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EVALUATION OF VARIOUS NAVIGATION SYSTEM CONCEPTS

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16. Abstract

The purpose of this study is to identify the capabilities and limitations of a particular set of navigation systems and evaluate their performance in the current airspace environment. The navigation systems evaluated are Loran-C, Omega, VHF Omnidirectional Range/Distance Measuring Equipment (VOR/DME), Global Positioning System (GPS), Doppler navigation system, and inertial navigation system (INS). In addition to detailed technical and operational analyses of each navigation system, consideration is also given to the constraints imposed by and the deficiencies existing in the standards by which accuracy and effectiveness of navigation systems are measured.

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Loran-C		

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METRIC CONVERSION FACTORS

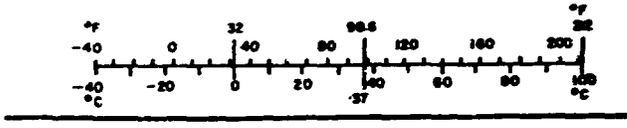
Approximate Conversions to Metric Measures

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	0.96	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

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

Approximate Conversions from Metric Measures

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



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SUMMARY

This report documents the work performed by ARINC Research under contract to the Federal Aviation Administration (FAA) to evaluate various navigation concepts. The purpose of this study is to compile and illuminate those technical and operational parameters that have the greatest impact on the compatibility of navigation systems operating in common airspace. The validity of analyses previously performed by recognized authorities in the field of navigation was assessed, and no need was found to conduct new analyses or to duplicate past analyses. The conclusions generated in this study are therefore based on existing reference material.

The navigation systems evaluated in this report, separately and in various combinations, are Loran-C, Omega, VHF Omnidirectional Range/Distance Measuring Equipment (VOR/DME), Global Positioning System (GPS), Doppler, and inertial navigation system (INS).

Although the primary focus of this study is on the technical and operational characteristics of navigation systems, economic and institutional issues are also discussed briefly. The technical performance capability of each navigation system is compared with existing accuracy requirements. Systems that are capable of satisfying the accuracy requirements are then evaluated to determine what limitations are imposed by signal coverage considerations. This analysis shows that, in terms of the currently used systems evaluated in this study -- Loran-C, Omega, VOR/DME, Doppler, and INS -- there is no unnecessary proliferation of navigation systems. This particular combination of navigation systems appears to satisfy current domestic, oceanic, and offshore navigation user requirements. No single system existing today as a fully operational system can meet all of these requirements.

Each system is also evaluated, separately and in various combinations, in an operational sense through the application of realistic flight procedure scenarios. These case studies identify a number of sources of conflict that could affect the integrity of position determination, pilot workload, Air Traffic Control (ATC) controller workload, and air safety. Although Loran-C, Omega, VOR/DME, and GPS navigation systems independently meet existing performance requirements as they apply to established VOR-referenced airways, the errors associated with their use in an area

navigation application can combine in a way that causes lateral deviations about a geographic centerline exceeding current specifications for route width. The results of this study indicate that unrestricted use of area navigation systems in the current structure of the airspace is not advisable until some form of standardization is established in a number of areas, including the following:

- Path definition (e.g., great circle or rhumb line)
- Earth model (e.g., spherical, Clarke 1866, or WGS-72)
- Propagation models (i.e., sky waves and ground waves)

CONTENTS

CONTENTS (continued)

CONTENTS (continued)

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CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND

The continuing growth of aviation traffic, in both general aviation and commercial airlines, places increasing demands on the national navigation system. Higher densities of commercial and general aviation aircraft will demand more accurate positioning en route than is now required. To ensure a satisfactory integrated national navigation system capable of meeting anticipated requirements, the Federal Aviation Administration (FAA) is conducting strategic studies and planning with regard to possible navigation concept scenarios to be adopted between now and 1995. The strategic studies of the FAA require an accurate, detailed assessment of these concepts and of the capabilities, costs, and interdependencies of the possible navigation systems that may be applied to meet anticipated navigation requirements.

Consequently, the FAA contracted ARINC Research to study critical aspects of current and future navigation systems and practices. This report presents the current status of work involving the evaluation of various navigation system concepts in the context of the existing airspace environment.

1.2 PURPOSE

The *Federal Radionavigation Plan* (FRP) directs the Departments of Transportation and Defense to select a suitable mix of radionavigation systems that can meet the diverse technical, operational, and economic requirements imposed by users, manufacturers, and the Air Traffic Control system. The purpose of this study is to compile and illuminate those technical and operational parameters that have the greatest impact on the compatibility of navigation systems operating in common airspace. The validity of analyses previously performed by recognized authorities in the field of navigation was assessed, and no need was found to conduct new analyses or to duplicate past analyses. The conclusions generated in this study are therefore based on existing reference material.

1.3 SCOPE

This study reviews the technical and operational characteristics of Loran-C, Omega, VHF Omnidirectional Range/Distance Measuring Equipment (VOR/DME, Global Positioning System (GPS), Doppler, and inertial navigation system (INS). The systems are evaluated both independently and in various combinations. The evaluations are in the form of comparative analyses -- the systems are compared with each other as well as with existing FAA technical and operational requirements. Conclusions are presented concerning the effectiveness of particular navigation systems in satisfying the stated requirements, together with recommendations for improving operational performance. Inadequacies in formulating accuracy are pointed out. Finally, the study recommends a combination of navigation systems that will provide the greatest potential for acceptance as the primary means for navigation in the context of the current airspace environment.

1.4 TECHNICAL APPROACH

Technical and operational capabilities of each navigation system under consideration were identified through literature searches and discussions with manufacturers and users. Performance requirements as specified by the FAA were obtained from the recently published FRP and from previously issued FAA advisory circulars. Technical capabilities of each system were then compared with the requirements. The results of these comparisons were used to categorize each system with respect to which flight phases could be accommodated in a purely technical sense, using both statistical and measured navigation system capabilities. The systems were then evaluated to determine their operational capability in specific case studies. The scenarios selected for the case studies were representative of typical situations that are encountered frequently. The operational capability of each navigation system in each scenario was defined on the basis of selected measures of performance. The degree of system interoperability was determined and discussed in terms of potential conflict in each scenario as a function of the relative differences in operational capability between system types. It was possible to interpret the capabilities and limitations of various system combinations by integrating the results of each case study with the results of the technical evaluation. This assessment led to recommendations of which system mixes should be supported by the FAA and also provided insight into the factors that tend to limit full exploitation of currently available navigation system capability. This report suggests steps that can be taken to overcome these limitations.

1.5 REPORT ORGANIZATION

Chapter Two defines terms used throughout the report and briefly describes the navigation systems discussed, together with a summary of the operational features of the airborne equipment associated with each of those systems.

Chapter Three details the performance requirements specified by the FAA that any navigation system must satisfy to be acceptable.

Chapter Four contains detailed analyses of the technical capabilities of each navigation system and compares these capabilities with the requirements.

Chapter Five provides insight into the operational capabilities of each navigation system, both independently and in combination with other systems, through specific case studies.

Chapter Six presents conclusions and recommendations.

Appendix A provides detailed descriptions of each navigation system.

Appendix B contains the equations used in computing some of the navigation errors specified in the report, and Appendix C illustrates the application of these equations.

Appendix D lists the references cited in this report, together with other source material.

CHAPTER TWO

NAVIGATION SYSTEMS OF INTEREST

2.1 DEFINITIONS

The following sections define navigation terms that are used throughout this report. The document, *American Practical Navigator* (Reference 1), was used as the preferred source of definitions. Modifications were sometimes necessary, however, to reflect the specific context in which navigation terms are applied in this report.

2.1.1 Navigation

Navigation is a means by which an aircraft is given guidance to travel from one known position to another known position. This process involves referencing the actual aircraft position to a desired course. The desired course is a path, between the two known locations, defined by a course generation method (e.g., great-circle, rhumb-line).

2.1.2 Radionavigation

Navigation systems characterized by their use of radio waves generated externally from the aircraft to determine position are known as radionavigation systems. They include Loran-C, Omega, VOR/DME, Tactical Air Navigation (TACAN), and GPS navigation systems; these will be discussed in detail in this report. Other navigation systems that utilize the radio wave spectrum but are not included in this report are Loran-A, instrument landing system (ILS), microwave landing system (MLS), the Navy Navigation Satellite System (TRANSIT), radio beacons, Decca, and radar.

The Loran-A navigation system has been replaced by Loran-C; ILS and MLS are landing systems; and TRANSIT navigation does not provide continuous coverage and is therefore not suitable as a primary means of navigation. Although radio beacons may be an element of a navigation system mix, their lack of sufficient navigational accuracy precludes their use as a primary system. The Decca navigation system has coverage limitations that make it less suitable for general use than Loran-C, and radar is primarily used for ground surveillance, not navigation. Radar vectors are issued by air traffic controllers and accepted by pilots as a means of navigation. However, because they do not constitute a primary form of navigation, they are not discussed as such in this report.

A number of navigation systems are derivatives of a primary system. For example, basic VOR has led to the development of wide-aperture (digital) VOR, Doppler VOR, and precision VOR. The study of system derivatives is outside the scope of this report.

2.1.3 Self-Contained Navigation

Navigation systems that do not require the use of externally generated radionavigation signals on a continuous basis for determining position are known as self-contained navigation systems. They include Doppler navigation systems and inertial navigation systems (INSs); these systems will be discussed in detail in this report.

The accuracy of self-contained navigation systems is specified differently than for the radionavigation systems discussed in this report. Whereas the accuracy of the radionavigation systems is defined as a position-determination discrepancy, the accuracy of self-contained navigation systems is defined as a rate of position-accuracy degradation, which is a function of elapsed operational time for INS accuracy and a function of distance traveled from the flight origin for Doppler accuracy. INS accuracy is specified in nautical miles per hour (nm/hr), and Doppler accuracy is specified as percentage of distance traveled from flight origin.

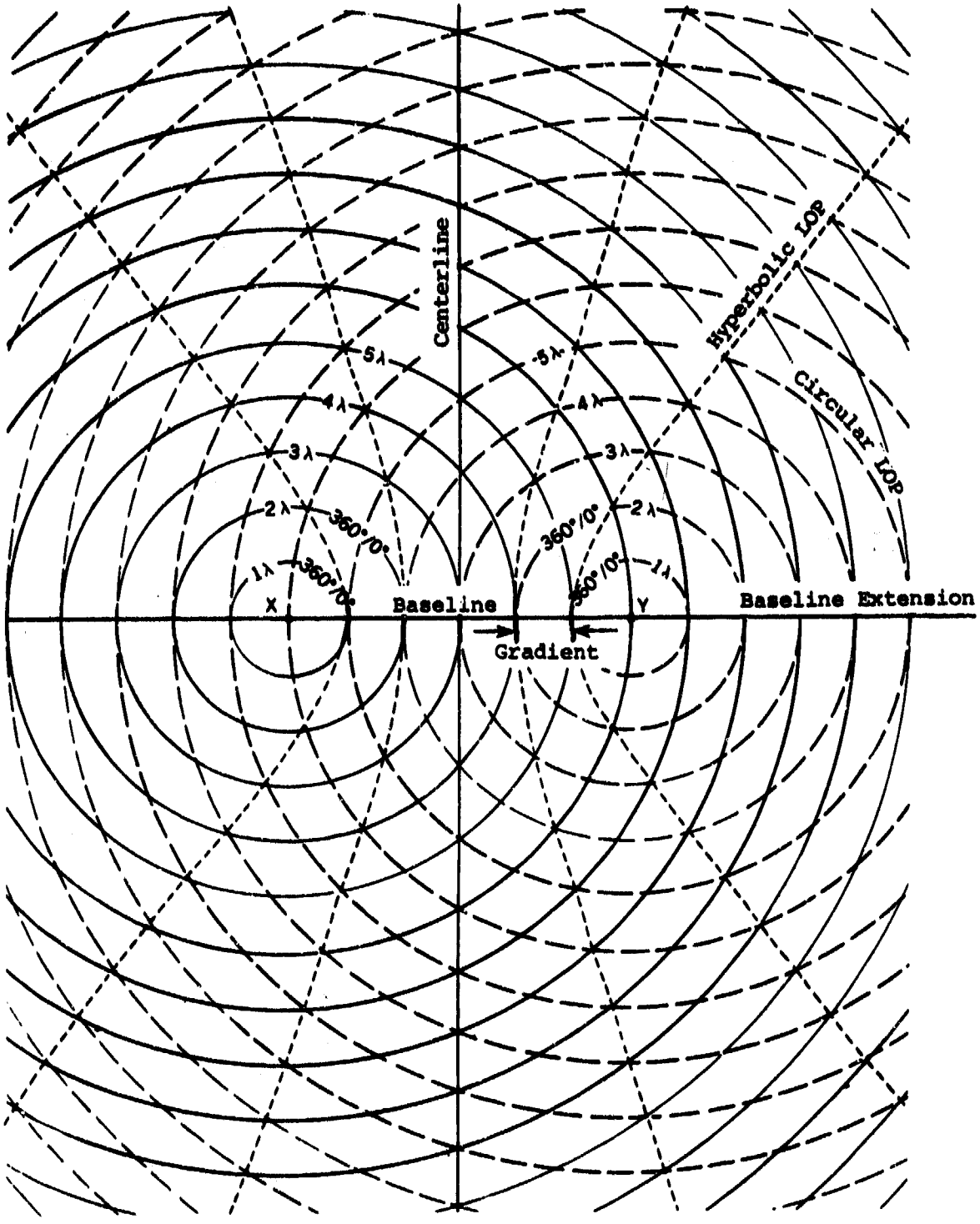
2.1.4 Area Navigation

Area navigation is an application of the navigation process providing the capability to establish and maintain a flight path on any arbitrarily chosen course that remains within the coverage area of the type of navigation signals being used. This random navigation capability is generally referred to as RNAV. Loran-C, Omega, GPS, Doppler, and INS are inherently RNAV navigation systems. VOR/DME in its basic form is station-referenced and therefore is not an RNAV system. However, more sophisticated airborne VOR/DME processors provide RNAV capability.

2.1.5 Hyperbolic Navigation

Hyperbolic radionavigation systems determine position through difference measurements of signals from three transmitting stations. These measurements can be either time differences (the elapsed time between the arrival of signals from two stations) or phase differences measured between two signals.

A transmitter that emanates signals in all directions creates a circular wavefront, with the transmitter at the center of the circle. A series of circles is generated, each at a successively larger distance (wavelength-λ) from the transmitter. If signals are transmitted from two stations at the same time, they will meet along a line equidistant from the two stations. This line, called the centerline, is the perpendicular bisector of a line drawn between the two stations, called the baseline. Figure 2-1 illustrates this pattern.

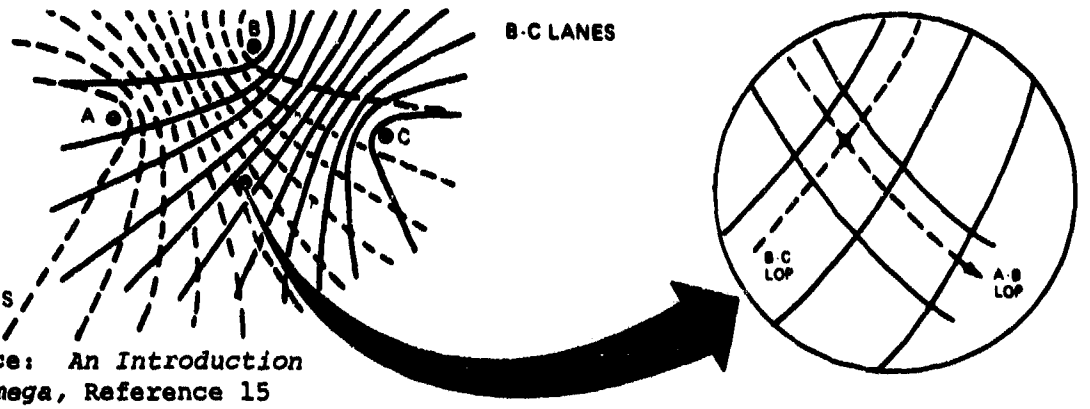


Source: *American Practical Navigator*, Reference 1.

Figure 2-1. HYPERBOLIC NAVIGATION GEOMETRY

Reception of the two signals from a point not on the centerline will result in a measured difference in time or phase. The locus of points at which the same difference can be measured defines a hyperbola. The time or phase difference measured corresponds to a distance difference. Each hyperbola in Figure 2-1 is a line of position (LOP), representing a constant range difference from the two transmitters. When a user is along the line connecting the two stations but is not between those two stations, the user is on a baseline extension. The farther a user is from the baseline along a given LOP, the larger the spacing, or gradient, between consecutive LOPs per unit measurement difference. The width of this spacing is referred to as a lane. In regions of a large gradient, a relatively small time- or phase-difference error will cause a relatively large position error. The gradient is so large along the baseline extensions that navigation accuracy is severely degraded in those areas.

Although a user can determine which LOP corresponds to his difference measurement, he is unable to locate his point of position along the LOP. A second LOP can be defined through the use of a third station, with a second baseline being drawn between the third station and either of the first two stations. The intersection of the two LOPs defines a position fix, illustrated in Figure 2-2.



Source: *An Introduction to Omega*, Reference 15 (reprinted by permission).

Figure 2-2. HYPERBOLIC POSITION FIX

2.1.6 Rho-Rho Navigation

In hyperbolic navigation, time or phase differences are measured to determine aircraft position in relation to the distance between stations. The distance between the aircraft and a ground station is commonly referred to as range, or rho. Rho-rho navigation involves directly measuring the total time it takes for each of two signals to travel from separate transmitters

to the airborne receiver. Each time measurement corresponds directly to a range measurement and defines a circular LOP. This form of operation is referred to as the ranging mode. The intersection of two circular LOPs provides two possible position fixes; the ambiguity is easily resolved by knowledge of approximate position.

The gradient between LOPs in the hyperbolic mode increases in accordance with the divergence of the hyperbolas. In the ranging mode, however, the gradient between the circular LOPs is constant, as shown in Figure 2-1. Therefore, navigation at extended ranges from the baseline is possible with use of the ranging modes; the coverage area of the stations is thereby effectively increased. In addition, whereas hyperbolic navigation requires three stations, rho-rho navigation requires only two stations. Greater freedom in selecting stations allows for consideration of station-to-user geometry to improve accuracy. The fact that the user need be within range of only two stations rather than three is another factor in providing extended coverage beyond that possible for hyperbolic navigation.

A disadvantage of rho-rho navigation is the user requirement for a highly stable, and therefore costly, time source (local oscillator or clock) against which the time measurements are made. Any clock drift will directly affect the range measurement. Clock bias is not a factor in the hyperbolic mode, since time differences between signals are measured.

2.1.7 Rho-Rho-Rho Navigation

When a third station is used to complement the two range measurements of the rho-rho mode, three circular LOPs are generated. The three LOPs will intersect at a common point only if there are no clock errors. If the range measurements are adjusted until common intersection is achieved, clock drift can be estimated and applied to subsequent range measurements. This technique allows the use of a less expensive clock, but necessitates the use of three stations.

2.1.8 Navigation Accuracy

Navigation accuracy is usually expressed in terms of a probability that deviation will be less than some stated magnitude of error. Different terms are used to define error, depending on the application. The terms "standard deviation" and "root mean square" are equivalent when they refer to one-dimensional zero-mean errors. Navigation errors typically have components in at least two dimensions -- along-track and cross-track. Terms commonly used in referring to two-dimensional navigation accuracy include circular error probability (CEP), standard deviation, and dimensioned root-mean-square error or radial error (drms).

CEP defines the radius of a circle for which there is a 50-percent probability that all position measurements will be inside. Standard deviation, or sigma (σ), in a two-dimensional analysis involves a radial rather than a linear distribution of errors. Numerically, 1σ corresponds to 39.95 percent (2σ = 86.47 percent) of a circular distribution, whereas it

corresponds to 68.27 percent (2σ = 95.45 percent) of a linear distribution. Reference to a circular standard deviation is meaningful only when the error figure, whose orthogonal axes are defined by one-dimensional errors (referred to as σx and σy), is a circle, a result that occurs only when $\sigma x = \sigma y$. Since σx and σy are generally not equal, reference to a position accuracy of 2σ can cause confusion as to whether the number describes the 86-percent two-dimensional probability circle or the 95-percent one-dimensional probabilities for each error axis.

The drms concept is introduced to give a single measure that will account for variations in both σx and σy that generate an error ellipse rather than a circle. One drms is defined as the radius of a probability circle, with the magnitude of the radius the RSS of the one-dimensional 1σ error components along the major and minor axes (σx and σy) of the error ellipse. The major drawback of this measure is that the value of probability associated with a fixed value of drms varies with the eccentricity of the error ellipse. Use of 2σ error components results in the computation of a 2-drms value. The 2-drms variation in probability is small (0.954 to 0.982).

Navigation accuracies or error components presented in this report are 2σ (95.45 percent) values unless specified otherwise. Relative accuracy is defined as the accuracy with which a user can measure relative position with respect to another user of the same navigation system at the same time. Repeatable accuracy is the accuracy with which a user can return to a position whose coordinates have been measured previously with the same navigation system.

2.1.9 Great-Circle Course

The shortest path between two points on a spherical earth is a great circle, which is created by the intersection of the earth's surface and a plane defined by the center of the earth and the points of origin and destination.

2.1.10 Rhumb-Line Course

A rhumb-line path connects origin and destination along a path that maintains constant true course (i.e., the course crosses successive lines of longitude at a constant angle).

2.1.11 Geometric Dilution of Precision (GDOP)

The effect that geometry between the user and the signal transmitters has on accuracy is expressed in terms of geometric dilution of precision (GDOP). A GDOP of 1 yields the value of accuracy associated with the best geometry configurations. Progressively larger values of GDOP indicate worsening geometry and correspondingly degrade the achievable accuracy of the system.

For hyperbolic navigation, geometrical considerations include the crossing angle of intersecting LOPs and the spacing between consecutive

LOPs. The most favorable geometry occurs along baselines with the two intersecting LOPs being nearly orthogonal. As the crossing angle becomes more shallow, it becomes more difficult for the system to resolve the point of intersection accurately. Uncertainty in time or phase measurement translates into a position error, the magnitude of which is a function of the distance between LOPs (the lane width). A certain percentage of uncertainty in determining position within a lane will result in larger errors for wider lanes. The lane width widens between hyperbolic LOPs with increasing distance from the baseline, resulting in degradation of accuracy corresponding to typical GDOPs of 2 to 3.

For rho-rho or rho-rho-rho navigation, the only geometrical consideration is the crossing angle of intersecting LOPs. Since the spacing between the consecutive circular LOPs is constant when ranging techniques are used, accuracy is not degraded by varying gradient between LOPs. The most favorable crossing angle geometry occurs when the two intersecting LOPs are nearly orthogonal. Since the use of ranging techniques allows freedom to select those stations that optimize the crossing angle of the LOPs, the corresponding GDOP can be reduced nearly to 1 under most conditions.

2.1.12 Body-Axis Coordinate Frame

The body-axis coordinate frame is a right-handed system that is fixed relative to the frame of the aircraft, with its origin at the aircraft's center of gravity. The X axis points outward through the nose of the aircraft. The Y and Z axes point respectively out the right wing and out the bottom of the aircraft.

2.1.13 Locally Level Coordinate Frame

Pitch, roll, and yaw are measured with respect to a locally level coordinate frame. This right-handed coordinate system has its origin at the aircraft's center of gravity. The yaw axis is coincident with the local vertical and points downward. The roll axis points in the direction of aircraft heading, and the pitch axis points 90 degrees to the right of aircraft heading.

2.1.14 Locally Level Geographic Coordinate Frame

This coordinate frame is also locally level but is referenced to geographic north. The axes point in the east, north, and "up" directions, regardless of the aircraft attitude or heading.

2.2 SYSTEM SUMMARIES

The following sections briefly summarize the systems evaluated in this report. Detailed descriptions are provided in Appendix A.

2.2.1 Loran-C

Loran-C is a hyperbolic radionavigation system that uses ground waves at low frequencies to obtain an operating range of 600 to 1,500 nautical miles (nm) independent of line-of-sight. It also uses pulse techniques to avoid skywave contamination. Accuracy of Loran-C is heavily dependent upon GDOP factors at the user's location within the coverage area. Loran-C is capable of achieving absolute 2-drms accuracies of 463 meters (0.25 nm) or better. The repeatable and relative accuracies of Loran-C are usually between 18 and 90 meters (0.01 and 0.05 nm). The Loran-C system currently consists of 16 chains operating throughout the world, comprising a total of 51 transmitting stations. Two-thirds of the conterminous United States and Alaska is currently within the Loran-C coverage area; there is no Loran-C coverage in the sourthern hemisphere. Loran-C coverage is concentrated in the coastal areas of the Atlantic and Pacific oceans and the Norwegian and Mediterranean seas.

2.2.2 Omega

Omega is another hyperbolic navigation system, but it utilizes sky waves rather than ground waves to give each transmitter an operating range of about 5,000 nm. The accuracy of the Omega system is limited by the accuracy of the propagation corrections that are applied to the received signal; a predictable accuracy of two to four nm is the design goal of the system. Statistical studies conducted in the North Atlantic show that rms positional accuracies of one to two nm are possible.

Omega signals transmitted from eight stations provide nearly worldwide coverage. There are also a number of United States Navy very low frequency (VLF) communication transmitters located around the world that can be used as supplementary signal sources for Omega navigation. Use of VLF communication stations improves the dependability and accuracy of continuous coverage during Omega/VLF navigation. A wider choice of candidate stations provides greater probability that GDOP can be minimized by judicious station selection. The extent of infusion into the marketplace of the Omega/VLF concept is making Omega/VLF the dominant form of civil Omega navigation.

Another recent development in the evaluation of Omega navigation has been the increasing use of ranging techniques rather than the hyperbolic technique in the airborne processor. The ranging mode requires reception from only two stations (rather than the three required in the hyperbolic mode) to obtain a position fix and provides capability for increased coverage and accuracy. However, it is necessary to employ a highly accurate, and therefore expensive, clock for rho-rho measurement. As explained previously, using a third station in a rho-rho-rho mode permits use of a less expensive clock.

2.2.3 Differential Omega

Differential Omega is a concept that supplements the standard Omega signal received by the airborne unit with differential correction terms

that compensate for localized variations in signal propagation characteristics. A more complete description of the differential Omega concept is contained in Section 2.8 of Appendix A. Use of differential Omega techniques has been demonstrated in marine applications to provide a 2σ accuracy capability of 0.2 to 0.4 nm, but only when within 50nm of the ground monitor station that provides the differential corrections. The level of accuracy diminishes with increasing distance from the monitor station.

Most data currently available on the performance capability of differential Omega are associated with marine usage in coastal regions. The testing of differential Omega in airborne applications has not been sufficient to provide conclusive evidence of expected performance. The lack of data in this regard precludes evaluation of differential Omega in this report as a currently existing means of airborne navigation. From the data that do exist, however, there are indications that differential Omega could be suitable as a means of providing navigational capability where other navigation systems are not suitable, thereby becoming an element of a mix of systems.

2.2.4 VOR/DME

The international standard en-route navigation system used within the conterminous United States is VOR/DME. VHF Omnidirectional Range provides the azimuth relative to the VOR ground station, and Distance Measuring Equipment (DME) furnishes a measurement of distance from the aircraft to the DME ground station. VOR and DME are usually collocated as a VOR/DME facility. TACAN is a combination of omnibearing and distance-measuring functions. TACAN is a military system, with the azimuth portion of a TACAN facility not widely used by nonmilitary users. The distance-measuring function of TACAN, however, is the international standard DME and is therefore accessible to anyone with a DME interrogator. So that both military and civil aircraft can navigate using the same airway network, TACAN facilities are collocated with VOR facilities. A VOR collcated with a TACAN is called a VORTAC. Since there is no difference in operation or performance between a VORTAC and a collocated VOR/DME, VORTACs will be included in the VOR/DME system classification in this report.

VOR and DME navigation aids (navaids) can be used in any of the following three configurations:

- VOR only
- VOR/DME
- DME/DME

The VOR system is the basis for defining airways and is therefore an integral part of air traffic control procedures. Use of VOR in the absence of DME results in navigation based solely on directional information. This singular capability is the basis upon which Victor airways were established -- VOR-to-VOR navigation. Two VOR stations can be used to define a radial intersection reporting point. By charting the bearing information obtained

from the two VOR stations, a position fix can be determined. The combination of VOR and DME at a single site provides the capability for position fixing by means of a single facility. This configuration forms the standard International Civil Aviation Organization (ICAO) short-range navigation system. The use of dual DME offers a significant improvement in position-determination accuracy in areas that have suitable dual-DME signal coverage.

The accuracy of VOR is the basis of the design specification for United States air traffic control standards and procedures. The magnitudes of both accuracy and signal coverage of VOR and DME are a function of aircraft altitude and distance from the station. Line-of-sight limitations restrict coverage to 30 nm or less at ground level, a distance that progressively increases with altitude to an upper limit approaching 200 nm.

VOR signal coverage is a function of the class of VOR station: terminal, low altitude, or high altitude. A terminal VOR provides coverage for an altitude range of 1,000 to 12,000 feet at radial distances out to 25 nm. A low-altitude VOR provides coverage from 1,000 to 18,000 feet at radial distances out to 40 nm. The coverage provided by a high-altitude VOR is a function of aircraft altitude, as shown below:

Coverage of radial distances of:	is provided at altitudes of:
40 nm	1,000 feet to 14,500 feet
100 nm	14,500 feet to 18,000 feet
130 nm	18,000 feet to 45,000 feet
100 nm	45,000 feet to 60,000 feet

These operational coverage areas can be expanded under special circumstances by extending the noninterfering coverage radius to no more than 110 nm at altitudes below 18,000 feet, or 185 nm above 18,000 feet.

2.2.5 GPS

The NAVSTAR Global Positioning System (GPS) is a proposed space-based radionavigation system that is intended to provide accurate navigation and position information to all properly equipped users. The fully operational system will enable continuous worldwide navigation, regardless of weather conditions. Current concepts are based on an 18-satellite constellation -- a reduction from the 24 in the original specification. Using signals from four satellites, a user can obtain three position dimensions (latitude, longitude, and altitude), determine time, and derive velocity.

Although GPS is a military system, its potential use for civil navigation is a major topic of discussion and study. Current plans call for exclusive military use of the precision code (P-code), which, in the context of an 18-satellite constellation, enables predictable positioning accuracy of 25 meters (0.013 nm) horizontally and 30 meters vertically (95 percent probability), depending on the capability of user equipment and the user-to-satellite geometries. The navigational accuracy to be made available by the military to civilian users of the coarse acquisition

(C/A code is uncertain; speculation ranges from 50 to 500 meters (0.016 to 0.268 nm).

Three-dimensional navigation coverage requires four GPS satellites to be in view of the user. The accuracy obtained depends on the geometry involved. A substantial increase in GDOP is predicted because of the reduction in the specified number of satellites from 24 to 18. The effect of increased GDOP on civilian use of GPS is somewhat dependent on which areas of the world are most adversely affected.

2.2.6 Doppler

A Doppler navigation system provides self-contained navigation capability for use in over-water and remote environments, by using inputs from a Doppler radar and a heading reference. The Doppler radar measures groundspeed, and the heading reference determines the aircraft's heading. These inputs are then used by the Doppler navigation system to continuously compute and display current aircraft position relative to the flight path origin.

The Doppler radar transmitter directs radar signals toward the ground; the signals are scattered by the ground surface and are then detected by the Doppler radar receiver. The frequency is shifted in the scattered radar signals by an amount related to aircraft velocity. The Doppler radar then determines the groundspeed of the aircraft by measuring this frequency shift in the detected signals. The heading reference typically used in a civil Doppler navigation system measures aircraft heading with a magnetic compass.

The cross-track accuracy of Doppler navigation is highly dependent on the heading reference accuracy. Doppler navigation accuracy degrades as a function of distance traveled from the flight path origin. Cross-track accuracy for current civil Doppler navigation systems is typically three percent of flight path distance, and along-track accuracy is one percent.

An operational problem that occurs over calm water is an occasional loss of signal due to insufficient scattering of the radar signals in the direction of the aircraft.

2.2.7 Conventional INS

Conventional INS also provides self-contained navigation capability, using measured aircraft acceleration to determine aircraft position. For computational convenience, the accelerometers used to measure aircraft acceleration are mounted on a gimbaled platform mechanized to maintain continuous alignment with the locally level geographic coordinate frame, regardless of aircraft orientation. Current position is determined by integrating the measured aircraft acceleration to obtain velocity and integrating a second time to obtain position displacement. Gyros are used to measure the deviations of the platform orientation. These measurements are then applied to the platform to correct its orientation. The accuracy of conventional INSs is highly dependent on the characteristics of these gyros. Since the error associated with the gyro measurements tends to

increase as a function of time elapsed during operation, the position determination of conventional INSs used in civil applications has typical rates of accuracy degradation of one to two nm per hour of use; conventional INSs being developed for use in military applications have demonstrated rates of accuracy degradation as low as 0.08 nm per hour, using electrostatically suspended gyros.

2.2.8 Strapdown INS

Strapdown INS will also provide self-contained navigation capability when commercially available. It is similar in concept to conventional INS; it differs in the manner in which the gyros and accelerometers are mounted. In strapdown INS, the accelerometers and gyros are mounted in fixed reference to the aircraft frame, and as a result measure acceleration and angular components in body-axis coordinates. These components must be transformed into the local coordinate frame before velocity and position are computed. Angular data provided by gyros are used in the transformation. Several types of gyros have been considered for this application, including ring laser gyros, tuned rotor gyros, and electrostatically suspended gyros, which are each described in Section 8.3 of Appendix A.

Strapdown INS has fewer moving parts and is therefore more reliable than conventional INS. Because of the coordinate transformations, however, strapdown INS has more computational requirements. These computations have recently become relatively easy to perform with the development of minicomputer technology.

The strapdown INS now being developed for use in civil applications combines a strapdown inertial reference system (IRS) using ring laser gyros, and a flight management computer (FMC). The strapdown IRS provides the FMC with current aircraft position. The FMC performs waypoint storage, flight path generation, and steering command computations. The term "strapdown INS" as used subsequently in this report refers to this IRS/FMC combination.

Accuracy of current civil strapdown INSs is primarily dependent on the characteristics of the ring laser gyros used. Currently achieved rates of position accuracy degradation are typically one to two nm per hour of use for these systems. Military strapdown INSs being developed have demonstrated rates of accuracy degradation as low as 1.1 nm per hour.

2.3 SYSTEM FEATURES

Airborne navigation units have evolved and continue to evolve in accordance with the needs of the various user communities. Consequently, the man-machine interfaces of airborne equipment differ from each other as manufacturers provide special features desired by particular users.

2.3.1 Loran-C

Use of Loran-C for airborne navigation evolved as a supplement to conventional VOR/DME in areas of poor VOR/DME signal coverage. The inability of VOR/DME to provide offshore signal coverage made Loran-C particularly appropriate for offshore helicopter operations. The Coast Guard uses Loran-C for over-water search and rescue missions, and offshore oil well operators use it for navigating between land and offshore drilling platforms. Since these users require the capability of precise position location, manufacturers have emphasized special features such as stored programmable search patterns and highly accurate ground position and track determination. Until Loran-C is more widely accepted for use along conventional domestic airways, there will be little incentive for manufacturers to include a data base of VOR/DME navaids to enable the construction of navaid-oriented area navigation routes.

2.3.2 Omega

Airborne Omega navigation is used primarily to serve the needs of international air carriers. Neither VOR/DME nor Loran-C can provide coverage over mid-ocean. Transoceanic navigation is typically performed by either inertial navigation systems (INSs) or Omega. The inertial systems, however, are limited in accuracy by the accumulation of gyro-drift errors. Omega is frequently used, therefore, to provide periodic updates to the INS and to serve as a back-up navigation system. However, Omega is also certified for use as a primary means of oceanic navigation. The ability of Omega to serve as a worldwide navigation system has prompted some manufacturers to provide capabilities that make it operationally efficient in almost any environment. Omega navigation systems may (1) include a data base of airports and navaids for use in flight planning (2) provide the capability for an extensive waypoint list that is useful for long transoceanic or transcontinental flights, and (3) allow selection of track-hold autopilot coupling.

2.3.3 VOR/DME

VOR/DME was developed in response to the basic need for an extensive network of omnidirectional navigation aids. As a result, the VOR/DME navigation system provided the means of successful navigation within the United States.

Some airborne VOR/DME navigation units can provide RNAV capability, but others cannot. A VOR-only unit is limited to a non-RNAV application, but single and multiple VOR/DME units are available for either non-RNAV or RNAV applications. The RNAV capability adds to the cost.

A multiple VOR/DME RNAV unit that utilizes two VOR/DME navaids (primary and secondary) offers increased automation as well as a substantial improvement in accuracy as a result of dual-DME processing capability. Since RNAV systems can be geographically oriented (e.g., referenced to latitude and longitude), VOR/DME RNAV units can generally maintain position in terms of latitude and longitude displacement in relation to

the coordinates of the reference VORTAC. To provide this capability, a navaid data base can typically be provided, containing the latitude and longitude coordinates of all relevant VORTAC navaids. The navaid information is entered into the data base through either preprogrammed memory elements provided by the manufacturer or manual input by the pilot. Access to this data base enables the use of automatic station-selection algorithms, which eliminate the need for both pilot selection of appropriate navaids and input of corresponding navaid frequencies.

2.3.4 GPS

The satellite-based GPS is still in the development stage. Development of GPS for civil aviation applications is motivated by a desire to replace currently existing navigation systems with a single system that can meet the requirements of all users throughout the world. Although no production units are commercially available yet, studies have been performed, based primarily on cost considerations, on the likely configurations and capabilities of airborne GPS receivers. The need to offset the initial high cost of new and complex technology will result in minimizing optional capabilities. Consequently, the "low cost" GPS receiver is projected to have functional capabilities comparable to the less expensive RNAV VOR/DME systems.

2.3.5 Doppler

Doppler navigation systems were developed in response to the need for navigation capability in areas with inadequate or nonexistent VOR/DME coverage. They were first used in transoceanic navigation before airborne INS or Omega units were available. These early Doppler navigation systems do not use great-circle course generation and do not compute current latitude and longitude. Doppler navigation systems now being developed will include more convenient man-machine interfaces.

2.3.6 Conventional INS

Conventional INS was developed to provide an accurate and convenient transoceanic navigation capability. INS has the additional capability of providing aircraft attitude information for use by the autopilot and other aircraft instruments. Because of accumulated error in an INS due to gyro drift, an independent INS cannot currently provide the level of accuracy required for many over-land applications. However, by providing the INS with periodic updates from a VOR/DME or other radionavigation system, INS can be used for over-land navigation. This feature has prompted manufacturers to include a data base of airports and navaids and an extensive waypoint list capability in recent INSs.

2.3.7 Strapdown INS

Strapdown INS was developed in response to the high maintenance cost of conventional INS. Strapdown INS is capable of providing the same capabilities as conventional INS with the same level of accuracy, but with lower maintenance costs. The current configuration of strapdown INS is an

inertial reference system (IRS) used in conjunction with a flight management system (FMS) to provide navigation capability.

2.4 SUMMARY

Table 2-1 summarizes the functions and features generally available in typical 1980-model airborne navigation units. The table should not be interpreted to suggest that a particular navigation unit always provides the features indicated or that features not included could not be accommodated. The differences between the man-machine interfaces of various RNAV units primarily reflect marketing decisions on the part of the manufacturers. There is no technical impediment to providing all navigation units with the same level of capability in terms of the man-machine interface. In fact, as the market potential for the various types of navigation system units becomes more obvious, units are being offered with more features in common.

Table 2-1. SUMMARY OF TYPICAL FEATURES OF AVAILABLE AIRBORNE NAVIGATION UNITS

Unit Feature	Non-RNAV	RNAV						
	VOR/DME	VOR/DME	Loran-C	Omega	GPS	Doppler	Conventional INS	Strapdown INS
Inputs								
Flight Planning								
By latitude/longitude waypoints	●	●	x	x	x	x	x	x
By place/bearing/distance waypoints	●	x	x	x	v	x	●	•
By navaid alpha designators	●	x	x	x	●	●	●	●
By desired magnetic heading	To VORTAC only	x	x	x	●	x	●	●
By in-flight updating	x	x	x	x	x	x	x	x
Flight Information								
Current position	●	●	x	x	x	x	x	x
Time (GMT)	●	●	●	x	x	●	x	●
Date	●	●	●	x	x	●	●	●
Magnetic variation								
Manual	●	●	x	x	x	●	x	●
Automatic prestored	●	●	x	x	●	●	●	x
Actual heading								
Manual	●	●	x	x	●	●	●	●
Automatic sensor	●	x	x	x	●	x	●	x
True airspeed								
Manual	●	●	x	x	●	●	x	●
Automatic sensor	●	●	●	x	●	●	x	x
Station Selection and Deselection								
Automatic	●	x	x	x	x	N/A	N/A	N/A
Manual	x	x	x	x	x	N/A	N/A	N/A
Operating Modes								
Navigation								
Direct to								
Great circle	x	x	x	x	x	x	x	x
Rhumb line	●	x	●	●	●	x	●	●
Leg change								
Manual	x	x	x	x	x	x	x	x
Automatic	●	x	x	x	x	x	x	x
Parallel offset	●	x	x	x	●	x	x	•
Dead reckoning								
With sensor updates (e.g., TAS, HDG)	●	●	●	x	●	●	●	●
Without sensor updates	●	●	x	x	●	●	●	●
Autopilot Coupling								
Track hold	Along radial	x	●	x	x	x	x	x
Turn anticipation	●	x	●	x	x	●	●	•
Display Parameters								
Current Position								
Latitude/longitude	●	●	x	x	x	x	x	x
Bearing/distance to or from stored waypoint	●	x	x	x	x	x	x	•
Bearing/distance from signal source	x	x	●	●	●	N/A	N/A	N/A
Time to waypoint	●	x	x	x	x	●	x	•
Current Heading								
Magnetic	●	●	●	x	●	●	x	x
True	●	●	●	x	●	●	x	x
Drift angle	●	●	●	x	●	x	x	x

(continued)

Table 2-1. (continued)

Unit Features	Non-RNAV	RNAV						
	VOR/DME	VOR/DME	Loran-C	Omega	GPS	Doppler	Conventional INS	Strapdown INS
Display Parameters (continued)								
Current Track								
Desired angle	To/From VORTAC only	X	X	X	X	X	X	X
Actual angle	To/From VORTAC only	X	X	X	X	X	X	X
Angle error	To/From VORTAC only	X	X	X	X	●	X	X
Cross-track deviation	X	X	X	X	X	X	X	X
Groundspeed	X	X	X	X	X	X	X	X
Atmospheric Conditions								
Wind speed	●	●	X	X	●	●	X	X
Wind direction	●	●	X	X	●	●	X	X
Warnings and Indications								
Operator error	●	●	X	X	*	●	X	●
Malfunction	X	X	X	X	X	X	X	*
Approaching or missed waypoint	X	X	X	X	*	X	X	*
Input and Output (I/O) Interfaces								
Directional Gyro	●	X	●	X	●	X	●	●
Course Deviation Indicator	X	X	X	X	*	X	X	*
Autopilot	●	X	X	X	*	X	X	*
Data Bus, Data Link	●	X	X	X	*	●	X	X
Flight Management Computer	●	X	X	X	X	●	●	X
Mechanical Characteristics								
Receiver/Processor Unit (RPU)	VOR / DME							
Weight (pounds)	3 / 5	11.0	11.0	26.0	12.0	17.0	57.0	44.0
Volume (cubic feet)	0.1 / 0.1	0.3	0.4	0.7	0.3	0.6	1.0	0.7
Control/Display Unit (CDU)								
Weight (pounds)	Integrated in RPU	0.4	5.0	4.0	Integrated in RPU	4.0	5.0	*
Volume (cubic feet)	Integrated in RPU	0.1	0.1	0.1	Integrated in RPU	0.1	0.1	*
Cost Range ($ thousands)	1 to 7 / 3 to 10	2 to 60	10 to 30	20 to 40	5 to 15	48	100	75 to 90

*Insufficient data.

Legend:

X - Available

● - Not available

This table is based on the following units:

Non-RNAV VOR/DME
- Collins VIR-351
- Narco DME-890

RNAV VOR/DME
- Collins ANS-31, ANS-351
- Bendix NP-2041A
- King KNR-665A, KNS-80
- Foster AirData VNAV-541, AD-611
- J.E.T. DAC-2000

Loran-C
- Teledyne TDL-711, TDL-424
- Offshore Navigation ONI-7000

Omega
- Litton LTN-211
- Norden Omega ONS-VII
- Global Nav ONS-500A Series 2
- Collins LRN-80, LRN-85
- Canadian Marconi CNA-771

GPS
- Design Studies

Doppler
- Bendix DRA-12
- Marconi AD660

Conventional INS
- Litton LTN-51, LTN-72, LTN-72R
- Delco Carousel IV, Carousel IV-A

Strapdown INS
- Litton LTN-90
- Honeywell RLG IRS

CHAPTER THREE

PERFORMANCE REQUIREMENTS OF NAVIGATION SYSTEMS

3.1 OVERVIEW

The process of selecting a navigation system or a particular mix of navigation systems for adoption as the United States standard involves a series of comparisons. The essential question to be answered is: Which candidate system(s) can provide a level of navigation capability that surpasses all others? The comparison cannot be based on a singular issue such as system accuracy, however. The criteria that must be used are the following:

- Technical
- Operational
- Institutional
- Economic

Technical considerations are primarily concerned with integrity, reliability, coverage, and accuracy; the means of achieving accuracy is an operational issue. The intent of this report is to evaluate only those elements of the technical and operational considerations which contribute to navigation system accuracy. Both technical and operational considerations are related to the environment in which the navigation system will be used. The airspace environment has been divided into two basic phases of air navigation:

- Approach/landing
- En route/terminal

The approach/landing phase includes flight operations generally conducted within 10 nm of the runway in preparation for touchdown. Two categories of approach are defined within this phase: nonprecision and precision.

The en route/terminal phase of flight is divided into categories defined by the following particular geographic areas and operating environments:

- Oceanic en route
- Domestic en route
- Terminal
- Remote areas
- Helicopter operations

Institutional considerations are concerned primarily with the effects and resolution of political issues such as international standardization; distribution of costs; and system ownership, control, operation, and maintenance. Economic considerations, for both ground and airborne facilities and equipment, include the initial investment; operating, maintenance, and replacement costs; and amortization of the capital investment.

3.2 TECHNICAL CONSIDERATIONS

The system-use accuracy necessary to meet current route requirements is summarized in Table 3-1, which is taken directly from Volume II of the July 1980 *Federal Radionavigation Plan* (FRP). "System-use accuracy" is defined by ICAO to be the square root of the sum of the squares (root sum square [RSS]) of the following error contributions:

- Ground station error
- Airborne receiver error
- Display system error
- Flight technical error

System-use accuracy is a measure of the ability of a navigation system user to remain within a specified distance (route width) from a desired point (track). Navigation accuracy is generally expressed in terms such as the following:

- Predictable accuracy (also called absolute accuracy): the accuracy associated with predicting position with respect to geographic coordinates
- Relative accuracy: the accuracy with which a user can measure relative position with respect to another user of the same navigation system at the same time
- Repeatable accuracy: the accuracy with which a user can return to a position whose coordinates have been measured previously with the same navigation system

Accuracy defines the difference between a measurement value and a reference value; precision defines the degree of refinement to which the value can be expressed.

System-use accuracy corresponds to predictable, or absolute, accuracy in a statistical sense. The interpretation of the 2-drms accuracy values (shown in Table 3-1) is that the along-track and cross-track error components cannot combine to yield a result exceeding the value given for 95 percent of the measurements taken.

Table 3-1. CONTROLLED AIRSPACE NAVIGATION ACCURACY TO MEET CURRENT REQUIREMENTS

Phase	Subphase		Altitude (Flight Level)	Traffic Density	Route Width (nmi)	Accuracy 2 dmrs (Meters)	System-Use Accuracy 2 dmrs (Meters)
En Route/ Terminal	Oceanic		FL 275 to 400	Normal	66		12.6nmi[1]
	Domestic		FL 180 to 600	Low	16	2000	7,200
				Normal	8	1000	3,600
			500 - 18,000 ft.*	High	8	1000	3,600
	Terminal		500 - 18,000 ft.*	High	4	500	1,800
	Remote		500 - 60,000 ft.*	Low	8 to 20	1000 to 4000	3,600 to 14,400
	Helicopter Operations		500 - 5000 ft.*	Low (Off-Shore)	Not Determined	1000 to 2000	3,600 to 7,200
			500 - 3000 ft.*	High (Land)	4	500	1,800
Approach and Landing	Non-Precision		250 to 3000 ft. above Surface	Normal	2	100	150
	Precision	Cat I	100 to 3000 ft. above Surface	Normal	±9.1 meters[2]	± 3 meters[3]	
					at 100 ft. above Surface		
		Cat II	50 to 3000 ft. above Surface	Normal	± 4.6 meters	± 1.4 meters	
					at 50 ft. above Surface		
		Cat III	0 to 3000 ft. above Surface	Normal	± 4.1 meters	± 0.5 meters	
					at Surface		

(1) The distribution of this error is detailed in the "Report of the Limited North Atlantic Regional Air Navigation Meeting," dated 1975; ICAO Montreal Canada.
(2) This column is lateral position 2 sigma accuracy in meters for Precision Approach and Landing.
(3) This column is vertical position 2 sigma accuracy in meters for Precision Approach and Landing.
*Feet above surface.

Source: Federal Radionavigation Plan.

Table 3-1 does not reflect the system-use accuracy requirements for area navigation systems. FAA Advisory Circular (AC) 90-45A provides the requirements for approval of area navigation systems for use in the United States National Airspace System (NAS). Figure 3-1, reproduced from AC 90-45A, presents the maximum allowable errors for VOR/DME-based area navigation systems. The figure indicates allowable cross-track and along-track errors as a function of distance from the VORTAC reference. Rather than defining

DISTANCE ALONG TRACK FROM TANGENT POINT

PERPENDICULAR DIST TO TANGENT POINT

	0	5	10	15	20	25	30	35	40	50	60	70	80	90	100	110	120	130	150	180
0 (x trk) (along trk)		.9 .9	.9 .9	1.1 1.9	1.3 1.8	1.6 1.9	1.8 1.8	2.1 1.8	2.3 1.8	2.1 1.8	2.1 1.9	2.4 2.2	2.8 2.5	2.8 2.8	3.0 3.0	3.4 3.3	3.6 3.6	3.8 3.9	4.2 4.3	4.6 5.0
5 (x trk) (along trk)	.2 .4	.3 .9	.4 .8	1.1 1.8	1.4 1.9	1.6 1.8	1.9 1.8	2.1 1.8	2.3 1.8	2.1 1.8	2.1 1.9	2.4 2.2	2.8 2.5	2.8 2.8	3.0 3.0	3.4 3.3	3.7 3.6	3.8 3.9	4.2 4.3	4.6 5.1
10 (x trk) (along trk)	.2 .8	.4 .8	.5 .9	1.1 1.9	1.4 1.8	1.7 1.8	1.9 1.8	2.1 1.8	2.3 1.8	2.1 1.8	2.1 1.9	2.4 2.2	2.8 2.5	2.8 2.8	3.0 3.0	3.4 3.3	3.7 3.6	3.8 3.9	4.2 4.3	4.6 5.1
15 (x trk) (along trk)	.2 1.1	.4 1.1	.5 1.2	1.2 1.8	1.5 1.8	1.7 1.8	2.0 1.8	2.2 1.8	2.4 1.8	2.2 1.8	2.2 1.9	2.4 2.2	2.9 2.5	2.9 2.8	3.2 3.0	3.5 3.3	3.8 3.6	4.1 3.9	4.3 4.3	4.7 5.2
20 (x trk) (along trk)	.3 1.5	.4 1.4	.6 1.6	1.4 1.8	1.6 1.8	1.8 1.8	2.0 1.7	2.2 1.8	2.4 1.8	2.2 1.8	2.3 1.8	2.5 2.2	2.9 2.5	3.1 2.8	3.2 3.0	3.6 3.3	3.9 3.6	4.2 3.9	4.4 4.3	4.8 5.2
25 (x trk) (along trk)	.3 1.8	.5 1.8	.7 1.9	1.7 1.7	1.8 1.8	1.8 1.8	2.1 1.6	2.4 1.8	2.7 1.8	2.3 1.8	2.5 1.8	2.7 2.2	3.1 2.5	3.2 2.8	3.5 3.0	3.8 3.3	4.1 3.6	4.3 3.9	4.5 4.3	4.9 5.3
30 (x trk) (along trk)	.4 1.9	.5 1.9	.7 2.0	1.8 1.8	1.7 1.8	1.9 1.8	2.2 1.8	2.5 1.8	2.7 1.8	2.5 1.8	2.7 1.8	2.9 2.2	3.1 2.5	3.4 2.8	3.7 3.0	3.9 3.3	4.2 3.6	4.3 3.9	4.5 4.3	5.0 5.4
35 (x trk) (along trk)	.5 2.2	.6 2.2	.8 2.4	1.8 1.8	1.8 1.8	2.0 1.8	2.3 1.8	2.5 1.8	2.8 1.8	2.6 1.8	2.8 1.8	3.0 2.2	3.2 2.5	3.4 2.8	3.6 3.0	3.9 3.3	4.2 3.6	4.4 3.9	4.6 4.3	5.1 5.5
40 (x trk) (along trk)	.5 2.5	.6 2.5	.8 2.6	1.8 1.8	1.9 1.8	2.1 1.7	2.3 1.7	2.6 1.8	2.9 1.8	2.6 1.8	2.9 1.8	3.0 2.2	3.2 2.4	3.4 2.6	3.6 2.8	3.9 3.0	4.2 3.3	4.5 3.6	4.5 4.3	5.3 5.7
50 (x trk) (along trk)	.6 3.1	.8 3.2	1.0 3.2	1.9 1.8	2.1 1.8	2.3 1.8	2.5 1.8	2.8 1.8	3.0 1.8	2.8 1.8	2.9 1.8	3.1 2.2	3.3 2.5	3.5 2.8	3.8 3.0	4.1 3.3	4.3 3.6	4.6 3.9	4.8 4.3	5.3 5.8
60 (x trk) (along trk)	.7 3.7	.9 3.8	1.0 3.8	2.1 1.8	2.3 1.8	2.5 1.9	2.7 1.9	3.0 2.0	3.2 2.0	2.7 2.1	2.9 2.3	3.0 2.4	3.4 2.6	3.6 2.8	3.8 3.0	4.1 3.3	4.3 3.6	4.6 3.9	4.8 4.3	5.4 6.0
70 (x trk) (along trk)	.8 4.4	1.0 4.4	1.1 4.4	2.4 1.8	2.6 1.8	2.7 1.9	2.9 1.9	3.2 2.0	3.4 2.0	3.0 2.0	3.2 2.3	3.3 2.4	3.6 2.6	3.8 2.8	4.1 3.0	4.3 3.3	4.5 3.6	4.8 3.9	5.0 4.3	5.5 6.0
80 (x trk) (along trk)	.9 5.0	1.1 5.0	1.2 5.0	2.7 1.8	2.8 1.8	3.0 1.9	3.2 1.9	3.4 2.0	3.6 2.0	3.1 2.0	3.4 2.3	3.5 2.4	3.7 2.6	3.8 2.8	4.0 3.0	4.2 3.3	4.5 3.6	4.8 3.9	5.0 4.3	5.6 6.0
90 (x trk) (along trk)	1.0 5.6	1.2 5.6	1.3 5.6	3.0 1.8	3.1 1.8	3.2 1.9	3.4 1.9	3.6 2.0	3.8 2.0	3.4 2.0	3.6 2.1	3.8 2.2	3.9 2.4	4.1 2.6	4.3 2.8	4.5 3.0	4.7 3.3	4.9 3.6	5.1 3.9	5.7 4.3
100 (x trk) (along trk)	1.1 6.2	1.3 6.2	1.4 6.2	3.2 1.8	3.4 1.8	3.5 1.8	3.7 1.8	3.9 2.0	4.0 2.0	3.8 2.0	3.9 2.0	4.0 2.2	4.2 2.4	4.3 2.6	4.5 2.8	4.7 3.0	4.9 3.3	5.1 3.6	5.3 3.9	5.8 4.3
110 (x trk) (along trk)	1.2 6.8	1.4 6.8	1.5 6.9	3.5 1.8	3.6 1.8	3.8 1.9	3.9 1.9	4.1 2.0	4.3 2.0	4.1 2.0	4.2 2.2	4.3 2.3	4.5 2.4	4.7 2.6	4.8 2.8	5.0 3.0	5.2 3.3	5.4 3.6	5.6 3.9	6.0 4.3
120 (x trk) (along trk)	1.3 7.4	1.5 7.5	1.7 7.5	3.8 1.8	3.9 1.8	4.0 1.8	4.2 1.8	4.4 2.0	4.5 2.0	4.3 2.0	4.5 2.2	4.6 2.3	4.8 2.4	4.8 2.6	5.0 2.8	5.2 3.0	5.4 3.3	5.6 3.6	5.8 3.9	6.2 4.3
130 (x trk) (along trk)	1.4 8.1	1.6 8.1	1.8 8.1	4.1 1.8	4.2 1.8	4.3 1.8	4.5 1.8	4.6 2.0	4.8 2.0	4.6 2.0	4.8 2.2	4.9 2.3	5.0 2.4	5.0 2.6	5.2 2.8	5.4 3.0	5.6 3.3	5.8 3.6	6.0 3.9	6.4 4.3
140 (x trk) (along trk)	1.5 8.7	1.7 8.7	1.9 8.7	4.4 1.8	4.5 1.8	4.6 1.8	4.7 1.8	4.9 2.0	5.0 2.0	4.8 2.0	5.0 2.2	5.1 2.3	5.2 2.4	5.2 2.6	5.4 2.8	5.6 3.0	5.8 3.3	6.0 3.6	6.2 3.9	6.6 4.3
150 (x trk) (along trk)	1.6 9.3	1.8 9.3	2.0 9.3	4.7 1.8	4.8 1.8	4.9 1.8	5.0 1.8	5.2 2.0	5.3 2.0	5.1 2.0	5.2 2.2	5.3 2.3	5.4 2.4	5.4 2.6	5.6 2.8	5.8 3.0	6.0 3.3	6.2 3.6	6.4 3.9	6.8 4.3
160 (x trk) (along trk)	1.7 9.9	1.9 9.9	2.1 9.9	5.0 1.8	5.1 1.8	5.2 1.8	5.3 1.8	5.5 2.0	5.6 2.0	5.4 2.0	5.5 2.2	5.6 2.3	5.7 2.4	5.7 2.6	5.9 2.8	6.1 3.0	6.3 3.3	6.5 3.6	6.7 3.9	7.1 4.3
170 (x trk) (along trk)	1.8 10.5	2.0 10.5	2.2 10.5	5.3 1.8	5.4 1.8	5.5 1.8	5.6 1.8	5.8 2.0	5.9 2.0	5.7 2.0	5.8 2.2	5.9 2.3	6.0 2.4	6.0 2.6	6.2 2.8	6.4 3.0	6.6 3.3	6.8 3.6	7.0 3.9	7.4 4.3
180 (x trk) (along trk)	1.9 11.1	2.1 11.1	2.3 11.1	5.6 1.8	5.7 1.8	5.8 1.8	5.9 1.8	6.1 2.0	6.2 2.0	6.0 2.0	6.1 2.2	6.2 2.3	6.3 2.4	6.3 2.6	6.5 2.8	6.7 3.0	6.9 3.3	7.1 3.6	7.3 3.9	7.7 4.3
190 (x trk) (along trk)	2.0 11.7	2.2 11.7	2.4 11.7	5.9 1.8	6.0 1.8	6.1 1.8	6.2 1.8	6.4 2.0	6.5 2.0	6.3 2.0	6.4 2.2	6.5 2.3	6.6 2.4	6.6 2.6	6.8 2.8	7.0 3.0	7.2 3.3	7.4 3.6	7.6 3.9	8.0 4.3
200 (x trk) (along trk)	2.1 12.3	2.3 12.3	2.5 12.3	6.2 1.8	6.3 1.8	6.4 1.8	6.5 1.8	6.7 2.0	6.8 2.0	6.6 2.0	6.7 2.2	6.8 2.3	6.9 2.4	6.9 2.6	7.1 2.8	7.3 3.0	7.5 3.3	7.7 3.6	7.9 3.9	8.3 4.3

TO FIND THE CROSS-TRACK AND ALONG-TRACK ELECTRONIC SYSTEM ERROR (LESS PILOTAGE) AT A POINT, ENTER TABLE WITH PERPENDICULAR DISTANCE AND DISTANCE ALONG TRACK FROM TANGENT POINT, i.e., when the Perp Dist is 30 and the along-track dist is 50, the cross-track error is ± 3.3 NM and the along-track error is 2.5 NM.

PERP DIST

Tangent Pt — ALONG TRACK DIST

ERROR ELEMENTS	
GROUND	
VOR	1.9°
DME	0.1 NM
AIRBORNE	
VOR	3.0°
DME	3% or 0.5 NM
RNAV SYSTEM	0.5 NM
PILOT	ZERO

Source: FAA Advisory Circular 90-45A.

Figure 3-1. VOR/DME/TACAN STATION-REFERENCED AREA NAVIGATION ERROR TABLE (95% PROBABILITY)

distance from the VORTAC as radial distance, Figure 3-1 resolves the distance into two orthogonal components (illustrated at the bottom of the figure). The radial distance is the hypotenuse of the right triangle thus formed.

As an example of how Figure 3-1 is used, consider an aircraft flying along a flight path that is offset from the VORTAC by 30 nm. This offset distance, sometimes referred to as the abeam distance, is defined as the perpendicular distance from the VORTAC to the flight path. At the time of interest, assume that the aircraft is 50 nm from the abeam point, from which the abeam distance to the VORTAC is measured. The block drawn in Figure 3-1 indicates the allowable error associated with an abeam distance of 30 nm and an along-track distance of 50 nm from the abeam point: ±3.3 nm cross-track and 2.5 nm along-track. The allowable error for any distance can be found in this manner.

Table 3-2 summarizes the requirements specified for non-VOR/DME-based two-dimensional (2-D) RNAV systems. All error values correspond to 95-percent confidence levels.

Table 3-2. ALLOWABLE ERROR BUDGETS FOR NON-VOR/DME-BASED RNAV SYSTEMS (NAUTICAL MILES)

Type of Error	Flight Phase Allowable Error Budgets					
	En Route		Terminal		Nonprecision Approach	
	Cross-Track	Along-Track	Cross-Track	Along-Track	Cross-Track	Along-Track
Equipment	1.50	1.50	1.12	1.10	0.33	0.30
Flight technical	2.00	--	1.00	--	0.50	--
Total system error (RSS)	2.50	1.50	1.50	1.10	0.60	0.30

3.3 OPERATIONAL CONSIDERATIONS

Operational requirements for navigation systems have been published in the FRP, Volume II, Section 2.1.1, titled "Aviation Requirements." These requirements are quoted below:

> "A. The system must be suitable for use in all aircraft types which may require the service without unduly limiting the performance characteristics of those aircraft types, e.g., maneuverability and fuel economy.

"B. The system must be safe, reliable, available and capable of providing service over all the used airspace of the world, regardless of time, weather, terrain, and propagation anomalies.

"C. The overall integrity of the system, including the presentation of information in the cockpit, shall be as near 100 percent as is achievable and to the extent feasible should provide flight deck warnings in the event of failure, malfunction, or interruption.

"D. The system must have a capability of recovering from a temporary loss of signal in such a manner that the correct current position will be indicated without the need for complete resetting.

"E. The system must automatically present to the pilot adequate warning in the case of malfunctioning of either the airborne or source portions of the system, and assure ready identification of erroneous information which may result from a malfunctioning of the whole system or incorrect setting.

"F. The system must provide in itself maximum practicable protection against the possibility of input blunder or misinterpretation of output data.

"G. The system must provide adequate means for the pilot to check the accuracy of airborne equipment.

"H. The system must employ navigational information source equipment which automatically and radically changes the character of its indication in case a divergence from accuracy occurs outside safe tolerance.

"I. The system must employ navigational information source equipment which provides immediate and positive indication of malfunction.

"J. The navigational information provided by the system must be free from unresolved ambiguities of operational significance.

"K. Any source-referenced component of the total navigation system shall be capable of providing navigational information simultaneously and instantaneously to all aircraft which require it within the area of coverage.

"L. The navigation system must be capable, in conjunction with other flight instruments, of providing to the pilot in convenient, natural, and rapidly assimilable form in all circumstances, and the appropriate phases of flight, information directly

applicable to the handling of the aircraft, for the purpose of:

1. Continuous track guidance.
2. Continuous determination of distance along track.
3. Continuous determination of position of aircraft, as resolved by the navigation system.
4. Position reporting.
5. Manual or automatic flight.

The system shall also provide for input and utilization of the above in conveniently operable form; and must permit design of indicators and controls which can be directly interpreted or operated by the pilot at his normal station aboard the aircraft.

"M. The system must be capable of being integrated into the overall ATC, communications, and navigation system.

"N. The system should be capable of integration with all phases of flight, including the precision approach and landing system.

"O. The system must permit the pilot to determine the position of the aircraft with an accuracy and frequency such as to ensure that the separation minima used can be maintained at all times, execute accurately the required holding and approach patterns, and to maintain the aircraft within the area allotted to the procedures.

"P. The system must permit the establishment and the servicing of any practical, defined, route structure for the appropriate phases of flight as required.

"Q. The system must have sufficient flexibility to permit changes to be made to the air-route structure and siting of holding patterns without imposing unreasonable inconvenience or cost to the providers and the users of the system.

"R. The system must be capable of providing the information necessary to permit maximum utilization of airports and airspace.

"S. The system must be cost-effective to both government and users.

"T. The system must employ equipment such as to minimize susceptibility to interference from adjacent radio-electronic equipment and shall not cause objectionable interference to any associated or adjacent radio-electronic equipment installation in aircraft or on the ground.

"U. The system must be free from signal fades or signal-to-signal plus noise ratios below which the system cannot operate in the operating area.

"V. The system avionics must be comprised of the minimum number of elements which are simple enough to meet, economically and practically, the most elementary requirements, yet be capable of meeting, by the addition of suitable elements, the most complex requirements.

"W. The system must be capable of furnishing reduced service to aircraft with limited or partially inoperative equipment.

"X. The system must be capable of integration with the flight control system of the aircraft to provide automatic tracking.

"No one set of aviation navigation operational requirements, even though they meet the basic requirement for safety, can adequately reflect the many different combinations of operating conditions encountered in various parts of the world, in that the requirements applicable to the most exacting region may be extravagant when applied to others."

3.4 INSTITUTIONAL CONSIDERATIONS

In addition to the technical and operational considerations, a number of institutional issues will play a major role in determining which mix of navigation systems will be used in the future. Although it is not within the scope of this study to evaluate in detail the influence that institutional issues will have on the selection process, some factors are considered to be significant enough to be discussed briefly.

3.4.1 International Standardization

The United States (and consequently the FAA) is an active participant in the international aviation community as represented by ICAO and other organizations. One function of ICAO is to facilitate international aeronautical activity and cooperation through coordination and recommendation of standardized equipment and procedures. In 1959, ICAO approved VOR/DME as the international standard for aeronautical navigation through 1984. Of the 2,609 VOR/DME facilities that currently exist worldwide, 1,152 are

registered in the ICAO Air Navigation Plans as international navigation aids. An additional 466 international facilities are scheduled for installation according to these plans. Consequently, there is strong international sentiment for maintaining VOR/DME as the international standard at least through 1995 -- a proposal that ICAO has recently adopted. Past experience has demonstrated that a particular type of navigation aid (e.g., Loran-A) continues to be used for 15 years or more after its official protection ceases. This being the case, it could be assumed that VOR/DME will continue to be used worldwide into the year 2010.

ICAO has no plans, formal or informal, to endorse either Loran-C, Omega, or GPS as an alternate or replacement international standard aeronautical navigation aid. Loran-C coverage areas are unlikely to extend beyond what is currently planned, which still excludes the southern hemisphere. Omega already provides essentially worldwide coverage, and the necessary international agreements for maintenance and operation of the transmitting stations have been negotiated and accepted. GPS is currently a United States military-sponsored satellite navigation system; its implementation does not require international cooperation other than for frequency allocation.

One of the central issues concerning international, and frequently domestic, endorsement of a particular navigation system standard involves the responsibility of control. The organization that controls the system can theoretically limit access to the system. Because VOR/DME, Loran-C, and, to some extent, Omega are systems where the control responsibility is distributed among many nations and organizations, they will likely remain available to all users of all nations. GPS, however, is a system that inherently requires centralized control. This control will have to be vested in either a single country or an international organization. If the former occurs, international support is likely to be difficult to obtain. If the latter occurs, the system may become unappealing to its most prominent supporters in the United States, and its acceptance may be delayed while institutional arrangements are prepared for international GPS management.

Intertwined closely with the issue of system control is allocation of operation and maintenance responsibility and cost. The distributed regional systems such as VOR/DME and Loran-C are well suited for the international environment, since the using, controlling, operating, and maintenance functions are typically the responsibilities of the country in which the facilities are located. Omega also presents no difficulties in this context, because the operational and maintenance considerations have already been agreed to by treaty. GPS, however, is likely to encounter significant institutional difficulties in allocation of operation and maintenance responsibility and cost.

3.4.2 Transitional Impact

National governments as well as the various user communities have significant capital investments in the existing VOR/DME-based navigation system. These investments must be protected over an extended period of time while any new system is being phased in, to allow for full amortization

of the old system. The institutional difficulties of effectively maintaining standards for two navigation systems over a period of possibly 15 to 20 years may be so cumbersome and uneconomical as to force retention of the VOR/DME system until the successor system can have a guaranteed useful life of at least 30 to 50 years.

3.4.3 Special Interest Groups

The acceptability and desirability of any single navigation system or combination of systems will ultimately be determined by the user community, either directly or indirectly. For example, the airlines provide the impetus for the application of Omega to en-route navigation in the continental United States, offshore oil prospectors generate the market for Loran-C, and private pilots continue to provide demand for VOR/DME. User preferences are evidenced through public statements of trade associations and, more important, through equipment purchases.

3.5 ECONOMIC CONSIDERATIONS

Both the Government, as the provider of navigation capability, and the user, as the purchaser of equipment for aircraft, are concerned about the life-cycle cost of the navigation system or combination of systems selected for future use. Consequently, numerous cost analyses have been performed for alternative navigation scenarios. The following two reports have quantified the total Government and user life-cycle costs of various navigation system combinations:

- *Economic Requirements Analysis of Civil Air Navigation Alternatives*, Reference 29
- *Economic Analysis of Future Civil Air Navigation Systems*, Reference 30

In broad terms, these studies have concluded that neither Loran-C, GPS, nor Omega can compete in cost with the single VOR receiver for low-budget aviation. However, if area navigation becomes the standard of the air traffic control system, the specific combination of systems used will have relatively little cost impact as long as the existing user capital investment in VOR/DME is utilized concurrently with any newly introduced system (e.g., VOR/DME with Loran-C or VOR/DME with GPS). If the existing VOR/DME network is discarded in favor of a totally new navigation concept such as GPS, the cost to retrofit all existing aircraft with the new navigation equipment will exact a significant cost penalty from the users, as compared with the other approaches. The quantitative conclusions of these two reports are summarized in Table 3-3.

Table 3-3. LIFE-CYCLE-COST COMPARISONS OF NAVIGATION SYSTEMS

Navigation System(s) Used	Total Life-Cycle Cost to U.S. Government and Users Normalized to Baseline	
	SCI*	MITRE Corp.**
VOR/DME (RNAV not required) in U.S.; Omega for global navigation	1.00 (baseline)	1.00 (baseline)
VOR/DME with Loran-C (RNAV required) in U.S.; Omega for global navigation	Not Studied	1.13
VOR without DME (RNAV not required) in U.S.; GPS for RNAV and global navigation	1.20	1.08
RNAV Loran-C in U.S.; Omega for global navigation	1.20	1.24
RNAV GPS -- both in U.S. and for global navigation	1.40	1.40

*Systems Control, Inc., *Economic Requirements Analysis of Civil Air Navigation Alternatives*, Reference 29.
**MITRE Corp., *Economic Analysis of Future Civil Air Navigation Systems*, Reference 30.

CHAPTER FOUR

TECHNICAL EVALUATION OF NAVIGATION SYSTEMS

4.1 OVERVIEW

The technical performance of a navigation system is strongly influenced by the properties of the received signal as well as the techniques used by the airborne receiver in processing the signals. Significant signal properties include stability, coverage, and availability. Signal acquisition and tracking continuity depend on both signal and receiver characteristics.

Accuracy of hyperbolic radionavigation systems such as Loran-C and Omega is primarily dependent on the accuracy and precision with which time or phase differences can be measured. When ranging techniques are used for Loran-C and Omega navigation, achievable accuracy is a function of the time synchronization of the transmitters, user clock biases, accuracy of propagation modeling, and the geometry of the user's position in relation to the transmitting stations.

Accuracy of VOR/DME is primarily influenced by the inaccuracies of VOR. The dominant VOR errors are caused by multipath effects. Multipath signals are caused by reflecting objects near the transmitter that scatter the original signal. These multipath signals create distortions in the desired signal resulting from different paths being simultaneously traveled by the signal between transmitter and receiver. The result is scalloping in the VOR bearing indications.

Accuracy of the space-based GPS radionavigation concept depends on accurate and continuous knowledge of the spatial position of each satellite in the system with respect to time and distance from the user.

Accuracy of Doppler navigation systems degrades as a function of the distance traveled from a known position. The accuracy capability is mainly dependent on the accuracy of the heading reference used.

Accuracy of conventional and strapdown INS degrades as a function of time. The accuracy is principally influenced by accumulated gyro drift.

Although compliance of a navigation system with technical performance requirements such as accuracy is necessary, it is not a sufficient condition for acceptability. Also important are operational considerations relating to the ability of the system to interact with the pilot and ATC to meet and maintain operational standards of safety and accuracy. The summary of features of typical navigation units presented in Table 2-1 provides an indication of the operational compatibility of various navigation systems in terms of the system-user interface. The following sections present the technical capabilities of each system in terms of an error budget.

4.2 ERROR BUDGET FOR LORAN-C

The error budget for Loran-C is broadly divisible into five categories as follows:

- Transmitter errors
- Signal detection errors
- Receiver clock errors
- Signal propagation variations
- Position fix calculation errors

Table 4-1 presents a summary of the effect of specific errors on the navigational accuracy of various Loran-C system use categories. As the table shows, inaccurate prediction of signal propagation variations is the main contributor to the total RSS system accuracy, excluding flight technical error. Although it may appear that hyperbolic navigation is more accurate than either rho-rho or rho-rho-rho navigation, that is not the case in an operational environment. When user distance from a Loran-C baseline is large in relation to the length of the baseline, the user is in a high GDOP situation. The relatively short baselines of Loran-C chains result in typical GDOPs of two to four when hyperbolic navigation is used. Use of rho-rho or rho-rho-rho techniques effectively eliminates GDOP considerations. Each error source is discussed in the following sections.

4.2.1 Transmitter Errors

Loran-C receivers presume that the received signal originated at a particular instant at a specific location. Jitters in the timing of the Loran-C pulse or errors in transmitter location are interpreted by the receiver as variations in signal propagation time. These propagation variations in turn directly translate into position fix errors. The errors presented are based on an assumed signal propagation velocity of 161,829 nm/sec.

4.2.1.1 Timing Error

Loran-C transmitters are synchronized with each other via extremely accurate internal atomic clocks and information from various monitor

Table 4-1. **POSITION ERROR BUDGET SUMMARY FOR LORAN-C**

Source of Error	Effect of Error (±nm) on Navigation System Use		
	Hyperbolic	Rho-Rho	Rho-Rho-Rho
Transmitter Errors			
Timing	0.03	0.03	0.03
Location	8×10^{-4}	8×10^{-4}	8×10^{-4}
Signal Detection Errors			
Zero crossing detection	2.4×10^{-3}	2.4×10^{-3}	2.4×10^{-3}
Phase comparison quantization	3×10^{-3}	3×10^{-3}	3×10^{-3}
Cycle jump*	1.62	1.62	1.62
Receiver Clock Errors**			
Initialization	Negligible	0.06	0.06
Drift	1.3×10^{-6}	3×10^{-3}†	1.3×10^{-6}
Signal Propagation Variations			
Prediction	0.06	0.06	0.06
Random*	0.01	0.01	0.01
Position Fix Calculation Errors*			
Earth model	0.2	0.2	0.2
Dead reckoning	5.5×10^{-4}	5.5×10^{-4}	5.5×10^{-4}
Total System Position Error (RSS 2 drms)			
GDOP = 1	0.07	0.09	0.09
GDOP = 4	0.28	--	--

*Excluded from RSS calculation.
**Quartz clock unless otherwise noted.
†Rubidium clock or better.

stations. The most critical types of timing errors include lack of proper signal phase or envelope coherence among stations, as follows:

- Master station timing error
- Master-slave timing error
- Slave-slave timing error
- Chain-chain timing error

The United States Coast Guard, which operates the Loran-C system in the United States, has specified the following four operational modes for transmitters:*

- "Optimum - achieved 95% of the time; full power - timing precision of ± 40 η seconds;
- "Precision - achieved 97% of the time; half power - timing precision of ± 40 η seconds;
- "Enhanced - achieved 98.6% of the time; full power - timing precision of ± 200 η seconds; and
- "Standard - achieved 99.7% of the time; half power - timing precision of ± 200 η seconds."

For this discussion, the standard operating mode is used to determine transmitter errors. Therefore, the sum of all timing errors within the transmitters is assumed to be less than ±200 nanoseconds (ns), corresponding with a propagation distance error of ±0.03 nm (±55.6 meters).

4.2.1.2 Station Location Error

Published locations of Loran-C stations are accurate to 0.1 arc second. Any variation of actual signal origin from these published position coordinates is reflected directly into an erroneous range measurement from the station. An accuracy of 0.1 arc second is the same as an error of ±0.05 arc second, which corresponds to a position fix error of $\pm 8 \times 10^{-4}$ nm (±1.5 meters) when assuming 60 nm/deg.

4.2.2 Signal Detection Errors

Each Loran-C pulse contains 20 cycles of radio frequency (RF) energy and exhibits a slowly rising and decaying amplitude envelope shaped much like a teardrop. The energy contained in the first two cycles of the pulse is insufficient for a good signal-to-noise ratio measurement. The fourth cycle is likely to be contaminated by sky waves. Therefore, receivers typically are designed to measure pulse arrival at the third cycle. The most accurate technique for measuring time of signal arrival is to detect the third pulse zero crossing and compare that time to a local oscillator. The exact time is measured in terms of a phase relationship between the local oscillator and the received signal. The following sections describe the three sources of error that contribute to Loran-C position uncertainty.

4.2.2.1 Zero Crossing Detection Error

The zero crossing is derived by comparing the squared-off Loran RF signal with the local oscillator clock. The squared-off Loran signal is derived by means of such a device as a saturating amplifier. There is

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*A Comparative Analysis of Area Navigation Systems in General Aviation, Reference 28.

approximately 1 degree of error in identifying the precise moment of zero crossing. This 1-degree error in a 100-kHz signal corresponds to 0.03 microsecond, or a propagation distance error of $\pm 2.4 \times 10^{-3}$ nm (±4.4 meters).

4.2.2.2 Phase Comparison Quantization Error

The phase difference between the local oscillator and the received Loran pulse is usually measured with a digital counter that runs several times faster than the basic RF carrier rate of 100 kHz. Current engineering designs typically provide resolution of 40 ns (±20 ns error), corresponding to a propagation distance error of $\pm 3 \times 10^{-3}$ nm (±5.6 meters).

4.2.2.3 Cycle Jump Error

Under certain atmospheric propagation conditions, differences between the phase and group velocities in the RF signal affect the shape of the Loran-C pulse so that it is distorted by the time it reaches the receiver. This pulse distortion may deceive the receiver into miscounting the true cycle crossings and thus locking onto the second or fourth cycle of the Loran pulse. This phenomenon is called cycle jump. Most Loran receivers have special circuitry and logic to prevent this from happening and to warn the operator if it does occur. The position error introduced by cycle jump is the equivalent propagation time of one Loran-C cycle, or 10 microseconds, corresponding to a propagation distance error of ± 1.62 nm.

4.2.3 Receiver Clock Errors

There are two types of clock errors. The first type is a function of initial synchronization, and the second is a function of stability.

4.2.3.1 Clock Initialization Error

In the hyperbolic mode, clock initialization errors have minimal effect on position accuracy, because only the time difference between incoming signals is measured, resulting in the cancellation of initialization errors. In the ranging mode, initialization errors are significant, because they add a constant error to the position fix. The accuracy of the initial clock synchronization is limited by knowledge of the exact distance from the receiver at the time of initialization, knowledge of the propagation characteristics at the time of initialization, and the receiver's signal detection accuracy at the time of initialization. These different types of error are presented in Table 4-2.

4.2.3.2 Clock Drift Error

If the local oscillator is unstable and drifts in relation to the transmitter clocks, the airborne system perceives the drift as a shift in time difference and computes an erroneous position.

Table 4-2. RECEIVER INITIALIZATION ERRORS			
Source of Error	Derivation	Report Section	Magnitude (±nm)
Range from transmitter	Limitation of accuracy of transmitter and receiver locations to ±0.05 arc second	4.2.1.2	8×10^{-4}
Propagation	Errors in prediction	4.2.4	0.06
Signal detection	Phase comparison quantization	4.2.2	3×10^{-3}

In the hyperbolic mode, only short-term clock stability is important. With a quartz crystal clock, drift is about 1.7×10^{-11} seconds for a representative measurement interval of 0.05 seconds. This drift corresponds to a propagation distance error of $\pm 1.3 \times 10^{-6}$ nm (±0.002 meters).

In the rho-rho mode, the clock is free-running during each leg of the flight and thus may not be resynchronized for two to six hours. During a six-hour flight, a quartz clock may drift 7.2 microseconds, corresponding to a propagation distance error of ±0.6 nm. A rubidium clock is more stable and will reduce this error to 3.6×10^{-8} seconds, or $\pm 3 \times 10^{-3}$ nm (±5.6 meters).

In the rho-rho-rho mode, a third Loran-C station is used to estimate and compensate for the error resulting from clock drift. Therefore, the effect of drift will be minimal for any high-quality clock used in the receiver.

4.2.4 Signal Propagation Variations

Accurate modeling of the propagation characteristics of the Loran-C signal enhances the accuracy of the system. Differences in propagation characteristics between the model and the received signal result from errors in predictive modeling and the occurrence of random, non-predictable variations in signal propagation.

4.2.4.1 Prediction Error

The propagation velocity of electromagnetic waves varies slightly as a function of the medium through which the waves are passing. For Loran-C, the characteristics of the medium depend on surface effects and atmospheric conditions. Surface effects are important, because Loran-C receivers derive range information from ground waves traveling along the surface of the earth. Propagation models that assume that the ground waves travel over water will introduce position errors when used over land. The uncertainty in determining the correct propagation velocity from the transmitter to the user is called prediction error. Estimates of the magnitude of

prediction error are typically around ±0.4 microsecond, corresponding to a propagation distance error of ±0.06 nm (±111.1 meters). Those Loran-C units that store propagation corrections to account for the land/sea shift minimize this error.

4.2.4.2 Random Error

Many sources of error in signal propagation cannot be adequately predicted. Their effect on position accuracy is primarily a function of the limit of signal detection possible, as a consequence of noise. The operational limit of most radionavigation systems, including Loran-C, is determined by the signal-to-noise ratio (SNR) at which the receiver must operate. Analyses have shown that the unpredictable error in an excellent SNR environment (1:1) is about 0.05 microsecond, or $\pm 4 \times 10^{-3}$ nm. In a typical SNR environment (1:3), unpredictable errors increase to a value of about 0.14 microsecond, corresponding to a propagation distance error of ±0.01 nm (±18.52 meters).

4.2.5 Position Fix Calculation Errors

The ability of Loran-C units to determine geographical position is dependent on the accuracy with which the unit converts transmitter-to-user range information to earth coordinates. Inaccuracies in the interpretation of the range measurements, due either to the effects of sudden changes to the input or improper earth modeling, will degrade position fix accuracy.

4.2.5.1 Earth Model

Once the range from the Loran-C transmitter has been determined, the geographical position of the user is computed on the basis of a mathematical model of the earth. Position fix errors resulting from the lack of agreement between earth models can be as great as ±0.2 nm (±370.4 meters).

4.2.5.2 Dead Reckoning

Initiation of a maneuver or a sudden change in the wind vector introduces an error rate of 5.5×10^{-3} nm per second (based on an along-track wind change of 20 knots), which decays to zero as the tracking loop of the receiver compensates for the change in dynamics during successive update cycles. Between 0.1-second measurement updates of Loran-C, an error of 5.5×10^{-3} nm per second results in a position fix error of 5.5×10^{-4} nm (±1.0 meters).

4.2.6 Total System Position Error

The individual error contributions are combined in RSS fashion to compute the total system position errors (2 drms) for hyperbolic, rho-rho, and rho-rho-rho implementations. The RSS totals corresponding to a GDOP of 1 assume best geometry conditions. A typical total error corresponding to a GDOP of 4 is also shown in Table 4-1 for hyperbolic navigation. It is assumed that a GDOP of 1 can be achieved under most conditions when rho-rho or rho-rho-rho navigation is used with Loran-C.

4.3 ERROR BUDGET FOR OMEGA

Errors for Omega are divided into the same five categories as defined for Loran-C:

- Transmitter errors
- Signal detection errors
- Receiver clock errors
- Signal propagation variations
- Position fix calculation errors

A summary of the effect of these errors on Omega navigation accuracy is presented in Table 4-3. As the table shows, propagation modeling errors overwhelmingly predominate and limit the overall accuracy of position fixing. The baselines between Omega transmitters are much longer than those for Loran-C; therefore, the typical GDOP associated with Omega hyperbolic navigation is 2, whereas it is 4 with Loran-C. The errors are discussed in the following sections.

4.3.1 Transmitter Timing Errors

Since the Omega system assumes perfectly synchronized and phase-locked VLF radio transmissions, any jitter will result in an erroneous position fix. The eight Omega transmitters are phase-locked by means of monitor stations and use very accurate atomic clocks at each station for frequency standards. Timing errors between stations are limited to 1 microsecond, corresponding to a propagation distance error of ±0.08 nm (±148.2 meters).

4.3.2 Signal Detection Errors

Position fixing for Omega in the hyperbolic mode requires comparison of the phase values of the received signals from several transmitting stations. In the ranging mode, the phase of the received signals is measured directly and not compared. Errors in phase detection and phase measurement quantization are described in the following sections.

4.3.2.1 Zero Crossing Detection Error

The phase of the Omega signal is measured by hard-limiting the signal and comparing signal zero crossing with reference clock zero crossing. The time difference between the two is converted to phase value.

Assuming a saturation ratio of 10:1, the transition from one limit to the other will take nearly 12 degrees ($2 \times \sin^{-1}$ [0.1] for a sinusoidal Omega signal). With 100:1 saturation, the transition is 1 degree. A 1-degree phase detection error corresponds to a position fix error of ±0.02 nm (±37.0 meters). (At an Omega frequency of 10.2 kHz, 16 nm corresponds to 360 degrees).

Table 4-3. **POSITION ERROR BUDGET SUMMARY FOR OMEGA**

Source of Error	Effect of Error (±nm) on Navigation System Use		
	Hyperbolic	Rho-Rho	Rho-Rho-Rho
Transmitter Timing Errors	0.08	0.08	0.08
Signal Detection Errors			
Zero crossing detection	0.02	0.02	0.02
Phase measurement quantization	0.04	0.04	0.04
Receiver Clock Errors*			
Initialization	Negligible	0.02	0.02
Drift	1.25×10^{-4}	0.005**	2.5×10^{-4}
Signal Propagation Variations			
Prediction	1.6	1.6	1.6
Random†	2.5	2.5	2.5
Position Fix Calculation Errors†			
Earth model	0.2	0.2	0.2
Dead reckoning	0.028	0.028	0.028
Total System Position Error (RSS 2 drms)			
GDOP = 1	1.6	1.6	1.6
GDOP = 2	3.2	--	--

*Quartz clock unless otherwise noted.
**Rubidium clock or better.
†Excluded from RSS calculation.

4.3.2.2 Phase Measurement Quantization Error

Omega receivers using hyperbolic techniques typically quantize phase in units of 1/100 of a phase-difference cycle (centicycle). Resolution accuracy along the baseline at a frequency of 10.2 kHz is therefore 0.08 nm, or ±0.04 nm (±74.1 meters).

4.3.3 Receiver Clock Errors

As with Loran-C, there are two types of clock errors for Omega. The first type is a function of initial synchronization, and the second is a function of stability.

4.3.3.1 Clock Initialization Error

In the hyperbolic mode, clock initialization errors have minimal effect on position accuracy, because only the phase difference between incoming signals is measured, resulting in the cancellation of initialization errors.

In the rho-rho mode, initialization errors are significant, because they add a constant error to the position fix. The clock is initialized by the use of either the four Omega navigation frequencies or differences between these frequencies. Frequency differences are used to resolve initial lane ambiguity. Nondifferenced frequencies subsequently are used for final correction of clock error.

If exact position and propagation characteristics are known at the time of initialization, and if the clock synchronization circuits provide comparable performance to the phase detection circuits, phase ambiguity of 1 degree can be expected in clock synchronization. This ambiguity corresponds to a position fix error of ±0.02 nm (±37.0 meters).

4.3.3.2 Clock Drift Error

If the local oscillator is unstable and drifts in relation to the transmitter clocks, the system perceives this drift as a phase shift and computes an erroneous position. Table 4-4 summarizes the effect of clock drift on navigation accuracy for different types of clocks.

The magnitude of position error is related to the elapsed time between independent measurements that enable timing synchronization. In a hyperbolic implementation, the elapsed time between phase measurements of the same frequency, but from two signals, is constant, although the value is dependent on which Omega station combinations are being tracked. It is therefore possible to synchronize the clock in accordance with this elapsed time. An elapsed time of five seconds is used in Table 4-4 to represent a worst-case station combination. For such short time intervals between timing synchronizations, the clock need have only good short-term stability. In fact, the effect of drift is minimal if any high-quality clock is used in the Omega receiver.

In the rho-rho mode, in which phase comparisons that allow timing synchronization are not utilized, the clock is free-running during each leg of the flight and thus may possibly not be resynchronized for two to six hours. Because of this extended operating period, clocks that are typically used are not stable enough to provide accurate rho-rho navigation over extended time periods.

Table 4-4. ESTIMATE OF CLOCK STABILITY EFFECTS ON POSITION ERROR FOR OMEGA NAVIGATION

Clock Type	Short-Term Stability*	Position Error (nm)		
		Hyperbolic (5-Second Period)	Rho-Rho (6-Hour Period)	Rho-Rho-Rho (10-Second Period)
Quartz	3×10^{9}	2.5×10^{-4}	1.8	5×10^{-4}
Rubidium	6×10^{11}	1.5×10^{-6}	1×10^{-2}	3×10^{-6}
Cesium	5×10^{12}	1.5×10^{-7}	1×10^{-3}	3×10^{-7}
Hydrogen Maser	1×10^{14}	1×10^{-8}	7×10^{-5}	2×10^{-8}

*Short-term stability is expressed as one part per the value given. By dividing the time period of interest by the short-term stability value and then multiplying the result by the speed of light, the position error is determined.

In the rho-rho-rho mode, a third Omega station is used to estimate and compensate for the error resulting from clock drift. This readjustment occurs every 10 seconds. Therefore, the effect of drift will be minimal for any high-quality clock used in the receiver.

4.3.4 Signal Propagation Variations

The accuracy of Omega is limited by the accuracy of the propagation corrections that are applied to the received signal. The corrections are developed on the basis of predicted signal behavior. Random, nonpredictable variations in signal propagation introduce errors that compound those inherent in the predictive modeling of signal propagation.

4.3.4.1 Prediction Error

Estimates of the error due to propagation modeling range from 3.2 to 8 nm. For this analysis, 3.2 nm, specified as ±1.6 nm, is assumed to be a typical propagation prediction error.

4.3.4.2 Random Error

Many influences on signal propagation that occur infrequently cannot be predicted -- for example: sudden phase anomalies (SPAs), produced by sudden ionospheric disturbances (SIDs); and polar cap absorption (PCA) events, caused by the concentration of solar protons in the vicinity of the earth's magnetic poles. These anomalies can cause position errors of 2 to 8 nm -- an average error of 5 nm.

4.3.5 Position Fix Calculation Errors

Geographical position is determined by converting to geographical coordinates the position of the user relative to the Omega stations, as determined by the receiver. This position fixing process is susceptible to errors in earth modeling and uncertainty in assumed position as a function of dynamic response to sudden changes in input.

4.3.5.1 Earth Model

As in Loran-C navigation, Omega navigation requires the use of a mathematical model of the earth. The possibility of a position fix error of ±0.2 nm is used in this analysis.

4.3.5.2 Dead Reckoning

If an error rate of $\pm 5.5 \times 10^{-3}$ nm per second is used (based on an along-track wind change of ±20 knots), a 5-second dead-reckoning period before the first update will result in a position fix error of ±0.028 nm. Some Omega/VLF units use processing techniques that reduce the period of dead reckoning. By processing the VLF signals in parallel rather than in series with the Omega signals, a more continuous update capability can be achieved.

4.3.6 Total System Position Error

The individual effects of the various sources of error are combined in RSS fashion to determine the total system position error (2 drms) for Omega. RSS totals corresponding to a GDOP of 1 are given in Table 4-3 for hyperbolic, rho-rho, and rho-rho-rho implementations. A typical total error corresponding to a GDOP of 2 is also shown for hyperbolic navigation. As discussed for Loran-C, when ranging techniques are used, it is assumed that a GDOP of 1 can also be achieved by Omega when supplemented with VLF.

4.4 ERROR BUDGET FOR VOR/DME

Errors for VOR/DME are divided into the following categories:

- Bearing error components
  - Ground component radial error
  - Airborne component radial error
  - Course selection error
- Distance measurement errors
  - Ground component distance error
  - Airborne component distance error
- Area navigation computation error
- Total system error

Table 4-5 summarizes the effect of specific errors on navigation accuracy for the VOR/DME navigation system use categories. Each error source is discussed in detail in the following sections.

Table 4-5. ERROR BUDGET SUMMARY FOR VOR/DME*

Source of Error	Effect of Error on Navigation System Use	
	Basic VOR/DME	RNAV VOR/DME
Bearing Errors		
Ground component	±1.4°	±1.4°
Airborne component	±3.0° (±1.0°**)	±3.0° (±1.0°**)
Course selection	±2.0° (±0.5°**)	±2.0° (±0.5°**)
Distance Errors		
Ground component	±0.1 nm	±0.1 nm
Airborne component	Between 0.1 nm and 1% of range	Between 0.1 nm and 1% of range
Area Navigation Computation Error	Not applicable	±0.5 nm
Total System Error (RSS 2σ)		
Radial	±3.9° (±1.8°**)	±3.9° ± 0.5 nm (±1.8° ± 0.5 nm**)
Distance	Between 0.5 nm (0.1 nm**) and 3% (1%**) of range	Between 0.5 nm (0.1 nm**) and 3% (1%**) of range

*All values reflect the proposed FAA standard for VOR, DME, and TACAN, unless otherwise noted.
**Obtainable.

4.4.1 Bearing Error Components

Some of the errors listed in the VOR/DME error budget can be attributed directly either to the VOR or DME element of the system. Bearing error reflects the error introduced specifically through use of VOR. The three individual components contributing to bearing error are described in the following sections.

4.4.1.1 Ground Component Radial Error (E_{gr})

Radial signal error is the difference between the nominal magnetic bearing from the VOR transmitter to a point of measurement and the bearing indicated by the signal at the same measurement point. Ground component radial error consists of (1) certain constant elements, such as course displacement errors and most site and terrain effect errors, which may be considered fixed for long periods of time, and (2) certain random variable errors that can be expected to vary about the essentially constant value. The ground component radial error is associated with the VOR transmitter and nominal signal path errors, but excludes other error factors.

Siting and propagation errors are the principal VOR signal errors. Alignment of electronic radials with magnetic radials, and deviations of signal because of roughness, scalloping, multipath effects, signal bending, and refraction, are mostly uncontrollable factors that contribute significantly to siting errors. Signal propagation variations in the atmosphere have been demonstrated to contribute to a course error of 0.2 degree.

Extensive data collection by the FAA indicates an E_{gr} error value of ±1.4 degrees (95 percent probability).

4.4.1.2 Airborne Component Radial Error (E_{ar})

Airborne component radial error is the error attributable to the inability of the airborne equipment to translate correctly the bearing information contained in the radial signal. This element embraces all factors in the airborne component that introduce errors in the information presented to the pilot. (Errors resulting from the use of compass information in some VOR and TACAN displays are not included.)

An E_{ar} value of ±3.0 degrees (95 percent probability) was used in defining the national aviation standard for the VORTAC system. The use of digital signal processing has reduced this error to a range between ±0.75 and ±2 degrees, according to various equipment manufacturers. A value of ±1 degree is specified in Table 4-5 as obtainable.

4.4.1.3 Course Selection Error (CSE)

Course selection error (CSE) is the accuracy limitation of the omnibearing selector (OBS) resulting from the resolution of the device and the error inherent in translating the pilot input to the avionic comparator. This comparator derives the difference between the actual computed course and the selected course entered by the pilot. This difference is usually displayed on a course deviation indicator (CDI). Errors of the CDI are considered to be part of E_{ar}.

A requirement of ±2.0 degrees for CSE was established on the basis of accuracies achievable with analog dials. The advent of digital processing and displays permits pilots to set a desired course to within the precision made available, either whole degrees, tenths of a degree, or better. In this analysis, ±0.5 degrees will be assumed achievable.

4.4.2 Distance Measurement Errors

Distance measurement errors reflect the errors introduced specifically through use of DME. The two components contributing to distance measurement errors are described in the following sections.

4.4.2.1 Ground Component Distance Error (E_{gd})

According to current requirements, ground component range accuracy must be maintained to within 0.1 nm.

4.4.2.2 Airborne Component Distance Error (E_{ad})

The airborne DME unit measures and displays the slant range distance between the aircraft and the ground station. The accuracy of this information must be maintained to within 3 percent of the actual distance, or ±0.5 nm, whichever is greater. The digital revolution has markedly improved the accuracy of airborne DMEs beyond standard requirements. Manufacturers commonly quote airborne equipment accuracy of ±0.1 nm to 1 percent of DME distance for general aviation equipment.

4.4.3 Area Navigation Computation Error (E_c)

When RNAV computation is used, an additional error contribution is specified and combined with the basic VOR/DME system error. The additional maximum RNAV equipment error allowed, per FAA AC 90-45A, is ±0.5 nm.

Computation error includes error components contributed (1) by any input, output, or signal conversion equipment used, (2) by any computing element used, (3) by the display as it presents either aircraft position or guidance commands (e.g., course deviation or command heading), and (4) by any course definition entry devices used. For systems in which charts are incorporated as integral parts of the display, E_c necessarily includes charting errors to the extent that these errors actually result in errors in controlling the position of the aircraft in relation to a desired path over the ground. To be consistent, for symbolic displays not employing integral charts, any errors in waypoint definition directly attributable to errors in reference charts used in determining waypoint positions should be included as components of E_c. This type of error is difficult to quantify; in general practice, highly accurate published waypoint locations are used to the greatest extent possible to avoid charting errors (and to reduce workload).

4.4.4 Total System Error (E_s)

Assuming that the variable errors from various sources discussed are normally distributed and independent, the error components are combined in RSS fashion as follows:

$$\text{System radial error } (E_{sr}) = \sqrt{E_{gr}^2 + E_{ar}^2 + CSE^2 + FTE^2 + E_c^2}$$

$$\text{System distance error } (E_{sd}) = \sqrt{E_{gd}^2 + E_{ad}^2}$$

4.5 ERROR BUDGET FOR GPS

GPS errors are divided into the following categories:

- Satellite errors
- Signal propagation variations
- Receiver errors

These errors directly affect the range measurements from each visible satellite. User position is determined by the processing of independent range measurements.

Two levels of accuracy are provided by NAVSTAR GPS, corresponding to two different signal codes -- the precision code (P-code) and the less accurate coarse/acquisition (C/A) code. The range error budget for GPS, summarized in Table 4-6, reflects error magnitudes relevant to use of the C/A code only, since that is the only code to be made available for civil aviation applications. Position error is a function of the combined effects of the errors arising from each range measurement.

Although the results shown in Table 4-6 are of interest, they are not necessarily indicative of the position fix accuracy that a civilian GPS user can expect when GPS becomes fully operational. The denial of accuracy that may be imposed by the Department of Defense will result in a degraded capability of determining position, possibly to a 2-drms accuracy of no better than 500 meters (0.27 nm).

The individual range error sources are discussed in the following sections.

4.5.1 Satellite Errors

The satellites are the source of the GPS navigation signals. Range from a satellite is determined on the basis of time measurements. The satellite clock provides the standard against which time intervals are measured. Satellite position is computed from the ephemeris parameters transmitted in the GPS signal. Perturbations in the orbit of a satellite will cause a position deviation relative to the ephemeris data. The effect on position accuracy of errors associated with the satellites is described in the following sections.

4.5.1.1 Clock Error

The rubidium clocks currently used in the satellites are periodically updated by the ground control facility to maintain an accuracy better than 1 meter (1σ).

Table 4-6. RANGE ERROR BUDGET SUMMARY FOR UNRESTRICTED GPS (C/A CODE)	
Source of Error	**Effect of Error (in Meters) on Navigation System Use**
Satellite Errors	
Clock	1.0
Ephemeris	1.5
Orbital perturbation	1.5
Signal Propagation Variations	
Atmospheric delay	3
Multipath	20
Receiver Errors	
Measurement noise	10.5
Range quantization	2.66
Navigation algorithm	1.0
Total System Range Error (RSS)	
1σ	23.1 (0.01 nm)
2 drms	46.2 (0.025 nm)

4.5.1.2 Ephemeris Error

Each satellite transmits its position to a user receiver in the form of predicted ephemeris data. Errors in the ephemeris translate into position fix errors. Techniques for charting the ephemeris are believed to be accurate to within 1.5 meters (1σ).

4.5.1.3 Orbital Perturbation Error

Influences such as variations in the earth's gravity gradient cause space vehicle perturbations. Such perturbations are projected to be 1.5 meters (1σ).

4.5.2 Signal Propagation Variations

The GPS signal propagates from the satellite to the user through several mediums, including a vacuum and an anisotrophic atmosphere. Consequently, the propagation velocity varies as the signal passes through the ionosphere and troposphere and may experience multipath effects from reflection and refraction at various boundary layers and from objects near the receiver. The uncertainty inherent in the modeling of these propagation characteristics contributes to the range error budget for GPS.

4.5.2.1 Atmospheric Delay Error

The time delay of the GPS signal passing through the ionosphere can be compensated for by one of two techniques. The first and most accurate means of calculating the delay involves comparing two frequencies of signal transmission, exploiting the fact that the overall delay is nearly inversely proportional to the square of the frequency. When dual-frequency measurements are not available, as is the case for the C/A signal, a second technique, modeling, provides the only means of compensation. The magnitude of the error depends on time of day, solar activity, geomagnetic latitude, and other factors, which result in uncertainties of 1 to 30 meters. On the basis of projections of recent studies, an average value of 3 meters seems reasonable.

4.5.2.2 Multipath Error

The effects of multipath cannot be characterized through modeling, because the creation of multipath signals depends on the nature and location of reflective objects in relation to the receiver antenna. The magnitude of multipath errors has been estimated to be between 1.2 and 2.7 meters (1σ) for P-code operation. The degree of signal interference due to multipath effects is inversely proportional to the code rate used. Since the code rate of the C/A signal is one-tenth that of the P-code, the multipath errors corresponding to the C/A code would be between 12 and 27 meters. For this study, an average magnitude of 20 meters is used.

4.5.3 Receiver Errors

In processing the received signal, the GPS receiver contributes to position fix error through suboptimal code lock-on caused by noise in the signal, internal accuracy limitations resulting from quantization effects, and inaccuracies inherent in the navigation solution.

4.5.3.1 Measurement Noise Error

The ability to determine GPS range accurately from a signal measurement depends on both the modulation of the selected code and the signal quality. In a signal environment characterized by a carrier-to-noise density ratio (C/N_o) of 30 db-Hz, a code measurement error of 10.5 meters (1σ) has been projected for C/A code operation. This level of accuracy degrades rapidly as the C/N_o worsens (approximately 22 meters at C/N_o = 25 dB-Hz), imposing a requirement for external inputs when the C/N_o falls below 20 dB-Hz. The addition of an external input, such as velocity, to the GPS position measurement process does not improve the accuracy of the GPS signals, but enhances the ability of the navigation algorithm to determine position.

4.5.3.2 Range Quantization Error

The user receiver generates replicas of the C/A codes and cross-correlates these locally generated signals with the signals received from the satellites. A tracking loop is used to establish synchronization

between the two signals. The code tracking loop establishes maximum correlation between the received signal code and the internally generated reference code, defining the quantization or the receiver range measurement. Code tracking errors directly affect the signal phase measurements, which are resolved into a position fix. Current designs for code tracking loops provide a code resolution capability of 1 to 1.6 percent. Each bit in the C/A code is 978 nanoseconds long. At the speed of light, the duration of the code bit, or chip width, corresponds to 293.2 meters. A resolution capability of 1.6 percent results in a range quantization of 4.6 meters. A quantization error of 2.66 meters (1σ) is specified when uniform distribution of the error is assumed over the range quantization value.

4.5.3.3 Navigation Algorithm Error

Implementation of a navigation algorithm contributes some error, because of computer limitations, mathematical approximations, algorithm uncertainties, and timing delays inherent in the sequential nature of the computations. The magnitude of this error is estimated to be about 1 meter.

4.5.4 Total System Range Error

The effects of the individual range error sources are combined in RSS fashion to compute the total system range error (1σ). The corresponding 2-drms value for total error is approximated as the 1σ-error value multiplied by a factor of 2.

4.5.5 Operational Considerations

In addition to the errors contributed by the various system components, two other factors that are not error sources in the conventional sense strongly influence the overall accuracy of GPS. These two factors, geometric dilution of precision (GDOP) and denial of accuracy, are included as operational considerations because they are not limitations in the same technical sense as the factors discussed in the previous sections.

4.5.5.1 GDOP

The concept of GDOP was initially developed in connection with Loran navigation, used in characterizing other radionavigation systems, and then extended to GPS. As applied to GPS, the value of GDOP is a composite measure that reflects the influence of satellite and user geometry on the accuracy of the navigation position fix.

The following parameters are contained in the GDOP composite:

- HDOP - Horizontal dilution of precision (two dimensions)
- VDOP - Vertical dilution of precision
- TDOP - Time dilution of precision
- PDOP - Position dilution of precision (three dimensions), or $\sqrt{(\text{HDOP})^2 + (\text{VDOP})^2}$

- $GDOP = \sqrt{(PDOP)^2 + (TDOP)^2}$

Extensive analyses have been conducted to determine values of these GDOP parameters corresponding to various satellite geometries throughout the world. Unfortunately, most of the results published to date have been based on a constellation of 24 satellites rather than the configuration of 6 orbital planes and 18 satellites currently proposed. The rms values* for the GDOP parameters that were determined for the 24-satellite system can be thought of as minimum values for an 18-satellite system, as follows:

GDOP Parameter	RMS Value
PDOP	2.60
HDOP	1.45
TDOP	1.20
VDOP	2.20
GDOP	2.90

By multiplying the total 1σ range error (shown in Table 4-6) by the value of the GDOP parameter of interest, the magnitude of the position error can be determined. When values for PDOP or HDOP are applied to the range error, the result is a radial error (1σ) in either three (PDOP) or two (HDOP) dimensions.

4.5.5.2 Denial of Accuracy

GPS is capable of providing extremely accurate global positioning of about 50 meters (2 drms). The possible impact on national security in allowing unrestricted access to the accuracy of GPS has prompted extensive discussion of methods for denial of accuracy. The method that will most likely be used will deny the signal accuracy by altering the ephemeris and clock correction terms in the satellite navigation message to create range errors of an order of magnitude not yet agreed upon. It is believed, however, that the level of accuracy to be made available to nonmilitary users of GPS will be somewhat better than 500 meters (2 drms); the actual level will be based upon national security considerations.

4.6 ERROR BUDGET FOR DOPPLER

The error budget for Doppler navigation systems is divisible into five basic categories as follows:

- Initialization errors
- Calibration errors
- Doppler signal errors

*Derived from "Principle of Operation of NAVSTAR and System Characteristics," Reference 3.

- Instrumentation errors
- Heading reference errors

Table 4-7 presents a summary of the effect of specific sources of error on the navigation accuracy of a Doppler navigation system. The various sources of error generally affect cross-track and along-track error independently. Therefore, the error budget is separated into cross-track and along-track components to illustrate the specific effects of the error sources.

Table 4-7. ERROR BUDGET FOR DOPPLER NAVIGATION SYSTEMS

Error Source	Effect on Navigation Accuracy (Percentage of Distance Traveled from Origin Unless Otherwise Indicated)	
	Cross-Track Distance Error	Along-Track Distance Error
Initialization Errors		
Course determination	1.75	--
Course selection	0.436	--
Distance setting	--	0.500 nm
Departure point	--	0.049 nm
Calibration Errors		
Scale factor	Negligible	0.100
Beam direction	0.058	0.128
Doppler Signal Errors		
Fluctuation	--	0.146
Altitude holes	--	Negligible
Over-water effects	--	1.05
Instrumentation Errors	0.175	0.040
Heading Reference Errors	2.62	--
Total Error (RSS 2σ)	±3.18% of distance traveled	0.502 nm ±1.07% of distance traveled
Error for 300-nm leg	9.54 nm	3.25 nm

As the table shows, error in the heading reference system input to the Doppler navigation system is the chief contributor to the overall navigation accuracy, affecting mainly the cross-track accuracy. Since heading reference error is an angular error, the corresponding cross-track distance error accumulates as a linear function of the distance traveled from the origin. The along-track distance errors are generally a result of errors in ground velocity as determined by the Doppler radar. Ground velocity errors,

which are caused by Doppler signal errors and calibration errors, are generally fractional errors rather than bias errors. A given percentage error in ground velocity results in a corresponding error in along-track position that accumulates as a linear function of the distance traveled from the origin. Both along-track and cross-track errors can be conveniently expressed as a percentage of distance traveled.

4.6.1 Initialization Errors

Commercial Doppler navigation systems generally establish a flight path by selecting a desired constant magnetic course and distance between an initial position and the next waypoint location. Since current position is determined by reference to an initial position, any errors in establishing the initial position result in position errors during flight.

4.6.1.1 Course Determination Error

The constant magnetic course computed for input to the Doppler navigation system in defining a flight segment depends on knowledge of magnetic variations. A representative accuracy for values of magnetic variation is ±1.0 degree. This corresponds to a cross-track error of 1.75 percent of distance traveled.

4.6.1.2 Course Selection Error

Any error in the mechanical tuning of the desired course (ε_{cs}) causes a cross-track distance error (σ_{cs}) that increases with the distance traveled from the initial position, as follows:

$$\sigma_{cs} = \text{distance traveled} \times \sin \varepsilon_{cs}$$

A typical Doppler navigation system provides 1/2-degree increments in course selection. The resulting mechanical tuning error is ± 1/4 degree and the associated cross-track distance error is the following:

$$\sigma_{cs} = .436\% \times \text{distance traveled}$$

4.6.1.3 Distance Setting Error

The resolution in the distance selector is 1 nm. The resulting error in along-track distance is ±0.5 nm, which does not increase as a function of distance traveled. By carefully selecting waypoints to be spaced at intervals of whole nautical miles, this error can be significantly reduced.

4.6.1.4 Departure Point Error

Because of the method often used in minimizing the effect of altitude holes (Section 4.6.3.2), the Doppler radar receiver cannot track the reflected signal below an altitude above ground level of about 50 feet. The departure point is therefore not known as accurately as it could be if

the radar receiver tracked the reflected signal while on the ground. A published estimate of the position error is 300 feet or 0.049 nm. This error does not increase with distance traveled.

4.6.2 Calibration Error

The Doppler radar is calibrated in two respects:

- Scale factor
- Beam direction

Any errors in the calibration result in position determination errors.

4.6.2.1 Scale Factor Error

Calibration of the relationship between the measured Doppler shift and the corresponding velocity to be computed involves the determination of a scale factor expressed in units of Hertz per knot. The accuracy of the scale factor is a function of the frequency stability of the Doppler transmitter. The velocity error corresponding to a typical scale factor accuracy is .1 percent of the actual velocity. This corresponds to an along-track position error of .1 percent of the distance traveled from the initial position. The cross-track error caused by scale factor error is negligible.

4.6.2.2 Beam Direction Error

The accuracy with which the directions of the radar beams are known affects the accuracy with which the measured velocity components can be resolved into the local coordinate frame. The resulting velocity error then affects the position determination accuracy, which accumulates with distance traveled. Errors in the knowledge of beam direction result from antenna installation alignment error and temperature effects in certain antenna types. Typical beam direction errors result in along-track position errors of 0.128 percent and cross-track position error of 0.058 percent of the distance traveled from the initial position.

4.6.3 Doppler Signal Errors

Several conditions affect the characteristics of the reflected Doppler signal. The following three conditions can significantly affect the navigation accuracy of the Doppler navigation system:

- Fluctuation error
- Altitude holes
- Over-water effects

4.6.3.1 Fluctuation Error

The frequency spectrum of the reflected Doppler radar signal has a random noise-like distribution of frequency components. The mean frequency in the received signal is estimated and compared with the transmitted frequency in order to determine the Doppler shift. The randomness of the

return signal results in a position determination error that accumulates as a function of the square root of distance from the origin. To represent the worst-case conditions, this error is generally expressed as a linear function of distance traveled from the origin. A typical 2σ along-track error due to fluctuation error is .146 percent of the distance traveled from the origin.

4.6.3.2 Altitude Holes

A complete blanking of the received radar signal can occur at altitudes at which the round-trip signal time is a multiple of the half-wave period of the FM continuous wave signal. In a Doppler system using pulsed transmission techniques, altitude holes occur where the round-trip signal time is a multiple of the pulse repetition period. This momentary loss in signal can lead to erroneous navigation data. However, this problem has been eliminated through the use of techniques that alter the modulation frequencies at selected altitudes. Therefore, in many currently used Doppler navigation systems, altitude holes do not produce significant position errors.

4.6.3.3 Over-Water Effects

Source of errors when traveling over water include the bulk motion of the water surface caused by currents, particle motion created by wind (sea spray), and sea shift. Bulk water motion and sea spray effects occur randomly; therefore, the resulting errors are not listed in Table 4-7 as generally predictable contributions to the error budget. Sea shift is related to the varying value of the scattering coefficient over calm water.

The scattering coefficient defines the amount of the transmitted radar signal that is reflected back to the Doppler receiver and is related to the angle of incidence of the transmitted signal on the reflecting surface. Since the angle of incidence varies slightly across the beam width, the scattering coefficient is also varied across the beam width. Over land, this effect is negligible, because the scattering coefficient is nearly constant for a wide range of incidence angles. However, the scattering coefficient over calm water is very sensitive to the angle of incidence. This tends to distort the shape of the frequency spectrum distribution envelope in the received Doppler radar signal. The mean frequency and the corresponding Doppler shift are therefore erroneously offset. The resulting computed velocity error can cause a position error as great as 5 percent of the distance traveled from the origin in very smooth sea conditions.

To reduce this effect, some designs compensate the velocity offset with a value preselected to represent the most likely sea conditions. When smooth sea conditions exist, this compensation is manually selected with a land/sea switch. A residual sea shift error using this method is typically between 0.6 and 1.5 percent of the distance traveled from the origin. An average value of 1.05 percent is shown in Table 4-7.

Another method, called lobe-switching, has been used in military systems to achieve position errors as small as .056 percent. This method, however, is not widely used in civilian applications.

4.6.4 Instrumentation Errors

Instrumentation errors are a result of data conversion and processing techniques. Along-track distance errors are a result of quantization and processing errors in ground velocity measurements; and cross-track distance errors are due to quantization and processing errors in drift angle determination. Typical instrumentation errors cause groundspeed errors of about .04 percent of the total groundspeed. This corresponds to an along-track position error of .04 percent of the distance traveled from the origin. Typical drift-angle instrumentation errors are about 6 minutes of arc. This corresponds to a cross-track error of about .175 percent of the distance traveled from the origin.

4.6.5 Heading Reference Errors

The accuracy of magnetic compasses used with Doppler navigation systems can vary significantly. A representative value for magnetic compass error is ±1.5 degrees. This corresponds to a cross-track position error of 2.62 percent of the distance traveled.

4.6.6 Total System Error

Assuming that the errors from the various sources discussed are normally distributed and independent, the error components are combined in RSS fashion for both along-track and cross-track total errors. These errors are expressed as a percentage of the total along-track distance traveled from the origin. For example, the accumulated position error for a 300-nm leg is shown in Table 4-7 to be 9.54 nm for cross-track and 3.25 nm for along-track.

4.7 ERROR BUDGET FOR CONVENTIONAL INS

The error budget for conventional INS can be divided into five categories, as follows:

- Initialization
- Gyros
- Accelerometers
- Sensor mounting
- Gravity anomaly

Table 4-8 summarizes the effect of the various sources of error on conventional INS navigation accuracy. All error components shown in Table 4-8 represent 2σ values. The main source of navigation error is related to gyro errors. Other significant sources of error are uncertainty in orthogonality of the sensor axes due to mounting errors, and initial platform azimuth error, which is due to gyro drift error during the initial alignment mode.

Table 4-8. ERROR BUDGET FOR CONVENTIONAL INS

Source of Error	Effect of Error on Navigation System Use (nm/hr)
Initialization Error	
Position entry	Negligible
Platform attitude	0.04
Platform azimuth	0.75
Gyro Errors	
Mass imbalance	0.70
Bias drift	0.54
Torquer scale factor	0.54
Accelerometer Error	
Random bias	0.09
Scale factor	0.08
Sensor Mounting Orthogonality	0.96
Gravity Anomalies	0.10
Total Position Error (RSS 2 drms)	1.61

There are various types of errors commonly associated with inertial navigation systems:

- Bias errors
- Time-dependent errors
  - Linear
  - Oscillatory
    - 84.4 minute (Schuler)
    - 24 hour

Since the gyros and accelerometers are mounted on a platform continuously oriented with respect to true north, some of the error effects due to sensor uncertainties are related to the direction of travel. The error effects cited in the following discussion are typical values for a west-to-east flight over a transatlantic route. However, most manufacturers of conventional INS consider the relationship between the direction of travel and the overall position error to be insignificant.

The effects of some of the error sources are sensitive to aircraft maneuvers. For example, the error effects of gyro mass imbalance, non-orthogonality in gyro and accelerometer mounting, and accelerometer non-linearity are functions of changes in aircraft altitude and velocity. The values in Table 4-8 are typical error effects for a flight path that includes typical civil aircraft maneuvers. The values were derived by using a statistical model of the relationship between sensor errors and their effect on position accuracy. The model used was chosen solely on the basis of availability of data and is not necessarily the most representative of actual INS performance. This model represented all errors as being linearly time-dependent, which is why the values in Table 4-8 are expressed in nautical miles per hour (nm/hr). The model assumes that the propagation of those errors which cannot be characterized as being linearly time-dependent can be bounded by a rate of degradation of position accuracy, which can also be expressed in nm/hr.

4.7.1 Initialization Errors

Before the system can be used for navigation, it must be initialized. The initial alignment mode, referred to as initialization, comprises the following three actions:

- Initial position is entered.
- Platform attitude is aligned with the local horizontal plane (perpendicular to the gravity vector).
- Platform azimuth is referenced to true north.

Initialization errors are due to uncertainties in each of these processes. Whereas the initial position is entered manually into the system, the platform attitude and azimuth are aligned automatically by measuring gravity with the accelerometers and earth rotation with the gyros. Uncertainties in both attitude and azimuth are mainly due to gyro drift. A gyro drift rate of .003 degrees per hour (rms) is typical for systems in current use and is used in the following discussions.

4.7.1.1 Initial Position Error

Initial position is entered into the system in terms of latitude and longitude during the initial alignment mode. The resolution provided by current designs is .1 (or ± .05) arc minutes in both latitude and longitude. This resolution corresponds to .05 nm in north position error and .04 nm (at 37° latitude) in east position error. These position errors either remain constant or decrease with time and do not represent a significant portion of the total error. These are not included in the root sum square total position error.

4.7.1.2 Platform Attitude Error

A 2-sigma error in the initial platform attitude of .2 arc minutes about both horizontal platform axes corresponds to a gyro drift rate of .003 degrees per hour (rms). This attitude error causes .04 nm/hr error.

4.7.1.3 Platform Azimuth Error

An initial platform azimuth error of 2 arc minutes, resulting from a gyro drift rate of 0.003 degrees per hour (rms) during alignment, produces a 0.75 nm/hr error during navigation.

4.7.2 Gyro Errors

Three types of gyro errors significantly affect the navigation error of a conventional inertial navigation system:

- Mass imbalance drift
- Bias drift
- Torquer scale factor instability

4.7.2.1 Mass Imbalance Drift

Mass imbalance drift is a result of an imbalance in the gyro's spinning mass and is a function of aircraft acceleration, and it is therefore related to aircraft maneuvers. Mass imbalance drift is expressed in terms of degrees/hour/g, where g is equivalent to the acceleration due to gravity. A typical mass imbalance drift of .5 degrees/hour/g causes a .70 nm/hr error.

4.7.2.2 Bias Drift

Bias drift is a result of unwanted torques introduced into the spinning mass by suspension wires, pivot friction, and back reactions of angular sensor pick-offs and torquer coils. This error takes on a random value each time the INS is turned on and also varies randomly as a function of time. Bias drift error has an impact on the initial platform azimuth accuracy (Section 4.7.1.3) and also directly affects the navigation accuracy. A bias drift of .003 degrees per hour (rms), which is typical of systems in current use, produces a .54 nm/hr error.

4.7.2.3 Torquer Scale Factor

A gyro torquer, which is a component of the gyros, is used to precess the gyro's spinning mass electrically. The resulting angular error measured by the pick-offs in the gyro is used to reposition the INS platform. The torquer is thus used in an INS to introduce earth-rotation and transport-rate compensation into the orientation of the INS platform. Since this process is open-loop, any fluctuations in the torquer scale factor results in angular drift in the platform orientation. The angular drift then produces position errors. Fluctuations in scale factor of .02 percent are typical of systems in current use. This uncertainty corresponds to a .54 nm/hr error.

4.7.3 Accelerometer Errors

The most significant effects of accelerometer error can be attributed to random bias error and scale factor error.

4.7.3.1 Random Bias Error

The acceleration bias in an accelerometer takes on a random value each time the INS is turned on. The estimated mean bias is usually compensated for in either the computer or the accelerometer itself. The remaining portion of the bias produces navigation errors. An rms residual bias of 0.000025 × g (g is the acceleration of gravity at sea level - approximately 32.2 feet per sec^2) is typical of systems in current use. This bias corresponds to a .09 nm/hr error.

4.7.3.2 Scale Factor Error

An accelerometer scale factor fluctuation of .05 percent is typical for INSs in current use. This uncertainty produces an 0.08 nm/hr position error.

4.7.4 Sensor Mounting Orthogonality

The uncertainty in the alignment of the input axes of the gyros and accelerometers with respect to the platform due to mounting inaccuracies causes navigation errors that are sensitive to aircraft maneuvers. A typical gyro mounting alignment accuracy of 100 arc seconds and a typical accelerometer alignment accuracy of 120 arc seconds produce a .96 nm/hr position error.

4.7.5 Gravity Anomalies

It has been suggested that the uncertainty in knowledge of the earth's gravitational field is the fundamental accuracy limitation in inertial navigation systems. The error associated with anomalies in gravity has been estimated to contribute a position error of .1 nm/hr. If all other instrument and mounting errors were significantly reduced through engineering advances, the error due to gravity anomalies would be the main source of error. In fact, accuracies of this order have been demonstrated by recently developed military inertial navigation systems utilizing highly accurate gyros and accelerometers.

4.7.6 Total System Error

The individual error components are combined in RSS fashion to determine the total position error. Since all the error components shown in Table 4-8 represent 2-sigma values, the total position error also represents the 2-sigma value.

4.8 ERROR BUDGET FOR STRAPDOWN INS

The error budget for a strapdown INS can be divided into four categories, as follows:

- Gyro errors
- Accelerometer errors
- Sensor axis mounting misalignment
- Gravity anomaly

Table 4-9 summarizes the effect of the various error sources on the navigation accuracy of the ring laser gyro (RLG) strapdown INS under current development. The main sources of error are related to the RLG characteristics. The various types of errors listed in Section 4.7 for conventional INS are also applicable to strapdown INS. As was the case for conventional INS, all strapdown INS errors are represented in terms of linear time-dependency as a function of the error propagation model used to relate the effect of sensor error to position accuracy.

Table 4-9. ERROR BUDGET FOR STRAPDOWN RING LASER GYRO INS

Source of Error	Effect on Navigation Accuracy (nm/hr)
Gyro Errors	
Bias drift	1.39
Scale factor	0.06
Random walk	0.67
Accelerometer	
Random bias	0.05
Scale factor	0.01
Sensor Mounting Orthogonality	0.10
Gravity Anomaly	0.10
Total System Error (RSS 2 drms)	1.55

In strapdown INS, the errors due to gyro bias and accelerometer bias are most pronounced when the aircraft heading during flight is different from the aircraft heading during initial alignment. During initial alignment, these bias errors, which are related to the inertial space orientation of the gyros and the accelerometers, are partially counteracted by biases in computed aircraft heading and attitude. Since the orientation of the gyros and accelerometers changes relative to inertial space as a function of aircraft heading, the bias errors do not remain entirely compensated for when the aircraft heading is changed following initial alignment. The worst-case situation is a 180° difference between aircraft heading during alignment and heading during flight. The error values shown in Table 4-9 include the effects of this worst-case situation.

4.8.1 Gyro Errors

Three major sources of error in the RLGs used in current strapdown INSs are the following:

- Bias drift
- Scale factor instability
- Random walk

4.8.1.1 Bias Drift

Bias drift in an RLG is caused by a circulating flow of gas within the laser cavity, a result of the direct current used to excite the lasing action. The gas flow alters the refraction properties of the laser cavity, producing a bias in the measured angular rate. The angular rate bias causes an angular measurement error to accumulate as a function of time. Current RLGs have a typical bias drift of .01 degrees per hour (rms). This causes a 1.39 nm/hr position error in the strapdown INS.

4.8.1.2 Scale Factor

The scale factor in an RLG defines the relationship between the measured frequency difference of the two laser beams and the corresponding angular rate. Any instability in the scale factor produces position error in the strapdown INS. A scale factor stability of 5 parts per million is typical for current RLGs. This uncertainty causes a position error of .06 nm/hr.

4.8.1.3 Random Walk

The mechanical dithering used to prevent lock-in (discussed in Appendix A, Section 8.3.1) causes an angular random walk error that is expressed as angular error per square root of elapsed time. Current RLGs have a typical random walk error of $.003°/\sqrt{\text{hour}}$ (rms), which causes a .67 nm/hr position error.

4.8.2 Accelerometer Errors

Inaccuracies in current accelerometers do not produce significant errors in strapdown INSs. The main sources of error in the accelerometers are random bias error and scale factor instability. For a typical rms random bias accuracy of $0.00005 \times g$ (g = acceleration of gravity), a position error of only .05 nm/hr results. A typical scale factor stability of 50 parts per million (rms) results in a .01 nm/hr position error.

4.8.3 Sensor Mounting Orthogonality

The gyros and accelerometers in a strapdown INS are typically mounted with an alignment accuracy of 10 arc seconds. The resulting position error is 0.1 nm/hr.

4.8.4 Gravity Anomaly

As described in Section 4.7.5, uncertainties in knowledge of the earth's gravitational field represent the fundamental accuracy limitation in INSs. This uncertainty has been estimated to produce a position error in INSs of 0.1 nm/hr.

4.8.5 Total System Error

The error effects of the individual sources in the RLG strapdown INS are combined in RSS fashion to determine the total position error (2σ). The total position errors listed for conventional and strapdown INS are indicative of accuracies achieved by commercially available units and do not represent the total spectrum of capabilities when including military developments. Whereas the accuracy of 1.61 nm/hr shown for conventional INS is representative of civil units, military designs have demonstrated accuracies of .08 nm/hr. This achievable accuracy for conventional INS is superior to the accuracies achieved by strapdown INS for both civil (1.55 nm/hr) and military (1.1 nm/hr) designs.

4.9 SUMMARY OF TECHNICAL CAPABILITIES

Tables 4-10 through 4-12 compare the technical capabilities of Loran-C, Omega/VLF, GPS, Doppler, conventional INS, and strapdown INS navigation systems with the requirements defined in FAA AC 90-45A. The nonprecision approach requirements specified in AC 90-45A are referenced to typical approach clearance zones. The FRP stipulates a nonprecision approach requirement of 100 meters, which is sufficient to allow currently available nonprecision approach capability. Since AC 90-45A is the currently acknowledged reference for certification of area navigation systems, it, rather than the FRP, will be used to provide the basis for comparing system capabilities. However, any navigation system considered as a replacement for VOR/DME as the national standard would have to demonstrate performance that equals or exceeds the performance of VOR/DME in all situations.

Flight technical error (FTE) refers to the accuracy with which the pilot controls the aircraft, as measured by his success in matching the indicated aircraft position with the indicated command or desired position on the display. (With autopilot coupling, FTE more appropriately refers to autopilot error and is typically lower than pilot-flown FTE.) FTE does not include blunder errors, which are gross errors in judgment or lapses in attentiveness that cause the pilot to stray far from his desired path.

The VOR/DME navigation system is not shown in the comparison, because the requirements were based on the capability of the VOR/DME system. Thus, that system, by definition, satisfies the requirements. The three levels of GPS capability shown in the table correspond to two possible levels of accuracy denial -- 300 meters or 500 meters -- and a nondegraded accuracy of 50 meters. All entries in the tables are 2σ values.

Table 4-10. SUMMARY OF TECHNICAL CAPABILITIES OF RNAV SYSTEMS RELATIVE TO EN-ROUTE REQUIREMENTS (± NM)

Type of Accuracy	En-Route Requirements†	Loran-C	Omega/ VLF††	GPS			Doppler	Conventional INS	Strapdown INS
				50m	300m	500m			
Equipment									
Cross-track	1.50	0.25	1.60	0.03	0.16	0.27	9.54*	1.61**	1.55**
Along-track	1.50	0.25	1.60	0.03	0.16	0.27	3.25*	1.61**	1.55**
Flight Technical									
Cross-track	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Along-track	--	--	--	--	--	--	--	--	--
Total System									
Cross-track	2.50	2.02	2.56	2.00	2.01	2.02	9.75	2.56	2.53
Along-track	1.50	0.25	1.60	0.03	0.16	0.27	3.25	1.61	1.55

*Error accumulated over a 300-nm flight path.
**Error accumulated after 1 hour of flight.
†Source: FAA AC-90-45A, Reference 23.
††Ranging, not hyperbolic, implementation.

Table 4-11. SUMMARY OF TECHNICAL CAPABILITIES OF RNAV SYSTEMS RELATIVE TO TERMINAL REQUIREMENTS (± NM)

Type of Accuracy	Terminal Requirements†	Loran-C	Omega/ VLF††	GPS			Doppler	Conventional INS	Strapdown INS
				50m	300m	500m			
Equipment									
Cross-track	1.12	0.25	1.60	0.03	0.16	0.27	9.54*	1.61**	1.55**
Along-track	1.10	0.25	1.60	0.13	0.16	0.27	3.25*	1.61**	1.55**
Flight Technical									
Cross-track	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Along-track	--	--	--	--	--	--	--	--	--
Total System									
Cross-track	1.50	1.03	1.89	1.00	1.01	1.04	9.59	1.90	1.84
Along-track	1.10	0.25	1.60	0.03	0.16	0.27	3.25	1.61	1.55

*Error accumulated over a 300-nm flight path.
**Error accumulated after 1 hour of flight.
†Source: FAA AC-90-45A, Reference 23.
††Ranging, not hyperbolic, implementation.

As shown in the tables, Loran-C systems are capable of satisying en-route, terminal, and approach accuracy requirements, assuming availability of a signal. The equipment accuracy of .25 nm specified for Loran-C, which corresponds to a GDOP of 3.6, was chosen on the basis of reported operational experience. The value of 1.6 nm specified for Omega/VLF accuracy is representative of rho-rho Omega/VLF equipment accuracy, corresponding to a GDOP of 1 rather than 2, which is typical of hyperbolic Omega. Omega/VLF is clearly unable to meet terminal and approach requirements and falls

Table 4-12. SUMMARY OF TECHNICAL CAPABILITIES OF RNAV SYSTEMS RELATIVE TO NONPRECISION APPROACH REQUIREMENTS (± NM)

Type of Accuracy	Requirements†	Loran-C	Omega/ VLF††	GPS			Doppler	Conventional INS	Strapdown INS
				50m	300m	500m			
Equipment									
Cross-track	0.33	0.25	1.60	0.03	0.16	0.27	9.54*	1.61**	1.55**
Along-track	0.30	0.25	1.60	0.03	0.16	0.27	3.25*	1.61**	1.55**
Flight Technical									
Cross-track	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Along-track	--	--	--	--	--	--	--	--	--
Total System									
Cross-track	0.60	0.56	1.68	0.50	0.52	0.57	9.55	1.69	1.63
Along-track	0.30	0.25	1.60	0.03	0.16	0.27	3.25	1.61	1.55

*Error accumulated over a 300-nm flight path.
**Error accumulated after 1 hour of flight.
†Source: FAA AC-90-45A, Reference 23.
††Ranging, not hyperbolic, implementation.

slightly short of the en-route accuracy requirements. However, measured accuracy during flight has shown that Omega/VLF navigation systems are capable of an accuracy of ±1.5 nm. Even with signal accuracy degraded to ±500 meters, GPS can provide nonprecision approach capability at some sites, although this capability is marginal and does not take into consideration the effect on accuracy if fewer than four satellites are visible. Doppler is unable to meet domestic en-route, terminal, and approach requirements. Both conventional INS and strapdown INS are unable to meet terminal and approach requirements, but can meet domestic en-route requirements for up to one hour in flight.

Table 4-13 summarizes the capabilities of the various navigation systems relative to operational environments. Suitability, as defined in the context of the table, reflects a possible rather than a certified capability to meet existing requirements. The capabilities of a particular system operating in a certain environment are judged on the basis of existing reference material. In addition, the suitability of a particular system to provide domestic navigation capability does not imply an ability to replace VOR/DME as the national navigation standard. Any navigation system considered as a replacement for VOR/DME must not only provide coverage and accuracy at the level that currently exists, but also demonstrate some degree of improvement, economic as well as operational.

Although Table 4-10 indicates that Loran-C is sufficiently accurate to meet en-route technical requirements, Loran-C chains do not provide oceanic coverage, as shown in Table 4-13. Also, there is currently no midwest Loran-C chain in the domestic United States, a situation that limits signal availability. The suitability of Loran-C for terminal and nonprecision approach navigation is contingent upon signal availability. Omega/VLF provides worldwide coverage with an accuracy suitable for en-route navigation but not sufficient for terminal or approach operations.

Table 4-13. SUMMARY OF NAVIGATION SYSTEMS' ABILITY TO PROVIDE ACCURACY AND COVERAGE

Navigation System	Operational Environment				
	En Route			Terminal	Nonprecision Approach
	Domestic	Trans-Oceanic	Remote Offshore		
Loran-C	Suitable[1]	No Coverage	Suitable	Suitable[1]	Suitable[1]
Omega/VLF	Suitable	Suitable	Suitable[2]	Insufficient Accuracy	Insufficient Accuracy
GPS	Suitable	Suitable	Suitable	Suitable	Suitable[2]
VOR/DME	Suitable	No Coverage	No Coverage	Suitable	Suitable[1]
Doppler	Insufficient Accuracy	Suitable[4]	Insufficient Accuracy	Insufficient Accuracy	Insufficient Accuracy
INS	Suitable[3]	Suitable	Suitable[2]	Insufficient Accuracy	Insufficient Accuracy

[1]When coverage is available.
[2]Under conditions allowing attainment of sufficient accuracy.
[3]For flights of less than one hour.
[4]For ocean tracks less than 400 nm.

Accuracy requirements are specified in FAA AC-90-45A.

GPS, even with a denial of accuracy to a level of 500 meters, would provide sufficient accuracy for en-route, terminal, and some nonprecision approach navigation, given the continuous availability of four satellites. The FAA maintains that five satellites are required, each above a 10 degree masking angle, in order to provide sufficient reliability and to allow economical antenna design. Redundancy of sources of navigation signals is an important consideration when evaluating the potential of a navigation system to adequately replace the VOR/DME system and the level of redundancy which it provides. The limitation of the application of VOR/DME is the result of lack of coverage in oceanic, remote, and offshore areas and the consequent cost of maintaining a large number of transmitters for covered areas. Since Doppler and INS are self-contained navigation systems, they provide worldwide navigation capability. Doppler accuracy is suitable for oceanic en-route navigation for distances up to 400 nm. Doppler accuracy is inadequate for all domestic and offshore operations. Accuracies of both conventional INS and strapdown INS are adequate for oceanic en-route navigation for as long as about 8 hours in flight, and for domestic en-route navigation for up to 1 hour in flight. INS accuracy is not sufficient, however, for terminal or approach operations.

CHAPTER FIVE

OPERATIONAL EVALUATION OF NAVIGATION SYSTEMS

5.1 INTEROPERABILITY CONSIDERATIONS

Interoperability of navigation systems can be defined as the ability of systems to operate effectively in an environment where dissimilar systems are operating concurrently. The degree of compatibility among systems provides a measure of their interoperability. The following factors influence compatibility:

- Coordinate systems
- Route structures
- Separation standards
- RF environment
- Equipment interface
- Flight procedures

Each of these is discussed in the following sections.

5.1.1 Coordinate Systems

All airborne navigation systems measure aircraft position in relation to a particular coordinate system. Basic VOR/DME employs a polar coordinate reference system with the VORTAC as the origin. The resulting distance and bearing (rho/theta) measurements define aircraft position in relation to the VORTAC. Knowledge of the geographical position coordinates of the VORTAC helps determine the geographical position of the aircraft. Geographically oriented navigation systems such as Omega, Loran-C, and GPS are referenced directly to latitude and longitude.

Any process for determining position on the earth's surface involves an assumption of the shape of the earth. One of the following three basic approximations to the earth's shape can be used:

- Flat
- Spherical
- Ellipsoidal

Through these approximations, the coordinate system used in the airborne navigation processor is defined.

The coordinate system accurately defines the surface of the earth to provide the capability to navigate between points on the earth's surface. Unfortunately, the shape of the earth is irregular and cannot be easily described mathematically. The geometrical figure that most closely approximates the shape of the earth is an oblate spheroid, or ellipsoid of revolution, created by an ellipse rotating about its minor axis. The irregularity of the earth's surface, however, prevents any one ellipsoid from approximating more than a particular section of the surface. Because of this restriction, a number of reference ellipsoids have been defined, each providing a fit only to localized areas. The geodetic and geophysical parameters used to define a reference ellipsoid are referred to as a datum. The datum origin is generally the point at which the reference ellipsoid is tangent to the earth geoid (the surface of the earth coinciding with mean sea level).

Navigation errors can be introduced when the navigation process involves different datums. The earth model used by the airborne navigation computer is based on one particular datum, such as the North American Datum. Charted locations of navaids, landmarks, airports, and other land sites may or may not be defined with respect to that same datum. The magnitude of differences between datums is primarily a function of the distance between datum origins. In addition, the accuracy within a given datum decreases as one travels progressively farther from the datum origin. Thus the error associated with nonstandardization of a coordinate system is not a constant bias, but depends on the actual ellipsoids used and the location of the user with respect to the datum origins of the ellipsoids. As an example, differences between the coordinates defined in the Tokyo Datum and a center-of-mass-referenced datum defining the World Geodetic System (WGS-72) can be as great as 500 meters (0.27 nm).

As the accuracy of navigation systems continues to improve, the effect of factors such as charting inaccuracies becomes increasingly more significant. Table 5-1 presents the effect that a charting error of 0.27 nm would have on the accuracy of a position fix determined by various navigation systems, in terms of the percentage of their respective system accuracy capability. The system accuracy of 2.5 nm listed for Omega corresponds to a GDOP of 1.6, which is considered typical for Omega navigation using hyperbolic techniques. Rather than specifying two values of Omega system accuracy, 1.6 nm for ranging implementation and 2.5 nm for hyperbolic implementation, the worst-case value of 2.5 nm will be used for the purpose of an operational evaluation.

5.1.2 Route Structures

The high cost of fuel emphasizes the need to provide for flexible routing of aircraft to maximize fuel efficiency. Direct routing between origin and destination provides the shortest distance path, but wind conditions may suggest selection of a less direct path.

Table 5-1. IMPACT OF CHARTING ERROR ON SYSTEM ACCURACY

Navigation System	System Accuracy	Percentage of Accuracy Degradation Due to Charting Error of 0.27 nm
Omega	2.5 nm	10.8
Loran-C	0.25 nm	108.0
RNAV VOR/DME	0.5 nm	54.0
GPS	0.16 nm	167.0
Doppler	9.5 nm*	2.8
INS	1.6 nm**	16.9

*Accumulated over 300 nm.
**Accumulated during one hour.

Although it would be desirable to allow aircraft equipped with RNAV equipment to fly direct routes from origin to destination without having to report intermediate VOR position fixes, such freedom can create conflicts. RNAV units generally compute great-circle flight paths. A great circle is constructed under the assumption that the earth is a perfect sphere. Corrections are sometimes applied to account for the oblateness of the earth, but the spherical-earth assumption is frequently considered to be sufficiently accurate. However, for a flight between New York and Los Angeles, the differences between a spherical-earth assumption and use of the Clarke 1866 oblate spheroid model of the earth result in an east-west discrepancy of 6.5 nm and a north-south discrepancy of 0.5 nm.*

Not only do the differences among the position-fixing processes used in airborne navigation systems present potential conflicts, but certain ATC computer capabilities can also create complications. The ATC computer can project flight paths forward in time to aid in the prediction of possible path conflicts. These extrapolations of current track are either great-circle projections or rhumb-line projections. The deviation between a great-circle path and a rhumb-line path connecting New York with Los Angeles is approximately 135 nm of lateral separation at the point of greatest divergence. This point occurs nearly midway between New York and Los Angeles. After this point, the paths begin to converge until they finally meet at the destination in Los Angeles. (It is interesting to note that there is a difference of only 1 percent in total distance traveled between the two paths.) Figure 5-1 is a comparison of the two flight

*Equations used to obtain values specified throughout this chapter are given in Appendix B.

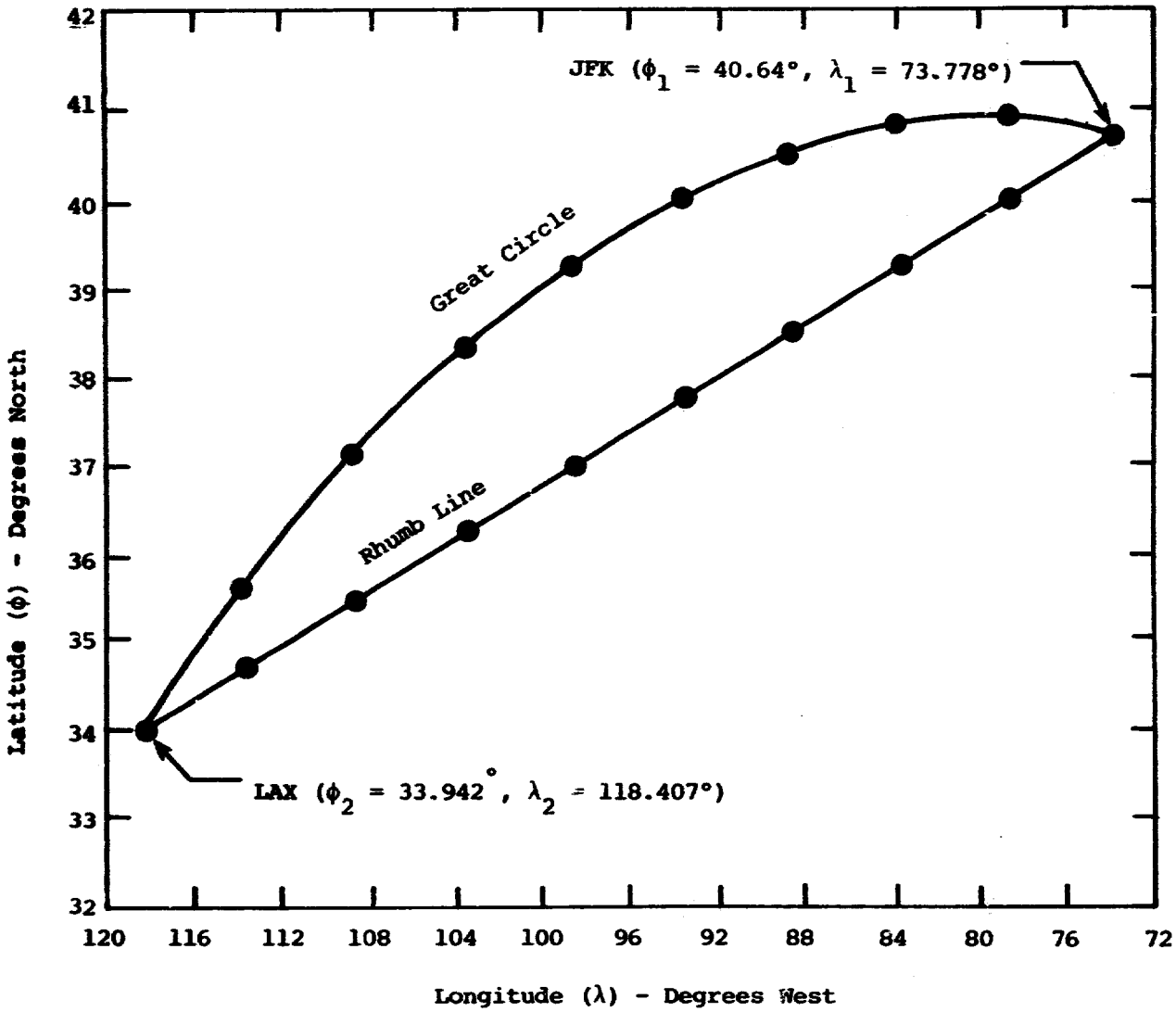

Figure 5-1. RHUMB-LINE ROUTE VERSUS GREAT CIRCLE ROUTE: NEW YORK (JFK) TO LOS ANGELES (LAX)

paths. The axes are, for simplicity, linear rather than representative of a Mercator or Lambert conformal projection. The computations used to determine the magnitude of greatest cross-track deviation betwee the rhumb-line and great-circle paths is presented in Appendix C.

The magnitude of deviation between a rhumb-line path and a great-circle path is dependent on both direction and distance of travel. The shorter the distance, the less the deviation. Since the current ATC computer provides flight-path projections for only short distances, possible discrepancies between rhmub-line and great-circle paths are minimized, regardless of direction of flight.

The following calculations illustrate the application of equations (given in Appendix B) to determine the flight path latitude (ϕ) at a given value of longitude (λ) for each path. The value of longitude used as an example is 93.778 degrees. ϕ_1 equals 40.64 degrees, λ_1 equals 73.778 degrees, ϕ_2 equals 33.942 degrees, and λ_2 equals 118.407 degrees.

Rhumb Line (RL):

$$\phi_{RL} = \phi_1 + (\lambda - \lambda_1) \times \left(\frac{\phi_2 - \phi_1}{\lambda_2 - \lambda_1}\right)$$

$$= 40.64 + (93.778° - 73.778) \times \left(\frac{33.942 - 40.64}{118.407 - 73.778}\right) = 37.64°$$

Great Circle (GC):

$$\phi_{GC} = \tan^{-1} [(\tan Lv) \times \cos (\lambda - \lambda_1 - DLov)]$$

where

$$Lv = \cos^{-1} (\cos \phi_1 \sin C) = 40.79°$$

$$C = \tan^{-1} \left[\frac{\sin (\lambda_2 - \lambda_1)}{(\cos \phi_1 \tan \phi_2) - (\sin \phi_1 \cos (\lambda_2 - \lambda_1))}\right] = 86.1564°$$

$$DLov = \sin^{-1} \left(\frac{\cos C}{\sin Lv}\right) = 5.8894°$$

Thus $\phi_{GC} = \tan^{-1} [0.8629 \times \cos (\lambda - 79.6674)] = 39.9247°$

If an aircraft is flying a great-circle route and the ATC computer provides the controller with a rhumb-line projection of that flight, a serious conflict may develop. Such a possibility could be avoided if the ATC computer were emulating the navigation techniques used by the aircraft. Unfortunately, standardization of a navigation technique does not exist. Radar surveillance is used to monitor deviations from intended routes, but the controller will not intervene unless a potential conflict is perceived.

5.1.3 Separation Standards

Separation standards have been developed historically on the basis of estimated system accuracies. The navigation system used as the reference standard in determining existing standards is VOR/DME. System accuracies are developed from estimates of the individual accuracies of the navigation signal, the receiver, and flight technical error and provide a measure of the bounds of position error.

Position error is defined in terms of the techniques used to determine position. GPS is a range system; VOR/DME is an angle and range system. Omega and Loran-C are hyperbolic navigation systems but can also be used in a ranging mode. The VOR contribution to VOR/DME position error is presented as an angle or a one-dimension distance at a defined range from the station. DME error is a function of a percentage of the distance from the station. Position error in relation to Loran-C, Omega, and GPS is an elliptical area, the dimensions of which are determined by the geometry of the aircraft position in relation to the transmitters. The problem of compatibility of accuracy specifications when different systems are compared should be resolved by adoption of the 2-drms position error probability method.

5.1.4 RF Environment

Of the radionavigation systems studied -- VOR/DME, Loran-C, Omega, and GPS -- only DME requires transmission of an RF signal by the airborne unit. There are no indications that DME signals cause interference with reception of the navigation signals of VOR, Loran-C, or Omega. However, the airborne DME interrogator may disrupt reception of GPS signals, depending on the proximity of the DME channel frequency to the frequency of the GPS signal.

Each radionavigation system is susceptible to certain types of external interference, but the question of compatibility is whether the existence of one navigation system adversely affects the use of another system. The only other known example of conflict is in the use of Loran-C when the user is in close proximity to the VLF transmitting stations used by Omega/VLF navigation systems. Test flights have indicated that reception of Loran-C signals is very poor when the user is within 15 nm of a VLF transmitter. The notch filters of airborne Loran-C units are unable to discriminate against the broad-band characteristics of the VLF signal. Doppler and INS systems are not susceptible to RF interference.

5.1.5 Equipment Interface

The purpose of a navigation system is to provide a means of establishing and maintaining a route by which one can travel from point A to point B. In most applications, display of the deviation from the prescribed route is more useful for maintaining correct course than display of actual geographical position along the route. For this reason, the course deviation indicator (CDI) has become the primary means of control display between the navigation system and the pilot. All the navigation systems studied provide capability for interface to a CDI.

The navigation systems are not, however, interchangeable in terms of cockpit installation. Unique requirements of each system, such as antenna type, generally create the need for modifications to existing cockpit interface wiring when a change is made from one type of navigation system to another.

5.1.6 Flight Procedures

The question of compatibility with respect to flight procedures involves technique as well as capability. To assess adequately the operational performance of a particular navigation system, case studies were selected to represent operational environments in which the system must perform. It is not necessary to emulate all possible scenarios to provide an adequate measure of system interoperability. Interoperability is a measure of the ability of ATC to maintain safe separation of aircraft without giving special consideration to the types of navigation systems used. The methods by which ATC maintains lateral separation of aircraft are specified in the Air Traffic Control handbook as follows:*

- "Clear aircraft on different airways or routes whose widths or protected airspace do not overlap.....
- "Clear aircraft below 18,000 [feet] to proceed to and report over or hold at different geographical locations determined visually or by reference to NAVAIDs.
- "Clear aircraft to hold over different fixes whose holding pattern airspace areas do not overlap each other or other airspace to be protected.
- "Clear departing aircraft to fly specified headings which diverge by at least 45 degrees."

Degrees of effectiveness of system interoperability can best be measured through scenarios that highlight the distinctions between system capabilities in different environments. Five scenarios were devised that were considered effective in demonstrating these differences, and representative of each of the operational methods used by ATC to maintain lateral separation of aircraft. Additional scenarios were considered, but the resulting values of operational merit for respective systems duplicated those determined in a previously defined scenario. Duplication of results, regardless of differences in scenarios, was avoided so that the possibility of bias would be minimized. The scenarios were applied to a mix of navigation systems operating concurrently in common domestic en-route airspace.

The scenarios provide the basis for case studies, which are defined in terms of response to the following controller requests:

1. "Turn left heading zero two five."
2. "Cleared to fly direct Fargo."

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*_Air Traffic Control_, Reference 31.

3. "Track outbound on the Green Bay VOR zero nine zero radial."

4. "Report crossing Jones intersection."

5. "Fly North Atlantic Track F."

The response is evaluated relative to the following criteria:

- Means of establishing course or track
- Means of maintaining course or track
- Consequence of loss of signal
- Pilot workload
- Controller workload

5.2 CASE STUDIES

The following case studies are intended to provide insight into the operational effectiveness of the navigation systems by exercising those systems in realistic situations. Differences in the functional characteristics of airborne control/display units (CDUs), such as push-buttons versus knobs for data entry, must not be considered relevant when the effectiveness of types of navigation systems is compared. The computational, rather than the mechanical, effectiveness associated with use of a particular navigation system is of interest. Although the functional design of a CDU can affect pilot workload, it is not the intent of this study to determine the optimal design of a CDU. Rather, this study must establish the inherent limitations of a navigation system without regard to packaging considerations that could theoretically be accommodated by any system. The limitations identified through application of the case studies are summarized in Section 5.3.

Conventional INS and strapdown INS are operationally identical. Subsequent reference to INS in this report applies equally to both conventional INS and strapdown INS. Since the Doppler navigation system is shown in Chapter Four to have insufficient accuracy in domestic en-route applications, it will not be discussed in terms of its operational capability in Case Studies One through Four, which deal with domestic en-route applications.

5.2.1 Case Study One

5.2.1.1 Description

Situation

The first case study considers pilot compliance with an ATC request to "turn left heading zero two five." The aircraft is assumed to be flying at a true airspeed of 350 knots at 17,500 feet en route due east over the continental United States. Choice of aircraft airspeed and altitude is completely arbitrary and does not reflect any intentional discrimination

relating to class of aircraft. The aircraft is being vectored under instrument flight rules (IFR) conditions to avoid a thunderstorm and is being monitored by radar. Wind is out of the northwest at 30 knots.

General Comments

The request calls for a left turn to establish a magnetic heading of 25 degrees. When responding to an ATC vector request, navigation guidance becomes more a function of ground control and monitoring than a function of the airborne navigation unit. Since all aircraft are equipped with a magnetic compass, they can comply with a request to fly a specified heading vector without reliance on anything more sophisticated. However, since issuance of vectors is one of the means by which ATC maintains lateral separation of aircraft, any possible relationship between such a request and the type of navigation equipment used should be examined. Also, a discussion of the ability of navigation equipment to be used to respond to a heading vector request will serve to underscore the distinction between heading vectors and track vectors.

Applicable Systems

In this scenario, single VOR and non-RNAV VOR/DME systems are considered separately. The five RNAV navigation systems - VOR/DME, Loran-C, Omega, GPS, and INS - are not evaluated separately, since the response is common to all.

5.2.1.2 Application of Scenario

Single VOR

A VOR receiver indicates the magnetic bearing of the VOR transmitter with respect to the aircraft antenna. This information is not sufficient to establish a heading reference. Therefore, a magnetic compass is still required to establish heading, even when the aircraft is equipped with a VOR receiver.

Non-RNAV VOR/DME

An airborne VOR/DME system provides distance as well as bearing to a VORTAC. Addition of the distance information makes possible a relative position fix with respect to the VORTAC from which the signals emanate. Although a VOR/DME system does not provide heading information, successive manual plotting of relative position fixes provides an indication of ground track. Knowledge of ground track, however, does not indicate heading. Consequently, a magnetic compass is used to verify heading.

RNAV

All RNAV units, regardless of type, demonstrate the same degree of operational capability in responding to a request for a heading change. For this reason, the following description applies equally to RNAV VOR/DME, Loran-C, Omega/VLF, GPS, and INS.

Area navigation systems establish a ground-track reference, rather than a heading reference, by which the desired flight path is maintained. To establish a flight path, origin and destination must be entered into the RNAV unit. In many RNAV applications, the origin of a flight path is the aircraft's present position, which does not need to be manually entered into the RNAV unit. A ground track is then computed by the airborne computer, and deviations from that track are measured by processing the navigation signals received.

Destination entered into the RNAV unit can be defined in a variety of formats, one of which is bearing and distance from some location already known to the RNAV unit. If the RNAV unit has been successfully navigating before the request for a heading change, current position is a known location. In most RNAV units, current position is defined as Waypoint 0. Another waypoint, which can then be entered into the unit, is at a bearing of 025 degrees from Waypoint 0. The distance entered can be nearly anything, since the object is to establish a direction of track, not a specific destination. However, for practical reasons relating to computational overflow and underflow, the distance used should be reasonable -- 100 nm, for example. Directing the RNAV unit to initiate a direct-to computation from current position to a waypoint defined as 025 degrees bearing, 100 nm distance from current position, establishes a ground-track angle of 025 degrees as the desired track.

A track of 025 degrees does not necessarily correspond to the heading of 025 degrees flown by aircraft using a magnetic compass to comply with the ATC request. The difference between track and heading is wind. Flying a heading of 025 degrees at a true airspeed of 350 knots in the presence of a 30-knot northwest wind results in a track of 029.6 degrees with a groundspeed of 341 knots, as illustrated in Figure 5-2. Therefore, to comply with a request to fly a heading of 025 degrees in this scenario, the pilot would have to input a track of 029.6 degrees when establishing his "to" waypoint. However, when a pilot is instructed to fly a heading, he is expected to fly a magnetic heading without regard to ground track.

Calculation of the required track of 029.6 degrees requires knowledge of wind speed, wind direction, and true airspeed, and application of the law of cosines. An alternative to this computation is to input the desired heading as the track angle and compensate for the wind by monitoring heading and modifying the track input accordingly. Although this alternative does not require manual calculations, it is no less demanding in terms of pilot workload because of the requirement to perform numerous operations with the RNAV unit over an extended time period.

Clearly it is difficult to use an area navigation system to fly a requested heading. Although heading may be a display parameter provided by area navigation systems, it is generally not a computational by-product of the area navigation process, but rather is the output of an external sensor. The source of heading information is a magnetic compass. It is therefore common practice for pilots to revert to the magnetic compass when responding to such requests. In aircraft equipped with area navigation systems, the magnetic compass is generally associated with a magnetic heading

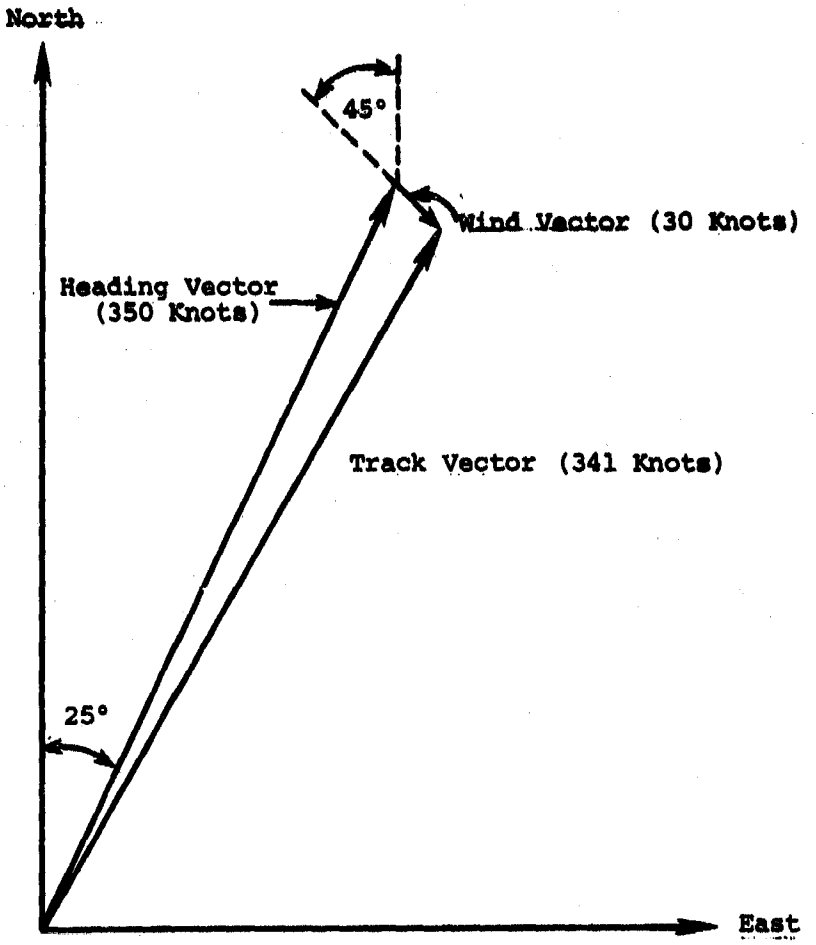


Figure 5-2. RELATIONSHIP BETWEEN HEADING AND TRACK VECTORS

reference system stabilized by a gyro, referred to as a gyro-stabilized magnetic compass. The horizontal situation indicator (HSI) is a magnetic heading reference system that allows either heading selection via the magnetic compass or course selection when coupled with an area navigation system. An HSI can also be operated in a VOR-only mode, in which case course selection represents a desired VOR radial. In the area navigation mode, desired course is an input rather than an output and is displayed on the HSI as a function of the current track leg.

5.2.1.3 Discussion of Results

Relative Comparisons

None of the navigation systems evaluated are suited for efficient response to a request for a heading change, because their primary function is to compute and display track, not heading.

System Mix Conflicts

A conflict could arise if two or more aircraft were requested to fly heading vectors and each pilot programmed the heading into the respective hold modes appropriate to the navigation systems used. The navigation systems are referenced to ground track, whereas ATC requests are referenced to heading through the magnetic compass. Depending on winds and direction of flight, an aircraft holding track might not respond satisfactorily in accordance with the controller's intentions. A burden would then be placed on the controller, who would find it necessary to issue new vectors to compensate for the inconsistencies. (A pilot flying track when instructed to fly heading would be in violation of ATC regulations.)

5.2.2 Case Study Two

5.2.2.1 Description

Situation

Case Study Two considers pilot response to an ATC clearance to "fly direct Fargo." At the time of clearance the aircraft is near Green Bay, Wisconsin, 390 miles east of the Fargo, North Dakota, VORTAC. The aircraft is operating in visual meteorological conditions in daylight. The pilot has first filed a flight plan originating at Chicago, flying direct to Fargo. Because of traffic considerations, the aircraft has been vectored to Green Bay; upon arrival, direct clearance to Fargo is issued.

Applicable Systems

All systems are considered independently in this scenario -- single VOR, non-RNAV VOR/DME, RNAV VOR/DME, Loran-C, Omega/VLF, GPS and INS.

5.2.2.2 Application of Scenario

Single VOR

In this situation, the aircraft is initially out of range of the Fargo VOR signal, regardless of altitude. Therefore, a direct-to clearance cannot be accommodated and is not issued when a single VOR receiver is used and the "to" destination is beyond reception range.

Non-RNAV VOR/DME

Addition of a DME receiver is of no consequence in this scenario. Because the VORTAC defining the destination is beyond range of the VOR/DME unit, any possibility of a direct-to capability is eliminated.

RNAV Single VOR/DME

When a VOR/DME-based area navigation system is used, position offsets can be applied to appropriate VORTACs along the flight path to establish intermediate waypoints between origin and destination. The waypoints

should be spaced along the flight path at distances that ensure overlapping of VORTAC signal coverage, thus making direct rounting possible between any two points. If a circular coverage area with a radius of 120 nm is assumed for each VORTAC, three VORTACs are necessary to provide continuous coverage between Green Bay and Fargo, as illustrated in Figure 5-3.

For the RNAV VOR/DME unit, all waypoints are entered in terms of bearing and distance from a particular navaid, which is defined by a frequency input. Waypoints other than origin and destination are optimally defined as points on the flight path that are directly abeam of the reference navaids. (An abeam point is defined as the intersection of the flight path and a line perpendicular to the flight path drawn to the navaid.) As the aircraft progresses along the flight path, the various waypoints defined in the stored flight plan list are sequentially activated.

As stated in the description of this scenario, the original flight plan was for a direct route between Chicago and Fargo. Appropriate navaids were manually selected from aeronautical charts to serve as waypoint references. Either manual calculations or a ground-based computer was then used to compute the magnetic bearing and distance of the navaid abeam points on the flight path. The diversion to Green Bay, which could not have been predicted, results in the necessity of manually charting a new course and defining new waypoints. If the pilot has access to an RNAV en-route chart for the area, an established RNAV route such as J976R can be used. The reference navaids and corresponding waypoint coordinates are already defined and need only to be entered into the RNAV unit. If such a chart is not available, however, or if none of the established RNAV routes are acceptable, the pilot must expend much effort to establish a new flight plan. This situation will now be considered.

The first task for the pilot is to draw a line connecting origin and destination on his aeronautical flight planning chart. A straight line on a Lambert conformal chart, the chart typically used, closely approximates a great-circle path with a constantly changing heading. If the only chart available is a Mercator projection, a straight line will define a rhumbline path, with constant true heading.

Once the path has been defined, the pilot must select navaids along the route that will provide adequate overlapping coverage. A line can then be drawn between the navaid and the flight path, optimally intersecting the flight path at a right angle. The point of intersection defines the waypoint. The magnetic bearing and distance from the navaid to the waypoint can then be approximated from the chart. On the flight path between Green Bay and Fargo, as indicated in Figure 5-3, at least two waypoints must be entered into the RNAV unit in addition to the destination (which has already been defined), so that adequate coverage is provided.

If, as the flight progresses, a navaid used to define a waypoint is not transmitting because of a sudden unannounced shutdown, a new navaid must be selected for use as soon as possible. Although this situation does not necessarily require charting a new course, it does require calculating new waypoint coordinates and entering them into the RNAV unit.

RNAV Multiple VOR/DME

The navaid data base typically included in RNAV multiple VOR/DME systems allows selection of any navaid and access to its identifying parameters (such as coordinates, frequency, elevation, and magnetic variation) through input of a three-letter navaid identifier (ident). The destination of Fargo, North Dakota, is entered simply as FAR. A waypoint list is used to enable definition of distinct flight legs. However, a direct-to clearance requires the input of only origin and destination. Waypoint 0 in the waypoint list is generally a reserved location that maintains current position. When a direct-to clearance is initiated, current position is designated the origin, and destination corresponds to the waypoint defining Fargo.

Selection of primary and secondary navaids to ensure continuous signal coverage throughout the flight is automatic. Station-selection algorithms first identify candidate navaids in terms of proximity to the flight path. Final selection of primary and secondary navaids is based on obtaining geometry that provides the greatest accuracy. Loss of a navaid while en route would pose no problem, since the station-selection algorithm would automatically search for and acquire a replacement.

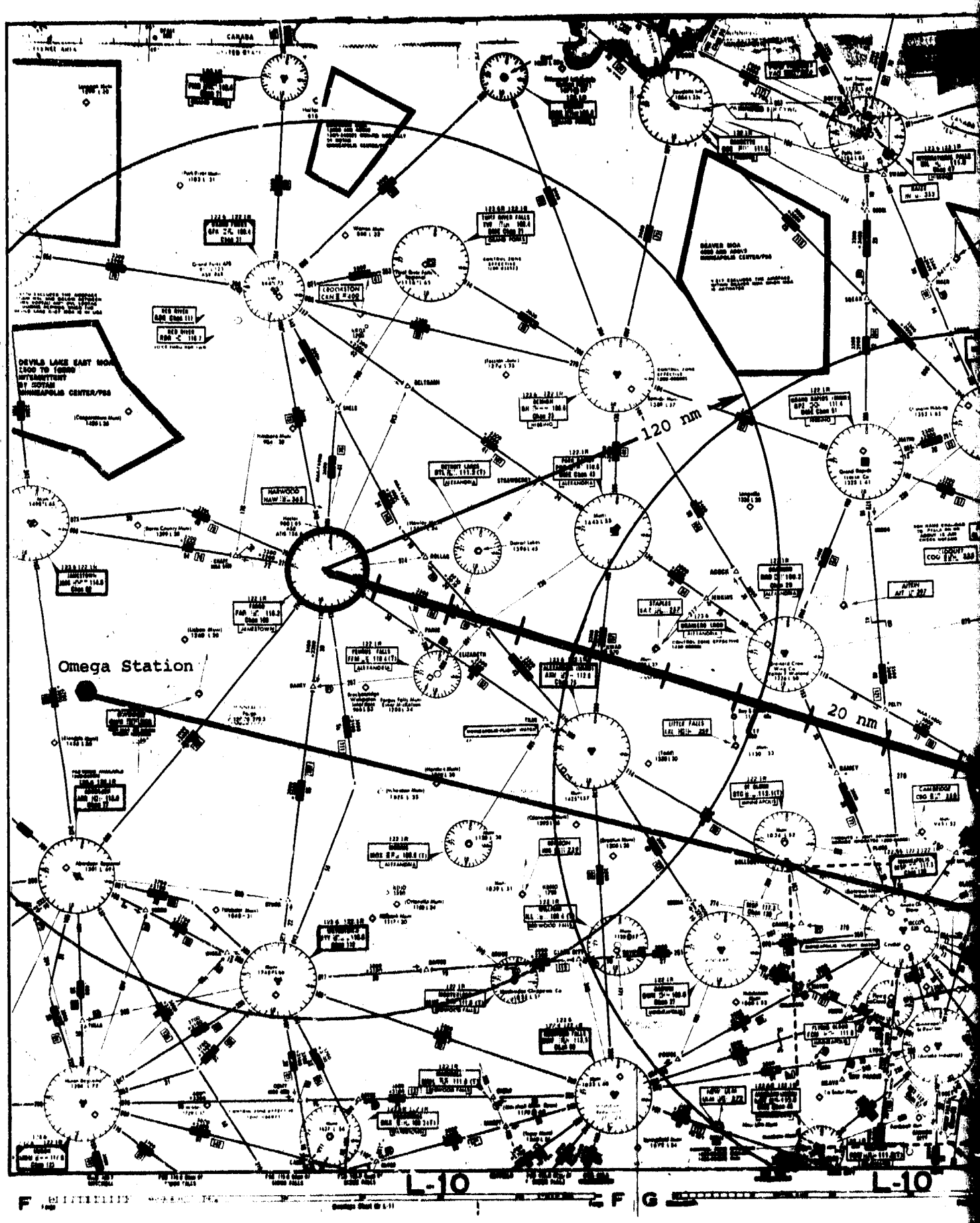
Loran-C

Loran-C is, by definition, an area navigation system. The only inputs required are origin and destination. As with RNAV VOR/DME units, a waypoint list is used to define intermediate flight legs. Current position is always maintained and made available through a reserved location in the waypoint list. Under the assumption that a navaid data base does not exist, the destination (Fargo) must be entered in terms of latitude, longitude, and magnetic variation.

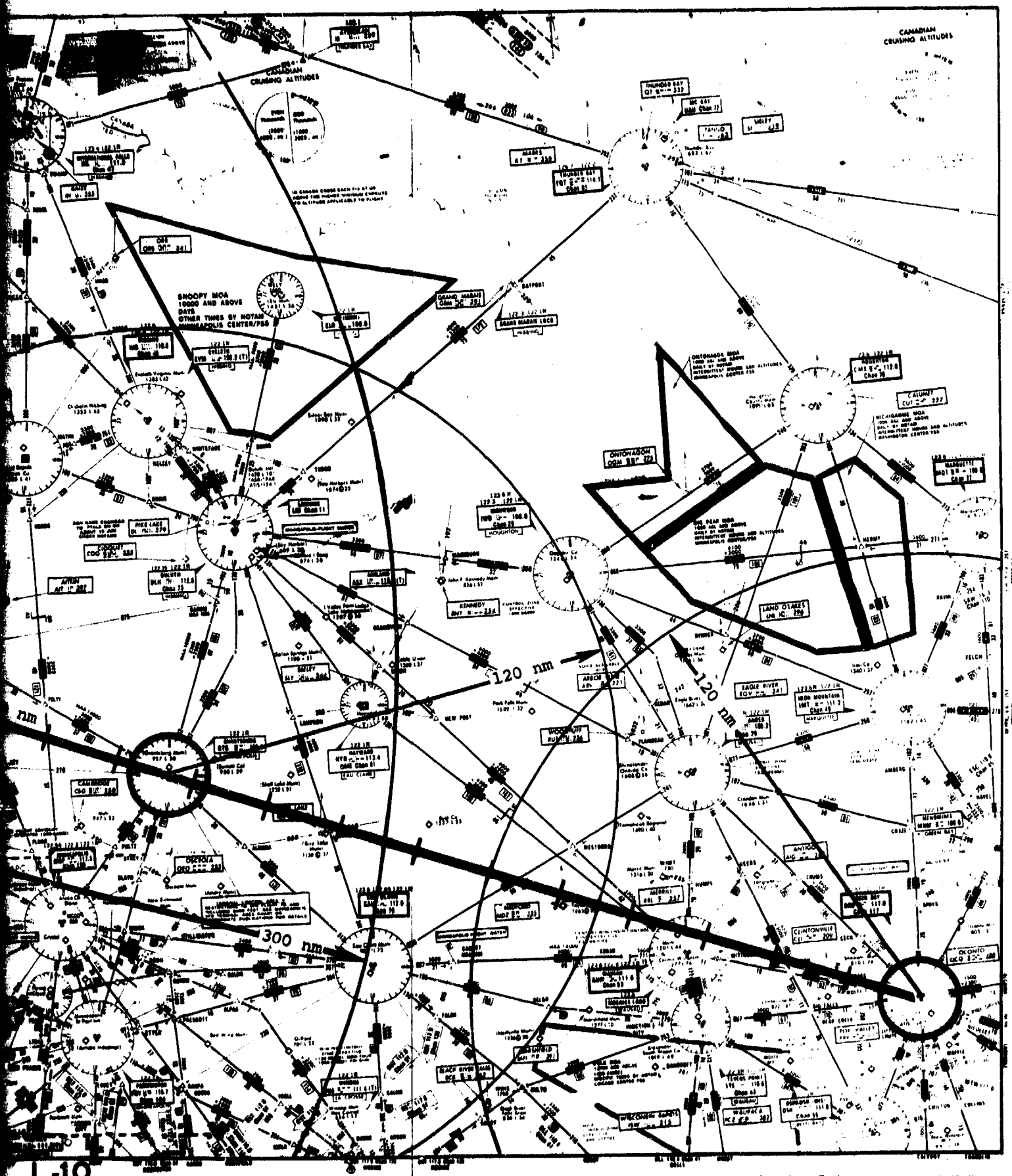
The flight from Green Bay to Fargo was selected in consideration of Omega and Loran-C coverage areas. The flight path passes through an area representing worst-case United States domestic coverage for Omega and Loran-C navigation. A midwest Loran-C chain, currently in the planning stages, would dramatically improve Loran-C coverage in the United States. The origin, Green Bay, Wisconsin, is well within the coverage area of the Loran-C Great Lakes chain. Fargo, North Dakota, however, is beyond the published coverage area of the Great Lakes chain and is also out of range of the Loran-C chain for the west coast of the United States. The published limits of Loran-C coverage are approximations based on a signal-to-noise ratio of 1:3 and a fix accuracy of 0.25 nm (95 percent, 2 drms). Therefore, as the pilot progresses toward Fargo from Green Bay, degradation in signal strength could cause loss of navigation integrity when the aircraft is 310 nm out of Green Bay, with 80 nm still remaining to Fargo.

Omega/VLF

Unlike Loran-C, Omega/VLF is considered a worldwide navigation system. As with Loran-C, however, the only inputs required for establishment of a direct-to great-circle route are specifications of origin and destination.



Source: *Enroute Low Altitude - U.S. Flight Information Publication*, Reference 27.



7.

Figure 5-3. FLIGHT PATH BETWEEN GREEN BAY, WISCONSIN, AND FARGO, NORTH DAKOTA

Several Omega sets provide access to a data base, allowing input of waypoints in terms of alpha designators.

For this scenario, then, the pilot inputs "FAR" as the "to" waypoint and selects current position as the "from" waypoint. A great-circle route between Green Bay and Fargo is thereby established, and Omega and VLF stations within reception range are used to monitor progress along the flight path.

Seven Omega transmitters are currently operational. They are located in Norway, Argentina, La Reunion, North Dakota, Hawaii, Liberia, and Japan. Norway, La Reunion, and Argentina cannot provide coverage over the route described in this scenario. (The Australian transmitter, when declared operational, will provide coverage over this flight path only at night.) During the time of flight (daytime), Green Bay is within the coverage area of North Dakota, Hawaii, and Liberia. Liberia and Hawaii provide coverage throughout the flight (assuming they are not shut down for scheduled maintenance). The flight enters the outer fringe of the coverage area of the Japan transmitter only upon arrival at Fargo.

Published Omega coverage areas are generally based on a signal-to-noise ratio of 1:10 (-20 dB) or 1:32 (-30 dB). Omega units generally deselect use of a station that is within 300 nm of the receiver to avoid near-field effects. Although some units deselect stations within 600 nm, 300 nm is considered more typical. The North Dakota Omega station is only 76 nm southwest of Fargo. Therefore, the North Dakota station will be deselected when the aircraft is approximately 166 nm out of Green Bay, as illustrated in Figure 5-3.

Coverage along the flight path is provided by the following stations:

Distance to Destination	Available Omega Stations
400 nm	North Dakota, Hawaii, Liberia
300 nm	Hawaii, Liberia
200 nm	Hawaii, Liberia
100 nm	Hawaii, Liberia
0 nm	Hawaii, Liberia, Japan

Satisfactory hyperbolic or rho-rho-rho navigation is possible when three Omega stations are being received. When only two Omega stations are available, hyperbolic navigation is not possible. Rho-rho navigation is possible with only two stations, but the accumulation of error associated with not having an independent measurement for determining user clock bias prevents extended use of this mode. These considerations make navigation using only Omega stations impossible along this flight path when the coverage charts published in Reference 21 are used as the basis for judgment.

However, use of VLF signals to augment Omega navigation provides capability not otherwise possible. Signals from several VLF transmitting stations can be received along the flight path between Green Bay and Fargo. Therefore, an Omega/VLF navigation system can provide satisfactory navigation in this case study. Addition of a VLF signal-processing capability to the Omega unit has no effect on the pilot interface with the unit.

GPS

GPS, a satellite-based navigation system, is also an area navigation system. The capabilities planned for a low-cost GPS navigation system are essentially similar to those previously described for the Loran-C receiver. It is assumed that a VOR/DME data base is not used. Origin and destination are entered in terms of latitude and longitude. A waypoint list is used to define intermediate flight legs if they are needed, and current position is available in a reserved location in the waypoint list. The route between Green Bay and Fargo is established by entering the latitude and longitude of Fargo into the waypoint list and defining that waypoint as the "to" waypoint; current position serves as the origin and is defined as the "from" waypoint. As has been assumed previously, the navigation unit in use has been operational for some time, and the received signals provide satisfactory navigation capability at the time the direct-to clearance is issued.

With an 18-satellite configuration of three satellites in six orbital planes, more than four satellites are not always in view over the continental United States above an elevation angle of 10 degrees. Four satellites are required for three-dimensional navigation by GPS; as long as four satellites remain in view, such navigation between Green Bay and Fargo is possible. After establishing origin and destination, all the pilot needs to do with the navigation system for the duration of the flight is to monitor and correct deviation from the flight path as indicated by the navigation system display. However, in a situation where fewer than four satellites are in view, the navigational capability of GPS is reduced dramatically. Even with an altimeter providing a vertical position measurement to the GPS receiver, having only three satellites in view would result in degraded position accuracy where satellite geometry, in conjunction with the altimeter measurement, creates a symmetrical arrangement resulting in poor HDOP. Without the altimeter input, user clock bias can not be estimated with only three satellites - again the result is degraded position accuracy.

INS

INS is a self-contained navigation system, which is by definition an area navigation system. Assuming that a VOR/DME data base is not used, origin and destination are entered in terms of latitude and longitude. Intermediate flight legs are defined by waypoints entered into a waypoint list. Current latitude and longitude are available in a reserved location in the waypoint list. The route between Green Bay (current position) and Fargo is established by entering the latitude and longitude of Fargo into the waypoint list and defining that waypoint as the "to" waypoint. The waypoint reserved for current position is then defined as the "from"

waypoint. As the aircraft progresses from Green Bay to Fargo, the position accuracy of the INS degrades as a function of time. Figure 5-4 illustrates how this degradation of position accuracy interacts with the flight technical error to produce a total position error that exceeds the ±4 nm route width after 2.2 hours of flight. Assuming an airspeed of 200 knots or more, the flight time from the point of departure (Chicago) to Fargo is less than 2.2 hours. Therefore, INS provides sufficient accuracy in this case study.

5.2.2.3 Discussion of Results

Comparisons

Comparison of the units considered in this case study leads to the following conclusions:

- Non-RNAV systems provide direct-to capability only when the intended destination is a VORTAC and the airborne receiver is within range of the transmitted signal.
- For RNAV VOR/DME-based navigation systems, automatic station selection eliminates the need for the pilot to concern himself with station acquisition and signal monitoring. Such capability makes the RNAV VOR/DME unit comparable to existing Loran-C and Omega/VLF units in terms of pilot interface. If a standard man-machine interface is incorporated into the design of all navigation system units, pilots can ideally operate any navigation system unit without regard to the type of signals processed.
- Manual station selection of navaids, although less desirable than automatic station selection, can be made acceptable in VOR/DME navigation systems through the use of a navaid data base. Specification of a navaid by either its three-letter ident or its frequency eliminates the need for time-consuming and error-prone entry of latitude, longitude, frequency, and magnetic variation of each desired navaid.
- Current designated airways are defined on aeronautical navigation charts in terms of VORs, justifying the use of existing airway descriptors in the design of non-VOR/DME-based systems. Such design philosophy includes the use of a VOR/DME data base, as well as versatility in input and output formats to include bearing and distance information.

System Mix Conflicts

This case study concerns an aircraft using the on-board navigation system to establish and maintain a direct course to a final destination. Assume that two aircraft, each with a different navigation system, are given clearance to the same destination from the same position fix. One aircraft is using an Omega navigation system, the other a VOR/DME RNAV system that has rhumb-line navigation capability. Obviously, both aircraft could not depart from the same fix at the same time. If the controller has

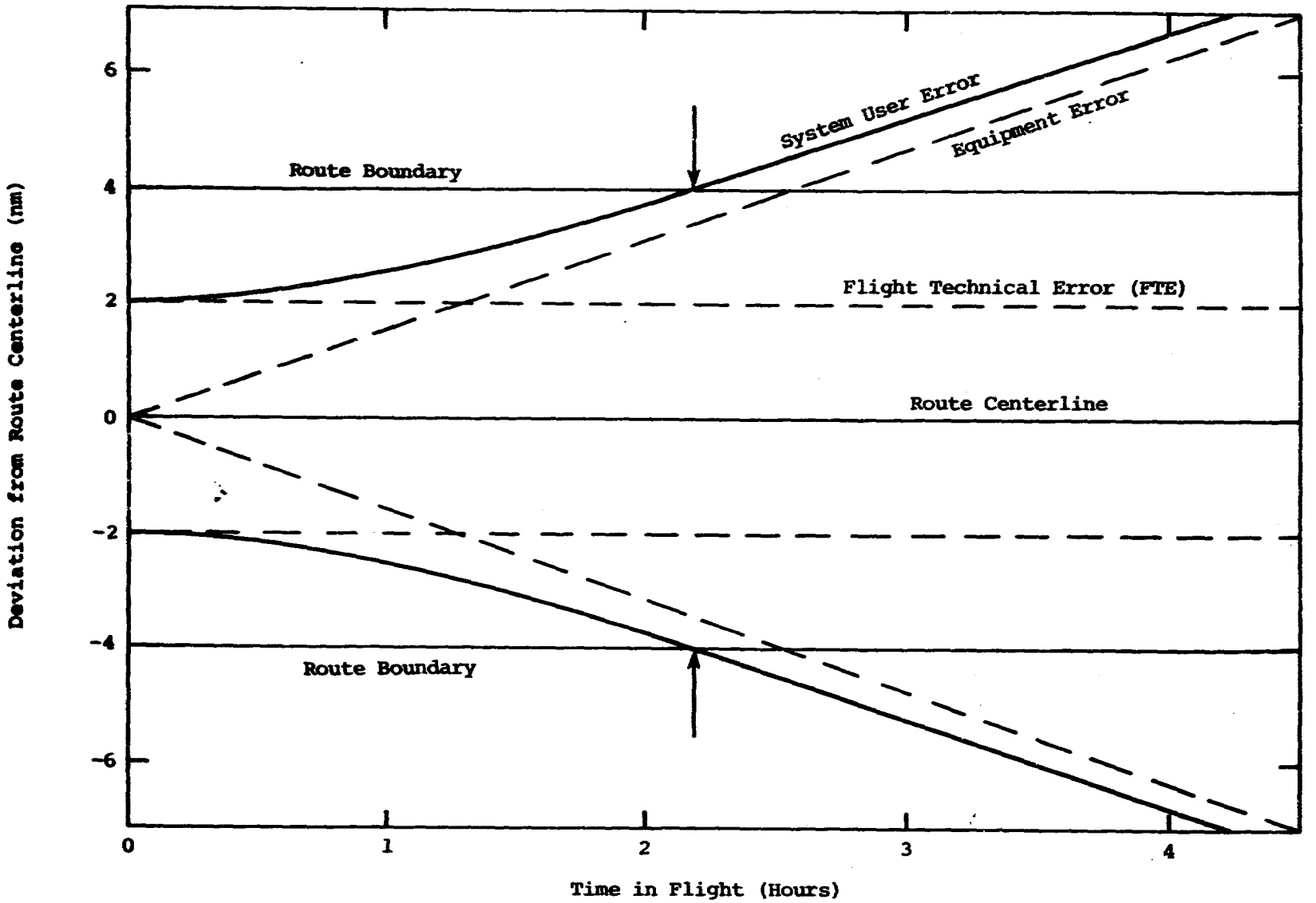


Figure 5-4. INS SYSTEM USE ACCURACY AS A FUNCTION OF TIME IN FLIGHT

spaced the aircraft to ensure adequate longitudinal separation, the controller can expect the aircraft to follow the same flight path, since they are traveling between the same origin and destination. However, differences in course-calculation techniques (rhumb-line versus great-circle), in the accuracy with which intermediate waypoints are defined (manual charting versus computer calculation), in the accuracies of systems (2.5 nm for Omega versus 0.5 nm for VOR/DME), and in the coordinate systems used (spherical versus Clarke 1866), all interact to cause varying degrees of deviation between flight paths. Again, the burden is on the controller to monitor the magnitude of the deviations and take appropriate corrective action when it is necessary. Table 5-2 shows the distance disparities of each of these conflicts for a flight of 392 nm between Green Bay, Wisconsin, and Fargo, North Dakota. (The difference in accuracy of path definition between manual charting and computer calculation is not easily quantified and is therefore not included in the table.) The equations used to obtain the distance differences associated with path selection and earth model are shown in Appendix B.

Table 5-2. ACCURACY CONFLICTS IN CASE STUDY TWO

Element of Conflict	Cause of Conflict	Resultant Distance Disparity (nm)
Path Selection	Rhumb line versus great circle	6.41
Navigation System	Omega versus VOR/DME	3.00
Earth Model	Spherical versus Clarke 1866	1.30

Figure 5-5 illustrates the way the navigation distance disparities shown in Table 5-2 can combine to result in a distance difference of 9.5 nm. Therefore, although each aircraft has been cleared to the same destination from the same origin, the route width required to contain all flight paths is greater than the current standard route width of 8 nm for domestic en route flights when within 51 nm of a VOR.

Case Study Two was for a flight of 392 nm. For longer flights, the relative position displacements resulting from differences in path selection and earth models increase. As an example, for a flight from New York to Los Angeles, the maximum cross-track distance between a rhumb-line path and a great-circle path is 135 nm.

5.2.3 Case Study Three

5.2.3.1 Description

Situation

Case Study Three considers an ATC request to "track outbound on the Green Bay VOR zero nine zero radial."

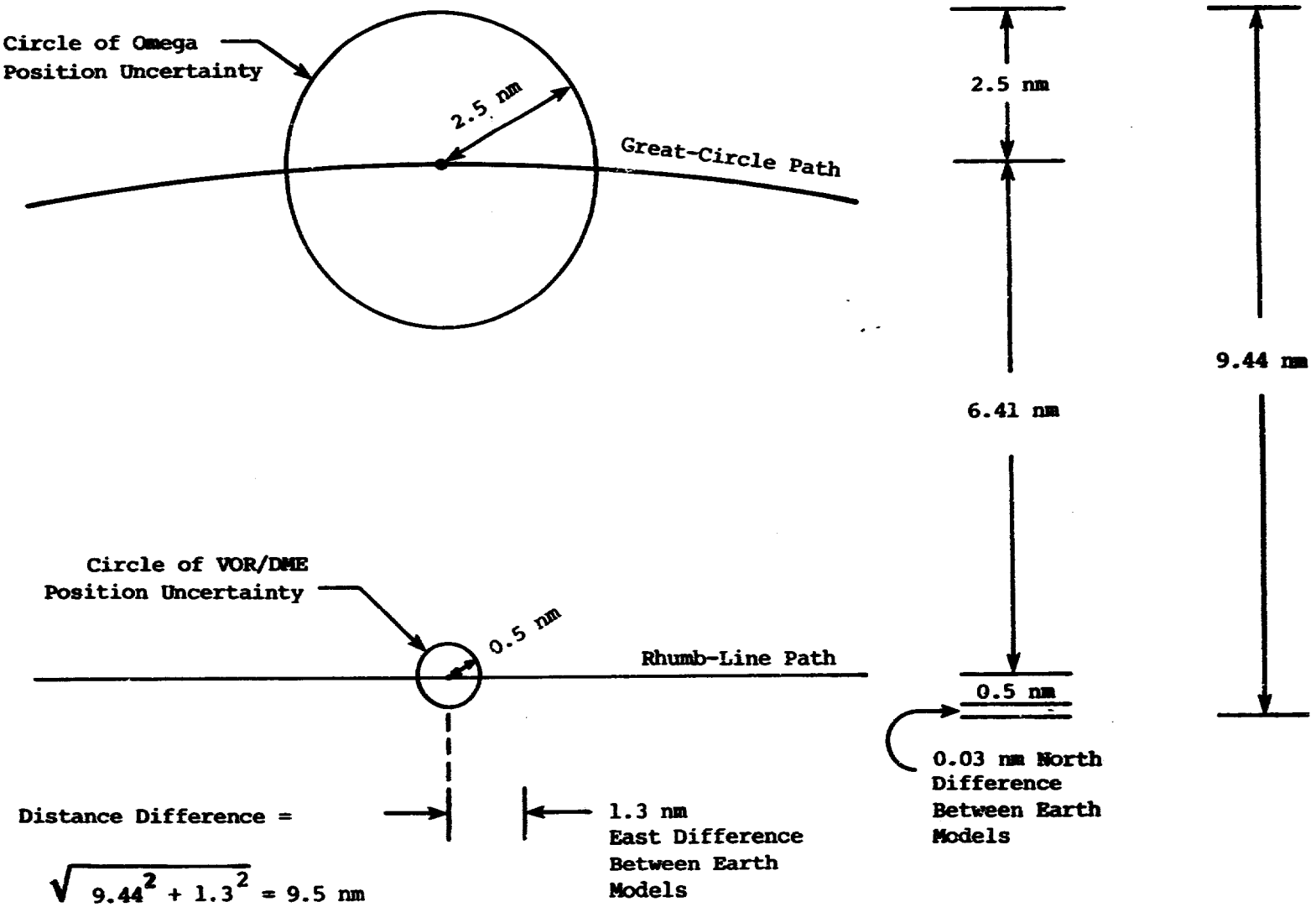


Figure 5-5. PICTORIAL REPRESENTATION OF SYSTEM MIX RELATIONSHIPS FOR CASE STUDY TWO

Applicable Systems

The single VOR system is discussed separately; non-RNAV VOR/DME systems, both single and multiple, are discussed jointly, as are both single and multiple RNAV VOR/DME systems. Also discussed, as common systems, are Loran-C, Omega, GPS, and INS.

5.2.3.2 Application of Scenario

In this scenario, the single VOR performs satisfactorily. The VOR receiver is tuned to the frequency of the Green Bay VOR. The pilot then establishes his position in terms of bearing from the VOR. Depending on the magnitude of difference between present course and desired course along the 090-degree radial, the pilot determines an appropriate course-cut angle by which the 090-degree radial can be intercepted without too much overshoot. Once track on the 090-degree radial is established, the pilot will continue to monitor the deviation from selected course to maintain a track of 090 degrees until the controller provides further instructions. The only difficulty that is encountered is the fading of the VOR signal if the request to maintain track is not altered before the aircraft is out of range of the VOR.

Non-RNAV VOR/DME

Existence of the DME does not significantly affect the capability of the system to satisfy the ATC request. The aircraft is still flown so that a VOR bearing indication of 090 degrees is maintained. The DME readout is helpful only in monitoring distance from the VOR so that ATC can be notified (before complete loss of signal) if this distance becomes too great.

RNAV VOR/DME

The workload necessary to establish an RNAV route to comply with this request can be avoided by recognition that the full capability of the navigation system is not needed in this situation. Rather, the response should be as described for the non-RNAV VOR/DME navigation system.

Loran-C, Omega, GPS, INS

For navigation systems not referenced to VOR signals, a flight path coincident with the Green Bay VOR radial of 090 degrees must be defined. This can be achieved by first defining the origin of the RNAV flight path to be the latitude and longitude of the Green Bay VOR. Destination can then be entered as a bearing and distance offset from the origin; the bearing would be 090 degrees, and the distance could be, say, 100 nm. Once this flight leg is activated, a course deviation is indicated. Response to the deviation would establish track along the 090-degree radial. An advantage of these RNAV systems is that they are not susceptible to loss of the VOR signal, and therefore loss of reference, as the aircraft becomes increasingly distant from the VOR along the radial.

5.2.3.3 Discussion of Results

Relative Comparisons

By requiring the aircraft simply to maintain a constant relative bearing to a VOR, this case study illustrates the most basic use of VOR-based navigation systems and the premise on which airways were established. Therefore, VOR-based navigation systems surpass other navigation systems in the ease with which compliance with the request is achieved. That does not mean, however, that Loran-C, Omega, GPS, or INS navigation systems would have difficulty defining a VOR radial; such a procedure is, in fact, quite easy. The point is that a VOR navigation system can perform more naturally in this environment than any other system.

System Mix Conflicts

The VOR station, which provides the signal used by the VOR-based navigation system, is at a fixed location on the earth. VOR receivers can navigate in relation to the VOR without regard to the actual geographical coordinates of the VOR as long as their destination or flight path is also defined with respect to the VOR.

Non-VOR-based navigation systems must use geographical coordinates to represent a VOR used for position reference. Conflicts can occur if the geographical coordinates used by Loran-C, Omega, GPS, or INS navigation systems do not correspond to the actual location of the VOR. This can result from error in pilot input for navigation systems with no access to a data base or from the airborne unit processor's use of an earth model substantially different from the model defining the reference chart.

The possibility that various types of navigation systems may not agree upon the absolute position of a reference VOR could create conflict. The seriousness of this situation is a function of the degree of difference in perceived location of the VOR. Error in pilot input presents the greatest potential for conflict. A mistake of only one arc minute in latitude would cause a displacement of 1 nm between the basis of reference and the actual VOR. Availability of a data base would eliminate the potential for such errors (if the data base was error-free).

In this case study, as in the previous situations, the controller is responsible for monitoring compliance with requests. If an aircraft does not satisfactorily respond to a request, the controller must take corrective action. It would be confusing if a pilot with a non-VOR-based navigation system had established a track on a 90-degree bearing from a waypoint corresponding with the coordinates of the Green Bay VOR and was then told by ATC that he was flying a track parallel to the requested track but with an offset of 10 nm. The pilot would lose confidence in his navigation system, revert to magnetic heading, and request vectors, thus increasing the burden on the controller.

5.2.4 Case Study Four

5.2.4.1 Description

Situation

Case Study Four considers an ATC request to "report crossing Jones intersection." The "Jones intersection" denotes a frequently used position fix defined in terms of two bearings from two VORs. The request is similar to "report crossing the Green Bay three one zero radial two five miles fix," which is referenced to a single VORTAC.

General Comments

An intersection is a defined waypoint in the National Airspace System (NAS). Intersections are referenced to VORs in terms of bearings, and/or bearing and distance, and are so specified on aeronautical charts.

Applicable Systems

Single VOR, non-RNAV single VOR/DME, and RNAV single VOR/DME are discussed separately; multiple VOR/DME, both non-RNAV and RNAV, are discussed jointly. Also discussed as common systems are Loran-C, Omega, GPS, and INS.

Single VOR

The VOR receiver can be tuned to one of the reference VORs and can provide a basis for navigation along the VOR radial on which the intersection is located. The pilot establishes track on the course radial, compensates for any drift resulting from wind, and estimates time of arrival at the intersection through knowledge of groundspeed. Before the estimated time of arrival at the intersection, the pilot tunes the VOR receiver to the off-course station and monitors radial crossings. Time of passage occurs when the desired intersecting radial is crossed.

Non-RNAV Single VOR/DME

Addition of DME to the VOR receiver allows navigation within the signal coverage of the VORTAC, in terms of both bearing and distance relative to the VORTAC. Two techniques are used to establish point of passage over the defined waypoint when a non-RNAV VOR/DME navigation system is used. One method is to establish track on the reference VOR radial on which the intersection is defined. The DME readout is then monitored for indication of convergence to the distance specification for the intersection. Coincidence of measured bearing and distance with desired bearing and distance signifies passage over the intersection and can be so reported to ATC. A second, less practical, method is used when a circular arc is flown about the reference VORTAC in which a DME range is held constant, corresponding to the specified distance of the intersection from the reference VORTAC. Monitoring of VOR bearing readout then indicates convergence on the intersection and subsequent passage.

Both of these techniques are routinely used; the choice corresponds to the flight path for which ATC clearance was granted. ATC may not require a report of passage over an intersection if the flight plan is not along one of the VOR radials defining the intersection.

RNAV Single VOR/DME

Each RNAV waypoint in a single VOR/DME navigation system is defined with respect to a particular VORTAC. The Jones intersection can be designated a waypoint, because it is intended to be on the flight path; it can therefore be defined in accordance with the charted bearing and distance from the reference VORTAC. Distance to this waypoint can then be directly monitored via the navigation system display. However, the need to establish a new waypoint imposes on the pilot the additional task of inputting the frequency of the reference VORTAC and the bearing and distance from that VORTAC, which define the waypoint. Since the addition of a new waypoint in a multiple waypoint RNAV unit does not have to overwrite existing waypoints, the pilot can easily revert to the previously designated waypoint once the aircraft has passed over the intersection.

Multiple VOR/DME

A multiple VOR/DME navigation system is well suited to meet the requirements imposed in this case study, regardless of whether the system has RNAV capabilities. One of the VOR/DME receivers of the non-RNAV system can be dedicated to the VORTAC providing the reference for the intersection, while the other receiver can be available for primary navigation. For an RNAV multiple VOR/DME system, the unit can be used in the manner described for an RNAV single VOR/DME system.

Loran-C, Omega, GPS, INS

All remaining RNAV systems (Loran-C, Omega, GPS, and INS) provide the capability to define waypoints in terms of latitude and longitude coordinates. Therefore, the coordinates of the Jones intersection can be entered into the RNAV system to define a waypoint, and subsequent distance to the intersection can be directly monitored.

The ease with which RNAV systems can comply with the ATC request in this case study is diminished by the infrequency with which position fixes on charts are specified in terms of latitude and longitude in addition to bearing and distance. As an alternative to entering the latitude and longitude of the intersection, the coordinates of the VOR from which the Jones intersection is referenced can be entered to define a waypoint reference. A bearing and distance offset from this reference can then be entered to define the Jones intersection, the actual desired waypoint. However, such capability in input format is currently limited in availability.

5.2.4.3 Discussion of Results

Relative Comparisons

VOR/DME systems are better suited for response to this case study request than are non-VOR/DME-based navigation systems for the reasons stated in the discussion of Case Study Three (Section 5.2.3.3).

System Mix Conflicts

Because this case study presents the same potential for conflict as the last case study, the discussion of Case Study Three also applies to this situation.

5.2.5 Case Study Five

5.2.5.1 Description

Situation

The last case study to be considered is the pilot response to an ATC clearance to "fly North Atlantic Track F." Track F is the over-water portion of a daytime flight from London to New York. About 3.7 hours is required to fly the 1806 nm track at Mach .84 (about 490 knots). Procedures during the over-land portions of the flight are similar to those described in Case Studies One through Four.

General Comments

The system of defining the North Atlantic tracks is called the Organized Track System (OTS). A set of tracks is selected twice each day according to meteorologic conditions. The selected tracks are separated laterally by 60 nm (± 30 nm track width) and are labelled with alpha designators (e.g., Track A) sequentially from north to south. Over-water air traffic control procedures include reporting position in terms of latitude and longitude at specified intervals along the tracks. Reporting points are located at whole 10-degree meridians and at whole-degree latitude lines. A chart that provides the latitude and longitude of the reporting points defining the North Atlantic tracks on a given day is called a route chart. Each track comprises, then, a series of great-circle segments between specified reporting points and is illustrated on the route chart. A track is terminated at each end by a waypoint called a track gateway or anchor point. On the day of this flight, Track F is defined between the anchor points Cork in Ireland and Springdale in Newfoundland.

Applicable Systems

Neither VOR/DME nor Loran-C provides adequate coverage, and they are not discussed. Omega and GPS are discussed jointly. The Doppler navigation system and INS are each discussed separately.

5.2.5.2 Application of Scenario

Omega and GPS

The pilot enters the latitude and longitude of the anchor points and the specified reporting points into the navigation unit. The unit then establishes a route comprised of great-circle segments defined between the entered waypoints. This route coincides with Track F. Both Omega and GPS provide continuous navigation accuracy in excess of that required throughout the over-water portion of the flight. As has been assumed previously, the navigation unit in use has been operational for some time, and the received signals provide satisfactory navigation capability at the time of crossing the Cork anchor point. A display of current latitude and longitude is available for monitoring, providing a convenient means for reporting position at the required intervals.

Doppler

Doppler navigation systems used in recent years in civil applications use a course generation method that is neither rhumb line nor great circle. Instead, a desired track angle is computed for each flight segment that defines a constant magnetic course. The pilot enters the desired track angle so defined, along with distance-to-go, to establish each segment of his desired path. A series of such segments is used to establish Track F in this case study.

The display of distance-to-go is used to indicate when the aircraft crosses a reporting point. As the aircraft traverses the segment, the distance-to-go display counts down to zero. When the display reaches zero nm, the pilot knows the aircraft is crossing a reporting point. The latitude and longitude of this point can then be obtained from the route chart for reporting purposes.

INS

The latitude and longitude of the anchor points and the reporting points are entered into the INS unit. As described for GPS and Omega, the great-circle route established by the INS coincides with Track F, and a display of current latitude and longitude is available for use if reporting position along the track. Because of the position error accumulated in the INS, VOR/DME is generally used to update the INS after the aircraft passes from the over-water phase to the over-land portion of the flight. The transition between the two navigation systems is typically performed automatically in a gradual manner. Any position discrepancy between the two units is eliminated slowly in order to avoid sudden changes of input to the autopilot.

5.2.5.3 Discussion of Results

Relative Comparisons

Each segment of a North Atlantic track is a great-circle track defined between two reporting points. Each reporting point is specified by its latitude and longitude. The navigation systems that establish great-circle tracks permit navigation of the North Atlantic tracks more naturally than current Doppler navigation systems.

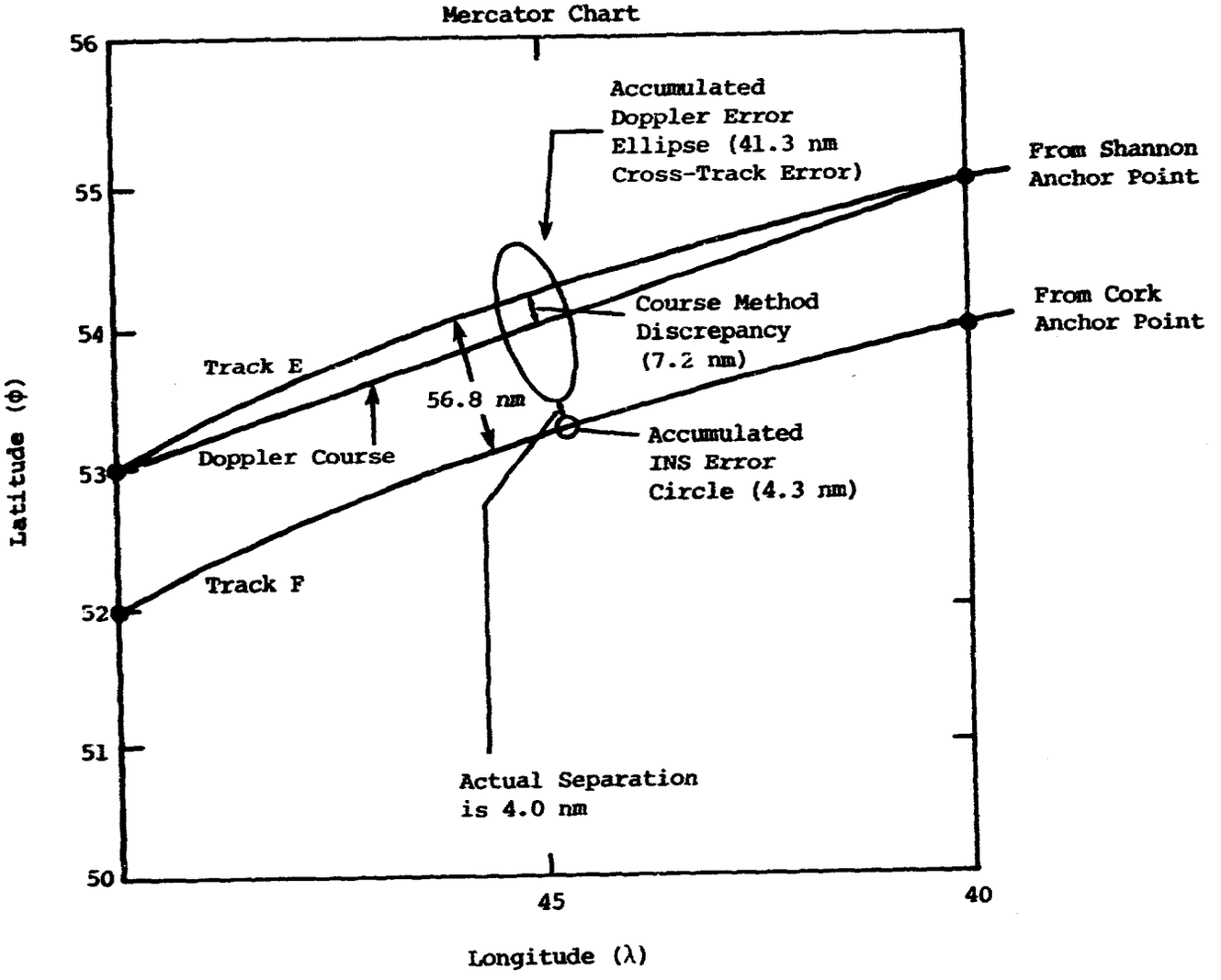
Since position reports are given in terms of latitude and longitude, the navigation systems discussed that can display current latitude and longitude provide a more convenient means of complying with position reporting requirements than most Doppler navigation systems that do not.

Many users of Doppler navigation systems have discontinued over-water use because of the pilot workload and the potential for errors in position reporting associated with the previously discussed accuracy deficiencies. However, Doppler navigation systems now under development provide both great-circle route generation capability and a display of current latitude and longitude. These features provide operational effectiveness for Doppler comparable to that demonstrated by INS in this case study.

System Mix Conflicts

In this case study an aircraft uses a navigation system to establish and maintain a course coincident with North Atlantic Track F. Consider two aircraft on adjacent Tracks E and F both at flight level 350. Both aircraft are westbound and are given clearance in Ireland at nearly the same time. The aircraft flying Track E is using a Doppler navigation system, and the aircraft flying Track F is using conventional INS. Although the track center lines are separated by one degree of latitude (i.e., 60 nm measured along a meridian), the actual lateral separation (i.e., perpendicular distance) between the two aircraft can be significantly less than 60 nm, as described below.

The required 60-nm track separation is based on one-degree intervals of latitude between adjacent tracks measured along a meridian. The perpendicular distance between the center lines of adjacent tracks can be somewhat less than 60 nm; it is a function of the course angles of the tracks. For example, the perpendicular distance between Tracks E and F midway between the reporting points at 40°W and 50°W is 56.8 nm, as shown in Figure 5-6. The maximum distance disparity between the course used by the Doppler navigation system and the corresponding great-circle track between these same two reporting points is 7.2 nm along Track E. The distance disparity resulting from differences in course generation methods interacts with the accuracies of the two navigation units to cause varying degrees of deviation from the intended lateral separation between the two aircraft. The distance from the anchor points in Ireland to points midway between the reporting points at 40°W and 50°W along Tracks E and F is about 1300 nm. The Doppler navigation system accumulates a cross-track error of 41.3 nm and an along-track error of 13.9 nm in traversing 1300 nm,



●Required position reporting point.

Figure 5-6. SYSTEM MIX RELATIONSHIPS FOR CASE STUDY FIVE

forming the error ellipse illustrated in Figure 5-6. Traveling at 490 knots, the aircraft will take about 2.7 hours to traverse 1300 nm. The conventional INS accumulates 4.3 nm of position error in 2.7 hours and is shown as a circular error in Figure 5-6. Figure 5-6 illustrates the way in which the system errors interact with the distance disparity to yield a lateral separation of only 4.0 nm between the two aircraft.

5.3 SUMMARY OF CASE STUDIES

Table 5-3 summarizes navigation system performance in each of the five case studies as they relate to six performance rating criteria. Case Study One demonstrated that navigation systems cannot replace the need for heading devices in the current ATC environment. The heading sensors currently in use range from low-cost "wet" compasses to gyro-stabilized flux-value compasses. The inability of navigation systems to provide heading information does not, however, preclude the possibility of unique advantages and disadvantages being attributed to particular navigation systems during use in other operational scenarios. Although the ratings are intended to indicate the relative operational capability of the systems relative to each case study, totaling the numbers in each column leads to some interesting observations. The level of capability for each system can be ranked according to the value of the sum of the codes; the lower the value, the more capable the system. This method of ranking system capability assumes that all case studies are of equal significance in their relationship to performance. In addition, it must be remembered that although VOR/DME, Omega, Loran-C, Doppler, and INS are ranked in accordance with existing levels of performance and coverage, GPS is evaluated with respect to a projected level of performance capability.

Table 5-3. RATING OF NAVIGATION SYSTEM PERFORMANCE IN CASE STUDIES*

Case Study	Non-RNAV			RNAV						
	Single VOR	Single VOR/DME	Multiple VOR/DME	Single VOR/DME	Multiple VOR/DME	Loran-C	Omega/VLF	GPS	Doppler	INS
1 (Fly Heading)	6	6	6	6	6	6	6	6	6	6
2 (Fly Direct To)	5	5	5	3	2	5	1	1	5	1
3 (Fly Radial)	1	1	1	1	1	2	2	2	5	2
4 (Report Position)	4	1	1	1	1	2	2	2	5	2
5 (Fly Ocean Track)	5	5	5	5	5	5	1	1	2	1
Total	21	18	18	16	15	20	12	12	23	12

*Performance rating criteria for this table are as follows:

1 = Primarily requires pilot monitoring.
2 = Requires some manual calculations and/or routine interaction between pilot and unit.
3 = Requires ancillary equipment or periodic manual corrections by pilot.
4 = Requires much manual calculation and/or a high level of pilot interaction with unit.
5 = Objective cannot be met because of lack of signal coverage or inadequate accuracy.
6 = Objective cannot be met because of limitations of system capability.

A Doppler navigation system is shown in the scenarios to be the least operationally capable system because of inadequate accuracy capability in en-route domestic applications. Omega/VLF, GPS, and INS are overall the most effective systems because of their transoceanic navigation capability, as discussed in the account of Case Study Five. The RNAV multiple VOR/DME system is ranked lower than Omega/VLF, GPS, and INS only because of lack of transoceanic coverage. It is otherwise the most effective system, since the current ATC environment over land is predicated on the VOR/DME system. Loran-C was given a lower ranking than Omega/VLF, GPS, and INS only because of lack of Loran-C coverage in the area of interest defined in Case Study Two and in the transatlantic route defined in Case Study Five. Recent developments in the design of Loran-C receivers indicate a potentially significant advancement in Loran-C operational capability. If the design goals are achieved and verified, there will be an impact on the performance rating of Loran-C as presented in this report.

As a result of the case study evaluations, the navigation systems may be ranked in descending order of effectiveness for world-wide applications as follows:

- Omega/VLF, GPS, INS
- RNAV multiple VOR/DME
- RNAV single VOR/DME
- Non-RNAV VOR/DME
- Loran-C
- Single VOR
- Doppler

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

Currently available navigation systems offer numerous combinations of capabilities. The multitude of choices results from the different requirements imposed by different users, mandated by particular applications. The most basic decision to be made by a user is the selection of the particular type of navigation system (Loran-C, Omega/VLF, VOR/DME, GPS, Doppler, or INS) that best meets his needs. The most critical criteria considered in this initial selection process are signal accuracy and coverage. Table 6-1 summarizes each navigation system's ability to provide sufficient coverage and accuracy to be considered acceptable in different operational environments and flight phases. VOR/DME, Omega, Loran-C, Doppler, and INS were evaluated in terms of existing levels of performance and coverage, whereas GPS was evaluated with respect to a projected level of performance capability.

Loran-C has sufficient accuracy to meet all en-route requirements, but the limited number and coverage area of Loran-C station chains restrict its current use to only a subset of domestic en-route applications. Although this restriction limits the suitability of Loran-C as an independent means of navigation, it does not impede its consideration for use in a system mix for domestic and off-shore applications. Recent developments in the design of Loran-C receivers indicate potential advances in operational capability that could improve the suitability of Loran-C for independent domestic en-route navigation. Use of Loran-C for terminal and nonprecision approach navigation, if approved, will be limited to areas where signals are available.

Omega/VLF provides worldwide coverage, with an accuracy suitable for en-route navigation but not sufficient for terminal or nonprecision approach operations.

GPS, even with a denial of accuracy to a level of 500 meters, would provide sufficient accuracy for en-route, terminal, and many nonprecision approach navigation operations, assuming continuous availability of four satellites.

Table 6-1. SUMMARY OF NAVIGATION SYSTEMS' ABILITY TO PROVIDE ACCURACY AND COVERAGE

Navigation System	Operational Environment				
	En Route			Terminal	Nonprecision Approach
	Domestic	Trans-oceanic	Remote Offshore		
Loran-C	Suitable[1]	No Coverage	Suitable	Suitable[1]	Suitable[1]
Omega/VLF	Suitable	Suitable	Suitable[2]	Insufficient Accuracy	Insufficient Accuracy
GPS	Suitable	Suitable	Suitable	Suitable	Suitable[2]
VOR/DME	Suitable	No Coverage	No Coverage	Suitable	Suitable[1]
Doppler	Insufficient Accuracy	Suitable[4]	Insufficient Accuracy	Insufficient Accuracy	Insufficient Accuracy
INS	Suitable[3]	Suitable	Suitable[2]	Insufficient Accuracy	Insufficient Accuracy

[1]When coverage is available.
[2]Under conditions allowing attainment of sufficient accuracy.
[3]For flights of less than one hour.
[4]For ocean tracks less than 400 nm.

Accuracy requirements are specified in FAA AC-90-45A.

Because VOR/DME navigation is the basis upon which domestic navigation standards were developed, it provides an acceptable level of accuracy. Lack of coverage in oceanic, remote, and offshore areas resulting from line-of-sight limitations and unavailability of suitable sites limits the application of VOR/DME.

Doppler navigation systems can provide sufficient capability to meet oceanic en-route accuracy requirements for limited path lengths, but insufficient accuracy for all domestic requirements.

INS provides sufficient accuracy for oceanic en-route requirements. Because INS accuracy degrades as a function of time in flight, INS can meet domestic en-route requirements only for flight durations of less than one hour. However, INS can be used for extended periods of time when position updates are available from suitable radionavigation units. The time between updates must not exceed that which would result in the INS exceeding the allowable error.

On the basis of the results of the case studies of operational performance capability, the navigation systems are ranked in descending order of overall (i.e., both domestic and oceanic) effectiveness as follows:

- Omega/VLF, GPS, INS
- RNAV multiple VOR/DME
- RNAV single VOR/DME
- Non-RNAV VOR/DME
- Loran-C
- Single VOR
- Doppler

The operational effectiveness of each navigation system was measured by comparing the systems in terms of the ease with which they could be used to meet the stated objective of the particular case study. Emphasis was placed on the limitations of the navigation system, not on the functional capabilities of particular CDU designs.

Selection of GPS, Omega/VLF, and INS as the most operationally effective systems is predicated on their transoceanic navigation capability. When oceanic operations are not considered (Case Study 5) the navigation systems are ranked in descending order of effectiveness in domestic operations as follows:

- RNAV multiple VOR/DME
- RNAV single VOR/DME, Omega/VLF, GPS, INS
- Non-RNAV VOR/DME
- Loran-C
- Single VOR
- Doppler

The high ranking of RNAV VOR/DME systems is to be expected, since the current domestic ATC environment is based on VOR/DME. GPS is ranked lower than multiple VOR/DME RNAV solely on the basis of perceived functional capability as demonstrated in the case studies. It must again be emphasized, however, that there is no technical impediment to enhancing the functional features attributed in this report to GPS units. Loran-C is given a lower ranking than Omega/VLF and GPS only because of limitations in current Loran-C coverage.

The case studies identified an effect on pilot and controller workload when a geographically referenced navigation system was utilized in a station-oriented, procedural environment. Pilot workload was primarily affected by the differences between non-RNAV and RNAV navigation systems and the operation of those systems in situations not optimally suited to their specific capabilities.

The case studies also revealed some potentially serious inadequacies regarding the characterization of performance of individual navigation systems. Accuracy of navigation systems has improved to the point where some systems are capable of a greater degree of accuracy then the reference against which accuracy is measured. Differences between the accuracies of earth models, which provide the basis for determining geographical position, can be greater than the accuracy capability of some navigation systems. Differences between possible flight paths (great-circle versus rhumb-line) when area navigation systems are used can far exceed specified route widths, even though the two paths have the same origin and destination. At the point of maximum deviation, there is a cross-track difference of 135 nm between the great-circle path and the rhumb-line path between New York and Los Angeles. Differences in sky wave propagation models used in Omega navigation systems can result in differences in accuracy ranging from 3.2 nm to 8 nm.

Unrestricted use of area navigation techniques could result in such diversity of routing that controllers would be overburdened in their attempts to maintain separation of aircraft without conflict. Two forms of action can be taken to promote safe and efficient use of the capabilities of area navigation systems:

- Adoption of standards that define accuracy reference parameters
- Modernization of the ATC system so that ATC can accommodate the capabilities of area navigation systems

Table 6-1 indicates which navigation systems are capable of providing service in each application area, reflecting a probable rather than certified capability to meet existing requirements. A navigation system and possible combinations of systems that can provide navigation capability in all operational environments and flight phases represented in Table 6-1 are as follows:

- GPS*
- GPS and VOR/DME
- GPS and Loran-C
- VOR/DME and Omega/VLF**
- VOR/DME and INS**
- VOR/DME and Doppler**
- VOR/DME, Omega/VLF, and Loran-C
- VOR/DME, INS, and Loran-C
- VOR/DME, Doppler and Loran-C

*Suitable only if approach accuracy requirement is achievable.
**Suitable only if remote and offshore accuracy is achievable.

This list seems to suggest that GPS is the leading contender for selection as the standard navigation system. It could meet all existing requirements. However, to support the adoption of GPS as the primary navigation system of the future would be premature at this time. Acceptance of GPS depends on the resolution of the technical, operational, economic, and institutional issues relevant to its benefit to the civil aviation community. The absence of GPS in the role of a primary navigation system requires the selection of a suitable navigation system mix of existing systems. Since Doppler meets oceanic en-route requirements only for flights less than 400 nm, the VOR-DME-Doppler combination is suitable for only a limited number of conditions. Eliminating the combinations including GPS and Doppler from the list leaves the following combinations:

- VOR/DME and Omega/VLF
- VOR/DME and INS
- VOR/DME, Omega/VLF, and Loran-C
- VOR/DME, INS, and Loran-C

Although it would seem that the first two of these four system combinations would be appropriate in terms of minimizing the number of required systems, neither of them currently provides the accuracy desired for offshore navigation. Loran-C provides not only increased accuracy for offshore navigation but also terminal navigation capability in remote areas where VOR/DME is not suitable. Therefore, Loran-C should be included in the navigation system combinations. By the process of elimination, only two combinations of proven navigation systems are able to meet the technical and operational requirements in the context of existing conditions:

- VOR/DME, Omega/VLF, and Loran-C
- VOR/DME, INS, and Loran-C

It should be noted that each of the various navigation signals identified in this report do not have to be utilized in singular packages exclusive of one another. Inputs from multiple navigation systems can be combined to take advantage of those systems most appropriate for use at any given time.

APPENDIX A

DETAILED SYSTEM DESCRIPTIONS

1. LORAN-C

1.1 History of Development

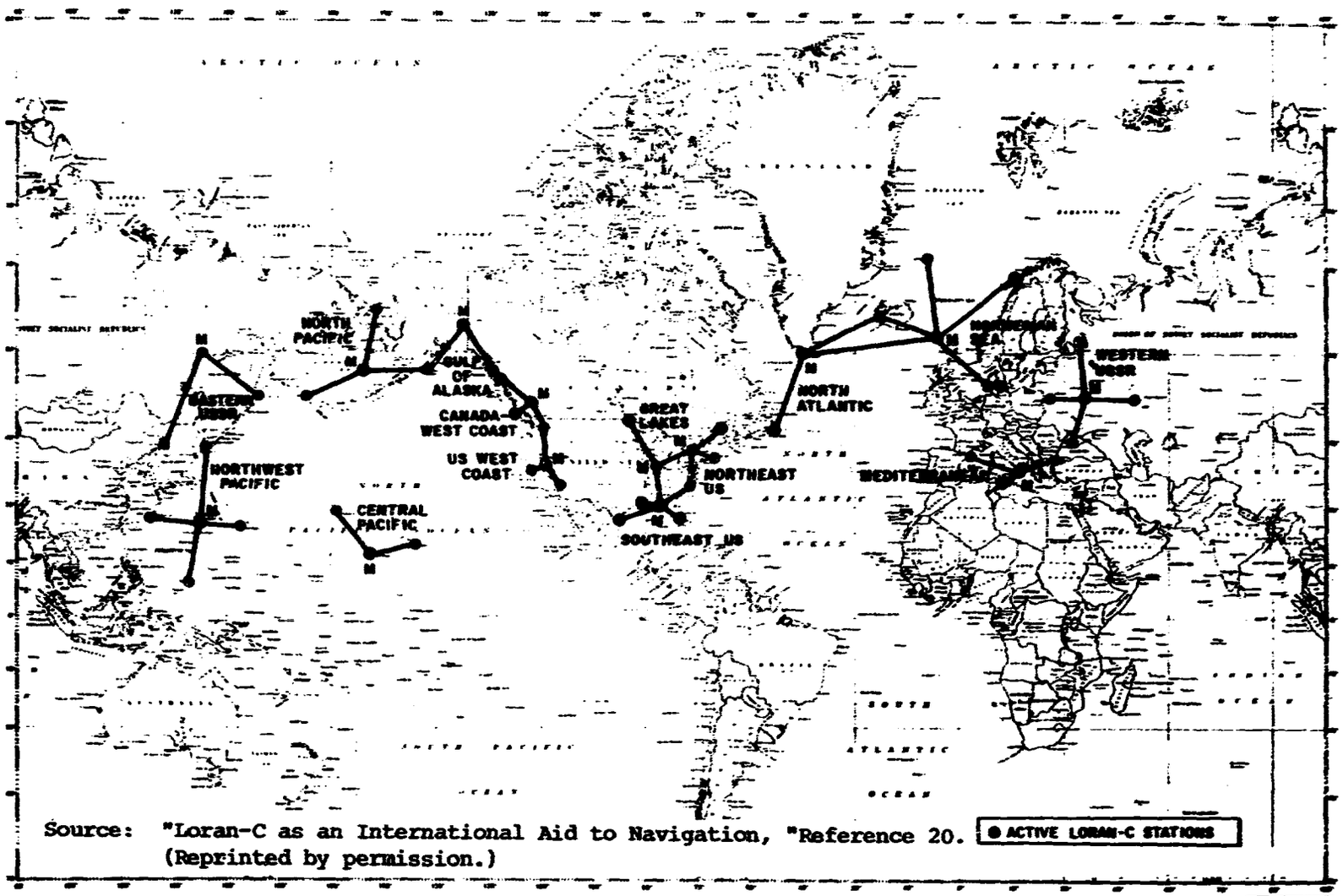
Loran-C (Long-Range Navigation) was developed in 1957 to provide greater accuracy and longer-range capability than Loran-A. The United States Coast Guard assumed responsibility for operation of the system in August 1958. In 1974, Loran-C was selected as the United States government-provided navigation system for civil marine use in United States coastal areas.

1.2 Facilities

All Loran-C transmitters operate at a fixed frequency of 100 kHz and must confine 99 percent of their radiated energy within the band of 90 to 110 kHz. The 100-kHz carrier frequency provides a nearly optimum signal-to-atmospheric-noise ratio for a range of 1,000 to 2,000 kilometers (621 to 1,242 nautical miles). Loran-C signals are transmitted with a peak power of four megawatts via a single vertical antenna tower, which may be as high as 1,350 feet. The ground plane required for transmission of Loran-C ground waves consists of an extensive network of wires buried in the ground to a radius of about 1,000 feet. All Loran-C transmitting stations are equipped with cesium frequency standards, which allow each station to maintain synchronization to absolute time without the need of reference to another station.

Loran-C transmitting stations form chains, each of which consists of a master and two to four secondary (slave) transmitting stations separated from the master by 600 to 800 miles. The geometry of the various chains is shown in Figure A-1. Figure A-2 shows the coverage provided by Loran-C, with the exception of the Canadian East Coast and Commando Lion chains. (The Commando Lion chain has stations in Korea and Japan. Although it is used by the United States Air Force, it is not officially available to civilian users. The Canadian East Coast chain uses existing stations of other chains -- two from the Northeast United States chain and one from the North Atlantic chain.)

Current proposals are to expand Loran-C coverage in Spain, France, Norway, Canada, Russia, Hawaii, and mid-continent United States. It is doubtful that Loran-C will ever be made available in the southern hemisphere.



Source: "Loran-C as an International Aid to Navigation, "Reference 20. (Reprinted by permission.)

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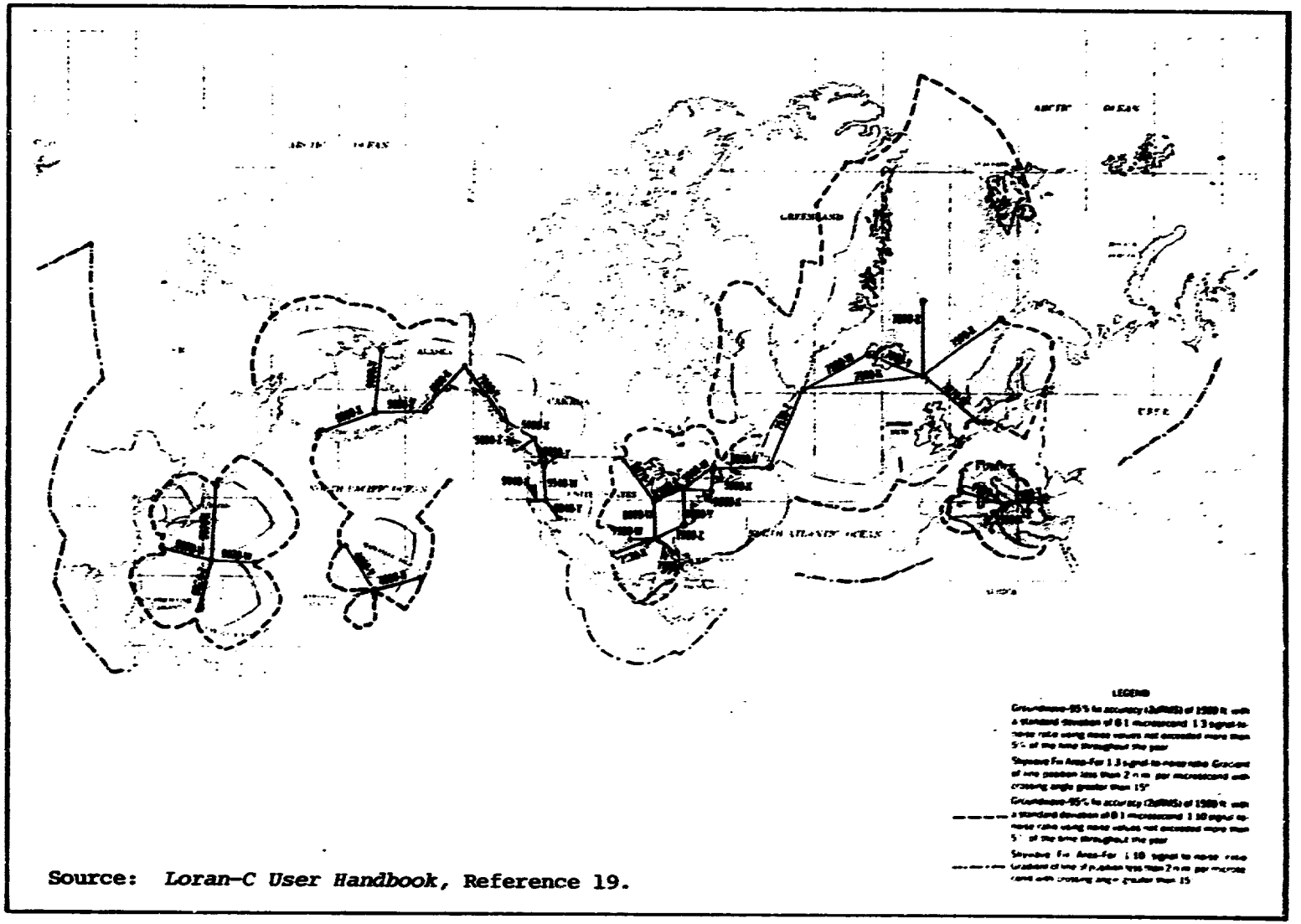
Figure A-1. LOCATIONS OF EXISTING LORAN-C TRANSMITTING STATIONS THROUGHOUT THE WORLD



Source: *Loran-C User Handbook*, Reference 19.

Figure A-2. COVERAGE PROVIDED BY LORAN-C

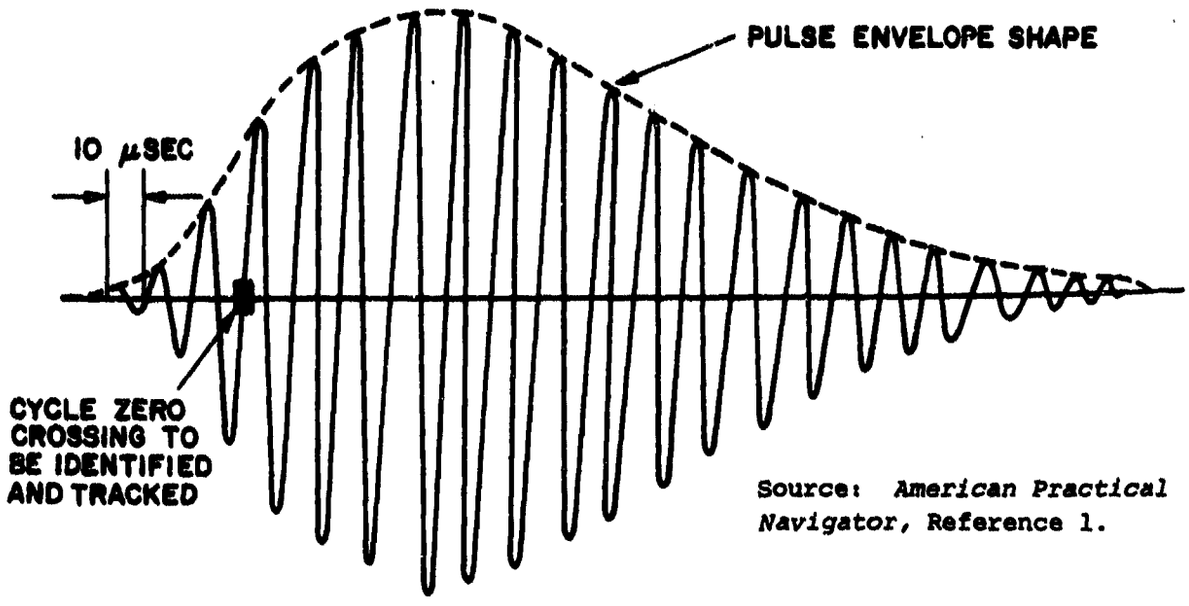
Loran-C navigation is based on time difference (TD) measurements between the user and the transmitters of the appropriate chain. Each chain is monitored by use of one or more system area monitor (SAM) stations within the coverage area to observe the TDs of each master-secondary pair. If an observed TD varies from the calibrated control TD by half of the prescribed control tolerance (±200 nanoseconds or better), the SAM directs a change in the timing of the secondary station to remove the error. If the observed TD differs from the control TD by more than the control tolerance, the transmitted signal is coded to advise users that the TD is unusable. For convenience, letters are used to designate the stations in a chain. The master station is referred to as M, and the secondary stations are denoted as W, X, Y, and Z.

1.3 Signal Characteristics

The transmitting stations of a Loran-C chain transmit groups of pulses at a specified group repetition interval (GRI). The master station transmits its pulses in groups of nine at a repetition rate of 10 to 25 groups per second. The transmissions of the secondary stations are delayed, with respect to the time of arrival of the signal from the master, by a specified time called the secondary coding delay. This delay ensures that signals from two or more stations in a chain cannot overlap in time anywhere in the coverage area. The GRI must be of sufficient length to allow time for transmissions of the master (10,000 microseconds [μs]) and each secondary station (8,000 μs per station) and for the secondary coding delays. The minimum GRI is therefore a direct function of the number of stations and the distance between them. The particular GRI specified for each chain is selected to minimize the mutual interference caused by adjacent chains.

Each station transmits one pulse group per GRI. The master pulse group consists of eight pulses spaced 1,000 μs apart. A ninth pulse, transmitted 2,000 μs after the eighth, is used for identification of the master. To warn of an error in the transmissions of a particular station, the ninth pulse is turned on and off in a specified code denoted as blink. Pulse groups for secondary stations contain eight pulses spaced 1,000 μs apart and use the first two pulses for blink. All secondaries use the same pulse format, which is automatically recognized by most modern Loran-C receivers.

Each pulse within a group is designed to build up and decay slowly, defining the envelope shape shown in Figure A-3. The zero crossing point near 30 μs from the start of the pulse is identified as the third-cycle zero crossing. The third cycle is typically identified by the slope of the pulse envelope. Confining transmission sampling to only the first three cycles eliminates interference from minimum time-delay sky waves. Distortion of the envelope shape, called cycle-to-envelope discrepancy (CED), can cause tracking of a cycle other than the third cycle. Tracking of a cycle zero crossing other than the third results in a bias error, the sign and magnitude of which are determined by the direction and number of cycle shifts. This form of error is commonly referred to as cycle-jump error. When it occurs, the error is typically a single cycle jump, which causes a constant error of ±10 μs in TD.



Source: *American Practical Navigator*, Reference 1.

Figure A-3. SHAPE OF LORAN-C PULSE

Because the amplitude of the signal envelope at the third-cycle zero crossing is only about 50 percent of the peak value, multiple pulses (eight per group) are used so that more signal energy is available at the receiver to improve the signal-to-noise ratio without the necessity of increasing the peak transmitted power capability of the transmitters.

Loran-C uses ground waves instead of sky waves, because the stable nature of the ground wave is not affected by ionospheric fluctuations, which affect the propagation characteristics of sky waves. Contamination of the ground waves by sky waves is eliminated in Loran-C by use of the pulse transmission technique. Receiver reception of a sky wave is delayed between 33 and 1,000 μs after reception of the ground wave. Sky wave reception with a minimum delay time is discriminated against by receiver sampling of the Loran-C transmission at the zero crossing point near 30 μs of the start of the pulse. This technique results in full ground wave stability. Long-delay sky waves could perturb the integrity of the transmission by overlapping the ground wave of the succeeding pulse. To prevent this from happening, the phase of the 100-kHz carrier of each pulse is changed in accordance with a predetermined pattern referred to as a phase code.

Phase coding of the pulses within a group also assists in identifying the master station. The phase of the 100-kHz carrier of each pulse is either in phase or 180 degrees out of phase with a defined reference carrier in accordance with the assigned code. Different phase codes are defined for the master and secondary pulse groups to identify master and secondary stations. Two sets of phase codes are used for master and secondary pulse groups, alternating between successive GRIs so that the phase code changes with each GRI and repeats every other GRI.

1.4 Signal Processing

A position fix is established by the intersection of two or more hyperbolic lines of position (LOPs), each of which represents a constant range difference from two transmitters. Range differences are based on TDs. TD measurements between the receiver and at least three transmitting stations are necessary to establish a position fix. A signal propagation model is used in the process of determining range differences from the measured TDs.

Although Loran-C receivers are designed for processing of ground waves, a sky wave mode can be used when the receiver is beyond the reception range of Loran-C ground waves. Although use of sky waves provides less accuracy than use of ground waves, a single-hop sky wave can be received at distances from the transmitter of about 2,300 nautical miles (nm) -- nearly double the range of the ground wave. Use of Loran-C in the hyperbolic mode does not require a precision oscillator in the receiver for measurement of TDs, because synchronization of time references is maintained by the transmitting stations. Therefore, user clock bias does not affect the measurement of TDs.

Another positioning technique used in some Loran-C receivers is called the ranging, range-range, or rho-rho mode. In the ranging mode, a time measurement provides a circular rather than a hyperbolic LOP, which allows a position fix using two individual stations rather than two station pairs. Another advantage of the ranging mode is the elimination of the geometric dilution due to using the hyperbolic mode at extended ranges. Geometric dilution is a function of the user's position relative to the transmitting stations. The gradient, or spacing between consecutive LOPs per unit of time difference, such as 1 μs, increases with the divergence of the hyperbolic LOPs. The effect is most pronounced along baseline extensions, which are beyond the two stations that define the end points of the baseline. When the gradient is large, a relatively small TD error will result in a relatively large position error. In the ranging mode, the gradient is a constant equal to the propagation velocity, thus eliminating the effect of gradient on geometric dilution. The ranging mode can therefore be used to extend the coverage area beyond that possible in the hyperbolic mode by overcoming the geometric dilution at extended ranges and by requiring the user to be within range of only two transmitting stations. Use of three stations enhances the accuracy of a position fix, because redundant information is used to estimate errors.

All of these advantages of the ranging mode are seriously compromised by one disadvantage -- the need for a very precise and stable time reference in the receiver. The high cost of this type of equipment limits the use of the ranging mode for Loran-C navigation systems.

Before any navigation mode is used, the necessary signals must be acquired by the airborne receiver. The time required for signal acquisition

is typically thirty seconds to two minutes, with a maximum delay of five minutes -- depending on geometry, signal strengths, and the accuracy with which current position is known. Use of Loran-C in the hyperbolic mode requires three stations (a triad); the loss of any single station requires selection of a new triad. Although only three stations are used for navigation, continuous tracking of all stations in a chain eliminates the loss of time during signal acquisition when a new triad is selected. The eventual capability of using all signals from a chain for navigation will provide sufficient redundancy to ensure continual tracking stability and accuracy, even during station loss.

A back-up mode is available on most receivers to allow master independence when the master station fails. Loss of the master station automatically initiates the blink code on all stations in the affected chain, since the integrity of master-secondary TDs can no longer be ensured through monitoring. However, because each station uses an independent clock for synchronization to absolute time, it is reasonable to assume that inter-station synchronization will not degrade rapidly. A problem is encountered when trying to interpret the blink code. If only one station in a chain is blinking, it can safely be assumed that only that station has a problem and should not be used. If all stations are blinking, loss of the master is definitely indicated, but the level of integrity of individual stations is not obvious. However, if caution is used and signal parameters are monitored, the blinking signals can still be used for navigation.

Loran-C receivers are susceptible to localized interference created by such things as VLF transmitters, arc-welding operations, and 100-kHz communication channels carried on power lines. Notch filters can be used to minimize continuous wave interference from Decca navigation chains and communication stations within the same band, but they are not effective in eliminating broad-spectrum interference.

The achievable accuracy of Loran-C depends on a number of factors, including the following:

- Number of stations processed
- Signal quality
- Geometry of stations in relation to aircraft
- Definition of propagation model
- Region of operation

As a function of these factors, typical observed absolute accuracy ranges from a few hundred feet to a few miles. Repeatable accuracy is highly stable, usually within 100 to 200 feet.

The high degree of repeatability is an indication of the significance of the propagation model. With accurate modeling of the propagation characteristics, absolute accuracy can approach repeatable accuracy. Biases

result from the relative differences between the fixed propagation model and the actual propagation characteristics of the signals received from each station.

1.5 Operational Characteristics

Because Loran-C was initially implemented for marine use, it had some operational disadvantages that prevented acceptance for airborne navigation. Many of those disadvantages have since been eliminated through system modifications and improvements in user equipment. The Loran-C system was initially master-dependent, in that only the master of each chain had a clock, to which each slave was referenced. If the master went off the air, the slaves lost their time reference, and the entire chain was out of operation. Independent synchronization to absolute time is now possible, since all stations are equipped with cesium clocks.

When Loran-C coverage provided only three stations in a given area, loss of any station led to system unavailability during hyperbolic navigation, because of the lack of redundancy. The addition of more stations now ensures coverage from at least four stations in a given area.

Advances in user equipment have evolved from the necessity of TD overlay charts to today's fully automatic Loran-C RNAV systems. The advent of microprocessor technology has brought not only increased technical capability but also increased reliability and low cost.

The first airborne antennas used with Loran-C were tail-cap and other electric dipole configurations. Signal loss and difficulty in reacquisition were significant problems, because of the antenna's susceptibility to precipitation (P) static. The tail-cap antenna also exhibited a null pattern problem. Use of H-field orthogonal loop antennas has resolved these problems.

2. OMEGA

2.1 History of Development

The Omega navigation system was developed to extend the range of a system like Loran-C to about 5,000 miles. For the past 25 years, the United States Navy has conducted intensive research and development for Omega. The first experimental Omega stations were established in Norway, Hawaii, Trinidad, and New York by 1964, when the Naval Research Laboratory conducted the first evaluation flights of a prototype airborne Omega receiver. Seven of the eight permanent Omega stations are now operational in Norway, Liberia, Hawaii, North Dakota, La Reunion, Argentina, and Japan; the eighth station, located in Australia, is not yet operational. A temporary station was operating in Trinidad until December 31, 1980. In July 1978, the United States Coast Guard assumed full responsibility for the operation and maintenance of United States-based Omega.

Until the eighth station is completed and resulting system accuracy and coverage can be measured and validated, the Omega network cannot be declared an operational system. However, coverage and accuracy of Omega are being verified on a regional basis.

2.2 Facilities

Omega stations transmit very low frequency (VLF) (10 to 14 kHz) continuous wave (CW) signals on a common carrier frequency on a time-shared basis. Except for the antenna, the complement of electronic equipment in each transmitting station is identical. The antenna system is either a vertical tower about 450 meters high supporting an umbrella of transmitting elements or a valley span typically 3,500 meters in length. Each Omega station has a transmission power of 10 kW. The major elements of each station are timing and control, transmitter, and antenna tuning.

Each Omega station synchronizes its transmissions with highly stable cesium-beam frequency standards, which are referenced to the atomic time scale. Monitor systems provide phase measurement data between stations. The data are used in an advanced optimal-estimation and control algorithm to provide corrections for any offset or divergence of a transmitter from mean Omega system time.

2.3 Signal Characteristics

All Omega stations transmit four frequencies (10.2, 13.6, 11.33, and 11.05 kHz) on a semicontinuous basis, with a basic repetition period of 10 seconds, as in the format shown in Figure A-4. The notations f_1 through f_8 in the figure denote transmitted frequencies unique to each station, as follows:

f_1 = 12.1 kHz	f_4 = 13.1 kHz	f_7 = 13.0 kHz
f_2 = 12.0 kHz	f_5 = 12.3 kHz	f_8 = 12.8 kHz
f_3 = 11.8 kHz	f_6 = 12.9 kHz	

The 0.2-second interval between successive transmissions eliminates the possibility of overlap of signals received from different stations and allows for a margin of error in alignment of the receiver commutator. The Omega signal format was designed so that each station could be identified by the transmission of a particular frequency at a prescribed time.

2.4 Signal Processing

Position determination for Omega can be obtained by either the hyperbolic or the circular (ranging) technique. Hyperbolic systems utilize phase differences so that any drift in the local oscillator will affect both phase measurements equally and will therefore be canceled. Therefore, a high-precision oscillator reference is not required for the hyperbolic mode. The ranging mode requires individual phase measurements rather than phase differences. The level of precision required in the receiver oscillator is determined by the mode of operation in which it will be used.

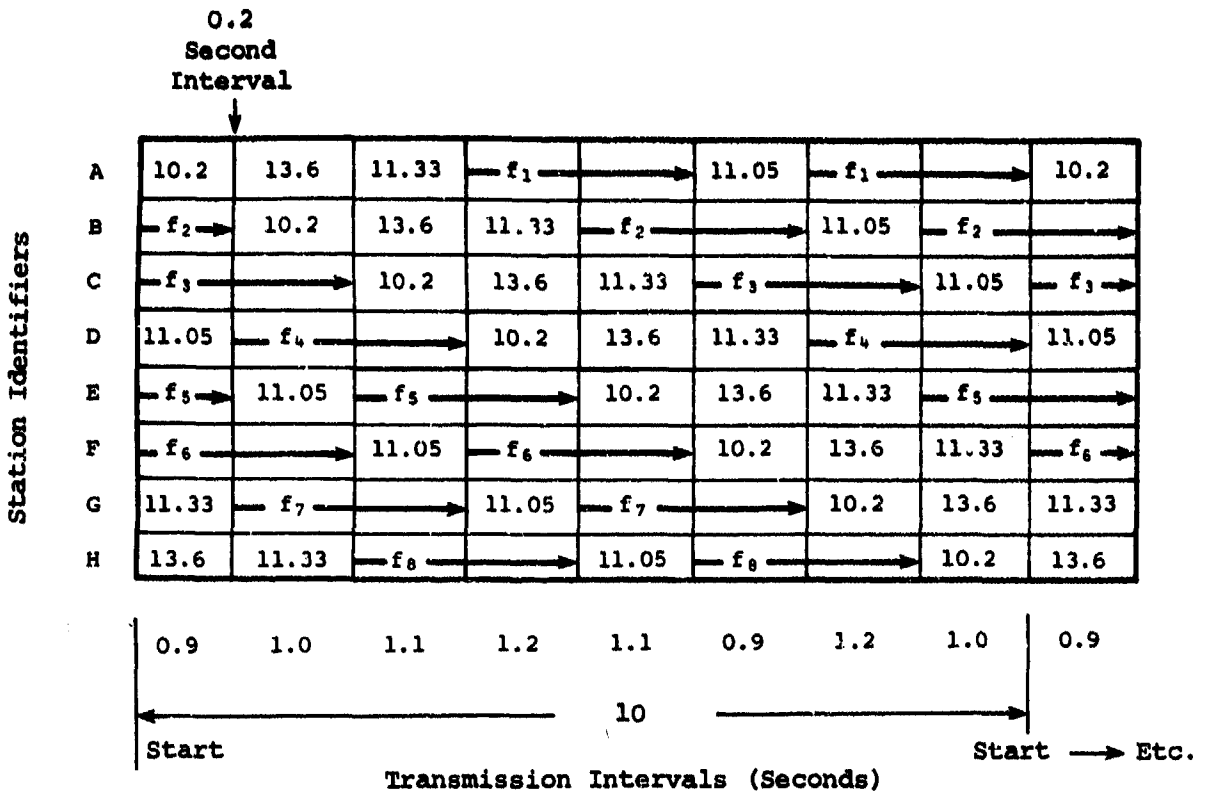


Figure A-4. SIGNAL FORMAT FOR OMEGA

2.4.1 Ranging Mode

Several methods of position determination can be implemented in the ranging mode. The rho-rho method requires direct measurement of the phase from only two stations. The intersection of the circular LOPs resulting from the phase measurements of the two stations defines position. The ambiguity caused by the existence of two points of intersection is resolved by proper initialization. Since there is no redundant information available for monitoring errors, the local oscillator must be highly precise - preferably of the atomic standard type - to achieve acceptable accuracy and reliability. In addition, because each phase measurement is used directly, the system is more susceptible to propagation anomalies, which are unpredictable.

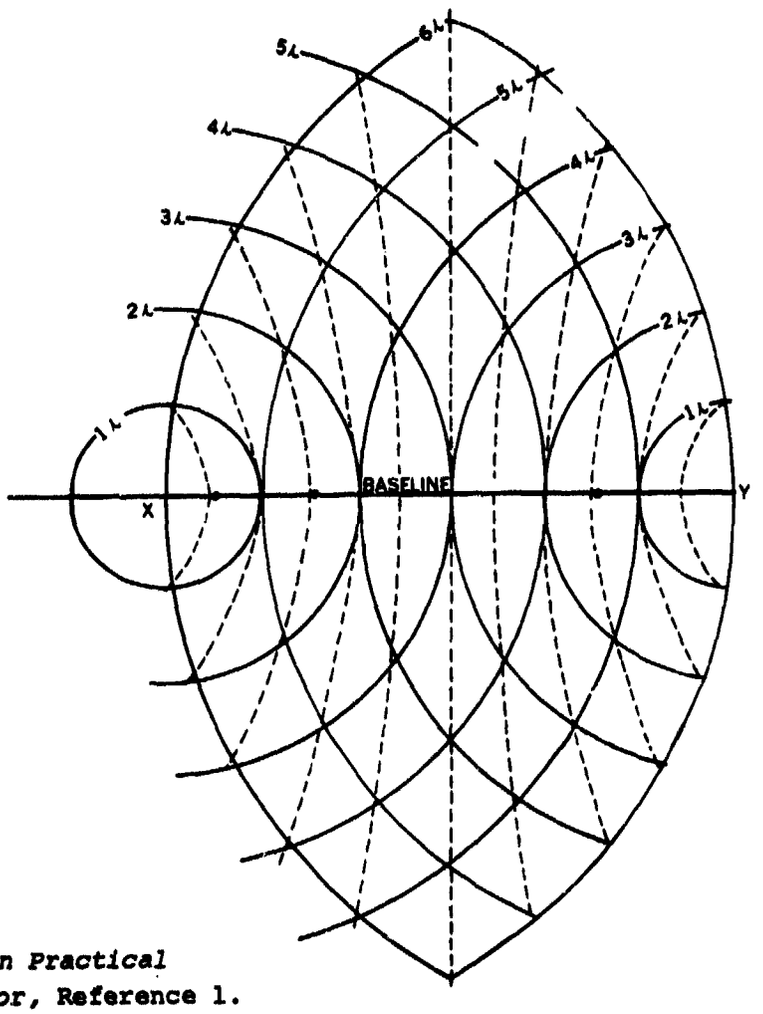
Use of three stations in a rho-rho-rho mode provides sufficient redundancy to permit limited self-calibration of the local oscillator. However, the assumption that any discrepancy in all LOPs meeting at a single point is wholly the result of oscillator drift may not be correct.

2.4.2 Hyperbolic Mode

Position fixing for Omega in the hyperbolic mode requires comparison of phase values obtained from signals of several transmitting stations. Loran-C provides hyperbolic LOPs defined by differences between the arrival times of signals from two transmitters. With Omega, hyperbolic LOPs are formed by contours of constant phase differences in the signal fields of

the transmitting stations. All points along a given contour have the same difference in distance from the two transmitting stations.

Identical phase angles emanating from each transmitter are repeated at every wavelength of the transmitted signal. Therefore, the same difference in phase angles occurs at the intersection of all integral-wavelength wavefronts radiating as circles from each transmitting station. The locus of these intersections is a hyperbolic contour of constant phase, called an isophase contour. The midpoint of the hyperbolic isophase contour line segment joining two points of intersection is a half-wavelength from either wavefront; since it is part of the isophase contour, it also has the same difference in phase angles as at the intersections of integral wavefronts. Thus, identical phase differences repeat not only every wavelength, but every half-wavelength, as illustrated in Figure A-5.



Source:
American Practical Navigator, Reference 1.

Figure A-5. ISOPHASE CONTOURS

2.4.3 Laning

In the ranging mode, all circular LOPs spaced one wavelength apart correspond to the same phase angle measurement. Phase differences, the form of measurement in the hyperbolic mode, repeat along the baseline at intervals of a half-wavelength. The repetition interval distance defines an Omega lane.

A representative baseline in the Omega system is about 5,000 nm in length. At a signal frequency of 10.2 kHz, with a propagation velocity of 161,829 nm per second, the wavelength corresponds to a distance of approximately 16 nm. For a baseline of 5000 nm, then, there are approximately 315 full wavelength lanes, 16 nm in width, which are applicable to the ranging mode. Since lane widths in the hyperbolic mode are defined by intervals of a half-wavelength, the lane widths along the baseline in the hyperbolic mode are approximately 8 nm. Divergence of the hyperbolic contours causes lane width in the hyperbolic mode to increase as a function of distance from the baseline.

Each lane between transmitting stations is numbered for identification. To aid in establishing position within a lane, phase measurements are expressed as the percentage of a cycle, with each 360 degrees constituting 100 centicycles. The difference between phase measurements in centicycles is numerically equal to the percentage value of the lane defining the LOP, generally expressed as centilanes. An observed phase difference corresponds to an LOP in each lane for a given station pair (600 to 700 lanes at 10.2 kHz in the hyperbolic mode). This ambiguity is overcome by initialization of the Omega receiver to current position accurate to within ±0.5 lane-width and continuous count of lane changes resulting from vehicle motion. For the example of 10.2 kHz, initial position must be known to within ±4 nm (±8 nm in the ranging mode).

The four frequencies used for Omega navigation (10.2, 13.6, 11.33, and 11.05 kHz) provide lane widths ranging from 6 to 8 nm in the hyperbolic mode. Additional frequencies can be formed to yield coarser lane widths by "beating" together Omega signals on two different frequencies. As an example, combined processing of 10.2-kHz and 13.6-kHz signals yields a phase difference value of 3.4 kHz, resulting in a hyperbolic mode lane width of 24 nm. The net effect is a relaxation of required initial position accuracy to only ±12 nm. Table A-1 shows the various lane widths possible with multiple frequency techniques for both hyperbolic and ranging modes of processing.

2.5 Propagation Modeling

Accuracy, and therefore practicality, of the Omega system depends on the inherent stability and predictability of the phase variations of a VLF signal over a very long propagation path. Propagation models characterizing VLF signals propagating in the earth-to-ionosphere waveguide are generally based on one of the following three approaches: hop theory, zonal harmonic series, and mode theory. Hop theory assumes that the VLF signal is composed of a ground wave in addition to a series of "hops" (or rays) generated by successive reflections between the ionosphere and the

Table A-1. INITIAL POSITION ACCURACY DETERMINATION FOR DUAL-FREQUENCY OMEGA

Frequency 1 (kHz)	Frequency 2 (kHz)	Frequency Difference (kHz)	Lane Width (nm)		Inital Position Accuracy Requirements (±nm)	
			Hyperbolic*	Ranging	Hyperbolic	Ranging
10.20	--	10.20	7.94	15.88	3.97	7.94
11.05	--	11.05	7.33	14.66	3.67	7.34
11.33	--	11.33	7.14	14.28	3.57	7.14
13.60	--	13.60	5.95	11.90	2.98	5.96
10.20	13.60	3.40	23.80	47.60	11.90	23.80
10.20	11.33	1.13	71.61	143.22	35.81	71.62
10.20	11.05	0.85	95.20	190.40	47.60	95.20
11.05	13.60	2.55	31.73	63.46	15.87	31.74
11.05	11.33	0.28	288.98	577.96	144.49	288.98
11.33	13.60	2.27	35.65	71.30	17.83	35.66

*Along baseline.

earth. The zonal harmonic series approach applies rigorous mathematical analysis to the physical interpretation of hop theory. Mode theory describes the total signal at any point within the waveguide in terms of the natural or characteristic modes of propagation. The prediction models used by Omega Navigation Systems Operations Detail (ONSOD) are based on the mode theory approach. Omega signal coverage diagrams are generated by predicting signal-to-noise ratio (SNR) and occurrences of excessive mode interference. Global computations of predicted phase corrections are used to develop predicted propagation corrections (PPCs), which are published in tables to provide phase corrections for various regions, times of day, and months.

The prediction models use propagation characteristics that are fairly well understood and highly repeatable. The most obvious influence on Omega signals is the effective height of the ionosphere. Increases in solar radiation advance ionization of the atmosphere, thereby effectively lowering the height of the ionosphere to about 70 km soon after sunrise; at night, the height is about 90 km. Because Omega phase is inversely proportional to phase velocity, the phase increases or decreases in step with the effective height of the ionosphere, referred to as diurnal phase shift.

The phase of the Omega signal received at a given point in space is determined by the phase velocity and distance to the source. If distance is held constant and phase velocity is increased, the previously measured phase will appear to have advanced beyond the given point in space, creating the impression that the point has moved closer to the transmitter.

Numerous other phenomena that influence signal propagation cannot be wholly taken into account because of their unpredictable nature. Geophysical parameters that affect propagation include ground conductivity, the earth's magnetic field, solar activity, latitude, and solar zenith angle. Sudden ionospheric disturbances (SIDs) are produced by solar flares. Those solar flares that generate significant X-ray radiation cause ionization changes to the ionosphere, an effect that manifests itself as an Omega phase anomaly. This effect is referred to as a sudden phase anomaly (SPA). Polar cap absorption (PCA) events are also caused by solar flares, but only those that produce significant quantities of solar protons, which concentrate at the earth's magnetic poles. These protons tend to absorb the effective energy of radio waves. However, in the case of low-frequency Omega transmissions through the polar regions, the dominant effect of the proton activity is manifested as another phase anomaly. Both SIDs and PCA events are random and unpredictable but occur more frequently during years of peak solar activity. A significant SID can cause position errors of about 2 to 3 nm only during daylight hours, whereas a severe PCA event could cause a position error of 6 to 8 nm, lasting for several days.

Another source of Omega signal error is modal interference, created by phase errors from additional ground and sky waves combining with the primary wave. This form of interference is minimized by automatic deselection of a station within a defined distance from the Omega receiver. This distance varies from 300 nm to 600 nm, depending on the equipment used. Beyond the prescribed distance, the limitation on range of ground and sky waves dilutes their impact on the primary wave.

The prediction models applied to the Omega system are based on monitor data taken for at least one year to exploit annual correlation fully. Therefore, at least this amount of time will be required following completion of the Australian station before Omega can be declared a fully operational navigation system.

2.6 Operational Characteristics

Use of all available Omega frequencies can provide greater accuracy in determination of position. Since each frequency propagates through the air with different characteristics, off-nominal conditions will not affect all frequencies the same way. Off-nominal conditions can therefore be isolated, and their effects can be compensated for, by proper filtering of multiple frequencies.

Even more important to accuracy than the number of frequencies processed is the number of Omega stations within reception range and their geometry in relation to the aircraft receiver. Hyperbolic navigation requires a minimum of three stations at all times, whereas navigation in the ranging mode can be accomplished with only two stations and a sufficiently accurate local oscillator. The best geometry for greatest accuracy results when the LOPs intersect at right angles. This configuration provides equal cross-track and along-track accuracy. As the LOPs approach a parallel configuration, the resulting accuracy in position fixing is correspondingly degraded. When more than three Omega stations can be received, sufficient redundancy exists to provide excellent accuracy. Generally good Omega signal coverage throughout the conterminous United States provides availability of a minimum of three stations. When an aircraft encounters loss of Omega signals, preventing satisfactory Omega navigation, the area in which this condition persists is referred to as a "hole" in signal coverage.

As was mentioned earlier, the Omega transmission format repeats every 10 seconds, with each Omega station transmitting different frequencies at any given time. It would therefore require a full 10 seconds to receive all transmitted frequencies from all Omega stations. As a result, when all phase information is processed to determine position, some information is no longer current, but is up to 10 seconds old. This loss of processing time synchronization is overcome by projecting each signal forward in time in accordance with its respective position in the processing cycle. This form of processing constitutes a dead-reckoning system with ground-referenced updates. The dead-reckoning system uses aircraft heading and speed information, with the ground-referenced updates provided by the Omega system. Aircraft heading and speed information can be supplied by on-board sensors or manual data entries or can be derived from progressive Omega measurements.

When Omega measurements are used to estimate aircraft heading and speed, filter time-constants of sufficiently long duration must be employed to minimize unwanted deviations resulting from noise and other spurious activity. A common predicament encountered in establishing a filter time-constant is that, although stability can be achieved with use of a long time-constant, quick response to maneuvers requires a short time-constant. Since

the most prevalent use of Omega is for en-route navigation with minimal heading or speed changes, a long time-constant has generally been preferred and is therefore the standard for Omega receivers. With increased use of Omega in the airborne environment, however, there is greater interest in the possible use of Omega in approach operations, where a great deal of maneuvering can occur. Acceptance of Omega for approach navigation will be predicated on the ability of the airborne Omega navigation system to respond quickly (a short filter time-constant) and accurately to course and speed changes.

Omega antennas are of either the E- or H-field type. The H-field antenna is an orthogonal loop that captures the magnetic (H-field) component of the signal. Various configurations of the H-field antenna have been designed to accommodate the many different installation requirements for both large and small aircraft. H-field antennas are desirable because of their immunity to the effects of precipitation static (P-static). However, since H-field antennas are designed for high sensitivity to magnetic fields, they are susceptible to magnetic noise.

On some aircraft, 400-Hz interference from power generation is so widespread that a suitable location for an H-field antenna cannot be found. In these cases, a capacitive (E-field) antenna is used. The E-field whip antenna is immune to magnetic noise but is susceptible to P-static.

Some manufacturers have offered custom antenna design to maximize antenna efficiency for the particular installation environment. One such design uses heading information to orient an H-field antenna electrically.

2.7 VLF Signal Processing

All Omega stations are VLF transmitters. There are additional VLF transmitters that are not part of the Omega system. The United States Navy maintains several VLF communication stations in various countries around the world to provide a worldwide military communications network. Although these stations were not intended to be used for navigation purposes, they are technically suitable for use as navigation aids. However, since the stations are not within the framework governing compliance with international navigation standards, they are used solely for secondary-mode navigation. VLF stations provide a means of navigating through regions of unacceptable Omega coverage without the necessity of reverting totally to dead reckoning. VLF can be implemented as the sole signal source or can be used in combination with Omega signal processing. In general, when the VLF mode is activated, one of the Omega frequency channels is deactivated, and the VLF signals are superimposed in a fixed sequence in the Omega transmission time slots of the deactivated Omega frequency channel. The phase of the VLF signal is initialized at the position of the receiver at the time the VLF station signal is first received. Subsequent phase measurements indicate position change.

The operational capabilities of Omega navigation systems heavily influence the potential accuracy of position fixing. Table A-2 presents some typical expected accuracies as a function of operational capability.

Table A-2. OPERATIONAL CAPABILITY VERSUS EXPECTED ACCURACY FOR OMEGA NAVIGATION SYSTEM

Number of Stations Received	Number of Frequencies Processed	VLF Processing	Accuracy of Position Fixing (nm)
0	0	X	≤ 4
2	3	X	≤ 2
>4	4	--	1 to 1.5
>4	3	X	1 to 1.5

2.8 Differential Omega

Omega signal accuracy is primarily dependent on the inherent stability and predictability of the phase variations of a VLF signal over a very long propagation path. This accuracy can be improved locally by taking into account localized Omega signal phase variations, which can be determined by differencing predicted phase values with measured phase values, a technique referred to as differential signal processing.

The differential Omega concept requires local area ground monitors, which receive the standard signals from the Omega transmitters. The measured phase values are then compared with predicted values, any difference being considered a phase error. The phase error measured at the ground monitor is relayed to aircraft in the vicinity of the monitor station. The airborne Omega unit compensates for the error by applying it as a differential correction to the standard Omega signal being received directly from the Omega transmitters.

The predicted Omega phase values are computed at the monitor stations as a function of assumed signal propagation speeds and precise knowledge of the distance between the monitor station and each transmitter. The assumed signal propagation speed is a function of the propagation model used at the monitor site. The differential correction term relayed to aircraft is the difference between the predicted and measured values of Omega phase as computed at the monitor site.

Ideally, application of the differential correction term would result in a position accuracy equivalent to the accuracy with which the geographical position of the monitor site had been surveyed. A number of error sources,

however, affect the accuracy capability of differential Omega. The instrumentation error of the monitor facilities will obviously have a direct influence on the accuracy provided by differential Omega. The most significant of the error sources other than those that are equipment-related are modal interference, non-modeled variations in phase velocity, and distance displacement of the user from the monitor site. Also, differential corrections cannot compensate for the effects of lack of signals or poor geometry.

A variation of the differential Omega concept, called "gradient-corrected" differential Omega, has been suggested as a means of reducing the effects of modal interference and phase velocity variations. In this technique, the phase correction terms provided by basic differential Omega are supplemented with phase velocity (phase gradient) correction terms. Implementation of this scheme requires the use of two neighboring ground monitor stations to enable measurement of local phase velocity. Again, the computation of the correction terms is dependent on the propagation model used at the monitor station.

The accuracy improvement provided by differential corrections is most pronounced when the user is directly over the monitor site, where the correlation with the differential correction terms is at its maximum. A position accuracy of 0.1 to 0.2 nm (1σ) is typically achievable in marine applications when the user is within 50 nm of the ground monitor station. This accuracy then degrades with increasing distance from the station in a roughly linear fashion. Although there is insufficient evidence to prove it conclusively, it is generally believed that application of differential corrections to Omega signals will improve position accuracy even when the user is 250 nm from the monitor station. Use of differential corrections beyond 500 nm of the monitor station could actually degrade the position integrity of the standard Omega signal being received by the user.

All Omega receivers utilize some form of propagation modeling to predict signal propagation characteristics. These models can be quite complex, taking into account diurnal and seasonal phase shifts, or be as simple as predicting a constant value of phase velocity. The differential corrections are computed relative to the propagation model used by the monitor station and are therefore most effective when applied as compensation to a receiver using the same propagation model. Differences between the airborne and ground monitor propagation models will compromise the effectiveness of the differential corrections in improving Omega accuracy. One solution to this problem would be to require all airborne receivers to utilize the model used by the ground monitor stations. However, such a solution could create another problem. As propagation anomalies become better understood, prediction models could be improved. But there would be lack of incentive to improve propagation models in an environment where standardization is mandated to ensure consistency in the effectiveness of application of differential corrections. Improvements in accuracy would have to be weighed against the cost of retrofitting all existing Omega receivers with the new propagation model.

An alternative approach would be simply to relay the Omega signal received by the ground monitor station directly to the aircraft for processing by the airborne receiver. Knowledge of the exact geographical position of the monitor station would enable the airborne processor to determine phase errors with the airborne propagation model. This form of implementation eliminates potential differences between the propagation model used to determine differential corrections and the one in which the corrections are applied to compute position. Also, there would be no impediment to improving propagation models, since there would be no need for standardization. There would, however, be an impact on the processing and memory requirements imposed on the airborne Omega unit.

3. VOR

3.1 History of Development

VHF Omnidirectional Range (VOR) was developed in response to the growth in air traffic in the 1930s. The unpredictable propagation characteristics of the low- and medium-frequency range navaids in use at that time severely limited their practical service area. As aircraft began flying at higher and higher altitudes, line-of-sight distances increased, making VHF frequencies useful to over 100 miles. The only directional guidance navaid available before VOR that did not require a direction finder on board the aircraft was limited to selection of one of four courses. VOR became the United States standard in 1946 and the international standard in 1949, combining communication and navigation within one band.

3.2 Facilities

The VOR ground station transmits two 30-Hz signals: one is a constant phase omnidirectional reference signal, and the second signal varies in phase in relation to the magnetic bearing of the aircraft from the VOR station.

VOR antenna systems use Alford loops, which generate horizontally polarized signals with the same field pattern as a vertical dipole. Conventional VOR systems use four Alford loops arranged in a square. The plane containing the Alford loops is horizontal and is located a half-wavelength above a circular and conducting ground plane, or counterpoise, that is approximately 30 feet in diameter. The counterpoise also acts as the roof of the transmitter house, with the loops protected from the weather by a radome. The radome is generally hemispherical in shape; if a Tactical Air Navigation (TACAN) antenna is included in a VOR installation (a VORTAC), the radome is conical. The VOR antenna system is designed to operate in two distinct modes, corresponding to the two distinct signals radiated -- the carrier mode and the sideband mode, described in the following section.

3.3 Signal Characteristics

VOR operates in the VHF band of 108 MHz to 118 MHz, divided into 50 kHz channels. Originally, the channel width was 100 kHz. The 30-Hz reference signal is generated by frequency modulation of a 9.960-kHz subcarrier signal, which amplitude-modulates the radio frequency (RF) carrier signal. This reference signal is radiated when the antenna is operated in the carrier mode, where all four loops are simultaneously driven in phase with carrier frequency currents, the result being an omnidirectional pattern. The variable phase signal is generated when the antenna is operating in the sideband mode, which causes each diagonal pair of loops to be excited so that at any instant of time the horizontal plane pattern of each pair of loops above the counterpoise is a figure eight. The relative phase between the pairs of loops is such that the combined effect of these phases in space produces a single figure-eight azimuthal pattern rotating at 30 revolutions per second. Combination of the carrier field with the total sideband field radiates a cardioid pattern that rotates at 30 revolutions per second, generating a 30-Hz sine wave at the output of the airborne receiver. The 30-Hz reference signal and the rotating pattern sine wave are synchronized so that they are exactly in phase when viewed from magnetic north. Therefore, the phase between the reference and the rotating cardioid varies directly with the bearing of the aircraft.

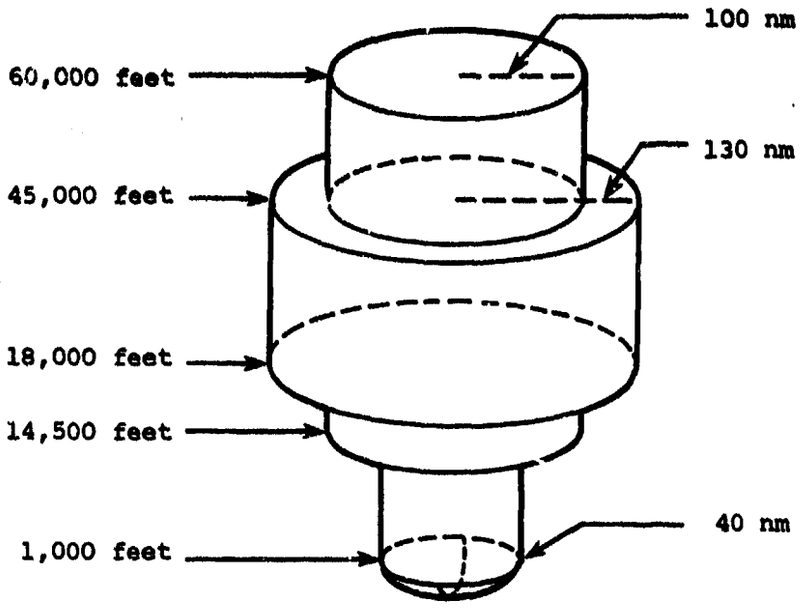
VOR signal reception depends on the standard service volume of the class of facility used and can range in radial distance from 40 nm to 130 nm from the VOR, depending on altitude, as shown in Figure A-6. The primary difference between Figure A-6 and the currently existing specifications for standard service volumes as defined in FAA Advisory Circular (AC) 00-31 (U.S. National Aviation Standard for the VORTAC System) is the FAA-proposed additional stipulation of a defined coverage area between 1,000 and 14,500 feet altitude for the high-altitude station.

3.4 Signal Processing

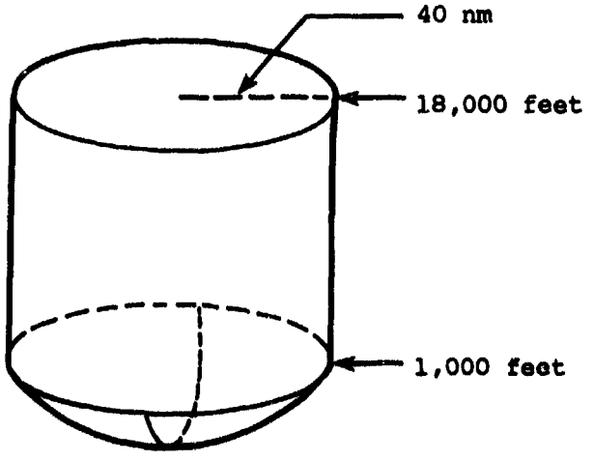
The airborne receiver detects the VOR signal and passes it through an amplitude modulation (AM) detector. The AM detector distinguishes the identity tone and any voice frequencies present and broadcasts them through the aircraft audio system. These components of the signal are removed via a 30-Hz filter, and the resulting 30-Hz amplitude modulation produced by the rotating pattern of the VOR is fed to phase comparison circuitry. The original signal is also passed through a 9.960-kHz filter, a limiter to remove 30-Hz amplitude modulation, and a frequency modulation detector, which then outputs the 30-Hz frequency-modulated reference. After one more stage of filtering, the reference frequency is compared with the variable phase signal in the phase comparator. The output of the phase comparator is the bearing of the aircraft with respect to magnetic north.

3.5 Operational Characteristics

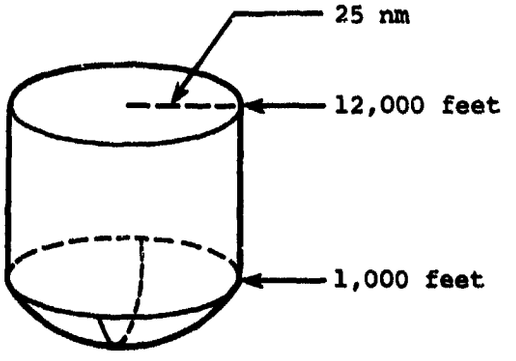
Use of VHF eliminates sky wave contamination of VOR signals and prevents interference from stations beyond line of sight. The most significant error sources are site errors and errors in measuring phase shifts at 30 Hz.



Standard High-Altitude Service Volume



Standard Low-Altitude Service Volume



Standard Terminal Service Volume

Source: FAA Order 9840, Reference 13.

Figure A-6. VOR STANDARD SERVICE VOLUMES

Site errors are caused by multipath effects at the ground station, resulting from signal reflections off trees, buildings, and other scattering objects near the transmitter. The multiple signal paths created by the reflections combine with the desired signals to alter the phase difference measured at the aircraft. This results in an error in the VOR bearing indicated by the airborne receiver. As the aircraft moves, the phase difference between the desired signal path and the reflected paths changes. The phase difference error fluctuates with a measurable frequency depending on the rate of change of path difference. This phenomenon, referred to as scalloping, becomes more pronounced with decreasing distance from the VOR. Coverage of VOR is restricted because of line-of-sight limitations. The coverage pattern of a VOR is additionally restricted by a limited elevation-angle of transmission, above which no VOR signal is available. VOR signals currently are guaranteed to be available within 60 degrees of elevation from the ground plane of the transmitter. In practice, however, signals can generally be received up to an elevation angle of nearly 80 degrees. The airspace directly above the VOR, in which no signal exists, defines a cone, the apex of which is at the transmitter with a central angle of 60 degrees. This cone, generally referred to as the cone of confusion, is illustrated in Figure A-7. As the figure shows, the effective area of the cone increases with altitude. At 5,000 feet altitude, the area of concern above the VOR has a radius of 0.4 nm. At an altitude of 30,000 feet, the radius is 2.5 nm.

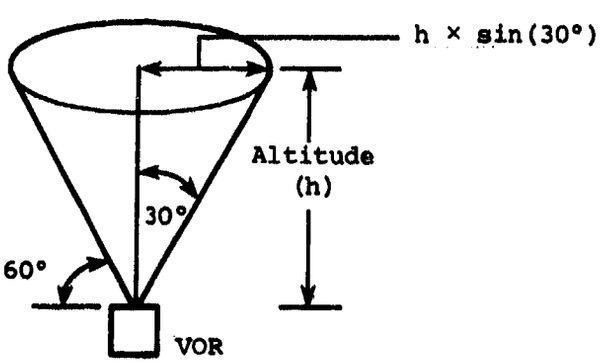


Figure A-7. VOR CONE OF CONFUSION

4. DME

4.1 History of Development

Distance measuring between aircraft and ground stations is provided through Distance Measuring Equipment (DME) and Tactical Air Navigation (TACAN). Since TACAN uses the same pulses and frequencies for distance measurement as are used by the standard DME system, all references to the operational design and performance of DME correspondingly apply to TACAN.

The history of DME dates back to the Rebecca-Eureka pulse ranging system developed during World War II, which operated at 200 mHz. By international agreement in 1946, DME was assigned for operation in the 960- to 1,215-mHz L-band. The exact frequencies and pulse techniques were not established until 1959, however.

4.2 Facilities

Ground-based DME consists of a receiver-transmitter and an antenna. DME is typically collocated with some other navigational aid, including the following station types:

- VOR/DME
- ILS/DME
- TACAN
- VORTAC

VOR/DME is a DME station located at the same site as a VOR station. ILS/DME denotes the presence of a DME at the site of an instrument landing system (ILS). TACAN provides both azimuth and distance information to suitably equipped aircraft. Although the azimuth signal from a TACAN is not the same type as from a VOR, the distance measuring function of TACAN is equivalent to DME. A VORTAC facility consists of a VOR station collocated with a TACAN station.

4.3 Signal Characteristics

The receiver-transmitter channels of DME stations located with a VOR station are paired with the respective VOR channel in accordance with a published table. The air-to-ground transmitted frequencies of DME are from 1,025 to 1,150 MHz; the ground-to-air transmitted frequencies are from 962 to 1,213 MHz. The VOR frequencies with which DME frequencies are paired are between 108 MHz and 118 MHz. VOR frequencies are divided into 100-kHz-wide channels, resulting in 100 channels. There are 126 DME channels between 1,025 and 1,150 MHz, spaced 1 MHz apart, allowing frequency pairing with the 100 VOR channels and leaving 26 unpaired DME channels. When the VOR channel width was changed to 50 kHz, an additional 100 VOR channels were made available, bringing the total to 200. As a result of this action, additional DME channels were made available by the designation of X and Y channels. The frequency spacing between DME channels was not changed.

X channels correspond to the original 100-kHz-spaced VOR frequencies and the corresponding DME frequencies. Spacing of the ground reply pulse for X channels is 12 μs. VOR channels that are offset 50 kHz from the X channels are designated Y channels; they have a ground reply pulse spacing of 30 μs. The airborne interrogating pulse-pair spacing is 12 μs on X channels and 36 μs on Y channels. With use of X and Y channels, 252 DME channels are available; 200 of these are paired with the available VOR

frequencies. The transmit and receive frequencies of any one channel are separated by 63 MHz.

DME ground stations are capable of handling approximately 100 aircraft interrogations simultaneously. When more than 100 aircraft interrogate the ground station, the ground station limits its sensitivity and replies only to the 100 strongest interrogations. Most airborne DMEs are designed to operate down to a reply efficiency of 50 percent, reflecting the situation where the DME receives replies to only half of its transmitted interrogations.

The ground station continuously transmits a squitter signal (filler signal) of 2,700 pulse pairs per second (pp/s), with an identification code signal of 1,350 pp/s at 30-second intervals. When interrogated by the airborne DME pulse pair, the ground station transmits a reply pulse pair that replaces a squitter pulse pair 50 μs after interrogation. Replies are considered valid by the airborne receiver when they occur at approximately the same time after every transmitted pulse pair. The pulse rate of the airborne DME transmissions is varied randomly (jittered) so that no two airborne DMEs are transmitting at the same rate. This jitter technique prevents transmitted pulse pairs from another aircraft DME being mistaken for reply pulses.

The airborne DME decreases the frequency of interrogations when it has established the validity and regularity of the reply pulses. These variations in level of frequency of interrogation are referred to as either the search mode or track mode -- the track mode indicates less frequent interrogation. Use of the track mode relieves the loading of the ground station to allow service of more aircraft.

The identification signal of 1,350 pp/s can be converted to an audio signal so that the pilot can monitor the signal to confirm that the airborne DME is tracking the station the pilot has selected.

4.4 Signal Processing

The DME system employs a pulse-ranging technique whereby an airborne unit, referred to as an interrogator, transmits a pair of pulses that the DME ground transponder retransmits after a fixed time delay. Paired pulses are used to reduce interference from other pulse systems. The peak pulse power of the airborne unit is about 50 watts to 2 kilowatts. The DME ground station (or transponder) receives these pulses and, after a fixed delay of 50 μs, retransmits them back to the aircraft on a frequency 63 MHz below or above the airborne transmitting frequency. The peak power of the ground station is between 1 and 20 kilowatts.

The airborne interrogator automatically compares the elapsed time between transmission and reception, subtracts the fixed delay of 50 μs, and displays the result in terms of nautical miles. The range thus computed is slant range, the actual distance between the aircraft and the DME ground station, rather than ground distance. If the aircraft is more than one mile

from the station for each 1,000 feet of altitude, the difference between slant range and ground distance is negligible. Correction of slant range to obtain ground distance is a function only of altitude above the station.

4.5 Operational Characteristics

If the DME signal is lost after the track mode has been established, the DME retains the last value of computed distance for a short period of time. If the signal is not reacquired within this period, the airborne DME enters the search mode.

The most potentially serious problem encountered when DME is used is false lock-on. This occurs when the airborne DME acquires and tracks transponder replies to a multipath signal instead of the direct signal. "Confirm/track" circuits in the airborne unit eliminate the possibility of false lock-on by scanning the interval just before the tracked pulse pair to confirm that the tracked signal is not an echo. The magnitude of error caused by false lock-on can be several miles. Multipath and siting errors other than false lock-on are small and nearly random.

5. GPS

5.1 History of Development

The Navigation System using Timing and Ranging (NAVSTAR) Global Positioning System (GPS) is currently being developed and evaluated as an advanced satellite-based positioning and navigation system. Although it was originally scheduled to be operational in 1982, current estimates reflect an initial 18-satellite deployment by 1987.

The concept of NAVSTAR GPS, being developed by the Department of Defense, evolved from the 1973 merger of the Navy's Time Navigation (TIMATION) Program and the Air Force 621B Project. Both projects were established in the mid-1960s to investigate satellite-ranging techniques to satisfy military navigation requirements. The Air Force used ground stations to simulate satellite signals, whereas the Navy actually launched satellites.

The Navy TIMATION satellites provided more accuracy and greater coverage through use of ranging techniques than was possible through use of previously developed satellite navigation systems, such as TRANSIT, which were based on frequency measurements. TRANSIT is the Navy Navigation Satellite System (NNSS or NAVSAT), currently used primarily for navigation of submarines and surface ships, both civil and military.

When the Department of Defense's GPS Joint Service Project Office was created, the Air Force was given the responsibility of program management through the Space Division in El Segundo, California. The Navy established the Navigation Technology Program to provide technical support and design of the navigation technology satellites (NTSs) currently used to evaluate

the components and systems being developed for the navigation development satellites (NDSs) of NAVSTAR GPS.

5.2 Facilities

NAVSTAR GPS involves the following segments of operation, each dependent on the others to provide precision worldwide navigation capability:

- Ground control segment
- Space system segment
- User segment

The ground control segment tracks the satellites, monitors the navigation signals, and provides correction terms to the satellites. The space system segment includes the satellites themselves and the navigation signals they transmit. The user segment comprises numerous receivers representing diverse applications of the navigation data.

5.2.1 Ground Control Segment

The primary function of the ground control segment is to maintain the precision of the navigation data supplied to the user. This function is performed via a network of four monitor stations (MSs), an upload station (ULS), and a master control station (MCS). The four unmanned MSs are remotely located from but directly linked to the MCS. Each MS receives and decodes satellite navigation data and collects local meteorological data. Data from each MS are relayed to the MCS, where they are processed to determine satellite ephemeris and clock errors. The MCS then generates correction terms to compensate for identifiable biases and provides them to the ULS for upload transmission to the satellite.

The ability of GPS to provide highly accurate navigation capability depends on precision timing and frequency control. The importance of precision timing in terms of navigation accuracy is illustrated by the fact that one nanosecond of time error corresponds to 0.3 meter (0.984 foot) of distance error (assuming the speed of light to be 3×10^6 m/s).

The MCS maintains GPS system time through the use of cesium clocks. Because the precision of GPS system time must be continuous, it is therefore not offset by leap-year seconds, which cause periodic adjustments to universal coordinated time (UTC). The MCS monitors the satellite clocks to determine their degree of synchronization with GPS system time. Clock corrections are uploaded by the ULS to the satellites and become part of the navigation message transmitted by the satellite to users.

5.2.2 Space System Segment

Great effort has been expended in the search for an optimal 18-satellite configuration. The most current, but not necessarily final, choice uses six orbital planes, with three satellites in each orbit. Each satellite orbits at 10,900 nm above the earth in a 12-hour period. The ascending nodes of

each orbit are equally spaced by 10 degrees in longitude around the equator. Each orbital plane is inclined by 55 degrees with respect to the equatorial plane, and the three satellites in each orbit are equally spaced by 120 degrees. The satellites are designed for an operating life of five years.

The four atomic clocks contained in each satellite are accurate to one second per 30,000 years. Two levels of navigation accuracy are provided by the GPS signals transmitted from the satellite. The greatest degree of accuracy is provided through acquisition of the precision code (P-code). Access to this code is limited to military users. A second code, the coarse acquisition (C/A) code, is less accurate; it will be made available to all users. The accuracy capability of the C/A code may be further degraded for reasons of national security.

5.2.3 User Segment

Several configurations of GPS user equipment are currently being developed and evaluated, as follows:

- X-set
- Y-set
- Z-set
- Manpack
- GPSPAC
- FAA Experimental Dual Channel Receiver
- DoD Phase II User Equipment

The X-set was developed as a means of evaluating the speed and accuracy of GPS position-determination under the most severe jamming and dynamic conditions that might be experienced on high-performance military aircraft. The X-set uses four receiver channels, which enable it to process data from four satellites simultaneously. It receives GPS signals on two frequencies, allowing measurement of propagation errors.

The Y-set is more compact than the X-set and costs less. It has only one receiver channel and therefore sequences between satellites. Performance of the Y-set is comparable to that of the X-set except under conditions of high dynamics.

The Z-set is a low-cost, compact configuration that sacrifices high accuracy and dynamic response. As with the Y-set, the Z-set sequences between satellites, using only one receiver channel. But unlike the X- and Y-sets, which process two frequencies, the Z-set processes only a single frequency. Because the Z-set is able to acquire only the C/A code, it provides less accuracy than the X- and Y-sets, which can also acquire the P-code.

Although Manpack does not require high dynamic capability, it does require high-accuracy, small-size, low-weight, low-power, and antijam capabilities. Manpack is essentially the Z-set with the addition of dual frequency and P-code processing.

GPSPAC is intended primarily for use in satellites and shares the design features of the Z-set and Manpack.

An experimental dual-channel GPS receiver is providing a means for the FAA to develop engineering requirements and cost estimates for a low-cost general aviation receiver. The Phase II user equipment is being designed and evaluated in preparation for production of equipment for the Department of Defense.

The many possible applications of NAVSTAR GPS include the following:

- Strategic aircraft and cruise missile navigation
- Battlefield operations
- Submarine navigation (update of INSs while surfaced)
- Tactical navigation
- Aircraft carrier navigation
- Harbor and sea lane operations
- Maritime shipping
- Search and rescue operations
- Spacecraft operations
- Surveying
- Oil exploration
- Air traffic control
- Civil air navigation

5.3 Signal Characteristics

5.3.1 Modulation

The signal transmitted by the satellite to the user is modulated by a sequence of bits in a pattern unique to each space vehicle. These patterns are referred to as pseudorandom noise (PRN) codes. PRN codes exhibit the characteristics of random thermal noise until the pattern is decoded and the receiver locks onto it. The signals are coded for two reasons. The first is to allow denial of access to the signal by withholding details of the code patterns. The user receiver must be able to match the incoming code to establish a lock-on. The second reason for using a code is that when the sequence generated by the user receiver is matched with the incoming signal, measurement of the phase shift required to maintain match of the codes provides a measurement of the transit time of the navigation signal.

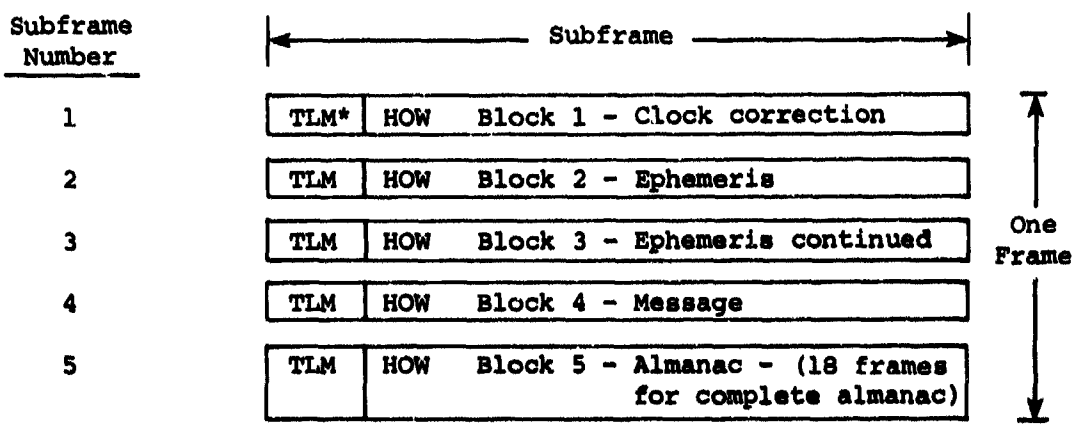
Two forms of PRN codes are used to modulate the NAVSTAR GPS navigation signal. The first and most precise PRN code is the precision code (P-code). The precision navigation accuracy attained from use of this code is made

possible by its transmission rate of 10.23 megabits per second, or 97.8 nanoseconds per bit. At the speed of light (3×10^8 m/s), each bit of the P-code corresponds to a distance resolution of 29.34 meters (96.8 feet). However, the repetition rate of the P-code pattern is only once per seven days, making it effectively impossible to lock onto it without knowledge of the code pattern. Even with such knowledge, aiding is generally required for rapid convergence on pattern synchronization. For this reason, a second PRN code is used -- the coarse acquisition, or clear access, (C/A) code. The C/A code repeats itself every millisecond, enabling easy acquisition and lock-on. The transmission rate of the C/A code is one-tenth that of the P-code, resulting in a distance resolution of 293.4 meters (968 feet). By locking onto the C/A code, the receiver can extract the navigation information contained in the signal. Included in the navigation message is a parameter referred to as the handover word (HOW), which is used in transferring from the C/A code to the P-code.

5.3.2 Format

The navigation message contains the handover word, data relating to space vehicle (SV) status, clock correction parameters, corrections for signal propagation delays, the ephemeris of the SV whose signal is being received, and almanac information that defines the approximate ephemerides and status of all other space vehicles.

The navigation message is contained in a 1,500-bit, 30-second data frame. The data frame is subdivided into five subframes, each of which contains 10 words, each word 30 bits in length. The first two words of each subframe are a telemetry word (TLM) and the C/A-to-P-code HOW. The TLM serves as an identifier to facilitate pattern synchronization and contains information primarily for use by the ground control segment, relating to upload operations. The HOW contains information that allows transition from the C/A code for users with access to the P-code. The remaining eight words in each subframe constitute a block of data, as illustrated in Figure A-8.



*TLM - Telemetry word.
HOW - Handover word.

Figure A-8. DATA FRAME FORMAT FOR GPS

Block 1, corresponding to subframe 1, contains the SV clock correction parameters and ionospheric propagation-delay model parameters. Blocks 2 and 3 contain the ephemeris of the SV. Block 4 is reserved for special alphanumeric messages, and Block 5 contains almanac data for all space vehicles. Only a single SV almanac is available per data frame. Therefore, it takes 18 frames, nine minutes, for the receiver to cycle through the almanac for a system complement of 18 satellites. The almanac information is required for use in signal acquisitions; the other information is necessary for accurate processing of the navigation signal.

5.4 Signal Processing

As previously mentioned, each satellite generates a particular C/A code. The user receiver generates replicas of these codes and cross-correlates the locally generated signals with the signals received from the satellites. A tracking loop is used to establish synchronization between the two signals. Tracking error is indicated by the output of the correlator, with minimum error representing the peak of the autocorrelation function. Maximum code tracking is achieved by advancing and retarding the phase of the locally generated signal with respect to user clock timing. If the user clock is synchronized to GPS system time, the time delay associated with the phase difference measured at a common clock time between the local and received signals indicates the travel time of the signal between satellite and receiver. The travel time measured corresponds with satellite-to-receiver range.

In reality, the quality of the user clock is not high enough to maintain synchronization to GPS system time. Therefore, the time, or range, measurement includes clock bias errors and is referred to as a pseudorange measurement.

By measuring range from any individual satellite, the user places himself on a sphere centered at that satellite. Two range measurements create two spheres, the intersection of which defines a circular LOP. The intersection of a third sphere under ideal circumstances would provide a single point of intersection and thereby a relative position fix with respect to the center of each sphere. Knowledge of the earth-referenced X, Y, and Z position coordinates of each sphere center -- that is, of each satellite -- would result in a three-dimensional fix of user position.

Satellite position can be accurately computed from the ephemeris parameters included in the navigation message of the received GPS signal. Data contained in the message are accessible once the format identifiers have been detected after track lock-on.

Although three satellites generate three spheres, they do not provide an accurate three-dimensional position fix. The clock biases included in the pseudorange measurements introduce errors into the navigation computations. Each pseudorange measurement is therefore composed of the three position parameters and a clock bias term. The existence of four unknowns requires four pseudorange measurements to obtain four equations, which can then be solved for the position in three dimensions and the user clock offset.

Before the four equations are simultaneously solved, however, each pseudorange measurement is compensated for ephemeris errors, propagation delay, and satellite clock offset. The terms providing these corrections are included in the navigation message. Additional accuracy can be achieved when the accumulated phase difference between the received signal and the locally generated reference code is measured over a fixed time interval. This delta range measurement has the accuracy and resolution of a fraction of the carrier wavelength.

The GPS signal from each satellite is transmitted over two carrier frequency links, both of which are in the lower microwave region called the L-band. Link 1 (L1) has a center frequency of 1,575.42 MHz, and Link 2 (L2) has a center frequency of 1,227.60 MHz. When the two frequencies are processed, propagation errors that vary with frequency can be identified, and appropriate corrections can be generated and applied. L1 currently carries both the C/A code and the P-code, whereas L2 carries only the P-code. Inability to process the C/A code on two frequencies prevents the civilian user receiver from determining propagation errors. However, propagation corrections available in the navigation message do improve the accuracy of the single-frequency signal processing.

5.5 Operational Considerations

It was stated earlier that four range measurements are necessary to obtain a three-dimensional position fix. This requirement for a minimum of four satellites to be visible at all times throughout the world is difficult to satisfy with only 18 satellites. Failure of a single satellite would result in a large area of the United States not having coverage by four satellites during certain times of the day. As an alternative to the severe degradation of accuracy resulting when clock biases cannot be accounted for via the fourth range measurement, an altimeter can be used to supply the Z (vertical) component of the range equations. Any inaccuracies in the vertical measurement will translate into lateral and longitudinal position errors. Although barometric altimeters provide satisfactory relative accuracy, they are a poor substitute for the fourth satellite in terms of absolute position measurement. The usefulness of altimeter aiding is further limited because of the geometry between the satellite and the user. Studies have indicated that the altimeter measurement and one of the satellite range measurements would generally lie in the same plane with the user, a situation seriously diluting the effectiveness of the measurement.

6. DOPPLER NAVIGATION

6.1 History of Development

Doppler navigation was first developed for use in long-range bombers and other military aircraft around the mid-1950s. By 1962, several international airlines were using Doppler navigation systems in over-water navigation and in other remote areas where VOR/DME coverage was not provided.

These early Doppler navigation systems do not provide some of the more convenient man-machine interfaces provided by more recent over-water navigation systems such as INS and, later, Omega. For example, the early Doppler systems do not use great-circle course generation and do not provide a display of current latitude and longitude. Doppler navigation systems under current development provide both great-circle route generation capability and a display of current latitude and longitude.

6.2 System Overview

A Doppler navigation system is a self-contained system that is used to navigate between position fixes. A Doppler radar is used to measure the aircraft's velocity vector relative to the aircraft body-axes. This velocity vector, together with an input of heading data, is then used for navigation from waypoint to waypoint.

The complete Doppler navigation system includes the following:

- Doppler radar
- Heading reference system
- Attitude reference system

The Doppler radar provides a measure of the aircraft's velocity vector in three dimensions. A simple attitude reference system is used to resolve the velocity vector into locally level coordinates. This velocity vector is used in conjunction with the heading provided by the heading reference system. The heading reference system is the limiting element in the cross-track accuracy of a Doppler navigation system.

A Doppler navigation system provides current position and cross-track deviation for use by displays and the autopilot. It also provides a display of drift angle, cross-track distance, and ground speed.

6.3 System Inputs

The Doppler navigation system requires inputs from a Doppler radar, a heading reference system, and an attitude reference system. The operation of each of these is discussed below.

6.3.1 Doppler Radar

The Doppler radar is used to measure the aircraft's velocity vector. The operation techniques and principles are discussed below.

6.3.1.1 Doppler Radar Operation

The Doppler radar comprises a radar transmitter, a receiver/processor, and an antenna. The transmitter antenna directs toward the ground two to four radar beams, which are scattered by the ground surface. Some of the

scattered radar energy that is reflected back toward the aircraft is then detected by the receiver antenna. The detected signal includes a frequency shift, called Doppler shift, which is proportional to the aircraft velocity relative to the ground surface. The receiver/processor then measures this Doppler shift in each beam and computes the corresponding component of velocity. The geometric relationship existing between the radar beams and the aircraft fuselage is then used to resolve these velocity components into the aircraft body-axis coordinates.

Since three velocity components are required to determine the aircraft's velocity in three-dimensional space, at least three radar beams are required. Two radar beams are sufficient only if barometric altitude rate is used to supply a third velocity component. A variety of beam configurations are possible. A Janus configuration directs radar beams both forward and rearward with respect to the aircraft and may use three or four beams. A non-Janus configuration uses two beams and directs both either forward or rearward. The non-Janus configuration requires barometric altitude rate as the third velocity component input.

6.3.1.2 Doppler Radar Principles

The backscattered radar energy is reflected from discrete surfaces on the ground (e.g. ocean waves, rocks, and leaves). The total signal received at the Doppler radar receiver antenna is composed of many separate reflections from these surfaces. These separate signal components have different amplitudes and phases, because of the randomly positioned reflecting surfaces. In addition, the angle of incidence of the various signal components varies slightly over the finite width of the radar beam. Since the relative velocity is dependent on the angle of incidence, the signal components have slightly different Doppler shifts. The resulting frequency spectrum of the received signal is roughly Gaussian. The mean frequency is estimated by the receiver/processor and compared with the transmission frequency to obtain the Doppler shift.

The ground velocity component corresponding to the Doppler shift in a given Doppler radar beam is determined by the following equation:

$$V_R = \frac{C\nu}{2f}$$

where C is the speed of signal propagation (i.e., speed of light), ν is the Doppler shift, and f is the frequency of transmission. Two frequencies, 8.8 GHz and 13.325 GHz, have been allocated for Doppler navigation operation by U.S. and international agreement. The factor of 2 in the above relationship reflects the concept that each radar beam experiences two Doppler shifts, which are additive, during the radar signal's round trip from the transmitter antenna to the ground and back to the receiver antenna. The first Doppler shift is due to the relative velocity between the transmitter and the ground. The second shift, which is added to the reflected signal, is due to the relative velocity between the ground and the receiver antenna.

6.3.2 Heading Reference System

The heading reference system provides a heading input to the Doppler navigation system. Because the Doppler navigation system accuracy is principally dependent on the accuracy of the heading reference, the heading reference system is required to be highly accurate. A flux-valve compass is commonly used to measure the nagmetic heading of the aircraft. The earth's magnetic field is passed through a three-phase coil fixed to the aircraft frame. The coil senses the components of the earth's magnetic field, which are then resolved to determine the aircraft's magnetic heading. The measured heading is generally gyro-stabilized to enhance the short-term response.

6.3.3 Attitude Reference System

The attitude reference system provides pitch and roll information to the Doppler navigation systems. Two different methods can be used:

- Body-fixed
- Stable-mounted

The distinction between the two methods lies in the manner in which the Doppler radar antenna is mounted to the aircraft.

The body-fixed antenna is mounted directly to the aircraft frame. The beam geometry is therefore fixed with respect to the aircraft body-axes. The attitude reference system provides pitch and roll data that are used to resolve the velocity vector into locally level coordinate frame components.

A stable-mounted antenna is controlled relative to the pitch and roll axes so that the beam geometry remains fixed with respect to a locally level coordinate frame, regardless of aircraft attitude. The orientation of the antenna is maintained by pitch and roll commands supplied by the attitude reference system.

With either method, the attitude reference system is not required to be highly accurate. The navigation error due to errors in the pitch and roll inputs is generally small. For example, the velocity error of a typical Janus configuration is only .014 percent per degree of error in pitch. The effect of aircraft roll angle on the navigation accuracy is also not considered to be significant, since the average roll for a typical flight tends to be zero. For this reason, some Doppler navigation systems only consider the effect of pitch and disregard roll effects. A low-cost, low-quality attitude reference system is typically used and is not considered to be a major component of the Doppler navigation system.

6.4 Navigation Processing

The navigation computer uses the inputs from the Doppler radar, the heading reference, and the attitude reference to navigate between position fixes. The Doppler radar provides the aircraft groundspeed vector in body-axis coordinates. The attitude input is then used to resolve the velocity

vector into suitable navigation coordinates (e.g., along-track and cross-track components of the locally level coordinate frame). This velocity vector defines the drift angle with respect to the aircraft body axes. By adding this relative drift angle to the true heading, the actual track angle is computed. Comparing the actual track angle with the desired track angle produces the track angle deviation, which can be used as a steering input to the autopilot to maintain track. The magnitude of the velocity vector is the groundspeed. The groundspeed is then integrated to provide distance displacement information.

6.5 Operational Characteristics

Doppler navigation systems in current civil use were developed in the late 1950s to early 1960s for navigation in areas where VOR/DME coverage was inadequate or non-existent. These Doppler navigation systems use a constant magnetic course generation method and do not provide a display of current latitude and longitude. In over-water environments such as North Atlantic tracks, which are great-circle tracks and which require position reporting in terms of latitude and longitude, current Doppler navigation systems are not convenient. However, Doppler navigation systems under current development use great-circle route generation and provide a display of current latitude and longitude, thereby providing a more convenient man-machine interface.

The characteristics of the detected return Doppler signal are not the same over water as they are over land. Current systems provide a land-sea switch that must be appropriately selected. If the switch is inadvertently left in the wrong position, the system will provide erroneous navigation data.

Another operational deficiency in over-water navigation applications is the potential for total signal loss when the water is very calm. Although total signal loss renders Doppler unsuitable for navigation, such situations occur infrequently.

7. CONVENTIONAL INS

7.1 History of Development

Conventional inertial navigation system (INS) techniques have evolved from principles used in aircraft gyro instruments and the marine gyrocompass. The earliest applications of INS techniques were for guidance in ballistic missiles and for ship navigation in the mid-1950s. The first INS aircraft applications were for navigation in various military aircraft, beginning in the late 1950s. The first civil airborne applications were for over-water navigation in the new wide-body "jumbo jets" introduced in the late 1960s. Conventional INSs were selected over Doppler navigation systems because of their better accuracy capability, more convenient man-machine interfaces, and provision of heading and attitude data.

7.2 System Overview

A conventional INS is another self-contained navigation system. Accelerometers are used to measure the aircraft's acceleration vector. The measured acceleration is then integrated twice to compute the aircraft's velocity vector and position displacement. By relating the position displacement to initial position, the INS determines current position.

The accelerometers are mounted on a platform that is so mechanized that the accelerometer axes are aligned with the axes of the local coordinate frame, regardless of the aircraft's orientation. The platform orientation is controlled by gyros to provide an angular reference. The navigation accuracy of the INS is highly dependent on the accuracy of these gyros.

The initial orientation must be established while the aircraft is stationary on the ground prior to flight. It is at this time that the pilot manually enters initial position. This mode of operation is called the initial alignment mode or, simply, alignment.

7.3 Platform Orientation

Gyros measure angular deviations with respect to inertial space. The local coordinate frame at a given location on the earth continually rotates with respect to inertial space because of earth rotation. Also, at any instant of time, the locally level geographic coordinate frames at different locations on the earth are not coincident, since the different "up" axes are not parallel. The INS must compensate for these variations between inertial space and the locally level geographic coordinate frame in order to use gyros as an angular reference in aligning the platform with the local coordinate frame. The compensation rates are computed relative to two effects:

- Earth rotation rate
- Aircraft transport rate

Two different methods have been used in mechanizing the platform:

- North-pointing method
- Wander-azimuth method

Each of these methods computes the compensation terms in slightly different ways and will be discussed separately.

7.3.1 North-Pointing Method

The platform axes in a north-pointing INS are parallel to the east, north, and "up" axes, respectively, of the locally level geographic coordinate frame. The input axes of the accelerometers (the axes along which the accelerations are measured) are parallel to the platform axes.

The gyro input axes (those about which the gyros measure angular deviations) are also parallel to the platform axes.

The earth rotates at an angular rate of 15.041 degrees per hour with respect to inertial space. A portion of the earth rotation rate is detected by the north axis and the "up" axis (also called the azimuth axis) gyros, as follows:

$$\omega_{north} = \Omega \cos \lambda$$

$$\omega_{azimuth} = \Omega \sin \lambda$$

where Ω is earth rate (15.041 degrees per hour), ω is the component of earth rate detected by the gyros, and λ is the latitude. No component of earth rate is detected by the east axis gyro, since it is perpendicular to the earth's spin axis.

The aircraft's transport rate can be thought of as a rotation about the earth's center of the "up" axis with respect to inertial space as the aircraft moves from point to point over the earth. The "up" axis rotates at an angular rate of V/R with respect to inertial space, where V is the aircraft's velocity and R is the radius of the earth. The north-south and east-west components of aircraft transport will be discussed separately.

North-south transport causes an angular rate about the east gyro axis as follows:

$$\omega_{east} = \frac{Vn}{R}$$

where Vn is the north-south component of aircraft velocity. The north and azimuth gyros do not measure an angular rate, since these axes are perpendicular to the rotation axis.

East-west transport causes angular rates, which are measured by both the north and azimuth axis gyros as follows:

$$\omega_{north} = \frac{Ve}{R}$$

$$\omega_{east} = \frac{Ve}{R} \tan\lambda$$

where Ve is the east-west component of aircraft velocity.

The combined effects, then, of both earth rotation and aircraft transport are obtained by summing the individual effects to obtain the following equations:

$$\omega_{east} = \frac{Vn}{R}$$

$$\omega_{north} = \Omega \cos\lambda + \frac{Ve}{R}$$

$$\omega_{azimuth} = \Omega \sin\lambda + \frac{Ve}{R} \tan\lambda$$

These terms are continually computed to complement the gyro measurements and are called the compensation rates. The compensation rates provide the interassociation between the local coordinate frame of the platform and inertial space.

North-pointing INSs are not suitable for navigation at latitudes above 80°. The azimuth-axis compensation rate ($\omega_{azimuth}$) is prohibitively large near the polar regions. For this reason, north-pointing INSs are not widely used.

7.3.2 Wander-Azimuth Method

The problem of excessive compensation rates near polar regions is solved by using the wander-azimuth method, in which the platform is allowed to assume an arbitrary azimuth angle. The azimuth-axis compensation rate ($\omega_{azimuth}$) is not applied to the platform. Instead, this term is integrated to determine the arbitrary azimuth angle, called the wander angle or alpha angle (α). The platform azimuth axis is designated the "Z" axis in a wander-azimuth INS. The two other axes, which are rotated about the "Z" axis with respect to true north by the angle α, are called the "X" and "Y" axes respectively. The compensation rates in a wander-azimuth INS are derived from the compensation rates computed for a north-pointing mechanization by resolving them as follows:

$$\omega_x = \omega_{east} \cos\alpha + \omega_{north} \sin\alpha$$

$$\omega_y = \omega_{east} \sin\alpha + \omega_{north} \cos\alpha$$

$$\omega_z = \omega_{azimuth}$$

The wander-azimuth method is the most widely used mechanization in current conventional INSs.

A variation of the wander-azimuth method intentionally rotates the platform about the "Z" axis at some known rate ($\dot{\alpha}$). This rate is added to the "Z" axis compensation term, and the sum is integrated to compute α. Each gyro input axis alternately points north and then south, thus cancelling some of the adverse effects of gyro drift.

7.4 Platform Mechanization

The preceding section describes methods of attaining the desired platform orientation. This section describes the mechanical implementation used to achieve the desired platform orientation. The platform mechanization comprises the following:

- Gimbal system
- Angle-measuring gyros

The gimbal system provides the platform with total angular freedom about the aircraft body-axes. The gimbal system includes gimbal motors for

positioning the platform and gimbal resolvers to measure aircraft attitude and heading. The angle-measuring gyros are used to measure angular deviations of the platform from the desired orientation. These measurements are used to position the platform properly with the gimbal motors. The gyros also include gyro-torquers, which are used in providing earth-rate and transport-rate compensation.

7.4.1 Gimbal System

The platform is mounted to the aircraft frame with a multi-order gimbal system. Because it is simple and its operation is basic to all higher-ordered gimbal systems, a third-order gimbal system will be discussed. However, a fourth-order system is typically used to avoid gimbal-lock, which occurs in third-order systems when the aircraft is in a 90° pitch attitude.

The platform is pivot-mounted to the pitch gimbal along the azimuth axis. The pitch gimbal is then pivot-mounted to the roll gimbal along the pitch axis. The roll gimbal, finally, is pivot-mounted to the aircraft frame along the roll axis. Torque motors are used at the pivot mounts to rotate the platform about each axis independently. The torque motors are then driven appropriately to orient the platform properly. Resolvers are used at each pivot mount to measure the aircraft's pitch, roll, and heading. These measurements are supplied to cockpit displays and to the autopilot.

7.4.2 Gyros

Three gyros are mounted orthogonally on the INS platform with their input axes parallel with the platform axes. The gyros are used to measure the angular deviations of the platform about the platform axes. The deviation measurements are used to drive the torque motors to maintain the desired platform orientation. Since the gyros measure rotation with respect to inertial space, the compensation terms (see Section 7.3 of Appendix A) are needed to define the relationship of inertial space to the platform axes. To apply the compensation to the gyro measurements, each gyro is provided with a gyro-torquer, which commands the orientation of the gyro's input axis according to the gyro-torquer input signal. In addition to providing a means of applying the compensation terms, the gyro-torquers are used in the initial alignment mode (discussed in Section 7.5.2 of Appendix A).

7.5 Operating Modes

INS operates in two basic modes:

- Navigation mode
- Initial alignment mode

The navigation mode is the normal operating mode, in which navigation data are provided by the INS to the autopilot and cockpit displays. The initial alignment mode is required to orient the platform properly before the navigation mode is selected.

7.5.1 Navigation Mode

In the navigation mode, the INS output data includes the following:

- Current position
- Groundspeed
- Altitude
- Track angle
- Wind speed
- Wind angle
- True heading
- Attitude (pitch and roll)
- Steering commands

Groundspeed and position displacement are derived from the acceleration vector measured by the accelerometers. This derivation can be thought of as integrating the acceleration vector twice. Current position is determined from initial position displacement. The vertical component of acceleration must be complemented with barometric altitude to provide stable outputs of vertical speed and altitude.

Track angle is the angle formed by the east and north components of groundspeed. Wind speed and wind angle are computed by comparing true airspeed (TAS) and true heading with groundspeed and track angle. True heading, pitch, and roll are provided by the resolvers used at the pivot mounts of the gimbal system. Whereas true heading is directly provided by the azimuth axis resolver in a north-pointing INS, the alpha angle must be added to the azimuth resolver measurement in a wander-azimuth INS to provide true heading. Steering commands are generated by comparing the current position with the desired course. The desired course is a great-circle track defined between waypoints entered into the INS.

7.5.2 Initial Alignment Mode

Before the navigation mode can be used, the initial alignment mode must be selected to orient the platform properly. Alignment comprises three phases:

- Manual entry of initial position
- Platform leveling
- Gyrocompassing

Initial position is used as a reference for computing compensation terms and for subsequent determination of position in the navigation mode. Platform leveling aligns the vertical axis of the platform with the direction of the gravity vector. Gyrocompassing is a technique for aligning the platform azimuth with true north. The entire alignment, which requires

from 8 to 15 minutes for completion, must be performed while the aircraft is stationary on the ground.

7.5.2.1 Initial Position

The initial latitude and longitude of the aircraft is manually entered into the INS. Initial latitude is used in the gyrocompassing phase of the alignment. Both the latitude and the longitude of the initial position are used later in the navigate mode as references for computing current position.

7.5.2.2 Platform Leveling

The platform is leveled with respect to the direction of the gravity vector ("up"). This places the X and Y axes (or east and north axes in a north-pointing INS) within the local horizontal plane. During the leveling phase, the components of gravity measured by the two horizontal accelerometers are monitored. The portion of gravity measured by the horizontal accelerometers is a function of unwanted platform tilt and is used to drive the gyro-torquers. The gyro-torquer signals cause the input axes of the gyros to rotate, producing angular deviation errors. These errors, measured by the gyros, are used to reposition the platform so that the platform tilt is removed. The platform is level when the horizontal accelerometers no longer measure any component of the gravity vector.

7.5.2.3 Gyrocompassing

Gyrocompassing orients the platform azimuth with true north. The implementation in a north-pointing INS is different from that in a wander-azimuth INS. The two implementations will be discussed separately.

North-Pointing

The platform is rotated about the azimuth axis to align the north platform axis with true north. The earth-rotation compensation rates (discussed in Section 7.3 of Appendix A) are applied to the appropriate platform axes. Any misalignment between the north platform axis and true north, however, causes the compensation to be misapplied, thus tilting the platform. The magnitude and direction of tilt are detected by the horizontal accelerometers. This information is used to rotate the platform about the azimuth axis so that the misalignment between the platform north axis and true north is removed. The platform is rotated by applying the detected tilt signal to the azimuth gyro-torquer. The resulting gyro error signal is then used to rotate the platform.

Wander-Azimuth

In a wander-azimuth INS, the platform "Z" axis is slaved to the aircraft heading during the gyrocompassing phase. The earth-rotation compensation is applied with the alpha angle assumed to be zero (i.e., aircraft heading is exactly true north). A nonzero alpha angle results in misapplied earth-rotation compensation and causes the platform to tilt. The

tilt rate, measured by the horizontal accelerometers, is used to estimate the actual alpha angle. A correct estimate of the alpha angle will cause the earth-rotation compensation to be correctly applied; therefore there is no further tilt in the platform.

In both the north-pointing and the wander-azimuth INSs, a fine-align mode is entered in which the platform tilt incurred during the gyrocompassing process is removed and further gyrocompassing is executed to obtain a precise true-north reference.

Some systems calculate the initial latitude, which is a function of the total tilt incurred during gyrocompassing. The computed latitude can then be used in further fine alignment and as a reference for a reasonableness check of entered initial latitude.

7.6 Operational Characteristics

Since INS is a self-contained navigation system, it can be used in over-water navigation and in remote areas in which VOR/DME coverage is inadequate. Although the position and groundspeed errors increase as a function of time, the navigation accuracy of INS is sufficient for most over-water flights of long duration without requiring position updates from a radionavigation system. However, to further enhance the accuracy, most INSs provide some form of update capability. Some provide a manual update capability in which the pilot can insert values of latitude and longitude for current position. Other systems mix DME/DME RNAV information with INS data, using the INS to smooth noisy DME/DME derived position. Still other INSs provide interface capability between the INS and an Omega receiver. The Omega unit automatically provides a position update when the Omega accuracy is estimated to be suitable, and the INS provides position data between updates. The INS can also provide position data during periods of inadequate Omega coverage, such as during scheduled transmitter maintenance or when the aircraft is within 300 nm of a transmitter station upon which the Omega navigation process is dependent.

8. STRAPDOWN INS

8.1 History of Development

Strapdown inertial navigation system (INS) development began in the late 1950s. Significant advances were impeded until recent years by technology limitations in gyros and computers. Development of nonconventional gyros such as the ring laser gyro and the electrostatically suspended gyro has overcome gyro dynamic range limitation. Recent minicomputer technology has supplied a throughput capability that is more than adequate for strapdown INS.

The accuracy capability of strapdown INS was first demonstrated to be suitable for aircraft navigation when the U.S. Air Force conducted evaluation flights at Holloman Air Force Base in 1975. The first civil strapdown INS applications will comprise a strapdown inertial reference system (IRS) and the use of a flight management computer (FMC). This capability will be commercially available in the early 1980s.

8.2 System Overview

A strapdown INS is a self-contained navigation system with basic principles similar to those of conventional INS. Accelerometers are used to measure the aircraft's acceleration, which is then integrated twice to calculate the aircraft's velocity and position displacement. Current position is then determined by relating the position displacement to initial position.

The accelerometers are mounted in fixed reference to the aircraft frame so that their input axes are aligned with the aircraft body-axes. The acceleration components measured by the accelerometers must be transformed into the locally level geographic coordinate frame before velocity and position displacement can be determined. The transformation is performed with gyros to measure the total angular attitude changes of the aircraft. The navigation accuracy of a strapdown INS is highly dependent on the accuracy of the gyros.

The initial orientation of the aircraft body-axes with respect to the locally level geographic coordinate frame is established during the initial alignment mode, while the aircraft is stationary on the ground prior to flight. During the initial alignment mode, the pilot manually enters the initial latitude and longitude.

8.3 Strapdown INS Gyros

The gyros used in a strapdown INS must be capable of measuring the total range of aircraft attitudes. In a conventional INS, the gyros are required to measure only the small incremental deviations of the platform and are not appropriate for use in a strapdown INS. Three types of gyros have been developed that are particularly suited for use in strapdown INS applications:

- Ring laser gyro
- Electrostatically suspended gyro
- Tuned-rotor gyro

8.3.1 Ring Laser Gyro

The ring laser gyro (RLG) can be used to measure the angular rate about a single axis. The RLG has no spinning mass and has the potential for very high reliability compared with gyros that do have a spinning mass. The operating principle of the RLG is based on relativistic principles first demonstrated in 1963.

The RLG uses two laser beams traveling around a single closed path in opposite directions from each other. If the RLG is rotated with respect to inertial space in the direction of one of the beams, the theory of general relativity predicts that the length of the closed path will decrease in the direction of rotation and increase in the opposite direction, in proportion to the rate of rotation. Since the oscillation frequency of a

laser is proportional to the length of the path along which it travels, the changes in path length due to rotation will cause the frequency of each beam to change in proportion to the rotation rate. Since the frequency of one beam increases while that of the other decreases, a difference frequency can be measured that is also proportional to the rotation rate. By applying the appropriate scale factor to the difference frequency measurement, the rotation rate can be determined.

The laser path is either a triangular or square shape, with reflecting surfaces at each corner. The reflecting surface at one corner allows a small amount of energy from each of the two beams to pass through to a special difference frequency detector. The size of the laser path and the quality of the reflecting surfaces affect the overall accuracy capability of the RLG. Generally, increasing the path length and improving the quality of the reflecting surface will improve the accuracy of the angular rate measurement capability.

A condition called lock-in occurs in an RLG because of interaction between the two beams. Lock-in places a lower bound on the measurable angular rate when it occurs. Lock-in can be prevented by mechanically dithering the entire laser cavity enclosure. Dithering is a small rotational vibration that has a zero angular mean. This technique is commonly used in most RLGs currently being developed to prevent lock-in.

8.3.2 Electrostatically Suspended Gyro

The electrostatically suspended gyro (ESG) can be used to measure large angular deviations about two orthogonal axes. ESG technology was first demonstrated in the late 1950s.

An ESG uses an electrostatic field to suspend a spherical rotor in a vacuum. The rotor is spun by rotating the field at a very high rate. The rotor is made to wobble as it spins by offsetting the center of mass slightly from the geometric center of the sphere. Modulation in the electrostatic field caused by the wobbling is detected by sensors mounted in the enclosure. The direction of the modulation is determined from the sensor signals and is a measure of the relative orientation of the rotor spin axis and the enclosure. Since there is no physical contact with the rotor, no unwanted torques are introduced. The ESG therefore exhibits a very low erroneous drift rate.

Because of the low drift rate capability, the ESG is also being developed for use in conventional INS military applications that require a high level of accuracy. The angle detection technique used in some of these developments uses an optical sensor. Rather than using a wobbling rotor, this technique uses a rotor with an optical pattern etched into it that is detected by the optical sensor.

8.3.3 Tuned-Rotor Gyro

The tuned-rotor gyro is a mechanical gyro with a spinning mass. It was originally developed for use in conventional INS, in which it measures

only small incremental angular deviations. By means of a special caging technique, the tuned-rotor gyro can measure angular rate, so it is suitable for use in strapdown INS.

The spinning mass (i.e., rotor) is connected to the shaft of the spin-motor by a special flexible coupling. The plane of the rotor is free to rotate slightly about the two axes perpendicular to the spin axis. Angular deviations of the rotor about these axes are detected by sensors attached to the gyro case. The gyro contains a two-axis electric torquer that can be used to introduce calibrated torques into the rotor. The rotor orientation can thus be commanded by an electric signal, which drives the torquer. The torquer is used to electrically servo the rotor to null, using the deviation signals from the case-mounted sensors. The signal level required to drive the torquer is, then, proportional to the angular rate of the gyro case. By using the appropriate scale factor, this signal provides a measure of angular rate. Using the torquer in this manner is called caging.

8.4 Navigation Mode

Three accelerometers are mounted orthogonally to the aircraft frame, with their input axes parallel to the aircraft body-axes. Aircraft acceleration components are therefore measured in body-axis coordinates and must be transformed into the locally level geographic coordinate frame in order to determine aircraft position.

A transformation matrix is used to perform the acceleration vector transformation and defines the relationship between the body-axis and locally level geographic coordinate frames. This relationship is defined in two stages. First, the relationship between the aircraft body-axis coordinate frame and inertial space is defined by the angular measurements of the gyros. Second, the relationship between inertial space and the locally level geographic coordinate frame is defined in calculated earth-rotation and transport-rate compensation terms. (Compensation terms are discussed in detail in Section 7.3 of Appendix A). These two relationships are then used to determine and continuously update the transformation matrix.

Once the acceleration vector is transformed from aircraft body-axis coordinates to the locally level geographic coordinate frame by means of the transformation matrix, it is integrated twice to obtain the aircraft's velocity vector and position displacement. Subsequent computations of the strapdown INS output data are identical to those described in Section 7.5.1 of Appendix A for conventional INS, except for the heading and attitude outputs, which are derived from the gyro input data in a strapdown INS.

8.5 Initial Alignment Mode

Before the strapdown INS can be used to generate navigation information, it must be initialized while the aircraft is stationary on the ground. This process is analogous to the initial alignment mode in the conventional INS. It requires up to 10 minutes.

Initial latitude and longitude is entered into the strapdown INS. The latitude is used to estimate the earth rate, which is then compared with that measured by the gyros. The error, together with the gravity vector measured by the accelerometers, is used to initialize the transformation matrix by means of an iterative technique. When the transformation matrix is properly initialized, no error will be detected between the computed and measured earth rate components.

8.6 Operational Characteristics

Strapdown INS is operationally the same as conventional INS, with the addition of acceleration output data that are referenced to body-axis coordinates. Strapdown INS is more reliable than conventional INS, since it has few moving mechanical parts.

APPENDIX B

EQUATIONS

This appendix contains the equations used to obtain the values of navigational errors specified in this report.

1. DEFINITION OF TERMS

ϕ_1 = Latitude of origin in degrees

λ_1 = Longitude of origin in degrees

ϕ_2 = Latitude of destination in degrees

λ_2 = Longitude of destination in degrees

$$\overline{\phi} = \left(\frac{\phi_1 + \phi_2}{2}\right)$$

$$DLo = \lambda_2 - \lambda_1$$

DLox = Interval of longitude measured from point of departure in degrees

2. RHUMB-LINE EQUATIONS

Rhumb-line course angle (α in degrees):

$$\alpha = \tan^{-1}\left(\frac{\phi_2 - \phi_1}{DLo \cos\overline{\phi}}\right)$$

Latitude of points on the rhumb-line track (ϕ_{RL} in degrees):

$$\phi_{RL} = \phi_1 + DLox \cos\overline{\phi} \tan\alpha$$

Rhumb-line distance (R in nautical miles):

$$R = 60 \sqrt{\left[(\phi_2 - \phi_1)^2 + (DLo \cos\bar{\phi})^2\right]}$$

3. GREAT-CIRCLE EQUATIONS

Initial great-circle course angle (C in degrees):

$$C = \tan^{-1}\left[\frac{\sin(DLo)}{\cos\phi_1 \tan\phi_2 - \sin\phi_1 \cos(DLo)}\right]$$

Latitude of the great-circle vertex (Lv in degrees):

The vertex of a great circle is defined as the point of greatest latitude.

$$Lv = \cos^{-1}[\cos\phi_1 \sin(C)]$$

Difference of longitude between the vertex and the point of departure (DLov in degrees):

$$DLov = \sin^{-1}\left[\frac{\cos(C)}{\sin(Lv)}\right]$$

Latitudes of points on the great-circle track (ϕ_{GC} in degrees):

$$\phi_{GC} = \tan^{-1}[\tan(Lv) \cos(DLox - DLov)]$$

Great-circle distance (D in nautical miles):

$$D = 60 \times \cos^{-1}[\sin\phi_1 \sin\phi_2 + \cos\phi_1 \cos\phi_2 \cos(DLo)]$$

4. GEODESIC ERROR EQUATIONS

Difference between a spherical-earth model and a Clarke 1866 ellipsoid model:

$$E_x = \left[9.12951 \cos\bar{\phi} - 2.92495 \cos(3\bar{\phi})\right] (\lambda_2 - \lambda_1) \left(\frac{\pi}{180}\right)$$

$$E_y = 0.37414 (\phi_2 - \phi_1) \left(\frac{\pi}{180}\right) - 8.88543 \left[\sin(2\phi_2) - \sin(2\phi_1)\right]$$

where

E_x = East error in nautical miles

E_y = North error in nautical miles

APPENDIX C

COMPUTATIONS

The following paragraphs illustrate the application of equations (given in Appendix B) to determine the maximum cross-track deviation between the rhumb-line and great-circle paths between New York and Los Angeles as defined in Figure 5-1. The cross-track deviation between the two paths is defined as the length of the line drawn perpendicular from the rhumb-line path to the great-circle path.

The rhumb-line course angle is determined from the following equation:

$$\alpha = \tan^{-1}\left[\frac{\phi_2 - \phi_1}{(\lambda_2 - \lambda_1)\cos\left(\frac{\phi_2 + \phi_1}{2}\right)}\right]$$

$$\alpha = \tan^{-1}\left[\frac{-6.698}{(44.629)\cos(37.291)}\right] = -10.683°$$

This course angle is relative to the predominant cardinal direction of travel, which in the case of JFK to LAX is west.

The maximum deviation in latitude between the rhumb-line path and the great-circle path occurs at a longitude of 93.778°. The latitude corresponding to this longitude along the rhumb-line path is found from the following equation:

$$\phi_{RL} = \phi_1 + (\lambda - \lambda_1)\cos\left(\frac{\phi_1 + \phi_2}{2}\right)\tan\alpha \qquad (1)$$

where $\lambda = 93.778°$ and α is defined as the angle whose tangent is the change in latitude divided by the change in longitude, also taking into account the convergence of the meridians. The course angle of -10.683° computed earlier is the appropriate angle to be used as α in the above equation. Hence,

$$\phi_{RL} = 40.64° + (93.778° - 73.778°)\cos(37.291°)\tan(-10.683°)$$

$$\phi_{RL} = 37.64°$$

The line of maximum cross-track deviation, a rhumb-line drawn perpendicular to the rhumb-line path toward the great-circle path, makes an angle of 79.317° (90° - 10.683°) with respect to west. The latitude and longitude of the point on the line of cross-track deviation which intersects the rhumb-line path have been defined as 37.64° and 93.778° respectively. Therefore, the latitude of any point on the line of cross-track deviation (ϕ_{XTRK}) can be determined by specifying a longitude (λ_{XTRK}) in equation (1). In this case, the appropriate value for α is 79.317°.

$$\phi_{XTRK} = 37.64° = (\lambda_{XTRK} - 93.778°)\cos\left(\frac{37.64° + \phi_{XTRK}}{2}\right)\tan(79.317°) \qquad (2)$$

The latitude (ϕ_{GC}) along a great-circle path corresponding to a given longitude (λ) is defined as:

$$\phi_{GC} = \tan^{-1}\left[\tan(Lv)\ \cos(\lambda - \lambda_1 - DLov)\right]$$

For the great-circle path between JFK and LAX,

$$Lv = \cos^{-1}(\cos\phi_1 \sin C) = 40.79°$$

where

$$C = \tan^{-1}\left[\frac{\sin(\lambda_2 - \lambda_1}{(\cos\phi_1\tan\phi_2) - (\sin\phi_1\cos(\lambda_2 - \lambda_1))}\right] = 86.1564°$$

$$DLov = \sin^{-1}\left(\frac{\cos C}{\sin Lv}\right) = 5.8894°$$

$$\text{Thus } \phi_{GC} = \tan^{-1}\left[0.8629 \times \cos(\lambda - 79.6674)\right] \qquad (3)$$

At the point of intersection of the rhumb line of cross-track deviation with the great-circle path, the solution of the great-circle and rhumb-line equations in terms of latitude as a function of longitude will be equal. We therefore have two equations with two unknowns (equations 2 and 3). Unfortunately, a closed-form solution of these two equations does not exist, so a graphical or iterative solution is required. Convergence of an iterative solution occurs at a longitude of 94.31° and a corresponding latitude of 39.85°.

Hence, the maximum cross-track deviation between the rhumb-line and great-circle paths between New York and Los Angeles is found to be the following:

$$\text{Cross-track deviation (nm)} = 60\sqrt{(\Delta\phi)^2 + (\Delta\lambda\ \cos\bar{\phi})^2}$$

where $\Delta\phi = 39.85° - 37.64° = 2.21°$

$\Delta\lambda = 94.31° - 93.78° = 0.53°$

$$\overline{\phi} = \frac{39.85° + 37.64°}{2} = 38.75°$$

Cross-track deviation = 134.90 nm

APPENDIX D

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