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Federal Radionavigation Plan

March 1982

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DEPARTMENT OF TRANSPORTATION UNITED STATES OF AMERICA

Volume III (of 4)
Radionavigation System Characteristics

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16. Abstract

The second edition of the Federal Radionavigation Plan (FRP) has been jointly developed by the U.S. Departments of Defense and Transportation to ensure efficient use of resources and full protection of national interests. The plan sets forth the Federal interagency approach to the implementation and operation of radionavigation systems.

Volume III describes present and planned navigation systems in terms of nine major parameters: signal characteristics, accuracy, availability, coverage, reliability, fix rate, fix dimensions, capacity, and ambiguity.

The volume addresses the characteristics, capabilities, and limitations of existing and proposed major radionavigation systems. All of the systems considered are defined in terms of system performance parameters which determine the utilization and limitations of the individual navigation system.

Volume I, Radionavigation Plans and Policy, has 80 pages; Volume II, Requirements, has 48 pages; and Volume IV, Radionavigation Research, Engineering and Development, has 32 pages.

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PREFACE

The Departments of Defense and Transportation have developed the second edition of the Federal Radionavigation Plan (FRP) to ensure efficient use of resources and full protection of national interests. The plan sets forth the Federal interagency approach to the implementation and operation of radionavigation systems.

Various existing and planned radionavigation systems used in air, land, and marine navigation are reviewed in terms of user requirements and current status. The FRP contents reflect a response to a unique combination:

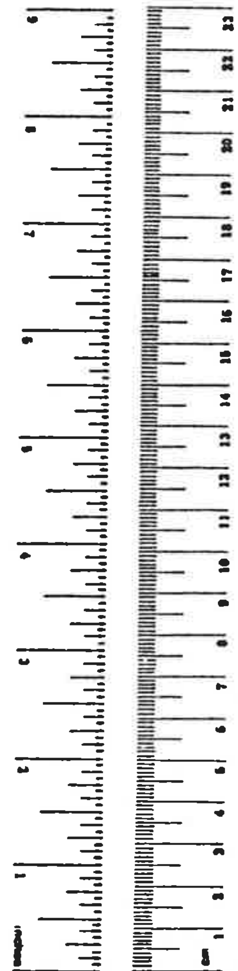
- o DOT responsibilities for public safety and transportation economy.
- o DOD responsibility for national security in normal and stressed situations.

This plan will be updated annually. The established DOD/DOT interagency management approach will enable continuing control and review of U.S. radionavigation systems. For further explanation of navigational terms used in this plan consult the American Practical Navigator, Volume 2, Publication No. 9, Defense Mapping Agency Hydrographic/Topographic Center, 1981.

METRIC CONVERSION FACTORS

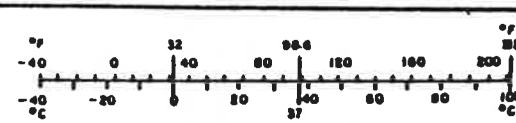
Approximate Conversions to Metric Measures

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



Approximate Conversions from Metric Measures

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



FEDERAL RADIONAVIGATION PLAN

VOLUME III

RADIONAVIGATION SYSTEM CHARACTERISTICS

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CHAPTER 1

GENERAL

1.0 INTRODUCTION

This volume addresses the characteristics, capabilities, and limitations of existing and proposed major radionavigation systems. These systems are sometimes used in combination with each other or with other systems. These combined systems are often implemented so that a major attribute of one system will supplement a weakness of another system. For example, a system having high accuracy but a low fix rate might be combined with a system with a lower accuracy but higher fix rate. The combined system would demonstrate characteristics of a system with both high accuracy and a high fix rate. Due to the large number of possible combinations, and their special usage, these hybrid systems are not treated in the FRP. The systems covered in this volume are:

- LORAN-C
- VOR, VOR/DME, VORTAC
- OMEGA
- TACAN
- Radiobeacons
- ILS
- MLS
- NAVSTAR GPS
- TRANSIT.

1.1 Differential Applications

Large area coverage systems such as OMEGA, GPS or LORAN-C may exhibit variances from a "predicted grid" established for navigation, charting or derivation of guidance information. This variance may be caused by propagation anomalies, errors in geodesy, accidental perturbations of signal timing or other factors. Intentional security protocols may also induce variances which might be destructive to precision use of a system (e.g. SPS degraded accuracy technique for GPS).

Adverse effects of these variances may be substantially reduced if not practically eliminated by different use of signals available. In such differential operation, a facility may be located at a fixed point (or points) within an area of interest. Signals from the system to be used (for example GPS) are observed in real time and compared with signals expected to be observed at the fixed point. Differences between observed signals and predicted signals are transmitted to users as a "differential correction" to upgrade the precision and performance of the user's receiver processor.

The area over which corrections can be made from a single differential facility depends on a number of factors including timeliness of correction dissemination, range of the correction transmission, area and uniformity of the system's grid, and user equipment implementations. For GPS, a differential facility might serve a radius of several hundred miles. For OMEGA the serving radius may be two to five hundred miles. For LORAN-C the serving radius may be up to two hundred miles.

The Federal Radionavigation Plan does not specifically address what kind of or how many differential facilities may be implemented in some future time frame. Research and development to assess the potential for differential operation remains as an element in current as well as future plans for specific applications.

VOLUME III

CHAPTER 2

RADIONAVIGATION SYSTEM PARAMETERS

2.0 SYSTEM PERFORMANCE PARAMETERS-DEFINITIONS

All of the systems considered are defined in terms of system performance parameters which determine the utilization and limitations of the individual navigation systems. These parameters are:

- o Signal Characteristics
- o Accuracy
- o Availability
- o Coverage
- o Reliability
- o Fix Rate
- o Fix Dimension
- o Capacity
- o Ambiguity.

2.1 SIGNAL CHARACTERISTICS

These parameters, which characterize the signal in space, are principally signal power levels, frequencies, signal formats, data rates, and any other data sufficient to completely define the means by which a user derives navigational information.

2.2 ACCURACY

In navigation, the accuracy of an estimated or measured position of a craft (vehicle, aircraft, or vessel) at a given time is the degree of conformance of that position with the true position of the craft at that time. Since accuracy is a statistical measure of performance, a statement of the accuracy of a navigation system is meaningless unless it includes a statement of the uncertainty in position which applies.

2.2.1 Statistical Measure of Accuracy*

Navigation system errors generally follow a known error distribution. Therefore, the uncertainty in position can be expressed as the probability that the error will not exceed a certain amount. A thorough treatment of errors is complicated by the fact that the total error is comprised of errors caused by instability of the transmitted signal, effects of weather and other physical changes in the propagation medium, errors in the receiving equipment, and errors introduced by the human navigator. In specifying or describing the accuracy of a system, the human errors usually are excluded. Further complications arise because some navigation systems are linear (one-dimensional) while others provide two or three dimensions of position.

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*Reference: Mathematical Considerations Pertaining to the Accuracy of Position Location and Navigation Systems Part 1; W. Allan Burt, et al; Stanford Research Institute April 1966, (NTIS AD 629 609).

When specifying linear accuracy, or when it is necessary to specify requirements in terms of orthogonal axes, e.g., along-track or cross-track, the 95 percent confidence level will be used. Vertical or bearing accuracies will be specified in one dimensional terms (2 sigma) 95% confidence level. When two dimensional accuracies are used, the two drms (distance root mean squared) uncertainty estimate will be used. Two drms is the radius of a circle that contains at least 95% of all possible fixes that can be obtained with a system at any one place. DOD specifies horizontal accuracy in terms of Circular Error Probable (CEP--the radius of a circle containing 50% of all possible fixes). For the FRP, it is agreed that the conversion of CEP to 2 drms would be accomplished by using 2.5 as the multiplier.

2.2.2 Types of Accuracy

Specifications of radionavigation system accuracy generally refer to one or more of the following definitions:

A. Predictable Accuracy: The accuracy of a position with respect to the geographic, or geodetic, coordinates of the earth.

B. Repeatable Accuracy: The accuracy with which a user can return to a position whose coordinates have been measured at a previous time with the same navigation system.

C. Relative Accuracy: The accuracy with which a user can measure position relative to that of another user of the same navigation system at the same time. This may be expressed also as a function of the distance between the two users. Relative accuracy may also refer to the accuracy with which a user can measure position relative to his own position in the recent past. For example, the present position of a craft whose desired track forms a specific geometric pattern in search operations or hydrographic survey, will be measured generally with respect to a previously determined datum.

2.3 AVAILABILITY

The availability of a navigation system is the percentage of time that the services of the system are usable by the navigator. Availability is an indication of the ability of the system to provide usable service within the specified coverage area. Signal availability is the percentage of time that navigational signals transmitted from external sources are available for use. It is a function of both the physical characteristics of the environment and the technical capabilities of the transmitter facilities.

2.4 COVERAGE

The coverage provided by a radionavigation system is that surface area or space volume in which the signals are adequate to permit the navigator to determine position to a specified level of accuracy. Coverage is influenced by system geometry, signal power levels, receiver sensitivity, atmospheric noise conditions, and other factors which affect signal availability.

2.5 RELIABILITY

The reliability of a navigation system is a function of the frequency with which failures occur within the system. It is the probability that a system will perform its function within defined performance limits for a specified period of time under given operating conditions. Formally, reliability is one minus the probability of system failure.

2.6 FIX RATE

The fix rate is defined as the number of independent position fixes or data points available from the system per unit time.

2.7 FIX DIMENSIONS

This characteristic defines whether the navigation system provides a linear, one-dimensional line-of-position, or a two or three-dimensional position fix. The ability of the system to derive a fourth dimension, i.e., time, from the navigational signals is also included.

2.8 SYSTEM CAPACITY

System capacity is the number of users a system can accommodate simultaneously.

2.9 AMBIGUITY

Ambiguity exists when the navigation system identifies two or more possible positions of the vehicle, with the same set of measurements, with no indication of which is the most nearly correct position. The potential for system ambiguities should be identified along with provision for users to identify and/or resolve them.

VOLUME III

CHAPTER 3

RADIONAVIGATION SYSTEM DESCRIPTIONS

3.0 SYSTEM DESCRIPTIONS

This section describes the characteristics of those individual radionavigation systems currently in use or under development. These systems are described in terms of the parameters defined in the previous section (2.0-2.9). All of the systems used for civil navigation are discussed. The systems which are used exclusively to meet the special applications of DOD are discussed in the JCS Master Navigation Plan.

3.1 LORAN-C

LORAN-C was developed to provide DOD with a radionavigation capability having longer range and much greater accuracy than its predecessor, LORAN-A. It was subsequently selected as the U.S. government-provided radionavigation system for civil marine use in the U.S. coastal areas.

3.1.1 Signal Characteristics

LORAN-C is a pulsed, hyperbolic system, operating in the 90-110 kHz frequency band. The system is based upon measurement of the difference in time of arrival of pulses of RF energy radiated by a chain of synchronized transmitters which are separated by hundreds of miles. The measurements of Time Difference (TD) are made by a receiver which achieves high accuracy by comparing a zero crossing of a specified RF cycle within the pulses transmitted by master and secondary stations within a chain. Making this comparison early in the pulse assures that the measurement is made before the arrival of the corresponding skywaves. Precise control over the pulse shape ensures that the proper comparison point can be identified by the receiver. To aid in preventing skywaves from affecting TD measurements, the phase of the 100 kHz carrier of every other pulse is changed in a predetermined pattern. Envelope matching of the signals is also possible but cannot provide the advantage of cycle comparison in obtaining the full system accuracy. The characteristics of LORAN-C are summarized in Table III-3.1.

3.1.2 Accuracy

Within the ground wave range, LORAN-C will provide the user, who employs an adequate receiver, with predictable accuracy of 0.25 nm (2 drms) or better. The repeatable and relative accuracy of LORAN-C is usually between 18 to 90 meters. All accuracy is dependent upon the Geometric Dilution of Precision (GDOP) factors at the user's location within the coverage area.

The LORAN-C ground wave is used primarily for navigation. Skywave navigation is feasible, but with some loss in accuracy. Ground waves and to some degree skywaves may be used for measuring time and time intervals. LORAN-C was originally designed to be a hyperbolic navigation system, however with the advent

SYSTEM: LORAN C/D

System Description: LORAN is a Low Frequency (LF) 100kHz hyperbolic radionavigation system. The receiver computes lines of position (LOP) based on the time of arrival difference between two time synchronized transmitting stations of a chain. Three stations are required (master and two secondaries) to obtain a position fix in the normal mode of operation. LORAN can be used in the Rho-Rho mode and accurate position data can be obtained with only two stations. Rho-Rho requires that the user platform have a precise clock. The Coast Guard operates 13 LORAN C chains and the Air Force operates a small number of LORAN C/D chains.

Accuracy (2drms)			Availability	Coverage	Realiability	Fix Rate	Fix Dimension	Capacity	Ambiguity Potential
Predictable	Repeatable	Relative							
.25nm (460m) 1:3 SNR	60-300 ft. (18-90m)	60-300 ft. (18-90m)	99+%	U.S. Coastal Areas, Cont-intental U.S., Selected Over-seas Areas	*	10-20 fixes/sec	2D	Unlimited	Yes, Easily Resolved

* Depends on mission time.

TABLE III-3.1 LORAN System Characteristics (Signal-in-Space) of the highly stable frequency standards, LORAN-C can now be used in the range-range (rho-rho) mode of navigation. This is accomplished by a comparison of the received signal phase to a known time reference to determine propagation time and, therefore, range from the stations. It can be used in situations where the user is within reception range of individual stations, but beyond the hyperbolic coverage area. The rho-rho method, using LORAN-C requires that the user have a very precise and stable time reference. The high cost of equipment of this type limits the use of this mode.

The inherent accuracy of the LORAN-C system makes it a suitable candidate for many land radiolocation applications. The purely numeric Time Difference (TD) readings (no names, words, or narratives) are easy and efficient to both store and retrieve in automated form. Since the data are purely numeric, there can be none of the ambiguity that results from attempting to retrieve narrative descriptors from traffic accident reports or highway inventory data. While the 100 kHz signal is affected to some extent by soil conductivity and terrain, it can be received in mountainous areas where VHF and UHF systems can be terrain limited; however, some distortion of the hyperbolic grid has been noted. Propagation anomalies may be encountered in urban areas where the proximity of large manmade structures affects the signal. The existence of these anomalies is predictable and can be compensated for, usually by surveying the area. The long range of the LORAN-C system makes it particularly desirable for application to remote areas, or where the user population is too low to justify the cost of a large number of short range facilities.

By monitoring LORAN-C signals at a fixed site, the receiver TD can be compared with a computed TD for the known location of the site. A correction for the area can then be broadcast to users. This technique (called Differential LORAN-C), whereby real-time corrections are applied to LORAN-C TD readings, provides improved accuracy. This method shows promise of providing the higher precision needed for marine navigation in harbor approaches and inland waterways. Another technique involves installing short-baseline, low power chains to serve specific restricted areas. Such a chain has been tested in the St. Marys River in the Great Lakes. The results of these tests are currently under evaluation.

In other locations a low-power transmitter can serve as an additional secondary station to improve the grid geometry and signal strength in a local area.

LORAN-C receivers are available at a relatively low cost and achieve the 0.25 nm (2 drms) accuracy that LORAN-C is capable of providing. A LORAN-C receiver which will be useful to the limits of the specified coverage areas for the U.S. coastal zone has the following characteristics:

- o It acquires the LORAN-C signals automatically, without the use of an oscilloscope.
- o It accomplishes cycle matching on all pulses to take advantage of the maximum accuracy of the system.
- o It automatically tracks the signals once they have been acquired.

- It displays at least two Time Difference readings, with resolution of at least 0.1 microsecond, to provide two lines of position.

3.1.3 Availability

The LORAN-C transmitting equipment is very reliable. Redundant transmitting equipment is used to reduce system downtime. Exclusive of infrequent periods of scheduled off-air for tower maintenance, LORAN-C signal availability is greater than 99% per year.

3.1.4 Coverage

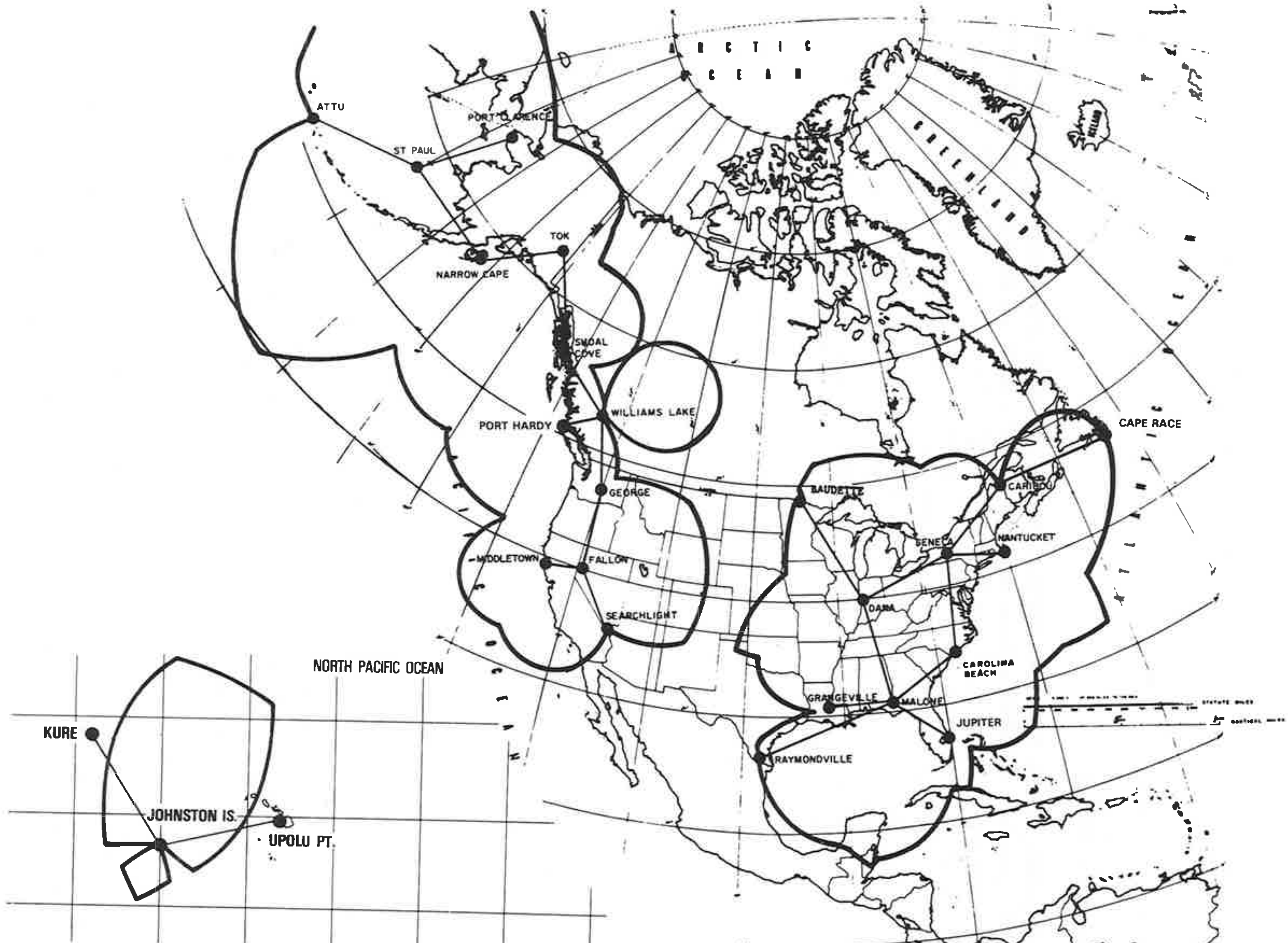
Until recently, there had been three LORAN-C chains providing coverage for the U.S. and Canadian coastal waters. An East Coast Chain comprised of five stations has provided groundwave coverage for most of the East Coast from Nova Scotia to Florida, a very small part of the coastal waters of the Gulf of Mexico, and a portion of the Great Lakes. A North Pacific Chain, comprised of four stations, has provided coverage for the Bering Sea, Aleutian Islands, and adjacent North Pacific and Alaska waters. A Hawaiian Chain, comprised of three stations, has provided coverage for the waters in the vicinity of the Hawaiian Islands north of Johnston Island between Midway and Kauai.

Expansion of the LORAN-C system, to meet the requirement for the U.S. coastal waters of the conterminous 48 states and southern Alaska was completed in late 1979. Stations have been built to provide service to the U.S. West Coast, the Gulf of Alaska, southeastern Alaska and the Gulf of Mexico. The Government of Canada has constructed two LORAN-C stations in British Columbia to operate in conjunction with U.S. stations in Washington and Alaska. Thus, coastal LORAN-C service is complete from the U.S.-Mexican border northward through the Gulf of Alaska and the Aleutians and into the Bering Sea. Required service to the East Coast and Great Lakes was provided by reconfiguring four stations of the existing East Coast Chain and constructing five new stations to form three new chains. LORAN-C service for the Great Lakes became a reality in early 1980. The coastal LORAN-C service also provides overland coverage to about two-thirds of the land area of the conterminous 48 states. Coverage of the reconfigured system is shown in Figure III-3.1. For further LORAN-C coverage information consult the LORAN-C Users Handbook which is available from the Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402.

The radionavigation requirements and benefits/cost of potential LORAN-C system expansion for Hawaii, and the north slope of Alaska are under study. A 1980 study indicated Puerto Rico and the U.S. Virgin Islands LORAN-C expansion was not cost-effective and a subsequent decision was made against such an expansion.

3.1.5 Reliability

LORAN-C stations are constantly monitored. The accuracy of system timing between the master and the secondary station serving the CCZ is kept to within ± 100 nanoseconds. Stations outside these limits are "blinked". Individual station reliability has exceeded 99.9% with chain availability exceeding 99.7%.



1:3 SIGNAL TO NOISE RATIO

FIGURE III-3.1 U.S. LORAN-C Coverage

3.1.6 Fix Rate

The fix rate available from LORAN-C ranges from 10-20 fixes per second which is dependent on the GRI.

3.1.7 Fix Dimension

LORAN-C will furnish two or more LOP's to provide a two-dimensional fix.

3.1.8 Capacity

An unlimited number of receivers may use LORAN-C simultaneously.

3.1.9 Ambiguity

As with all hyperbolic systems, theoretically, the LOPs may cross at more than one position on the earth. However, because of the design of the coverage area, the ambiguous fix is at a great distance from the desired fix and is easily resolved.

3.2 VOR, VOR/DME, TACAN

The three systems that provide the basic guidance for en route air navigation in the U.S. are VHF Omni-directional Range (VOR), Distance Measuring Equipment (DME), and Tactical Air Navigation (TACAN). Information provided to the aircraft pilot by VOR is the azimuth relative to the VOR ground station. DME provides a measurement of distance from the aircraft to the DME ground station. In most cases, VOR and DME are collocated as a VOR/DME facility. TACAN provides both azimuth and distance information and is used primarily by military aircraft. When TACAN is collocated with VOR, it is a VORTAC facility. DME and the distance measuring function of TACAN are the same.

3.2.1 VOR (VHF Omni-directional Range) - Signal Characteristics

The VOR transmits two 30 Hertz (Hz) modulations with a relative electrical phase angle equal to the azimuth angle of the receiving aircraft. A cardioid field pattern is produced in the horizontal plane and rotates at 30 Hertz. A non-directional (circular) 30 Hz pattern is also transmitted during the same time in all directions and is called the reference phase signal. The variable phase pattern changes phase in direct relationship to azimuth. The reference phase is frequency modulated while the variable phase is amplitude modulated. The receiver detects these two signals and computes the azimuth from the relative phase difference. For difficult siting situations, a system using the Doppler effect was developed which uses 50 instead of 4 antennas for the variable phase. The same avionics works with either type ground station. There are about 30 such stations out of approximately 1000 presently in operation. An additional 30 are being developed for additional difficult sites. VOR frequencies are assigned in the 108 to 118 megahertz frequency band and are separated by 100 kHz. The capability for 50 kHz separation has been developed but not yet implemented. The signal characteristics of VOR are summarized in Table III-3.2.

SYSTEM: VOR, VOR/DME

System Description: VOR provides aircraft with bearing information relative to the VOR signal and magnetic north. Used for landing, terminal and enroute guidance. VOR transmitters operate in the VHF frequency range. DME provides a measurement of distance from the aircraft to the DME ground station. DME operates in the UHF frequency range.

Accuracy (2 Sigma)			Availability	Coverage	Reliability	Fix Rate	Fix Dimension	Capacity	Ambiguity Potential
Predictable	Repeatable	Relative							
VOR: 90m ($\pm$1.4°) *	23m ($\pm$.35°) **	23m ($\pm$.35°) **	Approaches 100%. Warning if not providing published service	Line of sight (Present Air Routes)	Approaches 100%. Warning if not providing published service	Continuous	Heading in degrees or angle off course	Unlimited	None
DME: 185m ($\pm$.1nm)	185m ($\pm$.1nm)	185m ($\pm$.1nm)					Slant Range (nm)	100 Users per site, full service	

* The flight check of published procedures for the VOR signal is $\pm$1.4°. The ground monitor turns the system off if the signal exceeds $\pm$1.0°. The cross track error used in the chart is for $\pm$1.4° at 2nm from the VOR site. However, some uses of VOR are overhead and or 1/2 nm from the VOR.

** Test data shows that 99.94% of the time the error is less than $\pm$.35°. These values are for $\pm$.35° at 2 nm from the VOR.

TABLE III-3.2 VOR, VOR/DME Systems Characteristics (Signal-in-Space)

A. Accuracy (2 sigma)

1. Predictable

The ground station errors are approximately ±1.4 degrees. The addition of course selection, receiver and flight technical errors, when combined using root-sum-squared (RSS) techniques, is calculated to be ±4.5 degrees.

2. Relative

Although some course bending could influence position readings between aircraft, the major relative error consists of the course selection, receiver and flight technical components. When combined using RSS techniques, the value is approximately ±4.3 degrees. The VOR ground station relative error is ±0.35 degrees.

3. Repeatable

The major error components of the ground system and receiver will not vary appreciably in the short term. Therefore, the repeatable error will consist mainly of the Flight Technical Error (the pilots' ability to fly the system) which is ±2.3 degrees.

B. Availability

Recognizing the fact that the VOR equipments are redundant and that the facilities are overlapped by adjacent stations the availability is considered to approach 100% for new solid state equipment. Older DOD terminal VOR facilities exhibit service availability of approximately 93%.

C. Coverage

The VOR has line-of-sight limitations which could limit ground coverage to 30 miles or less. At altitudes above 5000 feet the range is approximately 100 nm and above 20,000 feet the range will approach 200 nm. These stations radiate approximately 200 watts. Terminal VOR stations are rated at approximately 50 watts and are only intended for use within the terminal areas. Actual VOR coverage information is contained in FAA Order 1010.55C.

D. Reliability

Due to advanced solid state construction and the use of remote maintenance monitoring techniques, the reliability of solid state VOR approaches 100%. In addition, the station monitors automatically shut down an out-of-tolerance station and the receivers give an immediate and positive indication of loss of signal. A large number of older terminals are still in service and require considerable maintenance.

E. Fix Rate

This system allows a continuous update of deviation from a selected course. Initialization is less than one minute after turn-on and will vary as to receiver design.

F. Fix Dimension

The system shows magnetic bearing to a VOR station and deviation from a selected course, in degrees.

G. Capacity

The capacity of a VOR station is unlimited.

H. Ambiguity

There is no ambiguity possible for a VOR station.

3.2.2 DME (Distance-Measuring Equipment) - Signal Characteristics

The interrogator in the aircraft generates a pulsed signal (interrogation) which, when of the correct frequency and pulse spacings, is accepted by the transponder. In turn, the transponder generates pulsed signals (replies) which are sent back and accepted by the interrogator's tracking circuitry. Distance is then computed by measuring the total round trip time of the interrogation and its reply. The operation of DME is thus accomplished by paired pulse signals and the recognition of desired pulse spacings accomplished by the use of a decoder. The transponder must reply to all interrogators. The interrogator must measure elapsed time between interrogation and reply pulse pairs and translate this to distance. All signals are vertically polarized. These systems are assigned in the 960 to 1213 megahertz frequency band with a separation of 1 megahertz. The capability to use "Y" channel service has been developed but not implemented. The signal characteristics of DME are summarized in Table III-3.2.

A. Accuracy (2 sigma)

1. Predictable

The ground station errors are less than ± 0.1 nm. The overall system error (airborne and ground RSS) is not greater than ± 0.5 nm or 3% of the distance, whichever is greater.

2. Relative

Although some errors could be introduced by reflections, the major relative error emanates from the receiver and Flight Technical Error.

3. Repeatable

Major error components of the ground system and receiver will not vary appreciably in the short term.

B. Availability

The availability of DME is considered to approach 100%, with positive indication when the system is out-of-tolerance.

C. Coverage

The DME has a line-of-sight limitation, which limits ground coverage to 30 nm or less. At altitudes above 5,000 feet, the range will approach 100 nm. En route stations radiate at 1000 watts. Terminal DME's radiate 100 watts and are only intended for use in terminal areas.

D. Reliability

With the use of solid state components and remote maintenance monitoring techniques, the reliability of the DME approaches 100%. The monitors automatically shut down an out-of-tolerance station.

E. Fix Rate

The system essentially gives a continuous update of distance to the facility. Actual update rate varies with the design of airborne equipment and system loading.

F. Fix Dimension

The system shows slant range to the DME station in nm.

G. Capacity

One hundred and ten interrogators are considered reasonable for present traffic capacity. Future traffic capacity could be increased when necessary through reduced individual aircraft interrogation rates and removal of beacon capacity reply restrictions.

H. Ambiguity

There is no ambiguity in the DME system.

3.2.3 TACAN (Tactical Air Navigation) - Signal Characteristics

The TACAN system is a combination of omni-bearing and distance-measuring functions. The important feature of this ground system is the rotating directional radiation pattern produced in a horizontal plane. The azimuth portion consists of coarse azimuth (15 Hz) and fine azimuth (135 Hz) elements. The rotation of the patterns at 15 Hz results in a modulation of the RF carrier with a composite 15 Hz sine wave to the aircraft. Reference signals in the form of pulse trains are added to the radiated signal to provide electrical phase. The 135 Hz sine wave signal provides an additional accuracy feature to the TACAN system, thereby reducing bearing error. Bearing is obtained by comparing the 15 and 135 Hz sine waves with the reference groups. TACAN operates in the 960-1215 megahertz band with frequency assignments separated by 1 megahertz. The capability to provide "Y" channel service has been developed but has not been implemented. The signal characteristics of TACAN are summarized in Table III-3.3.

A. Accuracy (2 sigma)

1. Predictable

The ground station errors are less than ±1.0 degree for azimuth for the 135 Hz element and ±4.5 degrees for the 15 Hz element. Distance errors are the same as DME errors in paragraph 3.2.2A.

2. Relative

The major relative errors emanate from course selection, receiver and Flight Technical Error.

3. Repeatable

Major error components of the ground station and receiver will not vary greatly in the short term. The repeatable error will consist mainly of the Flight Technical Error - the pilot's ability to fly the system.

B. Availability

The availability of TACAN service is considered to approach 100%. Older transponders typically provide 98.7% availability.

C. Coverage

The TACAN has a line-of-sight limitation which limits ground coverage to 30 nm or less. At altitudes of 5,000 feet the range will approach 100 nm; above 18,000 feet, the range approaches 130 nm. The station output power is 5 KW.

D. Reliability

With the use of solid state electronics and remote maintenance monitoring techniques, the reliability of the TACAN system approaches 100%. Monitors automatically shut down an out-of-tolerance station. Older DOD and DOT equipment is being replaced to achieve this reliability.

E. Fix Rate

This system provides a continuous update of the deviation from a selected course. Initialization is less than one minute after turn on. Actual update rate varies with the design of airborne equipment and system loading.

F. Fix Dimension

The system shows magnetic bearing, deviation in degrees, and distance to the TACAN station in nm.

SYSTEM: TACAN

System Description: A short range navigation system primarily used by the military. The system provides range, bearing and station identification. TACAN operates in the UHF band. When TACAN is collocated with a VOR it is called a VORTAC facility. The DME portion of TACAN is covered in the VOR/DME chart.*

Accuracy (2 Sigma)			Availability	Coverage	Reliability	Fix Rate	Fix Dimension	Capacity	Ambiguity Potential
Predictable	Repeatable	Relative							
Azimuth ± 1° (±63m at 3.75km) Distance*	Azimuth ± 1° (±63m at 3.75km) Distance*	Aximuth ± 1° (±63m at 3.75km) Distance*	98.7%	Line of sight	99% For new solid state stations	Continuous	Distance and bearing from station	110 for distance. Unlimited in azimuth	No ambiguity in range. Slight potential for ambiguity at multiples of 40°.

TABLE III-3.3 TACAN System Characteristics (Signal-in-Space)

G. Capacity

For distance information, 110 interrogators are considered reasonable for present traffic handling. Future traffic handling could be increased when necessary through reduced airborne interrogation rates and increased reply rates.

H. Ambiguity

There is no ambiguity in the TACAN range information. There is a slight probability of azimuth ambiguity.

3.3 OMEGA

The OMEGA system was proposed initially to meet a DOD need for worldwide general en route navigation but has now evolved into a system that has a majority of civil users. The system is comprised at present of seven of eight planned CW transmitting stations situated throughout the world. Worldwide position coverage will be attained when the eighth permanent station in Australia becomes operational in 1982.

3.3.1 Signal Characteristics

OMEGA utilizes CW phase comparison of skywaves from pairs of stations. The stations transmit time shared signals on four frequencies: 10.2 kHz, 11.33 kHz, 13.6 kHz, and 11.05 kHz. In addition to these common frequencies, each station transmits a unique frequency to aid station identification and to enhance receiver performance. The signal characteristics of OMEGA are summarized on Table III-3.4.

3.3.2 Accuracy

The inherent accuracy of the OMEGA system is limited by the accuracy of the propagation corrections that must be applied to the individual receiver readings. The corrections may be obtained in the form of predictions from tables or automatically in computerized receivers. The system has as a design goal a predictable accuracy of 2 to 4 nm (2 drms). Area validations conducted to date indicate this goal will be met. This depends on location, station pairs used, time of day, and validity of the propagation corrections.

Propagation correction tables are based on theory and modified to fit monitor data taken over long periods for localized areas. An extensive monitoring program is in use to verify the propagation model used to predict the corrections and the system accuracy in the area of the network stations. A number of permanent monitors will be maintained to update the model on a long-term basis. The system is currently usable and provides coverage over more than 90 percent of the earth and nearly all of the Northern Hemisphere. In mid 1982 when the Australian station becomes operational, the system will be available world wide. The specific accuracy and coverage depends on the type of equipment used, level of operator training, time of day, and related factors. In many cases, accuracies of 2 nm (2 drms) day and 4 nm (2 drms) night are being achieved or exceeded. Although the system is usable, a continuing program of monitoring and validating OMEGA signals must be completed before the system can be considered fully operational. This validation

SYSTEM: OMEGA

System Description: OMEGA is a very low frequency(VLF) 10.2-13.6kHz hyperbolic radionavigation system. There are seven transmitting stations now in full operation with an eighth and final transmitting station due on-air in Australia sometime in 1982. Position information is obtained by measuring relative phase difference of received OMEGA signals. OMEGA Trinidad (temporary G) terminated operation 31 December 1980.

Accuracy (2 drms)			Availability	Coverage	Reliability	Fix Rate	Fix Dimension	Capacity	Ambiguity Potential
Predictable	Repeatable	Relative							
2-4nm (3.7-7.4km)	2-4nm (3.7-7.4km)	.25-.5NM (463-926m)	99+%	Worldwide Continuous	*	1 Fix/ 10 Seconds	2D	Unlimited	Requires Knowledge to ±36nm **

* Depends on mission time.
** Three frequency receiver (10.2, 11.33, 13.6kHz).

TABLE III-3.4 OMEGA System Characteristics (Signal-in-Space) program, which will help define system capabilities and limitations, is being carried out on a regional basis. As each region is validated, it will be declared operational. Worldwide oceanic validation depends on the eighth and final permanent station being completed and its signals evaluated. At this time about 60% of the OMEGA oceanic coverage area has been validated, with the remaining validations to be completed in 1983-1986.

3.3.3 Availability

Exclusive of infrequent periods of scheduled off-air time for maintenance, OMEGA availability is greater than 99% per year for each station and 95% for three stations. An evaluation of performing tower maintenance during on-air operation is ongoing. If such maintenance procedures are determined feasible, availability can be increased accordingly. Annual system availability has been greater than 97% with scheduled off-air time included.

3.3.4 Coverage

When the OMEGA system is fully implemented, it will provide air and marine users with a worldwide navigation system.

3.3.5 Reliability

OMEGA system design requirements for reliability called for 99% single station availability and 95% three station joint signal availability. Three station joint signal availability exceeds 97%, including both emergency shutdowns and scheduled off-air periods.

3.3.6 Fix Rate

The OMEGA system provides independent positional fixes once every ten seconds.

3.3.7 Fix Dimension

OMEGA will furnish two or more LOP's to provide a two-dimensional fix.

3.3.8 Capacity

An unlimited number of receivers may be used simultaneously.

3.3.9 Ambiguity

In this CW system, ambiguous LOP's occur as there is no means to identify particular points of constant phase difference which recur throughout the coverage area. The area between lines of zero phase difference are termed "lanes." Single-frequency receivers use the 10.2 kHz signals whose lane width is about eight nautical miles on the baseline between stations. Multiple-frequency receivers extend the lane width, for the purpose of resolving lane ambiguity but these are more expensive than single-frequency receivers. Because of the lane ambiguity, receivers must be preset to a known location. Once set to a known location, the OMEGA receiver counts the number of lanes it crosses in the course of a voyage. This lane count is subject to errors which may be introduced by an interruption of power to the receiver, changes in propagation conditions near local sunset and sunrise, and other factors. To use OMEGA effectively for navigation, it is essential that a DR plot be maintained carefully, and that the DR and OMEGA positions be compared periodically so that "jumps" in the OMEGA lane count can be detected and corrected. The accuracy of an OMEGA phase-difference measurment is independent of the elapsed time or distance since the last update. Unless the OMEGA position is verified occasionally by comparison to a fix obtained with another navigation system or by periodic comparison to a carefully maintained DR plot, the chance of an error in the OMEGA lane count increases with time and distance. These errors are eliminated in airborne receivers since they use multiple frequency receivers capable of developing larger lane widths to resolve ambiguity problems. Lane widths of approximately 288 miles along the base line can be generated with a four frequency receiver.

3.4 RADIOBEACONS

Radiobeacons are nondirectional radio transmitting stations which operate in the low frequency (LF) and medium frequency (MF) bands to provide ground wave signals to a receiver. A radio direction finder (RDF) is used to measure the relative bearing of the transmitter with respect to the heading of an aircraft or vessel.

Presently, there are approximately 2000 LF and MF aeronautical Non-Directional Beacons (NDB). These are distributed about as follows: FAA: 600, non-Federal: 1200, and military: 200. No change in the navigational status of the civil facilities is expected before 1990 and probably not before 2000. At this time, the probability of change beyond the year 2000 cannot be accurately predicted.

There are approximately 200 Coast Guard-operated marine radiobeacons. Operation of these systems will be continued through the 1990's. The system is being modernized, expanded slightly and reconfigured to provide better serive in response to the increasing demand. This effort includes establishing 37 new stations, relocation of some others, changes in type of operation of selected beacons, and changes in frequency. These changes will improve service by providing more beacons, improving signal availability, and providing service in many areas where coverage does not exist. The changes in frequency will result in more efficient use of the RF spectrum and will allow for additional beacons in some areas if needed.

3.4.1 Signal Characteristics

NDB's operate in the 190-415 kHz and the 510-535 kHz bands. Their transmissions include a coded continuous-wave (CCW) or modulated continuous-wave (MCW) signal to identify the station. The CCW signal is generated by modulating a single carrier with either a 400 Hz or a 1020 Hz tone for morse code identification. The MCW signal is generated by spacing two carriers either 400 Hz or 1020 Hz apart and keying the upper carrier to give the morse code identification.

Marine radiobeacons operate in the 275-335 kHz band. Some of the longer-range marine radiobeacons operate on the same frequency and are time sequenced to prevent mutual interference. The signal characteristics for the aeronautical and marine beacons are summarized in Table III-3.5.

SYSTEM: RADIOBEACON NDB/ADF

System Description: Aircraft non-directional beacons are used to supplement VOR-DME for transition from enroute to airport precision approach facilities and as a non-precision approach aid at many airports. Only ADF(LF) is considered in the FRP since there is little common use of the VHF/UHF beacons. Marine radiobeacons are used to identify the entrance to harbors and also provide a means for low cost navigation in the coastal areas.

Accuracy (2 Sigma)			Availability	Coverage	Reliability	Fix Rate	Fix Dimension	Capacity	Ambiguity Potential
Predictable	Repeatable	Relative							
Aeronautical ± 3-10°	N/A	N/A	99%	Approximately 560 km for high power stations.	99%	Function of the type of beacon -Continuous- or -Sequenced-	One LOP per beacon	Unlimited	Potential is high for reciprocal bearing w/o sense antenna
Marine ± 3°				Marine beacons 50nm or the 100 fathom curve.					

TABLE III-3.5 RADIOBEACON SYSTEM Characterisics (Signal-in-Space)

3.4.2 Accuracy

Positional accuracy derived from the bearing information is a function of geometry of the LOP's, the accuracy of compass heading, measurement accuracy, distance from the transmitter, stability of the signal, nature of the terrain between beacon and craft, and noise. In practice, bearing accuracy is of the order of ± 3 to ± 10 degrees. Achievement of ± 3 degree accuracy requires that the RDF be calibrated before it is used for navigation by comparing radio bearings to accurate bearings obtained visually on a transmitting antenna that is within visual range. Since most directionfinder receivers will tune to a number of radio frequency bands, transmissions from sources of known location, such as AM broadcast stations, are also used to obtain bearings, generally with less accuracy than obtained from radiobeacon stations because these signals are not calibrated. For FAA flight inspection, NDB system accuracy is stated in terms of permissible needle swing: ± 5 degrees on approaches and ± 10 degrees in the en route area.

3.4.3 Availability

Availability of marine radiobeacons and aeronautical Non-Directional Beacons is in excess of 99%.

3.4.4 Coverage

The coverage of marine radiobeacons is shown in Figure III-3.2. Extensive coverage of NDBs is provided by approximately 2000 ground stations, of which the FAA operates about 600.

3.4.5 Reliability

Reliability is in excess of 99%.

3.4.6 Fix Rate

The fix rate is a function of whether the beacon is continuous or sequenced. In general, at least one line of position, or relative bearing, is provided continuously. If sequenced, fixing a position may require up to six minutes, depending on LOP's selected.

3.4.7 Fix Dimension

In general, one line of position is available from a single radiobeacon. If within range of two or more beacons, a fix may be obtained.

3.4.8 Capacity

An unlimited number of receivers may be used simultaneously.

3.4.9 Ambiguity

The only ambiguity which exists in the radiobeacon system is one of reciprocal bearing provided by some receiving equipment which does not employ a sense antenna to resolve direction.

FIGURE III-3.2 Atlantic, Great Lakes and Gulf Coast Marine Radiobeacon Coverage

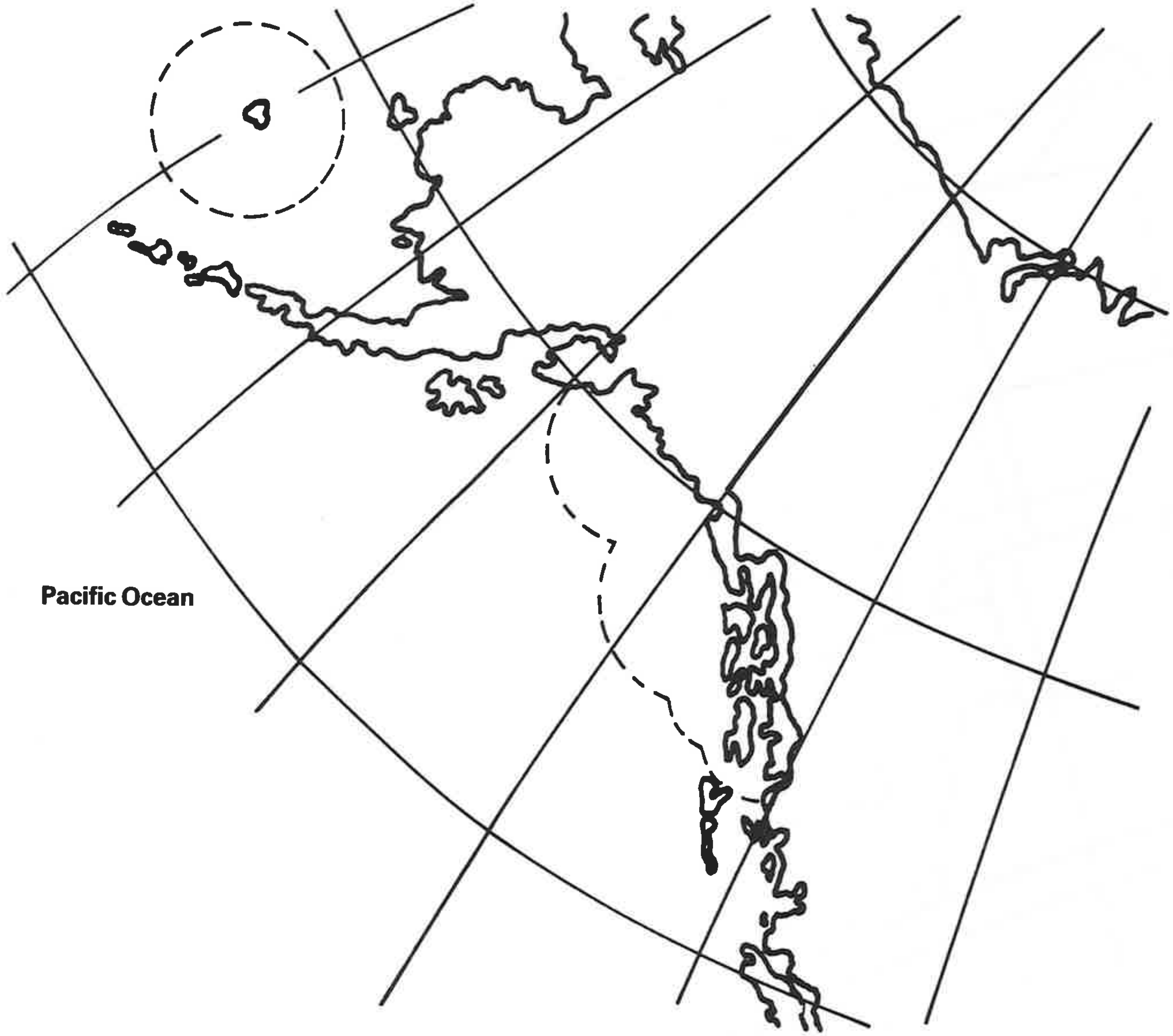


FIGURE III-3.2 Alaskan Marine Radiobeacon Coverage (Cont.)

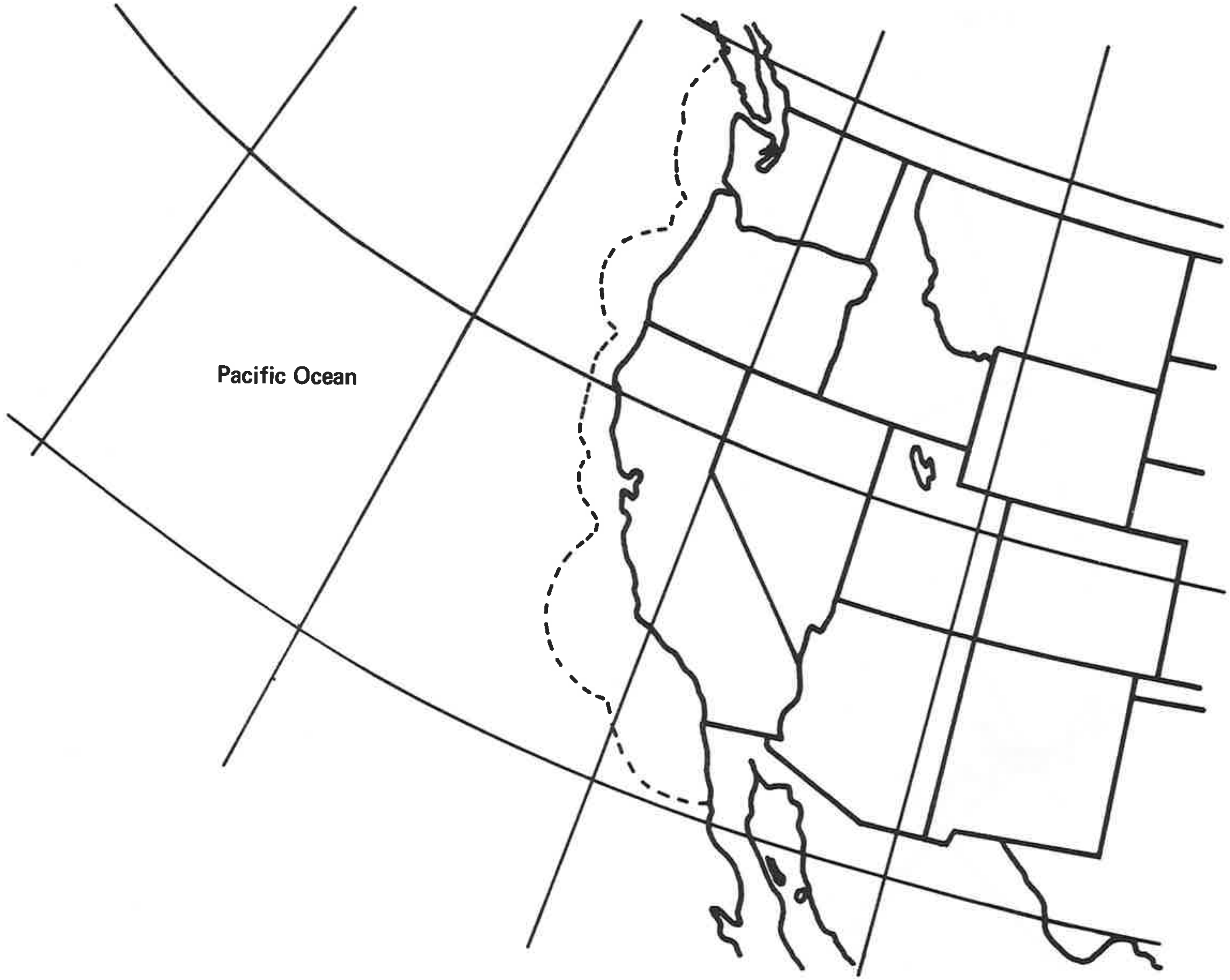


FIGURE III-3.2 Pacific Coast Marine Radiobeacon Coverage (Cont.)

3.5 AIRCRAFT LANDING SYSTEMS

At present, the Instrument Landing System (ILS) is the primary worldwide, ICAO-approved, precision landing system. This system is presently adequate, but has limitations in siting, frequency allocation, cost, and performance. An alternate system, scanning beam Microwave Landing System (MLS) has been developed and approved by the ICAO. This new system is expected to be implemented and eventually replace the ILS.

3.5.1 Instrument Landing System

ILS is a precision approach system normally consisting of a localizer facility, a glide slope facility, and two or three VHF marker beacons. It provides vertical and horizontal navigational (guidance) information during the approach to landing at an airport runway.

A. Signal Characteristics

The localizer facility and antenna are typically located 1000 feet beyond the stop end of the runway and provides a VHF (108-112 MHz) signal. The glide slope facility is located approximately 1000 feet from the approach end of the runway and provides a UHF (328.6-335.4 MHz) signal. Marker beacons are located along the extension of the runway centerline to indicate to the pilot decision height points or distance to the runway threshold, they emit a 75 MHz signal. The signal characteristics of ILS are summarized in Table III-3.6.

B. Accuracy

For typical air carrier operations at a 10,000 foot runway, the course alignment (localizer) at threshold is maintained within $\pm$25 feet. Course bends during the final segment of the approach do not exceed $\pm$ 0.06 degrees (2 sigma). Glide slope course alignment is maintained within $\pm$ 7.0 feet at 100 feet (2 sigma) elevation and course bends during the final segment of the approach do not exceed $\pm$ 0.07 degrees (2 sigma).

C. Availability

While the availability of existing installations has been adequate, many are vacuum tube installations and are being replaced with solid state equipment to further improve availability. The Air Force experienced approximately 95.2% overall availability in 1980, (92% tube, 97% old solid state, 99+% new solid state).

D. Coverage

Coverage for individual systems is as follows:

Localizer:	$\pm 2^{\circ}$ centered about runway centerline
Glide Slope:	Nominally 3° above the horizontal
Marker Beacons:	$\pm 40^{\circ}$ (approximately) on minor axis (along approach path) $\pm 85^{\circ}$ (approximately) on major axis.

SYSTEM: ILS

System Description: The Instrument Landing System (ILS) is a precision approach system consisting of a localizer facility, a glide slope facility and two or three VHF marker beacons. The VHF (108-112MHz) localizer facility provides accurate, single path horizontal guidance information. The UHF (328.6-335.4MHz) glide slope provides precise, single path, vertical guidance information to a landing aircraft.

Accuracy (2 Sigma)*			Availability	Coverage	Reliability	Fix Rate	Fix Dimension	Capacity	Ambiguity Potential
Predictable	Repeatable	Relative							
Cat I - N/A Cat II - N/A Cat III - N/A	9.1m 4.6m 4.1m	9.1m 4.6m 4.1m	Approaches 100% Positive indications when the system is out tolerance	Normal limits from center of localizer Ant ±10° out to 18 nm and ±35° out to 10 nm.	98.6% with positive indication when the system is out of tolerance	Continuous	Heading and deviation in degrees	Limited only by aircraft separation requirements	None

* Lateral accuracies at decision height.

TABLE III-3.6 ILS System Characteristics (Signal-in-Space)

E. Reliability

ILS reliability, which is adequate, will be improved as the vacuum tube equipment is replaced by newer solid state units. As a related factor, however, terrain and other factors may impose limitations upon the use of the ILS signal. Special account must be taken of terrain factors and dynamic factors such as taxiing aircraft which can cause multipath signal transmissions. In some cases, to resolve ILS siting problems, use has been made of localizers with wide aperture antennas and two-frequency systems. In the case of the glide slope, use has been made of wide aperture, two frequency-image arrays and single-frequency broadside arrays to provide service at difficult sites.

F. Fix Rate

The glide slope and localizer provide continuous fix information. Marker beacons which provide an audible and visual indication to the pilot are sited at specific points along the approach path as indicated in Table III-3.7.

TABLE III-3.7

AIRCRAFT MARKER BEACON

Marker Designation	Distance to Threshold	Height (Ft. Per Sec.)	Audible Signal	Light Color
Outer	4.5-4.7nm	Glide Slope Intercept	2 dashes	Purple
Middle	2000-6000 ft	200	1 dot-dash	Amber
Inner	1000 ft	100	6 dots	White

G. Fix Dimension

ILS provides both vertical and horizontal guidance with glideslope and localizer signals. At periodic intervals (passing over marker beacons) distance to threshold is obtained.

H. Capacity

ILS has no capacity limitations except those imposed by aircraft separation requirements since aircraft must be in trail to use the system.

I. Ambiguity

Any potential ambiguities are resolved by imposing system limitations as described in Section 3.5.1-E.

3.5.2 Microwave Landing System

The Microwave Landing System (MLS) is being developed by DOT, DOD, and NASA to provide a common civil/military landing system to meet the full range of user operational requirements to the year 2000 and beyond. It is intended as a replacement for the Instrument Landing System (ILS) used by both civil and military aircraft and the Ground Controlled Approach system used primarily by military operators. The signal is transmitted throughout a large volume of airspace, thereby permitting service to multiple aircraft, along multiple approach paths, throughout the approach, flare, touchdown, and rollout manuevers. The system permits greater flexibility in air traffic procedures, enhancing safety, and permits curved and segmented approach paths for purposes of noise abatement. It allows reduced intervals between aircraft to increase runway acceptance rates, and facilitates short field operations for short and/or vertical takeoff and landing (STOL and VTOL) aircraft.

A. Signal Characteristics

The MLS transmits signals that enable airborne units to determine the precise azimuth angle, elevation angle, and range. The technique chosen for the angle function of the MLS is based upon Time-Referenced Scanning Beams (TRSB). All angle functions of MLS operate in the 5.00-5.25 GHz band. Ranging is provided by DME operating in the 0.96-1.215 GHz band. An option is included in the signal format to permit a special purpose system to operate in the 15.4-15.7 GHz band. The system characteristics of MLS are summarized in Table III-3.8.

B. Accuracy (2 sigma)

The azimuth accuracy is ± 13.5 feet at touchdown on a 14,000 foot runway. The elevation accuracy is ± 2.0 feet at runway threshold. The flare guidance accuracy is ± 2.0 feet throughout the touchdown zone and the DME accuracy is ± 100 feet for the precision mode and ± 1600 feet for the non-precision mode.

C. Availability

Equipment redundancy, as well as remote maintenance monitoring techniques, should allow the availability of this system to approach 100%.

D. Coverage

MLS provides data over a wide volume, bounded by ± 60 degrees from runway centerline, 0 to 30 degrees elevation and up to at least 20 nm range from the threshold. The signal format also provides for 360^{o} azimuth coverage, a feature not presently required, but one which might possibly be considered useful at some future time. Present plans are that 340 MLS facilities will be installed by 1990. By the year 2000, approximately 1250 MLS facilities will be in place. There will be simultaneous operation of ILS and MLS during the transition period.

E. Reliability

The MLS signals are generally much less sensitive than ILS signals to the effects of snow, vegetation, terrain, structures, and taxiing aircraft. This allows the reliability of this system to approach 100%.

SYSTEM: MLS

System Description: Developed by DoD, DOT and NASA to provide a common civil/military landing system that will replace ILS and GCA/PAR. MLS operates in the 5-5.25 GHz band. Ranging is provided by DME operating in .96-1.22GHz band. Multimode receivers (MMR) will be the primary user equipment for the military.

Accuracy (2 Sigma)*					Availability	Coverage	Reliability	Fix Rate	Fix Dimension	Capacity	Ambiguity Potential
Predictable	Repeatable		Relative								
	Horz	Vert	Horz	Vert	Approaches 100% with Pos indication when the sys-tem is out of tolerance	±60° from center line of runaway out to 20nm in both directions. **	Approaches 100% with positive indication when system out tolerance	6.5-39 fixes/sec Depending on function.	Heading and devi-ation in degrees. Range in nm	Limited only by aircraft separation requirements	None
Cat I - N/A	9.1m	3.0m	9.1m	3.0m							
Cat II - N/A	4.6m	1.4m	4.6m	1.4m							
Cat III - N/A	4.1m	.5m	4.1m	.5m							

* Lateral accuracies at decision height.
** There are provisions for 360° out to 20nm.

TABLE III-3.8 MLS System Characteristics (Signal-in-Space)

F. Fix Rate

Elevation angle is transmitted at 39 samples per second and azimuth angle at 13 samples per second. Usually the airborne receiver averages several data samples to provide fixes of 3 to 6 samples per second.

G. Fix Dimensions

This system provides signals in all three dimensions and can provide time if aircraft are suitably equipped.

H. Capacity

DME signals of this system are capacity limited; the system limits are approached when 110 aircraft are handled.

I. Ambiguity

No ambiguity is possible for the azimuth or elevation signals. Only a very small probability for ambiguity exists for the range signals and then only for multipath caused by moving reflectors.

3.6 NAVSTAR GPS

NAVSTAR GPS is a space-based radionavigation system being developed by the Department of Defense under Air Force management. The fully-deployed operational system is intended to provide highly accurate position and velocity information in three dimensions and precise time and time interval on a global basis continuously, to an unlimited number of properly equipped users. It will be unaffected by weather and will provide a worldwide common grid reference system. The objective of the program is to provide very precise positional information for a wide spectrum of military missions. In addition, current policy calls for civil availability with a degradation in system accuracy required to protect U.S. national security interests.

3.6.1 Signal Characteristics

The NAVSTAR GPS concept is predicated upon accurate and continuous knowledge of the spatial position of each satellite in the system with respect to time and distance from a transmitting satellite to the user. Each satellite transmits its unique ephemeris data. This data is periodically updated by the master control station based upon information obtained from the system monitors in Hawaii, Alaska, Guam and California.

The system automatically selects appropriate signals from each of the four satellites (selected by the receiver from those in view with respect to optimum satellite-to-user geometry). It then solves time-of-arrival difference quantities to obtain distance between user and satellites. This information establishes the user position with respect to the satellite system. A time correction factor then relates the satellite system to earth coordinates. Each satellite continuously transmits a composite spread spectrum signal at 1227.6 and 1575.42 MHz consisting of a precise navigational signal, a coarse navigational signal, data such as satellite ephemeris, atmospheric propagation correction data and clock bias information. User equipment measures four independent pseudo-ranges and range rates and translates these to three-dimensional position, velocity and system time. The characteristics of NAVSTAR GPS are summarized in Table III-3.9.

3.6.2 Accuracy

Accuracy of a NAVSTAR GPS fix varies with the capability of the user equipment and the user-to-satellite geometries.

A. The most sophisticated user equipment will provide a best predictable positioning accuracy of 18.1 meters (2 drms), horizontally and 29.7 meters (2 sigma) vertically, a velocity accuracy of 0.1 m/sec (2 sigma) in each of the three dimensions and timing accuracy better than thirty-five nanoseconds with a maximum offset of 120 nanoseconds from UTC. The accuracy to be made available to civil users is in the form of the Standard Positioning Service (SPS). The highest level of accuracy from the SPS will be consistent with U.S. national security interests. It is presently projected that a predictable and repeatable accuracy of 500 meters (2drms) horizontally and 820 meters (2 drms) vertically will be made available during the first year of full NAVSTAR GPS operation with possible accuracy improvements as time passes.

B. Repeatable accuracy will be the same as predictable accuracy.

C. The best relative accuracy will be approximately 10 meters (2 drms) horizontally and 16.4 meters (2 sigma) vertically.

3.6.3 Availability

NAVSTAR GPS will provide a 95-100% availability to be refined based on orbital experience, for the PPS users. This is based upon a 18 satellite constellation, (a 5^{o} masking angle) with four satellites in view. Availability of the NAVSTAR GPS signal for less accurate positioning will be essentially 100%.

3.6.4 Coverage

NAVSTAR GPS will provide worldwide, continuous coverage on the surface of the earth and up to 600 nm.

3.6.5 Reliability

There are no operational reliability figures for the NAVSTAR GPS satellites. However, the planned satellite lifetime of 6 years corresponds to a single satellite reliability of about 90%. A constellation of 18 satellites will produce an overall reliability of 99+% for the satellite segment.

3.6.6 Fix Rate

The fix rate is essentially continuous. Actual time to a first fix depends on user equipment capability and precise satellite geometry.

SYSTEM NAVSTAR GLOBAL POSITIONING SYSTEM (GPS)

System Description: A space-based radio positioning navigation system that will provide extremely accurate three dimensional position, velocity and time information to suitably equipped users anywhere on or near the surface of the earth. The space segment will consist of 18 satellites in 12 hour orbits. Each satellite will transmit navigation data and time signals on 1575.4 and 1227.6 MHz.

Accuracy			Availability	Coverage	Reliability	Fix Rate	Fix Dimension	Capacity	Ambiguity Potential
Predictable	Repeatable	Relative							
PPS Horz - 18.1m Vert - 29.7m Vlcty - .1m/sec Time - 35 ns max offset 120ns	Horz - 18.1m Vert - 29.7m	Horz - 10m Vert - 16.4m	To be determined. Estimate 95-100%	Worldwide Continuous	Life of satellite projected to be 6 yrs.	Essentially Continuous	3D + Velocity + Time	Unlimited	None
SPS * Horz - 500m Vert - 820m Vlcty - ** Time - **	Horz - 500m Vert - 820m	Horz - 10m Vert - 16.4m							

* Degraded accuracy established by current DoD policy.
**To be determined.

TABLE III-3.9 NAVSTAR Global Positioning System (Signal-in-Space)

3.6.7 Fix Dimensions

NAVSTAR GPS provides three-dimensional positioning and velocity fixes. In addition, it provides extremely accurate time information.

3.6.8 Capacity

Unlimited.

3.6.9 Ambiguity

None.

3.7 TRANSIT

TRANSIT is a space-based radio positioning navigational system consisting of four or more satellites in approximately 600 nm polar orbits. The phasing of the satellites is deliberately staggered to minimize time between fixes for users. In addition, TRANSIT has four ground based monitors. The monitor stations track each satellite while in view and provide the tracking information necessary to update satellite orbital parameters every 12 hours.

3.7.1 Signal Characteristics

The satellites broadcast ephemeris information continuously on 150 and 400 MHz. One frequency is required to determine a position. However, by using the two frequencies, higher accuracy can be attained. A receiver measures successive Doppler, or apparent frequency shifts of the signal, as the satellite approaches or passes the user. The receiver then calculates the geographic position of the user based on knowledge of the satellite position that is transmitted from the satellite every two minutes, and a knowledge of the Doppler shift of the satellite signal. The characteristics of TRANSIT are summarized in Table III-3.10.

3.7.2 Accuracy

Predictable positioning accuracy for a single frequency receiver is 500 meters, for a dual frequency receiver is 25 meters. Repeatable positioning accuracy is 50 meters for a single frequency and 15 meters for a dual frequency receiver. Relative positioning accuracy of less than 10 meters has been measured through translocation techniques. Navigational accuracy is dependent upon the accuracy to which vessel course, speed, and time are known.

3.7.3 Availability

Availability is 99+% when a TRANSIT satellite is in view. It depends on user latitude, antenna mask angle, user maneuvers during a satellite pass, the number of operational satellites and satellite precession.

3.7.4 Coverage

Coverage is worldwide but not continuous due to the relatively low altitude of the TRANSIT satellites and the precession of satellite orbits.

SYSTEM: TRANSIT

System Description: TRANSIT nominally consists of four operational satellites in polar orbits. The satellites broadcast information on 150 and 400 MHz. A receiver measures the apparent frequency shift of the signals (doppler) as the satellite approaches and passes the user. The receiver then calculates the geographic position of the user, based on satellite position knowledge and corrections received from the transmitted signal. User speed and the time must be known accurately.

Position Accuracy (2 drms)			Availability	Coverage	Reliability	Fix Rate	Fix Dimension	Capacity	Ambiguity Potential
Predictable	Repeatable	Relative							
Dual frequency 25m Single frequency 500m	15m 50m	Under 10m with translocation.	99% When satellite is in view	Worldwide non-continuous	99%	Varies with latitude. 30 mins at 80° Lat. 110 mins at equator	2D	Unlimited	None

TABLE III-3.10 TRANSIT System Characteristics (Signal-in-Space)

3.7.5 Reliability

The reliability of the TRANSIT satellites is 99+%.

3.7.6 Fix Rate

Fix rate varies with latitude, theoretically from an average of 110 minutes at the equator to an average of 30 minutes at 80 degrees. Presently, due to non-uniform orbital precession, the TRANSIT satellites are no longer in evenly spaced orbits. Consequently, a user can occasionally expect periods from 6 to 11 hours between fixes.

3.7.7 Fix Dimensions

Two-dimensional.

3.7.8 Capacity

Unlimited.

3.7.9 Ambiguity

None.

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