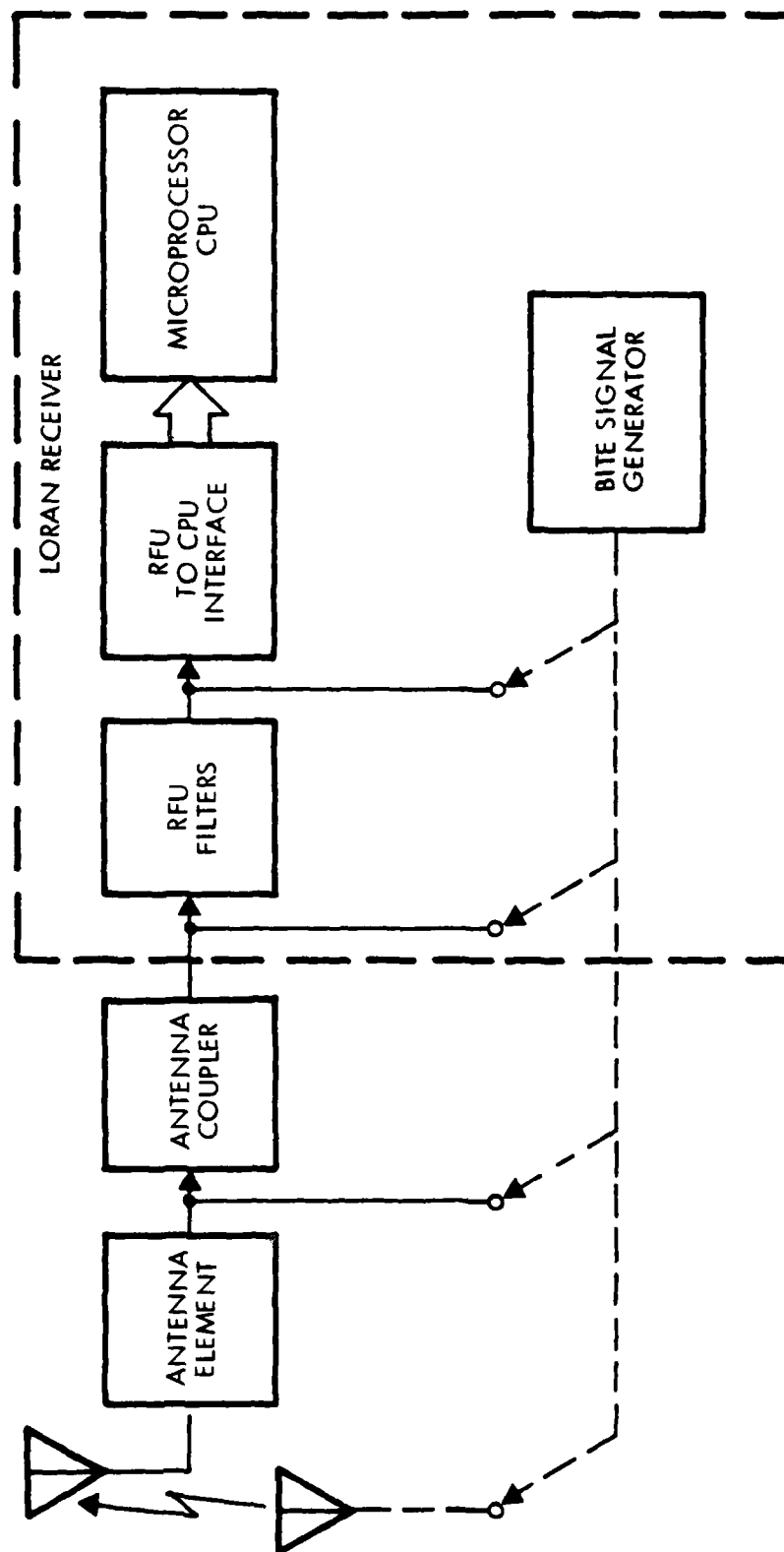
This BITE test can verify the functional integrity of almost all sections of the receiver including the antenna, antenna coupler, RF section, and the Loran receiver and navigation processors. With a sufficiently precise BITE signal generator, this technique can be used to perform pre-flight and in-flight signal envelope calibration to enhance cycle identification. To counter the effects of temperature on envelope processing circuits, which can result in cycle selection ambiguities, continuous envelope calibration could be performed using the precise BITE reference signal. For the purpose of selecting the most cost-effective BITE test mechanization the following variations will be analyzed:

- a. BITE signal injection point
- b. BITE signal characteristics required

4.5.3.1 BITE Signal Injection Point

To maximize functional verification of receiver hardware, the BITE signal should be injected as early into the RF channel as possible. Figure 4-21 shows possible signal injection points, these are:

- a. Radiate into antenna
- b. Couple directly into ACU
- c. Couple directly into receiver RFU
- d. Couple directly into RFU/CPU interface



T134691

Figure 4-21. Alternate BITE Signal Injection Points

The BITE signal generator is identical for all four alternatives; therefore, only the cost of the signal coupling hardware is significant in this comparison. Alternative 4 is immediately rejected because it provides lower performance benefits than Alternative 3 at the same cost. Since the RFU and BITE generator are physically located in the receiver, Alternative 3 is the lowest cost option. The most costly alternative is 1 because a separate radiating BITE antenna is required. While this method provides the most comprehensive test in that a broken antenna element can be detected, the low probability of this mechanical failure occurring does not warrant the additional costs. Alternative 2 couples the BITE signal directly into the ACU at the base of the antenna element. The additional cost of routing the BITE signal from the receiver to the ACU may not be worth the higher level of confidence achieved. Field experience has shown that "loss of signal" faults are infrequently traceable to the remotely installed ACU. Alternative 3 is, therefore, selected as the most cost-effective choice.

4.5.3.2 BITE Signal Characteristics

Only a simple BITE generator is required to functionally check out the receiver from end to end. Figure 4-22 presents a typical BITE signal generator (Alternate A) as implemented in Teledyne production receivers. Positive and negative pulses are used to ring the 100 KHz filter which is tuned to closely approximate the Loran pulse shape. Loran test pulses spaced 1000 microseconds apart are sent out continuously without forming separate pulse groups. A simple, alternating phase code pattern, that does not differentiate between Master and Secondary signals, was selected to reduce hardware complexity and cost.

The Loran receiver searches for the alternating phase code pattern with a correlation detector and uses the first detection as the designated Master. Two 8000 microsecond windows precisely spaced with respect to the designated Master allow the receiver to search and track two Secondary pulse groups. Except for the use of unique test signal phase codes, the receiver performs the same signal processing operations on BITE signals as on actual transmitted signals. After an approximate one minute search and settle period, valid time differences are computed. These time differences are converted to their corresponding Latitude/Longitude position which must fall within predetermined ± 0.1 minute limits in order to pass the GO/NO-GO test. The total per unit cost of implementing Alternate A BITE generator is \$10.00.

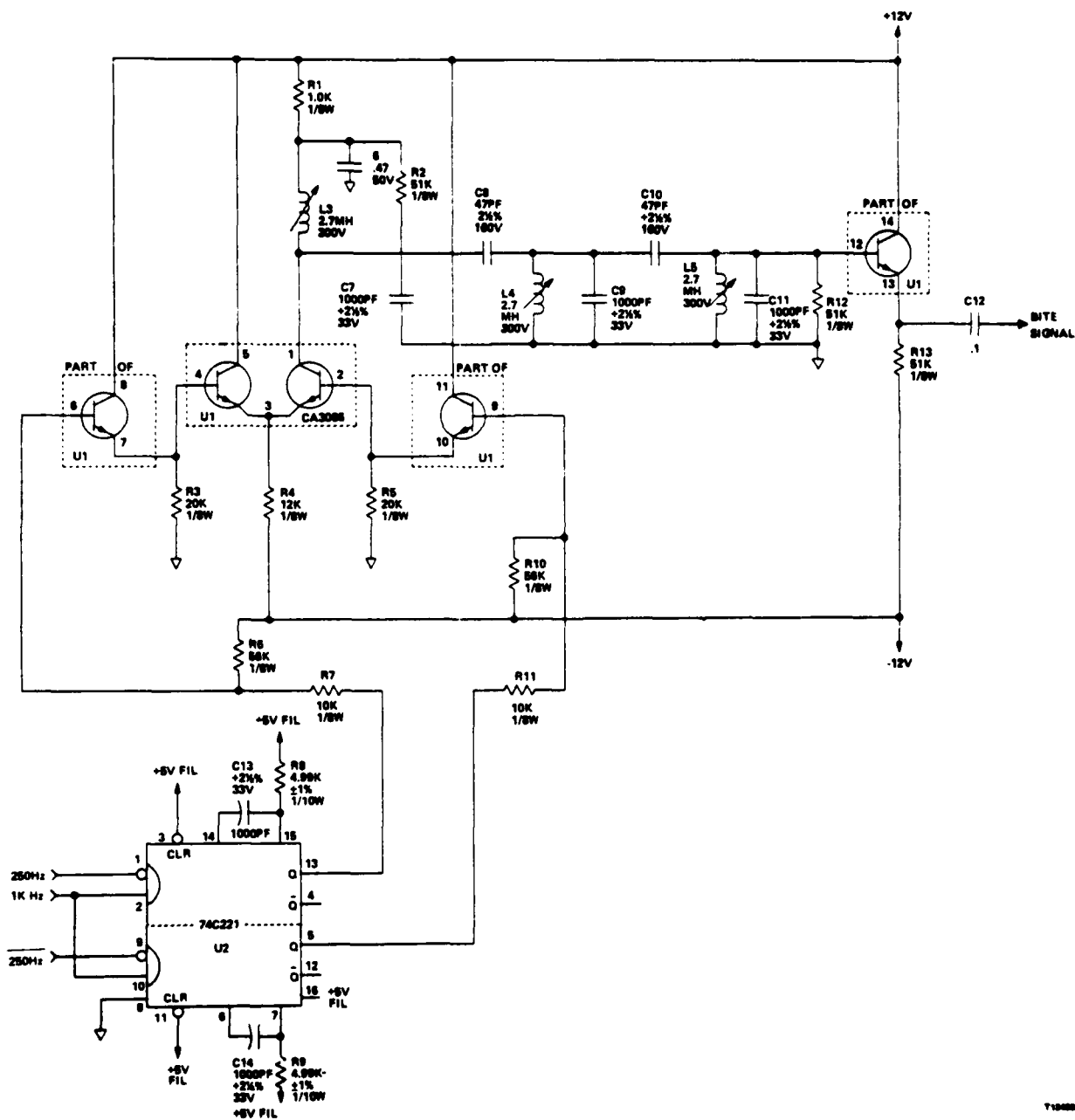


Figure 4-22. BITE Signal Generator, Alternate A

A more sophisticated BITE signal generator can be designed to perform continuous signal envelope calibration. The primary objective of envelope calibration is to eliminate cycle selection ambiguities. (Position errors on the order of 2 N.M. occur when the receiver settles on the wrong Loran cycle.) Envelope calibration can be accomplished by comparing the received Loran signals with pertinent envelope attributes of a precision test signal. A block diagram of such a precision BIT signal generator is presented in Figure 4-23 as Alternate B. The heart of this signal generator is the control memory which specifies the phase code and envelope characteristics for each Loran pulse. This type of signal generator is the standard test equipment used to calibrate envelope processing circuits in production test at Teledyne. Adding Alternative B BITE generator to the receiver will increase its cost by \$45.00.

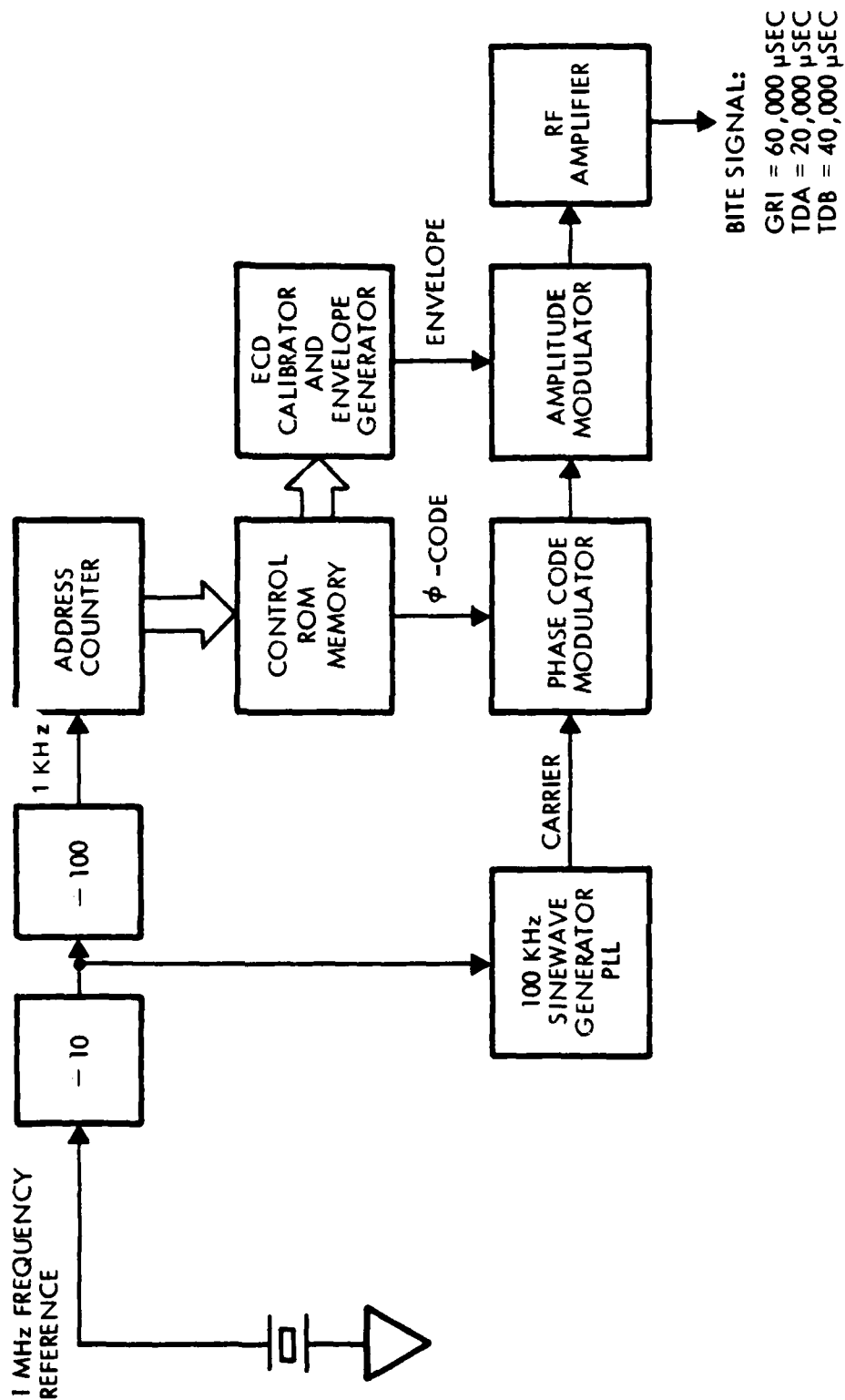
Because the cost of Alternative B is significantly higher than Alternative A for the added envelope calibration feature, it is probably more cost effective to place greater emphasis on the design of the receiver's envelope processing circuits so that they remain calibrated over time and temperature. End-to-end BITE tests performed with Alternative A provide very nearly the same level of confidence in the receiver as Alternative B at much lower cost. Alternative A is, therefore, selected as the most cost effective alternative for this receiver.

4.6 DATA INPUT/OUTPUT

The Loran receiver can be considered as an analog device which has a digital interface (via two channels A, B) to a CPU. The CPU also communicates with the CDU (control display unit) and has two analog outputs to a steering indicator. The block diagram with these functions is shown in Figure 4-24.

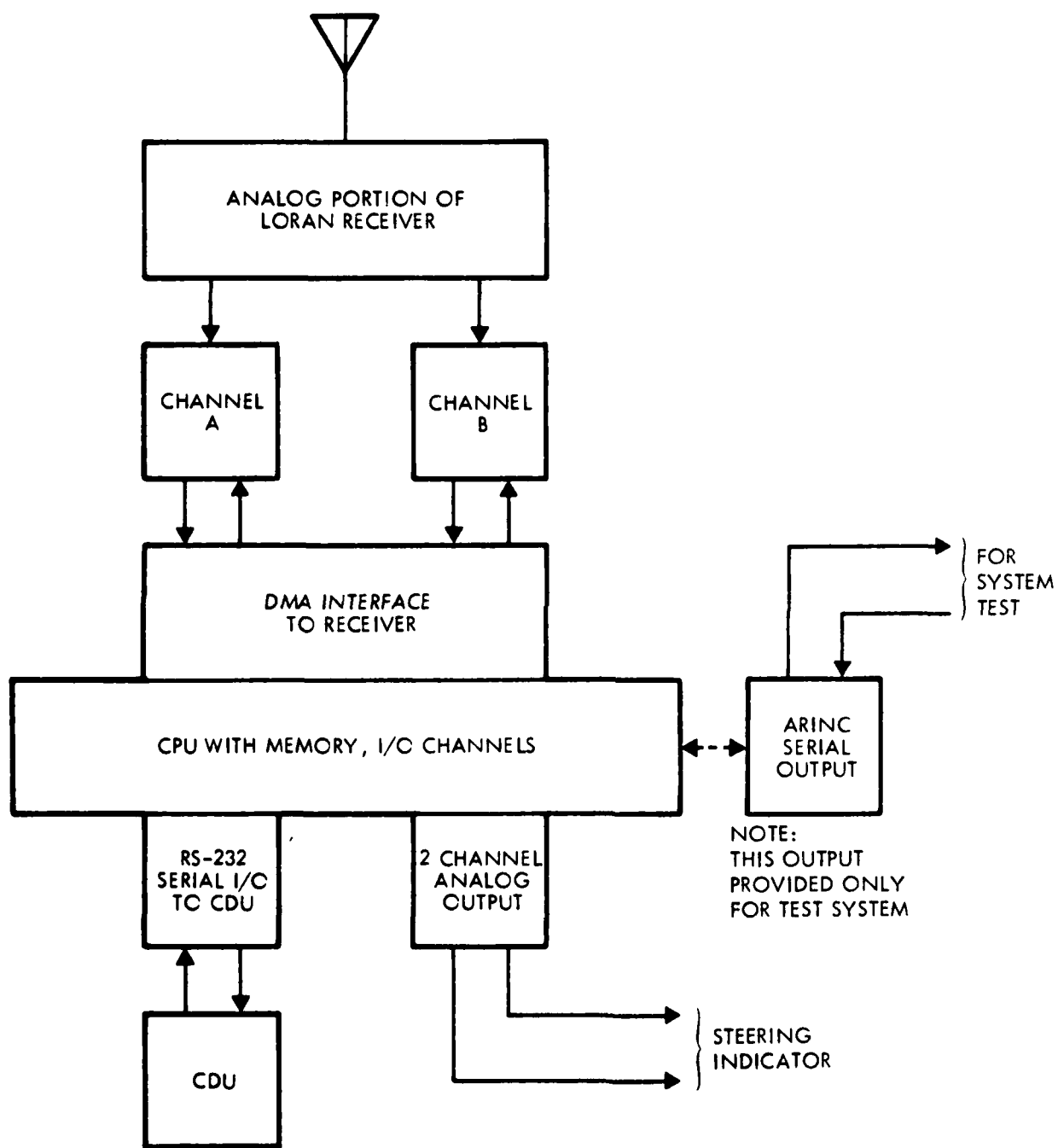
4.6.1 Requirements

The communication between the CPU and the analog portion of the receiver is the most critical. Each string of data consists of a sequence of measurements occurring at 2.5 microsecond intervals. This string is repeated eight times at millisecond intervals, and there is one set of these for each station of the chain. This group of signals has a period of 49.3 to 100 milliseconds (GRI), and the sequence is then repeated.



T134693

Figure 4-23. BITE Signal Generator, Alternate B



T134694

Figure 4-24. I/O to CPU

The data sequence is shown in Figure 4-25. The first line shows the string where each square of the lattice represents a time increment of 2.5 microseconds. Note that the DMA communication will transfer two bytes and then wait until the next request. The string consists of 64 pairs covering a period of 160 microseconds. Transmission from each station consists of a burst of eight pulses transmitted with a period of one millisecond. The second line shows this burst with the 160 microsecond sampling in each millisecond separation. Each square represents a time delay of 500 microseconds. The third line shows the full GRI (Group Repetition Interval) of 100 milliseconds with the bursts from the Master and three slaves. Here the time resolution is 5 milliseconds. In all cases, the dark vertical lines represent DMA functions occurring at the CPU.

The CPU must also be provided low rate interfaces to devices outside the receiver unit. There will be a bi-directional link with the CDU and an instrumentation output conforming to ARINC 429. The flag and one proportional axis of a steering indicator will also be driven from the CPU.

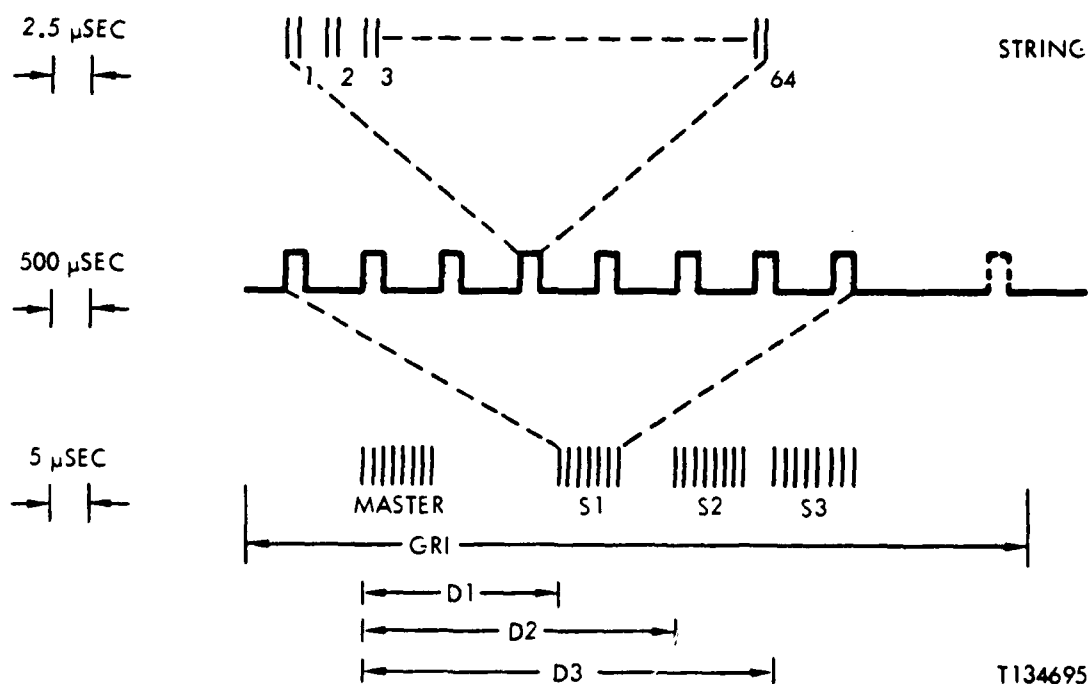


Figure 4-25. Data Stream from Loran Receiver to CPU (per Channel)

4.6.2 Mechanization

The CPU chosen is an Intel 8088. This was chosen as it is fast enough to perform all the I/O and generate all the algorithms necessary for this system. This microprocessor is but one member of a large family of mutually supporting devices. All the interface are memory mapped so that simple decoding selects channels for activation. The interfaces to the front end will be parallel DMA with two channels of DMA control. The CDU interface will have a standard UART which is specifically chosen to interface directly to the data bus of the CPU. The ARINC 429 output will use a monolithic device for parallel to serial conversion and clock/sync generation. The device will require intermediate buffering to mate with the data bus. Buffers, an 8 bit DAC, and a current driver will interface the proportional steering indicator movement to the CPU. The flag will be driven by a memory addressed latch and a current source.

4.7 MECHANICAL CHARACTERISTICS

The mechanical configuration of the Loran Navigation System was selected following evaluation of three candidate configurations. The three candidates are illustrated in Figures 4-26, 4-27, and 4-28.

The primary objective of the evaluation was to define the mechanical configuration that resulted in the lowest hardware costs while satisfying the performance constraints of the system. The performance constraints required that the Control Display Unit be located either on the console or pilot's instrument panel and that an Antenna Coupler be located at the antenna base to amplify the RF signal and minimize the effects of noise. Candidate No. 1 is a two box system with the major electronics unit located at the base of the antenna. While this configuration would be satisfactory for some aircraft installation, it is not satisfactory for most general aviation requirements for the following reasons:

- To counteract the effects of noise, a dual antenna configuration has been chosen for the Loran Navigation System (refer to Section 3.7), therefore, the unit cannot be located adjacent to both antennas because of their physical separation.
- In many aircraft there is insufficient space adjacent to the antenna to locate a unit of this size.

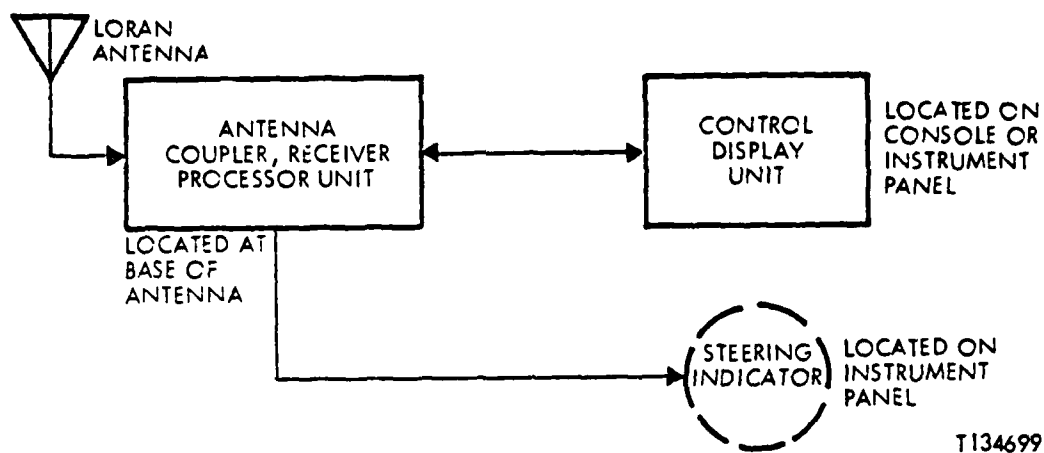


Figure 4-26. Candidate No. 1 Mechanical Configuration

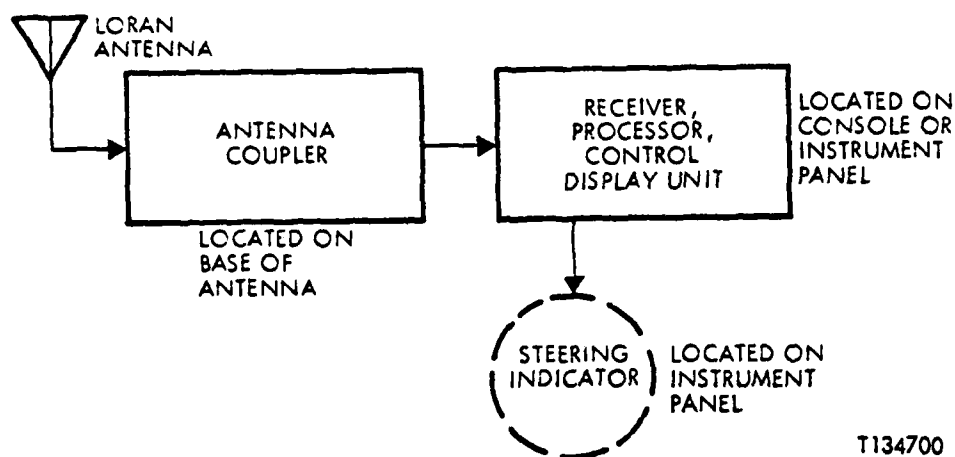


Figure 4-27. Candidate No. 2 Mechanical Configuration

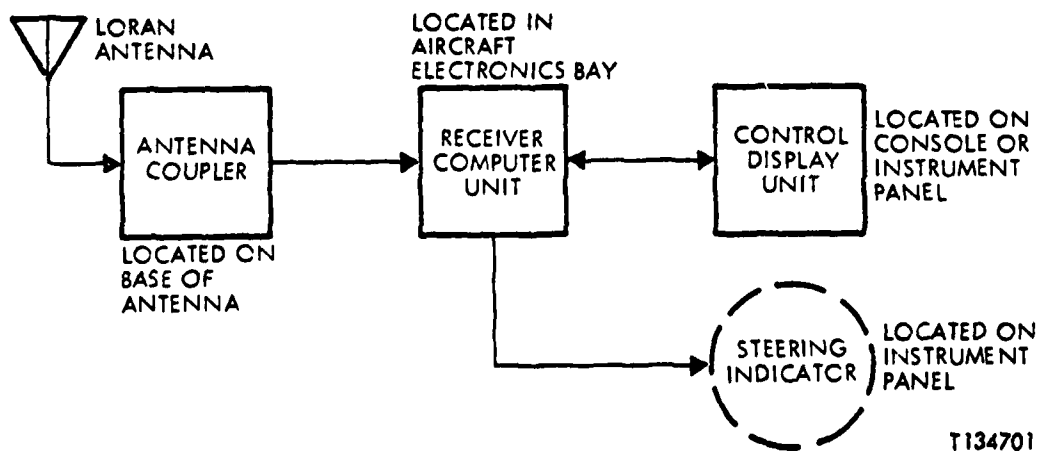


Figure 4-28. Candidate No. 3 Mechanical Configuration

The second candidate integrates the major electronic assemblies with the Control Display Unit. This configuration results in the simplest installation design and offers the cost advantage of a two box system. However, in many aircraft the console or instrument panel space is so restricted that there is not enough space for installation of a large Control Display Unit. Reduction of the unit to an acceptable size would require high density packaging and custom integrated circuits which results in unacceptable costs.

The third candidate is a three box system with the Loran receiver, computer, interface, and power supplies located separately from the Antenna Coupler and the Control Display.

This candidate configuration has been chosen for the following reasons:

- It avoids the installation constraints encountered with candidates No. 1 and No. 2.
- One design configuration will be acceptable for all types of aircrafts.
- The configuration permits simpler mechanical designs for both the Antenna Coupler and Control Display, thereby offsetting the cost associated with a three (rather than a two) box system.

The mechanical characteristics of the system will conform to the following criteria:

- The Antenna Coupler will be located in the base of the Antenna (as is currently done with Teledyne's TDL-711). This practice simplifies installation and saves the cost of a separate housing for the Antenna Coupler.
- The Receiver Computer Unit will be of rugged, yet simple, construction and will not require vibration isolators, or forced air cooling.
- The Control Display Unit will be designed for standard instrument panel installation. Minimum space behind the panel will be required.

The actual mechanical configuration of the units are described in paragraphs 5.1, 5.7, and 5.8.

SECTION 5

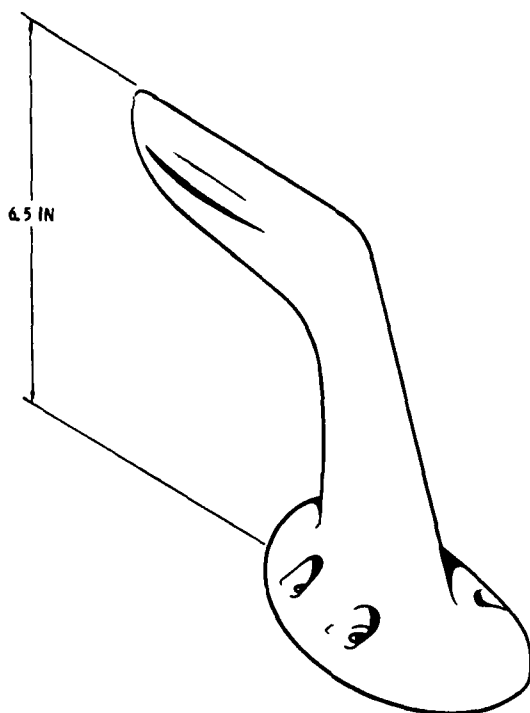
RECEIVER DESIGN APPROACH

Section 5 is intended to support the cost data in Section 6 with technical descriptions of the major functions of the navigation system. For the purpose of comparing the linear and hard limited variants of the receiver, Section 6 offers the cost analysis of both. Since the hard limited approach is well understood and has been contractor convention, the associated front end cost data are considered accurate and an exposition of it is not provided in Section 5. The linear receiver and signal processing concepts pursued in this report are not altogether conventional and are addressed in the appropriate portions of Section 5.

5.1 ANTENNA/ANTENNA COUPLER

The Antenna/Antenna Coupler subsystem consists of two vertical dipole assemblies provided with self-contained antenna coupler electronics. One such Antenna/ACU is shown in Figure 5-1. Two antenna elements are mounted above and below the aircraft fuselage to provide (1) signal addition by doubling the effective antenna height, and (2) noise cancellation of p-static fields generated at equal distances from both elements. Properly installed, balanced antennas and the application of standard p-static discharge control techniques result in a combined noise reduction of at least 60 dB.

The coupler electronics are stagger-tuned for a 40-KHz bandwidth and a nominal frequency of 100 KHz. The Antenna/ACU bandwidth is sufficiently wide so that the narrow bandpass characteristics of the receiver determine the overall bandpass characteristics of the system. A low noise FET amplifier is matched to a high impedance antenna element for maximum transfer of signal energy. The amplifier has sufficient gain (up to 20 dB) to raise the signal level above the set noise of subsequent signal transfer circuits and transmission lines. An output buffer amplifier performs the necessary impedance matching to drive a 50-ohm load in the receiver's RF section via a coaxial cable up to 30 meters long. This same coaxial cable supplies DC power from the receiver to the ACU.



T134728

Figure 5-1. One of Two E-Field Antennas With Internally Mounted Antenna Coupler

The specifications for each Antenna/ACU are summarized below:

Electrical

Effective height (H_e):	3 to 5 inches
3 dB Bandwidth:	80 KHz to 120 KHz
Voltage Gain:	10 to 20 dB
Dynamic range at Standard Sampling Point:	90 dB
Output drive capability:	50 ohms in parallel with 1200 pf max

Power Requirements:

+12 VDC $\pm 10\%$ @ 30 ma max

Mechanical

Size:	3.5 x 6.25 inches (BASE) 14.5 (Height)
Weight:	Approximately 1.5 lbs

Operating Environment

Airspeed:	0 to 250 KTS
Temperature:	-20°C to +55°C
Altitude:	0 to 15,000 meters
Relative Humidity:	100%

The antenna housing design is the result of considerable development effort expanded by the manufacturer to provide lightning protection. Extensive tests in a lightning simulation chamber have shown that this housing is immune to direct lightning strikes when properly bonded to an airframe. The housing is also provided with a high-resistivity coating designed to bleed off triboelectric charges to other conductive airframe members for eventual discharge at high potential aircraft extremities.

5.2 NOTCH AND BANDPASS FILTERS

The principal band shaping filters for the front end are located in the receiver unit. There is a fixed bandpass filter with a 20 KHz, 3-dB bandwidth and two fixed notches. The bandpass exhibits a Butterworth response and rolls off to greater than 30 dB at ± 13 KHz of band center. This is the only bandpass analog filter outside the antenna coupler; i.e., there is no search filter in the front end. The two notches are set by design at 88 and 115.3 KHz and have stop bands wide enough to reject the carrier and modulation on the respective interfering communications services. All filters are located on the RF module in the receiver unit.

5.3 RF UNIT

The RF Unit traditionally includes the switched amplifiers, envelope deriver, and detector circuits necessary to recover information from the band limited waveform. In this case, the RF module in the receiver integrates the amplifiers with the filters. There is no envelope deriver and the detector circuits are part of the timing and data conversion logic. The gain controlled amplifier chain consists of two switched stages of gain and one fixed gain amplifier section. The two switched stages provide 20 dB of gain each and may be bypassed by software direction. Both stages precede the filters. The fixed gain section follows the filters and provides approximately 80 dB of gain. In addition to the filters and amplifiers, the RF module has a shaping filter for the self-test signal.

The selected design approach for the Loran-C receiver calls for performing all possible functions in the digital processor. This minimizes the amount of special purpose analog and digital hardware external to the computer at the expense of additional processing power and program memory. In light of current technology trends, this promises to be an increasing cost effective trade-off.

It may first be asked what are the limits to this trade-off, i.e., why is it necessary to have any analog front end at all? The answer is dynamic range. Without fixed notches and bandpass filtering, the range of noise and interference levels relative to signal would simply be too great to digitize and enter into the processor.

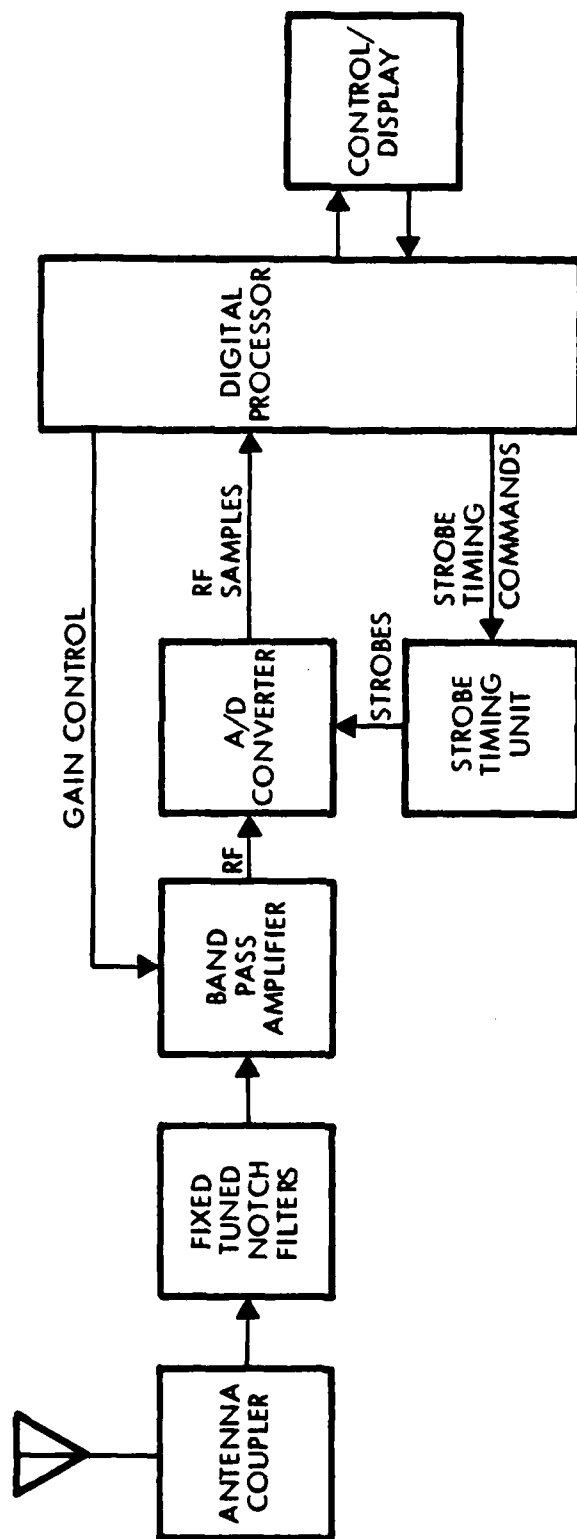
Processing of Loran-C signals involves locating the pulse groups (search), locating the front of the pulse, locating the proper tracking cycle, and phase locking. Referring to Figure 5-2, it is seen that all these functions are performed with the same hardware configuration. They differ only in the software routines used to command strobe patterns and timing based on the RF measurements.

5.4.1

Strobe Patterns and Timing

The Strobe Timing Unit performs two primary functions: maintaining a time reference and producing one of several strobe patterns on command from the processor. Maintaining a time reference is accomplished by counting a precision clock for a period longer than 0.1 sec (the longest GRI). In previous receivers, the period was chosen to be equal to the GRI and extra counts were inserted into (or removed from) the period to adjust the phase lock loop. In this way, a precise synchronism was maintained between the time reference and the time of arrival of the Loran pulse group.

In a linear receiver it is not necessary to hunt for a zero crossing in order to track phase. Amplitude measurements of quadrature samples (2.5 μ sec apart) are sufficient to measure phase error to a resolution at least as good as that provided by high speed logic. The Strobe Timing Unit is therefore a simplified device compared to previous designs, even with the requirement for simultaneous tracking of multiple GRI's. As expected, the trade-off is the increased intelligence with which the processor manages strobe deployment, i.e., increased processing power



T134686

Figure 5-2. Linear Receiver Block Diagram

and program memory. The time of arrival of the Loran pulses now precesses through the fixed interval between time references and the software must account for this precession. It must add the GRI time to the previous arrival time and take the result to modify the fixed reference interval. Distinction between master and secondary stations need not be made.

The strobe pattern is the relationship between members of a group strobe which is triggered at a fixed delay from the reference pattern. For most receiver modes a single pattern will suffice: 64 strobes at 2.5 μ sec intervals. This pattern is repeated eight times at 1 msec intervals corresponding to the eight received pulses. For the Search Mode a separate pattern is employed consisting of a quadrature pair every 100 μ sec.

5.4.2 Signal Processing Modes

During the acquisition process for a particular station, the receiver proceeds through several modes beginning with Search. In this mode there is no a priori information about the time of arrival of the desired signal and the receiver must deploy strobes over the entire GRI. Narrowbanding of the front end is replaced by a software digital filter which takes an appropriate linear combination of RF samples. Detection of the signal is by correlation with the Loran phase code which, when successful, will give a first estimate of the pulse group time of arrival.

After Search, the processor commands the standard strobe pattern which is then used to locate the front of the pulse. In this mode, the strobe pattern is advanced each time the accumulated samples exceed a certain threshold. When the leading strobes no longer accumulate samples which correlate with the Loran phase code, the leading edge of the pulse has been roughly determined.

Envelope detection is now used to select the proper cycle for phase tracking. Historically, this mode has been the most difficult in both linear and hard limited receivers. The present approach uses strobed samples at 2.5 μ sec intervals to reconstruct the envelope waveform and estimate its time of arrival. Admittedly, samples taken this frequently from a 20 KC bandlimited signal are highly correlated; nevertheless, all possible envelope information will be retained for use in the processor.

The actual algorithm used to select the tracking cycle is maximum likelihood estimation. This is a statistical procedure which selects from among several hypotheses that one for which the observed data is the most probable. In this case, the observed data consists of RF samples near the front of the Loran pulse (corrupted by noise) and the hypotheses are the possibilities that each of the carrier cycles within the 160 μ sec strobe pattern is in fact the desired tracking cycle.

5.4.3 Phase Tracking

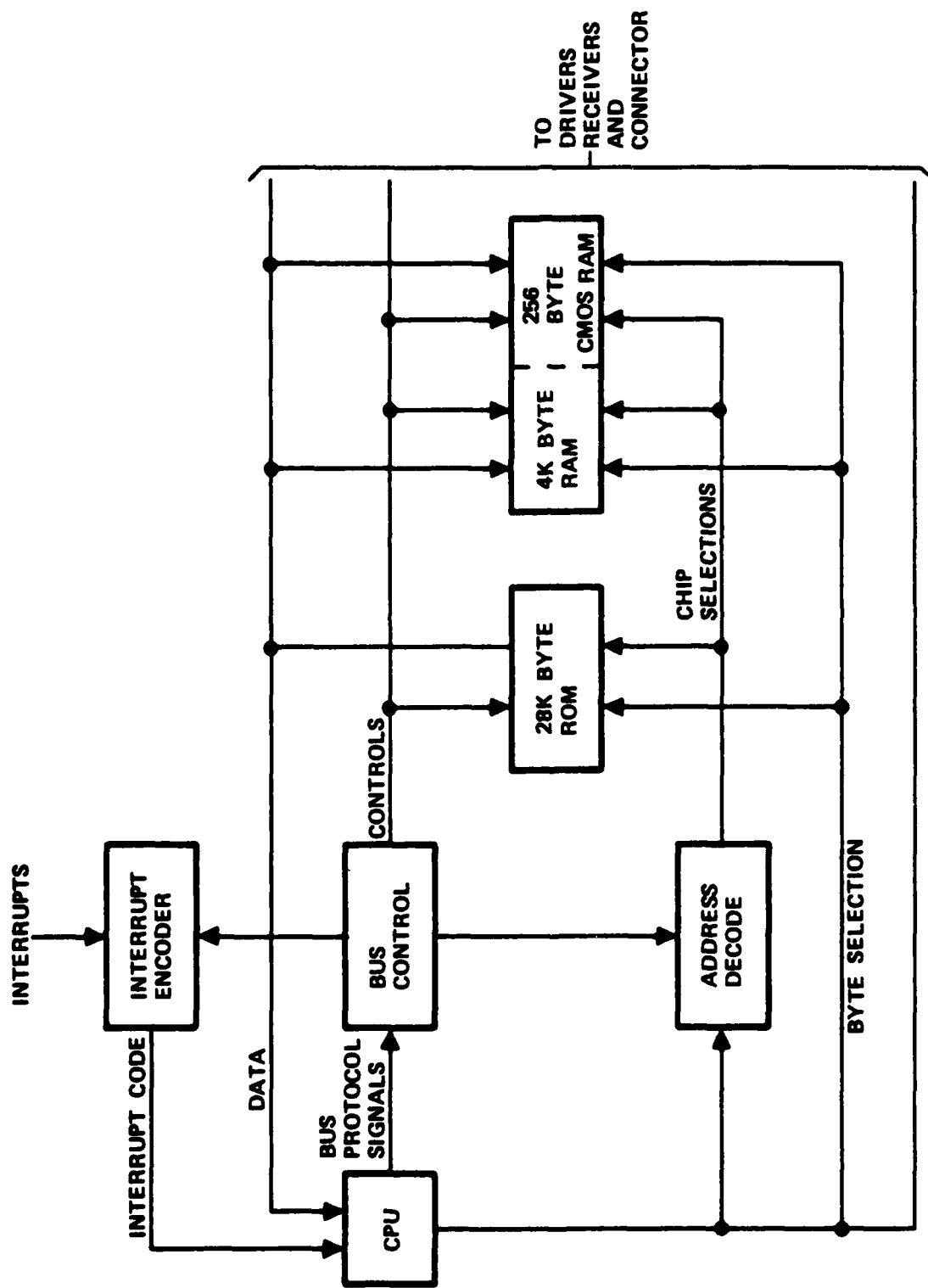
Quadrature samples of the RF waveform on the tracking cycle provide an instantaneous measure of the received phase as compared to the predicted phase based on previous measurements. After multiplication by a suitable gain, this error is used to update the predicted phase for the next GRI. The software not only maintains an estimate of phase but also of phase rate, i.e., it mechanizes a second order loop. The algorithm is constructed so that a constant input phase rate will give zero steady state error. Constant acceleration will, however, produce a dynamic lag.

5.5 DATA PROCESSOR

The data processor is fully centralized and consists of ROM, RAM, an interrupt encoder, CPU, data bus control logic, and address decode logic. These devices are all in one circuit board. The CPU is an Intel 8088, the member of the Intel 16 bit family which has 8 bit external data paths. The scratch pad area for the computer program is 4K bytes of NMOS RAM in one device plus 256 bytes of CMOS RAM in one device. The CMOS RAM is battery supported and stores waypoints and present position. Figure 5-3 shows a functional block diagram of the data processor. The program and constant data table are stored in three 8K byte EPROM devices plus one 4K EPROM device. The conductivity map consumes nearly all of two 8K byte EPROM chips.

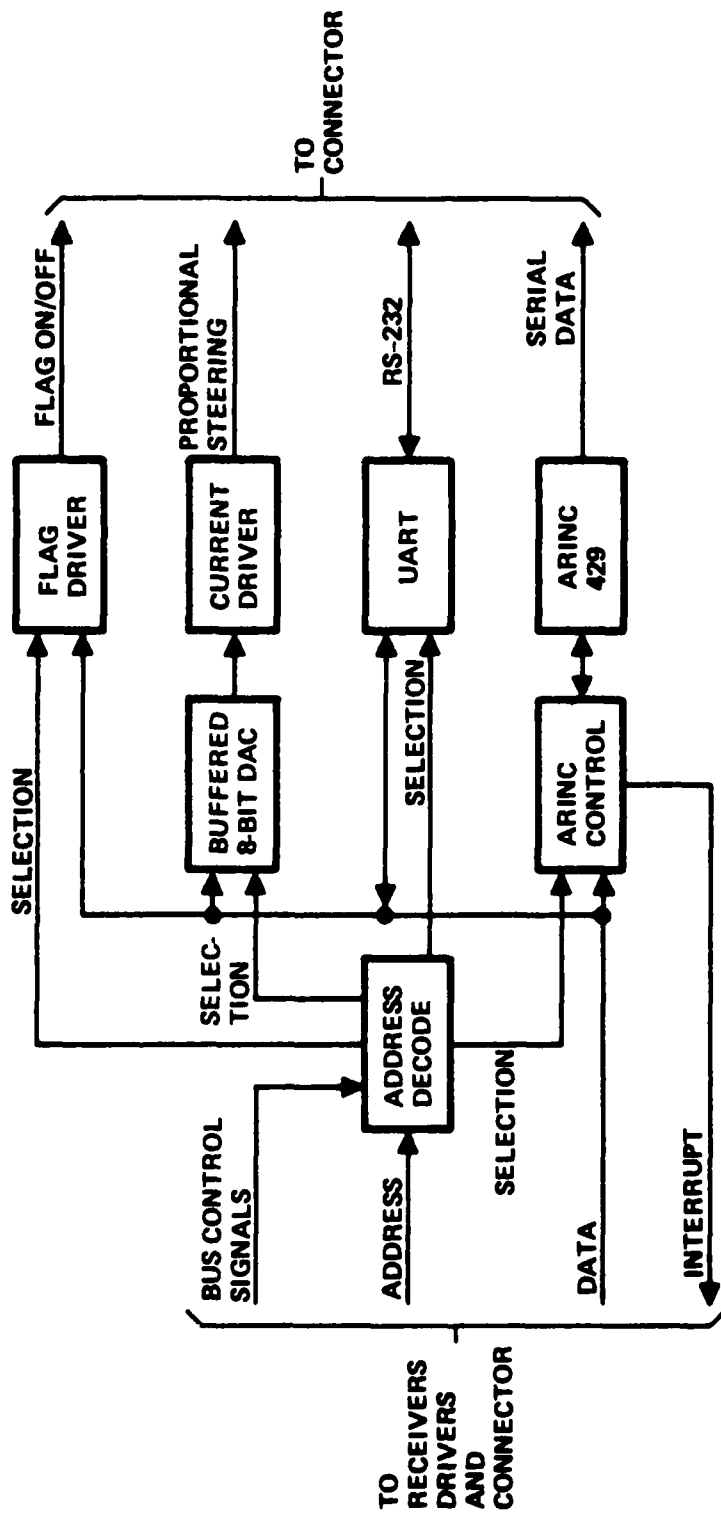
5.6 INPUT/OUTPUT

The receiver unit external interface facilities are provided on one multifunction circuit board. The ARINC 429 output port, the bidirectional RS-232 port to the CDU, and the outputs to the steering indicator are all implemented on this one module. The I/O module interfaces to the CPU data bus through the backplane connector. A functional block diagram of the module is given in Figure 5-4.



T134728

Figure 5-3. Data Processor



T134730

Figure 5-4. Input/Output Module

The ARINC 429 output port makes use of a monolithic receiver/transmitter/encode/decode device, which requires additional control and buffering logic to mate it with the CPU data bus. The CDU interface conforms to RS-232C full duplex characteristics and is implemented in one universal asynchronous receiver/transmitter (UART). This device is directly compatible with the CPU data bus, as is the digital-to-analog converter (DAC) which provides a proportional signal to the steering indicator. The DAC outputs to the indicator through a driver. A latched switching function is provided to drive the flag in the indicator. All of the input/output channels are memory mapped and the module contains address decoding logic to detect I/O channel selections for each function on the module.

5.7 CONTROL DISPLAY UNIT

The Control Display Unit design allows it to be installed on either the pilot's instrument panel or console. The front panel of the unit is shown in Figure 5-5. Selection of the control display functions and the operational features of the panel were described in Section 4.4.

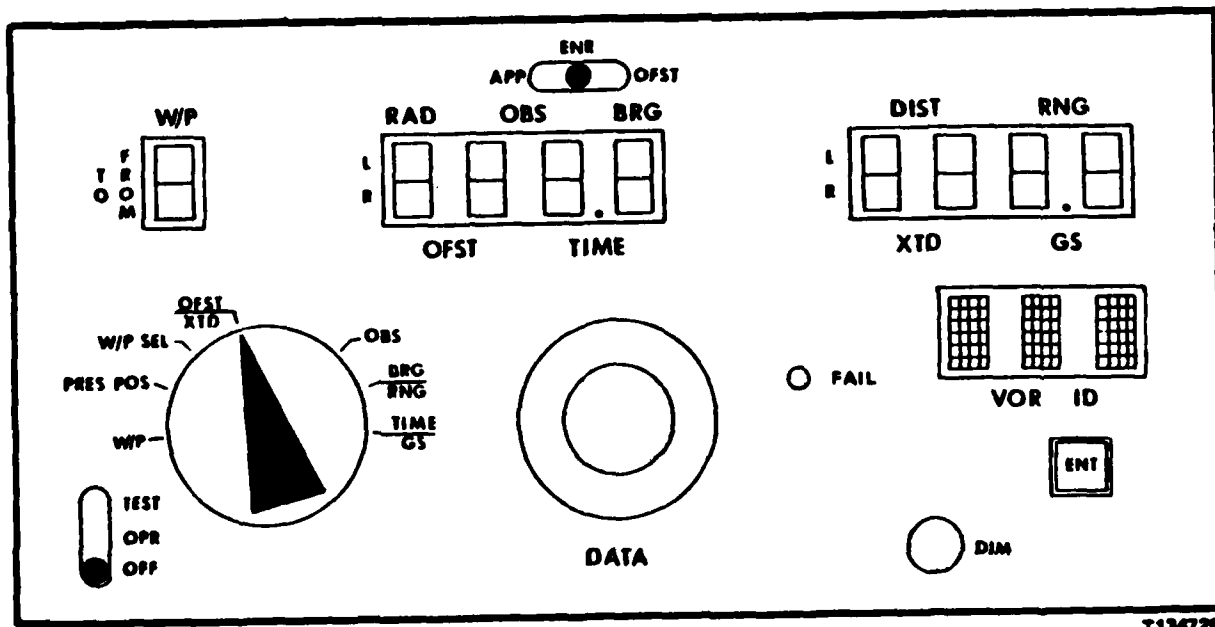


Figure 5-5. Control Display Unit Front Panel

The construction features of the CPU are shown in Figure 5-6. The design approach was selected to minimize cost of the unit. The unit consists of a front panel assembly, two printed wiring boards incorporating connectors and interconnect wiring, a top cover, and a bottom cover.

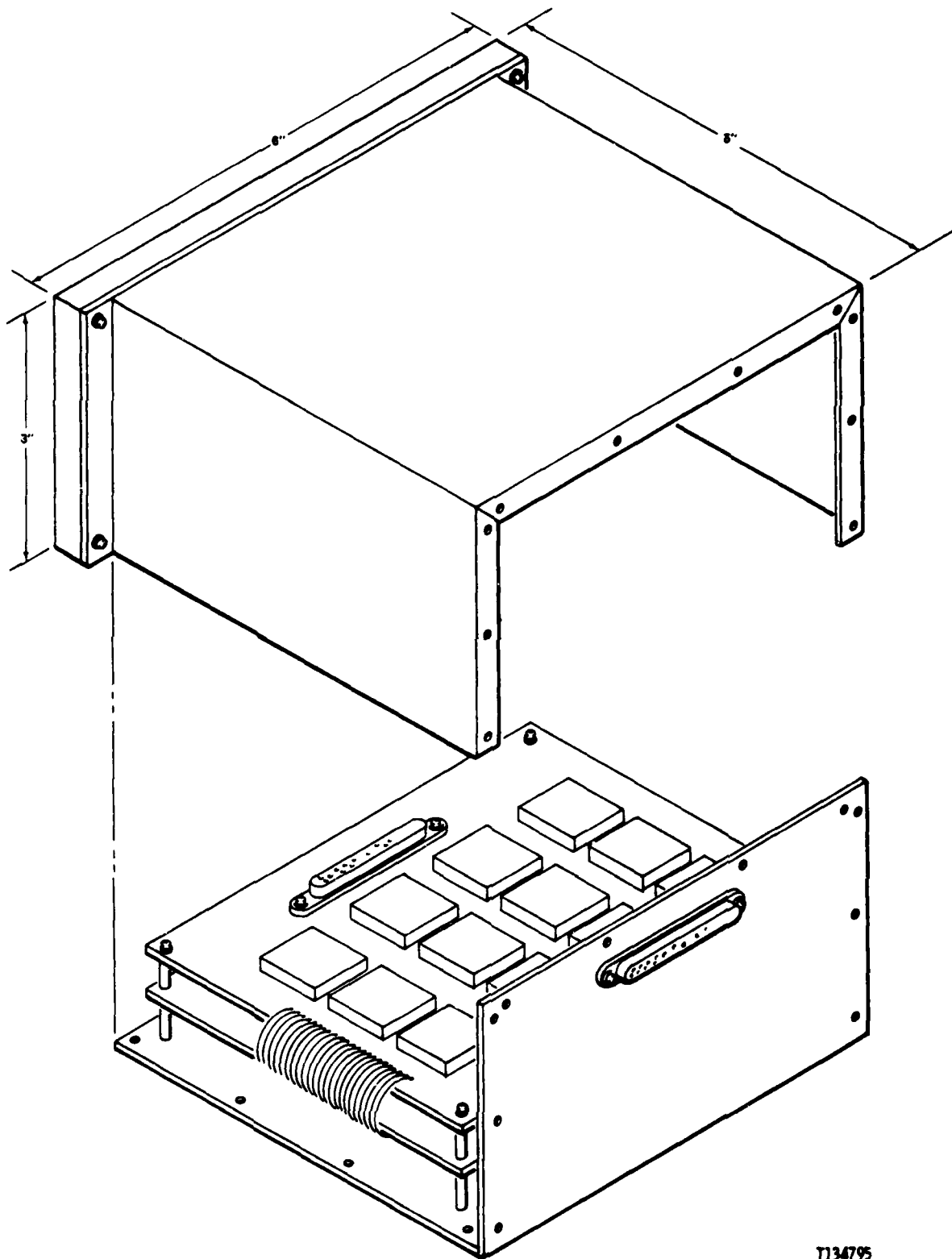
The CDU electronics are packaged on two circuit board which are connected by flexprint to each other and to the external connector. The electronics receive the RS-232 waveform which is sent from the receiver unit and drive the display with the coded data borne on the waveform. In addition, the panel switch positions are encoded and packed and returned to the receiver unit within the full duplex protocol. A contact closure derived from the "off" position of the mode switch is wired to the outside in order to control the system power supply. The receiver unit provides preregulated logic and lamp power to the CDU.

The RS-232 input stream contains framing characters and a string of display characters in a fixed order and format. The framing characters control the count of the addressing logic which scans the display. Receipt of a "top-of-form" character on the input port implies that the next character is to be addressed to leftmost digit. The display update sequence follows from there and the discrete lamps and indicators are coded and packed into characters at the end of the message. The string is terminated by an "end of text" character which also originates an output stream of switch position data.

The CDU electronics has a UART device identical to the one in the receiver unit. Display dimming is implemented entirely within the CDU. The display panel has internal electronics which decode the character address, demultiplex the data coming from the UART and drive the lamps.

5.8 HOUSING ASSEMBLY/MODULES

The Receiver Computer Unit housing has been designed to be constructed from sheet metal parts without requiring any machined parts. The housing assembly is illustrated in Figure 5-7. The major assemblies of the housing are as follows.



T134795

Figure 5-6. Control Display Unit Assembly

ASSEMBLY	NO. REQ'D
- 1 ENDPLATE/MOUNTING	2
- 2 END FRAME	2
- 3 CONNECTOR PLATE	1
- 4 EDGE PLATE	2
- 5 SIDEPLATE	2
- 6 POWER SUPPLY MOUNT	1
- 7 MODULE GUIDE	2
- 8 WIRING INTERCONNECT	1
- 9 POWER SUPPLY	1
- 10 RF MODULE	1
- 11 COMP/MEM MODULE	1
- 12 INTERFACE MODULE	1
- 13 (SPARE)	1

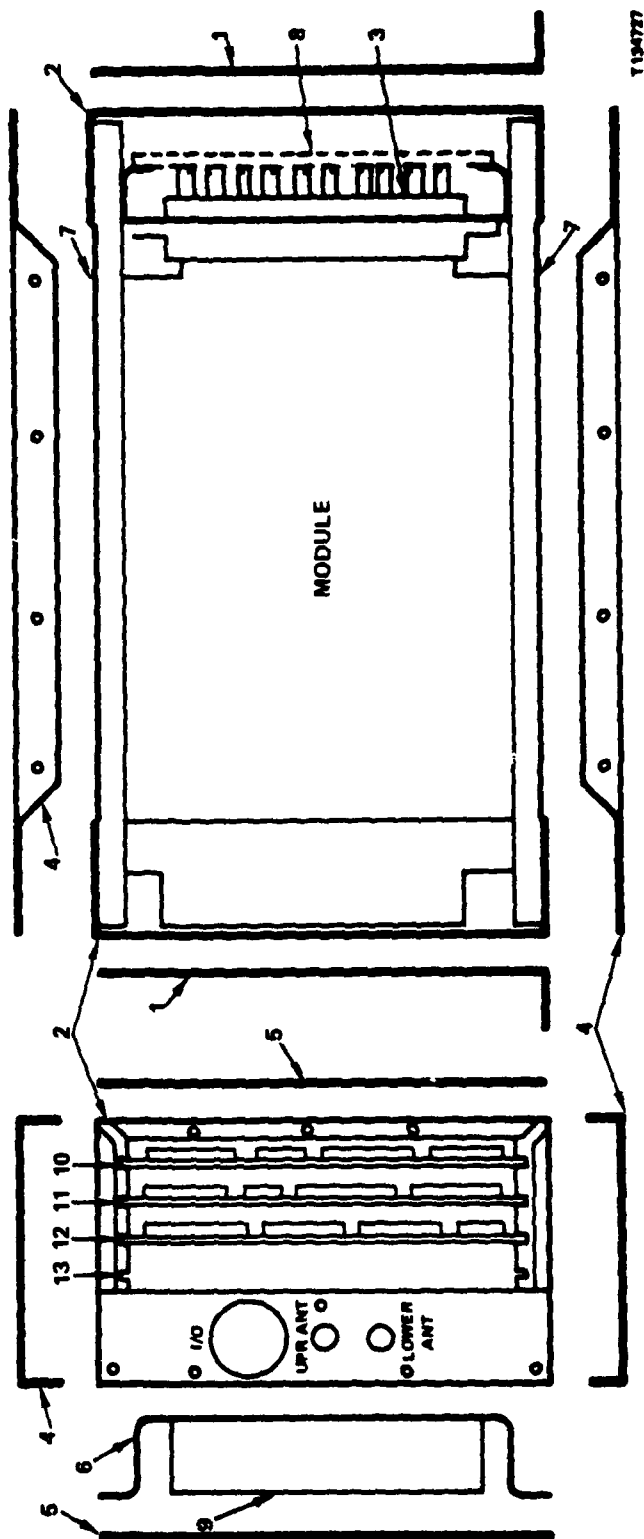
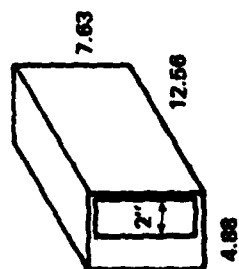


Figure 5-7. Receiver/Computer Housing Assembly

<u>Mechanical Assembly</u>	<u>No. Required/Unit</u>
-1 Endplate/Mounting (1 with connector cutout)	2
-2 End Frame	2
-3 Connector Plate	1
-4 Edgeplate	2
-5 Sideplate	2
-6 Power Supply Mount	1
-7 Module Guide	2
 <u>Electrical Assembly</u>	
-8 Wiring Harness (incl. connectors and PWB interconnect)	1
-9 Power Supply	1
-10 RF Module	1
-11 Comp/Mem Module	1
-12 Interface Module	1

Except for the module guide, all mechanical parts are formed from sheet metal. The module guide will be made from plastic or teflon. The end frames, power supply mount, and edgeplates will be riveted together to form a rigid mechanical structure. All other mechanical parts will be assembled with mechanical fasteners. All nuts will be of the captive and locking type.

The RF, Computer/Memory, and interface modules are two-sided PWB's with edge connectors on each end. (The front connector is used only for test purposes.) These modules are inserted and removed from the front of the unit. Each module provides 6 inches x 8 inches for installation of electrical components.

The housing assembly will mount directly to the aircraft structure by bolts attached through the endplates. Rack and panel mounting is possible by replacement of the endplates.

The housing is a standard short half ATR size, L - 12.56, W - 4.88, H - 7.63.

5.9 POWER SUPPLY

One of the design approaches selected early in the design of the Loran Navigation System was to minimize system cost by reducing the number of supply voltages required for the system. All the electronics in the system have been designed to operate from +5 VDC except for the RF unit which also requires ± 15 VDC. The overall power requirements are as follows:

	<u>Voltage</u>
Power Input	+24 VDC
Logic Power	+ 5 VDC
RF Unit	+15 VDC
	-15 VDC

All +5 VDC power will be supplied by a single module mounted within the Receiver Computer Unit. The power needed by the Control Display Unit, including display lighting, will be provided by this unit.

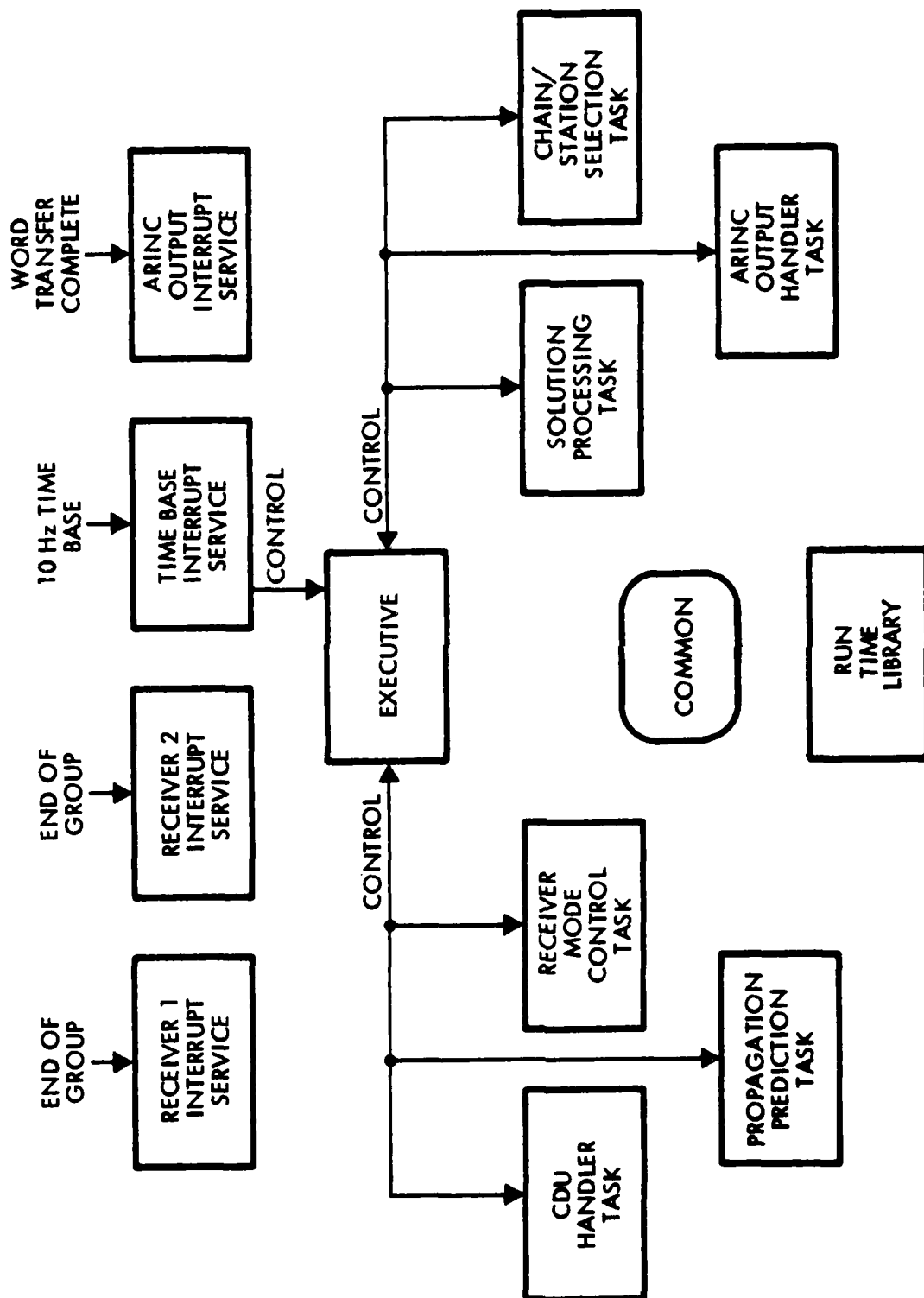
The ± 15 VDC power for the RF unit and notch filters will be supplied by a single module mounted within the Receiver Computer Unit. Power for the Antenna Coupler units will be supplied via the RF coax to minimize wiring and cost.

The following power supply modules have been selected:

+ 5 VDC
+15 VDC

5.10 SOFTWARE

The system software is a modular collection of interrupt service routines, task drivers, an executive, a run time library and a data base which are assembled into one computer program. There are six major tasks, each of which has a driver and a series of subroutines. There are four interrupt service routines. Machine time is allocated by a task dispatching executive which furnishes all control linkages to the six tasks. The tasks and interrupt handlers pass data through the common data base to other tasks. The library contains the mathematics functions supplied by the processor manufacturer including transcendental functions and some subroutines peculiar to the application. The program organization is shown in Figure 5-8.



T134697

Figure 5-8. Software Organization

The receiver interrupt service routines are identical and each is responsible for collecting and processing signal samples from its assigned timer and sampling logic. These routines do all the loop closures and detection functions for all receiver modes except search without passing control to the executive. Each service routine responds to directives from the receiver mode control task including self test initiation and provides timer values to the hardware. An interrupt occurs where the sampling for a pulse group is complete and the samples are retrieved from fixed memory locations. The interrupt processing is guaranteed to complete before the next interrupt.

The executive requires a permanent, fixed time base for the timing of several tasks. This time base is provided as a 10 Hz interrupt. The service routine passes control to the executive and has the highest priority of the four interrupts. The lowest priority is held by the ARINC 429 output service routine, which responds to a transfer complete event. This routine empties a buffer in memory prepared by the task of the same name.

Each time base event causes the executive to scan a table of task status discretely. The executive does not use time slicing but allows tasks to run until completion. Each task has self-suspension facilities so that the longest and lowest priority tasks may relinquish the machine by design. The status discretely are in the data base and provide signal mechanisms for the interrupt routines and the executive itself to ready tasks for execution. At each time base event, if no task is currently executing, the highest priority task is given control of the machine. Simple multi-tasking facilities are thus mechanized with flexibility and efficiency.

The receiver mode control task is scheduled by the two receiver interrupt service routines. Algorithms for receiver mode change decisions and search synchronization processing are the principal functions of this task. System mode is also controlled by this task, specifically self test direction and chain transitions. This is the only task that does not run at a rate set by the 10 Hz time base. Switch decoding and display manipulation are functions of the CDU handler task, which contains its own I/O driver for the CDU. This task does all steering processing and waypoint table management and also formats data for and commands the steering indicator. Neither of these tasks are self-suspending.

The secondary phase for each transmitter that the receiver is assigned to acquire is computed by the propagation prediction task. The task has access to the correction table and has the necessary facilities for correcting each time difference measurements.

The station selection task adds to and deletes from the list of selections. Since this task is laborious and should not have high priority, it suspends itself at several points in the pass for each station. The station selection task is scheduled at very low rates, i.e., one each 10 minutes, to anticipate chain transitions and direct the system accordingly. At power up, this task evaluates the geometry and signal strength of all chains stored in the permanent data base. The best chain is selected for acquisition and initial TD's are computed for all secondaries in that chain. If any other chains are receivable with adequate signal strength on the master, the one with the best geometry will be assigned to the second receiver channel. The system will begin navigating on the primary selection. If a chain transition is imminent, the selection task will have caused acquisition of the new chain well in advance. When the transition occurs, the receiver channels switch roles and this task continues to look for new opportunities. Self-suspension points will be coded into the flow of the selection task.

The solution processing task performs recursive coordinate conversion and smoothing on the measurements arriving from the channel designated as primary. The measurements are edited for poor SNR and acquisition events. The position and velocity estimates are supplied to the data base for use by other tasks. The ARINC output handler task formats the solution and steering parameters into the required packing and performs the first transfer. The packed data are loaded into a buffer which the corresponding interrupt service routine empties.

SECTION 6

COST TO THE USER

The goal of this design study has been to determine the minimum performance requirements for a Loran-C based RNAV system and to determine if that system can be provided at a cost to the user of \$3000 or less. A cost analysis has been conducted of the Loran Navigation System described in this report. The analysis shows that the cost to the user will be \$2884.79.

A cost summary is shown in Table 6-1. The detailed listing of material and labor costs are shown on the attached analysis sheets. A detailed breakdown of the costs is provided for each module and for each unit. Also shown is the manufacturing sequence for each item. The labor for each step is tabulated with the appropriate labor rate to arrive at the labor summary for each item. A priced out bill of materials is also shown.

The assumptions and conditions that apply to the cost analysis are as follows:

- All costs are in 1980 dollars.
- Costs are based upon a production quantity of 1000 units.
- It was assumed that integrated circuits would continue the cost decline trends that have been experienced in the past.
- It was assumed that the cost of labor in 1983, expressed in 1980 dollars, will be the same as labor costs in 1980.
- Because of the small quantities assumed, production costs are based upon manual rather than automated manufacturing methods.
- Tests are performed at the module level and at the unit level using semiautomated test equipment.
- The highest level of testing is at the unit (black box) level. Integrated system level test is not performed on each system.

While it may seem that \$2885 is a very low cost for a Loran Navigation System (and indeed it is) compared to similar equipments available in the marketplace, it should be noted that none of the currently available equipments utilize the latest integrated circuit technology and other low cost design approaches described in this report. The closest

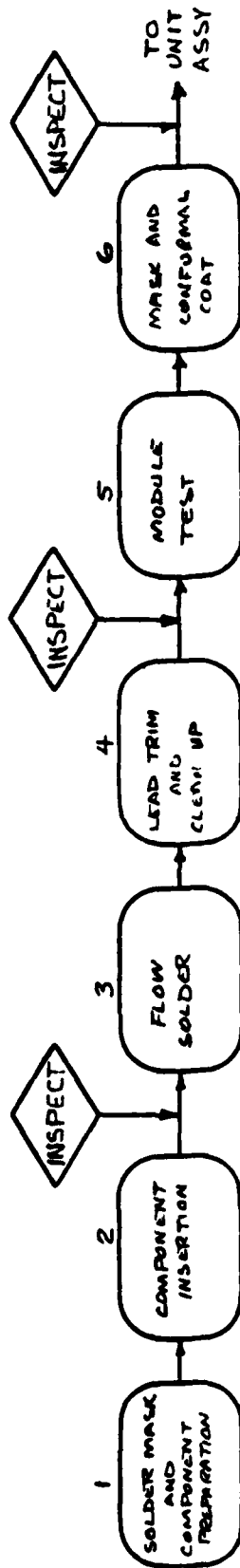
Table 6-1. Cost of Loran Navigation System

Material - Direct	689.00
- Overhead (25%)	172.25
Labor - Direct	165.58
- Overhead (40%)	66.23
Engr Support, Handbooks, Warranty (20%)	<u>218.61</u>
Factory Cost	1,311.67
G&A (12%)	157.40
Margin (Amortization, Profit)	<u>750.00</u>
Distributor Cost	2,219.07
Distributor Margin (30%)	<u>665.72</u>
Cost to User	2,884.79

comparison would be some of the Loran sets with coordinate converters for marine use that are currently selling for less than \$2000.

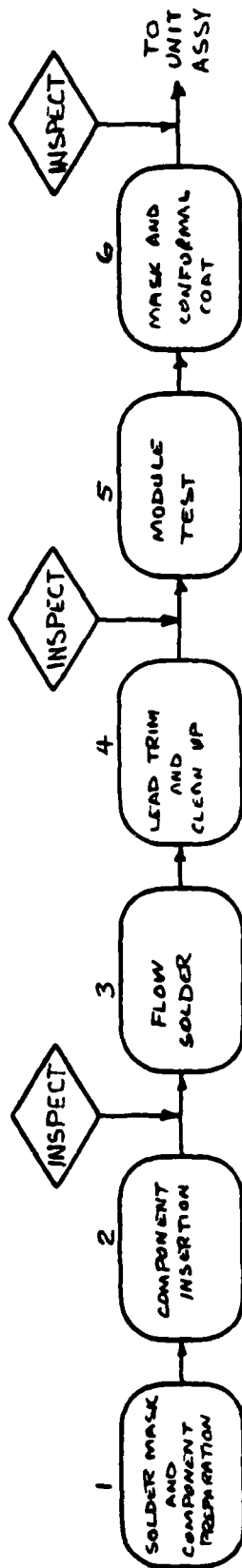
If Loran coverage was extended throughout the USA and the certification process simplified, Loran RNAV systems would experience both the acceptance and cost competition now occurring in the marine marketplace.

MANUFACTURING FLOW - R.F. MODULE



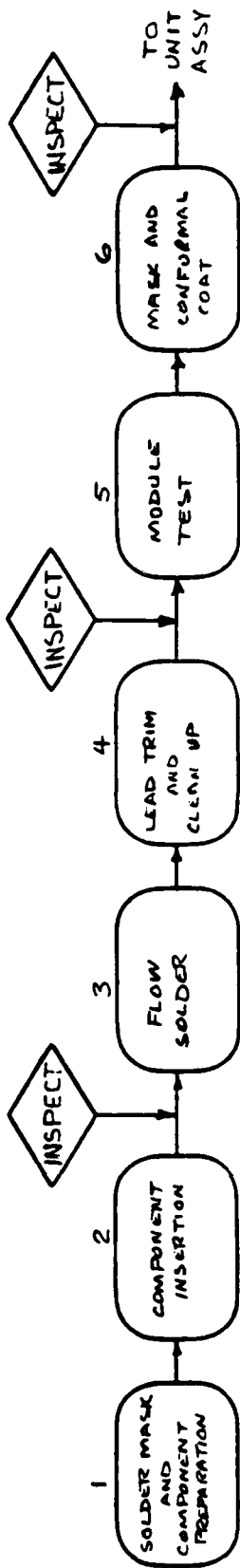
ITEM	PART NUMBER	DESCRIPTION	MANUFACTURER	QTY	MATERIAL COST	MFG STEP	LABOR GRADE	LABOR RATE	MFG HRS	LABOR COST
1	PA 733	Video Amp	Spencfield	2	2.50	1		6.40	0.80	5.12
2	HC9062	Coil	Miller	2	3.06	2		6.40	0.60	8.96
3	70F332AF	Inductor	Miller	2	1.16	3		6.40	0.07	1.45
4	SWD10000	Inductor	Nytronics	1	1.25	4		6.40	0.75	4.80
5	TL601	Timing Switch	TI	2	1.20	5		8.90	1.30	11.57
6	2655-5	Amp	Harvia	2	1.10	6		6.40	0.20	1.28
7	3069P	Striptet	Bourns	2	6.90	7				
8	8014866	Transformer	TSC	2	7.80					27.06
9	LH101	Op Amp	National	1	1.86					
10		Resistor		13	1.30					
11		Cap		7	1.40					
12		Transistor		4	3.20					
13		Printed Wiring Board		1	12.00					
14										
15										
16										
17										
8					44.73					

MANUFACTURING FLOW - COMPUTER/MEMORY MODULE



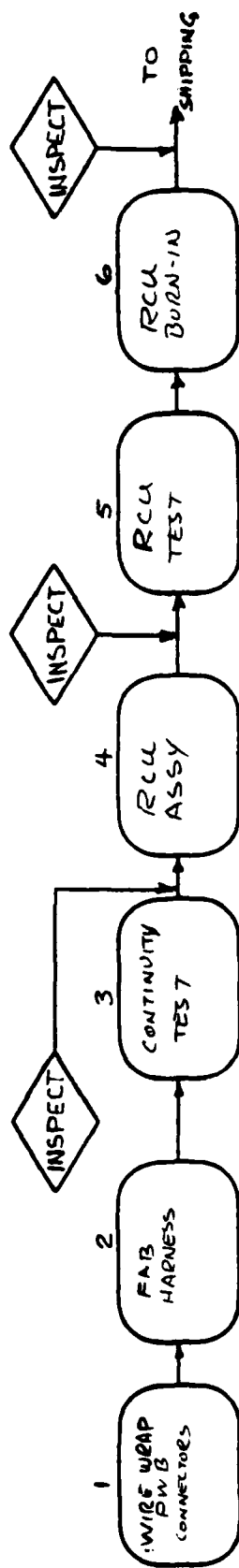
ITEM	PART NUMBER	DESCRIPTION	MANUFACTURER	QTY	MATERIAL COST	MFG STEP	LABOR GRADE	LABOR RATE	MFG HRS	LABOR COST
1	8088	CPU	INTEL	1	15.95	1		6.40	0.40	2.56
2	8284	Timing	"	1	2.45	2		6.40	0.40	2.56
3	8286	Bus Controller	"	1	6.90	3		6.40	0.07	.44
4	8205	Decoder	"	3	7.10	4		6.40	0.65	4.16
5	8251A	UART	"	1	2.80	5		8.90	1.10	9.79
6	8255	PIC	"	1	6.25	6		6.40	0.18	1.15
7	8237-2	DMA Controller	"	2	12.40	7				
8	8282	Latch	"	9	18.90					20.66
9	8286	Transceiver	"	4	11.10					
10		ROM		4	40.00					
11		RAM		2	24.00					
12		TC10-15.12		1	6.50					
13		Driver 1100 1000		1	12.00					
14										
15										
16										
17										
18										
					166.35					

MANUFACTURING FLOW - INTERFACE MODULE



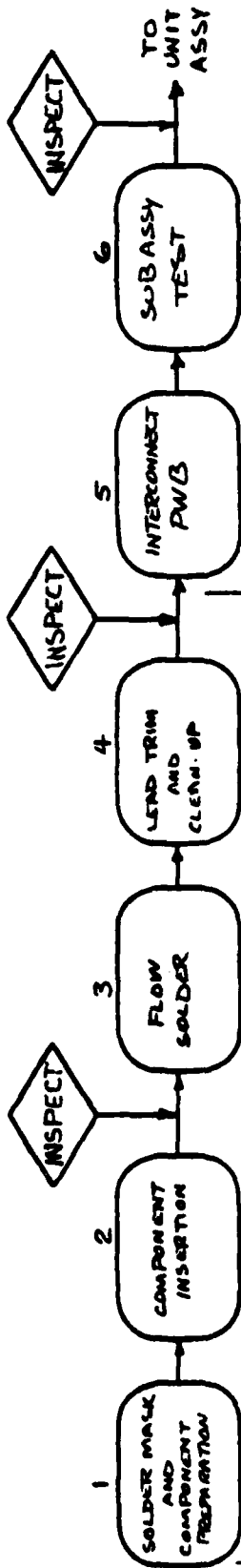
ITEM	PART NUMBER	DESCRIPTION	MANUFACTURER	QTY	MATERIAL COST	MFG STEP	LABOR GRADE	LABOR RATE	MFG HRS	LABOR COST
1	MC 3408	8 Bit DAC	Motorola	1	2.35	1		6.40	0.50	3.20
2	DM 74LS240	Buffer	Philips	2	2.80	2		6.40	0.50	3.20
3	AD7574	ADC	Analog Devices	4	16.00	3		6.40	0.07	.28
4	8255	PIO	Intel	4	28.00	4		6.40	0.70	4.48
5		TCXO		1	12.00	5		8.90	1.10	9.79
6	H5500	Gate array	Intel products	2	18.60	6		6.40	0.18	1.12
7	74XX1	I.C.		6	6.00	7				
8	AD582	S/H	Analog Devices	4	8.80					22.18
9		Resistor		~20	0.80					
10		Cap		~10	2.00					
11		Printed Wiring Board		1	12.00					
12										
13										
14										
15										
16										
17										
18										
					109.35					

MANUFACTURING FLOW - RECEIVER COMPUTER UNIT (RCU)



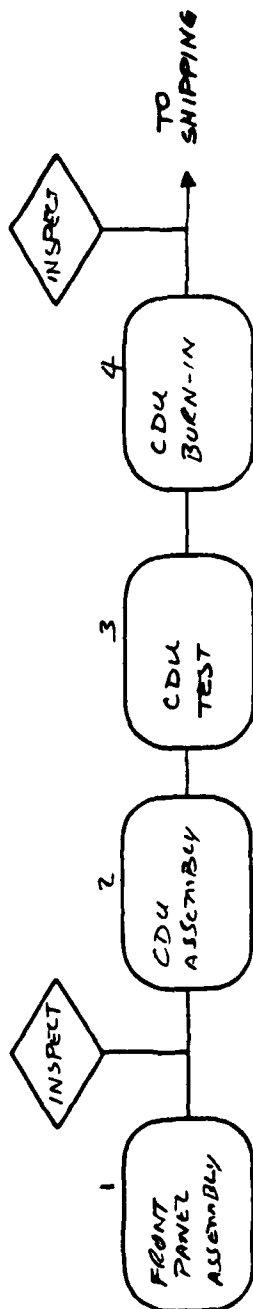
ITEM	PART NUMBER	DESCRIPTION	MANUFACTURER	QTY	MATERIAL COST	MFG STEP	LABOR GRADE	LABOR RATE	MFG HRS	LABOR COST
1		END PLATE / MOUNTING		2	12.00	1		6.40	2.00	12.80
2		END FLANGE		2	18.00	2		6.40	1.50	9.60
3		CONNECTOR PLATE		1	13.50	3		6.40	0.60	3.84
4		EDGE PLATE		2	14.00	4		7.20	0.50	3.60
5		SIDE PLATE		2	12.00	5		8.90	1.20	10.68
6		POWER SUPPLY MOUNT		1	9.00	6		8.90	0.70	6.73
7		CARD GUIDE		2	8.00	7				
8		POWER SUPPLY, ±5V		1	16.75					16.75
9		POWER SUPPLY, ±12V		1	14.50					
10	KPT02E18-325	CONNECTOR		1	8.30					
11		BNC CONNECTOR		2	0.86					
12		EDGE CONNECTOR		4	16.80					
13		RF MODULE		1	REF					
14		INTERFACE MODULE		1	REF					
15		COMPUTER/MEMORY MODULE		1	REF					
16										
17										
18										
					144.51					

MANUFACTURING FLOW - CDU NO.1 & CDU NO.2 MODULES



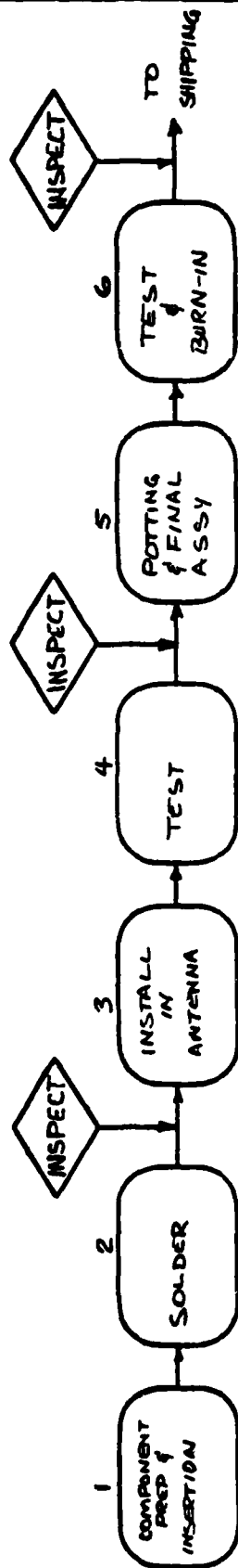
ITEM	PART NUMBER	DESCRIPTION	MANUFACTURER	QTY	MATERIAL COST	MFG STEP	LABOR GRADE	LABOR RATE	MFG MISC	LABOR COST
1	74LS163	÷ 16 Counter		3	2.40	1		6.40	0.30	1.92
2	74LS174	6 bit Reg		2	1.62	2		6.40	0.30	1.92
3	74LS09	RAM		2	2.92	3		6.40	0.10	.64
4	7442	Decoder		1	1.38	4		6.40	0.25	1.60
5	74LS138	Decoder		2	1.44	5		6.40	0.35	2.24
6	74LS158	OR Gate		2	1.38	6		8.90	0.80	7.12
7	74LS155	Decoder		1	0.91	7				
8	9642	Rev. Driver	Fairchild	1	1.38					15.44
9	75325	Quad Memory Driver		9	10.80					
10	8251	UART	Intel	1	2.80					
11	DM8160	Comparator	National	1	0.50					
12	74xxx	I.C.		16	12.00					
13		PWB		2	14.00					
14		CONNECTOR		2	8.90					
15										
16										
17										
18										
					62.33					

MANUFACTURING FLOW - CONTROL DISPLAY UNIT



ITEM	PART NUMBER	DESCRIPTION	MANUFACTURER	QTY	MATERIAL COST	MFG STEP	LABOR GRADE	LABOR RATE	MFG HRS	LABOR COST
1	4631140R	SWITCH - 3 POS SLIDE	SWITCHCRAFT	2	1.80	1		7.20	0.20	1.44
2	DA 2013	SWITCH - 10 POS ROTARY	CENTRALAB	1	4.09	2		7.20	0.15	1.08
3	503265-1-3N	SWITCH - 3 POS CONC-ROTARY	RAYNIEL	2	6.78	3		8.90	0.60	3.36
4	2076R	LIGHTS - 7 SEGMENT	IEE	13	14.30	4		8.90	0.30	2.67
5		CONNECTOR		1	4.45	5				
6		PANEL - DISPLAY		1	18.75	6				
7		HOUSING, TOP		1	8.50	7				
8		HOUSING, BOTTOM		1	7.00					10.53
9		CDU NO 1 & NO 2 MODULES		1	REF					
10		MISCL HDW			3.40					
11										
12										
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MANUFACTURING FLOW - ANTENNA / ANTENNA COUPLER UNIT



ITEM	PART NUMBER	DESCRIPTION	MANUFACTURER	QTY	MATERIAL COST	MFG STEP	LABOR GRADE	LABOR RATE	MFG HRS	LABOR COST
1	2655-S	Ampl	Alenia	1	1.20	1		6.40	0.40	2.56
2	SWD 10000	Inductor	Nytronics	3	3.75	2		6.40	0.25	1.60
3	538-0200B	Cap	Edie	2	1.68	3		7.20	0.30	2.16
4		Resistor		6	0.60	4		8.90	0.20	1.78
5		Cap		4	0.80	5		6.40	0.25	1.60
6	2N930	Transistor		1	0.30	6		8.90	0.20	1.78
7		PWB		1	3.00	7				
8		ANTENNA		1	35.00					11.48
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APPENDIX A
WORKLOAD ANALYSIS TECHNIQUE

APPENDIX A

WORKLOAD ANALYSIS TECHNIQUE

INTRODUCTION

The accurate quantitative evaluation of pilot workload is a very controversial topic in the human factors field. Not only are measurement techniques still being discussed, but the optimal level of operator workload is still in question. Perhaps the most quantitative measurement technique which is commonly accepted by researchers is the task analysis. This technique also has the advantage of being predictive in nature. When the inherent limitations are taken into consideration, this technique can be an effective tool in comparing the relative merit of several different operator/machine interface designs from a workload point of reference. Perhaps the most important limitation inherent in task analysis is the fact that it applies only to the physical aspects of workload, in most cases, time/motion related. A complete measure should include mental workload and stress inducements. Measurement of these workload components is often tied to controversial qualitative techniques. Additionally these techniques are non-predictive in nature and not applicable to a design study of this nature. The concepts of mental workload and induced stress should not be totally neglected in the design of a man/machine interface, however. Common sense and judgement should dictate the influence these aspects should have on any design decision.

TASK ANALYSIS

Task analysis is a means of obtaining predictive quantitative values for the workload (physical) involved in the accomplishment of complex tasks using a particular interface design. Often times these values do not relate to real world units of any type but instead are used as tools in comparative studies. Thus, the technique can be modified to relate directly to the specific type of interface being analyzed as long as care is taken that no prejudice to one particular design concept is introduced. Typically, the interface being studied involves the use of a keyboard and the standard workload unit is a keystroke. The interface

being evaluated in this study does not involve a keyboard, however, and relative values for the operation of rotary knobs, pushbuttons, toggle switches, and slew switches had to be established. In many cases subjective judgement was used to determine the quantitative value of these interrelationships. Care was taken to assume that no prejudicial influence was introduced, thus depending on the comparative nature of the evaluation to overcome the lack of direct reference to real world units. Time units are perhaps the closest recognizable units to which this technique can be allied, with each unit being conservatively associated with a second of time. This value is not an exact correlation but it can be used as an approximate reference.

Comparative analysis of the two concepts dictated that four types of operations be evaluated over a series of three operational scenarios:

- Waypoint loading (definition)
- Waypoint change (active waypoint)
- Course change (for the TO-FROM concept)
- Parallel Offset Maneuver

The evaluation of these operations required that a workload value be associated with four specific switches. The following is a listing of those switches and the assigned workload value:

- | | |
|---------------------|--------------------------|
| ● Data Selector | 2 units |
| ● Data Control | 1 unit/10 digit movement |
| ● Enter Button | 1 unit |
| ● Any Toggle Switch | 1 unit |

By evaluation of each required operation in terms of total units the workload for a complete scenario can be determined. Comparison of different interface design concepts over a single scenario result in relative workload evaluation values.

SCENARIOS

An important aspect of this process is the development of realistic operational scenarios. Because of the diversity of possible ATC interactions, a minimum of three scenarios is required to adequately represent the environment into which a low cost receiver would be introduced. To alleviate unnecessary variables in the analysis, aircraft

parameters were defined as remaining constant between the three scenarios. The aircraft category chosen to be representative was a cabin class turboprop aircraft used in a variety of business applications. In all cases, aircraft operations are assumed to be single pilot, IFR flight plan operations using the Loran-C equipment as the primary means of navigation with other radio navigation aids available as appropriate. Although slightly more sophisticated than a single engine, single pilot operation, it was felt that a turboprop, business oriented aircraft operation would be more conducive to realistic insertion into a wider range of ATC operational scenarios. Theoretical comparative workload values should be minimally effected due to this assumption.

Selection of representative scenarios was based on the diversity of ATC operations which could be incorporated without infringing on the facet of realism. Preliminary investigation revealed three general types of scenarios which should be included:

- A very structured route system operating primarily out of smaller non-hub airports. This type of operation would apply to a large corporation having a number of facilities located in a particular geographic region, such as New England, which might have a daily "courier" run between facilities located near general aviation airports.
- A flexible route structure covering a larger geographic area which would operate out of a variety of airport types on an as required basis. An example of this type of operation might be that used by a major product distribution corporation or a regional sales department.
- An in depth evaluation of the specific problems associated with a terminal area. Operations in this environment involve a unique set of constraints and pilot/controller interactions which should be examined independently.

Development of specific scenarios based upon these general concepts would include a majority of the operational situations which compose the environment applicable to the workload assessment of proposed Loran-C receiver designs. Specific scenario designs will be detailed in the following sections.

STRUCTURED CORPORATE COURIER ROUTE

This scenario is based on the requirements of a hypothetical corporation located in New England which maintains facilities in several cities in Connecticut, Rhode Island, and Massachusetts. In order to facilitate regular written communications between the facilities a daily courier flight has been established using a corporate turboprop aircraft. Flight routes are the same from day-to-day with stops scheduled at each of six general aviation airports for pickup and delivery. Takeoffs and landings are scheduled around specific time parameters to facilitate ground handling at each airport. Flight routes are based on RNAV principles and, in most cases are filed as "RNAV direct" flight plans. Although the daily routing involves operations at six general aviation airports (six legs) only two legs of the route will be specifically addressed by this scenario. These legs include Bradley International (Hartford, Conn.) to Theodore Francis Green State (Providence, RI) and Theodore Francis Green State to Lawrence Municipal (Lawrence, Mass.). As the aircraft is assumed to be based at Bradley International, these two legs comprise the first two legs of the daily schedule. For navigational purposes each leg consists of a departure fix, an arrival fix, a final approach fix and a runway end identification fix. All flights are considered to be RNAV direct from the departure fix to the arrival fix with a non-precision terminal procedure at the destination airport. Turnaround times at each intermediate airport are considered to be a significant factor in the design of this scenario, although weather conditions are such that an IFR flight plan is required throughout the flight and the aircraft is assumed to be operating in IMC.

This scenario has been designed to comparatively evaluate workload factors in a controlled relatively straight forward environment with a minimum number of unexpected route changes. Flight routes are highly amenable to a high level of preflight planning and inflight navigation workload can generally be kept to a minimum level.

FLEXIBLE SALES MANAGEMENT ROUTING

The flight requirements of a regional sales or distribution department differ significantly from the structured requirements of a corporate "courier" route. Operations can be assumed to originate principally from a single home base but destinations will be geographically scattered with destination repeatability a relatively random factor. Thus there will tend to be a greater dependence on the established ATC route structure for flight planning purposes with a greater probability of possible enroute delays. Turnaround times will be longer, as the primary purpose of the flight is people transportation rather than cargo transportation. Based on these general constraints a specific scenario has been selected involving a sales manager based in Birmingham, Alabama. For this particular scenario, he is to fly to Jacksonville, Florida and return later the same day. Although the corporate aircraft to which he has access makes an average of four trips a week, it has not been flown to Jacksonville in the last six weeks. Thus there is no preplanned stored routing in a cockpit navigation computer (if that capability exists) and all fixes must be hand entered. Additionally, the route to be followed for the flight will coincide with established ATC Victor routes (V168 to La Grange, V243 to Jacksonville). All enroute VORs and intersections will be input as waypoints, increasing the level of pilot workload and thus exaggerating the comparative workload values for ease of analysis. Finally, an unexpected inflight delay will be inserted in the route just prior to La Grange VOR to accommodate a traffic backup inbound to Atlanta. This scenario will be evaluated only on the Birmingham to Jacksonville leg and should be an effective measure of the impact of inflight waypoint definition and unexpected deviation requirements on each of the receiver designs evaluated.

TERMINAL AREA SCENARIO

The composition of this scenario will differ from the composition of the last two. Rather than consisting of a single operational entity defined from takeoff to landing, it will be a composite of terminal area operations including a takeoff, departure (SID), arrival (STAR),

and approach, and landing. Additionally selected route deviations will be introduced based on radar vector, parallel offset, and extended downward controller techniques.

Although any major hub terminal area employing standardized departures and arrivals would serve as a plausible geographic setting for this scenario, J.F. Kennedy International, New York has been chosen to analyze the unique problems associated with terminal area navigation.

The terminal area routing which will be considered will be based upon the Belle One Departure to Pawling VOR with a transition to the Kingston One Arrival to the Ellis Intersection. The route of flight will be terminated with an ILS Approach to Runway 13L. The route was chosen because of the variety of navigation techniques that is required to transit it, including VOR and intersection referenced navigation, radar vectors and transition to a precision approach. Controller techniques which will be incorporated during the outbound leg include parallel offset (if applicable) and "direct to" clearances while radar vector course clearances will be considered during the transition to the ILS final approach. The final approach and the scenario will be terminated with an unexpected missed approach due to an aircraft on the runway.

This scenario is the most workload intensive of the three presented here. Although each and every navigation concept considered could be encountered in a terminal area environment, it is doubtful whether they would all occur in the short time frame considered in this scenario. Thus, absolute workload levels may appear to be abnormally high during analysis, but these exaggerated levels will be beneficial in a comparative analysis such as contained in the following section.

PILOT WORKLOAD ANALYSIS

An important consideration in the design of the CDU for the low cost Loran-C receiver is the amount of pilot workload the unit will entail in its typical operation. This section will attempt to analyze one aspect of that workload based on the three operational scenarios which have been developed. The analysis technique used is comparative in nature rather than universal. It has been specifically designed to compare the two

concepts developed elsewhere in this report. Consideration of further design concepts will require modification of the technique as described here, but this technique can be used for comparison of the two concepts presented. It should also be remembered that this technique measures only the physical movement aspects of workload and doesn't consider the mental aspect or induced stress. No quantitative productive technique is available to measure these aspects.

This analysis makes several assumptions which affect the specific workload value results. First both concepts are considered to have four waypoint storage capacity. Consideration of alternate capacities will change the specific values but should not significantly change the comparative quantization of the two systems. Secondly, both systems are considered to have volatile memory storage for pilot entered data. This means that upon system shutdown all registers containing pilot entered data are zeroed out. This design is considered primarily because of its cost saving effect on the overall system. As will be seen from the results of this analysis, this assumption affects these comparative relationships between the two systems. Specific effects will be discussed at the conclusion of this section. Finally, it was assumed that the operator did not attempt to minimize the workload associated with waypoint definition by "saving" a waypoint which would be used later in the scenario or "grouping" waypoints according to common positions or alpha identifiers within the interface grid reference. This assumption has a minimal effect on the comparative results between design concepts.

Tables A-1 to A-6 are a tabulation of the results obtained in this analysis. Four operations were considered:

- Waypoint loading (or definition)
- Waypoint change (active waypoint selection)
- Course change (for the TO-FROM system)
- Parallel Offset Selection

These results are relatively self explanatory. Although a reduction in airborne workload is considered to be more intrinsically valuable than a reduction in ground workload, the large difference in total workload between the lat/lon and the rho/theta systems should be a consideration in future design decisions. The large value obtained for waypoint definition in the lat/lon system could be significantly reduced by the incorporation of non-volatile memory for pilot entered data. As can be seen, these large values are a result of the long data switch drive times incurred during waypoint definition immediately following system turn on. These drive times would normally be minimal if non-volatile memory storage were available.

Table A-1 Pilot Workload for the Lat/Lon System on the Corporate Route

Scenario #1- Corporate

Lat/Lon System

WAYPOINT		WAYPOINT LOAD	WAYPOINT CHANGE	COURSE CHANGE
Bradley	(1)	125* seconds	- seconds	- seconds
Skylark	(2)	125*	6	-
Steel	(3)	125*	6	-
Final				
Approach				
Fix	(4)	132*	6	-
Providence	(1)	14	-	-
Providence	(1)	4*	6*	-
Woons	(2)	5*	6	-
Haget ADF	(3)	10*	6	-
Valan	(4)	12*	6	-
Lawrence				
Muni	(1)	9	-	-
ground time		561 (538)seconds 23 Airborne Seconds	42 (6*)seconds 36 Airborne Seconds	0 seconds

TOTAL = 603 seconds GROUND = 544 seconds AIRBORNE = 59 seconds

Table A-2 Pilot Workload for The Rho/Theta System on the Corporate Route

Scenario #1 - Corporate

Rho/Theta System

WAYPOINT		WAYPOINT LOAD	WAYPOINT CHANGE	COURSE CHANGE
Bradley	(1)	15* seconds	4 seconds	5* seconds
Skylark	(2)	18*	4	4
Steel	(3)	15*	4	4
Final				
Approach				
Fix	(4)	15*	4	5
Providence	(1)	16	-	-
Providence	(1)	7*	4	5*
Woons	(2)	14*	4	5
Haget ADF	(3)	11*	4	4
Valan	(4)	13*	4	10
Lawrence				
Muni	(1)	8		-
ground time		132 (108) seconds 24 Airborne Seconds	32 (0*) seconds 32 Airborne Seconds	42 (10*) seconds 32 Airborne Seconds

TOTAL = 206 seconds GROUND = 118 seconds AIRBORNE = 88 seconds

Table A-3 Pilot Workload for The Lat/Lon System on the Sales Route
Scenario #2 - Sales Lat/Lon System

WAYPOINT		WAYPOINT LOAD	WAYPOINT CHANGE	COURSE CHANGE
Birmingham				
A/P (VUZ				
127/9.6)	(1)	134* seconds	- seconds	- seconds
Departure				
Fix (VUZ				
111/9.9)	(2)	132*	6	-
Gosse(VUZ				
111/47)	(3)	126*	6	-
Giffy(LGC				
293/25)	(4)	125*	6	-
LaGrange(LGC)	(1)	12	6	-
Langa (LGC				
119/15)	(2)	12	6	-
Caner (CSG				
067/23)	(3)	16	6	-
Pratz (MCN				
265/37)	(4)	14	6	-
Potar (VNA				
299/33)	(1)	16	6	-
Phyll (VNA				
299/20)	(2)	15	6	-
Vienna(VNA)	(3)	13	6	-
Dummy (VNA				
138/21)	(4)	11	6	-
Waycross(AYS)	(1)	13	6	-
Paffo (AYS				
126/25)	(2)	11	6	-
Folks (JAX				
318/25)	(3)	19	6	-
Final				
Approach				
Fix(JAX				
300/13.3)	(4)	16	6	-
Jacksonville				
Intl(JAX				
284/6.4)	(1)	13	-	-
ground time		689 (517) seconds	90 (0*) seconds	0 seconds
		181 Airborne Seconds	90 Airborne Seconds	
TOTAL = 788 seconds		GROUND = 517 seconds	AIRBORNE = 271 seconds	

Table A-4 Pilot Workload for the Rho/Theta System on the Sales Route
Scenario #2 - Sales Rho/Theta System

WAYPOINT		WAYPOINT LOAD	WAYPOINT CHANGE	COURSE CHANGE
Birmingham A/P (VUZ 127/9.6)	(1)	19* seconds	4 seconds	5* seconds
Departure Fix (VUZ 111/9.9)	(2)	15*	4	4
Gosse (VUZ 111/47)	(3)	19*	4	-
Giffy (LGC 293/25)	(4)	16*	4	4
LaGrange (LGC)	(1)	17	4	4
Langa (LGC 119/15)	(2)	15	4	-
Caner (CSG 067/23)	(3)	18	4	-
Pratz (MCN 265/37)	(4)	15	4	-
Potar (VNA 299/33)	(1)	18	4	-
Phyll (VNA 299/20)	(2)	15	4	-
Vienna (VNA)	(3)	17	4	5
Dummy (VNA 138/21)	(4)	16	4	5
Waycross (AYS)	(1)	21	4	5
Paffo (AYS 126/25)	(2)	18	4	5
Folks (JAX 318/25)	(3)	20	4	5
Final Approach Fix (JAX 300/13.3)	(4)	18	4	5
Jacksonville Intnl (JAX 284/6.4)	(1)	19		-
ground time		296 (69) seconds 227 Airborne Seconds	64 (0*) seconds 64 Airborne seconds	47 (5*) seconds 42 Airborne Seconds
TOTAL = 407 seconds		GROUND = 517 seconds		AIRBORNE = 333 seconds

Table A-5 Pilot Workload for the Lat/Lon System on the Terminal Route

Scenario #3- Terminal

Lat/Lon System

WAYPOINT		WAYPOINT LOAD	WAYPOINT CHANGE	COURSE CHANGE	OFFSET
Kennedy Intl (JFK)	(1)	134* seconds	- seconds	- seconds	
Belle (MAD 244/26)	(2)	127*	6	-	
Bridge Port (BDR)	(3)	135*	6	-	
Turn Point (PWL 151/31)	(4)	129*	6	-	
Pawling (PWL)	(1)	12	6	-	
Kingston (IGN)	(2)	17	6	-	6 seconds
Ellis (JFK 318/15)	(3)	15	6	-	
Kennedy Intl (JFK)	(4)	16	-	-	
ground time		585 (525) seconds	36 (0*) seconds	0 seconds	6 (0*) seconds
		60 Airborne Seconds	36 Airborne Seconds	0 Airborne seconds	6 Airborne Seconds

TOTAL = 627 seconds

GROUND = 525 seconds

AIRBORNE = 102 seconds

Table A-6 Pilot Workload for the Rho/Theta System on the Terminal Route

Scenario #3- Terminal

Rho/Theta System

WAYPOINT		WAYPOINT LOAD	WAYPOINT CHANGE	COURSE CHANGE	OFFSET
Kennedy Intl (JFK)	(1)	14* seconds	4 seconds	4* seconds	
Belle (MAD 244/26)	(2)	25*	4	5	
Bridgeport (BDR)	(3)	9*	4	8	
Turn Point (PWL 151/31)	(4)	29*	4	4	
Pawling (PWL)	(1)	14	4	7	
Kingston (IGN)	(2)	12	4	11	6 seconds
Ellis (JFK 318/15)	(3)	18	4	8	
Kennedy Intl (JFK)	(4)	19			
ground time		140 (44) seconds	24 (0*)seconds	47 (4*)seconds	6 (0*)seconds
		96 Airborne Seconds	24 Airborne Seconds	43 Airborne Seconds	6 Airborne Seconds

TOTAL = 217 seconds

GROUND = 48 seconds

AIRBORNE = 169 seconds