AD-A119 314 FEDERAL AVIATION ADMINISTRATION WASHINGTON DC OFFICE--ETC F/G 17/7
SUMMARY OF THE FAA'S FUTURE NAVIGATION SYSTEM MIX EVALUATION (T--ETC(U)
AUG 82 T H HIGGINS, K D MCDONALD, P D BLYTHE
UNCLASSIFIED DOT/FAA-EM-82-24 NL

1 of 1
AD A
119314

END
DATE
FILMED
10-82
DTIC

[redacted]

Report No. DOT/FAA-EM-82-24

9

SUMMARY OF THE FAA'S FUTURE NAVIGATION SYSTEM MIX EVALUATION (THROUGH MAY 1982)

DRAFT REPORT

August 1982

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

U.S. Department of Transportation
Federal Aviation Administration

[redacted]

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT/FAA-EM-82-24	A119 314	

4. Title and Subtitle	5. Report Date
Summary of the FAA's Future Navigation System Mix Evaluation (Through May 1982)	August 1982
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No. DOT/FAA-EM-82-24
9. Performing Organization Name and Address U.S. Department of Transportation Federal Aviation Administration Office of Systems Engineering Management Washington, D.C. 20591	10. Work Unit No. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Aviation Administration Office of Systems Engineering Management Washington, D.C. 20591	13. Type of Report and Period Covered Technical Report 14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

This document summarizes the activities of the Federal Aviation Administration (FAA) is formulating preliminary recommendations for the navigation system or system mix that best meets civil aviation navigation requirements of the post-1995 time period. This activity is part of the FAA program described in the Federal Radionavigation Plan (FRP). The FRP specifies that a joint Department of Transportation (DoT)/Department of Defense (DoD) initial recommendation be made on the future radionavigation system mix during 1983 and that a final decision be made in 1986. The 1986 decision will then become the basis for future civil/military navigational system implementation.

17. Key Words		18. Distribution Statement
Navigation	INS	Unlimited
VOR/DME	NDB	This document has been approved for public release and sale; its distribution is unlimited.
Omega/VLF	ILS	
Loran-C	MLS	
GPS		

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	54	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

ACKNOWLEDGMENT

This report is on work started several years ago by N. A. Blake, T. M. Johnson, A. A. Simolunas, F. C. Carr, and J. Bradley. The material reported on has been developed by the FAA Technical Center, TSC, ARINC Research Corporation, MITRE, Aerospace Corporation, TASC, SCT Incorporated, and others, with help from the U.S. Coast Guard, U.S. Department of Defense, the airline industry, user organizations, and avionics manufacturers. Special thanks go to T. H. Higgins, K. D. McDonald, P. D. Blythe, L. H. Hogle, R. Braff, and A. Winick for their help in compiling and preparing this report.

CONTENTS

CONTENTS (continued)

CONTENTS (continued)

CHAPTER ONE

INTRODUCTION

1.1 PURPOSE

This document summarizes the activities of the Federal Aviation Administration (FAA) in formulating preliminary recommendations for the navigation system or system mix that best meets civil aviation navigation requirements of the post-1995 time period. This activity is part of the FAA program described in the Federal Radionavigation Plan (FRP). (Reference 1.) The FRP specifies that a joint Department of Transportation (DoT)/Department of Defense (DoD) initial recommendation be made on the future radionavigation system mix during 1983 and that a final decision be made in 1986. The 1986 decision will then become the basis for future civil/military navigational system implementation.

1.2 SCOPE

The scope of the activity summarized in this document is limited to systems and system mixes considered feasible for a future civil aviation radionavigation system. The analyses, tests, and evaluation programs undertaken will provide the basis for the FAA's input to the recommendation of a future radionavigation system or system mix to be provided by the U.S. Government for all aviation users, as stated in the FRP.

The work is limited to investigations on the following systems:

- VOR
- VOR/DME - VORTAC
- Loran-C
- NAVSTAR GPS
- Omega
- NDB
- Inertial
- ILS
- MLS

Because it plays a significant role in worldwide flight operations, the Inertial Navigation System (INS) is included in this document. New inertial developments are likely to lead to an expanding role in domestic operations. Many of the factors investigated for other systems deal with the nature of electromagnetic propagation and clearly do not apply to inertial techniques.

Data on the Instrument Landing System (ILS) and Microwave Landing System (MLS) are provided so that a complete view of the navigation requirements from takeoff to landing can be made. However, it was not believed necessary to undertake additional ILS/MLS evaluation programs specifically for this selection process.

1.3 APPROACH

The approach taken by the FAA in formulating a recommendation for the future civil aviation navigation system/system mix will involve the following steps:

- Projection of the post-1995 civil aviation navigation requirements (presented in Chapter 2, Volume II of the Federal Radionavigation Plan)
- Selection of the navigation systems that are reasonable candidates to meet the requirements, and determination of their performance from an aviation standpoint
- Comparison of the performance of each system with the technical requirements of civil aviation to determine what services can be performed by each candidate system with and without enhancements
- Conduct of an economic comparison of acceptable systems and system mixes
- Examination of institutional problems

The end result of this activity will be an FAA preliminary recommendation to the Secretary of Transportation in late 1982 for the post-1995 U.S. Government-provided radionavigation service for civil aviation.

Technical/operational factors considered in this document are (1) accuracy, (2) coverage, (3) integrity, (4) reliability, and (5) operational suitability. While these requirements are neither mutually independent nor directly comparable among the candidate systems, they do provide for a relatively straightforward evaluation method from which useful results can be derived.

Some difficulty was found in making proper comparisons of the performance of each system with respect to accuracy requirements. Accuracy may be dependent on the measurement point of reference with respect to signal origin (e.g., VOR) or the crossing angle of lines-of-position (e.g., Loran-C). These factors have been taken into consideration. Most important, system accuracy is dependent on user avionics performance. To constrain this variable in the evaluation of accuracy, a Minimum Operational Performance Standard (MOPS) receiver has been postulated. Receivers meeting this standard are expected to find the most widespread use; this standard is therefore significant in defining overall system performance.

Coverage comparisons present similar problems. VOR/DME, for example, was originally implemented to provide coverage primarily along specified air routes, but the present system has broad coverage over the country. Loran-C was installed along coastal areas for maritime use but currently provides coverage down to the surface for all of the conterminous United States except for a mid-continent area. Consideration is therefore given in this study to adding facilities to meet coverage requirements. Coverage is also a function of receiver and antenna designs, which must be specified as part of the complete system. These factors have been considered in establishing the coverage capabilities of the systems under consideration.

Integrity is defined as the ability of a system to assure the user that he will always receive truthful information (i.e., the system does not lie). Different techniques are used to ensure integrity, and direct comparisons are difficult. The analyses must start with an understanding of how failures can occur, then consider techniques for warning the pilot and determine the adequacy of those techniques.

Reliability is defined as the probability that a system will provide adequate service over a given period of time. In this report, reliability has been treated primarily with respect to the signal-in-space, i.e., signal source characteristics and the propagation medium. Avionics reliability is, of course, significant, but there are insufficient data on new systems (such as GPS) to permit valid comparison with systems in use.

Operational suitability is also difficult to define, since many factors involved relate to other criteria. To make it a manageable area for assessment, operational suitability has been considered largely from the user's point of view.

The approach to obtaining useful economic data has been to develop a civil navigation economic model from which the cost of the candidate systems and system mixes can be determined for comparison. The model is flexible and allows for variation of any one parameter while all others are held constant. A cost-to-benefit capability is part of the model, but the civil aviation benefits of improved navigation systems have not been quantified.

Many institutional issues associated with each of the civil aviation candidate systems and mixes will not be fully resolved before the initial recommendation is made. When the DoT/DoD preliminary recommendation is made in 1983, the task of resolving institutional issues will become paramount. For this document, some of the issues are listed and discussed briefly.

In summary, the FAA's approach to formulating a preliminary recommendation for the future radionavigation system has been to undertake an analysis of candidate systems and to structure the data so that direct comparisons can be made.

CHAPTER TWO

IDENTIFICATION OF ISSUES

Three key concerns have been identified that must be addressed in the process of selecting a navigation system or mix of systems for adoption. Candidate systems (1) must meet the technical/operational requirements of civil aviation, (2) must be affordable, and (3) must be institutionally acceptable. This document is intended to provide the analysis to help develop preliminary recommendations in all three areas.

2.1 TECHNICAL/OPERATIONAL ISSUES

Technical considerations are accuracy, coverage, integrity, reliability, and operational suitability. Operational suitability concerns the manner in which a system meets the operational needs of a wide spectrum of aviation users and the National Airspace System (NAS).

2.2 ECONOMIC ISSUES

Economic considerations deal with the costs of single systems and system mixes, cost-versus-benefit considerations, and comparison of costs and cost-to-benefit ratios between single systems and system mixes. In the past, direct costs to the Government, as the operator of radionavigation services, have been treated separately from costs to the user, who must buy the equipment needed to use the services. However, under cost-recovery policies, such clear distinctions are no longer completely valid. The analysis of system costs must consider initial investment, operation, maintenance, and replacement costs, and the user's unamortized capital investment remaining at the time that replacement of the system is contemplated. In the civil sector, the cost of user equipment, rather than increased performance, often influences acceptance of a new system by the majority of civil users. Substantial unamortized investment in user equipment for an older system may cause strong resistance to early replacement and may lead to an extended transition period. Further, going beyond the FAA's recommendations, the Government must consider all users of navigation in determining what system or system mix is the most economical.

2.3 INSTITUTIONAL ISSUES

Institutional considerations involve issues beyond technical/operational and economic factors. For the systems under consideration, the issues can be considered under the general areas of cost recovery, control of signal access and accuracy, and international standardization.

CHAPTER THREE

DEFINITIONS OF CRITERIA

The merits and limitations of each candidate navigation system were judged relative to technical/operational, economic, and institutional criteria. For the assessments to be as consistent as possible for each system and system mix, definitions of the criteria were established.

3.1 TECHNICAL/OPERATIONAL CRITERIA

The following technical/operational criteria were used to characterize each system for purposes of comparison:

- Accuracy
- Coverage
- Integrity
- Reliability
- Operational suitability

Each of these is discussed in the following subsections.

3.1.1 Accuracy

Accuracy is the degree of correctness with which a measured value agrees with the true value. (Reference 2.)

The following description of accuracy is taken directly from Reference 3.

> Accuracy is the degree of conformance with the correct value. In navigation, the accuracy of a measured or estimated position of a vehicle at a given time is the degree of conformance of that position with the true position of the vehicle at that time. Some degree of error is unavoidable in navigation. This error represents inherent limitations on the ability of human beings to achieve perfection, either in the practice of navigation or in the design, construction, calibration, and operation of navigation systems. In the measurement of position with respect to external reference points, the error in position depends upon both the error in the measurement of individual lines of position and the angles at which these lines of position intersect.

Vehicle operators or navigators are concerned with accuracy in terms of error that does not exceed the bounds of their individual requirements. Controllers are concerned with the movements of many vehicles. Their concern with accuracy is in terms of a probability that error of all vehicle navigation systems will not exceed some value for a specified percent of the measurements taken. Errors considered in the specification of the accuracy of a navigation system do not include mistakes. These are known as blunders.

Because navigation errors are statistical in nature, a statement of the accuracy of a navigation system is meaningless unless it includes a statement of the probability or confidence level which applies. A statement of accuracy which includes no additional qualifications implies that the statement applies to a situation where equipment and practices used meet recognized specifications or standards, and that all sources of error have been considered in the calculation of the accuracy stated. In specifications of the accuracy of radionavigation systems in particular, more specific terminology has been devised to indicate the methods of use and/or sources of error which have been considered in the calculation of accuracy.

The convention adopted in the FRP for specifying accuracy is the 2 drms position error probability method defined in Reference 4. This method is directly applicable to both Loran-C and GPS; VOR accuracies have been converted to this notation.

As further stated in Reference 3, "system accuracy is the expected accuracy of a radionavigation system, exclusive of errors which may be introduced by the user, and geodetic or cartographic errors."

The International Civil Aviation Organization (ICAO) has established guidance for determining VOR system-use accuracy; this guidance has been used in this report for all systems. VOR system-use accuracy is the square root of the sum of the squares (RSS) of VOR aggregate error and the pilotage (flight technical error) elements. This combination is used to determine the probability of an aircraft's remaining within specified limits when using VOR. (Reference 5.) For this report, the term system error is the same as aggregate error in the ICAO definition and includes the signal-in-space error and airborne equipment error. System error is used to compare each system with accuracy requirements in this report.

Table 3-1 lists the accuracy requirements used in the navigation system selection process and in current RNAV approval. The requirements for the selection process were developed in conjunction with users and are specified in the FRP.

Table 3-1. AVIATION NAVIGATION ACCURACY REQUIREMENTS

Flight Phase	Subphase	Altitude (Flight Level)	Traffic Density	Route Width (nm)	Projected System Accuracy 2 drms (Meters)	Projected System-Use Accuracy 2 drms (Meters)	AC 90-45A System Accuracy 2σ (Meters) Cross-Track	AC 90-45A System Accuracy 2σ (Meters) Along-Track
En Route/ Terminal	Oceanic	FL 275 to 400	Normal	Less than 60	--	Better than 12.6 nm	N/A	N/A
	Domestic	FL 180 to 600	Normal	8	1,000	3,600	2,800	2,800
			High	8	1,000	3,600	2,800	2,800
		500 ft. to FL 180	Normal	8	1,000	3,600	2,800	2,800
	Terminal	500 ft. to FL 180	High	4	500	1,800	2,000	2,000
	Remote	500 ft. to FL 600	Normal	8 to 20	1,000 to 4,000	3,600 to 14,000	N/A	N/A
	Helicopter Operations	500 ft. to 5,000 ft.	Low (Off-shore)	8	1,000	3,600	N/A	N/A
		500 ft. to 3,000 ft.	High (Land)	4	500	1,800	N/A	N/A
Approach and Landing	Nonprecision	250 ft. to 3,000 ft. above surface	Normal	1 to 2	100	150	600	500

Flight Phase	Subphase		Altitude (Flight Level)	Traffic Density	Lateral Accuracy 2σ (Meters)	Vertical Accuracy 2σ (Meters)
Approach and Landing	Precision	CAT I	100 ft. to 3,000 ft. above surface	Normal	± 9.1 at 100 ft. above surface	± 3 at 100 ft. above surface
		CAT II	50 ft. to 3,000 ft. above surface	Normal	± 4.6 at 50 ft. above surface	± 1.4 at 50 ft. above surface
		CAT III	0 ft. to 3,000 ft. above surface	Normal	± 4.1 at surface	± 0.5 at surface

3.1.2 Coverage

The coverage area is that area within which a radionavigation system provides signals at a specified minimum level of availability, adequate to permit the navigator to determine position to a specified level of accuracy. (Reference 3.)

The system must provide sufficient signal strength and accuracy to support operations in the phase of flight of concern (see Table 3-1).

As stated in the FRP, coverage is influenced by system geometry, signal power levels, receiver sensitivity, atmospheric noise conditions, terrain conditions, and other factors that affect signal availability. Coverage is defined in terms of horizontal and vertical areas within which signals are normally usable.

Although various receiver designs can be expected to be available for any new system selected, the configuration of the ground or space elements must be able to accommodate receivers of minimal sophistication (MOPS-level equipment). Coverage corresponding to this level must be established as a basic attribute of the system design and configuration. Further, coverage must be provided for all expected modes of receiver operation (e.g., acquisition, tracking, en route, approach). In some systems higher signal levels are needed for initial acquisition than for tracking after the receivers have locked onto the signals. Coverage requirements in this context must provide for sufficient signal levels for receiver acquisition in all defined areas of coverage.

In Omega, Loran-C, and GPS, a single ground/space element contributes to coverage over wide geographic areas; therefore, a station failure affects large areas. For this reason, redundancy is often associated with meeting the coverage requirement. By nature of its deployment in the U.S., VOR/DME provides redundant coverage in much of the usable airspace and can tolerate single-facility failures without dramatic operational impact. The addition of satellites or Loran-C ground stations to accommodate single-station failure must be considered part of the system assessment.

3.1.3 Integrity

Integrity is the ability of a system to assure the user that he will always receive truthful information (i.e., the system does not lie).

To ensure integrity, the system must be capable of continuously monitoring radiated signal performance and must provide an immediate indication to the pilot when not operating within its specified performance limits. For all phases of flight except precision approach, the indication of an out-of-tolerance condition must be given within 7 seconds. For CAT I precision approach, the indication must be within 6 seconds for glide slope and 10 seconds for localizer. Indication must be within 2 seconds for CATs II and III.

The availability of the radiated signal and to some extent its quality can be measured by use of monitors. If an out-of-tolerance condition is detected, the malfunctioning transmitter can be shut down, or some other indication can be given to users that the signal is not suitable for navigation.

The navigation receiver must also aid the integrity process by alerting the pilot to system malfunctions. Simple devices can provide information concerning the radiated signal quality and status. Internal monitoring within the receiver can apply reasonableness and continuity tests to verify the integrity of signal processing. Built-in test equipment (BITE) can accomplish a complete receiver test and may be required where the signal processing circuitry is complex and liable to lead to a loss of integrity. The minimum techniques required to ensure integrity must be a part of the MOPS-level user equipment.

3.1.4 Reliability

Reliability is the probability that a service or system will perform its function within defined performance limits for a specified period of time under given operating conditions. (Reference 3.)

The frequency of interruption of acceptable system service must be sufficiently low so as to not impair the safety and efficiency of air traffic operations dependent on the availability of the system.

Reliability is traditionally expressed in terms of a failure rate and the probability that the system will provide service over a given time period. In the context of this report, such a single figure of merit is not adequate. A number of additional factors must be taken into consideration when a reliability value is associated with a particular system. These factors include avilability, probability of mission success, and redundancy.

3.1.5 Operational Suitability

Operational suitability is a measure of the ability of a navigation system or mix of systems to be flown safely and efficiently in the National Airspace System. (Reference 6.)

The system must demonstrate a level of operational utility that allows it to be safely and efficiently integrated into the overall Air Traffic Control (ATC) system. The system must be able to support civil aviation navigation operations without demanding excessive pilot workload. It is generally accepted that operational requirements are derived from the activities in which the users are engaged, the locations in which these activities occur, and to some extent the type of aircraft. Suitability for use in single-pilot IFR aircraft is an important consideration.

Factors that influence operational suitability from the user's viewpoint include pilot workload, use in single-pilot aircraft, integration with ATC, avionics flexibility, and pilot confidence. The importance of these factors in the selection of a suitable mix of navigation systems is recognized; however, the data are largely subjective, since they are derived from user judgments. Therefore, operational suitability is not amenable to numerical analysis as are such factors as accuracy and coverage.

3.2 ECONOMIC CRITERIA

Economic criteria are directed toward two items -- overall cost comparison between systems and system mixes, and cost-versus-benefit considerations. Overall system cost includes cost to the user, both direct and indirect, and cost to the Government. An important consideration is the ratio of Government costs to those which must be borne directly by the user (in addition to the user's contributions through cost recovery mechanisms). The cost comparisons have been made from a civil aviation point of view and on a total user basis (civil aviation, civil maritime, civil land, and military).

Cost-versus-benefit determinations require establishing a method for costing and quantifying all the benefits (and penalties). This is difficult: one user might put a high value on 50-meter accuracy, whereas another might be completely satisfied with 100 meters and not be willing to pay for the better accuracy. Although cost-versus-benefit considerations add insights to the total economic picture, cost comparison data have greater validity.

A part of the economic issue is being addressed in a DoT economic model that is capable of handling cost comparisons and cost-to-benefit ratio comparisons when and if the benefits are quantified.

3.3 INSTITUTIONAL CRITERIA

Representative institutional issues include cost recovery, control of signal access and accuracy, and international standardization.

CHAPTER FOUR

TECHNICAL EVALUATION RESULTS

This chapter presents the technical characteristics of the systems of interest as measured and/or predicted by use of the latest available data. The following systems were evaluated:

- VOR
- VOR/DME - VORTAC
- Loran-C
- NAVSTAR GPS
- Omega
- NDB
- Inertial
- ILS
- MLS

Five technical characteristics -- accuracy, coverage, integrity, reliability, and operational suitability -- were addressed for each system.

Although it is not radionavigation, inertial navigation is included because of its growing significance in worldwide flight operations. The ILS and MLS precision approach and landing systems are included to provide a complete view of navigation from takeoff to landing.

4.1 VOR

The Very High Frequency (VHF) Omnidirectional Radio Range (VOR) navigation system consists of a network of ground-based signal transmitters that use line-of-sight propagation. The VOR provides azimuth information to pilots in the form of bearing to or from the selected VOR station. Airborne instrumentation provides deviation information from the selected course.

The VOR system is the basis for defining airways and is therefore an integral part of current air traffic control procedures. Two VOR stations can be used to define a radial intersection reference or reporting point. By charting the bearing information obtained from the two VOR stations, a position fix can be determined. VOR along with DME forms the standard ICAO short-range navigation system.

The FAA is presently installing solid-state replacement electronics for VOR and TACAN facilities. This system, known as second-generation VORTAC, includes remote maintenance monitoring (RMM), which will provide for remote certification and fault diagnosis.

4.1.1 Accuracy

The system accuracy of VOR and the use of surveillance is the basis of the design specification for U.S. air route standards and procedures. Accuracy and signal coverage of VOR are a function of aircraft altitude, distance from the station, station classification, and quality of the receiver. The system accuracy (RSS 2σ) for VOR has been calculated to be ± 3.9 degrees for present equipment. With the use of modern avionics, this figure would be reduced. (Reference 7.)

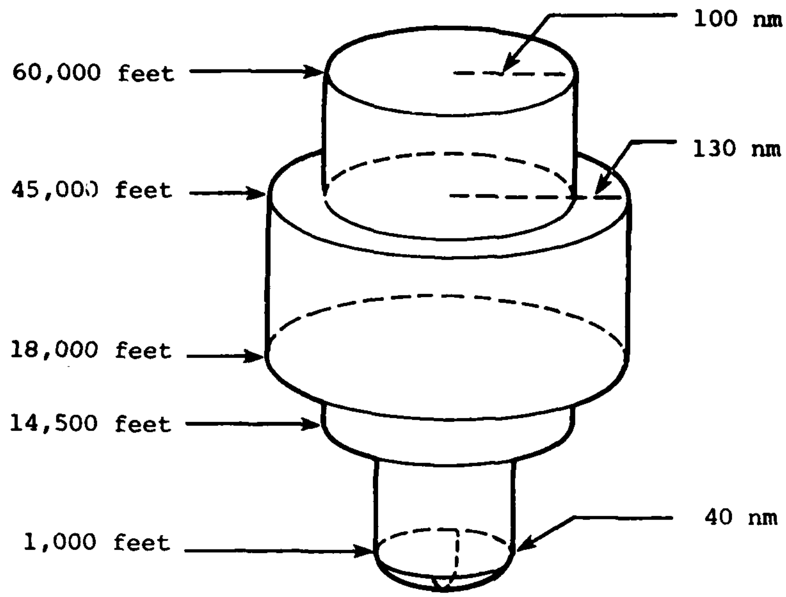
"Airways, routes, and terminal area procedures in the United States are designed on the basis of a VOR system use accuracy of ± 4.5 degrees (95 percent probability)." (Reference 7.)

A number of successful developments have shown that VOR can be made more accurate and less site-sensitive by installation of Doppler ground antennas. Several kinds of more accurate multilobe VOR concepts have been demonstrated over the years. There are ways to tighten up VOR airborne accuracy at relatively modest costs. However, these possibilities have not been taken advantage of, primarily because the community has not seen the need.

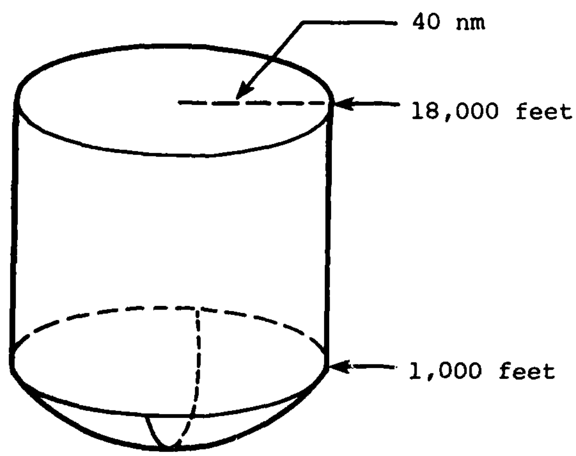
4.1.2 Coverage

VOR signal reception depends on the class of facility used -- terminal, low altitude, or high altitude. Line-of-sight limitations restrict coverage to 30 nautical miles (nm) or less at the lower altitudes, a distance that progressively increases with altitude to an upper limit approaching 200 nm. However, to accommodate the needed number of facilities and to prevent interference from adjacent facilties, standard service volumes are defined, as shown in Figure 4-1. 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.

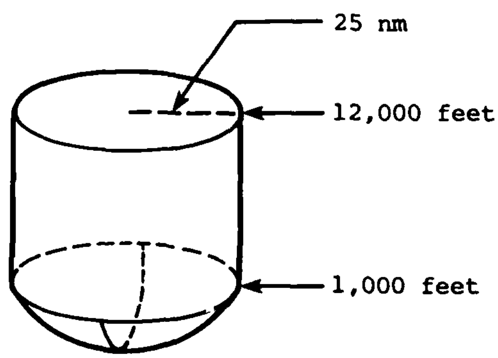
Redundant VOR coverage including extended coverage areas exists everywhere in the conterminous United States above 14,500 feet, except in a small portion of the North Central U.S. An addition of 40 VOR facilities would provide redundant coverage above 14,500 feet throughout the conterminous United States. (Reference 8.) No analysis has been conducted to determine the number of additional VOR facilities to provide complete coverage between 14,500 feet and 2,000 feet above the terrain. VOR coverage is currently provided in this altitude range in those geographic areas most frequently used by the majority of users.



Standard High-Altitude Service Volume



Standard Low-Altitude Service Volume

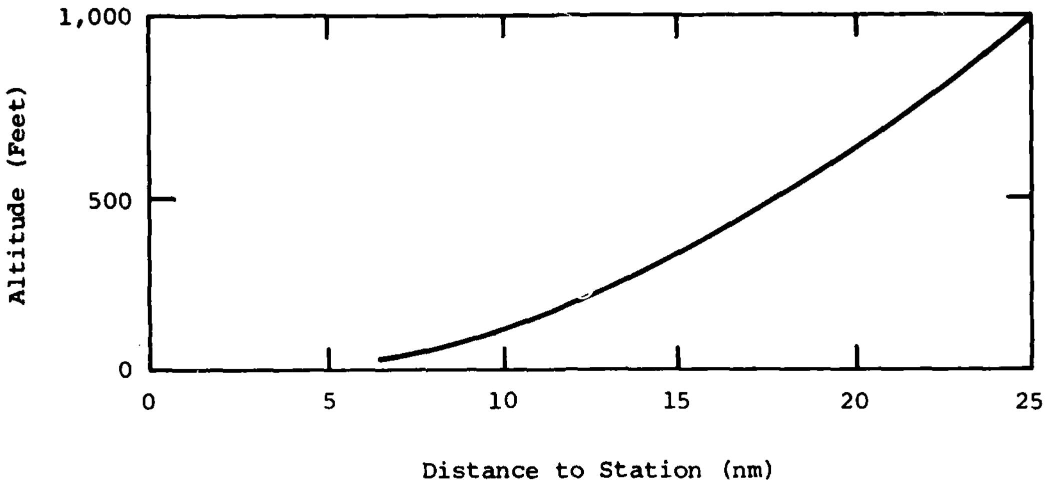


Standard Terminal Service Volume

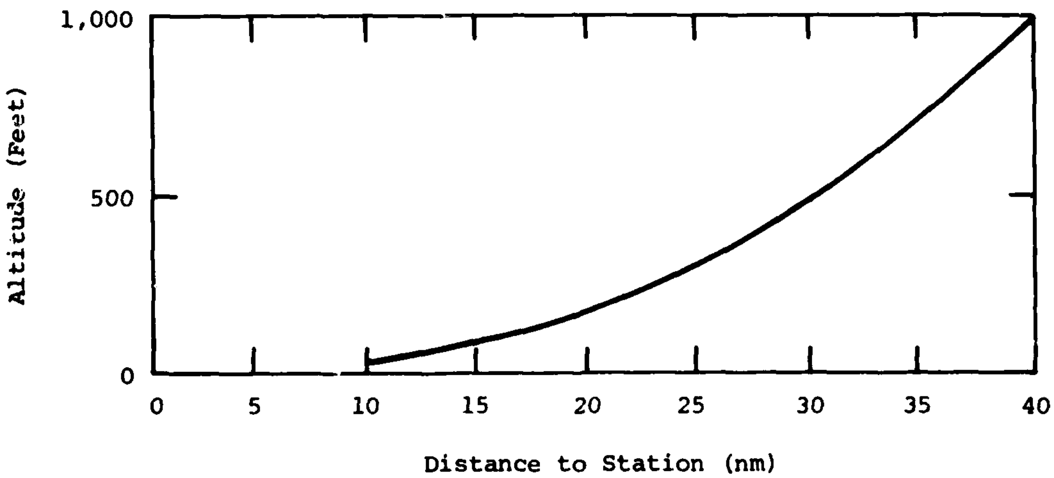
Source: Reference 7.

Note: All elevations shown are with respect to the station's site elevation (AGL).

Figure 4-1. VOR STANDARD SERVICE VOLUMES



Definition of the Lower Edge of the Standard T
(Terminal) Service Volume



Definition of the Lower Edge of the Standard H
(High) and L (Low) Service Volumes

Source: Reference 7.

Figure 4-2. LOWER EDGE OF VOR STANDARD SERVICE VOLUMES

4.1.3 Integrity

VOR signals are continuously monitored on the ground to ensure that accuracy is maintained within prescribed tolerances. (Reference 9.)

Currently, the FAA is procuring solid-state equipment to replace present VOR vacuum tube-type equipment. This equipment is to be implemented in the total NAS by 1985. The integrity of existing equipment is maintained through the use of a field detector located at every VOR site that checks VOR signal parameters to ensure that correct information is being radiated. The new equipment will use dual field detector monitoring systems. These detectors (located at the 90-degree and 270-degree azimuths) will be used in a "voting" type system. When the operational monitor is operating in a single-monitor mode, it is constantly checked, through software control, to ensure its integrity.

VOR avionics provide visual warning if either the received signal level or depth of modulation of the detected signal is inadequate.

4.1.4 Reliability

The FAA maintains records of VOR stations operated in the NAS. These records are summarized in the publication entitled "Facility and Service Outages Report 6040-20 and -21" kept by the Airway Facilities Service. In 1981, VOR stations achieved an average mean time between failures (MTBF) of 4,274 hours. These MTBF figures are calculated on the basis of unscheduled interruptions lasting longer than one minute and result in a probability of satisfactory operation of 99.977 percent for a one-hour period.

There are no operational MTBF figures for the second-generation VOR system now being installed. The design goal is an MTBF of 18,000 hours. (Reference 10.)

4.1.5 Operational Suitabilty

The current airway structure was designed on the basis of VOR performance. The VOR system is over 30 years old and is extensively used. It is well understood and accepted by pilots and controllers and is easy to use and visualize. VOR along with DME is the basis for determining civil aviation navigation operational suitability.

4.2 VOR/DME - VORTAC

The international standard en route navigation system used within the conterminous United States is VOR/DME. VOR provides 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. A VOR coaxially collocated with a Tactical Air Navigation (TACAN) system is called a VORTAC (in this case

TACAN provides the DME signal required). Since there is no difference to civil users in operation or performance between a VORTAC and a collocated VOR/DME, VORTACs are included in the VOR/DME system classification in this report.

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

- VOR only
- VOR/DME
- DME/DME

The combination of VOR and DME at a single site provides the capability for unambiguous position fixing by means of a single facility. The use of multiple DME in navigation computers offers a significant improvement in position determination accuracy in areas that have suitable multiple DME signal coverage. This use of multiple DME is foreseen to provide inputs for flight management computers and inertial navigation systems.

4.2.1 Accuracy

The accuracy of the VOR/DME system has been determined to be ± 3.9 degrees ± 0.5 nm (2σ). Some DME equipment exhibits accuracy of ± 0.5 nm or 3 percent of the distance from the station, whichever is greater. Either the 0.5 nm or the 3 percent accuracy is acceptable relative to certification standards. However, current equipment designs provide much greater accuracy and do not exhibit errors that increase with range.

A number of successful developments have shown that VOR can be made more accurate and less site-sensitive by installation of Doppler ground antennas. Several kinds of more accurate multilobe VOR concepts have been demonstrated over the years. There are ways to tighten up VOR airborne accuracy at relatively modest costs. Modern DME, more accurate than VOR, can also be improved. However, these possibilities have not been taken advantage of, primarily because the community has not seen the need.

4.2.2 Coverage

In the airspace above 14,500 feet, redundant VOR/DME, VOR/VOR, and DME/DME coverage is available everywhere in the conterminous United States except for a small area of the North Central U.S. (Reference 8.) Below 14,500 feet, VOR coverage is provided down to 2,000 feet above the facility in geographic areas used by the majority of users.

4.2.3 Integrity

The integrity of the VOR portion of the VORTAC system is maintained as described in Section 4.1.3. DME integrity is maintained in a similar fashion, through use of external monitors included as part of the ground station. The new solid-state replacement equipment will use a dual external monitor system rather than the current single-monitor system. The dual monitors will be used in a voting-type configuration, but can be operated as single monitors in case of a monitor failure. Both the current and replacement systems check DME signal parameters to ensure that correct information is being radiated by the ground facility. VOR avionics provide visual warning if either the signal level or depth of modulation is inadequate; DME provides a visual warning if the signal cannot be tracked.

4.2.4 Reliability

The FAA maintains records of VOR and TACAN stations operated in the NAS. The records are summarized in "Facility and Service Outage Report 6040-20 and -21." For the year 1981, VOR, DME, and TACAN stations achieved MTBF records of 4,274 hours, 2,263 hours, and 2,599 hours, respectively. The MTBF figures are calculated on the basis of unscheduled interruptions lasting longer than one minute. The design goal of the new second-generation DME system now being installed is an MTBF of 10,000 hours. (Reference 10.)

In many cases, VORTAC coverage overlaps. The overlap provides alternate backup service in the event of a failure. The backup availability increases system reliability, although the reliability figures have not been evaluated.

System reliability depends on all elements, including airborne receivers. The airborne reliability is greatly increased by the common practice of dual receiver equipage.

4.2.5 Operational Suitability

Operational suitability describes the ability of a system to fulfill the operational needs of a complete spectrum of users operating in the NAS. Can it do the job called for, not necessarily better than required, but in a manner that fits individual needs with minimum operational burden and cost? VOR/DME has fulfilled the short-range navigation function of civil aviation users throughout the world for more than 35 years, and operational suitability, in the broad sense, is one of its strongest attributes.

The pilot as a user, whether flying his own aircraft or flying commercially, remains the important source of information in the assessment of operational suitability. The following paragraphs discuss associated factors, treated under four broad categories -- installation flexibility of avionics components, integration of avionics, suitability for use in single-pilot aircraft, and pilot confidence.

The user can implement VOR/DME on a building-block basis. He can procure only that part of the system dictated by his operational needs. He can meet his navigation needs within the Air Traffic Control system with the single VOR receiver, but he has the ability to add full VOR/DME and RNAV if he sees fit. Capability levels in order of increasing cost are as follows:

- VOR with manual instrumentation (course selector and deviation indicator)
- VOR with automatic instrumentation (tie-in with remoting magnetic compass)
- VOR/DME

- VOR/DME and RNAV with limited waypoint storage
- VOR/DME with complete RNAV -- full storage and association with INS and Omega

VOR operates in the same VHF radio frequency band as the ILS localizer and ATC communications. As a result, the VOR receiver is frequently built together with the ILS localizer function. VHF communications receivers normally cover the VOR radio frequency band, which permits them to be used as a backup VOR receiver. The frequency relationship of VOR, ILS, and VHF communications permits the integration of avionics.

The operational suitability of navigation systems for use in single-pilot aircraft is difficult to quantify. It may be summed up by asking the question "Can a pilot fly the aircraft under IFR conditions (in turbulence), conduct the necessary ATC communications, and be able to operate the navigation system under consideration?" A positive response to this question is a requirement and is a true test of operational suitability. The elements to be assessed are pilot workload and the potential for blunder.

Pilot workload in the use of VOR/DME is low. A frequency selection (one control) and course selection (one control) are all that is required. DME is frequency-paired with VOR, so its use usually requires no additional manipulation. A selected course can be related to a compass heading, since VORs are aligned with magnetic North. This permits a pilot to fly a damped compass heading (after making wind corrections) if desired, with only periodic reference to the VOR deviation indicator.

When VOR/DME is used in the RNAV mode, additional pilot inputs are required, and additional blunders are to be expected. However, data input requirements to VOR/DME RNAV are less than those associated with some other candidate systems. VOR/DME may be, and is, widely used without RNAV, while essentially all other candidate systems must use some form of RNAV computer and control display unit (CDU) to obtain meaningful outputs.

Pilot confidence for low-approach use is a factor associated with the confidence a pilot has in committing his aircraft to a low approach and landing under instrument conditions. In addition to the ILS (or, in the future, MLS), VOR is the major source of low-approach guidance. The facility is usually located at or near the airport, which means that there is good signal strength and high confidence in the system. Other factors affect confidence, but use of a signal source near the desired landing point is significant.

4.3 LORAN-C

Loran-C is a hyperbolic radionavigation system that uses ground waves at low frequencies to provide operating ranges of 600 nm or more, up to 1,500 nm independent of line-of-sight. It uses pulse techniques to avoid skywave contamination. Loran-C is capable of achieving 2 drms system accuracies of approximately 556 meters (0.3 nm) or better in its defined coverage area. The Loran-C system currently consists of 16 chains operating throughout the world, comprising a total of 51 transmitting stations. Each chain includes one master station and from three to five secondary 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 Southern Hemisphere.

4.3.1 Accuracy

The most recent flight test data available for the determination of Loran-C accuracy were collected during evaluation of Loran-C in the state of Vermont. (Reference 11.) On the basis of over 45,000 data points collected by using one particular type of receiver, Loran-C system error was determined to be between ± 0.12 and ± 0.16 nm for cross-track and along-track error components in en route, terminal, and nonprecision approach navigation. The above 2σ error values listed are equal to a 2 drms system error of ± 0.3 nm.

In another evaluation, data collected at five airports in Eastern states and at a site in Kentucky have shown in detail the bias and seasonal errors that are characteristics of Loran-C. (Reference 12.) Short-term temporal errors have been found in the same data to be operationally insignificant. Along the East Coast, Loran-C position errors, due primarily to variations in ground conductivity, have been found to well exceed approach accuracy requirements, while the summer-to-winter variation in time-difference readings measured at one site was 1.5 microseconds. While these errors are insignificant for en route operations, additional analysis is required to determine their effect on approach procedures.

4.3.2 Coverage

Figure 4-3 illustrates the current coverage of Loran-C, derived as a function of geometric considerations and signal-to-noise standards. As can be seen, coverage over the 48 conterminous states is not complete, and additional transmitters would be needed to complete the coverage. A study was conducted to determine how many additional stations will be needed to provide fully redundant coverage. (Reference 13.) Any definition of signal coverage is based on the sensitivity expected from the minimum airborne receiver. The study concluded that if the minimum receiver is "master-dependent" (i.e., a master station signal must be continuously available), 16 additional transmitters are needed. With a "master-independent" minimum receiver, a total of 13 additional stations will be required.

4.3.3 Integrity

Loran-C navigation is normally based on measurements of the difference in time-of-arrival of signals from several transmitters of a chain. Each chain is monitored by the Coast Guard, with one or more system area monitor stations within the coverage area to observe and control the time differences of each master-secondary pair. If the observed time-difference value differs from the control time difference by more than the control tolerance, the transmitted signal is coded to advise users that the time difference is out of tolerance. It appears feasible for Loran-C receivers to perform internal reasonableness checks to ensure the integrity of inputs, internal computations, and outputs.

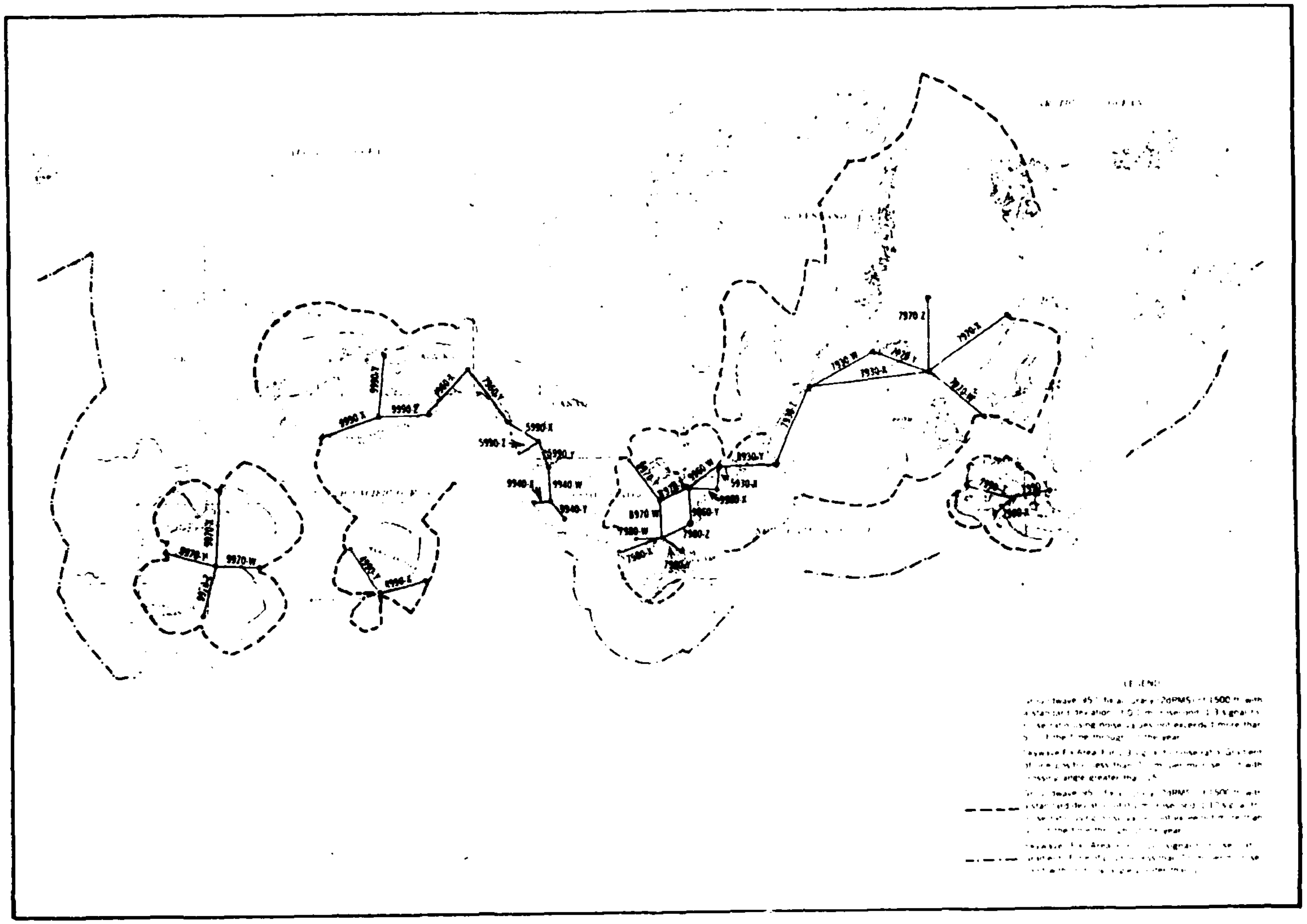


Figure 4-3. COVERAGE PROVIDED BY LORAN-C

To advise pilots of the current and expected status of Loran-C signals along the planned flight route, a Notice to Airmen (NOTAM) will be needed. An experimental model of an automatic Loran-C NOTAM monitor system was developed to serve as a test bed and to support subsequent specification of operational NOTAM units.

The possibility of an incorrect and undetected signal measurement by a Loran-C receiver (i.e., a "cycle slip") has become a greater concern as use of Loran-C in aircraft has increased. If Loran-C is to be used for approaches, the receiver will have to be able to recognize a "cycle slip" and warn the pilot of its existence.

4.3.4 Reliability

The reliability of Loran-C has been studied with respect to the present VOR system. (Reference 13.) The study objective was to determine the number of Loran-C stations necessary to provide the coverage and associated reliability equivalent to the present VOR system. Two performance measures were considered -- degree of coverage reliability and operational impact of station outage.

The station reliability performance analysis was based on historical data for four solid-state Loran-C stations. The study concluded that 13 to 16 additional stations and an upgrade of existing stations to solid-state would be necessary for VOR-equivalent reliability.

Loran-C solid-state stations currently achieve an MTBF of 465 hours based on unscheduled outages of greater than one minute. If all interruptions, including those of less than one minute, are considered, the MTBF is 100 hours.

Loran-C system reliability is highly affected by the receiver design. Some receiver designs require the use of the master station signal, which makes the system reliability highly dependent on the master station reliability. Another receiver design feature affecting reliability is dual-chain capability, because it reduces the receiver dependence on individual station reliability.

Two projects were conducted to examine the threat of interference to the reliable use of Loran-C. Types of interference investigated were those from natural causes (e.g., precipitation) (Reference 14) and those from man-made sources (e.g., power-line carrier systems) (Reference 15). In the case of natural sources of interference, including rain, snow, and ice crystals, it was found that with the installation of proper discharge devices and good electrical bonding between parts of the aircraft, the problem is reduced and becomes insignificant. However, without such protection, precipitation-caused noise can prevent the use of Loran-C. Lightning was found to cause some interference in receivers tested, but the disturbance would probably not be operationally significant. Man-made interference from power-line carrier systems and from the variety of noise sources near airports was examined. The airport environments investigated (i.e., San Francisco and Boston) did not have interfering signals significant to interface with Loran-C operations. However, the power-line carriers were found to interfere with Loran-C reception when the carrier frequency was synchronous with a frequency of the Loran-C pulse spectrum. The results of this synchronous interference were to prevent the initial acquisition by the test receiver of the Loran-C signal within 8,500 feet (2,590 meters) of the interfering source, and to prevent retention of signal tracking if acquisition was accomplished.

4.3.5 Operational Suitability

The Vermont flight tests that established a Loran-C system error of around ±0.15 nm also measured flight technical error, which was used to compute the system-use accuracy of Loran-C. Table 4-1 summarizes the operational performance capabilities of Loran-C.

Table 4-1. LORAN-C OPERATIONAL PERFORMANCE DATA

Flight Phase	Flight Technical Error (±nm)	System Use Accuracy (±nm)	
		Cross-Track	Along-Track
En Route	0.71	0.73	0.12
Terminal	0.58	0.60	0.15
Approach	0.28	0.32	0.16

The evaluation of Loran-C in Vermont (Reference 11) demonstrated a capability of Loran-C to satisfy current RNAV ATC accuracy requirements as specified in FAA Advisory Circular 90-45A. The VOR/DME and Loran-C systems installed in the test aircraft provided a measure of comparison between VOR/DME and Loran-C system performance. The comparison demonstrated that in navigation accuracy and functional performance, Loran-C is comparable to VOR/DME for en route and RNAV nonprecision approach operations in the test area.

To further investigate the operational suitability of Loran-C, a design study for a minimum, general aviation receiver was conducted. (Reference 16.) Conclusions of the study were that the receiver should use the following:

- Master-dependent operation with a master-independent capability as a secondary mode
- Simultaneous acquisition of signals from two chains to permit easy chain-to-chain transition
- Stored conductivity values for a propagation model
- Waypoint definition by radial and distance from a prestored point rather than latitude/longitude

A study is being conducted of the possible impact on FAA-provided services and operations if Loran-C were to replace VOR/DME. Of primary interest is the effect on air traffic control methods if the VOR system were to be replaced by the wide-area Loran-C system. The resulting station failure would have much broader effects on Loran-C than on VOR. Other considerations will be the provision of NOTAM services, flight inspection, and publication of charts.

4.4 NAVSTAR GPS

The NAVSTAR Global Positioning System (GPS) is a space-based radionavigation system 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 a 21-satellite constellation, including three active spares. By using signals from four satellites, a user can obtain three position dimensions (latitude, longitude, and altitude), determine time, and derive velocity.

Although GPS is being developed as 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 satellite-provided precision code (P-code, now called Precise Positioning Service, or PPS). In the context of the 21-satellite (18 plus 3) constellation, PPS enables predictable positioning accuracy of up to 18.1 meters horizontally and 29.7 meters vertically (95 percent probability) (Reference 1), depending on the capability of user equipment and user-to-satellite geometries. The navigation accuracy to be made available by the military to civilian users of the satellite-provided coarse acquisition code (C/A code, now called Standard Positioning Service, or SPS) is uncertain.

> The Department of Defense proposes that NAVSTAR GPS SPS signal will be made continuously available on a worldwide basis for civil and commercial use at the highest level of accuracy consistent with national security interests. It is presently projected that the predicted and repeatable accuracy will be 500 m (2 drms) horizontally and 820 m (2 sigma) vertically and the relative accuracy will be 10 m (2 drms) horizontally and 16.4 (2 sigma) vertically. This level of performance will be reviewed by DoD annually and the level of accuracy modified to accommodate any changes commensurate with our national security posture. It is anticipated that the SPS accuracy will be increased as time passes. (Reference 1.)

Three-dimensional navigation coverage requires four GPS satellites to be in view of the user. The accuracy obtained depends on the geometry of the satellites used. The proposed system implementation of 21 satellites (18 plus 3 spares) appears to be unacceptable to civil aviation because of inadequate satellite geometry, coverage, and redundancy. Minimum required levels of coverage and reliability for civil aviation use as a standalone system dictate the need for at least a 24-satellite implementation.

It should be noted that uncertainties are associated with GPS, since the system is still in development. Substantive changes to the system, such as system configuration, system capabilities, and user equipments, may still occur. The findings and related conclusions at this time are based on (1) limited testing, using four or five satellites, (2) no intentional signal degradation, (3) the characteristics of developmental proof-of-concept user equipment (the military Z-set) and (4) analytical methods to predict performance of hypothetically deployed constellations and systems. Further technical evaluations will be conducted to refine and improve confidence in current judgments and findings and to evaluate any substantive system changes if and when they are made.

4.4.1 Accuracy

System accuracy when GPS is used is a function of the collective effects of (1) geometry of the constellation at user locations, (2) satellite perturbations and errors, (3) signal propagation variations, and (4) receiver-related errors and the receiver's ability to cope with aircraft dynamics.

Geometric dilution of precision (GDOP) is a composite measure that reflects the influence of satellite and user geometry on the accuracy of the navigation position fix. This composite includes the impact of satellite geometry on horizontal accuracy (HDOP) and vertical accuracy (VDOP). By multiplying the ideal accuracy achievable by the value of HDOP or VDOP calculated for a given satellite configuration, the magnitude of position error is determined.

Accuracy tests were based on use of the undegraded SPS provided by four satellites. FAA tests to date were conducted with the Magnavox Z-set, a single-channel, sequential first-generation receiver developed for the U.S. Air Force. (References 17 and 18.) The Z-set employs a design concept that may be adopted for civil use in the future, depending on the MOPS established.

FAA tests were performed under various conditions of satellite geometry and aircraft dynamics. Statistics for flights involving a combination of turns and straight segments with various values of HDOP yielded an accuracy of 87 meters (95 percent probability). Accuracy achieved for typical nonprecision approaches, with good HDOPs, was 38 meters (95 percent probability). Z-set accuracies achieved by the FAA under ideal conditions appear to approach those reported by the Air Force previously.

The Z-set does not compute acceleration. Therefore, as expected, accuracy performance in turns was lower than that indicated above. Further detailed analyses are being conducted in this area. However, it should be noted that during these limited tests, accuracies in turns with 30-degree banking appeared quite good. In fact, in tight orbits with 50-degree banks, accuracy was on the order of 300 meters (95 percent probability), and in no case did the Z-set lose lock. This accuracy should improve with better tracking by the user set through the use of acceleration inputs.

The FAA has not conducted flight tests of vertical accuracy to date. However, since analysis shows that VDOP will be about 1.5 to 2 times greater than HDOP, vertical accuracy for the undegraded SPS is expected on the order of 150 meters.

It should be noted again that these findings were based on a particular set of operating conditions (e.g., satellite geometry, use of specific aircraft antennas, signal power levels in excess of design specifications) defined in References 17 and 18. Intentional degradation of the signal precision provided by the satellite would negate the validity of these findings.

4.4.2 Coverage

Analyses have shown that the currently planned GPS constellation consisting of 18 satellites in six planes with 3 operating spare satellites in alternating planes, for a 21-satellite constellation, is inadequate for civil use of GPS as a replacement for VOR/DME. (Reference 19.)

To preclude outages over large geographical areas, five satellites must be in view with good geometry and a 10-degree aircraft masking angle above the horizon. Four satellites in view with good geometry are the minimum needed for navigation; however, an additional satellite in view is required in order to provide for single-satellite failures. The resulting required constellation would require a minimum of 24 satellites. This could be attained by placing one additional satellite in each of the three remaining three-satellite planes in the currently planned constellation.

Good geometry is inherent to a 24-satellite constellation of this type. HDOPs would never exceed five, an acceptable value when all five satellites are operating within tolerance. With the currently planned 21-satellite constellation, however, poor geometry causes the system to be unusable at various times and places for varying durations. Maximum HDOPs exceed 100, which is not usable, in various areas for varying periods of time, including most of the Eastern part of the country. Therefore, the currently planned constellation is inadequate for reasons of poor geometry as well as insufficient redundancy.

The range of satellite visibility is primarily dependent on aircraft antenna pattern gain at a low elevation angle. The 10-degree masking angle value appears reasonable in view of findings to date involving the development of low-cost aircraft antennas and aircraft antenna patterns. (Reference 20.) The coverage improvements gained are substantial when a 5-degree masking angle is used above the horizon, which is often referred to by the DoD. However, FAA findings up to this time must be supplemented with more data on new antenna designs and their cost, multipath trade-offs, and shading effects of airframes (particularly the tail sections of aircraft) before conclusions can be reached about lowering masking angles for civil aviation.

4.4.3 Integrity

Current U.S. Air Force plans for ground monitoring and control of the NAVSTAR GPS satellite system are not considered adequate to ensure integrity for civil aviation use. (Reference 21.)

On the basis of FAA-sponsored efforts, a possible solution to the NAVSTAR GPS civil aviation integrity problem may be the installation of additional ground-based signal monitoring sites with appropriate control and communications to aircraft. (Reference 21.) Use of computational techniques in the receiver to successively compare each pseudorange measurement with a predicted value to determine "reasonableness" of the information may be required. (Reference 22.) Both of these integrity features will affect the cost of the system.

These findings are based on preliminary work; further refinements can be expected as newer receivers are developed and as improvements are made to the satellite control segment and signal structure.

4.4.4 Reliability

The currently planned constellation (see Section 4.4.2) is not likely to provide an adequate level of redundancy (i.e., it does not provide at least five satellites in view above an elevation of 10 degrees.) The U.S. Air Force NAVSTAR GPS satellite specification calls for a satellite design life of 7.5 years, which results in a mean time to failure (MTTF) of 6.2 years for any one satellite.

Analyses were performed to estimate the reliability of GPS service. (Reference 23.) The analyses considered individual satellite reliabilities, currently planned satellite replacement strategy, launch/launch schedule risks, and the configuration of various satellite constellations that can cause outages at various times and places for varying durations. For this analysis, an outage was defined as an HDOP greater than five or a VDOP greater than eight. To provide operationally meaningful results under such conditions, a Monte Carlo simulation of flights between Chicago and Miami and between Chicago and Salt Lake City was conducted. Results in the form of probability of incurring outages of varying lengths were obtained for various constellations. The currently planned constellation, as an example, has a probability of about .27 of causing 10 minutes of outage between Chicago and Miami, and about .18 between Chicago and Salt Lake City. Similar statistics for a 24-satellite constellation yield probabilities of about .06 and .03, respectively.

Another analysis looked at the criticality of the required number of satellites in view at any time. (Reference 24.) This analysis concluded that even a 24-satellite constellation may not be adequate for civil aviation reliability if it is the sole means for navigation.

Receiver reliability is difficult to predict at this time. However, subjective FAA experience with the prototype Z-set receiver has been very good. GPS receiver reliability is generally expected to be comparable to that of other airborne RNAV systems.

4.4.5 Operational Suitability

GPS was evaluated for civil aviation operational suitability on the basis of FAA tests that used the Z-set. (References 17 and 18.) As previously stated, the Z-set is an engineering first-generation receiver. However, it represents a design concept likely to be used in civil aviation applications.

Navigation performance was unaffected by operation at altitudes down to the surface, provided that the necessary number of satellites remained in view.

The time required for initial signal acquisition ranged from 5 to 14 minutes. For signal interruptions of less than one minute, one to three minutes were needed to reacquire the signal. These times appear to be high. There is some question as to their operational suitability.

The Z-set was able to maintain lock in various aircraft maneuvers. While accuracy was degraded somewhat during these maneuvers, recovery to acceptable accuracy was rapid and did not appear to be a serious problem. This is a function of receiver design.

En route, terminal, and nonprecision approach evaluations were conducted. System and system-use accuracies (achievable with undegraded SPS signals) met current and future requirements for all types of operations. It should be noted that at this time flight technical error data are based only on helicopter tests. Tests showed large errors during nonprecision approach when new satellite acquisition was required. This problem is also a function of receiver design.

As with all RNAV systems, CDU design is a significant factor in the assessment of operational suitability. This is particularly so for single-pilot aircraft in high-density ATC environments.

A major factor in the suitability of NAVSTAR GPS for civil aviation use is the accuracy to be made available. Also important is the technique proposed for accuracy denial. If a "drifting" signal is used, it may adversely affect the ability to conduct nonprecision approaches. Table 4-2 shows the different levels of use of NAVSTAR GPS as a function of the accuracy provided. As can be seen from the table, a value of 100 meters (2 drms) would make NAVSTAR GPS a suitable candidate to replace VOR/DME with respect to system accuracy.

Table 4-2. GPS ACCOMMODATION OF CIVIL AVIATION REQUIREMENTS ON THE BASIS OF ALLOWED ACCURACY

Allowed GPS Civil Aviation Service Accuracy (Meters)	Civil Aviation Application									
	Oceanic High Altitude En Route	Low Altitude En Route	Terminal	Helicopter	RNAV (AC 90-45A)			VOR Nonprecision Approach Replacement	ILS	MLS
					En Route	Terminal	Nonprecision Approach			
1,000	Yes	Yes	No	No	Yes	No	No	No	No	No
500	Yes	Yes	Yes	*	Yes	Yes	?	No	No	No
250	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No
100	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No

*There is some question about the navigation accuracy required to achieve the full potential of helicopters.

4.5 OMEGA

Omega is a very-low-frequency (VLF) hyperbolic navigation system in which each transmitter has an operating range of about 5,000 nm. Omega signals transmitted from eight stations provide nearly worldwide coverage at a relatively low data rate. There are also eight VLF communication transmitters located around the world that are being used as supplementary signal sources for Omega/VLF navigation.

4.5.1 Accuracy

The accuracy of the Omega system is limited primarily by the accuracy of the propagation corrections that are applied to the received signal; a predictable accuracy of 2 to 4 nm is the design goal of the system. Statistical studies conducted in the North Atlantic show that rms positional accuracies of 1 to 2 nm are being achieved. (Reference 25.) Omega has a basic ambiguity in its signal and thus requires reasonable signal continuity to avoid operational difficulties. The effect of short interruptions of the received signal can be overcome through the use of heading and airspeed information, appropriately mechanized into the RNAV computation. The multiple-frequency Omega signal can be used to resolve position ambiguities if position uncertainty is less than 72 nm (or 144 nm in a four-frequency receiver).

4.5.2 Coverage

Worldwide Omega coverage is provided by a network of eight transmitting stations, shown in Figure 4-4.

Use of VLF communication stations to supplement Omega signals improves the dependability of coverage. However, the VLF stations are maintained and operated by the U.S. Navy for communication and were not intended to be used for navigation purposes; they are used for navigation with no assurance of their continued availability.

4.5.3 Integrity

Validation of Omega signal coverage and accuracy parameters is accomplished through use of a fixed-site monitor network. Monitors are located at approximately 50 locations throughout the world. The Omega signal-phase data collected at the monitor sites are used to update and refine the semi-empirical propagation model used to generate propagation-phase-correction (PPC) tables. The accuracy of the Omega system is directly dependent on the degree of correlation of the propagation model to the actual signal environment. Operational reports from aircraft are used to supplement the fixed-site monitor data in assessing signal coverage and accuracy of the Omega systems.

Information concerning Omega station outages, signal-propagation anomalies, and other information affecting users of Omega is disseminated via the NOTAM service. At present, there are no real-time advisories on availability or quality of Omega signals. System integrity is also affected by the system's basic ambiguity and must be judged on the basis of the external dead-reckoning or other aiding provisions of the aircraft system.

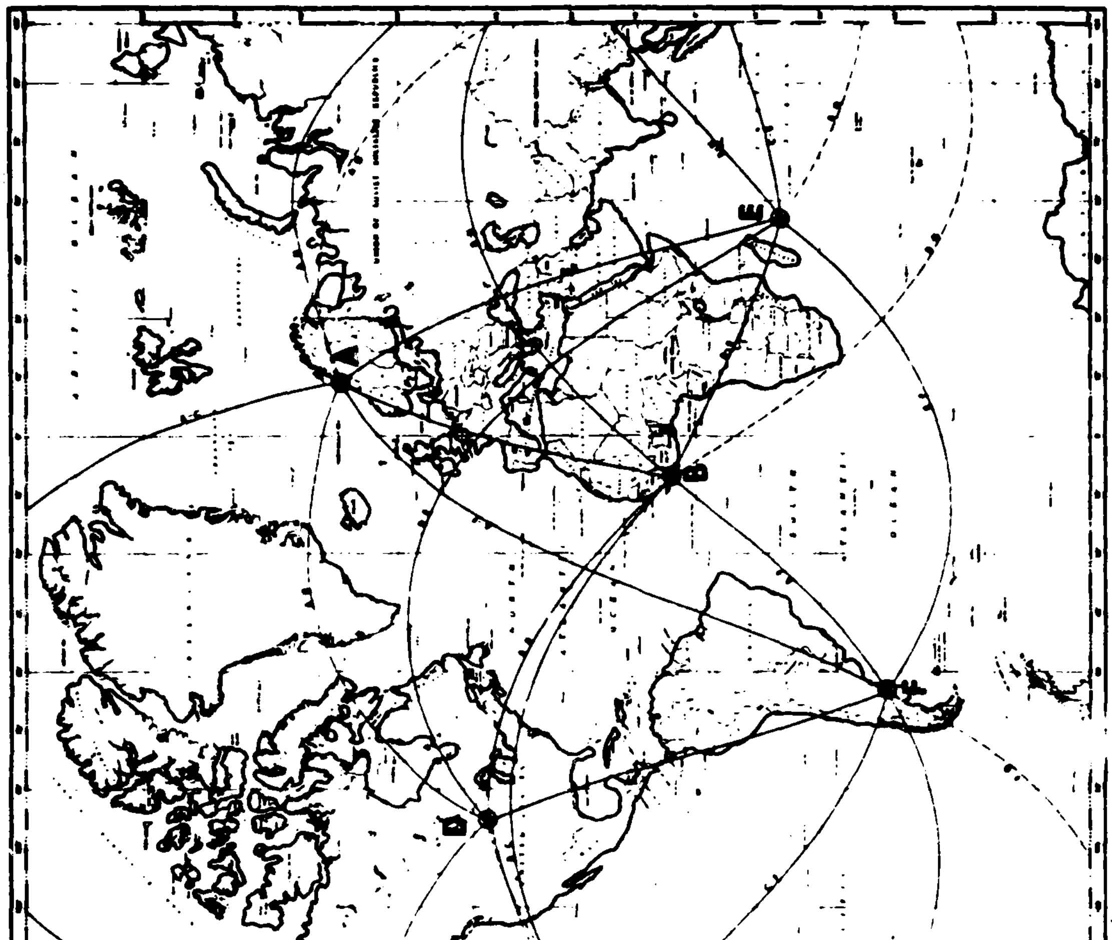


Figure 4-4. OMEGA STATION CONFIGURATION

4.5.4 Reliability

The basic Omega system consists of eight stations providing worldwide coverage. On the basis of 1979 data for nonscheduled outages of greater than two minutes, an Omega station has an MTBF of 216 hours. (Reference 26.)

Most current airborne receivers have the ability to use signals from VLF stations. Airborne Omega/VLF receivers have an MTBF value on the order of 1,000 hours.

4.5.5 Operational Suitability

The Omega station transmission format repeats every 10 seconds, with each Omega station transmitting different frequencies at any given time. It requires 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. This time lag is overcome in operational use through the use of aircraft heading and airspeed information.

Omega/VLF is suitable as an aviation aid to navigation for oceanic or domestic en route phases of flight.

As mentioned previously, use of Omega requires keyboard entry of data and therefore is susceptible to the blunder potential common to all RNAV systems.

4.6 NONDIRECTIONAL BEACONS

Nondirectional beacons (NDBs) are omnidirectional transmitters of signals which, when used with an automatic direction finder (ADF), provide a means for navigation. The facilities may be used as en route navigational aids and as compass locators to assist in transitioning to an ILS.

4.6.1 Accuracy

The bearing accuracy of an NDB is on the order of ±3 to ±10 degrees. Achievement of the ±3-degree accuracy is dependent in large part on the capability of the airborne receiver and calibration of the aircraft antenna. In the U.S., NDB system accuracy is stated in terms of permissible needle swing: ±5 degrees for approach use and ±10 degrees for en route operations.

4.6.2 Coverage

Presently, approximately 2,000 NDBs are used for aeronautical applications. The range of the NDB is dependent on radiated power. High-powered NDBs can provide coverage to a radius of greater than 300 nm and are used throughout the world and in the U.S., often for transition from oceanic areas. Lower-power facilities are used at many general aviation airports for homing and as compass locators.

4.6.3 Integrity

NDB/ADF is a technically simple system, and status monitoring of the ground stations by remote receivers has proven to be a satisfactory means of ensuring integrity.

4.6.4 Reliability

The reliability of NDBs has been demonstrated to comply with the specification (FAA-E-2541A) for transmitters of 50 watts or less (10,000-hour MTBF) and the specification (FAA-E-2658) for transmitters of 50 to 400 watts (8,760-hour MTBF). On this basis, the probability of satisfactory NDB operation is 99.990 percent for a one-hour period. The MTBF for newer NDBs is expected to exceed 10,000 hours for all types.

4.6.5 Operational Suitability

As a passive system, the NDB facility provides unlimited capacity to users who have appropriate receivers, providing means of navigation within a prescribed area. It may be used for homing or as an auxiliary aid with an ILS (i.e., compass locators).

Aviation nondirectional beacons are used to supplement VOR/DME for transition from en route to airport precision approach facilities and as a nonprecision approach aid at many airports. In many areas of the world where VOR/DME has not been installed, NDB/ADF provides the primary means of navigation. However, since the information derived is relative to aircraft heading, correction for wind must be made to permit flying a straight course. This factor, together with its inherent error, makes the NDB/ADF system unsuitable for precise navigation. Susceptibility to atmospheric noise is an additional historic factor that has limited its use in IFR operations.

4.7 INERTIAL

The Inertial Navigation System (INS) is a self-contained navigation system based on the measurement of aircraft acceleration. Two general techniques are used to determine aircraft orientation: conventional and strapdown.

4.7.1 Conventional INS

The accelerometers used in conventional INS to measure aircraft acceleration are mounted on a gimbaled platform mechanized to maintain continuous alignment with the local geographic coordinate frame, regardless of aircraft orientation. 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.

4.7.1.1 Accuracy

The accuracy of conventional INS is largely dependent on the characteristics of the gyros used to measure the deviation of the platform orientation. The error associated with these measurements tends to increase as a function of time elapsed. The position determination of conventional INS used in civil applications has typical rates of accuracy degradation of 1 to 2 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, with use of electrostatically suspended gyros.

4.7.1.2 Coverage

Since INS is a self-contained navigation system, it provides worldwide navigation capability.

4.7.1.3 Integrity

The complex nature of INS requires a comprehensive integrity monitoring and failure warning system.

INS drift errors can only be detected through comparison of position output data from the multiple INS units in the installation or through cross-checking with an independent source of navigation information. These comparisons can be performed automatically.

4.7.1.4 Reliability

INS is self-contained and does not depend upon external ground or satellite-transmitted signals. Therefore, the system reliability is based solely on airborne performance. Recent experience has shown actual MTBF of single units to be on the order of 900 to 2,300 hours. System reliability is of course greatly enhanced by use of redundant equipment.

4.7.1.5 Operational Suitability

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 INS mechanizations provide some form of update capability. INS, being a dead-reckoning system, must be updated after system outage and is therefore often used in conjunction with other navigation systems or other updating means.

4.7.2 Strapdown INS

Strapdown INS 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. As a result, they measure acceleration and angular components in body-axis coordinates. Several types of gyros have been considered for use in strapdown INS, including ring laser gyros, tuned rotor gyros, and electrostatically suspended gyros. Ring laser gyro mechanizations are coming into civil use.

4.7.2.1 Accuracy

Projected accuracy of the ring laser gyro implementation is 1 to 2 nm per hour of use.

4.7.2.2 Other Factors

There are no discernible differences between conventional and strapdown systems with respect to coverage, integrity, and operational suitability. The reliability of strapdown systems that use ring laser gyros is projected to be superior (MTBF of 2,500 to 5,000 hours) to that of conventional INSs, and cost of ownership is projected to be superior to that of conventional INSs.

4.8 ILS

The Instrument Landing System (ILS) is a precision approach and landing system that normally consists of a localizer facility, a glide slope facility, and two or three VHF marker beacons. It provides vertical and horizontal navigational guidance information to the pilot during approach to landing on an airport runway.

4.8.1 Accuracy

With respect to accuracy, ILS requirements are specified relative to three categories of operation -- CAT I, CAT II, and CAT III. For typical CAT I operations at a 10,000-foot runway, the course alignment (localizer) at threshold is maintained within ± 25 feet. Course bends during the final segment of the approach do not exceed ± 0.06 degree (2σ). Glide slope course alignment is maintained within ± 7 feet at 100 feet (2σ) elevation, and course bends during the final segment of the approach do not exceed ± 0.07 degree (2σ). (Reference 1.)

4.8.2 Coverage

The ILS localizer provides course guidance to the runway center line. The localizer signal is adjusted to produce an angular width from 3 to 6 degrees, depending on runway length, which then provides a standard linear width of approximately 700 feet at the runway threshold. The localizer provides clearance signals out to a range of 18 nm over a ± 35-degree sector. The glide path angle is normally adjusted to 3 degrees above the horizontal so that it intersects the middle marker at an elevation of 200 feet. An outer marker is located 4 to 8 nm from the runway threshold.

4.8.3 Integrity

The ILS is both ground-monitored and flight-inspected by the FAA to assure users of system integrity. Ground monitors indicate out-of-tolerance conditions and permit transfer to standby equipment within 6 seconds (glide slope) or 10 seconds (localizer) for a CAT I installation, 2 seconds for CAT II, and 1 second for CAT III. (Reference 27.) Provisions for avionics integrity are a function of the category of intended operations. CAT I may imply simple flag alarm circuits, whereas CAT III aircraft installations use redundancy and voting techniques to achieve the needed degree of integrity.

4.8.4 Reliability

The probability of satisfactory ILS operation for a one-hour period is 99.889 percent, based on an MTBF of 1,306 hours for the glide slope and an MTBF of 2,895 hours for the localizer. ILS reliability will be improved as the vacuum tube equipment is replaced by newer solid-state units.

4.8.5 Operational Suitability

ILS has provided a precision landing capability in the NAS quite satisfactorily during the past 35 years. However, there are some inherent limitations in the system that discourage potential further implementation. These limitations include inadequate channel capacity, the inflexibility of the approach path that aircraft must follow, and the impact that terrain and weather have on the effectiveness of the system.

4.9 MLS

The Microwave Landing System (MLS) has been developed in a joint effort by DoD, NASA, and DoT/FAA to meet the full range of civil and military requirements as a future replacement for ILS. The signal provides proportional guidance throughout a large volume of airspace, permitting the use of multiple approach paths. This flexibility will result in greater airport capacity and the use of curved and segmented approach paths for noise-abatement purposes. The ability to select desired glide path angles will provide for short and/or vertical takeoff and landing (STOL and VTOL) operations in an optimal manner.

4.9.1 Accuracy

MLS has exhibited the accuracy required for automatic landing guidance through CAT III-B. MLS has the ability to provide for flare guidance and rollout after touchdown.

4.9.2 Coverage

MLS provides proportional guidance within ±60 degrees from runway center line, 0 to 30 degrees elevation, and a range of up to at least 20 nm from runway threshold. The signal format provides for future expansion to a 360-degree azimuth coverage, a feature that is not currently required, but that might possibly be considered useful at some future time. (Reference 1.)

Current plans are that 340 MLS facilities will be installed by 1990. By the year 2000, approximately 1,250 MLS facilities will be in place. There will be simultaneous operation of ILS and MLS during the transition period.

4.9.3 Integrity

MLS will be ground-monitored and flight-inspected by the FAA to assure users of system integrity. System characteristics also allow high reliability and positive indication within one second when the system is out of tolerance. (Reference 28.)

4.9.4 Reliability

The MLS signals are generally far less sensitive than ILS signals to the effects of snow, vegetation, terrain, structures, and taxiing aircraft. This allows the operational reliability of the system to be very high. On the basis of an expected MTBF of 4,000 hours for both the azimuth and glide slope elements of the system, the computed probability of satisfactory operation for a one-hour period is 99.95 percent.

4.9.5 Operational Suitability

The basic MLS has been designed to meet the requirements of both commercial and general aviation aircraft. MLS is intended to eventually replace ILS to provide an improved, cost-effective precision-approach capability. MLS provides precision guidance to all types of aircraft in all categories of landings to satisfy the full range of operational requirements. It overcomes the inherent limitations of existing ILS. Radiated signals are minimally affected by surrounding terrain, structures, and weather effects. (Reference 29.)

CHAPTER FIVE

ECONOMIC EVALUATION RESULTS

The search for the future radionavigation system mix was triggered in part by a 1976 economic study prepared for the Office of Telecommunication Policy that promised huge savings to the U.S. Government (and thus the taxpayers) if all navigation systems and many surveillance systems were replaced by NAVSTAR GPS. Among the problems with the 1976 economic study was that it did not consider the impact on users, and some of the systems assumed to be replaced performed functions that NAVSTAR GPS could not do.

In 1975, the FAA began a study called "Economic Requirements Analysis of Civil Air Navigation Alternatives." (Reference 30.) When this study was completed in 1978, it showed that, aggregated across all civil aviation users, NAVSTAR GPS was the most expensive of the systems considered, while VORTAC was the least expensive.

In 1979 the Department of Transportation began development of a DoT Radionavigation Economic Analysis Model, which would cover all transportation modes. This multimodal effort has as its objective development of a cost and benefit analysis model for radionavigation planning. Full details on the model's operation will be available from DoT Research and Special Programs Administration in late 1982 or during 1983. Figure 5-1 is a simplified block diagram of the model. (The FAA has expanded the model to include other types of avionics and expects to use the model for communication and surveillance studies as well as navigation.)

The economic analysis model will be maintained at the DoT Transportation Systems Center (TSC) and will be available to aid in the selection and implementation of the future radionavigation system mix.

The model will not be delivered, and full analysis will not be completed, until sometime in late 1982 or early 1983. Results discussed here for civil aviation primarily deal with cost comparisons among candidate system mixes.

Model validation run data are available from the program at this time. While this information is preliminary and some initial assumptions are no longer valid -- such as the FAA paying for 6 NAVSTAR GPS satellites to provide for a 24-satellite constellation, in light of the current satellite constellation (18 plus 3 active spares) -- the comparisons can be used for ranking

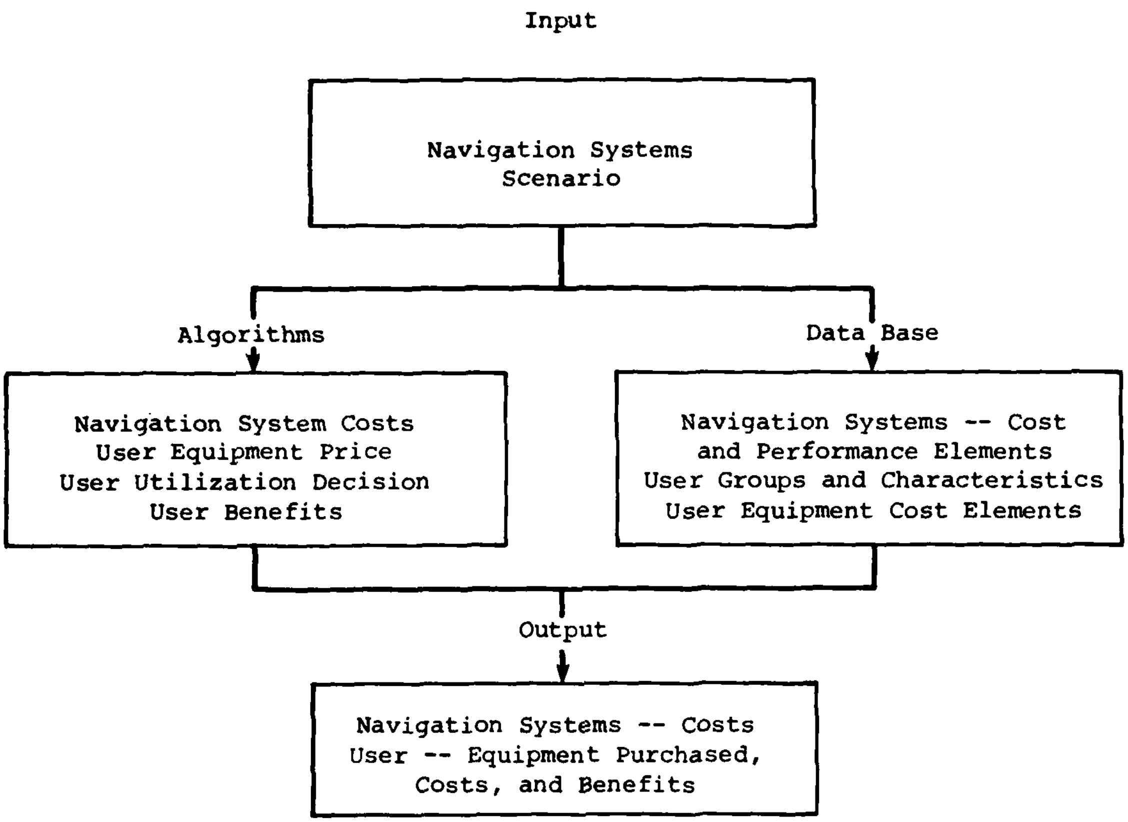


Figure 5-1. RADIONAVIGATION ECONOMIC ANALYSIS MODEL OPERATION

costs. The following four different conditions (model runs) have been examined:

- Run No. 1 -- This scenario is essentially keeping what is used today from 1981 through 2005. It has VOR/DME supplemented by Loran-C and Omega as they are now configured. The FAA pays for VOR/DME, while the U.S. Coast Guard pays for Loran-C and the U.S.-funded Omega stations.
- Run No. 100 -- In this case, Loran-C replaces VOR/DME, with a 10-year transition between 1990 and 2000. Omega supplements the expanded Loran-C system for areas where there is no Loran-C coverage. The FAA pays for Loran-C stations required for civil air navigation, but not for those required for civil marine use in the U.S. coastal areas and already in place by 1985, nor for the U.S.-funded Omega stations.
- Run No. 200 -- In this scenario, NAVSTAR GPS replaces all other radionavigation systems, with a 10-year transition between 1990 and 2000. In the year 2000 all other systems would be turned off (except precision landing systems, which are not included in the scenario). The FAA

pays for 6 satellites and their operation to increase the DoD constellation of 18 satellites to 24 satellites, which is currently the minimum number of satellites projected to meet civil aviation requirements. (Now that DoD will have a 21-satellite system -- 18 satellites plus 3 active spares -- the FAA may need to provide only 3 additional satellites).

- Run No. 201 -- This case is the same as Run No. 200, except VOR/DME is not decommissioned, and the respective aviation users select the avionics that are least costly to meet their requirements. The FAA in this run supports VOR/DME and six NAVSTAR GPS satellites.

All of the runs cover the time period from 1981 through 2005, and the examples given are in cumulative cash outlay in 1981 dollars (no current value discount or inflation), although the model can be run with any combination of current value discount and inflation. For these runs, the model did not consider any Government cost recovery for the service provided.

Preliminary results presented in Table 5-1 and Figures 5-2 and 5-3 show that, from a cost standpoint, the conditions of Run No. 201 are the best for civil aviation users.

Run No. 1 conditions, which are the current conditions, are the next best for civil aviation users and the best for civil aviation users and the FAA. From Figure 5-2, it can be seen that the "Personal/Other" category of general aviation user is a key element of the economic analysis.

Table 5-1. **DOT RADIONAVIGATION ECONOMIC ANALYSIS MODEL RESULTS OF CUMULATIVE CASH OUTLAY (BILLIONS OF 1981 DOLLARS, 0% CURRENT VALUE DISCOUNT, 0% INFLATION)**

Cost Category	Run Number and Scenarios			
	1 VOR/DME 1981-2005 Loran-C* 1981-2005 Omega 1981-2005	100 VOR/DME 1981-2000 Loran-C* 1981-2000 Omega 1981-2005	200 VOR/DME 1981-2000 Loran-C* 1981-2000 Omega 1981-2000 GPS** 1990-2005	201 VOR/DME 1981-2005 Loran-C* 1981-2000 Omega 1981-2000 GPS** 1990-2005
Aviation Users				
Air Carriers	1.155	0.988	0.992	0.993
Commuters	0.298	0.283	0.312	0.301
Air Taxi	0.878	0.816	0.870	0.826
Executive/ Business	6.435	5.966	6.030	5.664
Personal/ Other	2.875	4.078	4.141	2.796
Public Service	0.151	0.144	0.142	0.130
Total Aviation Users	11.792	12.275	12.487	10.710
FAA	0.831	1.669	1.825	2.001
Total Aviation	12.623	13.944	14.313	12.711

*For Run Nos. 1, 200, and 201, Loran-C is the current USCG-provided system; for Run No. 100, it is expanded to provide the coverage and redundancy required for civil aviation, with the FAA paying the difference.

**NAVSTAR GPS is a 24-satellite constellation, with the FAA paying for 6 satellites.

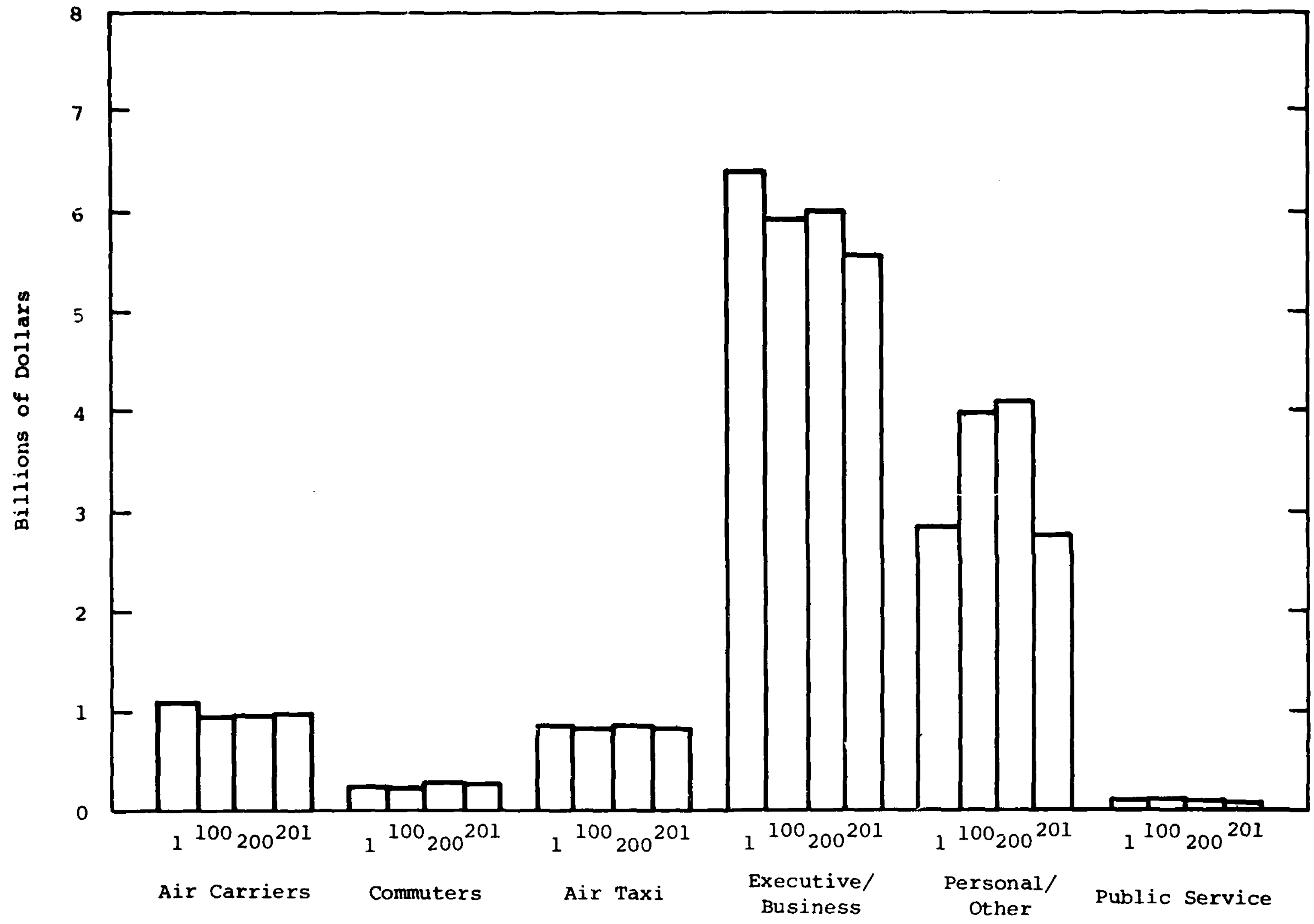


Figure 5-2. AVIATION USER RADIONAVIGATION COSTS CUMULATIVE CASH OUTLAY, 1981 THROUGH 2005 (1981 DOLLARS, 0% DISCOUNT, 0% INFLATION)

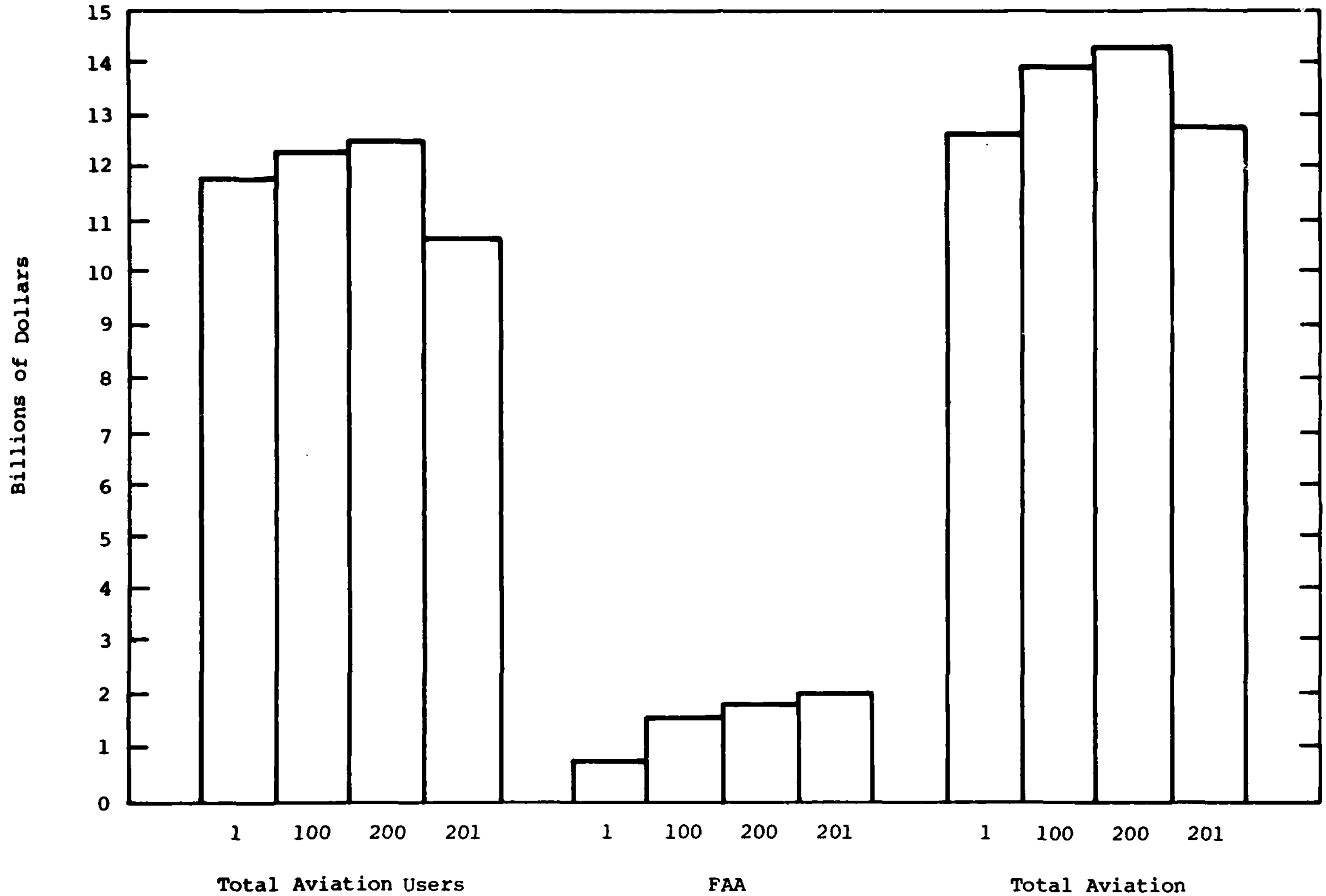


Table 5-3. AVIATION RADIONAVIGATION COSTS CUMULATIVE CASH OUTLAY, 1981 THROUGH 2005 (1981 DOLLARS, 0% DISCOUNT, 0% INFLATION)

CHAPTER SIX

INSTITUTIONAL CONSIDERATIONS

Congress and the executive branch have expressed the need for better planning and management of federally funded radionavigation resources to avoid duplication and to reduce the number of systems supported by the Federal Government. A central goal of this planning, as stated in the Federal Radionavigation Plan, is "to select a suitable mix of common civil/military systems which can meet diverse user requirements for accuracy, reliability, coverage, operational utility, and cost; provide adequate capability for future growth; and minimize duplication of services." (Reference 1.)

The technical and economic analyses and projections for the various operational and developmental radionavigation systems that are candidates for the future "suitable mix" usually consider empirical data and reasonable assumptions of performance, cost, and implementation schedules. However, in addition to technical/operational and economic factors, a number of issues are institutional in nature. Developmental systems such as NAVSTAR GPS bring such institutional issues to the forefront. Representative institutional issues include (1) cost recovery, (2) control of signal access and accuracy, and (3) international standardization.

6.1 COST RECOVERY FOR RADIONAVIGATION SERVICES

The Federal Government currently provides VOR, VORTAC, Omega, Loran-C, NDB, ILS, and MLS services for both civil and military users. The stated DoT policy is to require users of federally operated aids (including radionavigation aids) to bear their fair share of the costs of the system, which is commonly accepted as meaning that a charge will be imposed on anyone using a Government-furnished system. Currently, various approaches are taken to recover the cost of navigation and ATC services, such as fuel taxes, passenger ticket taxes, and other charges.

Congress has directed DoD "to develop a comprehensive plan for recouping from other federal government and civil users as much of the development, acquisition, and operating costs of the NAVSTAR GPS system as is deemed feasible." A DoD study is underway concerning the costs to be recovered from the various user groups and an enforceable system of national and international user charges suitable for this major new system. At DoD's request, DoT is participating in parts of the study.

A preliminary status report submitted by DoD to Congress on 1 March 1982 highlighted some of the many additional actions required to formulate a practical user charges program for NAVSTAR GPS.

The FAA has disagreed with the initial DoD cost recovery proposal, because the suggested collection method -- annual subscription from each civil user -- and the cost allocation basis were considered unacceptable. Resolution of the user charge/cost recovery issue is an essential part of the process of developing the joint recommendation in 1983.

6.2 CONTROL OF SIGNAL ACCESS AND ACCURACY

Availability of navigational signals of adequate accuracy at all times, including times of national emergency, is essential for reliance on a given system for safety of navigation. A preliminary evaluation of the proposed NAVSTAR GPS signals indicates that many civil requirements probably could be met with SPS. However, the need to guarantee availability of navigation data may affect national security objectives. A proposed national policy is being developed on the basis of criteria that will govern availability and accuracy. The Department of Defense has tentatively proposed that the NAVSTAR GPS SPS signal be made continuously available on a worldwide basis for civil and commercial use at the highest level of accuracy consistent with national security interests. It is currently projected that the accuracy provided will be 500 meters (2 drms) horizontally and 820 meters (2σ) vertically. This level of performance will be reviewed by DoD annually, and the level of accuracy will be modified to accommodate any changes commensurate with our national security posture. Although it is anticipated that SPS accuracy will be increased as time passes, it seems clear that the acceptability of GPS by the civil community will be strongly influenced by its accuracy and availability.

6.3 INTERNATIONAL STANDARDIZATION OF NAVIGATION SYSTEMS

VOR, DME, and NDBs are international standard systems and will no doubt remain so for years to come. Omega and Loran-C are widely recognized and used, although not officially standardized in the ICAO process. GPS is the most interesting system in international terms. The prospects for international standardization, regardless of how attractive GPS may be, are affected by the fact that GPS is operated under U.S. military control. The task of international standardization would be easier if GPS were proposed as a civil system, and would be even further facilitated if it were to be jointly financed by ICAO or some other form of international operating body.

CHAPTER SEVEN

CONCLUDING SUMMARY

TO BE DEVELOPED

APPENDIX

REFERENCES AND BIBLIOGRAPHY

1. Federal Radionavigation Plan, Volumes 1-4, Department of Transportation, TSC Report DOT-TSC-RSPA-81-12-1, March 1982.

2. IEEE Standard Dictionary of Electrical and Electronics Terms, IEEE, 1977.

3. Department of Transportation National Plan for Navigation, U.S. Department of Transportation, November 1977.

4. Bowditch, N., American Practical Navigator, Defense Mapping Agency Hydrographic Center, 1977.

5. International Standards and Recommended Practices -- Aeronautical Telecommunications, Annex 10, Volume 1, International Civil Aviation Organization, July 1972.

6. Heurtley, J.C., and Bradley, J.W., "Selecting the Post-1990 Civil Aviation Radionavigation System," FAA Office of System Engineering Management. Paper presented at the IEEE 1980 Position Location and Navigation Symposium, Atlantic City, New Jersey, 8 to 11 December 1980.

7. "Draft United States (U.S.) National Aviation Standard for the Very High Frequency Radio Range (VOR)/Distance Measuring Equipment (DME)/Tactical Air Navigation (TACAN) Systems," Federal Aviation Administration, Published in Federal Register, Volume 46, Number 58, 26 March 1981.

8. Wroblewski, Peter J., Estimate of the Number of Additional VORs and VOR/DMEs to Meet Future En Route Navigation Requirements, The MITRE Corporation, Draft Report, March 1982.

9. "Maintenance of VHF Omnirange Equipment," FAA Order 6790.4A, 1 October 1974 (and subsequent changes).

10. "VOR/VORTAC Equipment Replacement and Facility Modernization," FAA Specification FAA-E-2678a/1, 29 September 1978.

11. Mackenzie, F.D., and Lytle, C.D., Flight Evaluation of Loran-C in the State of Vermont, TSC and NASA Langley, TSC Report DOT-TSC-RSPA-81-10, September 1981.

12. Loran-C Data Analysis: Executive Summary, The Analytic Sciences Corporation, Publication SP-3030-6, 15 June 1982.

13. Wong, Gene A., Loran-C System Configuration Analysis for Civil Aviation, The MITRE Corporation, FAA Report DOT-FAA-RD-01-110, February 1982.

14. Nickum, James D., The Effects of Precipitation Static and Lightning on the Airborne Reception of Loran-C, Ohio University, FAA Report DOT/FAA/RD-82/45, April 1982.

15. Mauro, Peter G., The Effects of Primary Power Transmission Lines on the Performance of Loran-C Receivers in Experimental Terrestrial Applications, DOT/RSPA Report DOT-TSC-RSPA-79-8, October 1979.

16. Walker, H.L., and Ellerbe, R., Design Study Report for General Aviation Loran-C Receiver, Teledyne Systems Company, FAA Report DOT/FAA/RD-81/36, May 1981.

17. Connor, J., Esposito, R., and Lizzi, P., GPS En Route/Terminal Exploratory Tests, FAA Technical Center, Draft Final Report, February 1982.

18. Till, Robert D., Helicopter GPS Navigation with the Magnavox Z-Set, FAA Technical Center, Draft Final Report, February 1982.

19. Sahmel, R., "GPS Coverage Summaries," The Aerospace Corporation, Working Paper, 17 June 1982.

20. Sanford, Gary G., and Gross, Brian D., Advanced Microstrip Antenna Developments, Volumes 1 and 2, Ball Aerospace Systems Division, TSC Report DOT-TSC-FAA-80-15, March 1982.

21. Braff, R., Shively, C., and Bradley, J., "Navigation System Integrity and Reliability for Civil Aviation," The MITRE Corporation. Paper presented at IEEE Position Location and Navigation Symposium, Atlantic City, New Jersey, 8 to 11 December 1980.

22. "GPS Navigation Receiver for Civil Aviation," MIT Lincoln Laboratory, Quarterly Technical Letter for Period 1 October 1981 - 31 December 1981, 42 QTL-GPS-82-1, 23 February 1982.

23. Sahmel, R.H., Effect of Satellite Failures and Replacement Strategy on Civil Aviation Navigation with GPS, The Aerospace Corporation, Draft Repot ATR-82 (7680)-1ND, March 1982.

24. Shively, C.A., "Reliability of NAVSTAR GPS for Civil Aviation," The MITRE Corporation. Paper presented at ION National Aerospace Meeting, NASA Ames Research Center, Moffett Field, California, 24-25 March 1982.

25. Campbell, L.W., et al., North Atlantic Omega Navigation System Validation, Analytical Systems Engineering Corporation, U.S. Coast Guard Report CG-ONSOD-01-80, 21 July 1980.

26. Rzonca, Lorraine, Omega Transmitter Outages January to December 1979, FAA Technical Center, FAA Data Report FAA-RD-80-113, October 1980.

27. "Maintenance of ILS Equipments," FAA Order 6750.15A, May 1975.

28. "MLS Interoperability and Performance Requirements," Draft, FAA-STD-022.

29. National Airspace System Plan, FAA, December 1981.

30. Economic Requirements Analysis of Civil Air Navigation Alternatives, Systems Control, Inc., FAA Report FAA-ASP-78-3, April 1978.

ATE

MED