Reference
84-8

# Federal Radionavigation Plan

1984

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**Department of Defense** and
**Department of Transportation**

# LETTER OF PROMULGATION

This letter promulgates the third edition of the Federal Radionavigation Plan jointly prepared by the Departments of Defense and Transportation. It supersedes the Federal Radionavigation Plan dated March 1982.

The Federal Radionavigation Plan is issued for information on the management of those radionavigation systems which are used by both the military and civil sectors. It supports planning, programming and implementation of air, marine, land and space navigation systems to meet validated requirements as reflected in the President's FY 1985 budget submission to Congress. It is the official source of navigation policy and planning for the Departments of Defense and Transportation. The plan has been prepared with the assistance of the National Aeronautics and Space Administration and has its concurrence.

The Federal Radionavigation Plan will be revised biennially. Your suggestions for the improvement of future editions are welcomed.

Caspar W. Weinberger
Secretary of Defense

Elizabeth H. Dole
Secretary of Transportation

**Technical Report Documentation Page**

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16. Abstract

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

The Federal Radionavigation Plan delineates policies and plans for the Government provided radionavigation services. The Document describes respective areas of authority and responsibility, and provides a management structure by which the individual operating agencies will define requirements and meet them in a cost effective manner. It replaces the DOT National Plan for Navigation, and incorporates those sections of the DOD Joint Chiefs of Staff (JCS) Master Navigation Plan dealing with common use systems.

This edition of the Federal Radionavigation Plan contains the DOD/DOT Policy for the Future Radionavigation Systems Mix. This plan will be updated biennially, and is presently made up of four parts: Part I, Radionavigation Policy and Plans; Part II, Requirements; Part III, Radionavigation System Characteristics; and Part IV, Radionavigation Research, Engineering and Development.

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# PREFACE

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

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

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

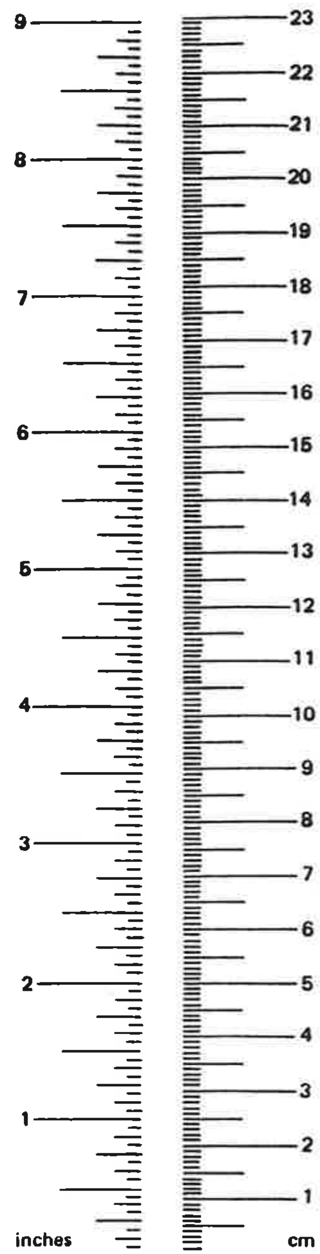
This plan will be updated biennially. The established DOD/DOT interagency management approach will enable continuing control and review of U.S. radionavigation systems. For further explanation of navigational terms used in this plan consult The American Practical Navigator, Volume 2, Publication No.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

# METRIC CONVERSION FACTORS

## Approximate Conversions to Metric Measures

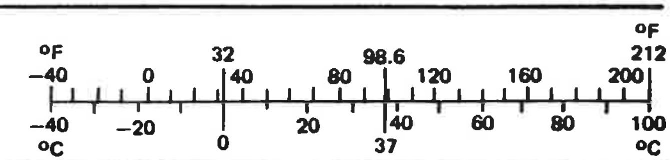
| Symbol | When You Know | Multiply by | To Find | Symbol |
|---|---|---|---|---|
| | **LENGTH** | | | |
| in | inches | *2.5 | centimeters | cm |
| ft | feet | 30 | centimeters | cm |
| yd | yards | 0.9 | meters | m |
| mi | miles | 1.6 | kilometers | km |
| | **AREA** | | | |
| $in^2$ | square inches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

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




## Approximate Conversions from Metric Measures

| Symbol | When You Know | Multiply by | To Find | Symbol |
|---|---|---|---|---|
| | **LENGTH** | | | |
| mm | millimeters | 0.04 | inches | in |
| cm | centimeters | 0.4 | inches | in |
| m | meters | 3.3 | feet | ft |
| m | meters | 1.1 | yards | yd |
| km | kilometers | 0.6 | miles | mi |
| | **AREA** | | | |
| $cm^2$ | square centimeters | 0.16 | square inches | $in^2$ |
| $m^2$ | square meters | 1.2 | square yards | $yd^2$ |
| $km^2$ | square kilometers | 0.4 | square miles | $mi^2$ |
| ha | hectares (10,000 $m^2$) | 2.5 | acres | |
| | **MASS (weight)** | | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.2 | pounds | lb |
| t | tonnes (1000 kg) | 1.1 | short tons | |
| | **VOLUME** | | | |
| ml | milliliters | 0.03 | fluid ounces | fl oz |
| l | liters | 2.1 | pints | pt |
| l | liters | 1.06 | quarts | qt |
| l | liters | 0.26 | gallons | gal |
| $m^3$ | cubic meters | 36 | cubic feet | $ft^3$ |
| $m^3$ | cubic meters | 1.3 | cubic yards | $yd^3$ |
| | **TEMPERATURE (exact)** | | | |
| °C | Celsius temperature | 9/5 (then add 32) | Fahrenheit temperature | °F |



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# EXECUTIVE SUMMARY

The Federal Radionavigation Plan (FRP) delineates policies and plans for government-provided radionavigation services. This plan will describe areas of authority and responsibility and provide a management structure by which the individual operating agencies can define and meet radionavigation requirements in a cost effective manner. It is the official source of radionavigation policy and planning for the Departments of Defense and Transportation. This edition of the FRP updates and replaces the FRP published in March 1982 and incorporates common user (civil/military) radionavigation systems covered in the DOD Joint Chiefs of Staff's Master Navigation Plan (MNP). The MNP has not been replaced by the FRP, since it covers many military only radionavigation systems.

This document describes the various phases of navigation and provides current and anticipated future requirements for each. Additional radionavigation systems may be added or deleted in subsequent revisions to this plan as requirements change. The U.S. LORAN-A system has now been phased out and deleted from the plan.

This plan covers Federally operated systems having a high degree of common use. These systems are sometimes used in combination with each other or with other systems. However, these hybrid systems are not covered in the FRP.

The systems covered in this plan are:

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

The goal is to select a suitable mix of these 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.

The process of selecting a system mix is a complex task, since user requirements vary widely and change with time. While all users require safe, expeditious services which are easy to use, military requirements stress unique defense capabilities such as performance under intentional interference, operations in high-performance vehicles, worldwide coverage and operational capability in severe environmental conditions. For the military, cost remains a major consideration but must be balanced with a needed operational capability.

Civil requirements are driven by needs which range from small single engine aircraft, or small vessels, which are highly cost-sensitive and may require only minimal capability, to highly sophisticated users such as airlines or large vessel operators to whom high accuracy, flexibility, and availability may be more important than initial cost. The selection of an optimum mix to satisfy the users, while holding the number of systems and government and user costs to a minimum, involves complex operational, technical, institutional, international and economic trade-offs. This plan establishes a vehicle for DOD and DOT to address these questions and arrive at an optimum mix determination. This edition of the FRP contains the preliminary joint DOD/DOT recommendation on the future radionavigation systems mix.

A significant portion of this plan is devoted to GPS since it has the potential to replace many existing radionavigation systems. Certain military applications, nevertheless, require covertness and redundancy, or multiple independent navigation systems and cannot be replaced by GPS. Technically and operationally GPS is more complex than existing systems and represents a significant challenge in the development of low-cost user equipment.

This document is composed of four parts:

Part I: Radionavigation Plans and Policy: Delineates plans, policies, and authority and responsibility for providing radionavigation services. An integrated management plan describing how DOD and DOT will determine requirements and coordinate research, development and implementation of radionavigation systems.

Part II: User Requirements: Civil and military requirements and the process for determining them are provided in this part. Both general requirements and specific requirements related to various applications and phases of navigation are discusssed. Present and future anticipated needs are both discussed.

Part III: System Characteristics: Describes present and planned navigation systems in terms of nine major parameters: signal characteristics, accuracy, availability, coverage, reliability, fix rate, fix dimension, capacity, and ambiguity.

Part IV: Research, Engineering and Development Plans: A summary of DOD, DOT, and NASA radionavigation R,E&D plans with primary emphasis on GPS.

# PART I

# RADIONAVIGATION PLANS AND POLICY

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PART I

# 1. INTRODUCTION TO THE FEDERAL RADIONAVIGATION PLAN

This section describes the background, purpose, and scope of the Federal Radionavigation Plan (FRP). It summarizes the events leading to the preparation of this document and the national objectives for assuring coordinated planning of radionavigation services. The remaining contents of Part I set forth National Policy, Radionavigation Authority and Responsibility, and Radionavigation System Planning. Three supporting sections (Requirements, Systems Characteristics, and Research, Engineering, and Development) are outlined briefly.

## 1.1 BACKGROUND

The FRP contains policy and planning for common use (civil and military) radionavigation systems. The Joint Chiefs of Staff (JCS) Master Navigation Plan (MNP) contains policy and planning for all radionavigation systems used by the DOD, including common use systems.

Prior to the time work started on the first edition of the FRP, the Office of Management and Budget (OMB) and National Telecommunications and Information Administration (NTIA) co-chaired an interagency working group to study planning among various government agencies responsible for providing radionavigation services for both military and civilian users. The working group was composed initially of representatives of DOD, DOT, the National Aeronautics and Space Administration (NASA), and the Department of Commerce (DOC). Later, representatives of the Department of State (DOS) and the Central Intelligence Agency (CIA) were added to the working group.

In April 1979, a DOD/DOT Interagency Agreement strengthened Federal radionavigation planning. Within DOT the Navigation Council and its supporting working group address civil and joint civil/military uses of navigation. This includes radionavigation interests of other federal agencies such as NASA and DOC, and state and municipal agencies. The DOD Positioning/Navigation Executive Committee (POS/NAV Committee) and POS/NAV Working Group address military and joint civil/military radionavigation system planning.

This FRP and subsequent revisions serve as the primary planning document for all common use civil/military Federal radionavigation services.

## 1.2 PURPOSE

The purpose of this FRP is to:

A. Present an integrated Federal, military and civil policy and plan for all common civil/military radionavigation systems.

B. Provide a document for comparing civil/military systems and requirements on a common basis.

C. Outline an approach for achieving maximum consolidation of radionavigation systems. Where concrete decisions can be made now, these are presented. Where decisions must be scheduled for a later date, these are identified together with the actions planned to reach such decisions in a timely fashion.

D. Define and clarify new or unresolved issues relating to navigational systems, e.g., operational, technical, economic, and institutional questions.

E. Provide a multi-year system planning schedule.

F. Provide government radionavigation planning information suitable for use by civil users, manufacturers, and non-government operators.

## 1.3 SCOPE

This plan covers government provided common use radionavigation systems. It does not include systems performing mainly surveillance, surveying, and communication functions.

### 1.3.1 Systems

The major radionavigation systems subject to the planning process described in this FRP are:

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

### 1.3.2 Phases of Navigation and Requirements

Part II of the plan defines phases of navigation and addresses radionavigation requirements for each phase of aviation, marine, land, and space operations. The phases are:

- o Air - Approach/Landing and en route/terminal.
- o Marine - Ocean, coastal, harbor approach, harbor and inland waterway.
- o Land - Automatic Vehicle Monitoring (AVM), Automatic Vehicle Location (AVL) and Site Registration.
- o Space - Launch, in-flight/orbit and re-entry.

### 1.3.3 System Characteristics

Descriptions of the salient features of radionavigation systems are summarized in Section 4 of Part I. Detailed technical descriptions for each of the radionavigation systems are presented in terms of nine primary system performance parameters in Part III.

### 1.3.4 Research, Engineering and Development

Federal radionavigation research, engineering, and development activities to improve existing operations or to assess future system alternatives are presented in Part IV.

PART I

# 2. FEDERAL RADIONAVIGATION OBJECTIVES AND POLICY

The radionavigation policy of the United States has evolved over a number of years through statute, use, and in the interest of national defense and public safety. The policy forms the basis for the development of the Federal Radionavigation Plan. The objectives of United States Government Radionavigation Policy are to:

A. Promote efficient transportation services.

B. Promote national security by providing necessary services.

C. Promote safety of travel.

## 2.1 POLICIES AND PRACTICES

The following policies and practices implement the above objectives:

A. Provide resources to implement and operate radio aids to navigation. Provide services which contribute to safe, expeditious, and economic air and maritime commerce and which support United States national security interests.

B. Provide for the installation and operation of radionavigation systems in accordance with international agreements.

C. Coordinate national planning for optimal use of the electromagnetic spectrum, achievement of system economies, and avoidance of unnecesary duplication of navigational systems and services. Achieve the highest degree of commonality/interoperability and system utility between military and civil users through early considerations of mutual requirements.

D. Require certain vessels and aircraft to be fitted with navigational equipment as a condition for operating in controlled U.S. airspace or in the navigable waters of the United States, to promote transportation safety and environmental protection.

E. Provide leadership to ensure that radionavigation services are available to civil users to meet projected demand, performance, safety, and enviromental protection requirements considering conservation and economic constraints on radionavigation systems providers and users.

F. Promote the scientific and operational evaluation of domestic and foreign radio aids to navigation and support development of those with potential to:

- o Satisfy unfulfilled operational requirements.
- o Offer major economic advantages over existing systems.
- o Provide significant benefits in the national interest.

G. Encourage and promote international exchange of scientific and technical information concerning radio aids to navigation.

H. Provide guidance and assistance in siting, testing, evaluating and operating radio aids to navigation to meet unique requirements not supported by the Federal Government.

I. Promote national and international standardization of civil and military radio aids to navigation.

J. Establish, maintain, and disseminate signal characteristics.

K. Develop, implement, and operate the minimum special radio navigational aids and services necessary to accomplish military operations.

L. Operate common use (civil/military) radionavigation systems only as long as the United States and its allies accrue greater military benefit than potential adversaries. Cease operations or change the operating characteristics and signal formats of radionavigation systems only during a dire national emergency.

M. In the control of LORAN-C stations, DOT will maximize the utility of service for other than marine users, within the constraints imposed by the need to maximize the quality of service provided to maritime navigation.

N. Make the GPS Standard Positioning Service (SPS) continuously available worldwide for civil, commercial and other use at the highest level of accuracy consistent with U.S. national security interests. It is presently projected that a predictable and repeatable accuracy of 100 meters (2 drms) horizontally and 156 meters (2 sigma) vertically will be made available during the first year of full GPS operation. During the development phase of the GPS program, the satellites will be transmitting both the PPS and SPS signals in the clear in support of government sponsored tests. Civil users are cautioned that the system is developmental and signal availability and accuracy are subject to change without advance warning, at the discretion of the Department of Defense. Therefore, until the system is declared operational, any use of the system is at the user's own risk.

O. Equip military vehicles, as appropriate, to satisfy civil aviation and maritime navigation safety requirements. U.S. military vehicles and users will be equipped with navigation systems which best satisfy mission requirements. In general, a combination of radionavigation and self-contained navigation aids is required. Standardization is a goal, however, this goal may be voided when unique military systems provide the capability to operate safely without reference to civil radionavigation systems.

P. Require, where practical, users of Federally operated radio aids to navigation and services to bear their fair share of the costs for development, procurement, operation, and maintenance of these systems insofar as technically and economically feasible.

Q. Provide, through DOD/DOT interagency agreements, comprehensive management for all government provided common use radionavigation systems.

R. Insure, in accordance with established national policy, reliance on the private sector to support the design, development, installation, operation, and maintenance of all equipment and systems required to provide common use radionavigation aids in support of this Federal Radionavigation Plan (within the constraints of national security).

## 2.2 PRELIMINARY RECOMMENDATION ON THE FUTURE RADIONAVIGATION SYSTEM MIX

Using the procedures and criteria to be described in Section 4.5, and the existing and proposed radionavigation systems identified in Sections 4.3 and 4.4, a preliminary recommendation on the future radionavigation systems mix has been jointly developed by DOD and DOT. The recommendation is in the form of the policy statement presented on the following pages.

DOD/DOT POLICY
FOR THE
FUTURE RADIONAVIGATION SYSTEMS MIX

PURPOSE: This statement sets forth the policy for Federally funded radionavigation systems to be supported for the remainder of this century and into the early part of the next.

BACKGROUND: Section 507 of the International Maritime Satellite Communications Act of 1978 (PL 95-564) requires the development of a plan to determine the most cost effective method of reducing proliferation and overlap of Federally funded radionavigation systems. That plan, the Federal Radionavigation Plan (FRP), was developed through the joint efforts of the Departments of Defense and Transportation. The FRP (current edition March 1982) cites key events in selecting radionavigation systems to be used in the future. One of these events is publication of a DOD/DOT policy statement that sets forth a preliminary selection of Federally funded radionavigation systems. This policy statement will provide the basis for revising the FRP. Subsequent reviews of the FRP will be undertaken, at least biennially or more frequently, if necessary.

All common user systems currently operating or planned were considered in reaching this selection for the future mix of Federally funded radionavigation systems. This policy statement addresses how and for what period each system should be a part of the Federal radionavigation system mix. When a decision is made to terminate a navigation system, an appropriate transition period will be provided.

The Department of Transportation (DOT) is responsible for ensuring safe and efficient transportation. Radionavigation systems play an important role in carrying out this responsibility. The two main elements within DOT that operate radionavigation systems are the United States Coast Guard and the Federal Aviation Administration (FAA).

The Coast Guard has the statutory responsibility to define the need for, and to provide aids to navigation and facilities needed for safe and efficient navigation. The FAA has the responsibility for development and implementation of radionavigation systems to meet the needs for safe and efficient navigation and control of all civil and military aviation, except for those needs of military agencies which are peculiar to air warfare and primarily of military concern. The FAA also has the responsibility to operate aids to air navigation required by international treaties.

The Department of Defense (DOD) is responsible for developing, testing, evaluating, implementing, operating, and maintaining aids to navigation and user equipment required for National Defense and ensuring that military vehicles operating in consonance with civil vehicles have the navigational capabilities required to operate in a safe and expeditious manner.

DEFINITIONS:

Sole Means Air Navigation System: An approved navigation system that can be used for specific phases of air navigation in controlled airspace without the need for any other navigation system.

Supplemental Air Navigation System: An approved navigation system that can be used in controlled airspace of the National Airspace System in conjunction with a sole means navigation system.

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

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

2 drms: The radius of a circle that contains at least 95 percent of all possible fixes that can be obtained with a system at any one place.

POLICY

RADIOBEACONS: Maritime and aeronautical radiobeacons serve the civilian user community with low cost navigation. They will remain part of the radionavigation mix well into the next century.

LORAN-C: LORAN-C provides navigation for both civil and military air and surface users. It is the Federally provided navigation system for the U.S. Coastal Confluence Zone (CCZ) and in the differential mode has been demonstrated capable of meeting the 8-20 meter 2 drms navigation accuracy requirements in harbor and harbor approach areas. LORAN-C is also approved as a supplemental air navigation system in some areas. DOD will phase out military use of overseas LORAN-C by 1992. The United States will discontinue LORAN-C transmitting stations established for military use that do not serve the North American continent, as military LORAN-C users become GPS equipped. The LORAN-C system serving the continental United States and its coastal areas will remain a part of the navigation system mix into the next century.

OMEGA: OMEGA is a global navigation system serving maritime and aeronautical users. It is a sole means of air navigation in some oceanic areas. DOD will phase out military air use of OMEGA by 1992. However, some naval receivers may continue in operation after that date. OMEGA will remain a part of the radionavigation system mix until at least 2000.

VOR/DME: VOR/DME provides users with a sole means of air navigation in the National Airspace System. DOD will phase out military support and use of VOR/DME by 1997. VOR/DME, as the international standard for civil air navigation in controlled airspace, will remain the short distance aviation navigation system well into the next century.

TACAN: TACAN is a short range navigation system used primarily by military aircraft. DOD will phase out land-based TACAN by 1997 assuming GPS, integrated with other onboard aircraft systems, proves acceptable as a sole means radionavigation system for military use in controlled airspace. Shipboard TACAN systems will continue in operation after that period.

ILS/MLS/PDME: These are precision approach systems for aircraft. MLS will replace ILS.

TRANSIT: TRANSIT is a satellite based radionavigation system operated by the DOD. It will be replaced with GPS by 1994. TRANSIT will not be operated by or transferred to a civilian agency of the U.S. Government.

GPS: GPS is a DOD developed worldwide satellite based radionavigation system that is scheduled to be operational with three dimensional coverage in 1988. The GPS Precise Positioning Service (PPS) will be restricted, due to national security considerations, primarily to the military. The GPS Standard Positioning Service (SPS) will be made continuously available to all users, worldwide, and will provide 100 meter 2 drms navigation accuracy.

AIR USE: GPS has the potential to become a sole means air navigation system for the United States. The adequate control of aircraft in national and international controlled airspace must be assured if GPS is relied upon, and those agencies with safety and operational responsibilities will determine when GPS, properly integrated with other aircraft navigation systems, is acceptable. Approval of civil navigation receivers to operate with the GPS system is initially expected to be on a supplementary system basis. Resolution of coverage and integrity issues is needed in order to certify GPS as a sole means system.

SURFACE USE: The GPS SPS, as currently proposed, provides better accuracy than the predictable accuracy of LORAN-C. It does not, however, have the capability of LORAN-C in the repeatable mode, and it cannot provide as good accuracy as LORAN-C in some locations. It is possible that some enhanced form of GPS may provide accuracy equivalent to existing systems for harbor and harbor approach areas, and for coastal and land radionavigation. Several enhancement techniques are currently being investigated.

CIVIL USER CHARGES: There should be no direct charges to civil users of GPS service. GPS costs should be underwritten through other mechanisms such as those provided for by existing statute(s).

PHASE OUT OF EXISTING SYSTEMS: It is the goal of the DOD to phase out use of TACAN, VOR/DME, OMEGA, LORAN-C and TRANSIT in military aircraft and other platforms. Civil user phase out of LORAN-C and OMEGA would be keyed to (a) resolution of GPS accuracy, coverage, integrity, and financial issues; (b) GPS meeting civil air, marine, and land needs currently met by LORAN-C and OMEGA; (c) GPS civil user equipment being available at prices that would be economically acceptable to LORAN-C and OMEGA users; (d) a transition period of 15 years; and (e) resolution of international commitments in the case of LORAN-C and OMEGA.

PART I

# 3. AUTHORITY AND RESPONSIBILITY

This section describes the DOD authority, responsibilities, and management structure to plan and provide for navigational systems for military missions. The DOT authority and responsibilities are then addressed in the context of its lead role to assure navigation services for the civil sector and to coordinate non-military navigational planning for other Federal agencies. The joint DOD and DOT management structure and actions necessary to reduce costs or to avoid duplication or gaps in combined military and civil navigational services are also presented.

## 3.1 DEPARTMENT OF DEFENSE

### 3.1.1 Responsibilities

The DOD is responsible for developing, testing, evaluating, operating, and maintaining aids to navigation and user equipment required for national defense, and ensuring that military vehicles operating in consonance with civil vehicles have the navigational capabilities required to operate in a safe and expeditious manner. Specific DOD responsibilities are to:

A. Define performance requirements applicable to military mission needs.

B. Design, develop, and evaluate systems and equipment to insure that peformance requirements are met in a cost-effective manner.

C. Maintain liaison with other government research and development activities affecting military radionavigation systems.

D. Develop forecasts and analyses as needed to support the requirements for future military mission needs.

E. Develop plans, activities, and goals related to military mission needs.

F. Define and acquire the necessary resources to accomplish mission requirements.

G. Identify special military route and airspace requirements.

H. Foster Rationalization, Standardization and Interoperability (RSI) of systems with NATO and other allied countries.

I. Operate and maintain ground radionavigation aids as part of the civil National Air Space System when such activity is economically beneficial and specifically agreed to by the appropriate DOD and DOT agencies.

The Defense Mapping Agency (DMA) is responsible for military mapping, charting, and geodesy aspects of navigation, including geodetic surveys, accuracy determination, and positioning. Within DOD, DMA acts as the primary point of contact with the civil community on matters relating to geodetic uses of navigation systems. Unclassified data prepared by the DMA are available to the civil sector.

### 3.1.2 Internal Management

The DOD internal management structure for navigational coordination is shown in Figure I-3.1. The two major parts of the structure represent the adminstrative and the operational chains of command reporting to the Secretary of Defense.

A. Operational Management

The Joint Chiefs of Staff (JCS) are the top level body in the operational chain of command (beneath the Secretary of Defense) and, by authority and direction of the President and the Secretary of Defense, serve as military advisors to the President and the Secretary of Defense. Additionally, the JCS provides guidance for use by Military Departments and the Armed Forces as needed in the preparation of their respective detailed navigational plans. The JCS maintains cognizance over operational navigation requirements and capabilities of the Unified and Specified Commands and the Services. In order to effectively and economically use the operational navigational resources serving the military worldwide, the JCS are responsible for the development, approval, and dissemination of the JCS MNP.

The MNP is the official document for JCS guidance for navigational policy and planning. It is the result of a coordinated effort by all operating elements to insure unanimity in navigational system planning to meet identified operational defense requirements. The MNP also facilitates the integration of required military navigational systems and helps to assure the most efficient and cost-effective implementation of JCS policy for radionavigation.

The following organizations also perform navigation management functions:

The Deputy Director for Defense-Wide Command, Control and Communications Support, Joint Staff, is responsible for:

- Analysis, evaluation, and monitoring of navigational system planning and operations.

- Navigational matters in general and, specifically, the JCS MNP.

The Commanders of the Unified and Specified Commands perform navigational functions similiar to those of the JCS. They may develop navigational requirements in support of contingency plans and JCS exercises requiring navigational resources external to that command. Additionally, they are responsible for review and compliance with the FRP.

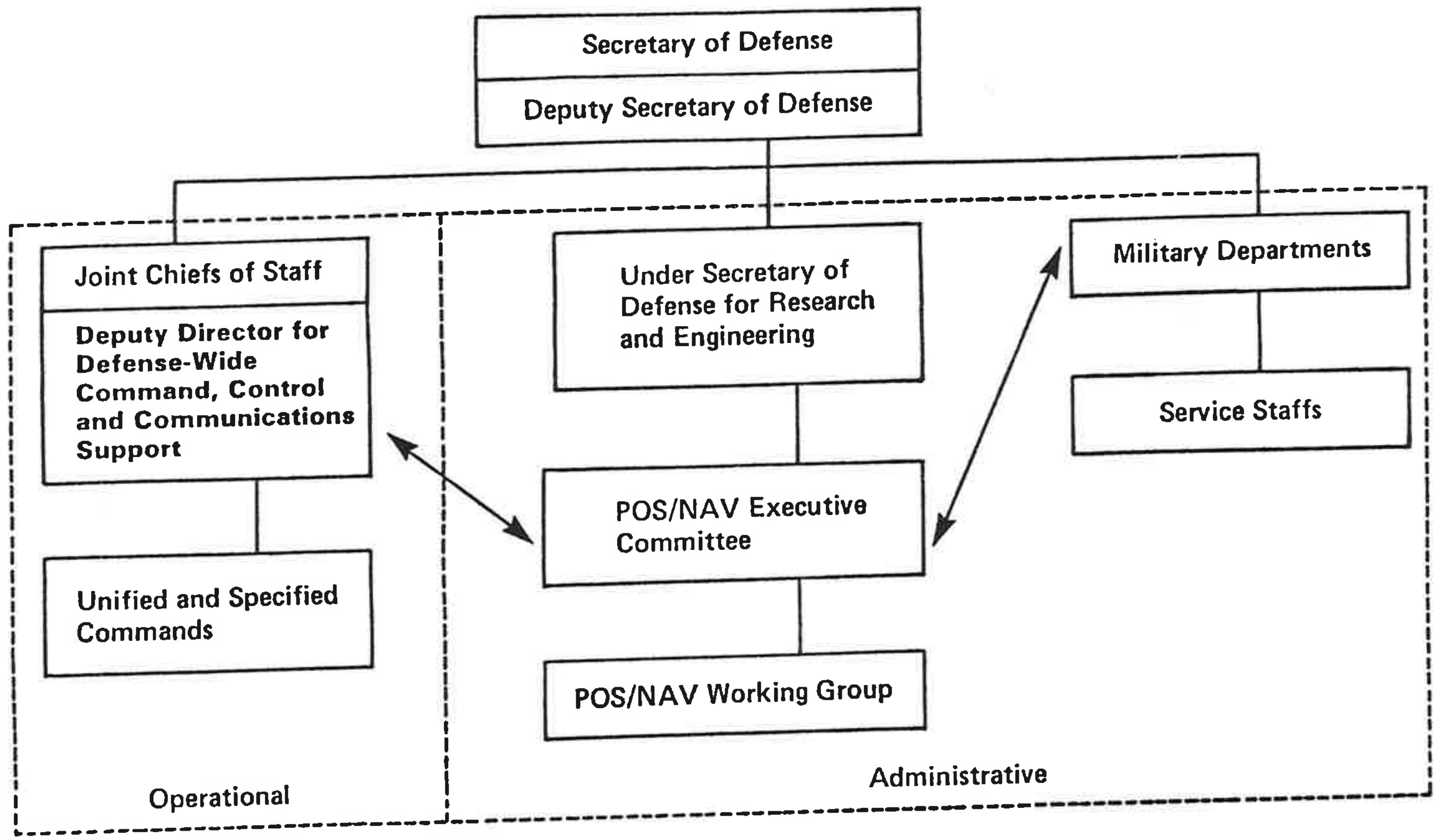


FIGURE I-3.1 DOD NAVIGATION STRUCTURE

B. Administrative Management

Three permanent organizations provide radionavigation planning and management support to the Under Secretary of Defense for Research and Engineering. These organizations are the Positioning/Navigation Executive Committee; the Positioning/Navigation (POS/NAV) Working Group; and the Military Departments/Service Staffs. Brief descriptions are provided below.

The DOD POS/NAV Executive Committee is the DOD focal point and forum for all DOD POS/NAV matters. It provides overall management supervision and decision processes, including intelligence requirements (in coordination with DIA and NSA). The Executive Committee contributes to the development of the FRP and coordinates with the DOT Navigation Council.

The DOD POS/NAV Working Group supports the Executive Committee in carrying out its responsibilities. It is composed of representatives from the same DOD components as the Executive Committee. The Working Group identifies and analyzes problem areas and issues, participates in the revision of the FRP, and submits recommendations to the Executive Committee.

The Military Departments/Service Staffs are responsible for participating in the development, dissemination and implementation of the JCS Master Navigation Plan and for managing the development, deployment and operation and support of designated navigation systems.

A special committee, the GPS Phase-In Steering Committee, has been established to guide the development and implementation of the policies, procedures, support requirements, and other actions necessary to enable DOD aircraft to operate in controlled airspace without reference to TACAN, VOR/DME, OMEGA, LORAN, or Radiobeacons. This committee also has an Aircraft Equipment and a Procedures panel. FAA representatives serve on both working panels.

## 3.2 DEPARTMENT OF TRANSPORTATION

### 3.2.1 Responsibilities

The DOT is the primary government provider of aids to navigation used by the civil community and of certain systems used by the military. It is responsible for the preparation and promulgation of radionavigation plans in the civilian sector of the United States. The National Aeronautics and Space Administration (NASA) participates in the development of DOT radionavigation plans.

The Secretary of Transportation, under the DOT Act (Public Law 89-670), is responsible for navigational matters within DOT and promulgates radionavigation plans. Three DOT elements have statutory responsbilities regarding the provision of aids to navigation: the U.S. Coast Guard, the Federal Aviation Administration (FAA) and the Saint Lawrence Seaway Development Corporation. In addition, several other elements of DOT have responsibilities and interests which may be satisfied by radionavigation or radiolocation systems.

The Coast Guard has the statutory responsibility to define the need for, and to provide, aids to navigation and facilities needed for safe and efficient navigation. Section 81 of Title 14, United States Code provides:

"To aid navigation and to prevent disasters, collisions, and wrecks of vessels and aircraft, the Coast Guard may establish, maintain, and operate:

(1) "Aids to maritime navigation required to serve the needs of the armed forces and the commerce of the United States;"

(2) "Aids to air navigation required to serve the needs of the armed forces of the United States peculiar to warfare and primarily of military concern as determined by the Secretary of Defense or the Secretary of any department within the Department of Defense and as requested by any of those officials;

(3) "Electronic aids to navigation systems (a) required to serve the needs of the armed forces of the United States peculiar to warfare and primarily of military concern as determined by the Secretary of Defense or any department within the Department of Defense; or (b) required to serve the needs of the maritime commerce of the United States; (c) required to serve the needs of the air commerce of the United States as requested by the Administrator of the Federal Aviation Agency.

"These aids to navigation, other than electronic aids to navigation systems, shall be established and operated only within the United States, the waters above the Continental Shelf, the territories and possessions of the United States, the Trust territory of the Pacific Islands, and beyond the territorial jurisdiction of the United States at places where naval or military bases of the United States are or may be located."

The Federal Aviation Administration (FAA), under the Federal Aviation Act of 1958 (Public Law 85-726), has responsibility for development and implementation of radionavigation systems to meet the needs for safe and efficient navigation and control of all civil and military aviation, except for those needs of military agencies which are peculiar to air warfare and primarily of military concern. The FAA also has the responsibility to operate aids to air navigation required by international treaties.

The Maritime Administration (MARAD) investigates position determination using existing and planned communications systems, conducts precision radar navigational experiments and investigates the application of radar transponders to navigation and collision avoidance. These efforts are designed to enhance U.S. Merchant Marine efficiency and effectiveness.

The Saint Lawrence Seaway Development Corporation (SLSDC) has responsibility for assuring safe navigation along the seaway. The SLSDC provides aids to navigation in U.S. waters in the St. Lawrence River and operates a Vessel Traffic Control System with the St. Lawrence Seaway Authority of Canada.

The Federal Highway Administration (FHWA), the National Highway Traffic Safety Administration (NHTSA), and the Urban Mass Transportation Administration (UMTA), under their respective statutory authorities, have the responsibility to conduct research, development, and demonstration projects. This could include projects on land uses of radiolocation systems. Also, they assist state and local governments in planning and implementing such systems and issue guidelines concerning their potential use and applications.

NASA supports navigation through the development of technologies for navigating aircraft and spacecraft. In addition to the user equipment, NASA is responsible for development of the ground-based equipment. NASA is also authorized to demonstrate the capability for civil application of military navigational satellite systems to aircraft, ships, and spacecraft navigation and position determination.

### 3.2.2 Internal Management

The DOT internal management structure for navigational systems planning for civil use is shown in Figure I-3.2. The structure was established by DOT Order 1120.32, dated April 27, 1979, for the following purposes:

A. Coordinate policy recommendations and integrate planning regarding navigation among the operating elements of DOT, and help to assure the most efficient implementation of those policies and plans without decreasing the responsibility or usurping the authority of the indiviual operating elements.

B. Provide a body which can. on a continuing basis, facilitate coordinated navigational planning on a multimodal basis within DOT; and serve as a focal point for recommendations on which DOT navigation policies and plans can be formulated.

C. Assure that the Secretary of Transportation gets consolidated information and provide the means to obtain coordinated high level review of proposed navigational policies and plans.

D. Establish a planning framework within which the DOT operating elements are allowed maximum latitude for navigational system research, development, and implementation consistent with the need to avoid duplication of effort.

E. Provide the technical resources to supplement the navigational planning, implementation, coordination, and decision making of the operating elements.

F. Provide a focal point for obtaining inputs from those elements of DOT which may not have a continuous interest in navigational problems.

G. Provide a DOT focal point for multimodal or interdepartmental navigational issues.

The DOT Navigation Council is the top-level body of the structure. It consists of the Science and Technology Advisor to the Secretary as Chairman, the Assistant Secretary for Budget and Programs and one policy-level representative each from the Coast Guard, FAA, MARAD, the Research and Special Programs Administration (RSPA), and the Saint Lawrence Seaway Development Corporation

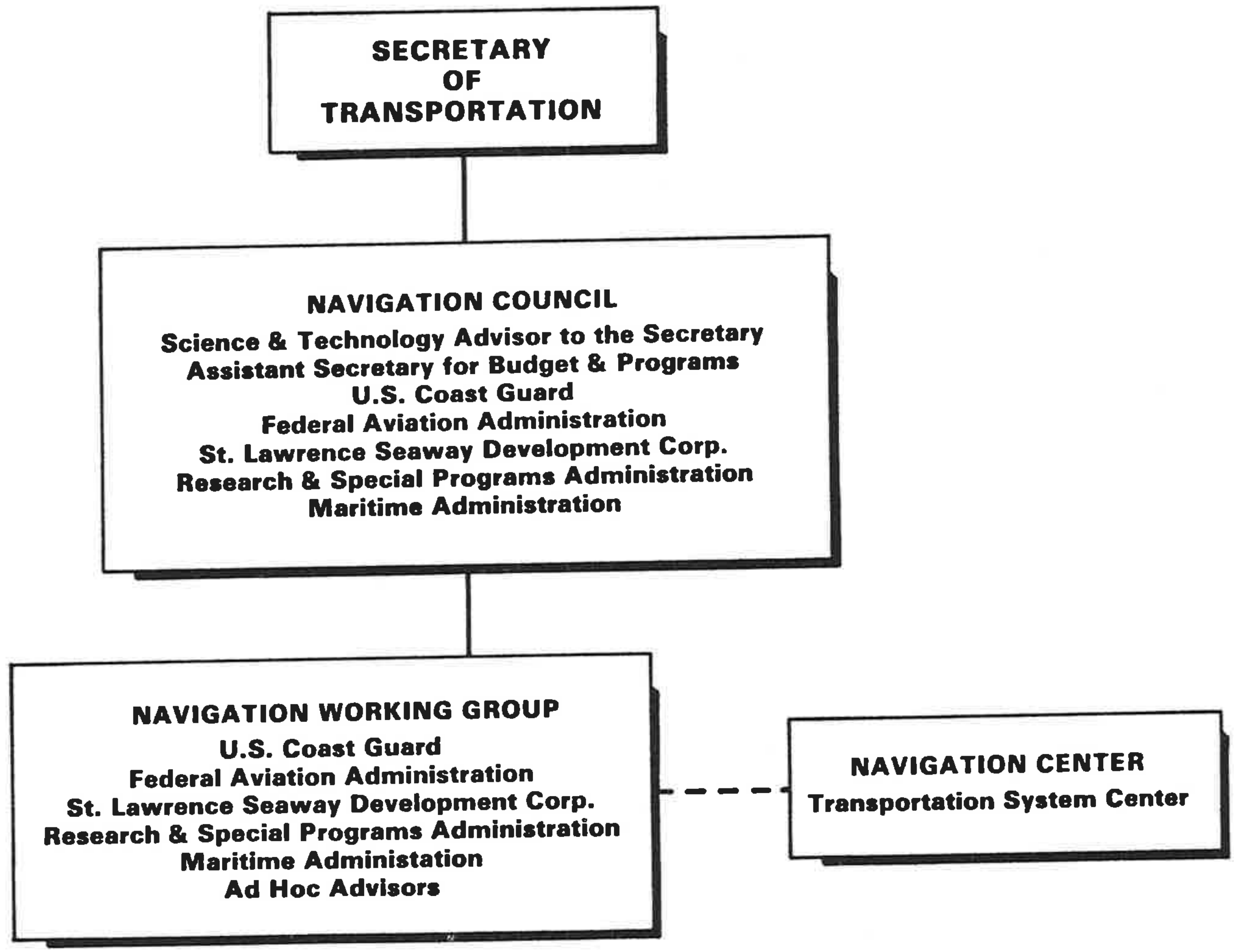


FIGURE I-3.2 DOT NAVIGATION STRUCTURE

(SLSDC). The Council meets as required and the designated members may be augmented by representatives of other operating elements to consider specific items. The DOT Navigation Council:

- Serves as the focal point to formulate coordinated policy recommendations to the Secretary;
- Coordinates with similar committees in other government agencies in accordance with any bilateral or multilateral agreements between DOT and those agencies; and
- Provides guidance to the subordinate Navigation Working Group.

The Navigation Working Group is the working core of the structure. It consists of one representative each from the Coast Guard, FAA, MARAD, RSPA, and SLSDC. Each representative may be assisted by advisors. Ad hoc advisors from other DOT operating elements which have an interest in navigation are invited to attend meetings as appropriate. These elements are the Federal Highway Administration (FHWA), the Federal Railroad Administration (FRA), the National Highway Traffic Safety Adminstration (NHTSA), and the Urban Mass Transportation Administration (UMTA). The Navigation Center at the DOT Transportation Systems Center (TSC) provides technical assistance to the Navigation Working Group, as requested. The Navigation Working Group facilitates the coordination of:

- Navigational requirements developed by the DOT operating elements;
- Navigational plans;
- Navigational R,E&D and implementation programs;
- DOT navigation planning with DOD, NASA, and other Federal Agencies, as required;
- Multimodal navigational issues with other governmental agencies, industry, and user groups, as directed by the Navigation Council, and
- Coordinates suggestions for the improvement of future editions of the FRP.

### 3.3 JOINT DOD AND DOT MANAGEMENT

An Interagency Agreement between DOD and DOT for radionavigation planning became effective in 1979 and was updated in 1984. This agreement requires coordination between the DOD and DOT internal management structures for navigational planning. The Interagency Agreement recognizes that DOD and DOT have joint responsibility to avoid unnecessary overlap or gaps between military and civil navigational systems/services. Further, it requires that both military and civil needs be met in a cost-effective manner for the government and civil user community. Implicit in this joint responsibility is assurance of civil sector radionavigation readiness for mobilization in national emergencies. The agreement provides that DOD and DOT will jointly:

A. Keep each other informed of the status of development, evaluation, installation, and operation of aids to navigation with existing or potential joint applications.

B. Coordinate all major navigational planning activities to ensure a high level of consistency while still meeting diverse navigational requirements.

C. Attempt, wherever consistent with diverse requirements, to utilize common systems, equipment, and procedures.

D. Undertake joint programs in research, development, design, testing, and operation of radionavigation systems.

E. Prepare a standard definition of requirements and a joint requirements document.

F. Assist in assuring that other government agencies involved in navigation system research, development, operation, or use are aware of and, where necessary, consulted on future plans.

G. Publish a single Federal Radionavigation Plan to be implemented by internal departmental actions. These plans will be reviewed and updated biennially.

## 3.4 LIAISON WITH THE PRIVATE SECTOR

Interested parties and advisory groups from the private sector are invited to submit their inputs to the Chairman of the DOT Navigation Working Group (Attn: DMA-26), Department of Transportation, Research and Special Programs Adminstration, Washington, DC 20590. This procedure allows for direct interaction between the users of radionavigation aids and the Federal authorities that manage and create policies for radionavigation systems.

PART I

# 4. RADIONAVIGATION PLANS

This section summarizes the plans of the Federal government to provide general purpose and special purpose radio aids to navigation for use by the civil and military sectors. It focuses on three aspects of planning: (1) the efforts needed to maintain existing systems in a satisfactory operational configuration, (2) the development needed to improve their present performance or to satisfy existing unsatisfied requirements in the near term, and (3) the evaluation of existing and proposed radionavigation systems to meet future requirements. Thus, the plan provides the framework for operation, development and evolution of systems.

The Government operates existing radionavigation systems which meet most of the current and projected civil user requirements for safety of navigation and promotion of reasonable economic efficiency. These systems are adequate for the general navigation of military craft as well, but none completely satifies all the needs of military missions nor provides highly accurate, three-dimensional, worldwide navigation capability. GPS is being developed to satisfy many of these general and special military requirements. GPS may have broad potential for satisfying current civil user needs or for responding to new requirements that present systems do not satisfy. Thus, it could ultimately become the primary worldwide system for military and civil navigation and position location. Likewise civil development of the Microwave Landing System promises to provide the technology required to satisfy unfilled military requirements for a highly mobile precision approach system.

## 4.1 EXISTING NAVIGATION REQUIREMENTS

It is generally accepted that the needs for navigational services derive from the activities in which the users are engaged, the locations in which these activities occur, the relation to other craft and physical hazards, and to some extent the type of craft. As these differences exist, the requirements for navigational services are divided by classes or types of users and the phases of navigation. These divisions are discussed in detail in Part II and are summarized in Tables I-4.1 through I-4.3. These tables also show the emphasis placed on the existing radionavigation systems in the various phases of navigation. Detailed descriptions of the existing and proposed radionavigation systems are given in Part III.

Systems are categorized in Tables I-4.1 through I-4.3 as primary system (P), secondary or supplementary systems (S), or a system under development or evaluation (E). These classifications are:

A. "P" indicates a system which now provides a primary service in one or more phases of the civil and military marine and air environments. Ongoing efforts applied to a given primary system and area of application are directed toward improving an existing service or enhancing system performance.

## TABLE I-4.1 RADIONAVIGATION SYSTEM CIVIL APPLICATIONS

| SYSTEM | VOR/DME | TACAN | OMEGA | LORAN-C | RADIO-BEACON (NDB/RBN) | ILS/MLS | TRANSIT | GPS/SPS |
|---|---|---|---|---|---|---|---|---|
| Phase of Navigation | | | | | | | | |
| AIR | | | | | | | | |
| ENROUTE/TERMINAL | | | | | | | | |
| *Remote Area | E | S | S | S | S | — | — | E |
| *Special Helicopter | E | — | E | S | S | — | — | E |
| Oceanic En route | — | — | P | — | — | — | — | E |
| Domestic En route | P | P | S | S | S | — | — | E |
| Terminal | P | P | — | S | S | — | — | E |
| APPROACH/LANDING | | | | | | | | |
| Non Precision | P | P | — | E | S | — | — | E |
| Precision | — | — | — | — | — | P | — | — |
| MARINE | | | | | | | | |
| Oceanic | — | — | P | S | S | — | P | E |
| Coastal | — | — | — | P | S | — | — | E |
| *Harbor & Harbor Approaches | — | — | — | E | P | — | — | E |
| *Inland Waterways | — | — | — | — | — | — | — | — |
| LAND** | | | | | | | | |
| AVM/AVL | — | — | — | E | — | — | — | E |
| Site Registration | — | — | — | E | — | — | S | E |
| SPACE | | | | | | | | E |

**LEGEND**
P — Primary System
S — Secondary/Supplemental System
E — System in Evaluation
*New Requirement
**This area is under assessment

TABLE I-4.2 DOD MISSIONS VS. SELECTED COMMON-USE RADIONAVIGATION SYSTEMS

| AVIATION MISSIONS | SYSTEM | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | LORAN-C | OMEGA | TACAN | TRANSIT | VOR | RADIOBEACONS | MLS/ILS | GPS |
| **ENROUTE ATOMOSPHERIC** | | | | | | | | |
| Foreign Domestic | S | S | P* | | P | S | | E |
| Domestic | S | S | P | | S | S | | E |
| Combat Theatre | S | S | P | | | S | | E |
| Overwater | S** | P** | | | | S | | E |
| Remote Area | S/P** | S/P** | P* | | | S | | E |
| **TERMINAL** | | | | | | | | |
| Non-Precision Approach/Landing | | | P* | | P | S | | E |
| Precision Landing | | | | | | | P | |
| General | | | P* | | P | S | | E |
| **SPACE** | | | | | | | | |
| Launch/Abort | | | S | | | | S | E |
| Orbital | | | | | | | | E |
| Re-Entry | | | | | | | | E |
| Terminal Approach | | | P | | | | | E |
| Terminal Landing | | | | | | | P*** | |
| **SITING/SURVEYING** | | | S | P | | | | E |
| **TARGET ACQUISITION** | S | S | S | | | S | | E |
| **AERIAL RENDEZVOUS** | | | P* | | | S | | E |

LEGEND
P - Primary System
S - Secondary System
E - System in Evaluation

* If Available or deployed
** Depending on aircraft configuration
*** Non-Standard MLS

## TABLE I-4.2 DOD MISSIONS VS. SELECTED COMMON-USE RADIONAVIGATION SYSTEMS (CONT.)

| NAVAL MISSIONS | SYSTEM | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | LORAN-C | OMEGA | TACAN | TRANSIT | VOR/DME | RADIOBEACONS | MLS/ILS | GPS' |
| **ENROUTE, GENERAL PURPOSE** | | | | | | | | |
| Ship | P/S | P/S | | P | | S | | E |
| Submarine | S | P/S | | P/S | | | | E |
| **SEARCH & RESCUE** | | | | | | | | |
| Ship | | S | | S | | | | E |
| Air | | | P | | | | | E |
| **MINE COUNTERMEASURES** | | | | | | | | |
| Ship | P | S | | P | | | | E |
| Air | | | P | | | | | E |
| **MINE LAYING** | | | | | | | | |
| Ship | P/S | | | P | | | | E |
| Submarine | | P/S | | | | | | E |
| Air | | P/S | | | | | | E |
| **AMPHIBIOUS WARFARE** | | | | | | | | |
| Ship | | | P | | P | S | E | E |
| Air | | | P | | P | S | E | E |
| **ANTI AIR WARFARE** | | | | | | | | |
| Ship | P/S | P/S | | S | P/S | | | E |
| Air | | | P | | | | | E |
| **SURFACE WARFARE** | | | | | | | | |
| Ship | P/S | P/S | | P | | | | E |
| Submarine | P/S | P/S | | P | | | | E |
| Air | | P/S | P | | | | | E |
| **ANTI SUBMARINE WARFARE** | | | | | | | | |
| Ship | | P/S | | P | | | | E |
| Submarine | | P/S | | P | | | | E |
| Air | S | P | P | | | S | | E |
| **LOGISTICS** | | | | | | | | |
| Surface | P/S | P/S | | | | | | E |
| Submarine | P/S | P/S | | S | | | | E |
| Air | P/S | P/S | | | | | | E |
| **SURVEYING** | | | | | | | | |
| Surface | P/S | P/S | | P | | | | E |
| Submarine | P/S | P/S | | | | | | E |
| Air | P/S | P/S | P/S | P | P/S | P/S | | E |

**LEGEND**

P – Primary System
S – Secondary System
E – System in Evaluation
P/S – Depending Upon Platform Configuration

TABLE I-4.3 DEFENSE MAPPING AGENCY MISSIONS VS. SELECTED COMMON-USE RADIONAVIGATION SYSTEMS

| MISSIONS | SYSTEMS | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | LORAN-C | OMEGA | TACAN | TRANSIT | VOR/DME | RADIOBEACON | MLS/ILS | GPS |
| WORLDWIDE POSITIONING OF SATELLITE (ORBITAL TRACKING) | | | | | | | | |
| Low Altitude | | | | P | | | | E |
| Medium Altitude | | | | P | | | | E |
| High Altitude | | | | | | | | E |
| WORLDWIDE POSITIONING BY SATELLITES | | | | P | | | | E |
| GEODETIC POSITIONING BY SATELLITE (RELATIVE) | | | | P | | | | E |
| GEODETIC POSITIONING (CONVENTIONAL) | S | | | | | | | |
| DEEP OCEAN BATHYMETRIC SURVEY | P | S | | P | | | | E |
| COASTAL HYDROGRAPHIC | S | | | P | | | | E |

**LEGEND**

P — Primary System
S — Secondary System
E — System in Evaluation

B. "S" indicates systems which provide an essential secondary or supplementary service for a primary system in a specified phase of navigation. For these designations, government activities relate to reducing operations and maintenance (O&M) costs of these systems.

C. "E" indicates a system and area of application which is being evaluated as a replacement for an existing primary or secondary system. Such a system may be an existing system which is being evaluated as a candidate for improved service in existing or newly identified phases of operations and applications. LORAN-C is an example of the latter category.

## 4.2 EXISTING SYSTEMS USED IN THE PHASES OF NAVIGATION

The systems listed in Table I-4.1 are used singly or in combination to support functions of the various phases of civil navigation. Tables I-4.2 and I-4.3 compare common use systems to mission applications for military use. The following sections describe the approach employed to define the needs, requirements, and degree to which existing systems satisfy these needs.

### 4.2.1 Oceanic En Route, Domestic En Route, and Terminal Phases of Air Navigation

Federal Aviation Regulations require that aircraft equipped with self-contained navigational systems, except for dual Inertial Navigation Systems (INS), now being used on oceanic air routes, monitor the performance of these systems through use of an externally referenced radio aid to navigation. It is expected that at least three OMEGA lines of position should be available throughout the North Atlantic and Pacific. Although the FAA has approved the use of OMEGA on oceanic routes, at present the International Civil Aviation Organization (ICAO) does not plan to adopt OMEGA as an international standard. ICAO has, however, provided users of OMEGA with an information publication on OMEGA system operation.

Domestic en route and terminal area air navigation requirements are presently being met except in some remote and offshore areas. The basic short distance aid to navigation in the United States is VHF Omnidirectional Range (VOR) alone or collocated with either Distance Measuring Equipment (DME) or Tactical Air Navigation (TACAN) to form a VOR/DME or a VORTAC facility. This system is used for en route and terminal navigation for flights conducted under Instrument Flight Rules (IFR). It is also used by pilots operating on Visual Flight Rules (VFR). The United States and all other member states of the International Civil Aviation Organization have agreed to provide VOR/DME service to international air carriers up to January 1, 1995.

VOR/DME forms the basis of a safe, adequate, and trusted air navigational system, and there is a large investment in ground equipment and avionics by both the government and users. In view of this it is intended to maintain the VOR/DME at its present capability at least through the year 2000.

There is increasing interest and usage of LORAN-C for air navigation, particularly in remote areas and for helicopter offshore operations. LORAN-C has been certified as a supplemental aid to navigation in certain areas of the U.S.

Area navigation (RNAV) offers potential benefits to users of the National Airspace through direct routing to many destinations, thereby reducing operating costs and conserving fuel.

### 4.2.2 Approach and Landing Phase of Air Navigation

Requirements for radio approach and landing aids are met by the Instrument Landing System (ILS). Non-precision approaches are based on VOR (with or without DME), TACAN, non-directional beacons (NDB), and RNAV procedures. The requirement for a common civil/military system is not yet met, although the Air Force relies on ILS as a primary precision approach system. The Microwave Landing System (MLS) now being deployed meets the need for a common user precision system. The MLS can provide lateral and vertical guidance over wide sectors with precise distance information.

### 4.2.3 Ocean Phase of Marine Navigation

Navigation on the high seas is now accomplished by the use of celestial fixes, self-contained navigation systems (e.g., inertial), LORAN-C, and OMEGA. TRANSIT is also available for use by the civil maritime community.

Worldwide coverage by most ground-based systems such as LORAN-C, is not practicable. The OMEGA system, however, with all eight stations operational does provide essentially worldwide coverage.

### 4.2.4 Coastal Phase of Marine Navigation

Requirements for operation within the coastal area are now fully met. In 1974 LORAN-C was designated as the Government-provided primary civil marine radionavigation system for coastal areas of the coterminous 48 states, southern Alaska, and the Great Lakes. LORAN-C was fully implemented in 1980.

The marine radiobeacon system provides primary service in the coastal area and Great Lakes for smaller marine operators, and backup service for all categories of users. Radiodirection finders (RDF) are the only externally referenced radionavigation equipment required in merchant ships by international agreement.

### 4.2.5 Harbor and Harbor Approach Phases of Marine Navigation

Navigation in the harbor and harbor approach areas is accomplished currently through use of fixed and floating visual aids to navigation, radar, and audible warning signals. The growing concern for means to reduce the incidence of accidents and to expedite movement of traffic during periods of restricted visibility and ice cover has resulted in the implementation of Vessel Traffic

Services (VTS) and investigation of the use of radio aids to navigation. Specific quantitative requirements for navigation in the Harbor and Harbor Approach phases, which will vary somewhat from one harbor to another, have not been developed and are significantly more demanding than for ocean and coastal navigation. LORAN-C is being investigated as a means to provide improved all-weather position fixing capability in harbor approach channels and harbors. It is anticipated that the use of LORAN-C will be extended progressively into major harbor approaches. Operations on the connecting waters and in harbors on the Great Lakes are similar to those in the Harbor and Harbor Approach phases, and generally have more stringent navigational requirements than the coastal phase of navigation. There is some commercial interest in differential LORAN-C with at least one system operational to a limited degree.

### 4.2.6 Inland Waterway Phase of Marine Navigation

This phase of navigation is concerned primarily with those vessels which are not ocean-going. Specific quantitative requirements for navigation on rivers and other inland waterways have not yet been developed. Visual and audio aids to navigation, radar, and intership communications are presently used to enable safe navigation in those areas. No change in this practice is expected in the immediate future.

### 4.2.7 Land Navigation Phases

The government does not have a specific responsibility under law to provide radiolocation systems for civil land use. However, under the general provisions for improving the safety and efficiency of transportation, a number of projects have been sponsored to evaluate the feasibility of using existing and proposed radionavigation systems for land applications.

## 4.3 EXISTING SYSTEMS - STATUS AND PLANS

### 4.3.1 LORAN-C

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

#### A. Operating Plan

In 1974, LORAN-C was designated as the U.S. Government provided navigational system for the U.S. coastal areas. Implementation of the program authorized at that time has been completed with the exception of some replacement transmitters now being procured. Studies have shown that further expansion to provide coverage to the Caribbean, Eastern Hawaii and Northern Alaska area are not cost beneficial at this time. An increase in user demand has prompted a re-examination of the elimination of the mid-continent gap. As required by the 1974 decision, methods have been investigated to make LORAN-C suitable for navigation in harbors and harbor approaches. It has been demonstrated that Differential LORAN-C is capable of meeting that requirement and the Coast Guard is working to establish a standard format for the transmission of differential corrections. Figure 1-4.1 outlines the operating plan for the LORAN-C system. The coverage is shown in Part III.

The Great Lakes chain, which reached full operational status in early 1980, for the first time provides a high accuracy navigational capability for the open waters of the Great Lakes.

B. User Community

Initially, the major user of LORAN-C was the military, since civil marine use was limited due to the high cost of LORAN-C receivers and the lack of coverage over much of the U.S. coastal areas. Technological advances have rapidly lowered user receiver costs, and coastal coverage limitations have been eliminated by system improvements and expansion. As a result, there is presently extensive civil marine use of LORAN-C. During the last few years, there has also been a tremendous surge of users in the civil aviation community. The projected number of civil and military users is shown in Table I.4.4.

C. Acceptance and Utilization

A high degree of user interest in LORAN-C has been shown by marine and aviation communities and acceptance is rapidly increasing. Because of system reliability as well as accuracy, coverage, and cost factors, continuous growth in user population is anticipated.

There are a number of LORAN-C chains in operation overseas to serve U.S. military requirements for navigational service. Some of the stations are operated by the U.S. Coast Guard, while others are operated by the host country under bilateral agreement. The service is available to all users, military and civilian, of all nations. Other than the United States, however, Canada is the only country that is committed to the operation of LORAN-C service for general use. One Canadian station has been built in British Columbia, and a second built on Vancouver Island. The former acts as a master to a combined U.S./Canada chain serving the U.S. Northwest, southern Alaska, and west coast of Canada. The second station closes coverage gaps in the areas of Dixon Entrance and Puget Sound. A third Canadian station has been built at Fox Harbor, Labrador and operates in the Labrador Sea Chain. In the U.S.S.R. there are two LORAN-C chains operating; one in the southwestern part of Russia, the other in eastern Siberia. Their coverage is mostly over land. Saudi Arabia has installed two chains with 6 stations to provide coverage over most of the country and parts of the Red Sea, Persian Gulf and the Gulf of Aden. Norway is also considering extending existing coverage by adding low powered stations in the North Sea. France is installing two stations which will operate in the Rho-Rho or ranging mode. Several other nations are known to be considering LORAN-C for their own requirements. The DOD currently uses LORAN-C; however, this use will phase down as GPS becomes operational.

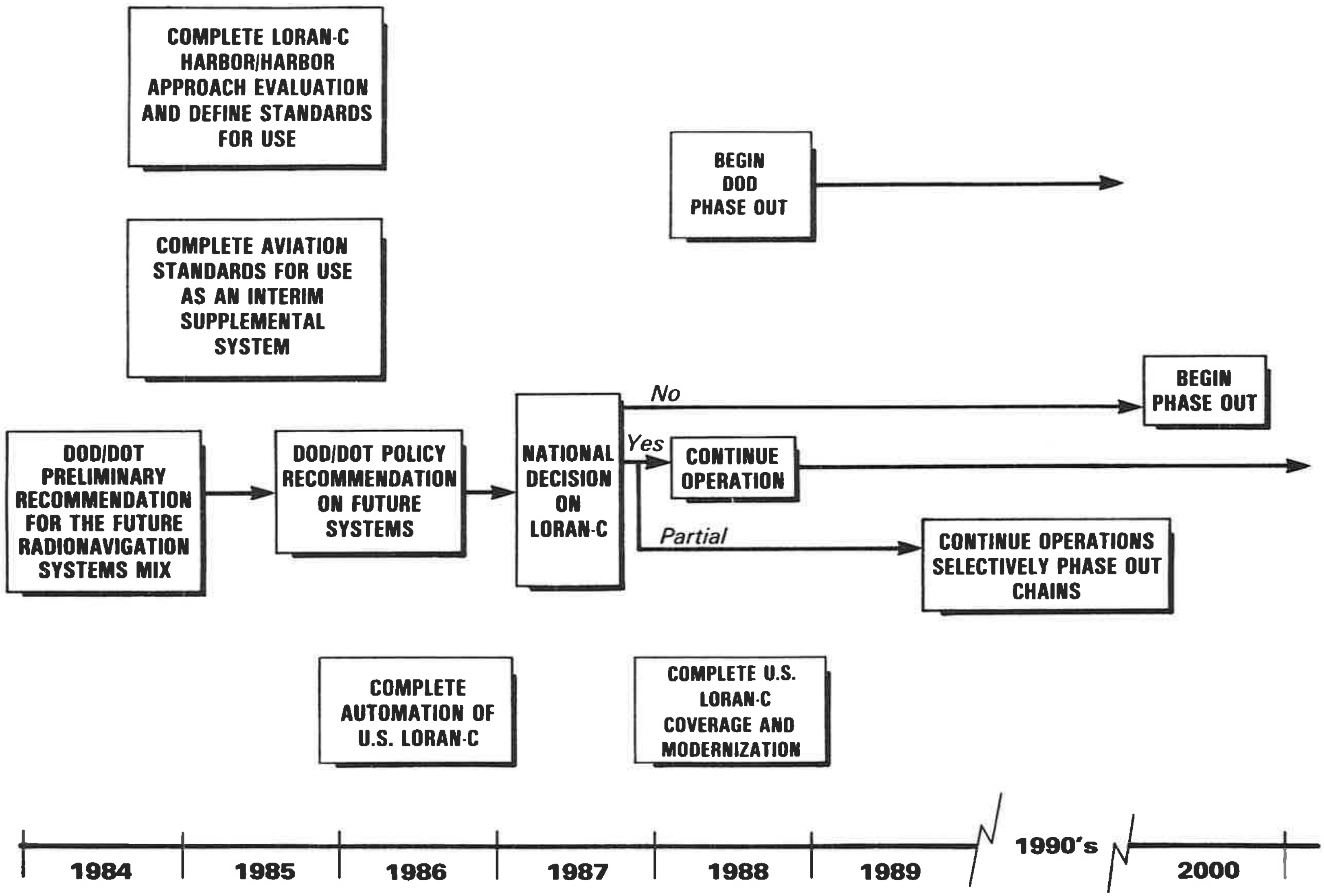


FIGURE I-4.1 OPERATING PLAN FOR LORAN-C SYSTEM

## TABLE I-4.4 LORAN-C USER SCHEDULE

| FACILITIES/USERS | FISCAL YEARS | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 84 | 85 | 86 | 87 | 88 | 89 | 90 | 91 | 92 | 93 | 94 | 95 | 96 | 97 | 98 |
| U.S./CANADIAN FACILITIES | 26 | 26 | 26* | 26 | 26 | 26 | 26 | 26 | 26 | 26 | 26 | 26 | 26 | 26 | 26 |
| U.S. OVERSEAS FACILITIES | 18 | 18 | 18 | 18 | 18 | 18 | 18 | 18 | *** | | | | | | |
| CIVIL USERS (MARITIME) U.S. AND FOREIGN | 66,500 | 71,500 | 76,500 | ** | | | | | | | | | | | |
| CIVIL USERS (AVIATION) | 6,000 | 15,000 | 20,000 | ** | | | | | | | | | | | |
| DOD USERS | 523 | 548 | 531 | 530 | 528*** | 501 | 431 | 407 | 378 | 337 | 160 | 68 | 49 | 47 | 46 |

* May increase to provide contiguous U.S. coverage.

** The 1987 national decision on the future radionavigation system mix may affect the number of facilities/users. Therefore, no estimates of facilities are projected for later years.

*** Phase-out based on 1984 GPS installation schedule.

Since the LORAN-C stations must be land-based, and they have a useful range of about 1,000 nm, it is not feasible to provide worldwide coverage utilizing this system. The coverage area is fixed by the area where adequate geometry and signal-to-noise ratio are available.

D. Outlook

The LORAN-C system for the coastal areas is expected to continue in operation at least until the year 2000. This estimate is based on the adoption and use of this system by a very large user population, and the absence of any near-term prospect for its replacement. It is anticipated that other than eliminating the mid-continent gap for civil aviation, there will be little future change in the LORAN-C coverage provided for the continental U.S. Some minor changes may be made, however, to improve the system's performance in selected areas.

The FAA has established that LORAN-C is an interim supplemental system in the National Airspace System. In order to fully implement LORAN-C the FAA and USCG are preparing a National Aviation Standard for LORAN-C. The FAA has prepared an airworthiness Advisory Circular (AC 20-120) and, with RTCA Special Committee #137, is preparing a Minimum Operation Performance Standard for LORAN-C. During 1986, procedures are expected to be available to approve non-precision approaches using LORAN-C.

The overseas chains operated in support of DOD will be closed or transferred to the host nation when the DOD requirements are phased out. All current DOD service plans call for phaseout of LORAN-C requirements in favor of GPS. Assuming the 18-satellite version of GPS is operational in 1988, the Navy has a continuing requirement for existing overseas LORAN-C coverage through 1992 at current performance levels.

### 4.3.2 OMEGA

The OMEGA system was developed and implemented by the Department of the Navy, with the assistance of the Coast Guard and with the participation of several partner nations. The Coast Guard has the U.S. responsibilities for the operation of the system. In addition, other countries are participating in a signal monitoring effort to assist in verifying system accuracy. Currently there are some 40 OMEGA monitor sites in operation. The purpose of OMEGA is to provide an all-weather, worldwide position determination aid to navigation for civil and military air and marine users.

A. Operating Plan

The permanent eight station configuration has been operational since August of 1982. The eight stations are located in Norway, Liberia, North Dakota, Hawaii, La Reunion Island, Argentina, Australia, and Japan. All stations are in normal operation, i.e., they are on air, synchronized, and transmitting at a nominal radiated power of 10 kw at 10.2 kHz. Figure I-4.2 outlines the operating plan for the OMEGA system.

The Coast Guard operates the two stations located in the U.S. The remaining stations are operated by the partner nations with varying degrees of technical and logistic support from the U.S. Coast Guard.

### B. User Community

In addition to the DOD air and marine users, many commercial and private ships and aircraft are using the OMEGA system. A number of air carriers and private aircraft operators have received approval to use OMEGA as an update for their self-contained systems or as a sole means of navigation on oceanic routes. The projected numbers of civil and military users are shown in Table I-4.5.

### C. Acceptance and Utilization

Because of OMEGA's extensive coverage, it is expected that civil use will involve vessels crossing the high seas and aircraft operating in oceanic airspace. It is also used as a supplement for high altitude domestic enroute airspace. Foreign ships and aircraft use this international system.

Current information indicates that the present permanent OMEGA system covers nearly 100 percent of the earth's surface. The coverage and accuracy of the system are being verified by a validation plan being conducted on a regional basis. This program includes collecting data from: fixed monitor receiver sites, shipboard monitor receivers and aircraft receivers. This data is used to correct and update propagation models and tables, and to confirm propagation parameters affecting coverage and availability. As each geographic area is validated, the OMEGA system will be declared operational in that area and users will be advised as to operational capabilities. To date the validations (North Atlantic, North Pacific, and South Atlantic) have shown that the OMEGA system is meeting the advertised performance. Use of OMEGA has been certified by the Federal Aviation Administration (FAA) for use on the North Atlantic and as a supplemental means of navigation for high-altitude domestic en route airspace.

The OMEGA system is limited in accuracy due to propagation effects, and restrictions on use of the signals when close to a station. For these reasons, OMEGA cannot meet the requirements for maritime navigation in U.S. coastal areas or for aircraft flying in U.S. terminal airspace.

### D. Outlook

No expansion in the number of stations is envisioned. However, an expanded transmission format, involving the addition of a fourth navigation frequency which helps to resolve lane ambiguity, and a unique frequency at each station to provide positive station identification, has been implemented.

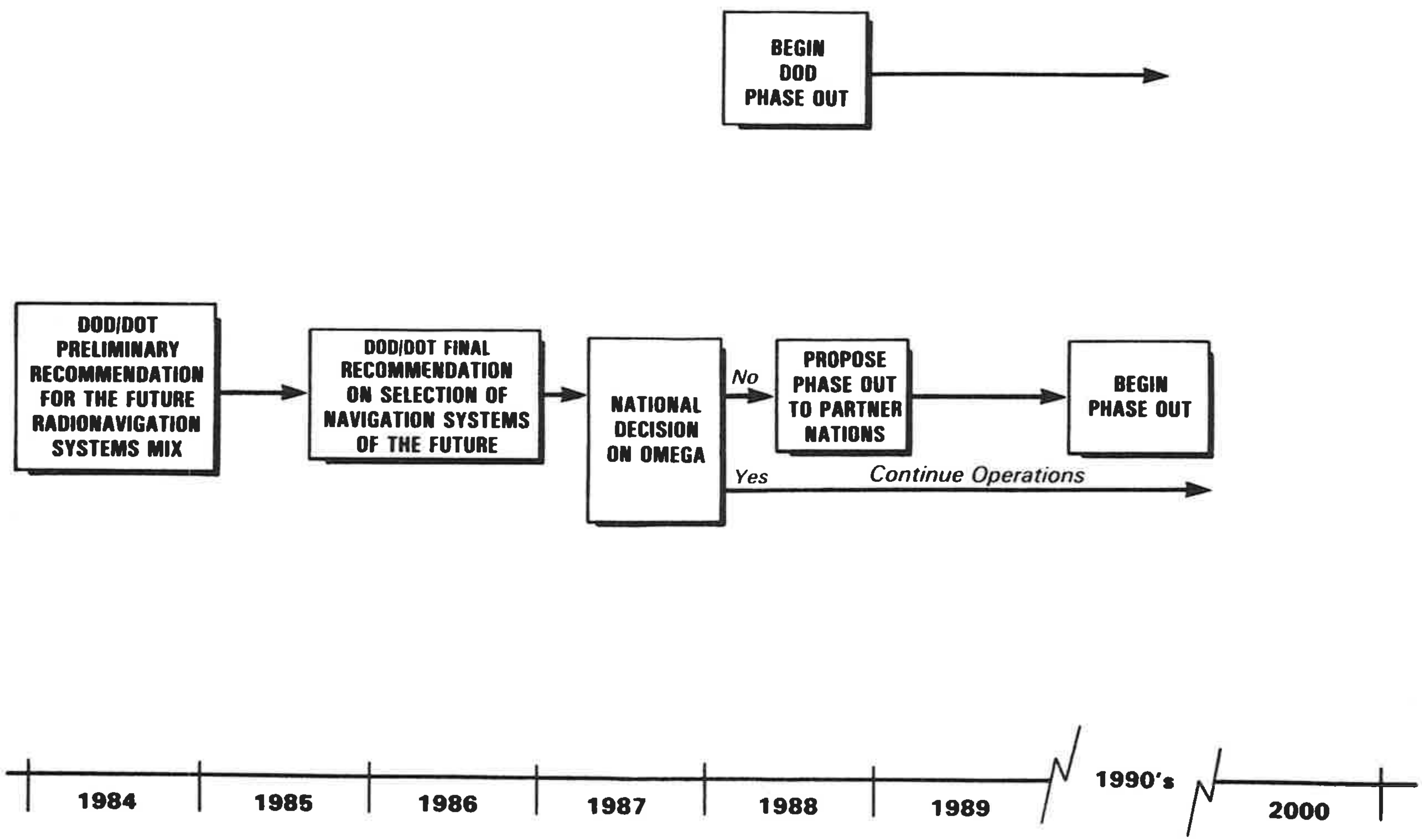


FIGURE I-4.2 OPERATING PLAN FOR OMEGA SYSTEM

TABLE I-4.5 OMEGA USER SCHEDULE

| FACILITIES/USERS | FISCAL YEARS | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 84 | 85 | 86 | 87 | 88 | 89 | 90 | 91 | 92 | 93 | 94 | 95 | 96 | 97 | 98 |
| U.S. FACILITIES | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| PARTNER NATION FACILITIES | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 |
| CIVIL USERS (AVIATION) U.S. AND FOREIGN | 9,200 | 9,500 | 9,800 | * | | | | | | | | | | | |
| CIVIL USERS (MARITIME) U.S. AND FOREIGN | 6,500 | 7,000 | 7,500 | * | | | | | | | | | | | |
| DOD USERS | 1,807 | 1,886 | 1,953 | 1,945 | 1,955** | 1,899 | 1,751 | 1,657 | 1,508 | 963 | 737 | 729 | 717 | 705 | 693 |

* The 1987 national decision on the future radionavigation system mix may affect the number of users of this system. Therefore, no estimates of the number of users are projected for later years.
** Phase-out based on 1984 GPS installation schedules

Differential OMEGA has been developed primarily by the French. The equipment meets the standards established by the International Association of Lighthouse Authorities (IALA) and extensive coverage is available along the coast of Europe and in parts of the Mediterranean. The Coast Guard operates one Differential OMEGA station at Punta Tuna, Puerto Rico. Expansion of this system is not planned by the Coast Guard and any expansion that took place would be only to meet a specialized need in an area not served by LORAN-C.

Because of the international character of the system and international user acceptance, operational decisions regarding system life must be coordinated with the partner nations. The military use of OMEGA will be phased out by the Army and by the Air Force by 1992. The Navy intends to reevaluate the use of OMEGA as a backup to GPS for selected platforms when GPS becomes fully operational.

### 4.3.3 VOR, VOR/DME, VORTAC

VHF Omnidirectional Range (VOR) was developed as a replacement for the Low-Frequency Radio Range to provide a bearing from an aircraft to the VOR transmitter. A collocated Distance Measuring Equipment (DME) provides the distance from the aircraft to the DME transmitter. At most sites the DME function is provided by the TACAN system which also provides azimuth guidance to military users. Such combined facilities are called VORTAC stations.

#### A. Operating Plan

The FAA operates 961 VOR/DME and VORTAC stations including 150 VOR stations. A small increase in the number of stations is planned during the next 5 to 10 years, to meet the requirements in specified areas. The DOD also operates a few stations in the U.S. and overseas. These are available to all users. The operating plan for VOR/DME/VORTAC is shown in Figure I-4.3.

Because much of the ground-based equipment was between 15 and 30 years old and reaching the end of its useful life, the FAA initiated cost studies which showed that replacing obsolete vacuum-tube equipment with solid-state equipment would pay for itself in savings on operating and maintenance costs. Based on this, the FAA began a replacement program in 1982 with completion projected for 1985. DOD also initiated action to improve reliability and extend the life of its VORTAC equipment until sufficient aircraft are GPS equipped.

#### B. User Community

Approximately 80 percent of the general aviation aircraft are equipped with at least one VOR receiver and over 50 percent of the aircraft have two or more VOR receivers . All air carrier aircraft depend on it for bearing information. DME is used to provide distance information for all U.S. air carrier aircraft and for a large number of general aviation and military aircraft operating in U.S. airspace. The projected civil and miltary user population is shown in Table I-4.6.

FIGURE I-4.3 OPERATING PLAN FOR VOR, VOR/DME

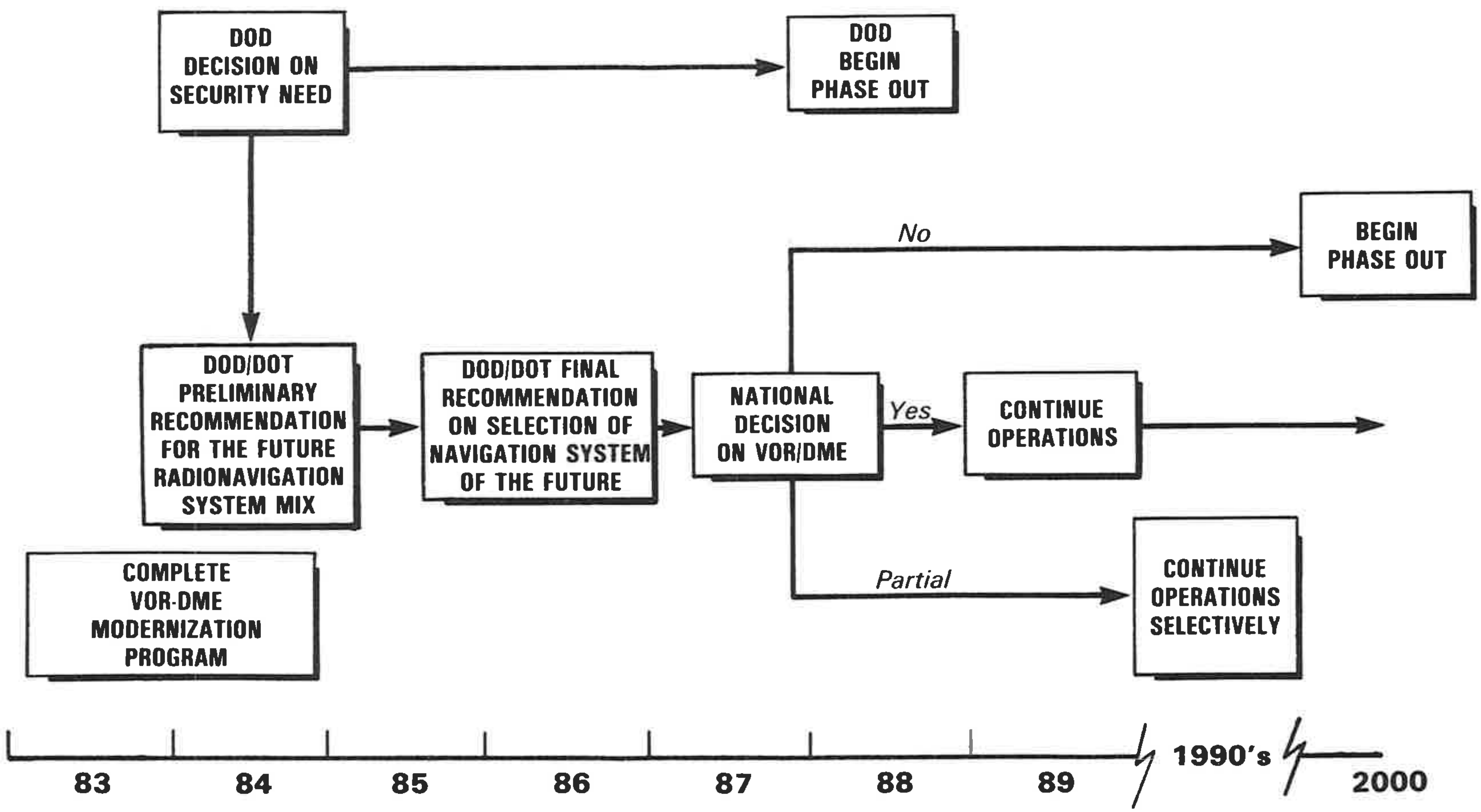

TABLE I-4.6 VOR, VOR/DME USER SCHEDULE

| FACILITIES/USERS | FISCAL YEARS | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 84 | 85 | 86 | 87 | 88 | 89 | 90 | 91 | 92 | 93 | 94 | 95 | 96 | 97 | 98 |
| FAA FACILITIES | 940 | 938 | 940 | 941 | 945 | 950 | 942 | 942 | 942 | 942 | 942 | 935 | 935 | 935 | 935 |
| DOD FACILITIES | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 35 | 8 | 8 | 8 |
| CIVIL USERS (VOR) | 192,000 | 199,000 | 206,000 | 212,000 | 219,000 | 226,000 | 233,000 | 239,000 | 246,000 | 253,000 | 261,000 | 269,000 | 277,000 | 285,000 | 294,000 |
| CIVIL USERS (DME) | 88,000 | 91,000 | 95,000 | 98,000 | 102,000 | 106,000 | 109,000 | 113,000 | 118,000 | 122,000 | 127,000 | 131,000 | 136,000 | 141,000 | 146,000 |
| DOD USERS** | 13,775 | 13,815 | 13,890 | 13,805* | 13,805 | 12,025 | 9,030 | 6,025 | 3,480 | 1720 | 696 | 661 | 621 | 612 | 610 |

* Begin DOD Phase-out.
** Includes Integrated VOR/ILS users.

## C. Acceptance and Utilization

VOR is part of a National Airspace System and is also the internationally accepted standard short distance radionavigation aid for overland and continental approach use in air carrier and general aviation IFR operations. It is easy to use and is generally liked by pilots. Because it forms the basis for defining the airways, its use is an integral part of the air traffic control procedures.

VOR/DME is protected until 1995 by ICAO agreement and the ground equipment is expected to be available until past the year 2000.

## D. Outlook

Only a small increase in the number of transmitting stations is projected over the next decade in the U.S. These will meet requirements for new airports and new airways, as well as special Alaskan requirements.

A substantial increase in the general aviation user category is anticipated with the continuing growth of the number of aircraft being operated in U.S. airspace and the accompanying decreasing equipment cost. Since line-of-sight signal propagation seriously limits coverage at ground level, little or no use of the system by non-aviation vehicles is expected.

VOR/DME supports the current airways structure which is the basis for air traffic control procedures and operations. At present, no system has been identified by the FAA as a replacement. However, OMEGA and LORAN-C have been certified as supplements to VOR/DME in specific areas. DOD will pursue GPS certification for military aircraft in lieu of VOR/DME/TACAN.

Although the VOR/DME system is protected by international agreement until 1995, it is expected to remain in service beyond the year 2000. Also, if an alternate system such as LORAN-C or GPS should prove acceptable to the international aviation community, full implementation would not start until the late 1980's or early 1990's. It would require a substantial period beyond that before phaseout of VOR/DME could be accomplished. At present, VOR/DME, in addition to its flexibility when combined with RNAV, is a highly cost-effective system.

The DOD VOR/DME operational concept is to maintain present system coverage until a suitable replacement is available. Present plans for expansion of the VOR/DME system are limited to site modernization or facility relocation. GPS is the planned replacement for DOD VOR/DME and VORTAC facilities. This transition will start in 1988. Planned phaseout of VOR/DME will be completed by the DOD in 1997. In the case of a military VORTAC site due for phaseout that has developed an appreciable civilian-use community, transfer of operational responsibility to the DOT will be discussed between DOD and DOT.

### 4.3.4 TACAN

The Tactical Aid to Navigation (TACAN) is a UHF radionavigation system which provides a pilot with relative bearing and distance to a beacon on the ground, ship, or to specially equipped aircraft. TACAN is the primary tactical air navigation system for the military services ashore and afloat. TACAN is often collocated with the civil VOR stations (VORTAC facilities) to permit military aircraft to operate in civil airspace.

#### A. Operating Plan

The DOD presently operates 680 and the FAA operates 718 TACAN beacons for DOD. Present TACAN coverage ashore will be maintained until phased out in favor of GPS. However, GPS in its present state cannot replace the TACAN function afloat (moving platforms).

Civil DME and the distance-measuring functions of TACAN will continue to be the same. The operating plan for TACAN is shown in Figure I-4.4.

#### B. User Community

There are presently approximately 14,000 aircraft which are equipped to determine bearing and distance to TACAN beacons. These consist primarily of Navy, Air Force, and to a lesser extent, Army aircraft. The projected miltary user populations are shown in Table I-4.7. Additionally, allied and third world military aircraft use TACAN extensively. NATO has standardized on TACAN until 1995.

#### C. Acceptance and Utilization

TACAN is used by DOD and NATO aircraft operating under Instrument Flight Rules (IFR) ashore and IFR and Visual Flight Rules (VFR) for tactical and enroute navigation afloat. TACAN provides good accuracy in range and azimuth and is easy to use.

Because of propagation characteristics, TACAN is limited to line of sight which approximates 180 miles at higher altitudes. To receive range information an aircraft must radiate, thereby increasing the probability of detection. As with VOR/DME, special consideration must be given to location of ground-based TACAN facilities, especially in areas where mountainous terrain is involved due to its line-of-sight coverage.

#### D. Outlook

Phase out of Army and Air Force TACAN systems will begin in 1988 and be completed by 1997. The Navy has plans for TACAN through the year 2000. It should be noted that ground stations will not be phased out until nearly all aircraft are GPS equipped. Several options will be available to replace TACAN on moving platforms. These options include GPS with a data link, GPS using the Joint Tactical Information Distribution System (JTIDS) as the data link, and maintaining existing TACAN beacons. The Navy will have a continuing requirement to perform the TACAN type function, both ashore and afloat. The decision on replacement of the shipboard TACAN function will be made at the time of GPS phase in.

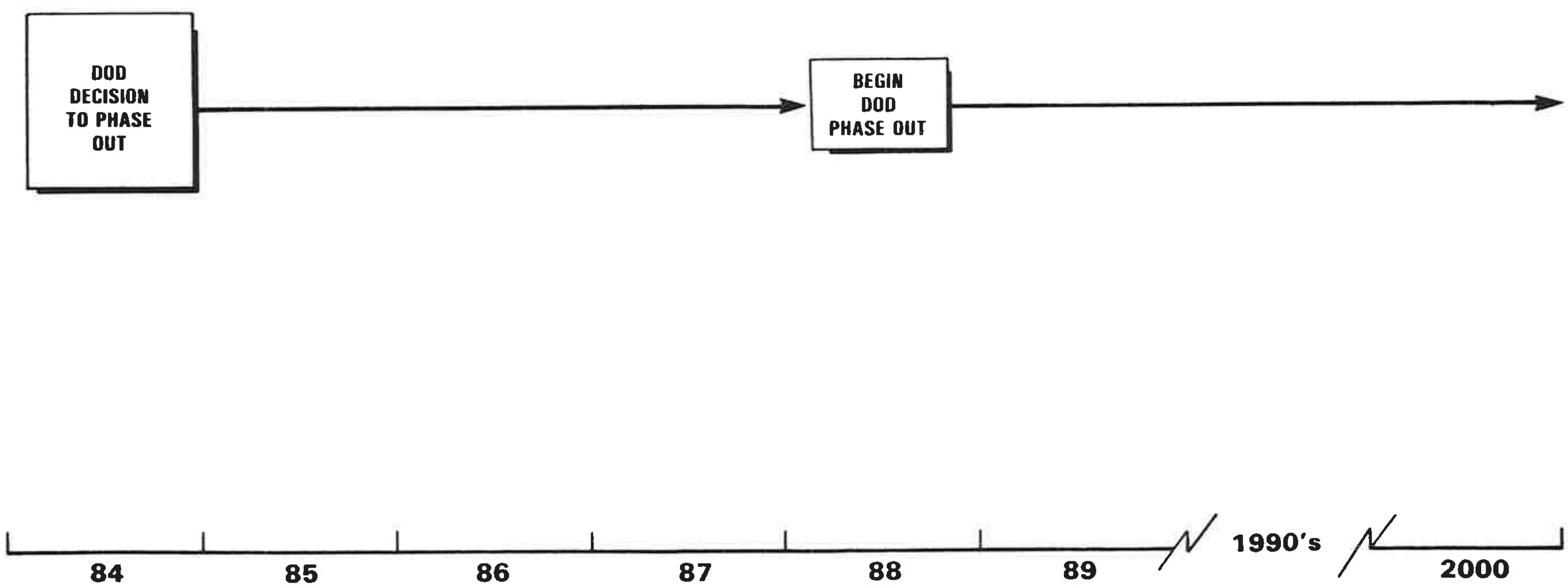


FIGURE I-4.4 OPERATING PLAN FOR TACAN

## TABLE I-4.7 TACAN USER SCHEDULE

| FACILITIES/USERS | FISCAL YEARS | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 84 | 85 | 86 | 87 | 88 | 89 | 90 | 91 | 92 | 93 | 94 | 95 | 96 | 97 | 98 |
| FAA FACILITIES OPERATED FOR DOD | 718 | 712 | 706 | 700 | 690 | 683 | 675 | 668 | 660 | 653 | 490 | 327 | 164 | 0 | 0 |
| DOD FACILITIES | 170 | 170 | 171 | 172 | 173 | 173 | 173 | 173 | 173 | 173 | 173 | 173 | 173 | 173 | 11 |
| CIVIL USERS | 70 | 60 | 40 | 20 * | | | | | | | | | | | |
| DOD USERS | 15,236 | 15,361 | 15,412 | 15,594 | 15,635** | 15,092 | 14,385 | 13,017 | 10,937 | 8,743 | 6,577 | 4,672 | 3,399 | 2,490 | 2,175 |

* The 1987 national decision on the future radionavigation system mix may affect the number of users of this system. Therefore, no estimates of the number of users are projected for later years.

** Phase-out based on 1984 GPS installation schedules

### 4.3.5 Instrument Landing System

The Instrument Landing System (ILS) provides aircraft with precision vertical and horizontal navigation (guidance) information during approach and landing. Associated marker beacons or DME equipment identify the final approach fix, the point where the final descent to the runway is initiated.

#### A. Operating Plan

In 1984 there were 718 ILS sites. Eventually, about 750 ILS sites will exist. In addition, there are approximately 165 ILS facilities operated by the DOD in the U.S. The operating plan is shown in Figure I-4.5.

Many ILS facilities are of obsolete vacuum-tube design and are being replaced with solid-state equipment. All present ILS facilities are expected to use solid state technology by 1985.

#### B. User Community

Federal regulations require U.S. air carrier aircraft to be equipped with ILS avionics. It is also extensively used by general aviation aircraft. Since ILS is the ICAO standard landing system, it is extensively used by air carrier and general aviation aircraft of other countries. The projected civil and military user population is shown in Table I-4.8.

#### C. Acceptance and Utilization

ILS is the standard civil landing system in the U.S. and the international standard for aircraft operating under IFR conditions. Since its introduction in the 1940's, it has been installed in steadily growing numbers throughout the world. Part of its attractiveness to aircraft owners lies in the economy of avionics costs. Since the ILS localizers and VOR stations operate in the same frequency band, common receivers are used.

Military services use ILS at fixed bases in the U.S. and overseas. Special systems are used to meet unique military requirements, including ship-board operations. Precision Approach Radar (PAR) is the NATO interoperable landing aid.

#### D. User Base Expansion

Based on a 1984 survey the number of civil aircraft equipped with ILS is estimated to be 157,000. This number is expected to increase at a rate of about 3 percent per year until MLS is fully deployed and then decline to zero at the end of the transition period.

#### E. Expected System Life

ILS is currently protected by international (ICAO) agreement through at least 1995. Protection past 1995 is a possibility. ILS is being replaced by MLS.

#### F. System Limitations

ILS limitations manifest themselves in three major areas:

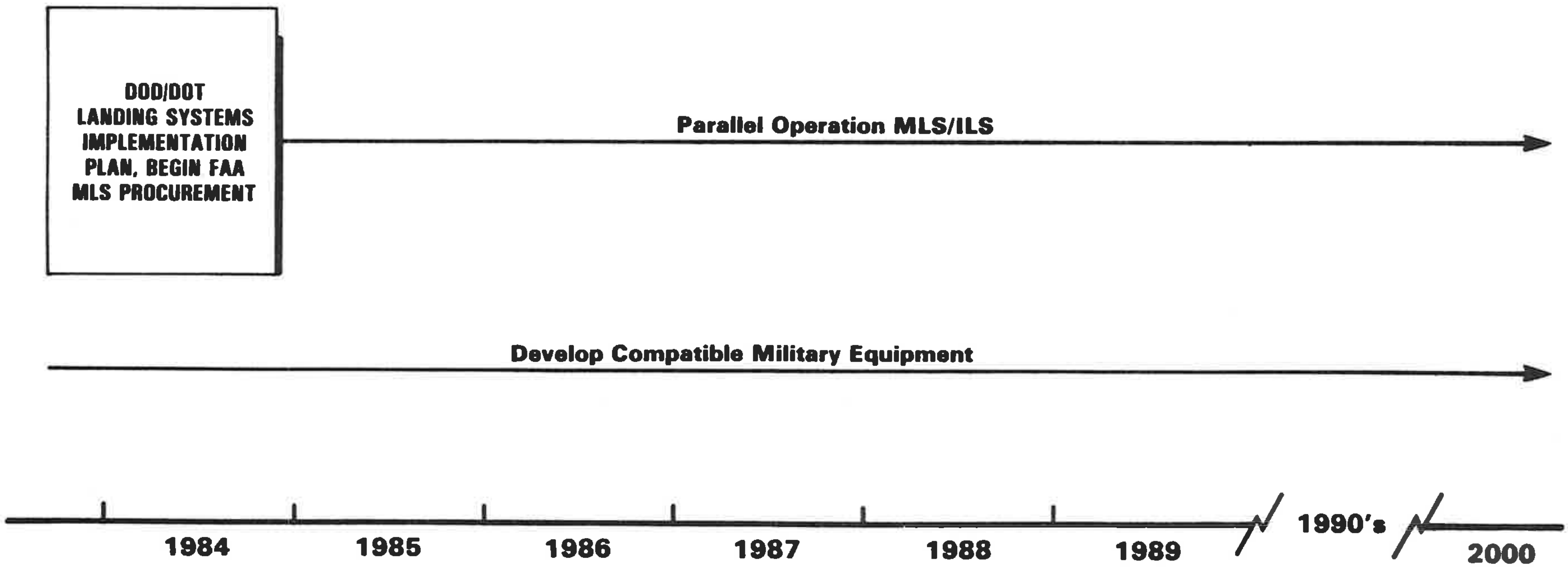


FIGURE I-4.5 OPERATING PLAN FOR MICROWAVE/INSTRUMENT LANDING SYSTEM (MLS/ILS)

TABLE I-4.8 INSTRUMENT LANDING SYSTEM (ILS) USER SCHEDULE

| FACILITIES/USERS | FISCAL YEARS | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 84 | 85 | 86 | 87 | 88 | 89 | 90 | 91 | 92 | 93 | 94 | 95 | 96 | 97 | 98 |
| FAA FACILITIES | 718 | 734 | 749 | 750 | 750 | 750 | 750 | 750 | 750 | 750 | 750 | 750 | 750 | 750 | 750 |
| DOD FACILITIES | 195 | 195 | 195 | 195 | 195 | 195 | 195 | 195 | 195 | 195 | 195 | 90 | 90 | 90 | 90 |
| CIVIL USERS | 157,000 | 163,000 | 169,000 | 175,000 | 182,000 | 188,000 | 195,000 | 195,000 | 185,000 | 174,000 | 163,000 | 152,000 | 141,000 | 130,000 | 119,000 |
| DOD USERS | 11,045 | 11,045 | 11,045 | 11,049 | 11,019 | 10,749 | 10,465 | 10,285 | 10,184 | 10,122 | 10,033 | 9,998 | 9,958 | 9,949 | 9,947 |

(1) Performance of individual systems can be affected by terrain, man-made obstacles; e.g., buildings and surface objects such as taxiing aircraft and snow banks. These items may impose permanent use constraints on individual systems or limit their use at certain times.

(2) The straight-line approach path inherent in ILS constrains airport operations to a single approach ground track for each runway. In contrast, MLS, as described in paragraph 4.4.1, will allow multiple ground track paths for approaches to the active runway as well as provide a steeper glide slope capability for STOL aircraft.

(3) Even though the new 50 kHz frequency spacing will eventually double the ILS channel availability, frequency saturation limits the number of systems that can be installed. Frequency saturation occurs when ILS facilities in close proximity, with inadequate frequency separation, produce mutual interference.

### 4.3.6 TRANSIT

The Navy Navigation Satellite System (NNSS), also referred to as TRANSIT, is a satellite-based positioning system which provides submarines, surface ships, and a few special aircraft with an accurate two-dimensional positioning capability. The TRANSIT system consists of a minimum of four low-altitude satellites in near polar orbits, ground-based monitor stations to track the satellites, and injection facilities to update satellite orbital parameters. Developed mainly to support the Navy Fleet Ballistic Missile Submarines, TRANSIT is now installed on many foreign and commercial vessels in addition to many military surface vessels.

#### A. Operating Plan

The DOD plans to continue as the operator of TRANSIT until 1994. Specifically, ground-based monitor and injection facilities and replenishment satellites will be funded and operated/supported by the Navy. Phase out by military TRANSIT users in favor of GPS is planned to begin in 1988 and end in 1994.

There are currently four operational OSCAR satellites (11, 13, 19 and 20) and one NOVA satellite in operation. The NOVA satellite has much greater capability than the OSCAR satellite in that it:

a. Has a 3 db gain in signal strength over the OSCAR Satellite;

b. Maintains a more precise orbit;

c. Provides almost zero precession;

d. Provides more precise time through a computer controlled clock system; and

e. Is capable of operating 10 days without a new data upload.

OSCAR and NOVA Satellites will appear identical to users. NOVA 2 will be reworked and maintained in storage for launch at a later date. NOVA 3 is currrently being modified to improve reliability concerns detected with NOVA 1.

Production of four kits to allow launch of two OSCAR satellites (SOOS) with one booster is in progress. This concept will allow storing OSCAR satellites in orbit after termination of launch capability scheduled for December 1989. These satellites are equipped with both a maintenance and operational mode so as to minimize on-orbit self jamming and coplanar interference conditions.

Current intentions are to maintain a mixed constellation of OSCAR and NOVA satellites to meet all military requirements. The operating plan is shown in Figure 1-4.6.

B. User Community

There are currently about 400 military TRANSIT users. Foreign and domestic commercial vessel use of the TRANSIT system has far outpaced the DOD use. It is estimated that 49,000 sets were in commercial use at the end of 1983, increasing to 62,000 by the end of 1984. Approximately 90 percent of all commercial TRANSIT receiver sales are for the single channel receivers. Determination of precise position (surveying) has become an important use of TRANSIT. The projected military user population is shown in Table I-4.9.

C. Acceptance and Utilization

TRANSIT provides periodic, worldwide, position-fixing information for Navy ships and submarines and commercial ships, as well as land users. Its acceptance is indicated by the large increase in commercial sales in recent years. The increased commercial demand for user equipment, and a continuing increase in the number of equipment manufacturers has reduced the user equipment costs.

From a military view point, TRANSIT provides precise positioning for fixed and low dynamic vehicles (ships, submarines, surveying). In a high dynamic, tactical environment (aircraft, missiles), TRANSIT has little use since it is a Doppler system and small errors in user estimates of platform speed can cause large errors in user position. (One knot of unknown speed can cause a position error of 0.2nm).

D. Outlook

The Scout vehicle, scheduled for phase out by NASA in 1987, is used to launch both OSCAR and NOVA satellites. These vehicles are no longer in production and only a small number remain for launching satellites. With the exception of storing OSCAR satellites as on-orbit spares through the Stack OSCAR on Scout (SOOS) program there are no plans for expansion of the TRANSIT system.

### 4.3.7 Aeronautical and Maritime Radiobeacons

In the contiguous 48 states, Aeronautical Non-directional Beacons (NDB) are used for transition from en route to precision terminal approach facilities and as non-precision approach aids at many airports. In addition, many of the

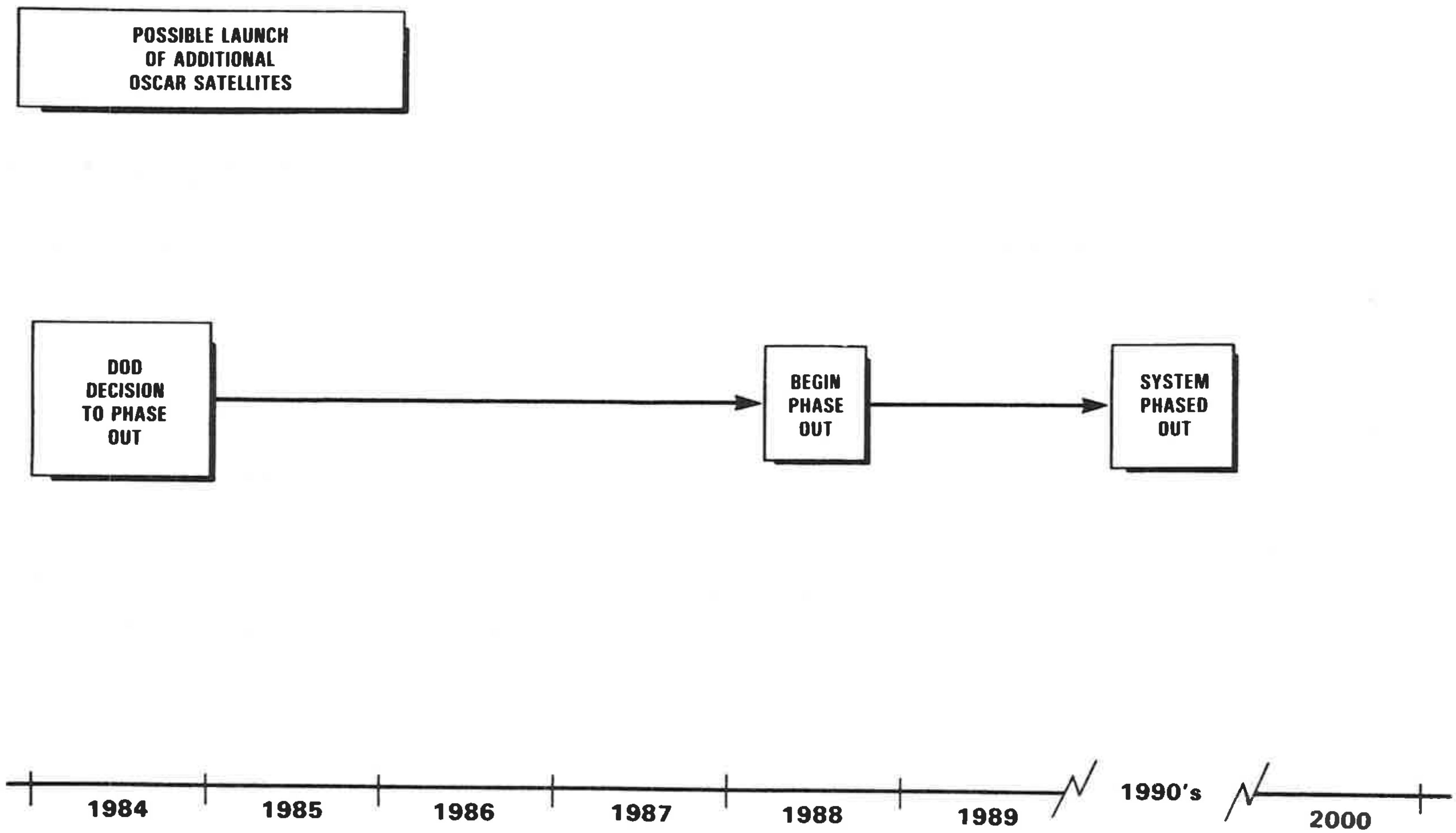


FIGURE I-4.6 OPERATING PLAN FOR TRANSIT SYSTEM

TABLE I-4.9 TRANSIT SYSTEM USER SCHEDULE

| FACILITIES/USERS | FISCAL YEARS | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 84 | 85 | 86 | 87 | 88 | 89 | 90 | 91 | 92 | 93 | 94 | 95 | 96 | 97 | 98 |
| CIVIL USERS (MARITIME)* | 42,000 | 42,000 | 42,000 | * * | | | | | | | | | | | |
| DOD TRACKING FACILITIES | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 0 | 0 | 0 | 0 |
| DOD USERS | 612 | 632 | 643 | 653 | 648* * * | 511 | 251 | 114 | 74 | 61 | 58 | 0 | 0 | 0 | 0 |

* A substantial number of these users are foreign
* * The decision to phase-out this system will affect the number of users, therefore, no estimates of the number of users are projected for later years.
* * * DOD phase-out based on 1984 GPS installation schedule

non-directional beacons are used to provide weather information to pilots. In Alaska, NDB's are also used as en route facilities.

Marine radiobeacons provide a backup to more sophisticated radionavigation systems and are the primary low-cost, medium accuracy system for vessels equipped with only minimal radionavigation equipment.

### A. Operating Plan

The FAA operates over 600 non-directional beacons. In addition, there are about 200 military aeronautical beacons and 1200 non-federally operated aeronautical beacons. During the next 10 years, FAA expenditures for beacons are planned to be limited to the replacement of deteriorated components, modernization of selected facilities, and an occasional establishment or relocation of an NDB used for ILS transition.

There are approximately 200 marine radiobeacons operated by the Coast Guard. Current plans are to augment and reconfigure the system to provide better service and response to the increasing demand. This effort will include installation of some new stations, relocation of others, changes in the transmitting procedures for selected maritime beacons, and changes in frequencies. The frequency changes will result in more efficient use of the radio spectrum and will provide for future expansion if needed.

The operating plan is shown in Figure I-4.7.

### B. User Community

Aeronautical Non-Directional Beacons (NDB): All air carrier, most military, and many general aviation aircraft carry Automatic Direction Finders (ADF).

Marine Radiobeacons: Beacons are utilized by all classes of users within the civil maritime community. They act as a backup for those users having more sophisticated radionavigational capability, and as a primary safety of operation service to the small recreational craft operating in open water. The projected civil and military population is shown in Table I-4.10.

### C. Acceptance and Utilization

Aircraft use radiobeacons as "compass locators" to aid in finding the initial approach point of an instrument landing system as well as for non-precision approaches at low traffic airports without convenient VOR approaches.

The large number of general aviation aircraft and pleasure boats which are equipped with radio direction finders attest to the wide acceptance of radiobeacons by the user community. The primary reason for this acceptance is that adequate accuracy can be achieved with low-cost user equipment.

An increasing number of recreational boats will use marine radiobeacons because of the low equipment cost. This use will continue, particularly where more costly systems are not justified.

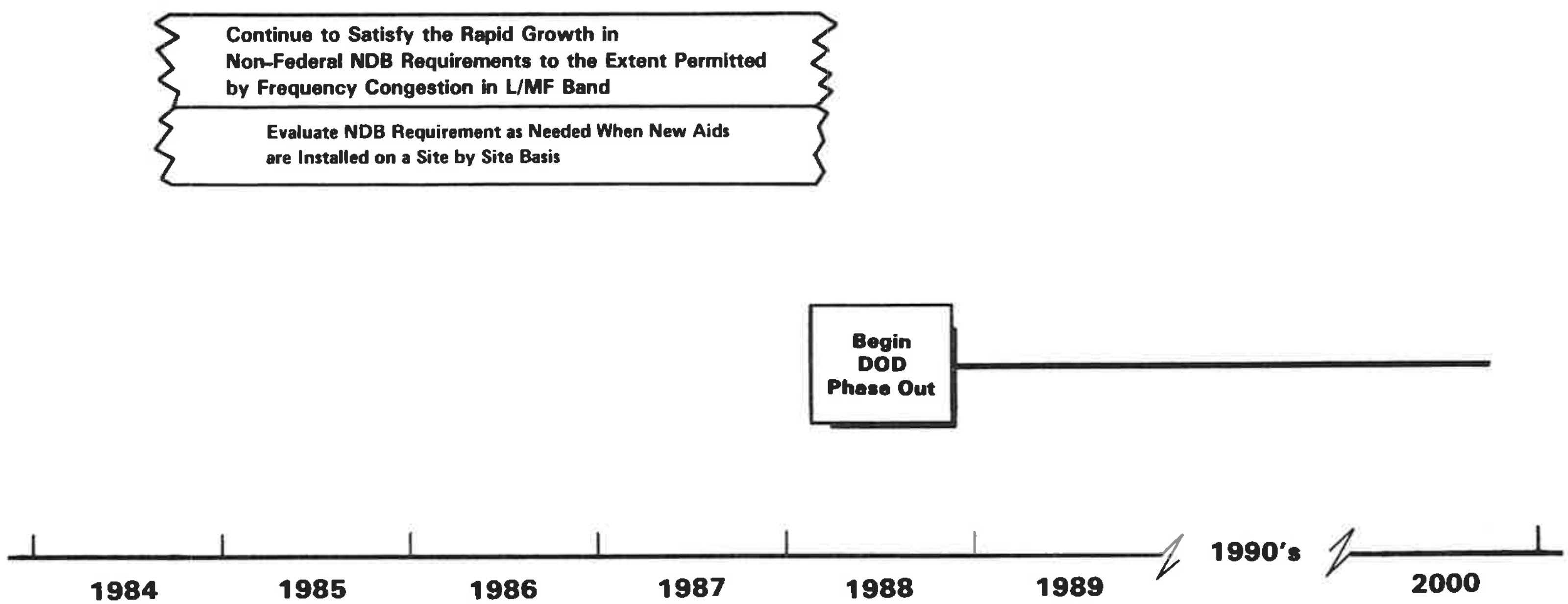


FIGURE I-4.7 OPERATING PLAN FOR RADIOBEACONS (AERONAUTICAL AND MARITIME)

TABLE I-4.10 RADIOBEACON USER SCHEDULE

| FACILITIES/USERS | FISCAL YEARS | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 84 | 85 | 86 | 87 | 88 | 89 | 90 | 91 | 92 | 93 | 94 | 95 | 96 | 97 | 98 |
| AVIATION FACILITIES (FEDERAL) | 660 | 670 | 675 | 675 | 675 | 675 | 675 | 675 | 675 | 675 | 675 | 675 | 675 | 675 | 675 |
| AVIATION FACILITIES (NON-FEDERAL) | 1,350 | 1,410 | 1,460 | 1,500 | 1,500 | 1,500 | 1,500 | 1,500 | 1,500 | 1,500 | 1,500 | 1,500 | 1,500 | 1,500 | 1,500 |
| MARITIME FACILITIES (FEDERAL) | 201 | 201 | 206 | 206 | 206 | 206 | 206 | 206 | 206 | 206 | 206 | 206 | 206 | 206 | 206 |
| DOD FACILITIES (AVIATION) | 195 | 195 | 195 | 195 | 195 | 195 | 195 | 185 | 185 | 185 | 170 | 80 | 50 | 50 | 50 |
| CIVIL USERS (AVIATION) | 143,000 | 149,000 | 154,000 | 160,000 | 166,000 | 172,000 | 178,000 | 185,000 | 192,000 | 199,000 | 206,000 | 214,000 | 221,000 | 229,000 | 237,000 |
| CIVIL USERS (MARITIME) | 462,000 | 484,000 | 502,000 | 518,000 | 532,000 | 544,000 | 554,000 | 564,000 | 574,000 | 584,000 | 594,000 | 604,000 | 604,000 | 604,000 | 604,000 |
| DOD USERS | 17,770 | 17,846 | 17,605 | 17,681 | 17,628* | 16,066 | 14,127 | 12,106 | 7,645 | 5,668 | 3,962 | 3,890 | 3,756 | 3,516 | 3,409 |

*DOD phase-out based on 1984 GPS installation schedules

Radiobeacons provide a bearing accuracy relative to vehicle heading on the order of ±3 to ±10 degrees. This might be considered a systemic limitation but, in actual use, it is satisfactory for many navigational purposes. Radiobeacons are not satisfactory for marine navigation within restricted channels or harbors. They do not provide sufficient accuracy or coverage to be used as a primary aid to navigation for large vessels in U.S. coastal areas.

D. Outlook

Growth in aeronautical beacon requirements is primarily non-Federal. During the 1975-1980 time period, FAA facilities increased about ten percent. Non-Federal systems, however, grew by forty percent. During the next 10 years, federal expenditures for aeronautical beacons are planned to be limited to the occasional establishment or relocation of NDB for ILS transition, replacement of deteriorated components, and modernization of selected facilities. Growth in the number of FAA beacons will be a function of these factors. It will also be influenced by the assumption of non-Federal facilities. Total growth in the number of FAA ground stations is expected to be somewhat smaller than the ten percent growth experienced in the 1975-1980 time period.

Growth in the total number of non-Federal aeronautical beacons is more diffcult to predict, particularly long-term. In the next five years, however, the total is expected to increase at a slightly slower rate than the forty percent growth experienced in the 1975-1980 time period.

Frequency congestion is one of the principal constraints which limits the expansion of NDB service. At FAA request, this problem has been addressed by the Radio Technical Commission for Aeronautics (RTCA), Special Committee 146 (SC-146). This committee developed a Minimum Operational Performance Standard (MOPS) for Automatic Direction Finder (ADF) receivers (RTCA DO-179). As existing ADF equipment are amortized, the tighter selectivity of new equipment will permit a greater number of NDB frequency assignments and will result in more efficient use of the radio spectrum.

Only a small expansion is planned for marine radiobeacon facilities. There is expected to be growth in the number of direction-finder-equipped pleasure boats.

At present, there is no known alternative system which would be as cost-effective for the user and the Government. No end of service can be foreseen between now and the year 2000 because of the wide and increasing acceptance by users and the lack of a low-cost alternative. DOD will phase out radiobeacons in favor of GPS by 1997.

Radar beacons (RACONS) are short-range radio devices used to provide radar reference points in areas where it is important to identify a special location or aid to navigation. The Coast Guard presently has approximately 75 RACONS in operation at various locations and has 35 more on order. They currently operate various types of RACONS but in the future will standardize on the frequency agile types. Plans are being developed to purchase a large quantity of frequency agile units in the future.

## 4.4 PROPOSED SYSTEMS - STATUS AND PLANS

### 4.4.1 Microwave Landing System

The Microwave Landing System (MLS) is a joint development of the DOT, the DOD, and the National Aeronautics and Space Administration (NASA) under FAA management. Its purpose is to provide a civil/military, Federal/non-Federal standardized approach and landing system with improved performance compared with the existing landing systems.

#### A. Operating Plan

The U.S. Time Reference Scanning Beam (TRSB) MLS technique was selected by ICAO as the international standard in 1978. MLS is expected to replace ILS. An MLS transition plan was approved in July 1981. The current operating plan is shown in Figure I-4.5. Precision DME (PDME) is also expected to be included with this system. The first production buy of airport MLS equipment was made in 1984 by the FAA.

#### B. User Community

MLS applications are limited to aviation. Widespread use by the U.S. civil and military aviation community is anticipated. Potential users include all segments of international civil and military aviation including NATO. Projected civil and military user population is shown in Table I-4.11.

#### C. Acceptance and Utilization

Within the U.S. there has been widespread support for a common civil/military MLS. MLS does not have the siting problems of ILS, offers higher accuracy and greater flexibility, permitting precision approach service to be provided at more airports. MLS provides DOD tactical flexibility due to its ease in siting and adaptability to mobile operations. When fully implemented MLS will replace PAR/GCA for the DOD.

#### D. Outlook

MLS will gradually replace ILS in national and international civil aviation. Military versions, including portable tactical systems and systems for shipboard use, are planned. MLS will replace or limit the deployment of non-standard or interim systems now in use.

MLS is expected to operate beyond the Year 2025. DOD phase in of MLS will begin in 1988 and will be completed by 1997. Inclusion of the L-band DME with MLS would require extension of the DME segment of VOR/DME through the same period.

### 4.4.2 GPS

GPS is a space-based navigation, time distribution system that will provide precise, continuous, all-weather, common grid, worldwide navigation and timing information to air, land, sea and space based users, both civil and military.

TABLE I-4.11 MICROWAVE LANDING SYSTEM (MLS) USER SCHEDULE

| FACILITIES/USERS | FISCAL YEARS | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 84 | 85 | 86 | 87 | 88 | 89 | 90 | 91 | 92 | 93 | 94 | 95 | 96 | 97 | 98 |
| FAA FACILITIES | 15 | 30 | 52 | 112 | 172 | 272 | 375 | 400 | 550 | 700 | 850 | 1,000 | 1,150 | 1,250 | 1,250 |
| DOD FACILITIES * | 0 | 0 | 0 | 2 | 60 | 117 | 181 | 272 | 373 | 459 | 535 | 585 | 627 | 661 | 668 |
| CIVIL USERS | * * | 30 | 90 | 150 | 1,000 | 2,000 | 4,000 | 8,000 | 16,000 | 32,000 | 64,000 | 99,000 | 134,000 | 169,000 | 204,000 |
| DOD USERS | 0 | 0 | 0 | 75 | 692 | 1,322 | 2,404 | 4,029 | 6,629 | 9,529 | 12,029 | 14,129 | 15,329 | 16,529 | 17,400 |

* Both Tactical and Fixed Base
* * Operational Test and Demonstration

## A. Operating Plan

GPS is in development by a DOD joint service program office with representation from NATO allies. It is currently in the full-scale development phase. DOD expects to deploy an operational system based on a demonstrated performance and expected cost merits. DOD awarded contracts for operational satellites in 1983 and will award contracts for user equipment in 1985. The operating plan is shown in Figure I-4.8.

The GPS program calls for satellite deployment throughout the full-scale development phase to support the Navy's Fleet Ballistic Missile Improved Accuracy Program and the GPS user equipment initial operational test and evaluation in the 1984 timeframe. As user equipment enters production and becomes available for operational use, the space segment will be gradually expanded to an initial 18-satellite deployment by the end of 1988. The control system facilities modification at Vandenberg AFB was completed in June 1982 to support the satellite constellation until the Master Control Station (MCS) at Colorado Springs is fully operational in 1987. The control segment will perform all system control functions, including ephemeris computation, tracking, telemetry, and command of the satellites.

## B. User Community

The DOD expects extensive use of GPS in almost every military mission area. The projected military user population is shown in Table 1-4.12. DOT and others are evaluating use and potential applications of GPS to meet civil navigation requirements.

## C. Acceptance and Utilization

GPS is being developed under the management of a joint service program office with the Air Force as the lead service. When deployed, the degree of its acceptance for civil use will be especially sensitive to the successful design of low-cost user equipment as well as the navigational and other services provided. The electronics industry is working to meet this challenge. A successful operational evaluation is also necessary before any system can be accepted as a civil radio aid to navigation. Present accuracy predictions indicate that, except for precision landing, civil aviation accuracy requirements can be met by the GPS Standard Positioning Service of 100 meters 2 drms. The maritime requirements for harbor approach, harbor, and inland waterway navigation can possibly be met by differential techniques currently being investigated.

## D. Outlook

GPS is a user passive radionavigation system designed to provide high positional accuracy on a global basis. The potential for many users is very high. The accuracy of the signal supplied and the cost of user equipments will be major factors in any expansion. There is no official service life prediction for GPS at this time. It is expected, however, to provide services into the next century. Full scale GPS operations will begin in 1988. DOD is currently working with the FAA in establishing rules, regulations, and procedures to permit military aircraft operation in the national airspace using GPS and ILS/MLS without reference to any other radionavigation aid assuming GPS integrated with other onboard aircraft systems

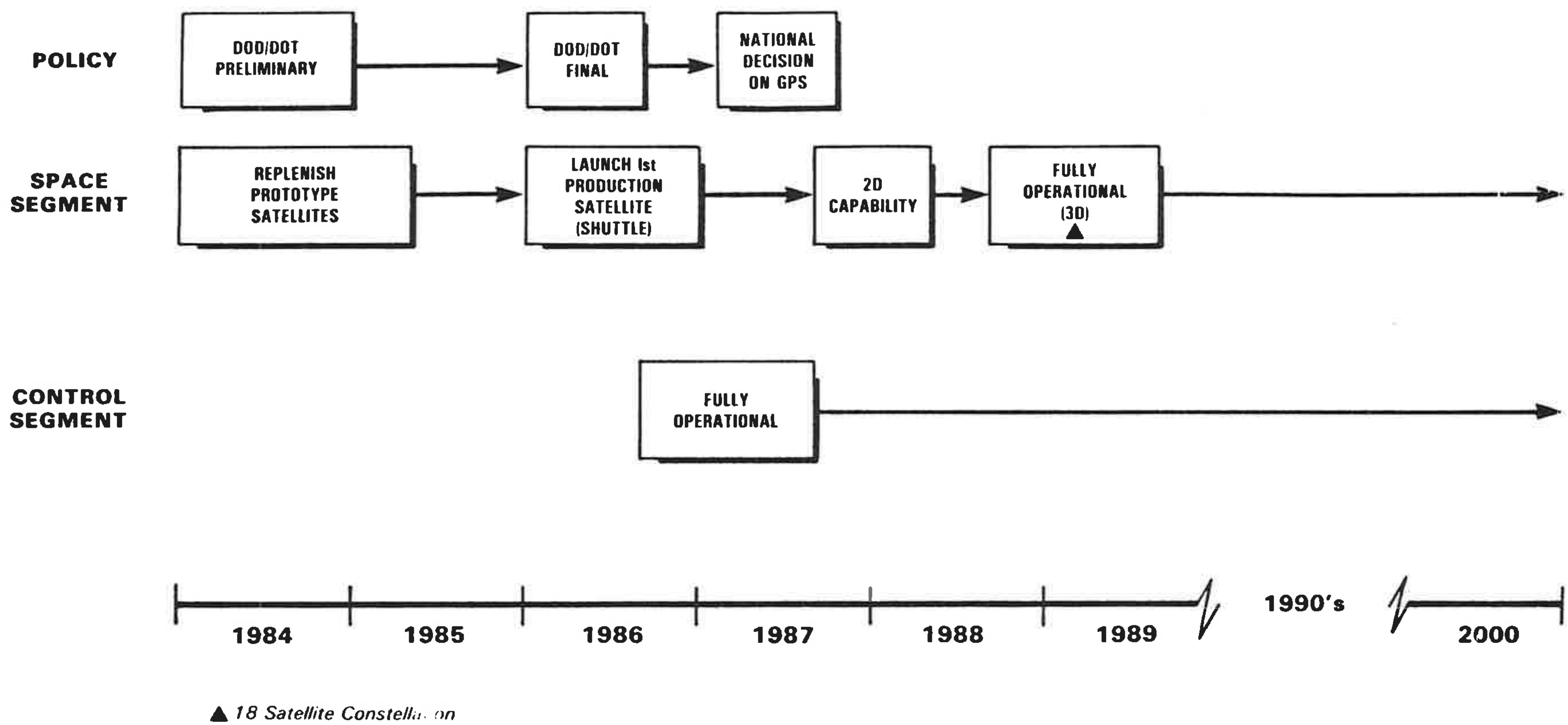


FIGURE I-4.8 OPERATING PLAN FOR GPS

TABLE I-4.12 GLOBAL POSITIONING SYSTEM (GPS) USER SCHEDULE

| FACILITIES/USERS | FISCAL YEARS | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 84 | 85 | 86 | 87 | 88 | 89 | 90 | 91 | 92 | 93 | 94 | 95 | 96 | 97 | 98 |
| DOD USERS * | ** | ** | ** | ** | 268 | 1,120 | 2,819 | 5,069 | 7,573 | 9,892 | 11,533 | 12,474 | 13,038 | 13,345 | 13,530 |
| CIVIL USERS | ** | ** | ** | *** | | | | | | | | | | | |

*Based on 1984 GPS installation schedules
**Less than 100
***The 1987 national decision on the future radionavigation system mix may affect the number of users of this system. Therefore, no estimates of the number of users are projected for later years.

proves acceptable as a sole means navigation system. The FAA is developing a National Aviation Standard for GPS and expects to request RTCA to prepare an aviation user equipment MOPS in 1985. Both of these efforts and an aviation user conference on the role of GPS in civil aviation are scheduled for completion by 1987. Based upon information available in 1984 and without any special user fee (reference paragraph 4.5.2 E1), the initial use of GPS by civil aviation will be as a supplemental system. GPS will be approved as a sole means civil aviation radionavigation system when all FAA requirements have been met. DOD, FAA, and industry are closely working to this end.

## 4.5 SELECTING RADIONAVIGATION SYSTEMS TO BE USED IN THE FUTURE

Many factors determine the choice of systems to meet user requirements. They may be categorized according to operational, technical, economical, institutional and/or international parameters. System accuracy and coverage are foremost among the technical parameters followed closely by systemic availability and reliability. Certain unique parameters, such as anti-jamming performance, apply to military needs. In most cases, current systems were developed to meet distinct and different requirements. They must be retained until suitable single or multi-user systems can be implemented. The current investment in ground and user equipment must also be considered. In some cases, there may be international commitments.

### 4.5.1 Approach to Selection

Figure I-4.9 shows the sequential process being used to select navigational systems to be used in the future. It represents a coordinated DOD/DOT effort to identify and resolve all outstanding issues and to recommend the optimal choices for the future radionavigation systems mix.

Three key events stand out in the process of selecting the future radionavigation systems mix: the DOD/DOT preliminary recommendation, the DOD/DOT final recommendation, and the national decision.

To provide the necessary information for this process a decision data base has been developed. The data base includes technical evaluations of candidate systems (including GPS), and assessments of the costs of different mixes of the candidate systems by the DOT Economic Planning Model.

The preliminary future radionavigation systems mix recommendation was jointly prepared by DOD and DOT in 1983 and 1984. The recommendation is presented in Part I, Section 2.2.

In the period 1984-1986 the decision data base will be updated by modifying the technical and economic material to reflect changes that have occurred. Estimates of benefits associated with the candidate systems will also be developed. In addition, consultations with civil users and international organizations will take place prior to the national decision in 1987.

The flow diagram (Figure I-4.9) illustrates the need to analyze both individual systems and system combinations sequentially. Even though similar analyses of civil suitability and national security objectives are necessary for individual systems, a comprehensive overview of all systems must also be compiled. This will ensure balance, consistency, completeness and equal treatment of all viable alternatives.

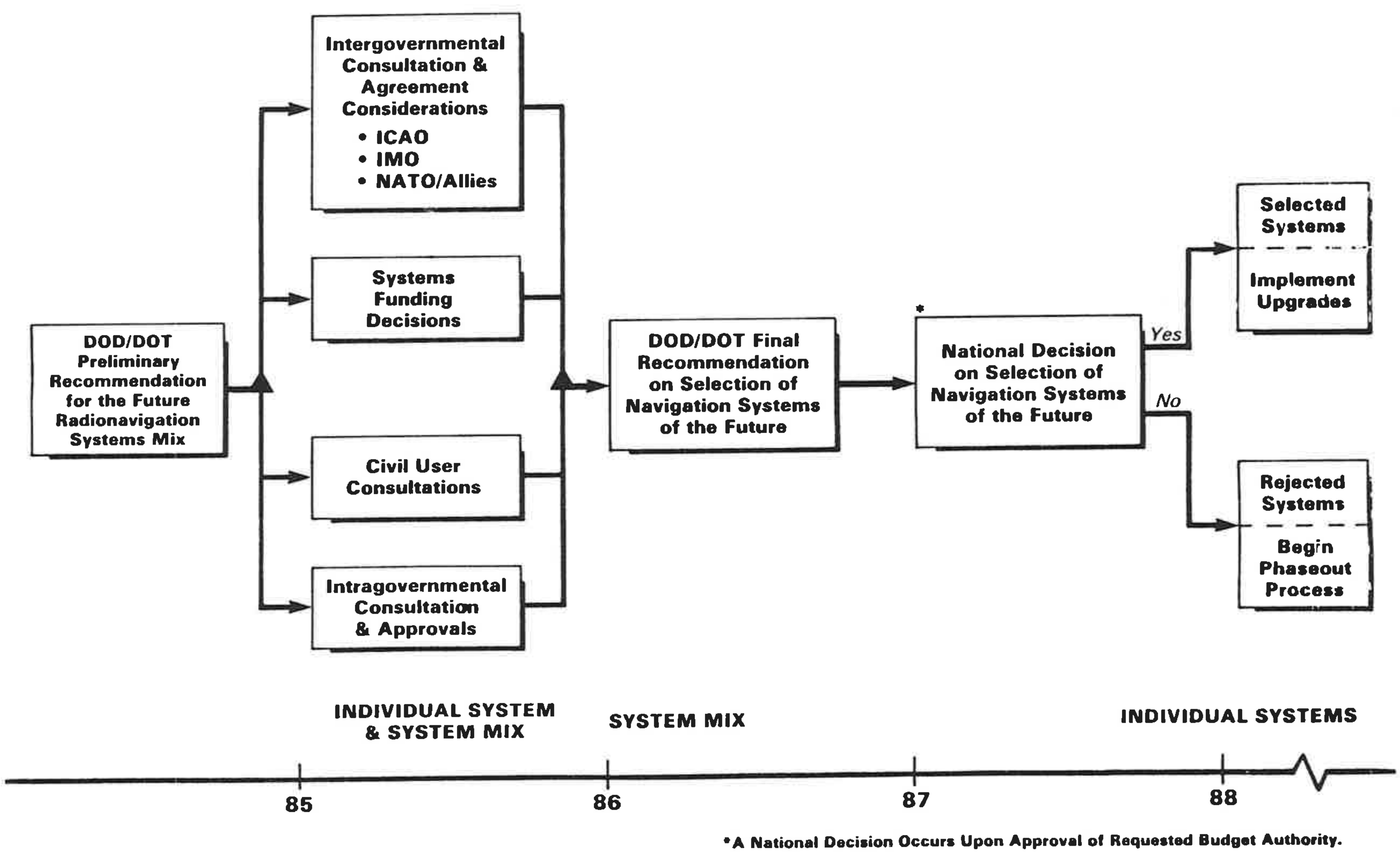


FIGURE I-4.9 SELECTION OF INITIAL RADIONAVIGATION SYSTEMS MIX

The flow diagram describes an ongoing process supporting the biennial revision of the Federal Radionavigation Plan. However, the process requires periodic status reviews and assessment of the impact on future decisions. The mechanism for doing this is incorporated into the DOD/DOT Federal Radionavigation Plan review process.

Four years are scheduled for consultations (1984-1987) with groups that will be affected by the pending national decisions. This includes U.S. allies, including the North Atlantic Treaty Organization (NATO), and both the International Maritime Organization (IMO) and the International Civil Aviation Organization (ICAO). An intensive effort is necessary and desirable to establish a stable framework for long-range planning by users and others affected by the transition to a new combination of systems.

A three-step selection process is visualized. First, DOD decisions are made whether a given system is necessary to meet national security requirements or not. If not, phase-out of their use of the system can begin. If security requirements are met, DOD requirements are incorporated into the decision data base for consideration with other systems. In either case, the second step of consolidated DOD/DOT recommendations follow. These consider meeting civil and military requirements with the minimum number of common use systems. Considerations of operational, technical, economical and institutional issues would dominate the selection process. Finally, the national decision will reflect the outcome of consultations as well as public policy and budgetary review of the DOD/DOT recommendations.

There are short and long term aspects that need to be addressed in the overall process. The long-term goal is to establish, through an integrated DOD/DOT planning and budgeting process, a cost-effective mix of multi-user systems for the post-1995 timeframe. However, before decisions can be implemented, there may be incremental improvements to existing systems that can be cost-effective for the time period 1984-1995, regardless of the final mix that is selected. Specifically, modernization of the VOR/DME, TACAN and LORAN-C transmitting segments are providing offsetting benefits to the required capital investment. The selection process for the system to be used in the future allows the flexibility to adopt incremental improvements where justified over the short term. Similarly, it permits systemic upgrading and research and development to allow the satisfaction of operational requirements which are not met by existing or planned systems.

The 1987 decision becomes the basis for navigational system implementation. Following the 1987 decision, it is intended that this process will be continued to reflect in the ongoing radionavigation planning such factors as new requirements and advances in technology.

### 4.5.2 Issues to Be Considered

This section describes radionavigation operational, special military, technical, economic, and institutional (including international) issues.

## A. Operational Issues

Part II defines the operational requirements of civil users of navigational systems. The following paragraphs address the operational issues that define user requirements.

### 1. The User/Operator Viewpoint

Mobile users/operators want the most direct, economical and safest path to their destinations or, in some cases, the user wants to locate a fixed point or boundary. They must be able to respond correctly and expeditiously to traffic control services. They must have the capability to navigate with accuracy consistent with their environment, the capability of others sharing their space, the performance of their craft, and the rules, regulations, and procedures which govern operations.

Areas of operation, mission, economics, personal preference and federal regulations largely determine the radionavigation aids which operators choose to employ. They can then choose from a number of equipments to use the particular aid selected. In the selection of equipment, operators generally wish to limit or minimize the cost. An aircraft must be equipped so that it may be operated safely and in accordance with a clearance and published regulations even in the event of failure of the surveillance or communications system. A ship must be equipped so that it can navigate safely without assistance other than that provided by established aids to navigation.

## B. Special Military Issues

### 1. Military Selection Factors

Operational need is the principal influence in the DOD selection process. Precise navigation is required for vehicles, anywhere on the earth's surface, on and under the sea and in and above the atmosphere. Other factors that affect the selection process are:

a. The need for flexibility to accommodate new weapon systems and technology.

b. The need for systems that are relatively immune to enemy interference or exploitation.

c. Interoperability with the systems used by allies and civil sector.

d. The need for reliability and survivability in combat.

e. Interruption, loss or degradation of system operation by enemy attack, political action, or natural causes.

f. Development of alternate means of navigation.

g. The need for geodetic accuracy relative to a common reference system to support strategic and tactical operations.

h. Worldwide mobility requirements.

The selection of DOD navigational systems is influenced by the fact that military operations may be conducted in areas where navigational facilities are inadequate or non-existent. Consequently, transportable navigational facilities may be needed. DOD navigational systems must operate in extreme environments and, in some cases, unattended. Moreover, in some applications, navigational systems must be very small and use little power.

2. Civil/Military Compatibility

DOD aircraft and ships operate in, and must be compatible with, civil environments. Thus, there are potential cost advantages in the development of common civil/military systems.

3. Review and Validation

The DOD radionavigation system requirement review and validation process:

a. Identifies the unique components of mission requirements

b. Identifies technological deficiencies

c. Determines, through interaction with DOT, the impact of new military requirements on the civil sector.

The requirement review and validation process will investigate system costs, cost effectiveness, potential cost offsets, user populations, and the relationship of candidate systems to other systems and functions. Validation of operational requirements will establish the necessity of a system to insure successful mission completion.

C. Technical Issues

In evaluating future navigational system candidates, there are a number of technical factors which must be considered:

a. Received Signal Strength

b. Multipath Effects

c. Signal Accuracy

d. Vehicle Dynamic Effects

e. Signal Acquisition and Tracking Continuity

f. Signal Coverage

g. Noise Effects

h. Propagation

i. Interference Effects (Natural, Man-Made)

j. Installation Requirements

k. Environmental Effects

l. Human Factors Engineering.

D. Economic Issues

A number of systems may play major roles in navigation in the future. Some of these systems, such as VOR/DME, are limited to use by a single class of users, e.g., aircraft, in specific areas. Others, such as LORAN-C, have wider coverage areas and application. Still others, such as GPS, have broad application and global coverage. Without adequate analysis, one could conclude, superficially, that the "optimal" policy would concentrate government investment in a single future radionavigation system to meet all user requirements. Such a conclusion, however, neglects the significant user investment in existing systems and other economic aspects which require a careful analysis of costs and benefits.

Benefits derived from radionavigation systems take many forms, but are summarized frequently in three easily recognized major categories: improved safety of navigation, greater efficiency in transportation and other commercial activity, and more effective protection of national security. Efficiency in commercial enterprise produces economic benefits which are generally obvious, but not so easily quantifiable. Improvements in general safety and security provide additional, significant economic benefits through the prevention of loss of life and limb and protection of capital investment.

Direct cost to the government, as the operator of radionavigational services, and to the user, who must buy the equipment needed to use the services, must be carefully analyzed. The analysis of these costs must consider initial investment, operation, maintenance and replacement costs; and the unamortized capital investment remaining at the time that replacement of the system is contemplated. In the civil sector, the cost of user equipment, more than any other single factor, influences the acceptability of a new system by the majority of civil users. Substantial unamortized investment in user equipment for an older system will cause strong resistance to replacement and demand extended phase in/out period.

DOD is a major investor in navigational systems, subsystems and components. The acquisition of a system which is not cost-effective diverts DOD resources from more productive uses; therefore, affordability from a life-cycle-cost view is a prime concern. As in the civil sector the cost of user equipment for cooperative navigation systems is often the single most important determinant of affordability.

The DOT has developed an economic model to evaluate costs of specific radionavigation scenarios. Such evaluations will be a part of the data supporting future decisions regarding the selection of civil and military navigational systems. Cost comparison for all major classes of systems and users is planned to be attained by 1985.

E. Institutional Issues

Section 3 of Part I defines the policy structure governing the development and planning of navigational systems. While all elements need to be addressed in formulation of strategy for system selection, the principal unresolved issues include the following:

1. Cost Recovery for Radionavigation Services

Because of the nature of the electromagnetic medium, radionavigation services presently provided to meet U.S. requirements are available to any suitably equipped user. Further, there is no direct charge or fee levied by the U.S. for the use of any of the Federally provided radionavigation systems. The only cost recovery for radionavigation services from civil users, either domestic or foreign, is obtained from the aviation community as part of the overall process of cost recovery for the DOT provided air transportation services. This cost recovery is achieved through indirect measures such as fuel taxes, registration fees, and/or ticket taxes and at this time covers only part of the DOT's costs. With the exception of the Saint Lawrence Seaway Development Corporation there is no corresponding cost recovery, at this time, from the marine users of DOT provided transportation services.

The DOT has proposed the implementation of fees sufficient in total, to approach full cost recovery from the civil transportation users who directly benefit from Government provided transportation related services. The various fees would be set at an amount so as to generate total revenue from each of the user groups consistent with the cost of the services provided to that group. This proposal is part of the Administration's effort to impose user fees where a service provides benefit to identifiable recipients above and beyond those which accrue to the general public. Under the DOT proposal, the costs of DOT provided services would be recovered through an appropriate and convenient fee system:

- The U.S. Coast Guard will attempt to establish a cost recovery program for those services where there is a direct transaction such as licensing and inspections, permits and similar programs. It is not anticipated that it would be cost effective to develop a mechanism to enforce collection of user fees for Radionavigation services provided by the Coast Guard.

- The cost of the services provided by FAA would be recovered through the following fee system: a passenger ticket tax, aviation gasoline fuel tax, jet fuel tax, freight waybill tax, international departure tax, and a tire and tube tax.

Independent of the DOT effort, the 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 GPS system as is deemed feasible." In response to Congressional guidance, a report was submitted by DOD to the Congress in May 1984. The report concludes that imposing GPS user charges for the Standard Positioning Service (SPS) signal is neither practical nor desirable.

2. Signal Available in Times of National Emergency

The availability of navigational signals of adequate accuracy at all times, including times of stress, is essential to reliance on radionavigation systems for safety of navigation. Conversely, guaranteed availability of optimum performance may diminish national security objectives, so that a trade-off or compromise is necessary. The U.S. national policy is that all radionavigation signals (LORAN-C, OMEGA, VOR/DME, GPS service, TRANSIT, etc.) will be available to serve safety of navigation at all times except during a dire national emergency when only those radionavigation signals that serve national interest will be available.

3. International Acceptance of Navigational Systems

The goals of standardization and cost minimization of user equipment drive the search for an international consensus on a selection of navigational systems. For civil aviation, ICAO establishes standards for internationally used navigational systems. In maritime navigation, the trend is toward international recognition of a minimum number of systems from which individual countries could prescribe one or more to be carried by ships in their territorial waters. For aviation, the heavy and growing international investment in VOR/DME has led to an extension of the ICAO protection date to 1995. A consideration in the international acceptance of GPS is the political ramifications resulting from the fact that it is a U.S. military system. Hence, further international consultations will be instituted with NATO allies, IMO, ICAO, etc., to explore the feasibiity of international acceptance of GPS.

### 4.5.3 Criteria for Selection

Criteria are defined to compare the relative attractiveness of alternative navigational systems' configurations. At the minimum, decisions on selection of future systems should meet the following criteria:

A. Provide the necessary service to meet the needs of the military and civil communities. (Service)

B. Be responsive and flexible to the changing operational and technological environments. (Viability)

C. Recognize and accommodate a necessary degree of standardization and interoperability for both domestic and foreign operations. (Standarization)

D. Achieve the required level of service in an economic manner. (Costs)

The major criteria may be further subdivided, as shown below:

A. Service

1. Military Operations: Provide, at a minimum, navigational services to support accomplishment of DOD tactical and strategic missions in an effective and efficient manner.

2. Transportation Safety: Provide, at a minimum, navigational services sufficient to minimize transportation risk to an acceptable level.

3. Economic Efficiency: Provide, to the extent possible and consistent with cost effectiveness, navigational services which benefit the economy.

B. Viability

1. Orderly Transition: Provide for orderly transitional operations and planned obsolescence of equipment as technical improvements evolve and operational requirements are modified or increased.

2. Flexibility: Provide navigational services to a variety of user classes with the minimum number of systems. The intent is to allow the use of special purpose systems only when justified by special circumstances and/or need.

3. Coverage: Provide navigational services in all relevant operating areas, i.e., worldwide, with specialized attention to the United States.

4. Future Systems: Provide for research and introduction of new systems and concepts, particularly where unfulfilled requirements exist or where cost savings appear possible.

C. Standardization

1. International Acceptance: Provide navigational services and systems technically and politically acceptable to diverse groups, including the North Atlantic Treaty Organization (NATO), International Civil Aviation Organization (ICAO), and International Maritime Organization (IMO).

2. Civil/Military Interoperability: Provide the basic capabilities to permit common use and common operational procedures by civil and military craft.

3. Equipment Standardization and Compatibility: Provide, to the extent feasible, compatibility between civil and military navigational equipment.

D. Costs

1. Combined User/Government Costs: Provide a mix whose life-cyle costs

for government and users are minimum, consistent with adequate service and reasonable benefits.

2. Transition Period Cost: Parallel (new and old) systemic operations will be carried out over a sufficient period to minimize user investment cost penalties and to permit equipment replacement to occur at normal intervals.

# PART II

# REQUIREMENTS

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## PART II

## 1. RADIONAVIGATION REQUIREMENTS

The requirements of civil and military users for radionavigational services are based upon the technical and operational performance needed for military missions, transportation safety and economic efficiency. For civil users, and for military users in missions similar to civil users (i.e., en route navigation), the requirements are defined in terms of discrete "phases of navigation." These "phases" are categorized primarily by the characteristics of the navigational problem as the mobile craft passes through different regions in its voyage. For example, the ship navigational problem becomes progressively more complex and risky as the large ship passes from the high seas, into the coastal area, and finally through the harbor approach and to its mooring. Thus, it is convenient to view each segment separately for purposes of analysis.

Unique military missions and national security needs impose a different set of requirements which cannot be viewed in the same light. Rather, the requirements for military users are more a function of the system's ability to provide services that equal or exceed tactical or strategic mission requirements at all times in relevant geographic areas, irrespective of hostile enemy action.

In the discussion that follows, both sets of requirements (civil and military) are presented in a common format of technical performance characteristics whenever possible. These same characteristics are used to define navigation system performance in Part III.

### 1.1 CIVIL REQUIREMENTS

Civil users' radionavigational requirements are determined by a DOT process which begins with acknowledgment of a need for service in an area or for a class of users. This need is normally identified in public safety and cost/benefit need analysis generated internally, from other Federal agencies, the user public or as required by Congress.

Radionavigation service requirements:

A. Provide a service adequate for safety

B. Enhance economic performance/benefit.

### 1.2 REQUIREMENTS DETERMINATION

Radionavigation system replacement candidates must be subjected to a total system analysis in terms of safety and economic performance. This involves the evaluation of a number of complex factors. Replacement decisions will not be made on the basis of a simplistic comparison of one performance characteristic such as system accuracy.

### 1.2.1 Process

The requirements for an area or class of users are not absolutes. The process to determine requirements involves:

A. Evaluation of the acceptable level of safety risks to the government, user and general public as a function of the service provided.

B. Evaluation of the economic needs in terms of service needed to provide cost effective benefits to commerce and the public at large. This involves a detailed study of the desired service by user group measured against the benefits obtained.

C. Evaluation of the total cost impact of any government decision on radionavigation users.

This process leads to the government selection of a system. The decision is driven primarily by considerations of safety and economic benefit.

### 1.2.2 User Factors

User factors requiring consideration are:

A. Vehicle size and maneuverability

B. Regulated and unregulated traffic flow

C. User skill and workload

D. Process and display requirements for navigational information

E. Environmental constraints, e.g., weather, terrain, manmade obstructions

F. Operational constraints caused by systemic technical factors

G. Economic benefits.

For most users, cost is generally the driving consideration. The price users are willing to pay for equipment is influenced by:

A. Activity of the vehicle or vessel. Various user groups have unique requirements that affect their ability to operate efficiently.

B. Vehicle performance variables such as fuel consumption, operating costs, and cargo value.

C. Cost/performance tradeoffs of radionavigation equipment.

Thus, in the civil sector, evaluation of a navigation system against requirements involves more than a simple comparison of accuracy and equipment performance characteristics. These evaluations must involve the operation, technical, and cost elements discussed above. Performance requirements are defined within this framework.

### 1.3 PHASES OF NAVIGATION

Each mode of transportation has various phases with different requirements to provide safe and cost-effective operation during that phase.

#### 1.3.1 Air

The two basic phases of air navigation are approach/landing and en route/terminal.

A. Approach/Landing

The approach/landing phase is that portion of flight conducted immediately prior to touchdown. It is generally conducted within 10 nm of the runway. Two sub-phases may be classified as non-precision approach and precision approach and landing.

B. En Route/Terminal

The en route/terminal phase includes all flight except that within the approach/landing phase. It contains five sub-phases which are categorized by differing geographic areas and operating environments as follows:

1. Oceanic En Route

This sub-phase covers operations over ocean areas generally characterized by low-traffic density and no independent surveillance coverage.

2. Domestic En Route

Operations in this sub-phase are typically characterized by moderate to high traffic densities. This necessitates narrower route widths than in the oceanic en route sub-phase. Independent surveillance is generally available to assist in ground monitoring of aircraft position.

3. Terminal

The terminal sub-phase is typically characterized by moderate to high traffic densities, converging routes and transitions in flight altitudes. Narrow route widths are required. Independent surveillance is generally available to assist in ground monitoring of aircraft position.

4. Remote Areas

Remote areas are special geographic or environmental areas characterized by low-traffic density and terrain where it has been difficult to cost-effectively implement comprehensive navigation coverage. Typical of remote areas are mountainous terrain, offshore areas, and large portions of the state of Alaska.

5. Low Altitude

The low altitude sub-phase is characterized by en route flights between ground level and 5,000 feet above ground level. Most rotorcraft operations are conducted in the low altitude sub-phase as well as some fixed wing operations. The low altitude sub-phase typically has limited communication, navigation, and surveillance service because radio signals are easily blocked by terrain and buildings. Traffic density is increasing which may require Air Traffic Control (ATC) services and structure.

### 1.3.2 Marine

Marine navigation in the United States consists of five distinct phases identified as Ocean, Coastal, Harbor Approach, Harbor, and Inland Waterway navigation. Standards or requirements for safety of navigation and reasonable economic efficiency can be developed around these five phases. Specialized requirements, which may be generated by the specific activity of a ship, must be addressed separately.

A. Ocean Navigation

Ocean navigation is considered that phase in which a ship is beyond the Continental Shelf and more than 50 nm from land, in waters where position fixing by visual reference to land or to fixed or floating aids to navigation is not practical. Ocean navigation is sufficiently far from land masses so that the hazards of shallow water and of collision are comparatively small.

B. Coastal Navigation

Coastal navigation is considered that phase in which a ship is within 50 nm from shore or the limit of the Continental Shelf (200-meter depth), whichever is greater, where a safe path of water at least one mile wide, if a one-way path, or two miles wide, if a two-way path, is available. In this phase, a ship is in waters contiguous to major land masses or island groups where transoceanic traffic patterns tend to converge in approaching destination areas; where interport traffic exists in patterns that are essentially parallel to coastlines; and within which ships of lesser range usually confine their operations. Traffic-routing systems and scientific or industrial activity on the Continental Shelf are encountered frequently in this phase of navigation. Ships on the open waters of the Great Lakes also are considered to be in the coastal phase of navigation.

The boundary between coastal and ocean navigation is defined by one of the following which is farthest from land:

1. 50 miles from land, or

2. The outer limit of offshore, offshore shoals, other hazards on the Continental Shelf or

3. Other waters where traffic separation schemes have been established, and where requirements for the accuracy of navigation are thereby made more rigid than the safety requirements for ocean navigation.

### C. Harbor Approach, Harbor

Harbor Approach and Harbor navigation are conducted, in general terms, in waters inland from those of the Coastal phase. For a ship entering from the sea or the open waters of the Great Lakes, the Harbor Approach phase begins generally with a transition zone between the relatively unrestricted waters where the navigational requirements of Coastal navigation apply, and narrowly restricted waters near and/or within the entrance to a bay, river, or harbor, where the navigator enters the Harbor phase of navigation. Usually the Harbor phase requires navigation of a well defined channel which, at the seaward end, is typically from 180 to 600 meters in width if it is used by large ships, but may narrow to as little as 120 meters farther inland. Channels used by smaller craft may be as narrow as 30 meters.

From the viewpoint of establishing standards or requirements for safety of navigation and promotion of economic efficiency, there is some generic commonality between the Harbor Approach and Harbor phases. In each case, the nature of the waterway, the physical characteristics of the vessel, the need for frequent maneuvering of the vessel to avoid collision, and the closer proximity to grounding danger impose more stringent requirements for accuracy and for real-time guidance information than for the Coastal phase. For analytical purposes, the phases of Harbor Approach and Harbor navigation are built around the problems of precise navigation of large seagoing and Great Lakes ships in narrow channels between the transition zone and the intended mooring.

### D. Inland Waterways

Inland Waterway navigation is conducted in restricted areas similar to those for harbors or harbor approaches. However, in the inland waterway case, the focus is on non-seagoing ships and their requirements on long voyages in restricted waterways, typified by tows and barges in the U.S. Western Rivers system and the U.S. Intracoastal Waterway.

In some areas, seagoing craft in the Harbor phase of navigation and inland craft in the inland waterway phase share the use of the same restricted waterway. The distinction between the two phases depends primarily on the type of craft. It is made because seagoing ships and typical craft used in inland commerce have differences in physical characteristics, manning, and equipment. These differences have a significant impact upon their requirements for aids to navigation. Recreational and other relatively small craft are found in large numbers in waters used by both seagoing and inland commercial traffic and generally have less rigid requirements in either case.

## 1.3.3 Land

The two basic phases of land location systems are:

A. Site Registration: recording the location of a place or event for record purposes or to return to it at a later time

B. Automatic Vehicle Monitoring (AVM): the tracking of land vehicles by measuring radionavigation or location signals in the vehicle and transmitting the results of that measurement to a central tracking facility for display.

### 1.3.4 Space

For earth orbiting space activities the mission phases can be generally categorized as launch phase, in-flight/in-orbit phase, and reentry and landing phase.

A. Launch Phase

This phase is defined as that portion of the mission from the point at which the Space Shuttle or expendable launch vehicle leaves the launch pad to the point wherein the Space Shuttle (or the payload launched by the expendable launch vehicle) is inserted into earth orbit.

B. In-Flight/In-Orbit Phase

This is the phase wherein key operations or data gathering from an experiment to meet the primary mission objectives is performed. During this phase, the Space Shuttle may deploy a satellite, perform positional maneuvers in support of onboard experiments, or retrieve a satellite for return to earth. This phase essentially ends when the Space Shuttle initiates de-orbit maneuvers. In this phase, free-flying spacecraft perform their experiments and/or operations in their required orbits. In those cases where the spacecraft will not be returned to earth, this operational phase continues until such time as the spacecraft is shut down or can no longer perform its functions. For those spacecraft to be returned to earth, this phase essentially ends when the spacecraft is retrieved by the Space Shuttle.

C. Reentry and Landing Phase

This phase begins when the Space Shuttle, possibly with onboard experiments and/or a retrieved spacecraft in the payload bay, initiates de-orbit maneuvers. The Space Shuttle goes through atmospheric entry and makes an unpowered landing. This phase ends when the Space Shuttle comes to a full stop.

PART II

# 2. CIVIL AIR RADIONAVIGATION

Aircraft navigation is the process of conducting aircraft from one place to another and includes position determination, establishment of course and distance to the desired destination, and determination of deviation from the desired track. Requirements for navigational performance are dictated by the phase of flight operations and their relationship to terrain, to other aircraft, and to the air traffic control process. Aircraft navigation may be achieved through the use of visual procedures during Visual Flight Rules (VFR) operations but requires use of electronic or other non-visual aids under low-visibility conditions and above Flight Level 180.

## 2.1 GENERAL CONSIDERATIONS

Aircraft separation criteria, established by the Federal Aviation Administration (FAA), take into account limitations of the navigational service available, and in some airspace the Air Traffic Control (ATC) surveillance service. Aircraft separation criteria are influenced by the quality of navigational service, but are strongly affected by other factors as well. The criteria relative to separation require a high degree of confidence that an aircraft will remain within its assigned volume of airspace. The dimensions of the volume are determined by a stipulated probability that performance of the navigational system will not exceed a specified error.

Since navigation is but one function performed by the pilot, the workload for navigation in conjunction with communications, flight control, and engine monitoring must be small enough so that the pilot has time to see adequately and avoid other aircraft operating using see-and-avoid rules.

### 2.1.1 Aviation Requirements

The following are basic requirements for the current and future aviation navigation system. The words "navigation system" means all of the elements to provide the necessary navigation services to each phase of flight. While navigation systems are expected to be able to meet these requirements, implementation of specific capabilities is to be determined by the users, and where appropriate, regulatory authorities.

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

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

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

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

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

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

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

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

H. The navigation systems must provide information indications which automatically and radically change the character of its indication in case a divergence from accuracy occurs outside safe tolerance.

I. The navigation system signal source element must provide immediate and positive indication of malfunction.

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

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

L. In conjunction with other flight instruments, the navigation system must in all circumstances provide information to the pilot and aircraft systems for performance of the following functions:

1. Continuous tracking guidance
2. Continuous determination of distance along track
3. Continuous determination of position of aircraft
4. Position reporting
5. Manual or automatic flight

The information (signals) provided by the navigation system must permit the design of indicators and controls which can be directly interpreted or operated by the pilot at his normal station aboard the aircraft.

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

N. The navigation system should be capable of integration with all phases of flight, including the precision approach and landing system. It should provide for transition from long range (overwater) flight to short range (domestic) flight with minimum impact on cockpit procedure/displays and workload.

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

P. The navigation system must permit the establishment and the servicing of any practical defined system of routes for the appropriate phases of flight.

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

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

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

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

U. The navigation system must be free from signal fades or other propagation anomalies within the operating area.

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

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

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

2.1.2 Navigation Signal Error Characteristics

The unique signal characteristics of a navigation system have a direct effect on determining minimum route widths. The distribution and rate of change, as well as magnitude of the errors, must be considered. Error distributions may contain both bias and random components. The bias component is generally easily compensated for when its characteristics are constant and known. For example, VOR radials can be flight-checked and the bias error reduced or eliminated through correction of the radial used on aeronautical charts.

Slowly varying errors such as the seasonal and diurnal variations can also be compensated for by implementing correction algorithms in aircraft equipment logic.

The distribution of the random or non-predictable varying error component becomes the critical element to be considered in the design of navigation systems. For any selected route width and system accuracy, those systems which have a broad error distribution tend to produce a higher risk of collsion than those with a narrow distribution. The rate of change of the error within the distribution is also an important factor, especially when the system is used for approach and landing.

Errors varying at a very high frequency can be readily integrated or filtered out in the aircraft equipment. Errors occurring at a slower rate can, however, be troublesome and result in disconcerting indications to the pilot. An example of one of these would be a "scalloped" VOR signal that causes the Course Deviation Indicator (CDI) to vary. If the pilot attempts to follow the CDI closely the plane will start to "S" turn frequently. The manuvering will cause unnecessary pilot workload and degrade pilot confidence in the navigation system. This indication can be further aggravated if navigation systems exhibit different error characteristics during different phases of flight or when the aircraft is maneuvering. The method of determining the total system error is affected by the navigation signal error characteristics. In most current systems the error components are ground system errors, airborne receiver errors, and flight technical errors. These errors are combined using the Root-Sum-Square (RSS) method. In analyzing new systems, it may be necessary to utilize alternative methods of combining errors, but each element must be properly considered.

In summary, the magnitude, nature, and distribution of errors as a function of time, terrain, aircraft type, aircraft maneuvers, and other factors must be considered. The evaluation of errors is a complex process, and the comparison of systems based upon a single error number will be misleading.

## 2.2 CURRENT AVIATION NAVIGATION REQUIREMENTS

### 2.2.1 En Route/Terminal Phase

The en route/terminal phase of air navigation (as defined in Part II, Section 1.3) includes the following subphases:

1. Oceanic En Route
2. Domestic En Route
3. Terminal
4. Remote Area
5. Low Altitude.

The general requirements in Section 2.1 of Part II are applicable to the en route/terminal phase of navigation. In addition, to facilitate aircraft operations in this phase, the system must be capable of being operationally integrated with the system used for approach and landing. The system used for domestic en route and terminal navigation must be suitable for non-precision approaches.

Federal Aviation Regulations (FAR) paragraphs 91.109 and 91.121 specify the vertical separation required below and above flight level 290 (29,000 feet). The current separation requirement is 1,000 feet below Flight Level 290, and 2,000 feet at and above Flight Level 290. In order to justify the 1,000 foot vertical separation below Flight Level 290, the RSS altitude keeping requirement is ±350 feet (3 sigma). This error is comprised of ±250 feet (3 sigma) aircraft altimetry system error, of which the altimeter error is limited to ±125 feet by TSO C-10B below Flight Level 290.

The minimum performance criteria currently established to meet requirements for the en route/terminal phase of navigation are presented in the following sections.

#### A. Oceanic En Route

The system must provide navigational capability commensurate with the need in specific areas in order to permit safe navigation and the application of lateral separation criteria. An organized track system has been implemented in the North Atlantic to gain the benefit of optimum meteorological conditions. Since an independent surveillance system such as radar is not available, separation is maintained by procedural means, i.e., position reports and timing.

A 60 nm lateral separation standard has gone into effect on the North Atlantic organized track system. The following system performance is required to achieve this separation:

(1) The standard deviation of the lateral track errors shall be less than 6.3 nm, 1 sigma (12.6 nm, 2 sigma).

(2) The proportion of the total flight time spent by aircraft 30 nm or more off track shall be less than $5.3 \times 10^{-4}$, i.e., less than 1 hour in about 2,000 flight hours.

(3) The proportion of the total flight time spent by aircraft between 50 nm and 70 nm off track shall be less than $1.3 \times 10^{-4}$, i.e., less than 1 hour in about 8,000 flight hours.

B. Domestic En Route

Domestic air routes are designed to provide as nearly direct airways as practical between city pairs that have significant air traffic. For altitudes below Flight Level (FL) 180 (18,000 feet), the airways are defined as 8 nm in width out to 51 nm from the VOR facility. Beyond 51 nm the airway increases uniformly in width on either side of the centerline $\pm 4.5$ degrees, with the apex of the angle at the VOR facility.

For altitudes above FL 180 (18,000 feet and above), the airways consist of jet routes which have the same protected airspace as the low-altitude structure except the VOR stations may be spaced farther apart and the route width may be as large as 20 nm.

Current accuracy requirements for domestic en route navigation are based on the characteristics of the VOR/DME/VORTAC system and therefore relate to the angular characteristics of the VOR and TACAN azimuth systems and range charateristics of the DME/TACAN range systems. "System Use Accuracy," as defined by ICAO, is the Root-Sum-Square (RSS) of the ground station error contribution, the airborne receiver error, the display system contribution and the Flight Technical Error (FTE). Flight Technical Error is the contribution of the pilot (or autopilot) in using the presented information to control aircraft position. Error values on which the current system is based are as follows:

1. Azimuth Accuracy in Degrees:

| ERROR COMPONENT | 2 SIGMA DEVIATION VALUES | SOURCE |
|---|---|---|
| VOR Ground | $\pm 1.4^{\circ}$ | Semi-Automatic Flight Inspection (SAFI) System |
| VOR Air | $\pm 3.0^{\circ}$ | Equipment Manufacturer |
| Course Selection (CSE) | $\pm 2.0^{\circ}$ | FAA Tests |
| Flight Technical (FTE) | $\pm 2.3^{\circ}$ | FAA Tests |
| Total System Error (95% Confidence) | $\pm 4.5^{\circ}$ | (RSS derived) |

2. Range Accuracy

Where DME service is used, the system use accuracy is defined as ±0.5 nm or 3 percent of distance (2 sigma), whichever is greater. This value covers all existing DME avionics. When DME is used with an RNAV system the range accuracy must be at least ±0.2 nm plus 1 percent of the distance (2 sigma).

3. Area Navigation (RNAV)

When RNAV computation equipment is used, an additional error contribution is specified and combined in RSS fashion with the basic VOR/DME system error. The additional maximum RNAV equipment error allowed, per FAA Advisory Circular AC 90-45A, is ±0.5 nm. RNAV system performance and route design are based on the following error budget:

| ERROR COMPONENT | 2 SIGMA DEVIATION VALUES | SOURCE |
|---|---|---|
| VOR Ground | $\pm 1.4^{o}$ | SAFI |
| VOR Air | $\pm 3.0^{o}$ | Equipment Manufacturer and FAA Tests |
| DME Ground | ±0.1 nm | SAFI |

The VOR/DME and RNAV error values identified below result in 95 percent of the aircraft remaining within ±4 nm of the airway centerline out to 51 nm from a VOR facility and within ±4.5 degrees (originating at the VOR facility) of the airway centerline when beyond 51 nm from a VOR facility.

| ERROR COMPONENT | 2 SIGMA DEVIATION VALUES | SOURCE |
|---|---|---|
| DME Air | ±0.2 nm + 1% of Range | Equipment Manufacturer* |
| FTE | ±1.0 nm | FAA Tests** |
| CSE | $\pm 2.0^{o}$ | FAA Tests |
| RNAV System | ±0.5 nm | Equipment Manufacturer and FAA Tests |

*Only DME aircraft equipment with this accuracy or better is used.
**FTE-0.5 nm in the approach phase.

C. Terminal

Terminal routes are transitions from the en route phase to the approach phase. The accuracy capability of navigation systems using the VOR/DME in terms of bearing and distance to the facility is defined in the same manner as decribed for en route navigation. However, the usually closer proximity to facilities provides greater effective system use accuracy, since both VOR and Flight Technical Error are angular in nature and are related to the distance to the facility. The DME distance error is also reduced, since it is proportional to distance from the facility, down to the minimum error capability. Thus the minimum terminal route width is ±2 nm within 25 nm of the facility, based on RSS combination of error elements.

D. Remote Areas

Remote areas are defined as regions which either do not meet the requirements for installation of VOR/DME service or where it is impractical to install this system. These include offshore areas, mountainous areas and a large portion of the State of Alaska. Thus the minimum route width varies and can be greater than ±10 nm. The minimum requirements are shown in Table II-2.1.

E. Low Altitude

Low altitude operations occur in offshore, mountainous, and high density metropolitan areas as well as on domestic routes. For operations from U. S. coastline to offshore points, the following requirements must be met:

(1) Range from shore to 300 nm.

(2) Minimum en route altitude of 500 feet above sea level or above obstructions.

(3) Accuracy adequate to support routes ±4 nm wide or narrower with 95 percent confidence.

(4) Minimum descent altitude to 100 feet in designated areas.

For helicopter operations over land, the following requirements must be met:

(1) Accuracy adequate to support ±2 nm route widths in both en route and terminal areas with 95 percent confidence.

(2) Minimum en route altitudes of 1,200 feet.

(3) Navigational signal coverage adequate to support approach procedures to minimums of 250 feet above obstruction altitudes at heliports and airports.

2.2.2 Approach/Landing Phase

This phase of flight is one of two types: (1) non-precision approach, or (2) precision approach and landing.

TABLE II-2.1 CONTROLLED AIRSPACE NAVIGATION ACCURACY TO MEET CURRENT REQUIREMENTS

| Phase | Sub-Phase | | Altitude (Flight Level) | Traffic Density | Route Width (NM) | Accuracy 2 drms (meters) | System Use Accuracy 2 drms (meters) |
|---|---|---|---|---|---|---|---|
| EnRoute/ Terminal | Oceanic | | FL 275 to 400 | Normal | 60 | | 12.6nm* |
| | Domestic | | FL 180 to 600 | Low | 16 | 2000 | 7,200 |
| | | | | Normal | 8 | 1000 | 3,600 |
| | | | 500 - 18,000 ft. | High | 8 | 1000 | 3,600 |
| | Terminal | | 500 - 18,000 ft. | High | 4 | 500 | 1,800 |
| | Remote | | 500 - 60,000 ft. | Low | 8 to 20 | 1000 to 4000 | 3,600 to 14,400 |
| | Special Helicopter Operations | | 500 - 5000 ft. | Low (Off-Shore) | Not Determined | 1000 to 2000 | 3,600 to 7,200 |
| | | | 500 - 3000 ft. | High (Land) | 4 | 500 | 1,800 |
| Approach and Landing | Non-Precision | | 250 to 3000 ft. above Surface | Normal | | 100 | 150 |
| | Precision | Cat I | 100 to 3000 ft. above Surface | Normal | | ±9.1 meters** at 100 ft. above Surface | ±3 meters*** at 100 ft. above Surface |
| | | Cat II | 50 to 3000 ft. above Surface | Normal | | ±4.6 meters at 50 ft. above Surface | ±1.4 meters at 50 ft. above Surface |
| | | Cat III | 8 to 3000 ft. above Surface | Normal | | ±4.1 meters 8 ft. above Surface | ±0.4 meters 8 ft. above Surface |

* The distribution of this error is detailed in the "Report of the Limited North Atlantic Regional Air Navigation Meeting," dated 1976; ICAO Montreal Canada

** This column is lateral position 2 sigma accuracy in meters for Precision Approach and Landing

*** This column is vertical position 2 sigma accuracy in meters for Precision Approach and Landing.

The general requirements of Section 2.1 apply to the approach/landing phase. In addition, specific procedures and clearance zone requirements are specified in TERPS (United States Standard for Terminal Instrument Procedures, FAA Handbook 8260.3B).

Altimetry accuracy requirements are established in accordance with FAR 91.170 (Federal Aviation Regulations, paragraph 91.170) and are the same as those for the en route/terminal phase.

The minimum performance criteria currently established to meet requirements for the approach/landing phase of navigation are presented in the following sections.

### A. Non-Precision Approach

Non-precision approaches are based on any navigational system that meets the criteria established in TERPS. Minimum safe altitude, obstacle clearance area, visibility minimum, final approach segment area, etc., are all functions of the navigational accuracy available and other factors. The unique features of Area Navigation (RNAV) for non-precision approaches are specified in FAA Advisory Circular No. 90-45A, "Approval of Area Navigation Systems for Use in the U. S. National Airspace System."

While the achieved capability for non-precision approaches varies widely, depending on the location of the navigational facility in relation to the fix location and type of navigational system, approximately 30 percent of the non-precision approach fixes based on VOR in the U. S., achieve a cross track navigational accuracy of $\pm$100 meters (2 sigma) at the missed approach point (MAP). This accuracy is based upon the $\pm$4.5 degrees VOR system use accuracy and the MAP being less than 0.7 nm from the VOR facility.

### B. Precision Approach and Landing

Precision approach and landing radio aids provide vertical and horizontal guidance and position information. The Instrument Landing System (ILS) and Microwave Landing System (MLS) are of this type. International agreements have been made to achieve an all-weather landing capability through an evolutionary process, reducing landing weather minima on a step-by-step basis as technical capabilities and operational knowledge permit. The performance objectives for the various landing categories are as follows:

OPERATIONAL PERFORMANCE OBJECTIVE FOR APPROACH AND LANDING

| Landing Category | Decision Height (feet) | (meters) | Runway Visual Range (feet) | (meters) |
|---|---|---|---|---|
| I | 200 | (61.0) | 2600 | (792) |
| II | 100 | (30.5) | 1200 | (366) |
| IIA | 0 | (0) | 700 | (213) |
| IIIB | 0 | (0) | 150 | (46) |
| IIIC | 0 | (0) | 0 | (0) |

| Category | Minimum Guidance Height (feet) | (meters) | Accuracy Lateral (feet) | (meters) | Vertical (feet) | (meters) |
|---|---|---|---|---|---|---|
| I | 100 | (30.5) | 30.0 | (9.1) | 10.0 | (3.0) |
| II | 50 | (15.3) | 15.0 | (4.6) | 4.0 | (1.2) |
| IIIABC | 8 | (2.4) | 13.5 | (4.1) | 1.2 | (0.4) |

### 2.2.3 Current System Requirements Summary

The system use accuracy criteria to meet the current route requirements are summarized in Table II-2.1. These route widths are based upon present capacities, separation requirements, and obstruction clearance requirements.

## 2.3 FUTURE AVIATION NAVIGATION REQUIREMENTS

Altimetry requirements for vertical separation of 1,000 feet, below Flight Level 290, are not expected to change. Increased altimetry accuracy is needed at and above Flight Level 290 to permit 1,000 feet separation. The required future 3 sigma value of the aircraft altimetry system error has not been specified, but it must be accurate enough to support the 1,000 feet vertical separation at all flight levels.

### 2.3.1 En Route/Terminal Phase

A. Oceanic

Lateral separation specifications have been designed to allow a lateral separation of 60 nm. This was put into effect for certain areas of the North Atlantic in early 1981. The 60 nm separation requires a lateral track error of less than ±12.6 nm (2 sigma). Further lateral separation reductions are desirable.

B. Domestic En Route

At the present time, the number of VOR/DMEs is sufficient to allow most routes to have widths of ±4 nm. This is possible as most VOR facilities are spaced less than 100 nm apart on the route. However, greater spacings are used in low traffic density areas, remote areas, and on most of the high-altitude route structure. Parts of the high-altitude route structure have a distance between VOR facilities resulting in route widths up to 20 nm.

Traffic forecasts indicate that IFR traffic will increase by more than 25 percent by 1990. This may cause route capacity problems before 1990. More use of RNAV will allow the implementation of random and parallel routes with the use of current VOR/DME facilities. No increase in VOR/DME ground accuracy is required to meet the navigational requirements imposed by the air traffic levels estimated for the Year 2000. The current nominal VOR system signal-in-space accuracy that permits 8 nm route widths is ±1,000 meters (2 drms). Any replacement system must have an equivalent accuracy.

C. Terminal

The major change forecasted for the terminal area is the increased use of RNAV and time control to achieve optimum runway utilization and noise abatement procedures. Some current multi-DME RNAV and VOR avionics can provide system use RSS cross track navigational accuracies better than ±500 meters (2 sigma) in terminal areas using the current VOR/DME facilities. A ±500 meter (2 sigma) cross track navigational accuracy is expected to meet the terminal requirements through the Year 2000.

D. Remote Areas

Many of these areas, such as Alaska, the Rocky Mountains and other mountainous areas, offshore, and other similar areas cannot be served easily or in some cases cannot be served at all by VOR/DME. Presently, Non-Directional Beacon (NDB), OMEGA, and privately owned systems such as TACAN are being used in combination to meet the user navigational needs in these areas. OMEGA, Differential OMEGA, and LORAN-C are being evaluated as supplements to VOR/DME to meet these needs. The accuracy and coverage of these systems seem adequate to handle the traffic densities projected for the different areas. For all-weather operations, a system signal in space accuracy of 4,000 meters (2 drms) is proposed, with 1,000 meters (2 drms) or higher accuracy in specific areas.

E. Low Altitude Operations

Both offshore and onshore low-altitude operations will have navigational requirements at least as stringent as those in paragraph 2.2.1 E. and coverage extended from 300 nm to 500 nm from shore. Area navigation should be implemented for low traffic density operations. As traffic density increases, the establishment of low altitude routes may be necessary. Operations in metropolitan areas will require integration of the enroute/terminal phase with non-precision and precision approaches.

## 2.3.2 Approach/Landing Phase

A. Non-Precision Approach

Changes in navigational requirements for non-precision approaches are expected due to new and/or modified noise abatement procedures and encroachment on obstacle clearance zones by urban development.

The requirement in the non-precision approach procedures is that the navigational system be able to perform as well as an on-airport VOR. This requirement has been selected for the following reasons:

- o Approximately 30 percent of the runways with non-precision approaches use on-airport VOR.
- o These are typically used at the busiest airports. Since they are in urban areas, they have had the most pressure for reduction of clearance areas for additional noise abatement and obstacle encroachment problems.
- o Any replacement navigational system must operate at least as well in all navigational phases as the system it is replacing.

The critical factor in the final approach segment of a non-precision approach is the size of the obstacle clearance area. This is determined by establishing an area defined by taking the 95 percent (2 sigma) lateral navigational system use error and adding a 1 nautical-mile buffer on either side of it from the VOR to the final approach fix. This is depicted in Figure II-2.1 for an on-airport VOR, where the VOR is the missed approach point (MAP). The critical dimensions in the figure are the widths of the obstacle clearance area at the VOR, the visibility minimum distance from the VOR, and the Final Approach Fix (FAF).

The ±100 m (2 sigma) system accuracy is based on a 0.7 nm visibility minimum distance from the VOR. This is the distance where the pilot should obtain visual cues of the airport and/or runway. Current RNAV equipments cannot meet this requirement; however, it seems feasible to provide improved RNAV systems that can meet this requirement.

B. Precision Approach and Landing

The requirements for precision approaches and landings are not expected to change by the Year 2020 and are presented in Paragraph 2.2.2 B.

In order to enhance all-weather operations, a uniform guidance accuracy requirement is proposed as follows:

Accuracy at 8 Feet (2.4 Meters) Above Surface (2 sigma)

| | |
|---|---|
| Lateral | ±13.5 feet (±4.1 meters) |
| Vertical | ±1.2 feet (±0.4 meters) |

### 2.3.3 Future System Performance Requirements Summary

Table II-2.2 represents the best estimate of future minimum accuracy and route criteria to meet the aviation navigational requirements up to the Year 2000.

The effectiveness of meeting one or more of these requirements with a combination of subsystems and alternatively with a minimum number of subsystems should be assessed and fully coordinated among government and users.

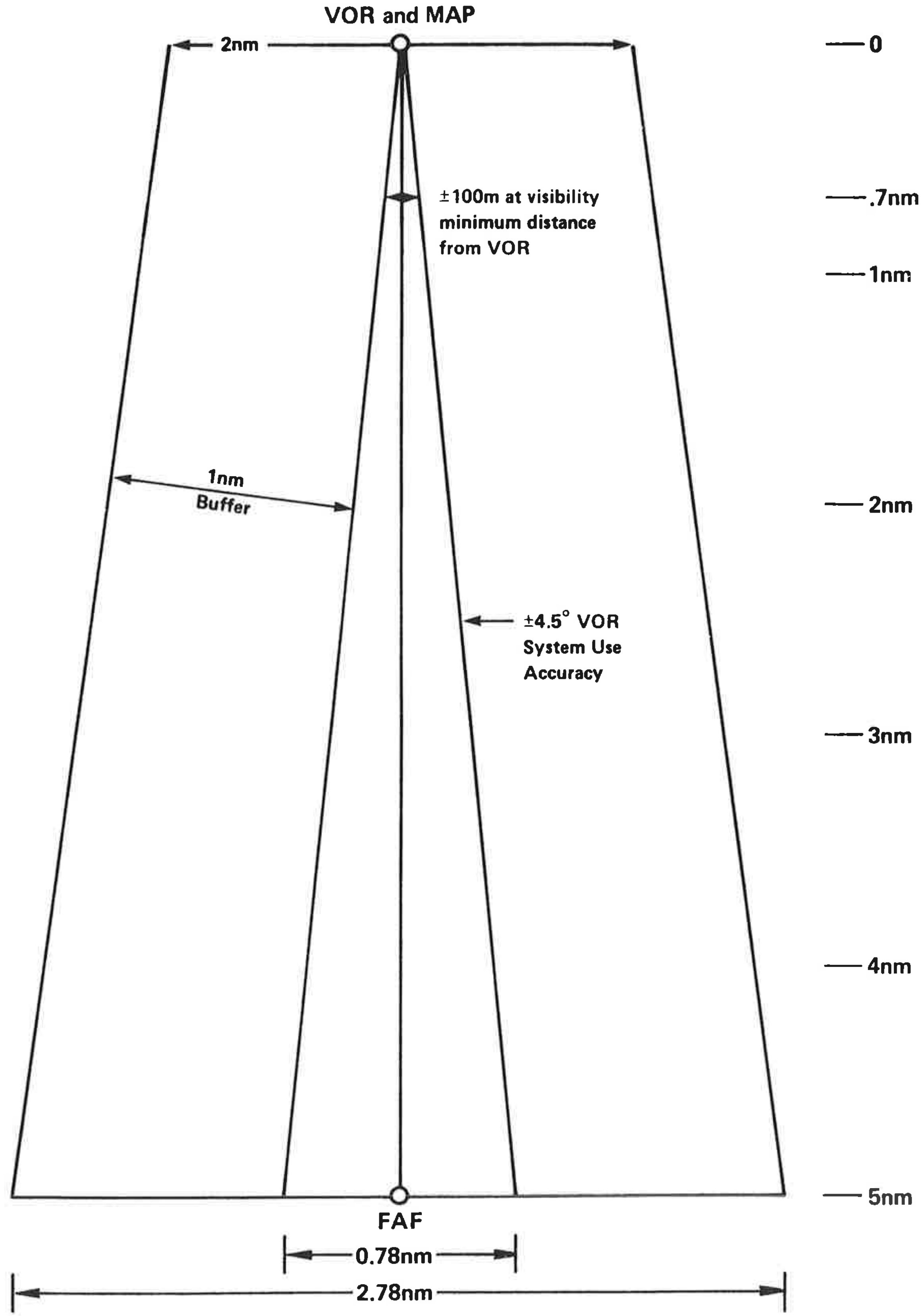


FIGURE II-2.1 NON-PRECISION APPROACH OBSTACLE CLEARANCE AREA FOR CURRENT VOR WITH MAP AT VOR FACILITY

TABLE II-2.2 CONTROLLED AIRSPACE AVIATION NAVIGATION ACCURACY TO MEET PROJECTED FUTURE REQUIREMENTS

| Phase | Sub-Phase | Altitude (Flight Level) | Traffic Density | Route Width (NM) | Source Accuracy 2drms (meters) | System Use Accuracy 2 drms (meters) |
|---|---|---|---|---|---|---|
| EnRoute/ Terminal | Oceanic | FL 275 to 400 | Normal | less than 60 | | better than 12.6nm |
| | Domestic | FL 180 to 600 | Normal | 8 | 1000 | 3,600 |
| | | | High | 8 | 1000 | 3,600 |
| | | 500 ft to FL 180 | Normal | 8 | 1000 | 3,600 |
| | Terminal | 500 ft to FL 180 | High | 4 | 500 | 1,800 |
| | Remote | 500 ft to FL 600 | Normal | 8 to 20 | 1000 to 4000 | 3,600 to 14,400 |
| | Special Helicopter Operations | 500 ft to 5000 ft | Low (Off-Shore) | 8 | 1000 | 3,600 |
| | | 500 ft to 3000 ft | High (Land) | 4 | 500 | 1,800 |
| Approach and Landing | Non-Precision | 250 to 3000 ft. above surface | Normal | | 100 | 150 |
| | Precision | 8 ft. above surface | Normal | | ± 4.1 meters * | +0.4 ** |

* This value is the 2 sigma azimuth accuracy in meters at the reference datum on the runway.
** This value is the 2 sigma elevation accuracy in meters at the runway threshold.

Due consideration should be given to the situation that not all users need all services. Pending the results of this assessment there is no compelling argument from the aviation user's standpoint for a single source of navigation information.

The life-cycle costs of each subsystem to the government and each category of user must be an important element of this continuing assessment.

PART II

## 3. CIVIL MARINE RADIONAVIGATION

The navigational requirements of a vessel depend upon its general type and size, the activity in which the ship is engaged, e.g., point-to-point transit, fishing, the geographic region in which it operates, e.g., ocean, coastal, and other factors. Safety requirements for navigation performance are dictated by the physical constraints imposed by the environment and the vessel, and the need to avoid the hazards of collision, ramming, and grounding.

The foregoing discussion of phases of marine navigation (Part II-1.3.2) sets the framework for defining safety of navigation requirements. However, the economic and operational dimensions also need to be considered for the wide diversity of vessels that traverse the oceans and U.S. waters. For example, accurate worldwide navigation (beyond that needed for safety) is important particularly to the economy of large seagoing ships whose hourly operating costs are high. For fishing and oil exploration vessels, the ability to locate precisely and return to productive or promising areas and avoid underwater obstructions provides important economic benefits. Search and Rescue (SAR) effectiveness is similarly dependent on accurate navigation in the vicinity of a maritime distress incident.

For purposes of system planning, the Government seeks to satisfy minimum safety requirements for each phase of navigation and to maximize the economic utility of the service for users. Since the vast majority of marine users are not required to carry any navigational equipment, and will do so only if persuaded by "individual cost-benefit analysis," this Governmental policy helps to promote maritime safety through the "carrot" of economic incentive being provided simultaneously.

Tables II-3.1, II-3.2 and II-3.3 identify system performance needed to satisfy current maritime user requirements or to achieve special benefits in four of the five phases of marine navigation. The tables are divided into two categories. The upper half are those related to safety of navigation. The Government recognizes an obligation to satisfy these requirements for the overall national interest. The lower half are specialized requirements or characteritics needed to provide special benefits to discrete classes of maritime users (and additional public benefits which may accrue from services provided by users). The Government does not recognize an absolute commitment to satisfy these, but does endeavor to meet them if achievable at a cost that is justified by the benefits derived which are in the national interest. For the purpose of comparing the performance of systems, the requirements are categorized in terms of system performance characteristics which represent the minimum performance considered necessary to satisfy the requirements or achieve special benefits.

TABLE II-3.1 CURRENT MARITIME USER REQUIREMENTS/BENEFITS FOR PURPOSES OF SYSTEM PLANNING AND DEVELOPMENT - OCEAN PHASE

| Requirements | Measures of Minimum Performance Criteria to Meet Requirements | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Accuracy (2 drms) | | | | | | | | | |
| | Predictable | Repeatable | Relative | Coverage | Availability | Reliability | Fix Interval | Fix Dimension | Capacity | Ambiguity |
| Safety of Navigation – All Craft | 2-4NM(3.7-7.4km) Minimum 1-2NM(1.8-3.7km) DESIRABLE | – | – | Worldwide | 95% full cap. 99% Fix at least every 12 hours | ** | 15 Mins. or Less Desired; 2 hrs Maximum | Two | Unlimited | Resolvable with 99% Confidence |

| Benefits | Measures of Minimum Performance Criteria to Achieve Benefits | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Large Ships Maximum Efficiency | 0.1-0.25NM (185-460m) * | – | – | Worldwide, except Polar Regions | 99% | ** | 5 min. | Two | Unlimited | Resolvable with 99% Confidence |
| Hydrography Science, Resource Exploitation | 10-100m * | 10-100 m * | – | Worldwide | 99% | ** | 1 min. | Two | Unlimited | Resolvable with 99% Confidence |
| Search Operations | 0.1-0.25NM (460m.) | 0.25NM | 185 m. | National Maritime SAR Region (NPAC, NWLAN) | 99% | ** | 1 min. | Two | Unlimited | Resolvable with 99% Confidence |

* Based on stated user need.

** Dependent upon mission time.

TABLE II-3.2 CURRENT MARITIME USER REQUIREMENTS/BENEFITS FOR PURPOSES OF SYSTEM PLANNING AND DEVELOPMENT - COASTAL PHASE

| Requirements | Measures of Minimum Performance Criteria to Meet Requirements | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Accuracy (2 drms) | | | | | | | | | |
| | Predictable | Repeatable | Relative | Coverage | Availability | Reliability | Fix Interval | Fix Dimension | Capacity | Ambiguity |
| Safety of Navigation – All Ships | 0.25nm (460m) | – | – | U.S. Coastal Waters | 99.7% Minimum | ** | 2 Min. | Two | Unlimited | Resolvable with 99.9% Confidence |
| Safety of Navigation – Recreational Boats & Other Smaller Vessels | 0.25nm-2nm (460-3700 m) | – | – | U.S. Coastal Waters | 99% Minimum | ** | 5 Min. | Two | Unlimited | Resolvable with 99% Confidence |

| Benefits | Measures of Minimum Performance Criteria to Achieve Benefits | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Commercial Fishing (including Commerical Sport Fishing) | 0.25 nm (460 m.) | 50-600 ft. (15-180m) | – | U.S. Coastal/ Fisheries Areas | 99% Minimum | ** | 1 Min. | Two | Unlimited | Resolvable with 99.9% Confidence |
| Hydrography Science, Resource Exploitation | 1.0-100 m * | 1.0-100m * | – | U.S. Coastal Area | 99% Minimum | ** | 1 Sec. | Two | Unlimited | Resolvable with 99.9% Confidence |
| Search Operations, Law Enforcement | 0.25 nm (460 m.) | 300-600 ft. (90-180m) | 300 ft. (90m) | U.S. Coastal, Fisheries Areas | 99.7% Minimum | ** | 1 Min. | Two | Unlimited | Resolvable with 99% Confidence |
| Recreational Sports Fishing | 0.25nm (460 m.) | 100-600 ft. (30-180m) | – | U.S. Coastal Areas | 99% Minimum | ** | 5 Min. | Two | Unlimited | Resolvable with 99.9% Confidence |

* Based on stated user need.
** Dependent upon mission time.

TABLE II-3.3 CURRENT MARITIME USER REQUIREMENTS/BENEFITS FOR PURPOSES OF SYSTEM PLANNING AND DEVELOPMENT - HARBOR APPROACH AND HARBOR PHASES

| Requirements | Measures of Minimum Performance Criteria to Meet Requirements | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Accuracy (2 drms) | | | | | | | | | |
| | Predictable | Repeatable | Relative | Coverage | Availability | Reliability | Fix Interval | Fix Dimension | Capacity | Ambiguity |
| Safety of Navigation – Large Ships & Tows | 25-65 Ft (8-20 m) *** | – | – | U.S. Harbor & Harbor Approaches | 99.7% Minimum | ** | 6-10 Seconds | Two | Unlimited | Resolvable with 99.9% Confidence (Minimum) |
| Safety of Navigation – Smaller Ships | *** | *** | | U.S. Harbors, & Harbor Approaches | 99.7% | ** | *** | Two | Unlimited | Resolvable with 99.9% Confidence (Minimum) |
| Hydrography Science, Resource Exploitation | 1-5 m * | 1-5 m * | | U.S. Harbors, & Harbor Approaches | 99% Minimum | ** | 1 Second | Two | Unlimited | Resolvable with 99.9% Confidence |

| Benefits | Measures of Minimum Performance Critieria to Achieve Benefits | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Fishing Recreational, and Other Small Vessels | *** | *** | – | U.S. Harbor, & Harbor Approaches | 99.7% | ** | *** | Two | Unlimited | Resolvable with 99.9% Confidence |

* Based on stated user need
** Dependent upon mission time
*** Varies from one harbor to another

## 3.1 OCEAN PHASE

The requirements for safety of navigation in the ocean phase for all ships are given in Table II-3.1. These requirements must provide the master with a capability to avoid hazards in the ocean (e.g., small islands, reefs) and to plan correctly the approach to land or restricted waters. For operational purposes, repeatability is necessary to locate and return safely to the vicinity of a maritime distress, as well as for special activities such as hydrography, research, etc. Economic efficiency in safe transit of open ocean areas depends upon the continuous availability of accurate position fixes to enable the vessel to follow the shortest safe route with precision and, thus, minimize transit time.

### 3.1.1 Requirements

For safe general navigation under normal circumstances, the requirements for the accuracy and frequency of position fixing on the high seas are not very strict. As a minimum, these requirements include a predictable accuracy of 2 to 4 nm coupled with a maximum fix interval of 2 hours or less. These minimum requirements would permit reasonably safe oceanic navigation, provided that the navigator understands and makes allowances for the probable error in navigation, and provided that more accurate navigational service is available as land is approached. While these minimum requirements would permit all vessels to navigate with relative safety on the high seas, more desirable requirements would be predictable accuracy of 1 to 2 nm and a fix interval of 15 minutes or less. The navigation signal should be available 95 percent of the time. Further, in any 12 hour period, the probability of obtaining a fix from the system should be at least 0.99.

Larger recreational craft and smaller commercial fishing vessels which sail beyond the range of coastal navigation systems require, for a reasonable level of safety, some means of establishing their position reliably at intervals of a few hours at most. Even more so than with larger ships, this capability is particularly important in time of emergency or distress. Many (perhaps most) of these craft, however, will accept the risk of ocean sailing without reliable radionavigation unless that capability is available at relatively low cost.

### 3.1.2 Minimum Performance Criteria

Economic efficiency in trans-oceanic transportation, special maritime activities and safety in emergency situations require or benefit from navigational accuracy higher than that needed for safety in routine, point-to-point ocean voyages. These requirements are summarized in Table II-3.1. The predictable accuracy requirements may be as stringent as 10 meters for special maritime activities, and may range to 0.25 nm for large, economically efficient vessels, including search operations. Search operations must also have a repeatable accuracy of at least 0.25 nm. As indicated in Table II-3.1, the required fix interval may range from as low as once per five minutes to as high as once per minute. Signal availability must be at least 95 percent and approach 99 percent for all users. These requirements are based on current estimates and are to be used for the purposes of system planning. There has not been sufficient analysis to establish quantitative relationships between navigational accuracy and economic efficiency. The expensive, satellite-based navigation systems used by ships engaged in science and resource exploration, and the increasing use of relatively expensive satellite navigation by merchant ships and larger, ocean-going fishing vessels are evidence of the perceived value attached to highly accurate ocean navigation by the vessel owners.

## 3.2 COASTAL PHASE

There is need for continuous, all-weather radionavigation service in the coastal area providing, at the least, the position fixing accuracy required to satisfy minimum safety requirements for general navigation. These requirements are delineated in Table II-3.2. Further, the total navigational service in the coastal area must provide service of useful quality, be within the economic reach of all classes of mariners, and be sufficient to assure that no boat or ship need be lost or endangered, or that the environment and public safety not be threatened, because a vessel could not navigate safely with reasonable economic efficiency.

### 3.2.1 Requirements

Requirements on the accuracy of position fixing for safety purposes in the Coastal phase are established by:

A. The need for larger vessels to navigate within the designated one-way traffic lanes at the approaches to many major ports, in fairways established through offshore oil fields, and at safe distances from shallow water.

B. The need to define accurately, for purposes of observing and enforcing U.S. laws and international agreements, the boundaries of the Fishery Conservation Zone, the U.S. Customs Zone, and the territorial waters of the U.S.

### 3.2.2 Minimum Performance Criteria

Government studies established that a navigation system providing a capability to fix position to an accuracy of 0.25 nm will satisfy the minimum safety requirements if a fix can be obtained at least every 15 minutes. As a secondary economic factor, it is required that relatively higher repeatable accuracy be recognized as a major advantage in the consideration of alternative candidate radionavigation systems for the coastal area. As indicated in Table II-3.2, these requirements may be relaxed slightly for the recreational boat and other small vessels.

In such activities as marine scientific research, hydrographic surveying, commercial fishing, and petroleum or mineral exploration, as well as in Navy operations, there may be a need to establish position in the coastal area with much higher accuracy than that needed for safety of general navigation. In many of these special operations which require highly accurate positions, the use of radiodetermination would be classified as radiolocation rather than radionavigation. As shown in Table II-3.2, the most rigid requirement of any of this general group of special operations is for seismic surveying with a repeatable accuracy on the order of 1 to 100 meters (2 drms), and a fix rate of once per second for most applications.

## 3.3 HARBOR AND HARBOR APPROACH PHASES

The pilot of a vessel in restricted waters must direct its movement with great accuracy and precision to avoid grounding in shallow water, and avoid collisions with other craft in congested waterways. Unable to turn around, and severely limited in the ability to stop to resolve a navigational problem, the pilot of the large vessel (or a tow boat and barge combination) may find it necessary to hold the total error in navigation within limits measured in tens of feet, while negotiating the straight channel segments and turns dictated by the configuration of the channel.

### 3.3.1 Requirements

To navigate safely, the pilot needs highly accurate verification of position almost continuously, together with information depicting any tendency for the vessel to deviate from its intended track and a nearly continuous and instantaneous indication of the direction in which the pilot should steer. These requirements are given in Table II-3.3.

### 3.3.2 Minimum Performance Criteria

The required accuracy varies from one harbor to another. In the most restricted channels, predictable accuracy in the range 8 to 20 meters (2 drms) is needed. A need exists for additional studies to more accurately determine the radionavigation requirements of various sized vessels while navigating in the restricted confines of inland waterways and the Harbor and Harbor Approach phase of navigation. Table II-3.3 represents a limited attempt to identify system requirements. Further studies are also needed to identify those harbors which could benefit most from an improvement in system accuracy. The requirements for smaller vessels are currently under study but, in a given harbor, these requirements are somewhat less stringent than for large ships. For seismic surveying, the accuracy needs increase to one to five meters (2 drms) with a fix rate of one second.

## 3.4 INLAND WATERWAY PHASE

Very large amounts of commerce move on the United States Inland Waterway system, much of it in slow-moving, comparatively low-powered tug and barge combinations. Tows on the inland waterways, although comparatively shallow in draft, may be longer and wider than large seagoing ships which call at U.S. ports. Navigable channels used by this inland traffic are often narrower than the harbor access channels used by large ships. Restricted visibility and ice cover present problems in Inland Waterway navigation, as they do in Harbor Approach and Harbor navigation. The long, ribbon-like nature of the typical inland waterway presents special problems to the prospective use of precise, land-based area navigation systems. The continual movement of the navigable channels in some unstable waters creates additional problems to the prospective use of any radionavigation system which provides position measurements in a fixed coordinate system. The probable consequences of a grounding in inland waterway navigation, however, and thus the overall level of risk, are somewhat lower than for large, seagoing ships in restricted waters.

3.4.1 Requirements

Requirements based on the consideration of practically achievable performance and expected benefits have not been defined. However, Research, Engineering & Development (R,E&D) in Harbor Approach and Harbor navigation is expected to produce results which will have some application to Inland Waterway navigation. Thus, no table or chart is provided for Inland Waterway navigation.

3.4.2 Minimum Performance Criteria

These criteria have not been determined. The R,E&D plans in Section IV discuss the current and future efforts in the area of Inland Waterway navigation.

3.5 DISCUSSION OF FUTURE REQUIREMENTS

The marine navigational requirements presented in the preceding discussions and tables represent the best quantitative judgment of current performance that would satisfy a broad range of needs. However, they are the products of current technology and current operating practices, and therefore are subject to revision in an evolutionary and dynamic manner. The principal factors which will impact the formulation of future requirements are safety, economics, environment, energy conservation, and Chart Reference Systems.

3.5.1 Safety

A. Increased Risk from Collision, Grounding and Ramming

Cargoes of particular hazard (petroleum, chemicals, etc.) are carried in great volumes in U.S. coastal and inland waterways. Energy imports of bulk crude oil and Liquefied Natural Gas (LNG) may increase to meet demand as U.S. domestic supplies decrease. Casualties involving vessels carrying these materials pose grave potential dangers to the enviroment and public at large.

B. Increased Size and Decreased Maneuverability of Marine Vessels

The desire to minimize costs and to capture economics of scale in marine transportation have led to design and construction of larger vessels and unitized tug/barge combinations, both of which are relatively less powerful and maneuverable than their predecessors. Consequently, navigational requirements need to compensate for their relative shortfalls.

C. Greater Need for Traffic Management/Navigational Surveillance Integration

The foregoing trends foreshadow a growing governmental involvement in marine traffic control in order to assure reasonable safety in U.S. waters. Navigation systems are an essential component of such traffic management systems.

### 3.5.2 Economics

A. Greater Congestion in Harbor Approaches and Inland Waterways

In addition to the safety penalty implicit in greater congestion in restricted waterways, there are economic disadvantages if shore facilities are not used effectively and efficiently. Navigation systems can contribute to better productivity and decreased delay in transit.

B. All Weather Operations

Low visibility and ice-covered waters presently impede full utilization of the marine transportation mode. Joint government/industry efforts may be applied to remove these restrictions.

### 3.5.3 Environment

Greater Emphasis on Offshore Resource Exploitation: As onshore energy supplies are depleted, resource exploration and exploitation will move further offshore to the U.S. Outer Continental Shelf and to harsher environments, such as the North Slope of Alaska. Further, more intensive U.S. fishing activity is anticipated as the result of legislative initiatives and the creation of the U.S. Fishery Conservation Zone. In sum, both sets of activities may generate demands for navigational services of higher quality and for broadened geographic coverage in order to allow environmentally sound exploitations.

### 3.5.4 Energy Conservation

Increased Fuel Cost: Six percent of free world fuel consumption is devoted to marine transportation. The need to conserve energy resources and to reduce costs provides powerful incentives for increased transportation efficiency, some of which could come from better navigation systems.

### 3.5.5 Chart Reference Systems

Most nautical charts, as presently published by various authorities, including those produced by the Defense Mapping Agency Hydrographic/Topographic Center (DMAHTC) and the Office of Charting and Geodetic Services (C&GS) of the National Ocean Service, National Oceanic and Atmospheric Administration (NOS/NOAA), are based on regional horizontal datums which have been defined over the years independently of each other. In addition, in many parts of the world the positional accuracy of chart features such as hazards to navigation sometimes varies from chart to chart and, in some cases, within a chart. Certain charts for waters in the Southern Hemisphere, for example, do not show islands in their correct geodetic positions, absolute or relative.

Nautical charts serve a definite role by communicating details of hydrography and the adjacent landmass to the mariner for the purpose of permitting safe navigation. A navigational fix, however, based on any positioning or geodetic system other than the chart's datum, will not be directly plottable on that chart. A practical solution in such a case is to transform the navigational position coordinates to the local or regional datum on which the chart is based.

Modern sophisticated navigational positioning is based on satellite systems which are geocentric by definition, and these satellite coordinate systems differ significantly in many cases with the local or regional datums of nautical charts. In addition to this difference, the plotted detail such as soundings and navigational aids, contain a minimum plottable error that ranges between 0.5 mm to 1.0 mm on paper. Therefore, datums and limited chart accuracy must be considered when a navigational fix is plotted by a navigator on a nautical chart.

The satellite system positions are now computed on a world geodetic system known as WGS 72. This system is scheduled for updating as WGS 84 by December 1984. Transformation values from WGS 72 to most regional datums are available by DMAHTC and these will be recomputed for the new WGS 84. By means of datum shift notes on a nautical chart, navigational "fixes" or positions, based on the modern satellite systems, can normally be referred to the identifiable geodetic control of the chart and vice-versa. For charts based on WGS, the satellite-derived navigational position can be plotted directly on the chart. DMAHTC in the last decade published all new and recompiled charts on WGS 72, and on many others issued datum shift notes for the navigator.

Through the auspices of the International Hydrographic Organization, the United States is promoting WGS as the internationally recognized coordinate system to which most of the various national datums on the charts can be referred. Decision No. 28 at the XII$^{th}$ International Hydrographic Conference held at Monaco in April 1982, in fact, recommended that WGS be used as a basic worldwide reference system with the International Hydrographic Bureau acting as the focal point for distributing WGS transformation parameters, initially provided by the United States.

Improvements in worldwide navigational accuracy, which are anticipated with the implementation of the GPS in the late 1980's will be significant. However, one's ability to safely navigate with relation to hazards along the coastlines of the world and on the high seas will remain limited where accurate, up-to-date hydrography and associated topographic features are not all positioned on the same satellite-based WGS reference system.

# PART II

## 4. CIVIL LAND RADIONAVIGATION

Government studies have identified a number of areas in both the automatic vehicle monitoring (AVM) and site registration phases where productivity and operational improvements have been predicted. Since land application of radiolocation adopted systems has not been widely adopted by the civil community, no official requirements or systems have been recognized by the Government.

### 4.1 AUTOMATIC VEHICLE MONITORING PHASE

#### 4.1.1 Preliminary Requirements

There is no definitive statement of requirements for AVM service since it is still under investigation. It appears that there are requirements in safety, transportation management and economic areas.

#### 4.1.2 Preliminary Minimum Performance Characteristics

Study efforts and field measurements to date have led to some preliminary estimates of accuracies and other performance characteristics required to make radiolocation service beneficial to various user groups. These data are shown in Table II-4.1. No other characteristics have been determined.

### 4.2 SITE REGISTRATION PHASE

#### 4.2.1 Preliminary Requirements

There are no definitive statements of requirements for this service since it is still under investigation. It appears that there are requirements in both the safety and economic areas.

#### 4.2.2 Preliminary Minimum Performance Characteristics

Study efforts and field measurements to date have led to some preliminary estimates of accuracies required to make radiolocation service beneficial to various user groups. These data are shown in Table II-4.1. No other characteristics have been determined.

## TABLE II-4.1 LAND NAVIGATION REQUIREMENTS

MINIMUM REQUIREMENTS

| APPLICATION | REPEATABLE ACCURACY (2 drms) * | COVERAGE | AVAILABILITY | FIX RATE ** | FIX DIMENSION | CAPACITY | AMBIGUITY |
|---|---|---|---|---|---|---|---|
| Public Safety<br>Urban Police, EMS<br>Rural Police, EMS<br>State Police | <br>250 ft.<br>1000 ft.<br>1000 ft. | <br>Urban Area<br>County<br>State | 99.7% | <br>1 sec.<br>1 sec.<br>1 sec. | Two | Unlimited | Resolvable with 99.9% Confidence |
| Transportation<br>Urban Buses<br>Taxi<br>Delivery Truck<br>Truck<br>(Hazardous Cargo) | <br>500 ft.<br>500 ft.<br>1000 ft.<br>10000 ft. | <br>Urban Area<br>Urban Area<br>Urban Area<br>Nationwide | 99.7% | <br>1 sec.<br>1 sec.<br>1 sec.<br>1 sec. | Two | Unlimited | Resolvable with 99.9% Confidence |
| Highway Safety<br>Planning<br>(Traffic Records,<br>Highway Inventory,<br>Highway Main.) | 100 ft. | State | 99.7% | 1 sec. | Two | Unlimited | Resolvable with 99.9% Confidence |
| Resource Management | 100 ft. | Nationwide | 99.7% | 1 sec. | Two | Unlimited | Resolvable with 99.9% Confidence |

* Requirement under study, values noted are current estimates.

** Fix Rate of navigation system, user update rate dependent on application and characteristics of communication link.

PART II

# 5. MILITARY RADIONAVIGATION

Military forces must be prepared to conduct operations anywhere in the world, in the air, on and under the sea, on land, and in some cases, above the atmosphere. During peacetime, military platforms must conform to applicable national and international "rules of the road" in controlled airspace, on the high seas, and in coastal areas. However, military planning must consider the possibility of operations in a hostile environment.

## 5.1 GENERAL REQUIREMENTS

Military navigation systems should have the following characteristics:

A. Provide worldwide coverage

B. Be user passive

C. Be capable of denying use to the enemy

D. Have no saturation limit

E. Be resistant to meaconing,* interference, jamming and intrusion (MIJI)

F. Be resistant to natural disturbance and hostile attack

G. Provide effective realtime response

H. Be available for combined military operations with allies

I. Have no frequency allocation problem

J. Provide common grid for all users

K. Provide position accuracy not degraded by changes in altitude for air and land forces or by time of year or time of day

L. Retain accuracy while the user vehicle is employed in high "G" maneuvers

M. Be maintained by operative level personnel

N. Be continuously available for fix information

O. Be self-contained in the user vehicle.

*Meaconing refers to imitative navigational signal deceptions.

No single system or combination of systems currently in existence meets all of the approved military navigation requirements. No known system can provide a common grid for all users, be passive, and at the same time be self-contained and yield the world-wide accuracies required. The nature of military operations requires that essential navigational services must be available with the highest possible confidence that these services will equal or exceed mission requirements. This, among other considerations, requires that military operations use a variety of navigational techniques and redundant installations on the various weapon system platforms.

While general military requirements remain fairly constant, continuous review is required because of the impact of new technology, weapon system modifications, the dynamics of our national policy interests and non-military environment to which the military must respond. Current indications are that a navigation concept based on an advanced navigation satellite system with global precision coverage, incorporating supplementary self-contained special-purpose systems, will be the most effective combination of systems over the next decade. This system, the Global Positioning System (GPS), is currently in the Full Scale Development phase. GPS will have a major impact on military operations. As this system becomes operational, the use of older systems will be constantly reviewed. In some cases, unique military requirements will also be affected. However, unique requirements will be considered as additional data and experience with GPS become available.

## 5.2 SERVICE REQUIREMENTS

The JCS Master Navigation Plan provides specific Service and Defense Mapping Agency (DMA) requirements for navigation and positioning accuracy organized by primary missions and functions with specifically related accuracy requirements. These requirements are used for information and guidance in the development and procurement of military navigation systems.

PART II

# 6. SPACE RADIONAVIGATION

Several program areas within NASA are engaged in the evaluation of GPS for precise position determination as a means of meeting space needs, for scientific studies, and for effecting economics in the use of space. These include the following uses of GPS which are discussed herein:

A. For control and navigation of space missions, such as the Space Shuttle and automated spacecraft.

B. For determining in real time a position reference system for space platforms for in-orbit pointing of remote sensing devices.

C. For real-time spacecraft position data to $\pm 1$ km to be incorporated in the telemetered data stream of geophysical (solar-terrestrial) spacecraft or Spacelab payloads.

D. For further post-pass refinement of orbit data for data analysis when greater accuracy is required.

## 6.1 NAVIGATION AND CONTROL

NASA is considering use of the GPS as the primary basis for navigation of the Space Shuttle in the future. This is to include the launch phase, in-flight position determination, and the reentry phase. Other methods (range and range rate tracking, inertial navigation Tracking and Data Relay Satellite System (TDRSS), etc.) will be backup modes. This assumes that GPS determined positions will be within the 10-meter Circular Error Probable (CEP) design point.

Since 1982, the Shuttle has been transporting free-flyer payloads into orbit. Many of these payloads, after release, will transfer to other earth orbits or will be placed in escape trajectories. For some of these missions, GPS would be useful to assure proper orbit insertions or would be useful in minimizing ground control.

To minimize the cost of operating in space, NASA is planning for Shuttle to retrieve and return payloads to earth. This requires that free-flyers be capable of adjusting orbit to rendezvous with Shuttle. The free-flyer must be brought within close proximity of the Shuttle to permit capture by a crew-operated Remote Manipulator System. Obviously, the safety of the Shuttle crew and successful retrieval depends on an accurate knowledge of the realtime position of the satellite and of the Shuttle. Here again, it is anticipated that GPS would be useful in simplifying satellite rendezvous procedures.

## 6.2 REAL-TIME POSITION REFERENCE SYSTEM

Many experiments to be flown on the Space Shuttle or free-flyers would benefit from knowing precisely the platform location as a reference for pointable observing systems. Payloads aboard the orbiter will receive ephemeris data of the orbiter with no reduction in accuracy. The importance of this information derives primarily from the efficiencies achievable by acquiring optimized data for a particular study. For instance, Lidar and limb scanning sensors intended to measure atmospheric aerosols and particulates, imagery of specific locations on the earth's surface, and direct narrow-band communication experiments would all benefit from an accurate knowledge (5 to 10 meters) of the three-dimensional location of the platform. With less accurate information, more data would have to be collected to assure that the primary area is covered.

Geophysical payloads need to know the positions where measurements are made. Generally, a precision of $\pm 1$ km in realtime is adequate, but more accurate data are sometimes needed for special studies. In those cases, post-flight determinations are acceptable.

In 1983, NASA initiated the TDRSS service. This is to be followed by the closing of most of the currently existing network of ground stations for satellite communication and tracking. The TDRSS (two satellites at synchronous orbit) is capable of realtime satellite positioning to 30 to 50 meters in cross track and 150 to 250 meters in along track. Precision, non-realtime, orbit determination via TDRSS is expected to yield 20-meter CEP. While these capabilities will meet most of NASA tracking requirements for near-earth missions, they are not adequate for direct registration of multispectral scenes acquired using Landsat.

## 6.3 POST-PASS PRECISION ORBIT DETERMINATION

At present, missions requiring precise orbital data make use of Doppler tracking, range and range rate tracking, and laser ranging. Computation of the orbit is achieved at considerable expense using complicated modeling which incorporates satellite frontal area as a function of orientation (for drag, radiation pressure, and earth albedo), gravity field to degree and order 32, and all available tracking data. For missions such as GEOS-3 or Seasat final orbits are accurate to a few meters (GEOS-3 orbit calculations were adjusted using altimetric data for ascending and descending orbits).

Altimetric measurements of the ocean, radar and optical imaging of land areas and geopotential field measurements must be related to points on the earth. In the case of Landsat multi-spectral data, it is required that successive images be registrable to one-half of a pixel (minimum detectable spatial resolution). For Landsat-D (1983), registration is required to 15 meters. Later missions will require registration to 0.1 pixel or better than 2 meters. This is beyond the current GPS capability. It is apparent that for long-life missions (3 to 5 years), which require this accuracy, significant economies could be achieved by replacing post-pass determinations with actual GPS data. Hence, for remote sensing missions, it is particularly important that the precision-coded signal from the GPS be available to NASA for onboard satellite tracking. Otherwise, expensive ground processing of intermittent range and Doppler tracking samples from the Ground Satellite

Tracking and Data Network (GSTDN) or TDRSS must be accomplished. These tracking samples are normally used to determine spacecraft position many days, weeks, or even months after mission sensor images of interest are transmitted from the NASA spacecraft. With the availability of Precise Positioning Service (PPS) GPS signals, accurate position estimates would be available every 100 milliseconds for transmission with the telemetry stream from the satellites directly to image users instantaneously.

# PART III

# RADIONAVIGATION SYSTEM CHARACTERISTICS

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## PART III

## 1. RADIONAVIGATION SYSTEMS

This part of the report addresses the characteristics, capabilities, and limitations of existing and proposed major radionavigation systems. The systems covered are:

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

### 1.1 HYBRID SYSTEMS

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

### 1.2 DIFFERENTIAL APPLICATIONS

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

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

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

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

It should be noted however, that no standards have been developed for the transmission of differential corrections with the exception of OMEGA. The Performance Standards for Differential OMEGA Correction Transmitting Stations, Resolution A.425 (XI), published by the Inter-Governmental Maritime Consultative Organization (IMCO) on November 15, 1979, provides guidelines for the transmission of Differential OMEGA corrections.

PART III

## 2. RADIONAVIGATION SYSTEM PARAMETERS

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

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

### 2.1 SIGNAL CHARACTERISTICS

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

### 2.2 ACCURACY

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

#### 2.2.1 Statistical Measure of Accuracy*

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

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

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

#### 2.2.2 Types of Accuracy

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

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

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

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

### 2.3 AVAILABILITY

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

### 2.4 COVERAGE

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

## 2.5 RELIABILITY

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

## 2.6 FIX RATE

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

## 2.7 FIX DIMENSIONS

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

## 2.8 SYSTEM CAPACITY

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

## 2.9 AMBIGUITY

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

## PART III

## 3. RADIONAVIGATION SYSTEM DESCRIPTIONS

This section describes the characteristics of those individual radionavigation systems currently in use or under development. These systems are described in terms of the parameters previously defined in Part III, Section 2. All of the systems used for civil navigation are discussed. The systems which are used exclusively to meet the special applications of DOD are discussed in the JCS Master Navigation Plan.

### 3.1 LORAN-C

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

#### 3.1.1 Signal Characteristics

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

#### 3.1.2 Accuracy

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

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

TABLE III-3.1 LORAN SYSTEM CHARACTERISTICS (SIGNAL-IN-SPACE)

**System Description:** **LORAN is a Low Frequency (LF) 100kHz hyperbolic radionavigation system. The receiver computes lines of position (LOP) based on the time of arrival difference between two time synchronized transmitting stations of a chain. Three stations are required (master and two secondaries) to obtain a position fix in the normal mode of operation. LORAN can be used in the Rho-Rho mode and accurate position data can be obtained with only two stations. Rho-Rho requires that the user platform have a precise clock. The United States is the primary provider of LORAN-C coverage, although several nations in Europe and the Middle East have or are planning to initiate LORAN-C service.**

| Accuracy (2drms) | | | Availability | Coverage | Realiability | Fix Rate | Fix Dimension | Capacity | Ambiguity Potential |
|---|---|---|---|---|---|---|---|---|---|
| Predictable | Repeatable | Relative | | | | | | | |
| 0.25nm (460m) 1:3 SNR | 60-300 ft. (18-90m) | 60-300 ft. (18-90m) | 99+% | U.S. Coastal Areas, Some Continental U.S., Selected Overseas Areas | * | 10-20 fixes/sec | 2D | Unlimited | Yes, Easily Resolved |

* Depends on mission time.

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

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

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

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

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

### 3.1.3 Availability

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

### 3.1.4 Coverage

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

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

### 3.1.5 Reliability

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

### 3.1.6 Fix Rate

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

### 3.1.7 Fix Dimension

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

### 3.1.8 Capacity

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

### 3.1.9 Ambiguity

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

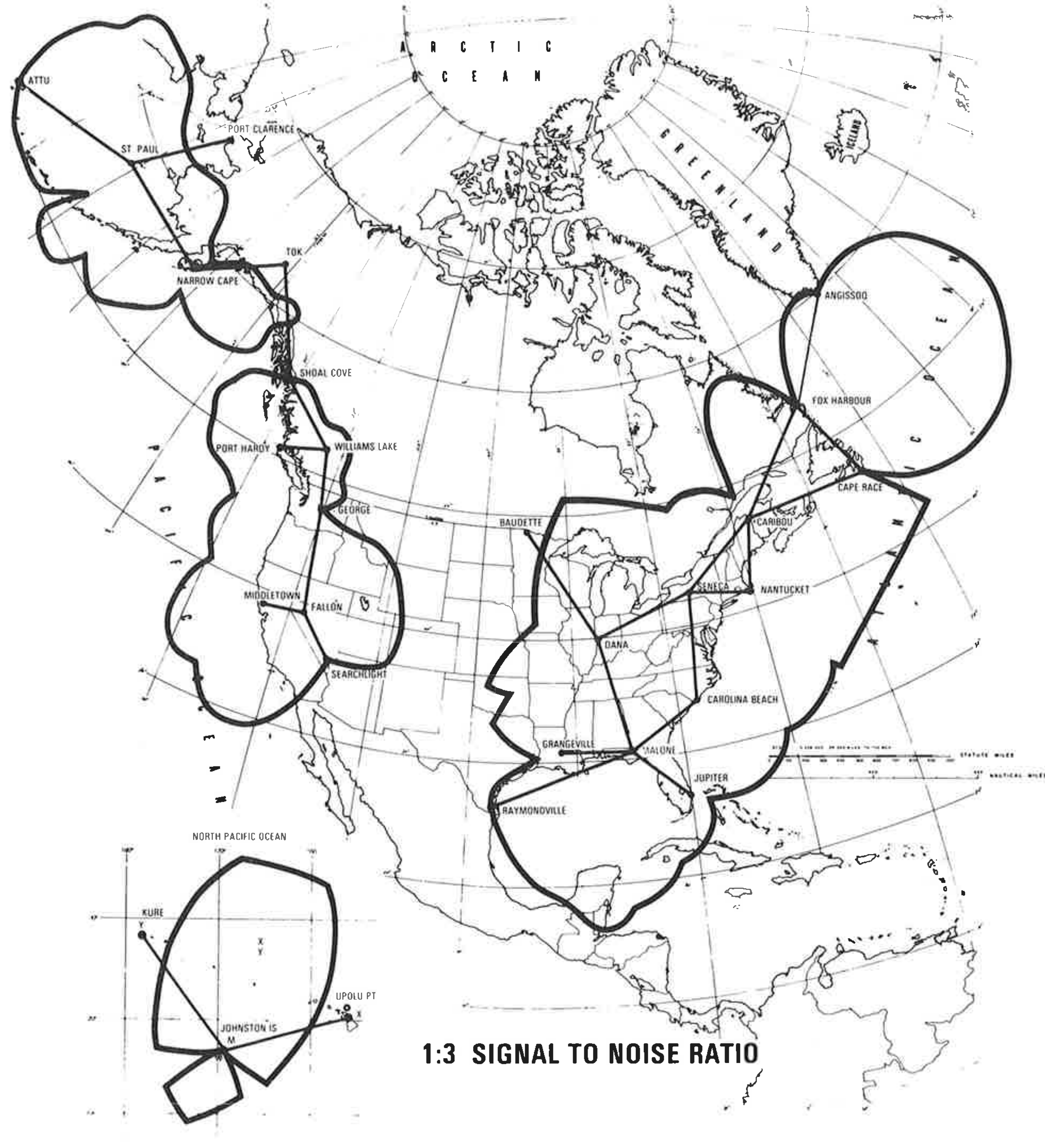


FIGURE III-3.1 U.S. LORAN-C COVERAGE

## 3.2 VOR, VOR/DME, TACAN

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

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

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

A. Accuracy (2 sigma)

1. Predictable

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

2. Relative

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

3. Repeatable

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

# TABLE III-3.2 VOR, VOR/DME SYSTEMS CHARACTERISTICS (SIGNAL-IN-SPACE)

**SYSTEM: VOR, VOR/DME**

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

| Accuracy (2 Sigma) | | | Availability | Coverage | Reliability | Fix Rate | Fix Dimension | Capacity | Ambiguity Potential |
|---|---|---|---|---|---|---|---|---|---|
| Predictable | Repeatable | Relative | | | | | | | |
| VOR: 90m (±1.4°) * | 23m (±0.35°) ** | 23m (±0.35°) ** | Approaches 100%. Warning if not providing published service | Line of sight (Present Air Routes) | Approaches 100%. Warning if not providing published service | Continuous | Heading in degrees or angle off course | Unlimited | None |
| DME: 185m (±0.1nm) | 185m (±0.1nm) | 185m (±0.1nm) | | | | | Slant Range (nm) | 100 Users per site, full service | |

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

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

B. Availability

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

C. Coverage

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

D. Reliability

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

E. Fix Rate

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

F. Fix Dimension

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

G. Capacity

The capacity of a VOR station is unlimited.

H. Ambiguity

There is no ambiguity possible for a VOR station.

3.2.2 DME (Distance-Measuring Equipment) - Signal Characteristics

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

A. Accuracy (2 sigma)

1. Predictable

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

2. Relative

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

3. Repeatable

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

B. Availability

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

C. Coverage

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

D. Reliability

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

E. Fix Rate

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

F. Fix Dimension

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

G. Capacity

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

H. Ambiguity

There is no ambiguity in the DME system.

### 3.2.3 TACAN (Tactical Air Navigation) - Signal Characteristics

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

A. Accuracy (2 sigma)

1. Predictable

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

2. Relative

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

3. Repeatable

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

## TABLE III-3.3 TACAN SYSTEM CHARACTERISTICS (SIGNAL-IN-SPACE)

**SYSTEM: TACAN**

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

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

B. Availability

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

C. Coverage

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

D. Reliability

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

E. Fix Rate

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

F. Fix Dimension

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

G. Capacity

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

H. Ambiguity

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

## 3.3 OMEGA

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

### 3.3.1 Signal Characteristics

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

### 3.3.2 Accuracy

The inherent accuracy of the OMEGA system is limited by the accuracy of the propagation corrections that must be applied to the individual receiver readings. The corrections may be obtained in the form of predictions from tables or automatically in computerized receivers. The system was designed to provide a predictable accuracy of 2 to 4 nm (2 drms). That accuracy depends on location, station pairs used, time of day, and validity of the propagation corrections.

Propagation correction tables are based on theory and modified to fit monitor data taken over long periods for localized areas. An extensive monitoring program is in use to verify the propagation model used to predict the corrections and the system accuracy in the area of the network stations. A number of permanent monitors will be maintained to update the model on a long-term basis. The system currently provides coverage over most of the earth. The specific accuracy attained depends on the type of equipment used as well as the time of day and the location of the user. In most cases the accuracies attained are consistent with the 2-4 nm system design goal and some cases much better accuracy is reported. An area validation program is being conducted by the Coast Guard to verify that the OMEGA system meets its design goal of 2-4 nm accuracy. Validations to date of the North and South Atlantic and North Pacific Oceans indicate that goal is being met.

A Differential OMEGA system has been developed and there are approximately 15 stations in operation primarily along the coast of Europe and in the Mediterranean. The coast Guard operates one Differential OMEGA station at Punta Tuna, Puerto Rico. The Differential OMEGA stations operate on the principal of a local area monitor system comparing the received OMEGA signal with the predicted signal for the location and then transmitting a correction factor based on the observed difference. The correction factor is usually transmitted over an existing radiobeacon system and can provide an accuracy ranging from 0.3 nm at 50 miles to 1 nm at 500 miles. The range of transmission of the correction factor varies with the range of the beacon, but is roughly three times the advertised range of the beacon. Reception of the Differential OMEGA signal requires the use of a Differential OMEGA receiver.

### 3.3.3 Availability

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

### 3.3.4 Coverage

The OMEGA system provides essentially worldwide coverage.

## TABLE III-3.4 OMEGA SYSTEM CHARACTERISTICS (SIGNAL-IN-SPACE)

**SYSTEM: OMEGA**

**System Description:** OMEGA is a very low frequency (VLF) 10.2-13.6kHz hyperbolic radionavigation system. There are eight transmitting stations now in full operation. Position information is obtained by measuring relative phase difference of received OMEGA signals. The system is multinational, being operated by seven nations with day to day operational control exercised by the U.S. Coast Guard.

| Accuracy (2 drms) | | | Availability | Coverage | Reliability | Fix Rate | Fix Dimension | Capacity | Ambiguity Potential |
|---|---|---|---|---|---|---|---|---|---|
| Predictable | Repeatable | Relative | | | | | | | |
| 2-4nm (3.7-7.4km) | 2-4nm (3.7-7.4km) | 0.25-0.5nm (463-926m) | 99+% | Worldwide Continuous | * | 1 Fix/ 10 Seconds | 2D | Unlimited | Requires Knowledge to ±36nm ** |

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

### 3.3.5 Reliability

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

### 3.3.6 Fix Rate

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

### 3.3.7 Fix Dimension

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

### 3.3.8 Capacity

An unlimited number of receivers may be used simultaneously.

### 3.3.9 Ambiguity

In this CW system, ambiguous LOP's occur as there is no means to identify particular points of constant phase difference which recur throughout the coverage area. The area between lines of zero phase difference are termed "lanes." Single-frequency receivers use the 10.2 kHz signals whose lane width is about eight nautical miles on the baseline between stations. Multiple-frequency receivers extend the lane width, for the purpose of resolving lane ambiguity. Lane widths of approximately 288 nm along the base line can be generated with a four-frequency receiver. Because of the lane ambiguity, a receiver must be preset to a known location at the start of a voyage. The accuracy of that position must be known to sufficient accuracy to be within the lane that the receiver is capable of generating (i.e., 8 nm for a single-frequency receiver or approximately 288 nm for a four-frequency receiver). Once set to a known location, the OMEGA receiver counts the number of lanes it crosses in the course of a voyage. This lane count is subject to errors which may be introduced by an interruption of power to the receiver, changes in propagation conditions near local sunset and sunrise and other factors. To use the single frequency OMEGA receiver effectively for navigation, it is essential that a DR plot of similar means be carefully maintained and the OMEGA positions compared to it periodically so that any lane ambiguities can be detected and corrected.

The accuracy of an OMEGA phase-difference measurement is independent of the elapsed time or distance since the last update. Unless the OMEGA position is verified occasionally by comparison to a fix obtained with another navigation system or by periodic comparison to a carefully maintained plot, the chance of an error in the OMEGA lane count increases with time and distance. These errors are eliminated in multiple frequency receivers since they are capable of developing larger lane widths to resolve ambiguity problems.

## 3.4 RADIOBEACONS

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

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

There are approximately 200 Coast Guard-operated marine radiobeacons. Operation of this system will be continued indefinitely. The system is being modernized and expanded slightly with some reconfiguring to better serve the recreational boater who is the main user of the system. This effort includes establishing some new beacons and the relocation of others. Some long range sequenced beacons are being changed to short range continuous beacons to provide more effective homing characteristics for the recreational user. Elimination of some long range beacons and some changes in frequency assignments will result in more efficient use of the allotted RF spectrum and allow for additional beacons in some areas if needed.

### 3.4.1 Signal Characteristics

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

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

### 3.4.2 Accuracy

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

### 3.4.3 Availability

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

## TABLE III-3.5 RADIOBEACON SYSTEM CHARACTERISTICS (SIGNAL-IN-SPACE)

**SYSTEM: RADIOBEACON NDB/ADF**

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

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

### 3.4.4 Coverage

The coverage of marine radiobeacons is shown in Figures III-3.2 and III-3.3. Extensive coverage of NDBs is provided by approximately 2000 ground stations, of which the FAA operates about 600.

### 3.4.5 Reliability

Reliability is in excess of 99 percent.

### 3.4.6 Fix Rate

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

### 3.4.7 Fix Dimension

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

### 3.4.8 Capacity

An unlimited number of receivers may be used simultaneously.

### 3.4.9 Ambiguity

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

## 3.5 AIRCRAFT LANDING SYSTEMS

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

### 3.5.1 Instrument Landing System

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

#### A. Signal Characteristics

The localizer facility and antenna are typically located 1000 feet beyond the stop end of the runway and provides a VHF (108-112 MHz) signal. The glide slope facility is located approximately 1000 feet from the approach end of the runway

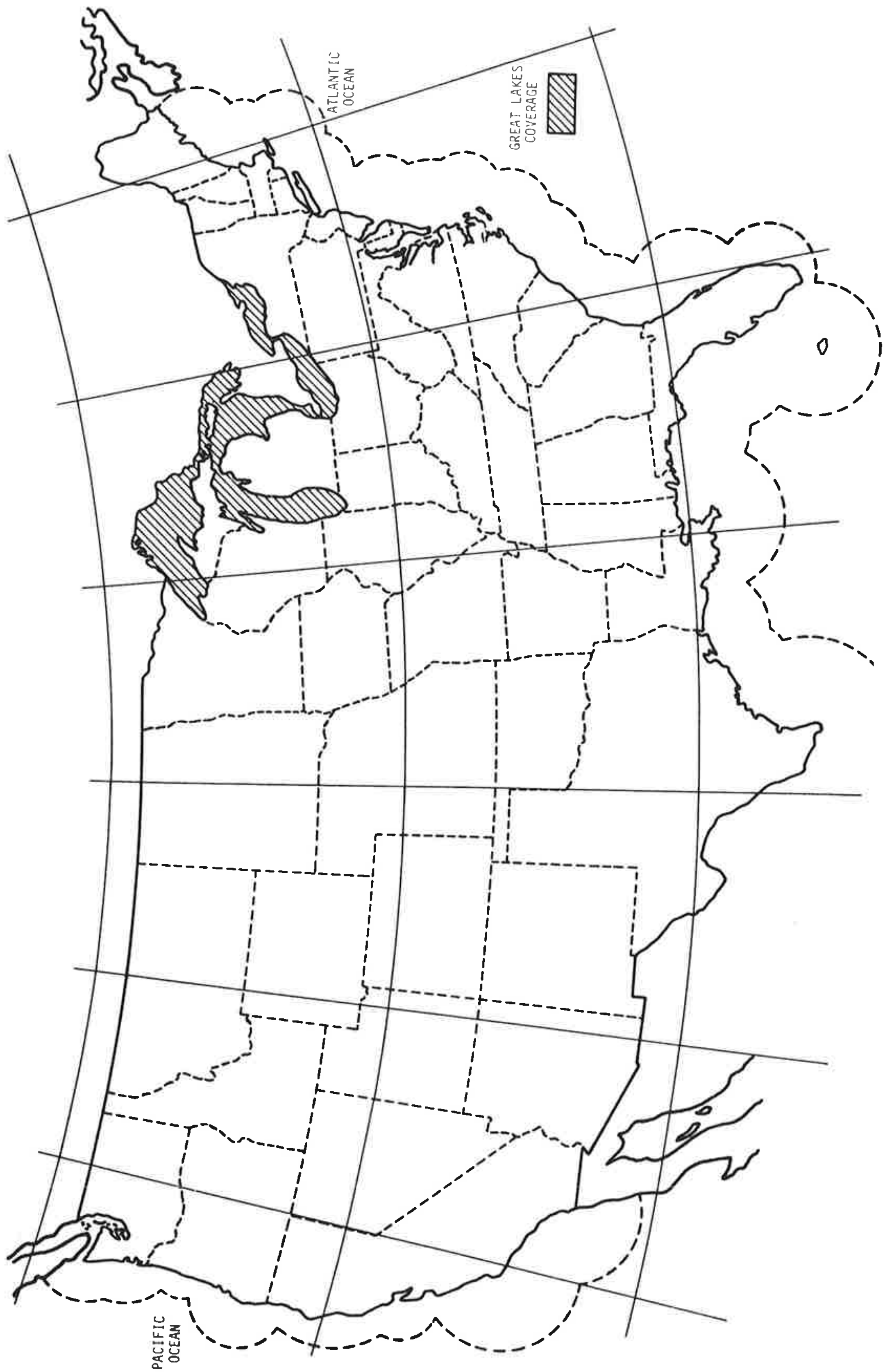


FIGURE III-3.2 CONTINENTAL U.S. MARINE RADIOBEACON COVERAGE

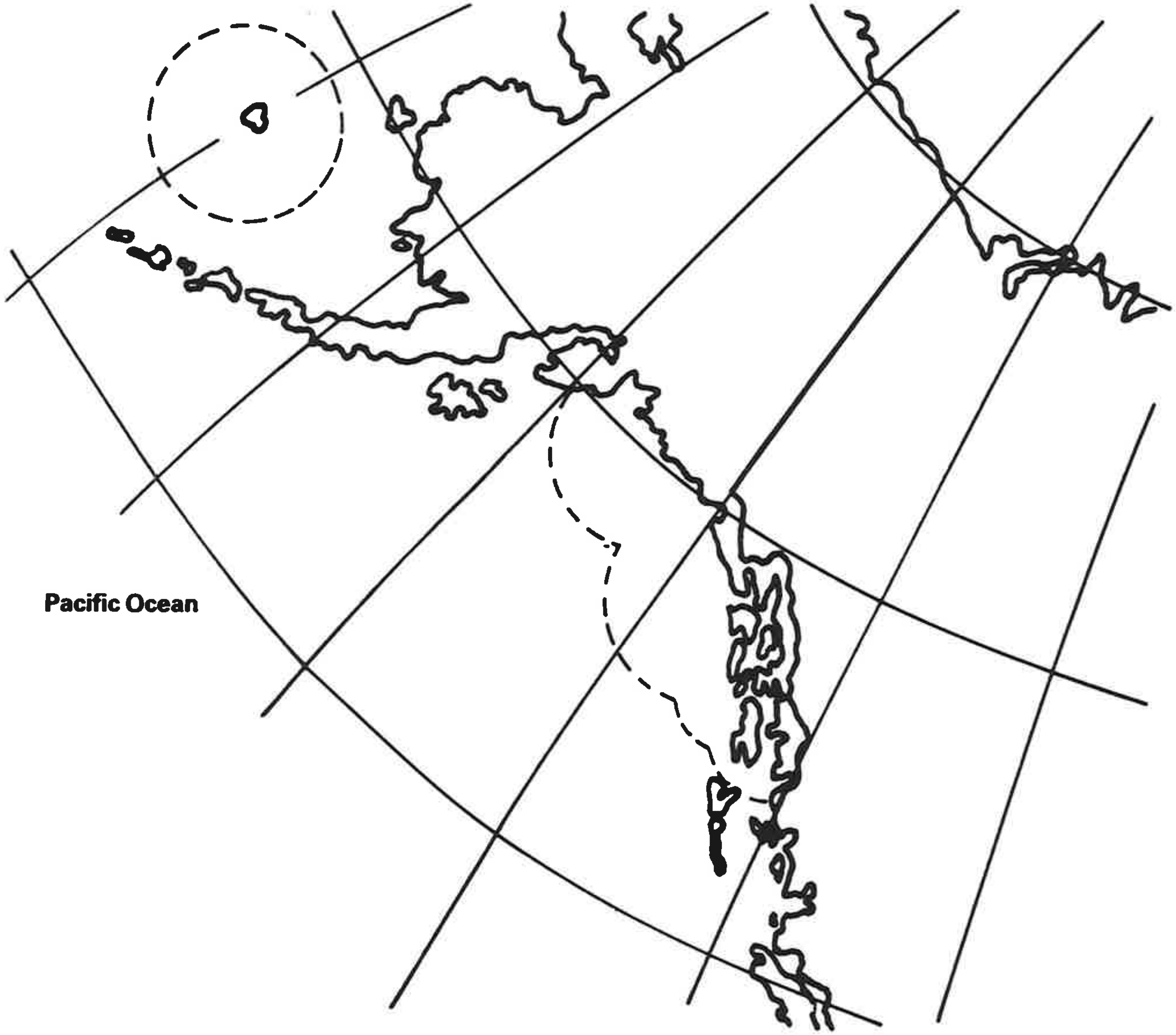


FIGURE III-3.3 ALASKAN MARINE RADIOBEACON COVERAGE and provides a UHF (328.6-335.4 MHz) signal. Marker beacons are located along an extension of the runway centerline and identify particular locations on the approach. Ordinarily, two 75 MHz beacons are included as part of the instrument landing system: an outer marker at the initial approach fix (typically 4 to 7 miles from the approach end of the runway) and a middle marker located 3500 feet plus or minus 250 feet from the runway threshold. The middle marker is located so as to note impending visual acquisition of the runway in conditions of minimum visibility for Category I ILS approaches. An inner marker, located approximately 1000 feet from the threshold, is normally associated with Category II and III ILS approaches. The signal characteristics of ILS are summarized in Table III-3.6.

B. Accuracy

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

C. Availability

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

D. Coverage

Coverage for individual systems is as follows:

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

E. Reliability

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

# TABLE III-3.6 ILS SYSTEM CHARACTERISTICS (SIGNAL-IN-SPACE)

**SYSTEM: ILS**

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

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

*Lateral accuracies at decision height.

F. Fix Rate

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

TABLE III-3.7 AIRCRAFT MARKER BEACON

| Marker Designation | Typical Distance to Threshold | Audible Signal | Light Color |
|---|---|---|---|
| Outer | 4-7nm | continuous dashes (2/sec) | Blue |
| Middle | 3250-3750 ft | continuous alternating dot-dash | Amber |
| Inner | 1000 ft | continuous dots (6/sec) | White |

G. Fix Dimension

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

H. Capacity

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

I. Ambiguity

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

### 3.5.2 Microwave Landing System

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

A. Signal Characteristics

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

B. Accuracy (2 sigma)

The azimuth accuracy is ± 13.5 feet at touchdown on a 15,000 foot runway. The elevation accuracy is ± 1.2 feet at runway threshold. The lower surface of the MLS beam crosses the threshold at 8 feet (2.4 meters) above the runway centerline. The flare guidance accuracy is ± 1.2 feet throughout the touchdown zone and the DME accuracy is ± 100 feet for the precision mode and ± 1600 feet for the non-precision mode.

C. Availability

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

D. Coverage

Current plans call for the installation of systems with azimuthal coverage of ± 40° on either side of the runway centerline, elevation coverage from 0° to 30° over the azimuthal coverage area, and out to 20nm. A few systems will have ± 60° azimuthal coverage. MLS signal format has the capability of providing coverage to the entire 360° area but with less accuracy in the area outside the primary coverage area of ± 60° of runway centerline. Present plans are that 15 MLS facilities will be installed by the end of 1984 and 172 by 1988. There will be simultaneous operations of ILS and MLS during the transition period.

E. Reliability

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

F. Fix Rate

Elevation angle is transmitted at 39 samples per second, azimuth angle at 13 samples per second, and back azimuth angle at 6.5 samples per second. Usually the airborne receiver averages several data samples to provide fixes of 3 to 6 samples per second. A high rate azimuth angle function of 39 samples per second is available and is normally used where there is no need for flare elevation data.

TABLE III-3.8 MLS SYSTEM CHARACTERISTICS (SIGNAL-IN-SPACE)

**SYSTEM: MLS**

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

| Accuracy (2 Sigma) | Availability | Coverage | Reliability | Fix Rate | Fix Dimension | Capacity | Ambiguity Potential |
|---|---|---|---|---|---|---|---|
| 8 ft. above surface<br>Azimuth Elevation<br>±4.1m ±0.4m | Approaches 100% with Pos indication when the system is out of tolerance | ±40° from center line of runway out to 20nm in both directions. * | Approaches 100% with positive indication when system out tolerance | 6.5-39 fixes/sec Depending on function. | Heading and deviation in degrees. Range in nm | Limited only by aircraft separation requirements | None |

* There are provisions for 360° out to 20nm.

G. Fix Dimensions

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

H. Capacity

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

I. Ambiguity

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

## 3.6 GPS

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

### 3.6.1 Signal Characteristics

The GPS concept is predicated upon accurate and continuous knowledge of the spatial position of each satellite in the system with respect to time and distance from a transmitting satellite to the user. Each satellite transmits its unique ephemeris data. This data is periodically updated by the master control station based upon information obtained from five widely dispersed monitor stations.

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

TABLE III-3.9 GLOBAL POSITIONING SYSTEM CHARACTERISTICS (SIGNAL-IN-SPACE)

**GLOBAL POSITIONING SYSTEM (GPS)**

**System Description:** A space-based radio positioning navigation system that will provide accurate three dimensional position, velocity and time information to suitably equipped users anywhere on or near the surface of the earth. The space segment wil consist of 18 satellites plus 3 operational spares in 12 hour orbits. Each satellite will transmit navigation data and time signals on 1575.4 and 1227.6 MHz.

| Accuracy | | | Availability | Coverage | Reliability | Fix Rate | Fix Dimension | Capacity | Ambiguity Potential |
|---|---|---|---|---|---|---|---|---|---|
| Predictable | Repeatable | Relative | | | | | | | |
| PPS*<br>Horz - 17.8m<br>Vert - 27.7m<br>Vlcty - 0.2m/sec<br>Time - 48ns<br>max offset 120 ns | Horz - 17.8m<br>Vert - 27.7m | Horz - 7.6m<br>Vert - 11.7m | Approximately 100% | Worldwide Continuous | **<br>Design Life of the Satellite is 7.5 years | Essentially Continuous | 3D<br>+<br>Velocity<br>+<br>Time | Unlimited | None |
| SPS<br>Horz - 100m<br>Vert - 156m<br>Vlcty - **<br>Time - ** | Horz - 100m<br>Vert - 156m | Horz - 28.4m<br>Vert - 44.5m | | | | | | | |

* For US and Allied military, US Government, and selected civil users specifically approved by the US Government.

**To be determined.

3.6.2 Accuracy*

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

A. The most sophisticated military user equipment will provide the best predictable positioning accuracy of 17.8 meters (2 drms), horizontally and 27.7 meters (2 sigma) vertically, a velocity accuracy of 0.2 m/sec (2 sigma) in each of the three dimensions and timing accuracy. The accuracy to be made available to civil users is in the form of the Standard Positioning Service (SPS). The accuracy from the SPS will be consistent with U.S. national security interests. It is presently projected that a predictable accuracy of 100 meters (2 drms) horizontally and 156 meters (2 drms) vertically will be made available from the beginning of full GPS operation.

B. The best relative accuracy for SPS will be 28.4 meters (2 drms) horizontally and 44.5 meters (2 sigma) vertically.

3.6.3 Availability

GPS will provide availability approaching 100 percent to be refined based on orbital experience, for the PPS users. This is based upon a 18 satellite constellation plus three orbital spares with four satellites in view above a 5° masking angle.

3.6.4 Coverage

GPS will provide worldwide, continuous coverage on the surface of the earth, in the atmosphere and in space.

3.6.5 Reliability

Operational reliability figures for the GPS satellites will be obtained when operational satellites are launched. However, a GPS satellite has a design life of 7.5 years. With the planned replenishment strategy, a constellation of 18 satellites plus 3 orbital spares will provide a 0.98 probability of having 18 or more satellites operational at any time.

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*Reference System: The geodetic reference system selected for use by the Global Positioning System (GPS) is the DOD World Geodetic System (WGS). The GPS currently uses the 1972 version which is designated as WGS 72. The Defence Mapping Agency (DMA) has the responsibility of developing and maintaining the WGS and is currently producing a revised version WGS 84.DMA plans to publish the completed report as well as the system parameters by December 1984. The system parameters will include the geophysical parameters defining the ellipsoid model and its rotation rate, datum transformation parameters and the gravitational potential model coefficients of the earth along with a corresponding geoid height model. The datum transformation will permit coordinates to be transformed between WGS 84 and WGS 72 as well as most of the major and local datums in the world. DOD plans to implement WGS 84 in GPS.

### 3.6.6 Fix Rate

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

### 3.6.7 Fix Dimensions

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

### 3.6.8 Capacity

The capacity is unlimited.

### 3.6.9 Ambiguity

There is no ambiguity.

## 3.7 TRANSIT

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

### 3.7.1 Signal Characteristics

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

### 3.7.2 Accuracy

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

### 3.7.3 Availability

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

TABLE III-3.10 TRANSIT SYSTEM CHARACTERISTICS (SIGNAL-IN-SPACE)

**SYSTEM: TRANSIT**

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

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

### 3.7.4 Coverage

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

### 3.7.5 Reliability

The reliability of the TRANSIT satellites is 99+ percent.

### 3.7.6 Fix Rate

Fix rate varies with latitude, theoretically from an average of 110 minutes at the equator to an average of 30 minutes at 80 degrees. Presently, due to non-uniform orbital precession, the TRANSIT satellites are no longer in evenly spaced orbits. Consequently, a user can occasionally expect a period greater than 6 hours between fixes. This condition exists for less than 5 percent of system availability.

### 3.7.7 Fix Dimensions

TRANSIT satellites provide a two-dimensional fix.

### 3.7.8 Capacity

TRANSIT satellites have unlimited capacity.

### 3.7.9 Ambiguity

There is no ambiguity.

# PART IV

# RADIONAVIGATION RESEARCH, ENGINEERING AND DEVELOPMENT

PART IV

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# PART IV

## 1. RADIONAVIGATION RESEARCH, ENGINEERING AND DEVELOPMENT SUMMARY

This part describes the Federal government research, engineering and development (R,E&D) activities relating to the U.S. government-provided radionavigation systems and their worldwide use by the U.S. Armed Forces and the civilian community. This part is organized in two segments: (1) civil R,E&D efforts to be conducted mainly by DOT and to a lesser extent by NASA and (2) DOD R,E&D for military uses.

The DOT R,E&D activities consist of parallel efforts to develop current and future navigation systems in order to improve existing operations or to identify systems which can replace or supplement those now being used in civil air, marine, or land applications. The parallel efforts are described in two major sections, one covering GPS and the other covering all existing systems (such as VOR, OMEGA, and LORAN-C) now in use or being considered by DOT to meet new or emerging navigational requirements.

Although the DOT R,E&D activities for GPS will proceed in much the same manner as those for other systems, GPS has been identified separately because of its potentially broad multimodal civil and military application and the consequent need for close cooperation between Federal agencies in its evaluation. Such cooperative effort will minimize duplication of effort and promote maximum productivity from the limited resources available for civil research. The cooperation should also insure DOT participation in the early stages of DOD evaluation and development of GPS so that benefits can be derived from a continued assessment of DOD's advances in receiver technology and an improved government planning process.

From the point of view of DOT, the analysis of performance requirements of civil navigation systems involves a variety of complex factors before it can be concluded that a specific system satisfies the principal objective to ensure safety and economy of transportation. These factors involve an evaluation of the overall economics of the system in relation to technical and operational factors, including vehicle size and maneuverability, vehicle traffic patterns, user skills and workload, the processing and display of navigation information, and environmental restrictions (e.g., terrain hazards and man-made obstructions). For this reason, a DOT comparison of one navigation system to another requires more than just a simple evaluation of accuracy and equipment performance characteristics. As a first step in the comparison of system capabilities, nine performance parameters, discussed in Part III (System Characteristics), have been identified and are listed below:

1. Signal Characteristics

2. Accuracy

    a. Predictable Accuracy
    b. Repeatable Accuracy
    c. Relative Accuracy

3. Availability
4. Coverage
5. Reliability
6. Fix Rate
7. Fix Dimension
8. System Capacity
9. Ambiguity

As implied above, for DOT, the user's equipment cost is a major consideration if universal civil participation is to be achieved. DOT R,E&D activities will therefore also involve evaluations and simulations of low-cost receiver designs, evaluation of future technologies (in conjunction with NASA) and determination of future requirements for the certification of equipment.

In contrast to DOT, the DOD R,E&D activities mainly address GPS evaluation by user groups in the Armed Forces which are identified by military mission requirements and national security considerations. For this reason, DOD R,E&D is defined to include all activities before the final acquisition of a navigation system in accordance with detailed system specifications. The DOD view of TRANSIT, LORAN, TACAN, VOR, and OMEGA is that these systems are already developed and, therefore, do not require R,E&D. This leaves GPS as the only military radionavigation system which must be evaluated in order to make a DOD decision on the best mix of Federal radionavigation services.

Although there are some similarities between the DOD and DOT analyses of the nine system performance parameters, DOD military missions place much greater emphasis on security and anti-jam than those for civil systems. Such factors as anti-jam, updating of inertial navigation systems, portability, and reliable operation under extreme environmental or combat conditions become very important in establishing the costs of the navigation equipment.

Concurrent with the Federal R,E&D programs, the major cost issues will be evaluated with the aid of a DOT Navigation Economic Model. This model has been constructed by DOT. Outputs of this model and R,E&D programs will be used to form joint positions related to system mix, phase in/phase out, and transition strategies for common use systems and individual agency positions on special purpose systems.

The relationship between DOT and DOD R,E&D programs is based on a continuing interchange of operational and technical information to select the best future mix of radionavigation systems. DOD R,E&D will be coordinated with DOT R,E&D under the following guidelines:

A. DOT will evaluate the costs of all radionavigation systems, including GPS, which meet identified civil user requirements.

B. DOT will provide DOD with the most current information on user requirements which may have a significant impact on the selection or performance specifications of DOD-operated radionavigation systems.

C. Consistent with existing DOD policy, DOD will provide information to DOT on GPS receiver designs that may be applicable to low-cost civil receiver development.

D. DOT will conduct studies of GPS performance capabilities using low-cost receiver designs in order to provide an assessment of its applicability to the civil sector.

PART IV

## 2. CIVIL RADIONAVIGATION RESEARCH, ENGINEERING AND DEVELOPMENT ACTIVITIES

The specific civil R,E&D activities and their relationships to the Federal Radionavigation Plan and the major Federal decisions on system implementations described in Part I (Radionavigation Plans and Policy) are outlined below in two segments: 1) GPS R,E&D, and 2) R,E&D for all existing civil navigation systems which include VOR, TACAN, DME, OMEGA, LORAN-C, and MLS. These two segments have been coordinated to achieve efficient use of the limited funds available for R,E&D and to avoid duplication of effort. R,E&D tasks for the individual DOT agencies (FAA, USCG, MARAD, etc.) and related tasks by the NASA are addressed and schedules have been specified so that the results of the efforts will be of maximum usefulness to all participants in the program. R,E&D schedules and activities for the FAA, the USCG, and the Research and Special Programs Administration (RSPA) have been identified respectively under civil aviation, marine, and land activities in this document.

### 2.1 DOT GPS R,E&D

#### 2.1.1 General

The major DOT marine, air, and land R,E&D activities for the Global Positioning System/Standard Positioning Service (GPS/SPS) are described as follows:

A. Coast Guard activities focus on establishing the performance of GPS/SPS for maritime navigation. There is a particular focus upon the Harbor Approach and Harbor phases of marine navigation, where augmentation of visual piloting using radio aids to navigation is needed. Three major efforts are involved:

1. An evaluation of GPS for vessel navigation in the Harbor and Harbor Approach phases will be conducted. The evaluation will establish the technical capability of GPS in its Standard Positioning Service mode to meet the stringent requirements of these phases.

2. A comparative evaluation of GPS/SPS and existing aids to navigation will be performed. This evaluation will compare the relative cost and performance trade-offs of GPS/SPS with LORAN-C for all phases of marine navigation as an input to Federal decisions on the mix of future radionavigation systems.

3. An evaluation of marine receiver designs will be conducted under the guiding principle that marine users choose navigational aids for their vessels based on cost and performance assessments. There are few governmental regulations that influence their decision. Consequently, development of low-cost receiver designs will influence the use of GPS by the civil user population. Additional evaluation of receiver designs could ultimately permit the development of minimum performance standards for civil GPS receivers.

B. The FAA's basic R,E&D activities for GPS/SPS have generally been completed with coverage reliability and integrity being the only remaining major issues to be resolved. These activities have included substantial efforts to evaluate technical, operational, and economic characteristics of future aeronautical navigation systems including GPS. The GPS work has included simulations, engineering models, GPS user equipment design, technical analysis, and flight tests.

C. RSPA land R,E&D activities in connection with GPS will focus on evaluating differential GPS, evaluating GPS/SPS signal performance in the urban and rural land environment and conducting simulation and analysis to assist in defining system performance and user equipment cost. RSPA will continue to review the results of work in the design of low-cost GPS receivers and field tests of GPS performance conducted by other organizations.

D. Information developed by the DOT Navigation Economic Model and other DOT analyses will be compared at various stages of the R,E&D program. Other factors which influence each individual agency's R,E&D on GPS will be assessed. These include FAA evaluations of the ability of GPS/SPS to meet user performance requirements, the preparation of national standards for avionics, and USCG receiver studies and field evaluations.

### 2.1.2 Civil Aviation

The FAA, through its R, E&D GPS program, is developing the requirements for use of GPS in the national airspace, both as a supplemental and as a sole means navigation system. This includes determining the appropriate standards for GPS airborne receivers and developing the air traffic control methodology for handling GPS RNAV aircraft operation in an environment with non-GPS equipped aircraft. The FAA expects to be ready to certify GPS as a supplemental means of navigation by the time DOD declares it operational. There is close cooperation between the FAA, DOD, and industry in these efforts.

A. Results of FAA R,E&D GPS efforts to date:

1. GPS/SPS accuracy of 100 meters 2 drms where there is adequate coverage, is suitable for all current civil aviation requirements except precision approach and landing.

2. The proposed GPS (18 plus 3 on-orbit spares) satellite configuration is not suitable for sole means aviation use.

3. GPS operation is basically the same as other RNAV systems and presents the same problems and benefits.

4. GPS user equipment will cost more than VOR receivers for general aviation.

5. No compelling near-term requirement for GPS has been expressed by the civil aviation user community. The general sentiment appears to be that, when GPS is implemented, the marketplace will bring about

civil use, at least for certain navigation applications in the longer term.

B. Planned FAA R,E&D GPS activities:

1. Additional studies will be conducted to determine methods to resolve the coverage reliability issue. These studies will include satellite constellation changes and receiver design requirements.

2. Methods to detect and notify the pilot of GPS out of tolerance conditions within 10-15 seconds will be developed and analyzed.

3. A National Aviation Standard for GPS will be developed.

4. A Minimum Operational Performance Standards (MOPS) for GPS avionics will be developed.

5. An aviation users conference on the role of GPS in the National Airspace System will be held.

6. An RTCA committee and an ICAO panel are investigating future aviation needs. Both of these groups will influence the role of GPS in civil aviation.

7. Investigations of GPS user equipment cost will continue.

2.1.3 Civil Marine

The major R,E&D activities of the U.S. Coast Guard related to marine uses of GPS are low-cost receiver technology studies, user field tests for comparative assessment of GPS versus alternative aids to navigation, and assessment of Standard Positioning Service performance potential. The purpose of the marine program is to acquire a sufficient data base to determine those missions of the marine fleet for which the GPS system can satisfy the navigation performance requirements. Issues important to the use of GPS for marine navigation include:

1. ACCURACY: Can it serve only as a one-quarter nautical mile navigation system suitable for en route navigation through the U.S. coastal area? Can it provide the higher accuracies needed by commercial fishing, coastal shipping and offshore industry? Can it give the accuracy required for Harbor, Harbor Approach and Inland Waterway Navigation?

2. TECHNICAL AND ECONOMIC: What are the technical and economic issues that dominate a GPS receiver designed for civil marine use? What is a realistic estimate of receiver cost, and what technological factors might significantly alter this estimate? What receiver performance and cost trade-offs are feasible to develop GPS equipment acceptable for: (1) commercial ships over 1600 gross tons, and (2) smaller ships or tugs with barges?

3. COMPARISON WITH MARINE RADIONAVIGATION SYSTEMS: Comparison of GPS with current marine radionavigation systems is

required. This comparison must be made with regard to navigational accuracy and repeatability, operational features and human factors considerations. Various missions must be considered, as well as a range of vessels from supertankers to Coast Guard cutters. This work must also consider the effect on electronics design and installation of the peculiarities of operations in protected waters and on the open ocean.

4. OPERATIONAL TEST RESULTS: What are the practical results of testing GPS receivers in the marine environment, such as: installation criticalities, marine and harbor environment peculiarities (RFI/multipath), and the suitability of performance and display for typical operations (e.g., fishing)?

The Coast Guard completed its initial studies and tests for the Harbor and Harbor Approach phases of navigation. GPS/SPS was found to have potential use in these phases. Additional Coast Guard R,E&D may be indicated, as follows:

1. Promote the development by industry of low-cost GPS/SPS receivers for marine use.

2. Evaluate the potential of GPS/SPS for navigation on inland waterways.

3. Define the role of harbor surveillance systems and alternative navigation systems as a backup for GPS/SPS where requirements exist for additional reliability, special vessel activities, or during emergencies.

Since GPS/SPS does not totally satisfy the performance and cost-effectiveness requirements for the Harbor and Harbor Approach phases, studies are being initiated to evaluate the increased use of alternative systems in these phases. Among these are harbor surveillance systems, improved short range aids to navigation, differential LORAN-C with retransmissions from shore-based monitor stations and differential GPS.

The initial GPS cost information for the Coast Guard and maritime users was provided to the DOT Navigation Economic Model in 1980. Future GPS performance and cost improvements will be included in the model to provide an assessment of alternative systems.

The near-term U.S. Coast Guard R,E&D program has the following elements:

A. Receiver Technology Studies

The initial effort in the study of GPS receiver technology is directed toward:

1. A thorough understanding of the receiver design characteristics required for GPS system operation in the marine environment.

2. An analysis of the GPS system identifying all performance factors and error sources, and assessing the effect of alternative designs on receiver performance.

3. An in-depth survey of current and projected technology for all components of the GPS receiver system.

4. An investigation of the capabilities and potential of available GPS/SPS receivers to satisfy the requirements of the marine user.

2.1.4 Civil Land

A. GPS R,E&D

In contrast to the case with the air and marine communities, land applications of GPS are relatively new and do not fall under the jurisdiction of a single agency (such as the FAA or the U.S. Coast Guard). For this reason, coordination and identification of user requirements and applications is being performed by the Research and Special Programs Administration (RSPA). The specific task areas of the GPS Land R,E&D program are described as follows:

1. GPS Land Analysis and Simulation: The GPS/SPS receiver performance requirements which are unique to land vehicles and their environments will be identified, including design modifications which may be required for current GPS/SPS receivers.

2. Land User Equipment Cost: This activity involves a review of the FAA, Coast Guard, NASA, and industry GPS/SPS low-cost receiver design studies.

3. Land Use Cost Evaluation: This will be accomplished using the DOT Navigation Economic Model. The Land portion of the DOT Navigation Economic Model will be used to generate GPS/SPS user system implementation and operating costs, user costs, and predictions on user equipment purchases, as well as system costs to the government.

4. GPS/SPS Land Performance: The GPS/SPS signal will be measured in the urban, suburban, and rural environments to assess the practicality of meeting land navigation requirements.

5. Differential GPS Land Applications: The performance of differential GPS will be evaluated in respect to the accuracy needs of the land user community.

## 2.2 DOT R,E&D FOR EXISTING CIVIL NAVIGATION SYSTEMS

2.2.1 General

The main purposes of DOT R,E&D on existing civil navigation systems are to improve reliability and service, decrease costs, and satisfy new requirements. The major DOT R,E&D for existing systems is outlined in the context of air, marine, and land areas of operation as follows:

A. Air

The FAA will continue its ongoing modernization and maintenance/sustaining engineering of VOR/DME and TACAN in order to reduce the O&M costs and improve the performance of ground-based air navigation aids in the United States and U.S. territories.

The FAA will continue to monitor the performance of OMEGA on oceanic air routes and the use of OMEGA and LORAN-C as supplements to VOR/DME.

The FAA will evaluate LORAN-C and GPS as supplements to VOR/DME, and GPS as a sole means air radionavigation system. These evaluations will involve field tests, low-cost user set design studies, analysis of accuracy, coverage, reliability, integrity, and operational suitability which includes an assessment of impacts on pilot workload, and blunder potential. In addition Minimum Performance Standards and Certification Criteria including Flight Inspection Requirements for both LORAN-C and GPS must be established. Also institutional issues, e.g., international acceptance, signal availability, signal degradation, etc, and economic issues will be assessed. The developmental activities for MLS and ILS will continue.

B. Marine

The DOT marine R,E&D for existing systems is composed of several U.S. Coast Guard programs and one program being conducted by the Saint Lawrence Seaway Development Corporation (SLSDC). These programs can be grouped by agency:

1. Coast Guard advanced R,E&D projects focus on system enhancements and improved techniques for the Harbor and Harbor Approach phases of operation. These include LORAN-C projects on chain enhancements, signal analysis, differential LORAN-C techniques and projects on shipboard display systems, applicable for GPS, LORAN-C or other systems and GPS applications.

2. The SLSDC has an ongoing program, coordinated with the Canadian Seaway Authority and the U.S. and Canadian Coast Guards, aimed at the identification and field testing of one or more precise all-weather navigation systems for the Seaway system, followed by selection and operational implementation. In addition to the obvious safety benefits, the system must provide significant increases in system capacity and attendant reductions in vessel transit times by reducing the frequency and duration of periods when vessel movements are halted due to removal of floating, lighted navigation aids and/or insufficient visibility.

C. Land

As navigation benefits to land users become apparent, and as receiver equipment costs decrease due to technology improvements and expanding user markets, adaptation of the existing navigation systems to serve a variety of land users may prove cost-effective. Therefore, RSPA R,E&D activities are planned to investigate the potential benefits of radionavigation applied to public and private land use. Typical applications include site registration for remote site location, highway records, land management and resource exploration, and AVM/AVL for truck fleets, rail vehicles, buses, and police and emergency vehicles.

The Departments of Energy, Agriculture, Interior, Commerce, Health, and Human Services, and agencies involved in security and law enforcement, as well as a number of states, have conducted or planned projects involving land applications of a radionavigation capability. For example, the Bureau of the Census of the DOC is investigating the application of LORAN-C and other radionavigation systems to register the location of rural housing units for the 1990 Decennial Census. In addition, DOE has investigated the application of LORAN-C as well as GPS to monitoring the position of vehicles carrying hazardous materials.

These investigations have resulted in identifying land users, and preliminary estimates of users requirements and needs relative to land radiolocation system parameters, and identification of areas in which additional R,E&D is required.

There is no RSPA R,E&D activity planned in FY'85 and later years for radionavigation systems other than GPS. RSPA will, however, monitor activities of other government agencies relative to other radionavigation systems.

### 2.2.2 Specific Civil R,E&D Activities

#### A. Civil Aviation

The R,E&D activities of the FAA are broadly directed toward improving navigation systems serving civil and military air users. Activities described here have two specific goals: (1) to provide information that will support the FAA recommendation on the future mix of navigation aids, and (2) to assist in the near-term integration of existing aids into the National Airspace System (NAS) as supplements to VOR-DME. The activities will be presented in six categories: (1) Oceanic and Domestic En Route, (2) Non-Precision Approach, (3) Remote Areas, (4) Helicopter IFR Operations, (5) RNAV and (6) Precision Approach and Landing.

1. Oceanic and Domestic En Route

The FAA has approved the use of OMEGA on oceanic routes as a sole means of navigation when used in conjunction with Doppler or inertial systems. Limited supplemental approval has also been granted for use of OMEGA/VLF avionics in the NAS with the provision that VOR-DME be available on the aircraft. LORAN-C has also been approved as a supplemental system where there is coverage.

A study for cost comparison purposes is being made of the number and locations of additional LORAN-C stations needed in the 48 contiguous states to provide complete and redundant signal coverage. The current work will enlarge on a prior study, that dealt with the same subject, by considering potential problems from cross-rate interference, and by using improved computer programs for signal coverage analysis. Work is also being done to determine how to provide better coverage in the Gulf of Mexico.

2. Non-Precision Approach

Performance requirements for navigation aids are most stringent when used for non-precision approaches. Available LORAN-C receivers will be flight tested and the results compared with established approach accuracy requirements.

Measurements of navigation accuracy during approaches will be made with a multiple-DME system developed by the FAA for that purpose. A program will be conducted to examine LORAN-C signal stability along approach paths to several selected airports; daily and seasonal variations and any other instabilities found will be analyzed to determine adequacy. A signal simulator will be developed to permit controlled tests of LORAN-C avionics in approach and other modes of flight.

3. Remote Areas (Including Off-shore)

While the present VOR/DME coverage meets most civilian user requirements, there are areas, such as some mountainous regions and low altitude airspace areas, where there is a requirement for air navigation service that VOR/DME does not presently provide. Alternatives being investigated to provide the required coverage include additional VOR/DME facilities, and supplementing the existing VOR/DME system with GPS or LORAN-C. Currently, OMEGA/VLF and LORAN-C (in specific areas) are approved as a supplement to VOR/DME.

4. Helicopter IFR Operations

The FAA is addressing special helicopter navigation requirements attributable to operations at low altitudes and in remote areas which are frequently below and beyond service volumes associated with conventional VHF navaid systems. The examination of LORAN-C and GPS for use in en route, terminal, and approach phases of operation are being emphasized. The feasibility of enhancing ADF/NDB systems and the suitability of military doppler navigators for civil helicopter use are also being explored. Approach capabilities using Airborne Radar Approach (ARA) have been established for offshore platforms. Further target and target processing enhancement work, to improve operational capabilities at poorly equipped landing sites, will be conducted with NASA using ARA, a technique which uses airborne weather radar in the ground mapping mode. Also in support of helicopter approach operations, data for revised helicopter Terminal Instrument Procedures (TERPS) criteria are being collected with various helicopters and navaids, including VOR/DME, LORAN-C, NDB, ILS, and MLS. A navigation-based system of automatic aircraft position reporting and display for ATC is being evaluated for application in areas lacking radar surveillance. The system, LORAN-C Flight Following (LOFF), has been installed in the Houston Air Route Traffic Control Center (ARTCC) and will be used to enhance ATC operations in the offshore helicopter sector of the Gulf of Mexico.

The FAA is also addressing the proper integration of the helicopter, with its unique set of characteristics and attributes, into the air traffic control system. Activities establishing the foundation for direct random routing are being planned for helicopters. Fixed, indirect routes have a most adverse effect on helicopters which predominantly operate on relatively short flights. Separate, reduced-width routes are also being used in high traffic density areas where it is desirable to segregate helicopters and other low speed aircraft. Simultaneous airport landings and departures of helicopters and fixed wing aircraft are being used today and will increase with the introduction of MLS with its flexible approach path capability. The special nature of navigation requirements for these helicopter operations, as well as for others, such as holding airspace and curvilinear/decelerating approaches, are aimed at the integration of helicopters into the National Airspace System.

5. RNAV

The object of the RNAV program is to develop avionics standards which permit direct routing of RNAV aircraft. This FAA activity is closely coordinated with the aeronautics industry. The end products of the RNAV program will be the development of National Aviation Standards and MOPS for avionics prepared with the coordination of industry.

The advent of latitude/longitude grid navigation systems such as LORAN-C, OMEGA and GPS has increased awareness of the pilot workload, pilot blunder and system integration problems involved in using latitude/longitude RNAV equipment. RNAV procedures with such systems may differ from RNAV based on the VOR/DME system.

6. Precision Approach and Landing

The objective of the FAA is to support the integration of MLS, in an evolutionary manner, into the National Airspace System. The first procurement of production MLS ground equipment was made in 1984.

B. Civil Marine

The plans of the USCG for improving marine navigation systems, which serve the civil maritime user, are described below. The discussions are presented in terms of the phases of marine navigation as follows: Oceanic, Coastal, Harbor Approach, Harbor, and Inland Waterways.

1. Oceanic

The USCG is in the process of validating the coverage and accuracy of the OMEGA system as an oceanic aid to navigation for marine and aviation users. The OMEGA system provides general purpose en route navigation service worldwide for marine and air users from a network of eight stations.

The Coast Guard will promulgate progressively, on a regional basis, the results of a worldwide general assessment of the coverage and accuracy of the OMEGA system. As each given geographic area is validated, the OMEGA user will be advised concerning operational limitations as appropriate. The OMEGA system cannot be declared fully operational, worldwide, until accuracy and coverage are measured and validated. Validation will be completed in 1987. Operation and validation of the OMEGA navigation system, and the progressive improvement of corrections for OMEGA propagation errors, are the major Coast Guard activities associated with oceanic navigation.

2. Coastal

The primary system in use for U.S. coastal marine radionavigation is LORAN-C. With the possible exception of the Western Gulf of Mexico, no R,E&D activities are ongoing or planned. A survey of LORAN-C signal strengths in the Galveston/Houston area is being conducted to determine if corrective measures are necessary for LORAN-C to meet the required 0.25nm accuracy requirements in the Western Gulf of Mexico.

3. Harbor and Harbor Approach and Inland Waterways

There currently is no radionavigation system capable of meeting the 8-20 meter accuracy required for marine navigation in Harbor/Harbor Approach areas. While LORAN-C can meet the requirement in some areas, it will require some improvements in other areas. R,E&D projects are ongoing to determine which areas will require improvements and the extent of improvements needed in each harbor area. One system being investigated to meet the Harbor/Harbor Approach requirements is differential LORAN-C. The Coast Guard is developing a differental system and, based on knowledge gained from that project, will develop a specification for differential LORAN-C corrections and format. The Coast Guard is also evaluating a commercially available differential LORAN-C system.

The Coast Guard is working with other DOT modes and various members of the civil community to develop a differential GPS system. That system is anticipated for use in the Harbor/Harbor Approach areas.

No efforts are being expended by the Coast Guard to develop any radionavigation systems for Inland Waterways.

The Saint Lawrence Seaway Development Corporation (SLSDC) has undertaken a program, in cooperation with the Canadian Seaway Authority and the U.S. and Canadian Coast Guards, to provide a precise all-weather navigation system for the Seaway system. The program is expected to result in a three- to four-fold increase in system capacity and similar decreases in vessel transit times during those periods at the beginning and end of the shipping season when conventional, lighted, floating aids to navigation have been removed because of ice. Improvements in system safety, capacity, and transit time improvements during periods of low-visibility are also expected. Under the leadership of an international Seaway/Coast Guard Steering Committee the program will include:

a. Establishment of operational requirements such as accuracy, reliability, and minimum allowable visibility for the system.

b. Review of available electronic systems that have the potential for application to the Seaway problem.

c. Selection of candidate systems, which may comprise one or more electronic positioning systems, integrated with conventional navigation aids.

d. Integration and field testing of candidate systems.

From the results of field testing, the SLSDC, in consultation with its Canadian counterpart, will assess the costs and benefits of candidate systems. The decision to proceed with an operational system will depend on the results of the field tests and the cost benefit analysis.

## 2.3 DOT RADIONAVIGATION ECONOMIC PLANNING MODEL

### 2.3.1 General

The DOT has developed a radionavigation economic planning model which can be used by the DOT Navigation Council, the DOT Navigation Working Group and DOT Administrations in evaluating various radionavigation mixes. The model was developed jointly by RSPA, the FAA and the USCG. The model is operational at the Transportation Systems Center (TSC).

### 2.3.2 Model Description

The model is designed to consider various radionavigation system mix scenarios selected by the model user and to provide cost data associated with a selected scenario. The model will predict future populations for each user group. Equipment costs are determined by such factors as: equipment complexity, production volume, production technology rates, inflation rates and discount rates. For each radionavigation system mix scenario considered, the model will provide user and system operator costs.

## 2.4 GPS R,E&D PLANNED BY THE NASA OFFICE OF AERONAUTICS AND SPACE TECHNOLOGY (OAST)

While OAST has no requirements per se, survey of potential space users indicates that most scientific missions require position accuracy no greater than 50 meters. However, to perform onboard image registration, position accuracies of 5 to 10 meters will be required.

An outline of space and aeronautics activities is as follows:

### 2.4.1 Space R,E&D

OAST is developing techniques and procedures to provide accurate onboard orbit, altitude, and time; and defining components necessary for onboard imaging registration capability for earth-pointing imaging spacecraft such as LANDSAT-4 and 5.

### 2.4.2 Aeronautics R,E&D

NASA Ames is currently investigating the potential use of differential GPS to support precision approaches for helicopters and non-runway environments where there are no aids to landings. Flight tests are being conducted at Crow's Landing near Mountain View, California. The airborne GPS receiver being used is a prototype low cost airborne receiver known as the "Z" set developed under contract by Magnavox. Initial results have proved very promising.

PART IV

# 3. DOD RADIONAVIGATION RESEARCH, ENGINEERING AND DEVELOPMENT

The DOD R,E&D activities described in this section are those associated with radionavigation systems that have clearly defined common use capabilities. At this time, these systems are GPS and MLS.

## 3.1 OBJECTIVES

DOD R,E&D activities are primarily driven by the mission requirements of the commanders of the Unified and Specified Commands and the Military Departments/Services. These mission requirements normally include accurate navigation within the continental United States, in oceanic areas, and in overseas theaters. Other requirements include security, resistance to meaconing, interference, jamming and intrusion and saturation limit and world-wide coverage. These radionavigation requirements form the basis for the overall DOD R,E&D program.

## 3.2 RESPONSIBILITIES

DOD and its component elements are responsible for developing, testing, evaluating, operating, and maintaining aids to navigation and user equipment for military missions. DOD is also responsible for assuring that military vehicles, operating in consonance with civilian vehicles, have the required navigation capabilities to operate in a safe and expeditious manner.

## 3.3 GPS R,E&D EFFORT

### 3.3.1 Background

Since the early 1960's both the Air Force and Navy have actively pursued the idea that navigation and positioning could best be performed using signals transmitted from space vehicles. The impetus for developing a space-based system was the desire for an accurate, continuous, all-weather, global radionavigation system that could meet the diverse needs of a broad spectrum of both military and civil users. Additionally, considerable cost benefits could be realized by reducing the proliferation of specialized navigation and positioning systems that are limited in coverage and capabilities.

GPS has entered the Production and Deployment phase of the program. The system, when fully operational and certified for use in controlled airspace, will replace DOD use of LORAN-C, OMEGA, TACAN, TRANSIT, VOR/DME and other military and common use radionavigation systems. Civil applications of GPS are under study by the Department of Transportation and others. It is DOD policy to make the SPS portion of the GPS system continuously available on an international basis for civil, commercial and other use at an accuracy of 100 meters (2 drms).

3.3.2 Description

GPS is a space-based radio positioning, navigation and time-transfer system that operates on two L-band frequencies of 1575.42 MHz (L1), and 1227.6 MHz (L2). GPS is composed of three major segments: Space, Control and User.

A. Space Segment

The space Segment, when fully operational in 1988, will be composed of 18 plus 3 on orbit spare satellites, with possible expansion to a 24-satellite constellation at some future date. The satellites will be in a 12 hour circular orbit of 20,200 km (10,900 nm). Precise spacing in each plane will ensure a minimum of four satellites in view to a user at all time ($5^o$ above user's horizon). World-wide three-dimensional positioning accuracy is provided by both the Precise Positioning Service (PPS) and the Standard Positioning Service (SPS). PPS is designed for military use and will be released to civil users on a case by case basis. The Standard Positioning Service (SPS) will provide predictable accuracies of 100 m (2 drms) horizontally and 156 m (2 sigma) vertically and a relative accuracy of 28.4 m (2 drms) horizontally and 44.5 m (2 sigma) vertically. The above accuracies will be available worldwide. Each satellite will transmit both the PPS and SPS signals. The spare satellites will be maintained in orbit (fully operational) to ensure an operational constellation of 18 satellites.

B. Control Segment

The Control Segment consists of a Master Control Station which will be located at the Consolidated Space Operations Center in Colorado Springs, supported by five remote Monitor Stations and three Ground Antennae. The Monitor Stations receive the satellites' navigation signals and provide data to the Master Control Station. The Master Control Station uses the Monitor Station's data to calculate updates to the navigation message and sends the updates to the satellites via the Ground Antennae.

C. User Segment

The User Segment will consist of user equipment, test instrumentation and unique support equipment. The user equipment, utilizing data transmitted by the satellites, will derive navigation and time information for use in a number of different types of vehicles.

3.3.3 System Development Phases

The GPS program was divided into three discrete phases: Concept Validation (Phase I); Full Scale Development (Phase II); and Production and Deployment (Phase III).

A. Phase I (Concept Validation) 1973-79

During this phase a number of test satellites were launched to provide a constellation to permit testing of conceptual user equipment and prove the viability of the overall system concept. The constellation provided up to four hours per day of accurate navigation and timing signals over a western test site. During this phase four contractors were selected to develop conceptual user equipment for validation and testing.

B. Phase II (Full Scale Development) 1979-85

Phase II, currently underway, verified the operational effectiveness of the GPS concept. Two of four contractors, previously selected to develop conceptual military user equipment, were chosen to develop prototype military user equipment and appropriate support hardware and software to be installed on a variety of test vehicles for Development Test & Evaluation/Initial Operational Test and Evaluation (DT&E/IOT&E) testing. The results of the DT&E/IOT&E testing, cost, production and support considerations, will lead to selection of one prime contractor for Phase III production contracts for user equipment. The DT&E/IOT&E testing is now scheduled for completion in 1984 with a production contract for user equipment scheduled for 1985. Throughout Phase II, satellites will be replenished on an as needed basis so that six satellites will be available during all of the testing of prototype user equipment. The GPS Initial Control System at Vandenberg Air Force Base is fully operational and will support the test constellation until the new Master Control Station (MCS) becomes operational.

C. Phase III (Production and Deployment) 1985

Production of user equipment is scheduled to begin in 1985 with installations starting in 1986 and continuing for at least ten years. Additional production satellites will be produced during this phase and be launched from the space shuttle during 1986-88.

3.3.4 Test Planning

DT&E/IOT&E test objectives will determine whether GPS user equipment can provide adequate positioning, navigation and timing information to accomplish typical military missions.

3.3.5 NATO Involvement

The United States encouraged NATO participation in the development and deployment of the GPS. In response, ten NATO nations signed a Memorandum of Understanding (MOU) in June 1978 (updated in 1984) for participation in the Phase II development of GPS. These nations include Belgium, Canada, Denmark, France, Germany, Italy, the Netherlands, Norway and the United Kingdom.

The objective is to establish a flow of information among the participating nations in all GPS Program activities, which should facilitate national decisions to support the application of GPS. To this end, personnel of these nations are fully integrated within the GPS Joint Program Office (JPO) to contribute to the U.S. development program and to advise on and coordinate NATO applications, development and testing. This group is referred to the "NATO team" and is headed by a NATO Deputy Program Manager (DPM) who plans, controls and coordinates the NATO GPS project. The NATO DPM is directly responsible to a Steering Committee composed of one representative from each participating nation, and which carries the responsibility for the effective implementation of the MOU. Each member of the Steering Committee acts as a national consultant and coordinator for GPS-related activities.

The Steering Committee allocates funds for the execution of studies and tests considered to be of special interest to the NATO community. Major current NATO GPS activities include:

1. Standardization of User Equipment. Since it is highly desirable to achieve some standardization of GPS User Equipment, a NATO Standardization Working Group was established. It recommended that, at this stage in the program development, it would be most cost-effective to define a form, fit and function ($F^3$) specification for NATO GPS receiver-processor units, thereby enhancing NATO interoperability. This is a significant activity in that standardization is being addressed during R&D for the first time in NATO history.

2. Mission Effectiveness Study. This study was initiated to determine the impact of GPS on European/Canadian military tactics for various scenarios.

3. Antenna Studies. Theoretical studies and operational tests intended to determine the optimal antenna configuration in a jamming environment.

4. GPS/INS tests that evaluate the advantages and increased capabilities of integrating ship and airborne inertial navigation systems and the GPS.

5. Numerous operational tests on a variety of military platforms.

### 3.3.6 Other Allied Military

In addition to formal NATO involvement in the development of GPS User Equipment, the DOD has working relationships with other allied nations and is sharing information that is designed to create interest in the military use of GPS.

### 3.3.7 Schedule

Figure I-4.8 of Part I of this plan provides a detailed schedule of events for each segment of the program.

### 3.3.8 Microwave Landing System (MLS)

DOD is committed to transitioning to MLS in conjunction with FAA and NATO. The USAF has initiated a 15 year program to phase out ILS airborne and ground equipment. The program is timed to coincide with FAA, ICAO and NATO transition plans. Maximum use will be made of avionics and ground equipment developed for civil applications. USAF R,DT&E will be limited to developing ground equipment for use in mobile or high threat applications and to acquiring military avionics for those platforms for which commercial civil avionics are not suitable.

## GLOSSARY

The following is a listing of abbreviations for organization names and technical terms used in this plan:

| | |
|---|---|
| ADF | Automatic Direction Finder |
| AFSCF | Air Force Satellite Control Facility |
| ARTCC | Air Route Traffic Control Center |
| ATC | Air Traffic Control |
| ATMSMN | Air Traffic Management System Material Need |
| AVL | Automatic Vehicle Location |
| AVM | Automatic Vehicle Monitoring |
| C/A | Coarse/Acquisition |
| CCW | Coded Continuous Wave |
| CCZ | Coastal and Confluence Zone |
| CDI | Course Deviation Indicator |
| CEP | Circular Error Probable |
| CIA | Central Intelligence Agency |
| CNI/NAV | Communications, Navigation & Identification/Navigation |
| CONUS | Continental United States |
| CS | Control Segment |
| CSOC | Consolidated Space Operations Center |
| CSE | Course Selection |
| CW | Continuous Wave |
| DH | Decision Height |
| DMA | Defense Mapping Agency |
| DMAHTC | Defense Mapping Agency Hydrographic Topographic Center |
| DME | Distance Measuring Equipment |
| DOC | Department of Commerce |
| DOD | Department of Defense |
| DOE | Department of Energy |
| DOI | Department of the Interior |
| DOS | Department of State |
| DOT | Department of Transportation |
| DPM | Deputy Program Manager |
| DR | Dead Reckoning |
| drms | distance root mean squared |
| DSARC | Defense System Acquisition Review Council |
| DT&E | Development Test & Evaluation |
| ECCM | Electronic Counter-Countermeasures |
| ECD | Envelope-to-Cycle Difference |
| EHT | Extremely High Frequency |
| EMI | Electromagnetic Interference |
| EMS | Emergency Medical Service |
| ERDA | Energy Research & Development Administration (Now Department of Energy) |
| $F^3$ | Form, Fit, and Function |
| FAA | Federal Aviation Administration |
| FAATC | Federal Aviation Administration Technical Center |

| | |
|---|---|
| FAF | Final Approach Fix |
| FAR | Federal Aviation Regulation |
| FCZ | Fishery Conservation Zone |
| FHWA | Federal Highway Administration |
| FL | Flight Level |
| FM | Frequency Modulation |
| FRA | Federal Railroad Administration |
| FRP | Federal Radionavigation Plan |
| FSD | Full-Scale Development |
| FTE | Flight Technical Error |
| GA | General Aviation |
| GBF/DIME | Geographic Base File/Dual Independent Map Encoding |
| GCA | Ground Control Approach |
| GDOP | Geometric Dilution of Precision |
| GPS | Global Positioning System |
| GRI | Group Repetition Interval (LORAN) |
| GSTDN | Ground Satellite Tracking and Data Network |
| HHE | Harbor and Harbor Entrance Area |
| Hz | Hertz |
| IAP | Improved Accuracy Program |
| ICAO | International Civil Aviation Organization |
| IFR | Instrument Flight Rules |
| ILS | Instrument Landing System |
| IMO | International Maritime Organization |
| INS | Inertial Navigation System |
| IOT&E | Initial Operational Test & Evaluation |
| JCS | Joint Chiefs of Staff |
| JPO | Joint Program Office |
| JTIDS | Joint Tactical Information Distribution System |
| JTMLS | Joint Tactical Microwave Landing System |
| kHz | KiloHertz |
| LF | Low-Frequency |
| LOFF | LORAN Flight Following |
| LOP | Line of Position |
| LORAN | Long-Range Navigation |
| MAP | Missed Approach Point |
| MARAD | Maritime Administration |
| MCS | Master Control Station |
| MCW | Modulated Carrier Wave |
| MDA | Minimum Descent Altitude |
| MF | Medium Frequency |
| MHz | MegaHertz |
| MIJI | Meaconing, Interference, Jamming, and Intrusion |
| MLS | Microwave Landing System |
| MNP | Master Navigation Plan |
| MOPS | Minimum Operational Performance Standards |
| MOU | Memorandum of Understanding |
| MPA/TAC | Maritime Patrol Aircraft/Tactical Support Center |
| MTBF | Mean Time Between Failures |
| MTTR | Mean Time to Repair |
| NAS | National Airspace System |
| NASA | National Aeronautics and Space Administration |
| NATO | North Atlantic Treaty Organization |

| | |
|---|---|
| NDB | Non-Directional Beacon |
| NEEDS | NASA End-to-End Data System |
| NHTSA | National Highway Traffic Safety Administration |
| nm | nautical miles |
| NNSS | Navy Navigation Satellite System (TRANSIT) |
| NOAA | National Oceanic and Atmospheric Administration |
| NOTAM | Notice to Airmen |
| NPN | National Plan for Navigation |
| NSF | National Science Foundation |
| NSWC | Naval Surface Weapon Center |
| NTIA | National Telecommunications and Information Agency |
| O&M | Operation & Maintenance |
| OAST | Office of Aeronautics and Space Technology (NASA) |
| OCS | Operational Control Sêgment |
| OJCS | Office of the Joint Chiefs of Staff |
| OMB | Office of Management and Budget |
| OMEGA | (Not an abbreviation) |
| OPS/QTV | Operations/Qualification Test Vehicle |
| OSD | Office of the Secretary of Defense |
| OTP | Office of Telecommunications Policy |
| PAR | Precision Approach Radar |
| PDME | Precision Distance Measuring Equipment |
| PILOT | Precision Intracoastal LORAN Equipment |
| PLAD | Portable LORAN Assist Device |
| POS/NAV | Positioning and Navigation |
| PPS | Precise Positioning Service |
| PRN | Pseudo-Random Noise |
| PSE | Peculiar Support Equipment |
| R&D | Research & Development |
| RACON | Radar Transponder Beacon |
| RD&D | Research, Development, & Demonstration |
| RDF | Radio Finder |
| R,E&D | Research, Engineering & Development |
| RF | Radio Frequency |
| RFI | Radio Frequency Interference |
| RNAV | Area Navigation (Radio) |
| RSPA | Research and Special Programs Administration |
| RSS | Root Sum Square |
| RTCA | Radio Technical Commission for Aeronautics |
| RVR | Runway Visual Range |
| SAFI | Semi-Automatic Flight Inspection |
| SARPS | Standard and Recommended Practics |
| SEP | Spherical Error Probable |
| SHF | Super High Frequency |
| SLSDC | Saint Lawrence Seaway Development Corporation |
| SPS | Standard Positioning Service |
| STOL | Short Take-Off and Landing |
| STS | Satellite Test System |
| SV | Space Vehicle |
| TACAN | Tactical Air Navigation |

| | |
|---|---|
| TCV | Terminal Configured Vehicle |
| TD | Time Difference |
| TDRSS | Tracking and Data Relay Satellite System |
| TDSS | Time Difference Survey System |
| TERPS | Terminal Instrument Procedures |
| TIP | Transit Improvement Program |
| TIWG | Test Integration Working Group |
| TOA | Time of Arrival |
| TRANSIT | (Not an abbreviation) |
| TRSB | Time Referenced Scanning Beam |
| TSC | Transportation Systems Center |
| TSO | Technical Standard Order |
| TT&C | Telemetry Tracking and Control |
| TVOR | Terminal VOR |
| UE | User Equipment |
| UHF | Ultra High Frequency |
| UMTA | Urban Mass Transportation Administration |
| USCG | United States Coast Guard |
| USDA | United States Department of Agriculture |
| USGS | United States Geological Survey |
| UTC | Universal Coordinated Time |
| VFR | Visual Flight Rules |
| VHF | Very High Frequency |
| VLF | Very Low Frequency |
| VNAV | Vertical Navigation |
| VOR | Very High Frequency Omnidirectional Range |
| VORTAC | Collocated VOR and TACAN |
| VTOL | Vertical Take-Off and Landing |
| VTS | Vessel Traffic Service |
| WGS | World Geodetic System |

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