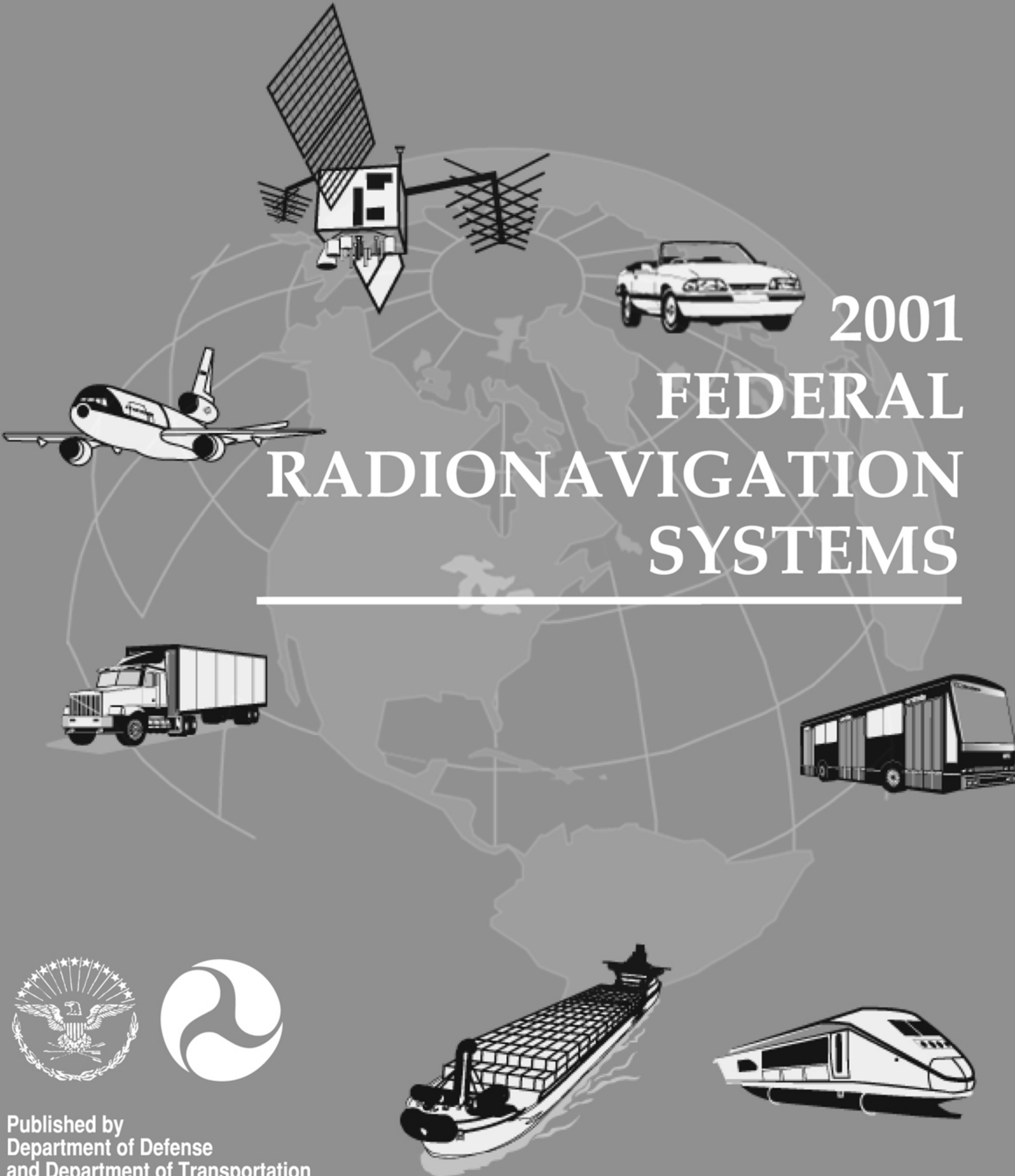

2001 FEDERAL RADIONAVIGATION SYSTEMS

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2001 Federal Radionavigation Systems

The *Federal Radionavigation Systems* (FRS) document is a companion document to the *Federal Radionavigation Plan* (FRP). It is prepared jointly by the Departments of Defense (DoD) and Transportation (DOT) with the assistance of other government agencies. The FRS covers common-use radionavigation systems (i.e., systems used by both civil and military sectors). Systems used exclusively by the military are covered in the Chairman, Joint Chiefs of Staff (CJCS) Master Positioning, Navigation, and Timing Plan (MPNTP).

Prior to this edition, Federal radionavigation information was contained in a single document, but is now published in two separate documents: the FRP and the FRS. The 2001 FRP includes the introduction, policies, operating plans, and R&D sections and will allow more efficient and responsive updates of policy and planning information. The more static sections relating to government roles and responsibilities, user requirements, and systems descriptions are now contained in the 2001 FRS and will be updated as necessary.

Your suggestions for the improvement of future editions are welcomed. Interested parties may submit their inputs to the Chairman of the DOT Positioning and Navigation (POS/NAV) Working Group (Attn: OST/P-7), Department of Transportation, Office of the Assistant Secretary for Transportation Policy, Washington, D.C. 20590.

Norman Y. Mineta Secretary of Transportation	Donald H. Rumsfeld Secretary of Defense
Date: December 12, 2001	Date: March 19, 2002

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Executive Summary

This edition of Federal Radionavigation Systems (FRS) updates and replaces sections in the 1999 Federal Radionavigation Plan (FRP) relating to Government roles and responsibilities, system selection considerations, civil user requirements, and systems descriptions. The FRS is jointly prepared by the Department of Transportation (DOT) and the Department of Defense (DoD), and will be updated as necessary. Inputs for the next edition of this document are welcome. Interested parties and advisory groups from the private sector are invited to submit their inputs to the Chairman of the DOT Positioning and Navigation (POS/NAV) Working Group (Attn: OST/P-7), Department of Transportation, Office of the Assistant Secretary for Transportation Policy, Washington, D.C. 20590.

The FRS covers common-use radionavigation systems (i.e., systems used by both civil and military sectors). These systems are sometimes used in combination with each other or with other systems. Systems used exclusively by the military are covered in the Chairman, Joint Chiefs of Staff (CJCS) Master Positioning, Navigation, and Timing Plan (MPNTP).

Privately operated radionavigation systems may be discussed in order to provide a complete picture of U.S. radionavigation. The document does not include systems that mainly perform surveillance and communication functions.

The Federally provided radionavigation systems covered in this document are:

- Global Positioning System (GPS)
- Augmentations to GPS
- Loran-C
- VOR and VOR/DME
- Tactical Air Navigation (TACAN)
- Instrument Landing System (ILS)
- Microwave Landing System (MLS)
- Aeronautical Nondirectional Radiobeacons (NDB)

This document describes the authorities and responsibilities of Federal agencies and describes the management structure established to guide individual operating agencies in defining and meeting radionavigation requirements in a cost-effective manner.

The March 28, 1996 Presidential Decision Directive (PDD) approved a comprehensive national policy on the future management and use of GPS and related U.S. Government augmentations. The PDD assigns specific responsibilities to DoD, DOT, Department of State (DOS), and Department of Commerce (DOC) in executing the provisions of the President's national policy on GPS. The PDD also established an Interagency GPS Executive Board (IGEB), jointly chaired by the DoD and DOT, to manage the dual civil/military use GPS and U.S. Government.

Many factors are considered in determining the optimum mix of Federally provided radionavigation systems. These factors include operational, technical, economic, institutional, international parameters, and the needs of national defense. System accuracy, integrity, and coverage are the foremost technical parameters, followed by system availability, continuity, and reliability. Radio frequency spectrum issues also must be considered. Certain unique parameters, such as anti-jamming performance, apply principally to military needs but also affect civil availability.

The requirements of civil and military users for radionavigation services are based upon the technical and operational performance needed for military missions, transportation safety, and economic efficiency. Requirements will differ depending upon what the user intends to do, the type of transportation system used, and the user location within that particular transportation system. All users require that systems used for safety service must be adequately protected.

All of the systems described in this document are defined in terms of system parameters that determine the use and limitation of the individual navigation system's signal-in-space.

This document is composed of the following sections:

Section 1 – U.S. Government Agency Roles and Responsibilities: Presents the DoD, DOT, and other Federal agency roles and responsibilities for providing radionavigation services.

Section 2 – Radionavigation System Civil User Requirements: Describes both navigation and non-navigation user requirements and needs for radionavigation systems.

Section 3 – System Descriptions: Describes present and planned navigation systems in terms of eleven major parameters: signal characteristics, accuracy, availability, coverage, reliability, fix rate, fix dimensions, system capacity, ambiguity, integrity, and spectrum.

Section 4 – Geodetic Datums and Reference Systems: Discusses geodetic datums and reference systems, and also provides relevant details for U.S. civilian usage and applications.

Appendix A – Definitions

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U.S. Government Agency Radionavigation Roles and Responsibilities

This section outlines the roles and responsibilities of the Government agencies involved in planning for and providing radionavigation services.

The March 28, 1996 Presidential Decision Directive (PDD) (Ref. 1) on GPS provides a comprehensive national policy and guidelines on the future management and use of GPS. An Interagency GPS Executive Board (IGEB), jointly chaired by the Departments of Defense (DoD) and Transportation (DOT), manages the dual civil/military use GPS and U.S. Government augmentations and supports the implementation of GPS national policy in accordance with the provisions of the PDD. The IGEB ensures that GPS and U.S. augmentations are operated in a manner that is consistent with national policy and that best serves the military and civil user communities. In addition to DoD and DOT, IGEB membership currently includes the Department of State (DOS), Chairman, Joint Chiefs of Staff (CJCS), Department of Commerce (DOC), Department of the Interior (DOI), Department of Agriculture (USDA), Department of Justice (DOJ), and the National Aeronautics and Space Administration (NASA). The IGEB management structure is shown in Figure 1-1.

The PDD assigns responsibilities to DoD, DOT, and DOS related specifically to GPS. (Ref. 1). Radionavigation responsibilities listed below for DoD and DOT include, but are not limited to, the responsibilities directed by the PDD for GPS. The responsibilities listed for the Department of State are exclusively those listed in the PDD.

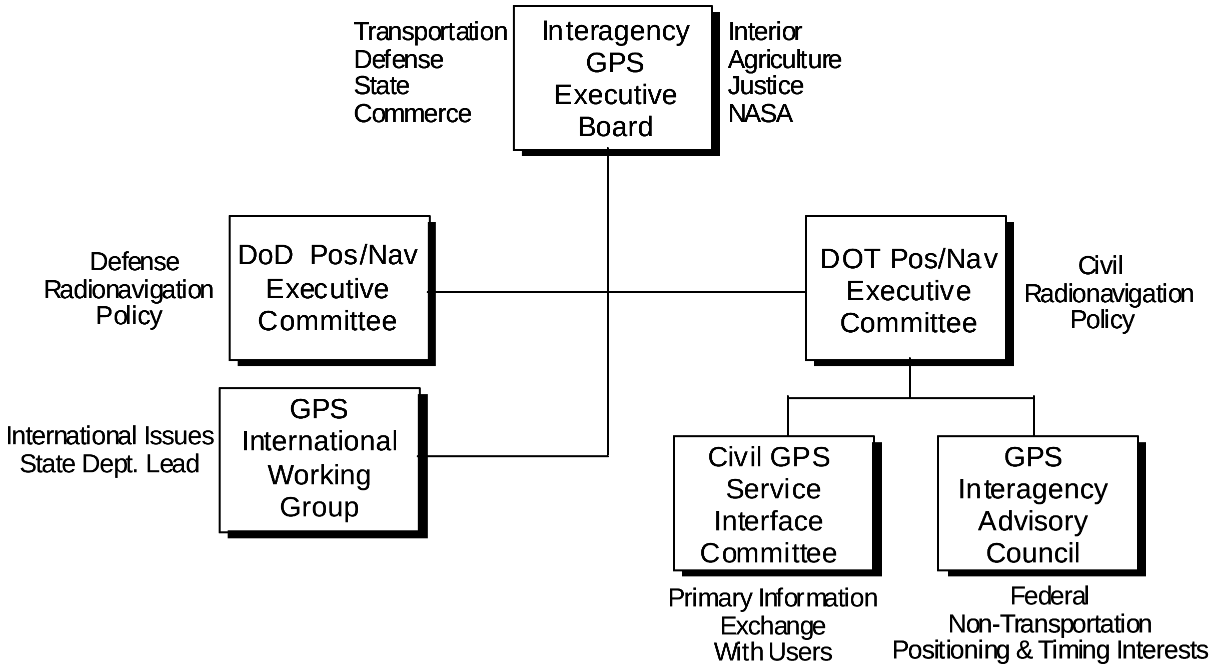

Figure 1-1. Interagency GPS Executive Board Management Structure

1.1 DoD Responsibilities

The Department of Defense is responsible for developing, testing, evaluating, implementing, operating, and maintaining aids to navigation and user equipment required for national defense. DoD is also responsible for ensuring that military vehicles operating in consonance with civil vehicles have the necessary navigation capabilities.

The DoD is also required by statute 10 U.S.C. 2281(b) (Ref. 2) to provide for the sustainment and operation of the GPS Standard Positioning Service (SPS) for peaceful civil, commercial, and scientific uses on a continuous worldwide basis free of direct user fees.

Specific DoD responsibilities are to:

a. Define performance requirements applicable to military mission needs.

b. Design, develop, and evaluate systems and equipment to ensure cost-effective performance.

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 missions.

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

f. Define and acquire the necessary resources to meet mission requirements.

g. Identify special military route and airspace requirements.

h. Foster standardization and interoperability of systems with North Atlantic Treaty Organization (NATO) and other allies.

i. Operate and maintain radionavigation aids as part of the NAS when such activity is economically beneficial and specifically agreed to by the appropriate DoD and DOT agencies.

j. Derive and maintain astronomical and atomic standards of time and time interval, and to disseminate these data.

k. Continue to acquire, operate, and maintain GPS including a Standard Positioning Service that will be available on a continuous, worldwide basis and a Precise Positioning Service (PPS) for use by the U.S. military and other authorized users.

l. Cooperate with the Director of Central Intelligence, the Department of State and other appropriate departments and agencies to assess the national security implications of the use of GPS, its augmentations, and alternative satellite-based positioning and navigation systems.

m. Develop measures to prevent the hostile use of GPS and its augmentations to ensure that the U.S. retains a military advantage without unduly disrupting or degrading civilian uses.

n. Ensure that the United States Armed Forces have the capability to use GPS effectively despite hostile attempts to prevent use of the system.

The National Imagery and Mapping Agency (NIMA) is responsible for mapping, charting, and geodesy (MC&G) support to DoD navigation systems which includes international maps, charts, digital terrain elevation data, digital feature analysis data, digital hydrographic chart data, point-positioning databases, geodetic surveys, and the World Geodetic System 1984 (WGS 84). This support also includes geodetic positioning of transmitters for electronic systems and tracking stations for satellite systems, maintenance of GPS fixed site operations, and generation and distribution of GPS precise ephemerides. Within DoD, NIMA acts as the primary point of contact with the civil community on matters relating to geodetic uses of navigation systems and provides calibration support for certain airborne navigation systems. Unclassified data prepared by NIMA are available to the civil sector.

The U.S. Naval Observatory (USNO) is responsible for determining the positions and motions of celestial bodies, the motions of the Earth and precise time; for providing the astronomical and timing data required by the Navy and other components of DoD and the general public for navigation, precise positioning, and command, control and communications; and for making these data available to other government agencies and to the general public. The Department of the Navy serves as the country’s official timekeeper, with the master clock facility at the Washington Naval Observatory.

DoD carries out its responsibilities for radionavigation coordination through the internal management structure shown in Figure 1-2. Figure 1-2 shows the administrative process used to consider and resolve positioning and navigation issues. The operational control of DoD positioning and navigation systems is not shown here, but is described in the Chairman, Joint Chiefs of Staff (CJCS) Master Positioning, Navigation and Timing Plan (MPNTP) and other DoD documents.

1.1.1 Operational Management

The President or the Secretary of Defense, with the approval of the President, is the National Command Authority. The Chairman, Joint Chiefs of Staff, supported by the Joint Staff, is the primary military advisor to the National Command Authority. The Service Chiefs provide guidance to their military departments in the preparation of their respective detailed navigation plans. The JCS are aware of operational navigation requirements and capabilities of the Unified Commands and the Services, and are responsible for the development, approval, and dissemination of the CJCS MPNTP.

The MPNTP is the official positioning, navigation, and timing policy and planning document of the CJCS, which addresses operational defense requirements.

The following organizations also perform navigation management functions:

The Deputy Director for Command, Control, Communications and Computer Systems Support, Joint Staff (J-6), is responsible for:

- Analysis, evaluation, and monitoring of navigation system planning and operations.
- General navigation matters and the CJCS MPNTP.

The Commanders of the Unified Commands perform navigation functions similar to those of the JCS. They develop navigation requirements as necessary for contingency plans and JCS exercises that require navigation resources external to that command. They are also responsible for review and compliance with the CJCS MPNTP.

1.1.2 Administrative Management

Three permanent organizations provide radionavigation planning and management support to the Assistant Secretary of Defense (C^3I). These organizations are the POS/NAV Executive Committee, the 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 the Defense Intelligence Agency (DIA) and the National Security Agency (NSA)). The Executive Committee contributes to the development of the FRP and coordinates with the DOT POS/NAV Executive Committee.

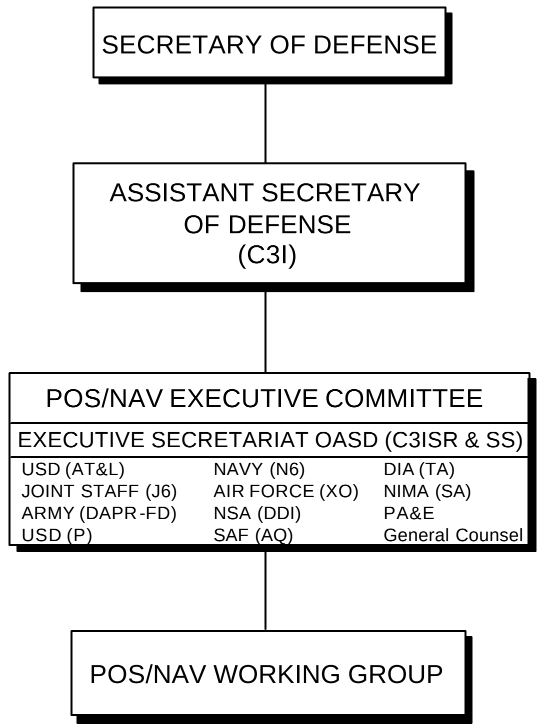

Figure 1-2. DoD Navigation Management Structure

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 with the DOT POS/NAV Working Group 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 CJCS MPNTP and for managing the development, deployment, 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 effectively phase GPS into the military operational forces.

1.2 DOT Responsibilities

The Department of Transportation is responsible under Title 49 United States Code (U.S.C.) Section 301 for ensuring safe and efficient transportation. Radionavigation systems play an important role in carrying out this responsibility. The three elements within DOT that operate radionavigation systems are the United States Coast Guard (USCG), the Federal Aviation Administration (FAA), and the St. Lawrence Seaway Development Corporation (SLSDC). The Assistant Secretary for Transportation Policy (OST/P) is responsible for coordinating radionavigation planning within DOT and with other civil Federal elements.

Specific DOT responsibilities are to:

a. Provide aids to navigation used by the civil community and certain systems used by the military.

b. Prepare and promulgate radionavigation plans in the civilian sector of the United States.

c. Serve as the lead agency within the U.S. Government for all Federal civil GPS matters.

d. Develop and implement U.S. Government augmentations to the basic GPS for transportation applications.

e. Take the lead in promoting commercial applications of GPS technologies and the acceptance of GPS and U.S. Government augmentations as standards in domestic and international transportation systems.

f. Coordinate U.S. Government-provided GPS civil augmentation systems to minimize cost and duplication of effort.

DOT carries out its responsibilities for civil radionavigation systems planning through the internal management structure shown in Figure 1-3. The structure was originally established by DOT Order 1120.32 (April 27, 1979) and revised by DOT Order 1120.32C (October 11, 1994).

The DOT POS/NAV Executive Committee is the top-level management body of the organizational structure. It is chaired by the OST/P, and consists of policy level representatives from the General Counsel's Office (OST/C), the Office of the Assistant Secretary for Budget and Programs (OST/B), the Assistant Secretary for Administration (OST/M), USCG, FAA, the Federal Highway Administration (FHWA), ITS-JPO, the Federal Railroad Administration (FRA), the National Highway Traffic Safety Administration (NHTSA), the Federal Transit Administration (FTA), SLSDC, the Maritime Administration (MARAD), the Research and Special Programs Administration (RSPA), and the Bureau of Transportation Statistics (BTS). Non-transportation Federal civil users of GPS are represented in the POS/NAV Executive Committee by the GPS Interagency Advisory Council (GIAC). The Civil GPS Service Interface Committee (CGSIC), chaired by OST/P, is DOT's official committee for information exchange with all GPS users.

The POS/NAV Working Group is the staff-working core of the organizational structure. It is chaired by the OST/P Program Manager and consists of one representative each from OST/C, OST/B, OST/M, USCG, FAA, FHWA, ITS-JPO, FRA, NHTSA, FTA, SLSDC, MARAD, RSPA, BTS, the Volpe National Transportation Systems Center (Volpe Center), and other DOT element representatives as necessary. Each representative may be assisted by advisors. The Center for Navigation, Volpe Center, also provides technical assistance to the POS/NAV Working Group.

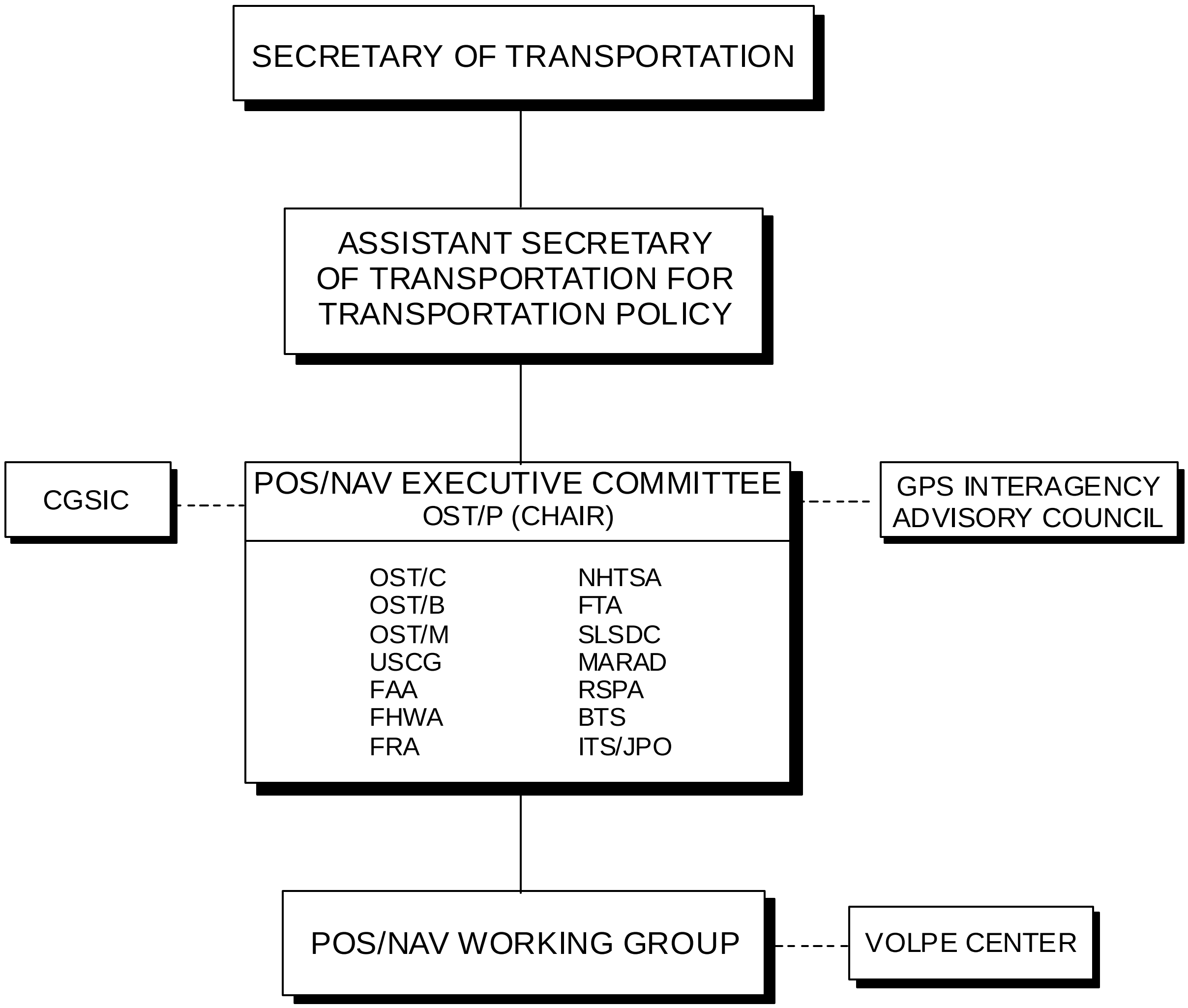

Figure 1-3. DOT Navigation Management Structure

The Secretary of Transportation, under 49 U.S.C. Section 301, has overall leadership responsibility for navigation matters within DOT and promulgates radionavigation plans. Three DOT elements have statutory responsibilities for providing aids to navigation: the USCG, the FAA, and the SLSDC.

OST/P coordinates radionavigation issues and planning which affect multiple modes of transportation, including those that are intermodal in nature. OST/P also interfaces with agencies outside of DOT on non-transportation uses of radionavigation systems.

DOT's Civil GPS Service Interface Committee is an outreach to the user, and facilitates the exchange of issues and requirements between DOT and the GPS user, in the U.S. and internationally. The Coast Guard manages the operations of the Committee for DOT.

The USCG defines the need for, and provides, aids to navigation and facilities required for safe and efficient navigation. 14 U.S.C. Section 81 states the following:

"In order 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 or of 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; and

(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; or (c) required to serve the needs of the air commerce of the United States as requested by the Administrator of the Federal Aviation Administration.

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 Coast Guard may establish, maintain, and operate aids to marine navigation under paragraph (1) of this section by contract with any person, public body, or instrumentality."

The FAA has responsibility for development and implementation of radionavigation systems to meet the needs of all civil and military aviation, except for those needs of military agencies that are peculiar to air warfare and primarily of military concern. FAA also has the responsibility to operate aids to air navigation required by international treaties.

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

MARAD investigates the application of advanced technologies for navigation, as well as the training of shipboard crews in all aspects of ship operations. These efforts are intended to enhance the efficiency and safety of ship operations in U.S. waters.

FHWA, ITS-JPO, NHTSA, FRA, FTA, and RSPA have the responsibility to conduct research, development, and demonstration projects, including projects on land uses of radiolocation systems. They also assist state and local governments in planning and implementing such systems and issue guidelines concerning their potential use and applications. Due to the increased emphasis on efficiency and safety in land transportation, these organizations are increasing their activities in this area.

Other elements of the Federal government are involved with radionavigation systems in terms of evaluation, research, or operations. For example, NASA supports navigation through the development of technologies for navigating aircraft and spacecraft. NASA is responsible for development of user and ground-based equipment, and is also authorized to demonstrate the capability of military navigation satellite systems for civil aircraft, ship, and spacecraft navigation and position determination.

1.3 DoD/DOT Joint Responsibilities

A Memorandum of Agreement (MOA) between DoD and DOT provides for radionavigation planning (Ref. 3). This agreement requires coordination between the DoD and DOT internal management structures for navigation planning. The MOA recognizes that DoD and DOT have joint responsibility to avoid unnecessary overlap or gaps between military and civil radionavigation systems and services. Furthermore, it requires that both military and civil needs be met in a manner cost-effective for the Government and civil user community.

1.4 Department of State Responsibilities

As stated above, the responsibilities listed for the Department of State are exclusively those listed in the PDD. The PDD directs that the Department of State:

- In cooperation with appropriate departments and agencies, consult with foreign governments and other international organizations to assess the feasibility of developing bilateral or multilateral guidelines on the provision and use of GPS services.
- Coordinate the interagency review of instructions to U.S. delegations to bilateral consultations and multilateral conferences related to the planning, operation, management, and use of GPS and related augmentations.
- Coordinate the interagency review of international agreements with foreign governments and international organizations concerning international use of GPS and related augmentation systems.

2

Radionavigation System Civil User Requirements

As it is used in this document and in the FRP itself, the term “requirements” encompasses a broad spectrum of user wants, needs, and “must haves.” Not all agencies of the Government arrive at their requirements in the same way. The DoD, for example, employs a rigorous process to develop and formally validate user requirements. At the other end of the spectrum, since Government has no statutory authority to provide radionavigation services for land applications, no such formalized process exists to validate land navigation requirements. The government agencies involved in land application oversight exercise their best judgment in attempting to derive user needs in the areas where no formalized validation process exists. There is no attempt in this document to differentiate between user requirements based upon the rigor with which they have been derived.

The requirements of civil and military users for radionavigation services are based upon the technical and operational performance needed for military missions, transportation safety, and economic efficiency. For civil aviation and maritime users, and for military users in missions similar to civil users (e.g., en route navigation), the requirements are defined in terms of discrete “phases of navigation.” These phases are differentiated primarily by the characteristics of the navigation problem as the vehicle passes through different regions in its voyage. Phases of navigation are not as applicable to land transportation, due to the greater flexibility afforded land users to assess their position. Requirements will differ depending upon what the user intends to do, the type of transportation system used, and the user location.

Unique military missions and national security needs impose a different set of requirements that 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. All users require that systems used for safety service must be adequately protected. In the discussion that follows, both sets of requirements (civil and military) are presented in a common format of technical performance characteristics whenever possible.

2.1 Civil Radionavigation System Requirements

The radionavigation requirements of civil users are determined by a DOT process that 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 by the operating administration, from other Federal agencies, from the user public, or as required by Congress. The requirements for an area or class of users are not absolutes. The process to determine requirements involve evaluation of:

- The acceptable level of safety risks to the Government, user, and general public as a function of the service provided.
- 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 service desired measured against the benefits obtained.
- The total cost impact of any government decision on radionavigation system users.

The provision of Government provided radionavigation services are subject to the Congressional budgetary process and priorities for allocations among programs by agencies.

2.2 Civil Aviation Radionavigation Requirements

Aircraft navigation is the process of piloting 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 navigation performance are dictated by the phase of flight, the aircraft proximity to terrain and other aircraft, and the air traffic control process.

Navigation may be achieved through the use of visual procedures during Visual Flight Rules (VFR) operations and may use sophisticated navigation avionics. Navigation avionics are required when operating under Instrument Flight Rules (IFR) or VFR above Flight Level (FL) 180.

Aircraft separation criteria, established by the FAA, take into account limitations of the navigation service, communication and surveillance available and air traffic control's intervention capabilities.

Note: Surveillance service normally falls into three categories:

- Dependent: Surveillance of a target by depending on information (position measurements, ID, etc.) provided by the target.
- Cooperative: Surveillance in which the target cooperates with the surveillance process by using onboard equipment in the acquisition or derivation of surveillance information (position measurements, ID, etc.).
- Independent: Surveillance of a target without depending on information (position measurements, ID, etc.) provided by the target.

Aircraft separation criteria are influenced by the communications, navigation and surveillance (CNS) service, but are strongly affected by other factors, e.g., air traffic management, 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, in part, by a stipulated probability that performance of the navigation system will remain within a specified error budget.

The following are basic requirements for aviation navigation systems. "Navigation system" means all of the elements necessary to provide navigation services throughout each phase of flight. No single set of navigation and operational requirements, even though they meet the basic requirement for safety, can adequately address the many different combinations of operating conditions encountered in various parts of the world. Requirements applicable to the most exacting region may be considered extravagant when applied to other regions. In general, the requirements for navigation are:

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

b. The navigation system must be safe, reliable, and 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 near 100 percent and should provide timely alarms in the event of failure, malfunction, or interruption.

d. The navigation system must recover from a temporary loss of signal without the need for complete resetting.

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

f. The navigation system must provide adequate means for the pilot to confirm the performance of airborne equipment.

g. The navigation information provided by the system must be free from unresolved ambiguities of operational significance.

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

i. In conjunction with other flight instruments, the navigation system shall provide information to the pilot and aircraft systems for performance of the following functions:

- Continuous determination of aircraft position.
- Continuous track deviation guidance.
- Continuous determination of along-track distance.
- Position reporting (manual or automatic).
- Continuous monitoring of navigation system performance.
- Manual or automatic flight.

j. The navigation system must be compatible with the overall ATC system that includes the performance requirements for communications and surveillance.

k. The navigation system should provide for efficient transition through all phases of flight, for which it is designed, with minimum impact on cockpit procedure/displays and workload.

l. 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 aircraft is bounded within established protected airspace areas at all times, (b) execute required holding patterns and approach procedures, and (c) annunciate to the aircraft when the system does not satisfy the requirements for the operation.

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

n. 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.

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

p. The navigation system must be cost-effective for both the Government and the users.

q. The navigation system must be designed to reduce 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.

r. The navigation system must compensate for signal fades or other propagation anomalies within the operating area.

s. The navigation system must be capable of furnishing reduced service to aircraft with limited equipment.

t. The navigation system must operate in appropriate radio spectrum and there must be suitable radio spectrum available to support the navigation system.

For any route, procedure or operation, an aircraft is required to have navigation equipment appropriate to the route to be flown. In many cases, this requires carriage of a specific navigation system, such as VOR or ILS. New RNAV-based routes and procedures are being developed to accommodate a variety of navigation systems although operations will continue to be restricted to the available and qualified systems.

The signal error 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. Under certain conditions, the bias component is generally easily compensated for when its characteristics are constant and known. 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 or incorrect.

2.2.1 Air Navigation Phases of Flight and Current Accuracy Requirements

The phases of navigation are en route (including oceanic/remote areas), terminal, approach/landing, and surface. The typical system use accuracy and route widths for all phases of flight are summarized in Table 2-1. These route widths are based upon present capacities, separation requirements, and obstruction requirements.

2.2.1.1 En Route Phase

This phase is the portion of flight after departure and prior to the transition to approach. The general requirements in Section 2.2 are applicable. In addition, to facilitate aircraft navigation in this phase, the navigation system used must be operationally compatible with the system used for approach and landing.

Altimeter information is also required for safe and efficient flight. The current separation requirement is 1,000 feet below FL 290, and 2,000 feet at and above FL 290. In order to permit the 1,000-foot vertical separation below FL 290, the root sum square (RSS) altitude-keeping requirement is ±350 feet (99.7 percent or 3 sigma). This error is comprised of ±250 feet (99.7 percent or 3-sigma) aircraft altimetry system error, of which the altimeter error is limited to ±125 feet by Technical Standard Order (TSO) C-10B below FL 290.

2.2.1.1.1 Oceanic/Remote Areas En Route

This subphase covers operations over the ocean and remote areas generally characterized by low traffic density and no independent surveillance coverage.

Table 2-1. Airspace Navigation Performance Requirements

PHASE	SUBPHASE		ALTITUDE FL/FT	TRAFFIC DENSITY	ROUTE WIDTH (nm)	SOURCE ACCURACY[1] CROSS –TRACK (95%)	SYSTEM USE ACCURACY[2] CROSS -TRACK (95%, nm)
EN ROUTE/ TERMINAL	Oceanic		FL 275 to 400	Normal	100/60/50*	12.6/10* nm	12.6*/10*
	Domestic		FL 180 to 600	Low	16	2.8 nm	3.0
				Normal	8	2.8 nm	3.0
			500 FT to FL 180	High	8	2.8 nm	3.0
	Terminal		500 FT to FL 180	High	4	1.7 nm	2.0
APPROACH LANDING	Nonprecision		250 to 3,000 FT	Normal	N/A	0.5 nm**	0.6
	Precision	CAT I	N/A	Normal	N/A	16m*** / 4.1 m****	N/A
		CAT II	N/A	Normal	N/A	TBD[3]	N/A
		CAT III	N/A	Normal	N/A	TBD[3]	N/A

[1] *The requirements of the navigation sensor.*

[2] *The combination of Source Accuracy and Flight Technical Error.*

[3] *Precision approach accuracy characteristics are specified by characteristics unique to ILS (e.g., beam bend tolerances, glide path alignment). Studies are underway to derive a total accuracy (in meters).*

* *Lateral separation requirements in the Pacific. FAA Order 8110.12 defines these requirements, and includes a lateral accuracy requirement of 10 nm.*

** While nonprecision approaches do not inherently provide vertical guidance, provision has been made for the use of barometric vertical navigation (VNAV) (see FAA Advisory Circular 20-129).

*** *Lateral position accuracy in meters at minimum applicable decision height.*

**** *Vertical position accuracy in meters at minimum applicable decision height.*

The navigation system used must provide 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 and in the Pacific to gain the benefit of optimum meteorological conditions. Since an independent surveillance system such as radar is not available, nor use of Automatic Dependent Surveillance (ADS) operationally approved on a large scale, separation is maintained by procedural means (e.g., position reports and timing) and implementation of communications, navigation and surveillance (CNS) performance requirements.

The lateral separation standard on the Organized North Atlantic Track System is 60 nm. The lateral separation standard has been reduced to 50 nm in parts of the Pacific Ocean. Current planning seeks a reduction to 30 nm lateral/30 nm longitudinal separation based on the implementation of both ADS and controller pilot data link (CPDLC) within oceanic domains. In this regard, an RNP-4 oceanic implementation plan has been announced.

For Minimum Navigation Performance Specification (MNPS) airspace (an RNP 12.6 equivalent) and RNP-10, INS and GPS are approved means of navigation.

Reduced Vertical Separation Minima (RVSM) is currently implemented on an exclusionary basis[*] in North Atlantic MNPS airspace between FL 310-390 (inclusive). It is scheduled to be expanded to FL 290-410 (inclusive) in January 2002.

RSVM is currently implemented on an exclusionary basis in the Pacific Oceanic Flight Information Regions (FIR). Most Pacific FIRs, including Oakland and Anchorage Oceanic, have implemented exclusionary airspace between FL 290-390 (inclusive). In most Pacific FIRs, including Oakland and Anchorage Oceanic, RSVM may be applied on a tactical basis to aircraft at FL 400 and 410. This means that if aircraft at these FLs are RSVM approved, 1,000-foot vertical separation can be applied. If either aircraft is not RSVM approved, 2,000-foot vertical separation is applied.

2.2.1.1.2 Domestic En Route

Operations in both the high and low altitude routes are typically characterized by moderate to high traffic densities. This necessitates narrower route widths than in the oceanic en route subphase. Independent surveillance is generally available to assist in ground monitoring of aircraft position

Area navigation (RNAV) is not restricted to fixed air routes. Under VFR, area navigation is conducted direct between the origin and destination. Under IFR, area navigation can be used at any altitude; however, radar monitoring is required for operations below flight level 450. When aircraft are given an off-route clearance, separation assurance is provided by ATC.

2.2.1.1.3 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. Thus the minimum route width varies and can be greater than 10 nm.

GPS and INS are approved for operations in remote areas.

2.2.1.1.4 Operations Between Ground Level and 5,000 Feet Above Ground Level (AGL)

Operations between ground level and 5,000 feet AGL occur in offshore, mountainous, and high-density metropolitan areas as well as on domestic routes. Operations from the U.S. coastline to points 300 nm offshore are characterized by:

- Minimum en route altitude of 500 feet above sea level or above obstructions.
- 100-foot minimum descent altitude to 100 feet in designated areas.

[*] Exclusionary means that, with agreed exceptions, aircraft and operators must be approved to fly in designated RSVM airspace. Examples of agreed exceptions are humanitarian, maintenance, aircraft delivery, and military flights. Prior to such flights, operators must coordinate with the appropriate air traffic service.

- Navigation accuracy sufficient to support 4 nm wide routes (or narrower) with 95 percent confidence.

Helicopter operations over land are characterized by:

- Minimum en route altitude of 1,200 feet AGL.
- Navigation accuracy sufficient to support 2 nm route widths, in both en route and terminal areas, with 95 percent confidence.
- Navigation signal coverage adequate to support approach procedures to minimums of 250 feet above obstruction altitudes at heliports and airports.

2.2.1.2 Terminal Phase

Operation in the terminal area 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.

Terminal procedures provide transition from the en route to the approach phase of flight. Surveillance facilities support controller vectoring of aircraft to intercept precision approach services in higher density terminal areas. As RNAV-equipped aircraft can support more precise navigation, new terminal procedures have been developed to support these operations.

2.2.1.2.1 Departure

Departure begins after reaching the departure end of the runway and continues until interception of the en route airway structure or until air traffic terminal services make a handoff to en route air traffic services.

2.2.1.2.2 Arrival

Arrival begins when the aircraft leaves the en route altitude and ends upon reaching the final approach fix (FAF) prior to landing.

2.2.1.3 Takeoff, Approach and Landing Phases

The general requirements of Section 2.2 apply to the takeoff, approach and landing phases. In addition, specific procedures and clearance zone requirements are specified in TERPS (United States Standard for Terminal Instrument Procedures, FAA Handbook 8260.3B) (Ref. 4).

Altimetry accuracy requirements are established in accordance with FAR 91.411 and are the same as those for the en route and terminal phases.

The minimum performance criteria currently established to meet requirements for the approach and landing phases of navigation vary between precision and nonprecision approaches.

2.2.1.3.1 Takeoff

Takeoff begins with initial roll and ends at the departure end of the runway.

2.2.1.3.2 Approach

The Basic classifications of approach include:

- Nonprecision Approach: Nonprecision approach aids provide a landing aircraft with horizontal position information (2-dimensional approaches).

- Approach with Vertical Guidance: This is a new type of operation that was adopted by ICAO in May of 2000. This approach classification allows the use of a stabilized descent, using vertical guidance, without the accuracy required for a traditional precision approach procedure. The U.S. has developed criteria for lateral/vertical navigation (LNAV/VNAV) approach procedures that meet this approach classification. The LNAV/VNAV approach provides guidance in both the lateral and vertical planes.

- Precision Approach: Precision approach aids provide landing aircraft with vertical and horizontal guidance and positioning information.

Note: A missed approach procedure is conducted when a landing cannot be completed safely.

2.2.1.3.2.1 Nonprecision Approach (LNAV)

Nonprecision approaches are based on specific navigation systems. Minimum safe altitude, obstacle clearance area, visibility minimum, final approach segment area, etc., are all functions of the navigation accuracy available and other factors.

The achieved capability for nonprecision approaches varies significantly, depending on the location of the navigation facility in relation to the fix location and type of navigation system used. VOR accuracy is based on the $\pm$4.5 degrees VOR system accuracy.

The integrity time-to-alarm requirement for nonprecision approaches provides the pilot with either a warning or a removal of signal within 10 seconds of the occurrence of an out-of-tolerance condition.

2.2.1.3.2.2 Approach with Vertical Guidance (LNAV/VNAV Criteria)

The U.S. is developing RNAV approaches that provide benefits for aircraft with vertical navigation (VNAV). LNAV/VNAV approaches provide both lateral and vertical guidance for the approach. Some flight management systems (FMS) have this capability by incorporating lateral guidance and deviations and barometric aided (vertical) guidance and deviation information.

2.2.1.3.2.3 Precision Approach

A precision approach aid provides an aircraft with vertical and horizontal guidance and position information. The current worldwide standard systems for precision approach and landing are the Instrument Landing System (ILS), Microwave Landing System (MLS), Ground Based Augmentation Systems (GBAS), and Space Based Augmentation Systems (SBAS). 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 accuracy requirements for the various landing categories are shown in Table 2-1. The 95 percent accuracy requirement depends upon the error characteristics of the system, such as the frequency and correlation of errors. ILS has an angular error characteristic and has both low frequency and high-frequency components. The 95 percent accuracy for ILS at a 200-foot decision height is 4.1 meters. The Category II and III accuracy requirement is being evaluated. Aircraft use a combination of the precision approach guidance from the ILS, MLS, GLS, and a radar altimeter to accomplish a Category III approach.

Precision approach and landing systems must warn the pilot of an out-of-tolerance condition during precision approaches by removing these signals from service. The response time for providing these warnings is six seconds for Category I and two seconds for Category II and III.

2.2.1.3.3 Landing

The landing phase begins at the final approach fix (FAF) and continues through touchdown and rollout. The final approach can be based on:

- Precise lateral and vertical positive course guidance/deviation information (precision approach).
- Lateral and vertical positive course guidance/deviation information derived from an area navigation system (e.g., LNAV/VNAV).
- Lateral course guidance/deviation information and minimum descent altitudes (i.e., nonprecision approaches).

2.2.1.4 Surface Phase

Surface operations include navigation on the airport surface to and from the active runway. These operations are conducted visually.

2.2.2 Evolving Aviation Navigation Requirements

In accordance with the ICAO Global Air Navigation Plan for CNS/ATM Systems (ICAO Document 9750) and international agreements, the concepts of RNAV, RNP and RNP RNAV are being applied to aircraft operations.

Basic RNAV (RNP-x) is currently implemented within the airspace of several ICAO states, as well as some areas of international airspace. Use of RNAV permits greater flexibility in the design of routes and procedures.

Use of RNP by United States operators is currently limited to certain international operations and domestic special procedures. However, RNP is evolving as the foundation for global navigation definition and supports the worldwide goals of increasing efficiency and safety in airspace use, aircraft separation, and terrain/obstacle avoidance.

2.2.2.1 En Route Phase

Within U.S. airspace, there will be an increased emphasis on the use of RNAV.

2.2.2.1.1 Oceanic En Route

The oceanic domain seeks a reduction of the 50 nm separation standard to 30 nm. This reduction would require the implementation of ADS and CPDLC and is covered under the auspices of ICAO Review of General Concept of Separation Panel (RGCSP) plans for RNP-4 operations.

2.2.2.1.2 Domestic En Route

Traffic increases may soon exceed capacity. The increased use of RNAV allows the implementation of routes not possible with the use of current VOR/DME facilities. This may increase system efficiency and help provide relief from current capacity constraints.

Steps are underway to redesign en route airspace under the High Altitude Airspace Concept. High altitude airspace could provide for the use of user defined flight paths (free flight) and increased conflict management flexibility for controllers through the possible:

- Implementation of RVSM to reduce the required vertical separation between aircraft. The FAA is coordinating a phased implementation plan with the aviation industry. Phase 1 options being discussed include the implementation of RSVM exclusionary airspace either between FL 350-390 or between FL 290-390, with a possible implementation date of December 2004.

- Removal of directional altitude constrains that currently limit eastbound operations to FL 290, 330, 370, 410, and 450, and westbound operations to FL 280, 310, 350, 390, and 430.

2.2.2.1.3 Remote Areas

The implementation of RNAV systems and improved surveillance technologies provide increased airspace utilization for operations in remote areas.

2.2.2.2 Terminal Phase

The major change forecasted for the terminal area is the increased use of RNAV.

2.2.2.3 Takeoff, Approach and Landing Phases

The major change forecasted for takeoff, approach and landing phases is the increased use of RNAV to achieve optimum airspace utilization and noise abatement.

2.2.2.3.1 Takeoff

The use of RNAV for departure procedures will allow for increased flexibility in departure procedure design and will increase the ability of procedures to avoid noise sensitive areas.

2.2.2.3.2 Nonprecision Approach

Nonprecision approach obstacle clearance areas have been introduced to take advantage of the increased performance provided by GPS.

2.2.2.3.3 Approach with Vertical Guidance (LNAV/VNAV Criteria) Approach

LNAV/VNAV procedures provide a stabilized vertical path, improving upon the guidance provided to runways not previously supported by precision approach procedures. The provision of a stabilized vertical path increases flight safety.

2.2.2.3.4 Precision Approach

It is envisioned that LAAS and WAAS will help to enable complex operations that may include closely spaced parallel runway operations and complex precision approaches as well as all-weather surface operations.

A precision capability, i.e., navigation with vertical guidance as well as lateral guidance, to at least a point in space will be possible everywhere in the United States with the advent of WAAS, something not formerly available to aviation users.

2.2.2.3.5 Landing

Increases in navigation performance accuracy increase safety levels for landing operations and could support landing and rollout surveillance systems.

2.2.2.4 Surface Phase

Navigation could act as an input source to advanced surface movement operations, e.g., surveillance systems. This use of surveillance increases situational awareness; however, surface operations remain primarily tied to the use of visual reference.

2.3 Civil Marine Radionavigation Requirements

2.3.1 Phases of Marine Navigation

Marine navigation in the U.S. consists of four major phases identified as inland waterway, harbor entrance and approach, coastal, and ocean navigation. Standards or requirements for safety of navigation and reasonable economic efficiency can be developed around these four phases. Specialized requirements, which may be generated by the specific activity of a ship, must be addressed separately.

2.3.1.1 Inland Waterway

Inland waterway navigation is conducted in restricted areas similar to those for harbor entrance and approach. 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 System.

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, personnel, 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.

2.3.1.2 Harbor Entrance and Approach

Harbor entrance and approach navigation is conducted 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 navigation 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, harbor entrance 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 in harbor entrance and approach. 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 phase of harbor entrance and approach is 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.

2.3.1.3 Coastal Navigation

Coastal navigation is that phase in which a ship is within 50 nm from shore or the limit of the continental shelf (200 meters in depth), whichever is greater, where a safe path of water at least one nm wide, if a one-way path, or two nm 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:

- 50 nm from land.
- The outer limit of offshore shoals, or other hazards on the continental shelf.
- 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.

2.3.1.4 Ocean Navigation

Ocean navigation is that phase in which a ship is beyond the continental shelf (200 meters in depth), 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 landmasses so that the hazards of shallow water and of collision are comparatively small.

2.3.2 Current Marine Navigation Requirements

The navigation 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) and the geographic region in which it operates (e.g., ocean, coastal), as well as 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 above discussion of phases of marine navigation 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, navigation accuracy (beyond that needed for safety) is particularly important to the economy of large seagoing ships having high hourly operating costs. For fishing and oil exploration vessels, the ability to locate precisely and return to productive or promising areas and at the same time avoid underwater obstructions or restricted areas provides important economic benefits. Search and Rescue (SAR) effectiveness is similarly dependent on accurate navigation in the vicinity of a maritime distress incident.

For 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 required to carry only minimal navigation equipment, and even then do so only if persuaded by individual cost/benefit analysis, this governmental policy helps to promote maritime safety through a simultaneous economic incentive.

Tables 2-2, 2-3, 2-4, and 2-5 identify system performance needed to satisfy maritime user requirements or to achieve special benefits. The requirements are related to safety of navigation. The Government recognizes an obligation to satisfy these requirements for the overall national interest. The benefits are specialized requirements or characteristics 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 requirements, but does endeavor to meet them if their cost can be justified by benefits that are in the national interest. For the purpose of comparing the performance of systems, the requirements are categorized in terms of system performance characteristics representing the minimum performance considered necessary to satisfy the requirements or achieve special benefits.

2.3.2.1 Inland Waterway Phase

Very large amounts of commerce move on the U.S. 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 that 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 entrance and approach navigation. The long, ribbon-like nature of the typical inland waterway presents special problems to the prospective user of precise, land-based area navigation systems. Continual shifting of navigable channels in some unstable waters creates additional problems to the prospective user of any radionavigation system that provides position measurements in a fixed coordinate system.

Special waterways, such as the Saint Lawrence River and some Great Lakes passages, are well defined, but subject to frequent fog cover which requires ships to anchor. This imposes a severe economic penalty in addition to the safety issues. If a fog rolls in unexpectedly, a ship may need to proceed under hazardous conditions to an anchorage clear of the channel or risk stopping in a channel. Current requirements for the inland waterway phase of navigation are provided in Table 2-2.

Visual and audio aids to navigation, radar, and intership communications are presently used to enable safe navigation in those areas. However, DGPS is expected to play an increasing role in this phase of navigation.

Table 2-2. Current Maritime User Requirements for Purposes of System Planning and Development - Inland Waterway Phase

REQUIREMENTS	MEASURES OF MINIMUM PERFORMANCE CRITERIA TO MEET REQUIREMENTS								
	ACCURACY (meters, 2drms)		COVERAGE	AVAILABILITY	RELIABILITY	FIX INTERVAL (seconds)	FIX DIMENSIONS	SYSTEM CAPACITY	AMBIGUITY
	PREDICTABLE	REPEATABLE							
Safety of Navigation (All Ships & Tows)	2-5	2-5	US Inland Waterway Systems	99.9%	*	1-2	2	Unlimited	Resolvable with 99.9% confidence
Safety of Navigation (Recreational Boats & Smaller Vessels)	5-10	5-10	US Inland Waterway Systems	99.9%	*	5-10	2	Unlimited	Resolvable with 99.9% confidence
River Engineering & Construction Vessels	0.1**-5	0.1**-5	US Inland Waterway Systems	99%	*	1-2	2 or 3	Unlimited	Resolvable with 99.9% confidence

* Dependent upon mission time.
** Vertical dimension.

Table 2-3. Current Maritime User Requirements/Benefits for Purposes of System Planning and Development - Harbor Entrance and Approach Phase

(a)

REQUIREMENTS	MEASURES OF MINIMUM PERFORMANCE CRITERIA TO MEET REQUIREMENTS								
	ACCURACY (meters, 2drms)		COVERAGE	AVAILABILITY	RELIABILITY	FIX INTERVAL (seconds)	FIX DIMENSIONS	SYSTEM CAPACITY	AMBIGUITY
	PREDICTABLE	REPEATABLE							
Safety of Navigation (Large Ships & Tows)	8-20***	-	US harbor entrance and approach	99.7%	**	6-10	2	Unlimited	Resolvable with 99.9% confidence
Safety of Navigation (Smaller Ships)	8-20	8-20	US harbor entrance and approach	99.9%	**	***	2	Unlimited	Resolvable with 99.9% confidence
Resource Exploration	1-5*	1-5*	US harbor entrance and approach	99%	**	1	2	Unlimited	Resolvable with 99.9% confidence
Engineering & Construction Vessels Harbor Phase	0.1****-5	0.1****-5	Entrance channel & jetties, etc.	99%	**	1-2	2 and 3	Unlimited	Resolvable with 99.9% confidence

(b)

Benefits	MEASURES OF MINIMUM PERFORMANCE CRITERIA TO MEET REQUIREMENTS								
Fishing, Recreational & Other Small Vessels	8-20	4-10	US harbor Entrance and approach	99.7%	**	***	2	Unlimited	Resolvable with 99.9% confidence

* Based on stated user need.
** Dependent upon mission time.
*** Varies from one harbor to another. Specific requirements are being reviewed by the Coast Guard.
**** Vertical dimension.

Table 2-4. Current Maritime User Requirements/Benefits for Purposes of System Planning and Development - Coastal Phase

(a)

REQUIREMENTS	MEASURES OF MINIMUM PERFORMANCE CRITERIA TO MEET REQUIREMENTS								
	ACCURACY (meters, 2drms)		COVERAGE	AVAILABILITY	RELIABILITY	FIX INTERVAL	FIX DIMENSIONS	SYSTEM CAPACITY	AMBIGUITY
	PREDICTABLE	REPEATABLE							
Safety of Navigation (All Ships)	0.25nm (460m)	-	US coastal waters	99.7%	**	2 minutes	2	Unlimited	Resolvable with 99.9% confidence
Safety of Navigation (Recreation Boats & Other Smaller Vessels)	0.25nm-2nm (460-3,700m)	-	US coastal waters	99%	**	5 minutes	2	Unlimited	Resolvable with 99.9% confidence

(b)

BENEFITS	MEASURES OF MINIMUM PERFORMANCE CRITERIA TO MEET REQUIREMENTS								
Commercial Fishing (Including Commercial Sport Fishing)	0.25nm (460m)	50-600 ft (15-180m)	US coastal/ Fisheries areas	99%	**	1 minute	2	Unlimited	
Resource Exploration	1.0-100m*	1.0-100m*	US coastal areas	99%	**	1 second	2	Unlimited	
Search Operations, Law Enforcement	0.25nm (460m)	300-600 ft (90-180m)	US coastal/ Fisheries areas	99.7%	**	1 minute	2	Unlimited	
Recreational Sports Fishing	0.25nm (460m)	100-600 ft (30-180m)	US coastal areas	99%	**	5 minutes	2	Unlimited	Resolvable with 99.9% confidence

* Based on stated user need.

** Dependent upon mission time.

Table 2-5. Current Maritime User Requirements/Benefits for Purposes of System Planning and Development - Ocean Phase

(a)

REQUIREMENTS	MEASURES OF MINIMUM PERFORMANCE CRITERIA TO MEET REQUIREMENTS									
	ACCURACY (2 drms)			COVERAGE	AVAILABILITY	RELIABILITY	FIX INTERVAL	FIX DIMENSION	SYSTEM CAPACITY	AMBIGUITY
	PREDICTABLE	REPEATABLE	RELATIVE							
Safety of Navigation (All Craft)	2-4nm (3.7-7.4km) minimum 1-2nm (1.8-3.7km) desirable	-	-	Worldwide	99% fix at least every 12 hours	**	15 minutes or less desired; 2 hours maximum	2	Unlimited	Resolvable with 99.9% confidence

(b)

BENEFITS	MEASURES OF MINIMUM PERFORMANCE CRITERIA TO MEET REQUIREMENTS									
Large Ships Maximum Efficiency	0.1-0.25nm* (185-460m)	-	-	Worldwide, except polar regions	99%	**	5 minutes	2	Unlimited	Resolvable with 99.9% confidence
Resource Exploration	10-100m*	10-100m*	-	Worldwide	99%	**	1 minute	2	Unlimited	Resolvable with 99.9% confidence
Search Operations	0.1-0.25nm (185-460m)	0.25nm	0.1nm (185m)	National Maritime SAR regions	99%	**	1 minute	2	Unlimited	Resolvable with 99.9% confidence

* Based on stated user need.

** Dependent upon mission time.

2.3.2.2 Harbor Entrance and Approach Phase

The pilot of a vessel in restricted waters must direct its movement with great accuracy and precision to avoid grounding in shallow water, hitting submerged/partially submerged rocks, and colliding with other craft in congested waterways. Unable to turn around, and severely limited in the ability to stop to resolve a navigation problem, the pilot of a large vessel (or a tow boat and barge combination) may find it necessary to hold the total error in navigation within limits measured in a few feet while navigating in this environment.

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. Table 2-3 was developed to present estimates of these requirements. To effectively utilize the requirements stated in the table, however, a user must be able to relate the data to immediate positioning needs. This is not practical if one attempts to plot fixes on a chart in the traditional way. To utilize radionavigation information that is presented at less than 10-second intervals on a moving vessel, some form of an automatic display is required. Technology is available which presents radionavigation information along with other data.

Minimum Performance Criteria: The radionavigation system accuracy required to provide useful information in the harbor entrance and approach phase of marine navigation varies from harbor to harbor, as well as with the size of the vessel. In the more restricted channels, accuracy in the range of 8 to 20 meters (2 drms) may be required for the largest vessels. A need exists to more accurately determine these radionavigation requirements for various-sized vessels while operating in such restricted confines. Radionavigation user conferences have indicated that for many mariners, the radionavigation system becomes a secondary tool when entering the harbor entrance and approach environment.

Continuing efforts are being directed toward verifying user requirements and desires for radionavigation systems in the harbor entrance and approach environment.

Navigation in the harbor entrance and approach areas is accomplished through use of fixed and floating visual aids to navigation, radar, and audible warning signals. The growing desire 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 VTS along with AIS in certain port areas and investigation of the use of radio aids to navigation. DGPS coverage includes all coasts of the continental U.S. and parts of Alaska, Hawaii, and the Great Lakes. Typical system performance is better than 1 meter in the vicinity of the broadcast site. Achievable accuracy degrades at an approximate rate of 1 meter for each 150 km distance from the broadcast site.

2.3.2.3 Coastal Phase

There is a need for continuous, all-weather radionavigation service in the coastal area to provide, at the least, the position fixing accuracy to satisfy minimum safety requirements for general navigation. These requirements are delineated in Table 2-4. Furthermore, the total navigation service in the coastal area must provide service of useful quality and be within the economic reach of all classes of mariners.

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

- 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.
- 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.

Minimum Performance Criteria: Government studies have 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 indicated in Table 2-4, these requirements may be relaxed slightly for the recreational boaters 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 that require highly accurate positions, the use of radiodetermination would be classified as radiolocation rather than radionavigation. As shown in Table 2-4, 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.

Navigation service for operation within the coastal area is provided by Loran-C, GPS and DGPS. Radio Direction Finders (RDFs), required in some merchant ships by international agreement for search and rescue purposes, are also used with the radiobeacon system for navigation.

2.3.2.4 Ocean Phase

The requirements for safety of navigation in the ocean phase for all ships are given in Table 2-5. 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 many 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, minimizing transit time.

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 navigation 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 99 percent.

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 operators of these craft, however, will accept the risk of ocean sailing without reliable radionavigation unless that capability is available at relatively low cost.

Minimum Performance Criteria: Economic efficiency in transoceanic transportation, special maritime activities and safety in emergency situations require or benefit from navigation accuracy higher than that needed for safety in routine, point-to-point ocean voyages. These requirements are summarized in Table 2-5. The predictable accuracy benefits 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 2-5, the required fix interval may range from as low as once per 5 minutes to as high as once per minute. Signal availability must be at least 95 percent and approach 99 percent for all users.

Navigation on the high seas is accomplished by the use of dead reckoning, celestial fixes, self-contained navigation systems (e.g., inertial systems), Loran-C and GPS. GPS is now the system of choice. Worldwide coverage by most ground-based systems such as Loran-C is not practicable.

2.3.3 Future Marine Navigation Requirements

The marine radionavigation requirements presented in the preceding discussions and tables are based on a combination of requirements studies, user inputs, and estimates. However, they are the product of current technology and operating practices, and are therefore subject to revision as technologies and operating techniques evolve. The principal factors that will impact future requirements are safety, economics, environment, and energy conservation.

Special radionavigation requirements may arise from new environmental laws and regulations designed to reduce marine vessel casualty events. Also, the role of commercial ships in military sealift missions may require additional navigation systems capabilities.

2.3.3.1 Safety

2.3.3.1.1 Increased Risk from Collision and Grounding

Hazardous cargoes (petroleum, chemicals, etc.) are carried in great volumes in U.S. coastal and inland waterways. Additionally, the ever increasing volume of other shipping, the ability to operate at increased speed, and the increasing numbers of smaller vessels act to constantly increase the risk of collision and grounding. Economic constraints also cause vessels to be operated in a manner which, although not unsafe, places more stringent demands on all navigation systems.

2.3.3.1.2 Increased Size and Decreased Maneuverability of Marine Vessels

The desire to minimize costs and to capture economies 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, improved navigation performance is needed.

2.3.3.1.3 Greater Need for Traffic Management/Navigation Surveillance Integration

The foregoing trends underlie the importance of continued governmental involvement in marine vessel traffic management to assure reasonable safety in U.S. waters. Radionavigation systems may become an essential component of traffic management systems. Differential GPS and Automated Identification Systems (AIS) are expected to play an increasingly important role in areas such as Vessel Traffic Services (VTS).

2.3.3.2 Economics

2.3.3.2.1 Greater Congestion in Inland Waterways and Harbor Entrances and Approaches

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. Accurate radionavigation systems can contribute to better productivity and decreased delay in transit.

2.3.3.2.2 All Weather Operations

Low visibility and ice-covered waters presently impact maritime operations. The Cost Guard is working to identify the proper mix of systems and equipment that would enable all weather operations.

2.3.3.3 Environment

As onshore energy supplies are depleted, resource exploration and exploitation will move farther offshore toward the U.S. outer continental shelf and to harsher and more technically demanding environments. In addition, fishing is expected to continue in the U.S. Exclusive

Economic Zone. In summary, both sets of activities may generate demands for navigation services of higher quality and for broadened geographic coverage in order to allow environmentally sound development of resources.

2.3.3.4 Energy Conservation

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.

2.4 Space Radionavigation Requirements

2.4.1 Space User Community

NASA is currently using GPS to support earth-orbiting satellites conducting space and earth science missions and is beginning to extend the use of GPS for human space exploration missions as well. In addition, other government agencies may use GPS on satellites in the future. There are also numerous examples of GPS use by the U.S. commercial space community for Low Earth Orbiting (LEO) communication satellite constellations and aboard commercial earth sensing satellites.

2.4.2 Space User Community Application of GPS

The U.S. space community uses GPS in a number of spacecraft and science instrument applications. On satellites, GPS is being used to determine satellite position as an input to navigation software that calculates and propagates the satellite's orbit. GPS also can provide accurate time synchronization for satellites as well as spacecraft attitude determination.

The setting of the Selective Availability (SA) to zero increased the accuracy with which satellite orbital position can be determined using GPS. However, since LEO satellites (below roughly 1300 km altitude) are still below the ionosphere, additional improvement in orbit accuracy can be achieved when the second civil signal becomes operationally capable.

NASA is also experimenting with the use of dual frequency GPS receivers aboard science satellites to conduct atmospheric occultation experiments. In this application, the GPS receiver actually becomes an instrument for measuring atmospheric temperature and moisture content. Receiver complexity will be reduced and performance enhanced when the second civil signal becomes available. The National Polar-Orbiting Observational Environmental Satellite System (NPOESS) is currently planning to use GPS atmospheric occultation for routine atmospheric measurements aboard its satellites beginning in the next decade.

The U.S. space community also plans to use GPS for various launch vehicle applications in the future. DoD is currently planning to convert the national spacelift ranges to use GPS for range safety. This is an important aspect of DoD's Range Standardization and Automation (RSA) program. NASA will begin using GPS for the re-entry and landing phases for the Space Shuttle in 2001.

2.4.3 Current Space Radionavigation Requirements

Space radionavigation requirements fall into three different applications categories:

1. Onboard spacecraft vehicle navigation support where GPS and GPS augmentations will be used in near real-time applications for navigation, precise time, and attitude determination. In this role, onboard navigation and attitude accuracy requirements are:

    - Three-dimensional position error not to exceed 1 m (1 sigma) with three-dimensional velocity error not to exceed 0. 1 m/sec (1 sigma).

    - Attitude determination error not to exceed 0.01 degree in each axis (1 sigma).

    - Clock offset between coordinated universal time (UTC) as maintained at the U.S. Naval Observatory (USNO) and the GPS time scale not to exceed 1 microsecond (1 sigma).

It should be noted that the required accuracies above result from filtered GPS data and do not represent instantaneous solution requirements but are considered real-time requirements.

NASA is planning on the use of GPS to enable new techniques of Earth observation in the future by flying small satellites in formation with each other. The satellites will use GPS to maintain their relative positions while making coordinated Earth observations such as stereoscopic images. The first use of GPS aided formation flying is planned for implementation in early 2001 with the launch of the EO-1 satellite. The same GPS-aided relative positioning technique will be used for orbital rendezvous of autonomous supply vehicles approaching the International Space Station (ISS).

2. GPS supports scientific data analysis in a post-processing mode to accurately locate instrument position in space when measurements are taken. Accuracy requirements are to determine position within 5 cm. However, more accurate positioning in the 1 to 2 cm range will be required in the future for some earth observation instruments.

3. Use of GPS receivers aboard satellites as scientific instruments for atmospheric research. These receivers require dual frequency GPS signals in order to measure the occultation of the GPS signals as they pass through the atmosphere. This application has been demonstrated in the GPSMET experiment and is the basis behind planned instruments for the future NPOESS where the technique will be employed in an operational mode supporting weather observation.

Planned and proposed future NASA spacecraft will require continued use of GPS. Examples of GPS space applications include the following:

- The Space Shuttle will implement GPS for re-entry and landing phases beginning in 2001, and will evolve to on-orbit operations in the near future. Space Shuttle experiments in the use of GPS in the ascent phase of flight will also continue.

- The International Space Station will use GPS for position and navigation, attitude determination, and as a precise time source. Present planning is for the ISS GPS system to become active on ISS in 2001.

- Crew Return Vehicle (CRV) is the emergency return vehicle that would be used in the event of a crew emergency aboard the ISS and it will depend upon GPS for critical navigation and attitude determination functions. It will use GPS to initially align its avionics systems after separation from the ISS, use GPS for orbit phase navigation and attitude determination, for navigation during descent, and for navigation to its recovery area.

- New small satellite programs to explore low-cost access to space will implement GPS for navigation, time, and attitude determination functions. The use of low cost onboard GPS receivers for these basic functions of space flight will become a significant factor in providing inexpensive access to space for future NASA and commercial small satellite projects.

- Where scientific data position accuracy is required with precision greater than that readily available from the GPS receiver onboard a spacecraft, post-pass processing of orbit data will be used. NASA has developed post pass-process techniques using GPS on the TOPEX/POSEIDON satellite that routinely provides satellite positioning accuracy at the 5 cm level. However, in order to obtain this level of precision, accurate GPS satellite position data must be obtained. This accurate GPS satellite tracking data is developed using an extensive global network of ground monitoring stations.

- The use of GPS out to geosynchronous orbit altitudes is being explored by NASA and may prove to be useful to the commercial space industry in the future. However, it is essential that future GPS satellite power levels and beam coverage patterns remain consistent with the current signal characteristics in order to meet the needs of future space users in the geosynchronous orbital region.

2.5 Civil Land Radionavigation Requirements

In comparison with the air and marine communities, phases of land navigation are not well defined. Radionavigation requirements are more easily categorized in terms of applications. The land navigation applications fall into three basic categories; highway, transit, and rail applications. Ongoing work on Intelligent Transportation Systems (ITS), which includes research and development (R&D) and operational test programs funded by the Department of Transportation's modal administrations (including FHWA, FTA, FRA, NHTSA, and the

Federal Motor Carrier Safety Administration (FMCSA)) as well as by State and local governments and private industry, will aid in clarifying and validating user requirements.

2.5.1 Categories of Land Transportation

2.5.1.1 Highways

Radionavigation techniques in highway applications are used autonomously or are integrated with vehicle-to-roadside communications and map-matching techniques to provide various user services. These are public sector operational tests ongoing for integrated ITS systems, where radionavigation is a part of the system. However, a number of consumer products and products for use by the public sector are on the market today. Deployment of these systems is accelerating at a rapid pace. Vehicle location systems for emergency service, providers of mayday services, route navigation for private automobiles, and tracking and scheduling of commercial vehicles are in use. Examples of systems in development include augmentation of GPS vehicle location data by providing DGPS correction values over wireless communications. Also under development is a system for vehicle location monitoring using GPS integrated with wireless packet data systems. Examples of systems used in operational tests for ITS funded by FHWA include the use of radionavigation for automatic vehicle location for mayday response, route guidance, mass transit scheduling, and mileage determination. Examples of systems that are fielded and operational include radionavigation for dispatching roadside assistance vehicles and automated location tracking and scheduling of commercial vehicles. In addition to these examples, radionavigation is used by various highway departments for asset management by using GPS coordinates to identify locations of bridges, highway signs, and overpasses. Table 2-6 shows examples of ITS user services requiring the use of radionavigation. A complete description of all of the ITS user services can be found in ITS Architecture documentation (Ref. 5).

2.5.1.2 Transit

Transit systems also benefit from the same radionavigation-based technologies. Automatic vehicle location techniques assist in fleet management, scheduling, real-time customer information, and emergency assistance. In addition, random route transit operations will benefit from route guidance in rural and low-density areas. Also, services such as automated transit stop annunciation are being implemented. Benefits of radiolocation for public transit, when implemented with a two-way communications system, have been proven in a number of deployments across the U.S. Improvements in on-time performance, efficiency of fleet utilization, and response to emergencies have all been documented. Currently, there are over 60,000 transit vehicles that employ automatic vehicle location using GPS for these fleet management functions and the deployment is continuing to spread.

Table 2-6. ITS User Services Requiring Use of Radionavigation

Travel and Transportation Management Pre-Trip Travel Information En Route Driver Information Route Guidance Incident Management Travel Demand Management
Public Transportation Operations Public Transportation Management Personalized Public Transportation
Commercial Vehicle Operations Commercial Fleet Management
Emergency Management Emergency Vehicle Management Emergency Notification and Personal Security
Advanced Vehicle Control and Safety Systems Intersection Collision Avoidance

2.5.1.3 Rail

Nationwide DGPS can significantly aid the development of positive train control (PTC) systems by providing an affordable and reliable location determination system that is available to surface and marine transportation throughout the contiguous United States and Alaska.

New PTC systems will be communication-based; they will depend upon use of data communication over a variety of paths, including radio, to gather information for integration by microprocessors. One of the principal issues related to PTC is affordability. If systems are highly affordable, they will be widely deployed for both safety and business purposes. Wide deployment will mean that collision avoidance and other safety features will be available over a larger portion of the national rail system. Universal equipping of trains with on-board systems will be necessary to realize maximum safety benefits.

Railroads and their suppliers have evaluated their requirements for train location in relation to NDGPS as follows:

- The single most stressing requirement for the location determination system to support the PTC system is the ability to determine which of two tracks a given train is occupying with a very high degree of assurance* (an assurance that must be greater than 0.99999

* The assurance of a navigation system is the probability over both time and area, that the services will be sufficiently robust to meet the requirements of the user. This differs from availability in that it goes beyond time and beyond a single navigation system. An example is the system envisioned for PTC. This system, as currently envisioned, will use NDGPS, inertial sensors, transponders at critical junctions, map matching, and other techniques to form an integrated navigation solution.

or (0.9_5)). The minimum center-to-center spacing of parallel tracks is 11.5 feet. While GPS alone cannot meet the specified continuity of service and accuracy, NDGPS in combination with map matching, inertial navigation systems, accelerometers, and other devices and techniques will provide both the continuity of service and accuracy required to meet the stringent requirements set forth for PTC.

- Train location is a *one*-dimensional issue, with well-defined discrete points (switches) where the potential for diverging paths exists. NDGPS narrows the location to less than 3 meters (less than 10 feet). The most frequent interval at which successive turnouts can be located (locations at which a train may diverge from its current route over a switch) is 48 feet. Since the train is constrained to be *located on a track*, as opposed to somewhere within an area, this collapses the problem from a two- or three-dimensional problem into a *one*-dimensional problem.
- The *detailed* track geometry data for a specific route are stored on-board the locomotive (needed for calculating the safe braking distance algorithm). Which of two parallel tracks a train is occupying can then be determined by maintaining a continuous record of which direction the train took over each diverging switch point (normal or reversed). There are several heading reference system techniques available to make this determination.

Private sector freight railroads and public sector passenger and commuter railroads own and maintain their rights-of-way, and many are using GPS for surveying to establish more accurate track maps and property inventories.

2.5.2 Current Land Transportation Requirements

Requirements for use of radionavigation systems for land vehicle applications continue to evolve. Many civil land applications that use radionavigation systems are now commercially available. Examples of highway user applications that are now available include in-vehicle navigation and route guidance, automatic vehicle location, automated vehicle monitoring, automated dispatch, and hazardous materials tracking. Other applications continue to be investigated and developed, including resource management, highway inventory control, and positive train separation. At the present time, there are many hundreds of thousands of GPS receivers in use for surface applications. Many of these are finding their way into land vehicle applications.

In order for some of the envisioned applications to be useful, they need to be coupled with a variety of space and terrestrial communication services that relay information from the vehicle to central dispatch facilities, emergency service providers, or other destinations. An example of such an application includes relaying the status of vehicle onboard systems and fuel consumption to determine allocation of fuel taxes.

ITS operational tests are yielding results that make it clear that large-scale deployment will include a number of navigation mechanisms shared with other systems and services. For example, several ITS operational tests use GPS and NDGPS have been completed that use in-vehicle navigation systems and electronic mapping systems to provide real-time route guidance information to drivers. Additionally, GPS and NDGPS are used for automatic vehicle location for bus scheduling and fleet management. Such an approach for sharing brings benefits of more efficient use of the scarce radio frequency spectrum as well as reduction of capital costs of infrastructure and related operations, administration and maintenance costs.

The navigation accuracy, availability, and integrity needs and requirements of land modes of transportation, as well as their associated security needs and requirements (including continuity of service), have been documented in the *February 2000 Air Force Command Operational Requirements Document (ORD) AFSPC/ACC 003-92-I/II/III for Global Positioning System (U)* (Ref. 6). Examples of land transportation positioning and navigation system accuracy needs and requirements are shown in Table 2-7. In addition, terrain is a very important factor and must be considered in the final system analysis.

Of special interest is the concept of collision avoidance. There has been a trend to move away from infrastructure-based systems towards more autonomous, vehicle based systems. It is too early in the development of these applications to determine what final form they will take, but an appropriate mix of infrastructure and vehicle based systems will likely occur that may incorporate radionavigation services.

Table 2-7. Land Transportation Positioning/Navigation System Accuracy Needs/Requirements

MODE	ACCURACY (meters) 95%
Highways:	
Navigation and route guidance	5-20
Automated vehicle monitoring	30
Automated vehicle identification	30
Public safety	10
Resource management	30
Accident or emergency response	30
Collision avoidance	1
Geophysical survey	5
Geodetic control	< 1
Rail:	
Train control	2
Transit:	
Vehicle command and control	30-50
Automated voice bus stop annunciation	5*
Emergency response	75-100
Data collection	5

* *25-30 meters before the bus stop.*

Railroads have been conducting tests of GPS and differential GPS since the mid-1980s to determine the requirements for train and maintenance operations. In June 1995, FRA published its report, *"Differential GPS: An Aid to Positive Train Control,"* (Ref. 7) which concluded that differential GPS could satisfy the Location Determination System requirements for the next generation positive train control systems. In November 1996, FRA convened a technical symposium on *"GPS and its Applications to Railroad Operations"* to continue the dialogue on accuracy, reliability, and security requirements for railroads.

Integrity requirements for land transportation functions are dependent on specific implementation schemes. Integrity values will probably range between 1 and 15 seconds, depending on the function. In order to meet this integrity value, GPS will most likely not be the sole source of positioning. It will be combined with map matching, dead reckoning, and other systems to form an integrated approach, ensuring sufficient accuracy, integrity, and availability of the navigation and position solution to meet user needs. Integrity needs for rail use are 5 seconds for most functions. Those for transit are under study and are not available at this time. The availability requirement for highways and transit is estimated as 99.7 percent. The availability requirement for rail is estimated as 99.9 percent.

While the Government has no statutory responsibility to provide radionavigation services for land radionavigation applications or for non-navigation uses, their existence and requirements are recognized in the Federal radionavigation systems planning process. Accordingly, the Government will attempt to accommodate the requirements of such users.

GPS, in conjunction with other systems, is used in land vehicle navigation. Government and industry have sponsored a number of projects to evaluate the feasibility of using existing and proposed radionavigation systems for land navigation. Operational tests have been completed that use in-vehicle navigation systems and electronic mapping systems to provide real-time route guidance information to drivers. GPS is used for automatic vehicle location for bus scheduling and fleet management. Operational tests are either planned or in progress to use radionavigation for route guidance, in-vehicle navigation, providing real-time traffic information to traffic information centers, and improving emergency response. Several transit operational tests will use automatic vehicle location for automated dispatch, vehicle re-routing, schedule adherence, and traffic signal pre-emption. Railroads have tested and continue to test GPS and DGPS as a part of positive train control systems for freight as well as high-speed passenger train operations. GPS and dead-reckoning/map-matching are being developed as systems that take advantage of radionavigation systems and at the same time improve safety and efficiency of land navigation.

2.6 Non-Navigation Applications and Requirements

The use of radionavigation systems, especially GPS, for non-navigation applications is very large and quite diverse. Most of these applications can be grouped under the following five broad headings:

- Geodesy and surveying
- Mapping, charting, and geographic information systems (GIS)
- Geophysical applications

- Meteorological applications
- Timing and frequency

The nature of these applications is discussed in Sections 2.6.1 through 2.6.5 below.

2.6.1 Geodesy and Surveying

Since the mid-1980s, the geodesy and surveying community has made extensive use of GPS for worldwide positioning. Today, GPS is used almost exclusively by the geodesy and surveying community to establish geodetic reference networks. The National Geodetic Survey (NGS) currently uses GPS to provide the Federal component of the National Spatial Reference System (NSRS) through the establishment of a small number of monumented points (about 1200) positioned using GPS, and the provision of GPS observations from a nationwide GPS network of national CORS for use in post processing applications. The national CORS system currently provides data over the Internet from 232 stations, including the USCG stations and U.S. Army Corps of Engineers (USACE) stations. Stations to be established by components of DOT to support air navigation (e.g., WAAS) and land navigation (e.g., NDGPS) will be included in national CORS as they become available.

GPS is used extensively in a large number of surveying applications. These include positioning of points in support of reference system densification, mapping control, cadastral surveys, engineering projects, and terrain mapping. These applications involve both positioning of fixed points and after-the-fact positioning of moving receivers using kinematic methodologies. All high-accuracy (few centimeter) geodetic and surveying activities involve differencing techniques using the carrier phase observable.

2.6.2 Mapping, Charting and Geographic Information Systems (GIS)

GPS technology is extensively used to provide positions of elements used to construct maps, charts, and GIS products. These have many applications, including supporting air, sea, and land navigation. Almost all positioning in this category is DGPS positioning and involves the use of both code range and carrier phase observations, either independently or in combination. Many groups at all government levels, as well as universities and private industry, have established fixed reference stations to support these applications. Most of these stations are designed to support after-the-fact reduction of code range data to support positioning at the few decimeter to few meter accuracy level. Examples of this type of positioning application include 1) location of roads by continuous positioning of the vehicle as it traverses the roads, and 2) location of specific object types such as manhole covers by occupying their locations. Another very important mapping/GIS application of GPS is post mission determination of the position and/or attitude of photogrammetric aircraft. For this application, code range or carrier phase data are used depending upon the accuracy required.

2.6.3 *Geophysical Applications*

The ability of GPS carrier phase observations to provide centimeter level differential positioning on regional and worldwide bases has lead to extensive applications to support the measurement of motions of the Earth's surface associated with such phenomena as motions of the Earth's tectonic plates, seismic (earthquake related) motions, and motions induced by volcanic activity, glacial rebound, and subsidence due to fluid (such as water or oil) withdrawal. The geodetic and geophysical communities have developed an extensive worldwide infrastructure to support their high accuracy positioning activities.

The geophysical community is moving rapidly from post processing to real-time applications. In southern California and throughout Japan, GPS station networks currently transmit data in real time to a central data facility to support earthquake analysis. The International GPS Service for Geodynamics (IGS) is moving to provide the ability to compute satellite orbit information, satellite clock error, and ionospheric corrections in real time. Many projects for the monitoring of motion are currently being supported by the National Science Foundation (NSF), the U.S. Geological Survey, and NASA, as well as state, regional, and local agencies.

Another geophysical application is the determination of the position, velocity, and acceleration of moving platforms carrying geophysical instrumentation both to determine the position of measurements and to provide a means of computing measurement corrections. An example of this is the use of GPS in conjunction with an aircraft carrying a gravimeter. Here, GPS is used not only to determine the position of measurements but also to estimate the velocity and acceleration necessary for corrections to the observations. GPS position measurements are also being used extensively to monitor motions of glaciers and ice sheets.

2.6.4 *Meteorological Applications*

The international meteorological community launches three quarters of a million to a million weather radiosondes and dropwindsondes each year worldwide to measure such atmospheric parameters as pressure, temperature, humidity, and wind speed and direction. Currently Loran-C, Radio Direction Finding and recently GPS are methods used for weather instrument tracking. With the loss of the Omega system, which had been widely used by the international community for tracking weather radiosondes, and the projected phaseout of Loran-C, there has been a concerted effort to use GPS technology for tracking and wind speed and direction determination. GPS-based upper-air systems will be in wide use early in the next millennium. Measurements of refraction of the two GPS carrier phases can be used to provide continuous estimates of total precipitable water vapor. The ability to provide accurate water vapor information has been demonstrated in the research mode. Development of research meteorological GPS station networks has begun.

2.6.5 *Time and Frequency Applications*

GPS and Loran-C are being used extensively for communication network synchronization by, for example, telephone companies. Power companies are using GPS for measuring phase differences between power transmission stations, for event recording, for post disturbance analysis, and for measuring the relative frequency of power stations. GPS is also being used for worldwide time transfer. Another timing application of GPS is synchronization of clocks to support astronomical observations such as Very Long Baseline Interferometry (VLBI)/pulsar astronomical observations.

2.6.6 Summary of Requirements

Almost all non-navigation uses of GPS involving positioning have accuracy requirements that necessitate differential positioning and therefore augmentation through the use of one or more reference stations located at point(s) of known position. The accuracy requirements for various applications are indicated in Table 2-8 and lie in the few millimeter to few meter range. Non-navigation requirements differ from navigation requirements in several respects. Many non-navigation applications do not have real-time requirements and can achieve their objectives through post processing of observations. This reduces communications needs and means that reliability and integrity requirements are much less stringent. Even when real-time applications exist the penalties for data loss are usually economic rather than related to safety of life and property considerations. However, non-navigation uses have much more stringent accuracy requirements in many cases.

There are several consequences of these accuracy requirements. First, the carrier phase observable is used in many non-navigation applications rather than the code range observable, which is the primary observable used on most navigation applications. Second, two-carrier phase frequencies are essential to achieve the few millimeter to few centimeter accuracies needed for many applications. Dual frequency carrier phase capability is also required for recovery of precipitable water vapor information in support of meteorological applications. The non-navigation GPS user community has developed an extensive worldwide augmentation infrastructure to support their applications. Under the auspices of the International Association of Geodesy (IAG), the IGS has been established. The IGS operates a worldwide network of GPS stations. Data from these stations are used to produce high accuracy (better than 10 cm) orbits and to define a worldwide reference coordinate system accurate at the 1 cm level. Currently, the high accuracy orbits are produced a few days after the fact. However, slightly less accurate orbits are being produced with less than 24 hour delay and IGS members are rapidly moving toward this production of real-time orbits at the few decimeter level. Member groups of the IGS are also moving toward the production of satellite clock corrections and ionospheric corrections in real time.

In addition to these integrated worldwide efforts many groups at national, state, and local levels have or are in the process of establishing networks of GPS reference stations. The bulk of these station networks now in existence provide observational data that can be used to compute correction information needed to perform code range positioning at the few decimeter to few meter level. Increasingly, reference station networks that provide both carrier phase and code range observations are being introduced. Almost all of these reference station networks support post processing at present, but many state groups are looking toward providing code range correctors in real time. The nature of GPS reference station requirements of non-navigation

Table 2-8. Requirements for Surveying, Timing and Other Applications

Surveying

TASK	MINIMUM PERFORMANCE CRITERIA: ACCURACY - 1 SIGMA: POSITION: ABSOLUTE (m) HORIZONTAL	ABSOLUTE (m) VERTICAL	RELATIVE (cm) HORIZONTAL	RELATIVE (cm) VERTICAL	COVERAGE %	AVAILABILITY %	INTERVAL: MEASUREMENT RECORDING (seconds)	INTERVAL: SOLUTION FIX	REMARKS
Static Survey	0.3	0.5	1.0	2.0	99	99	5	30 min	0 - 25 km
Geodetic Survey	0.1	0.2	1.0	2.0	99	99	5	4 hr	0 - 6000 km
Rapid Survey	0.3	0.5	2.0	5.0	99	99	1	5 min	0 - 20 km
"On The Fly" Kinematic Survey	0.3	0.5	2.0	5.0	99	99	0.1 - 1.0	0.1 - 1.0 sec	0 - 20 km Real Time
Hydrographic Survey			300	15	99	99	1	1 sec	

Timing and Other Applications

REQUIREMENTS	MEASURES OF MINIMUM PERFORMANCE CRITERIA TO MEET REQUIREMENTS: ACCURACY (2 drms) PREDICTABLE	ACCURACY (2 drms) REPEATABLE	ACCURACY (2 drms) RELATIVE	COVERAGE	AVAILABILITY	FIX INTERVAL	FIX DIMENSION	SYSTEM CAPACITY	AMBIGUITY
Communications Network Synchronization	-	1 part in 10^{-10} (freq)*	-	Nationwide	99.7%	Continuous	N/A	Unlimited	N/A
Scientific Community	-	1 part in 10^{-10} (freq)	-	Worldwide	99.7%	Continuous	N/A	Unlimited	N/A
Meteorology	Velocity 1m/sec	-	-	-	TBD	TBD	TBD	-	TBD
Power Network Synchronization	-	1ms**	-	North America	99.7%	1 second	Two	Unlimited	Resolvable with 99.9% confidence

* Proposed ITU Standard based on American Telephone and Telegraph "Stratum 1 Requirement."

** At any substation. 8ms (1/2 cycle) systemwide.

users is cost as well as accuracy driven. Thus, where real-time code range positioning is not required and user equipment cannot receive real-time correctors it may be more cost effective to perform post processing rather than upgrade equipment. Also, if user equipment and software is designed to use local area DGPS correctors, as is currently the case for most non-navigation users employing code range positioning, it is cost effective to continue to use local area DGPS if possible. With high accuracy carrier phase positioning in areas such as surveying, minimizing the observation time required to achieve a given accuracy is an important cost consideration. Thus, observation time minimization may result in a need for GPS reference stations at intervals of 40 to 200 km to meet carrier phase positioning requirements.

Geophysical users have special references station requirements in that they are using fixed stations to monitor motions and must place reference stations at spacings and at locations that allow them to monitor the motions of interest. Organizations such as USACE have positioning requirements for hydrographic surveys to locate waterway channels, construction and obstructions. Meeting these requirements necessitates the establishment of DGPS stations along inland waterways.

3

System Descriptions

This section addresses the characteristics, capabilities, and limitations of existing and proposed common-use radionavigation systems. The systems covered are:

- GPS
- GPS Augmentations
- Loran-C
- VOR, VOR/DME, and TACAN
- ILS
- MLS
- Aeronautical Nondirectional Beacons
- Maritime Radiobeacons

3.1 System Parameters

All of the systems described are defined in terms of system parameters that determine the use and limitations of the individual navigation system's signal-in-space. These parameters are:

- Signal Characteristics
- Accuracy
- Availability
- Coverage
- Reliability
- Fix Rate
- Fix Dimensions
- System Capacity
- Ambiguity
- Integrity
- Spectrum

3.1.1 *Signal Characteristics*

Signals-in-space are characterized by power levels, frequencies, signal formats, data rates, and any other information sufficient to completely define the means by which a user derives navigation information.

3.1.2 *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 that applies.

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.

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 2 drms (distance root mean squared) uncertainty estimate will be used. Two drms is twice the radial error drms. The radial error is defined as the root-mean-square value of the distances from the true location point of the position fixes in a collection of measurements. It is often found by first defining an arbitrarily oriented set of perpendicular axes, with the origin at the true location point. The variances around each axis are then found, summed, and the square root computed. When the distribution of errors is elliptical, as it often is for stationary, ground-based systems, these axes can be taken for convenience as the major and minor axes of the error ellipse. Then the confidence level depends on the elongation of the error ellipse. As the error ellipse collapses to a line, the confidence level of the 2 drms measurement approaches 95 percent; as the error ellipse becomes circular, the confidence level approaches 98 percent. The GPS 2 drms accuracy will be at 95 percent probability.

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 FRS, the conversion of CEP to 2 drms has been accomplished by using 2.5 as the multiplier.

Types of Accuracy

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

- Predictable accuracy: The accuracy of a radionavigation system's position solution with respect to the charted solution. Both the position solution and the chart must be based upon the same geodetic datum. (Note: Chapter 4 discusses reference systems and the risks inherent in using charts in conjunction with radionavigation systems).
- Repeatable accuracy: The accuracy with which a user can return to a position whose coordinates has been measured at a previous time with the same navigation system.
- 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.

3.1.3 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 navigation 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.

3.1.4 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 that affect signal availability.

3.1.5 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.

3.1.6 Fix Rate

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

3.1.7 *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 (e.g., time) from the navigation signals is also included.

3.1.8 *System Capacity*

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

3.1.9 *Ambiguity*

System 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 resolve them.

3.1.10 *Integrity*

Integrity is the ability of a system to provide timely warnings to users when the system should not be used for navigation.

3.1.11 *Spectrum*

FAA, DoD, and the USCG require spectrum as providers and operators of radionavigation systems.

3.2 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 Section 3.1. All of the systems used for civil navigation are discussed. The systems that are used exclusively to meet the special applications of DoD are discussed in the CJCS MPNTP.

3.2.1 *GPS*

GPS is a space-based dual use radionavigation system that is operated for the Government of the United States by the U.S. Air Force. The U.S. Government provides two levels of GPS service. The Precise Positioning Service (PPS) provides full system accuracy to designated users. The Standard Positioning Service (SPS) provides accurate positioning to all users.

The GPS has three major segments: space, control, and user. The GPS Space Segment consists of a nominal constellation of 24 satellites in six orbital planes. The satellites operate in circular 20,200 km (10,900 nm) orbits at an inclination angle of 55 degrees and with a 12-hour period.

The GPS Control Segment has five monitor stations and four dedicated ground antennas with uplink capabilities. The monitor stations use GPS receivers to passively track all satellites in view and accumulate ranging data from the satellite signals. The information from the monitor stations is processed at the Master Control Station (MCS) to determine satellite clock and orbit states and to update the navigation message of each satellite. This updated information is transmitted to the satellites via the ground antennas, which are also used for transmitting and receiving satellite health and control information.

The GPS User Segment consists of a variety of configurations and integration architectures that include an antenna and receiver-processor to receive and compute navigation solutions to provide positioning, velocity, and precise timing to the user.

The characteristics of GPS are summarized in Table 3-1. Further details on the performance of GPS SPS may be found in the GPS SPS Performance Standard (Ref. 8).

A. Signal Characteristics

Each satellite transmits three spread spectrum signals on two L-band frequencies, L1 (1575.42 MHz) and L2 (1227.6 MHz). L1 carries a Precise P(Y) Pseudo-Random Noise (PRN) code and a Coarse/Acquisition (C/A) PRN code; L2 carries the P(Y) PRN code. (The Precise code is denoted as P(Y) to signify that this PRN code can be transmitted in either a clear unencrypted "P" or an encrypted "Y" code configuration.) Both PRN codes carried on the L1 and L2 frequencies are phase-synchronized to the satellite clock and modulated (using modulo two addition) with a common 50 Hz navigation data message.

The SPS ranging signal received by the user is a 2.046 MHz null-to-null bandwidth signal centered about L1. The transmitted ranging signal that comprises the GPS-SPS is not limited to the null-to-null signal and extends through the band 1563.42 to 1587.42 MHz. The minimum SPS received power is specified as -160.0 dBW. The navigation data contained in the signal are composed of satellite clock and ephemeris data for the transmitting satellite plus GPS constellation almanac data, GPS to UTC (USNO) time offset information, and ionospheric propagation delay correction parameters for use by single frequency (SPS) users. The entire navigation message repeats every 12.5 minutes. Within this 12.5-minute repeat cycle, satellite clock and ephemeris data for the transmitting satellite are sent 25 separate times so they repeat every 30 seconds. As long as a satellite indicates a healthy status, a receiver can continue to operate using these data for the validity period of the data (up to 4 or 6 hours). The receiver will update these data whenever the satellite and ephemeris information are updated - nominally once every 2 hours.

Conceptually, GPS position determination is based on the intersection of four separate vectors each with a known origin and a known magnitude. Vector origins for each satellite are computed based on satellite ephemeris. Vector magnitudes are calculated based on signal propagation time delay as measured from the transmitting satellite's PRN code phase delay. Given that the satellite signal travels at nearly the speed of light and taking into account delays and adjustment factors such as ionospheric propagation delays and earth rotation factors, the receiver performs ranging measurements between the individual satellite and the user by dividing the satellite signal propagation time by the speed of light.

Table 3-1. GPS/SPS Characteristics

SPS ACCURACY (METERS) 95%* PREDICTABLE	SERVICE AVAILABILITY*	COVERAGE	SERVICE RELIABILITY**	FIX RATE	FIX DIMENSION	SYSTEM CAPACITY	AMBIGUITY POTENTIAL
Horz ≤ 13 Vert ≤ 22 Time ≤ 40ns	99%	Global Service Volume	99.94%	1-20 per second	3D + Time	Unlimited	None

Accuracy and availability percentages are computed using 24-hour measurement intervals. Statistics are representative for an average location within the global service volume. Predictable horizontal 95% error can be as large as 36 meters and predicted vertical 95% error as large as 77 meters at the worst-case location in the global service volume. Accuracy statistics do not include contributions from the single-frequency ionospheric model, troposphere, or receiver noise. Availability statistic applies for worst-case location predicted 95% horizontal or vertical position error values.

*** Reliability threshold of 30 meters for a not to exceed SPS signal-in-space User Range Error (URE), for any satellite. Reliability measurement interval is one year, averaged over the globe. Use 99.79% when daily averages are computed from the worst point on the globe.*

B. Accuracy

SPS is the standard specified level of positioning, velocity and timing accuracy that is available, without restrictions, to any user on a continuous worldwide basis. SPS provides a global average predictable positioning accuracy of 13 meters (95 percent) horizontally and 22 meters (95 percent) vertically and time transfer accuracy within 40 nanoseconds (95 percent) of UTC. Decisions to change operational modes of GPS to include degrading GPS accuracy provided to civil users will be made by the NCA. For more detail, refer to Ref. 8.

C. Availability

The SPS provides a global average availability of 99 percent. Service availability is based upon the expected horizontal error being less than 36 meters (95 percent) and the expected vertical error being less than 77 meters (95 percent). The expected positioning error is a predictive statistic, and is based on a combination of position solution geometry and predicted satellite ranging signal errors.

D. Coverage

GPS coverage is worldwide. The coverage of the GPS SPS service is described in terms of a global terrestrial service volume, which covers from the surface of the earth up to an altitude of 3,000 kilometers.

E. Reliability

The probability that the SPS signal-in-space URE will not exceed 30 meters is 99.94 percent (global average).

F. Fix Rate

The fix rate is essentially continuous, but the need for receiver processing to retrieve the spread-spectrum signal from the noise results in an effective user fix rate of 1-20 per second. Actual time to a first fix depends on user equipment capability and initialization with current satellite almanac data.

G. Fix Dimensions

GPS provides three-dimensional positioning and time when four or more satellites are available and two-dimensional positioning when only three satellites are available.

H. System Capacity

The capacity is unlimited.

I. Ambiguity

There is no ambiguity.

J. Integrity

The GPS system architecture incorporates many features including redundant hardware, robust software, and rigorous operator training to minimize integrity anomalies. The best response time, however, may be on the order of several minutes, which is insufficient for certain applications. For such applications, augmentations such as Receiver Autonomous Integrity Monitoring (RAIM), a receiver algorithm, may be required to achieve the requisite integrity.

K. Spectrum

GPS satellites broadcast at two L-Band frequencies: L1 in the 1559-1620 MHz aeronautical radionavigation/satellite service band and L2 in the 1215-1260 MHz band. The planned third civil signal, L5, is to be centered at 1176.45 MHz in the 1164-1215 MHz aeronautical radionavigation satellite service band.

3.2.2 Augmentations to GPS

GPS may exhibit variances from a predicted grid established for navigation, charting, or derivation of guidance information. This variance may be caused by propagation anomalies, accidental perturbations of signal timing, or other factors.

The basic GPS must be augmented to meet current civil aviation, land and marine integrity requirements. DGPS is one method to satisfy integrity requirements.

DGPS enhances GPS through the use of differential corrections to the basic satellite measurements. DGPS is based upon accurate knowledge of the geographic location of one or more reference stations, which is used to compute corrections to GPS ranging measurements or resultant positions. These differential corrections are then transmitted to GPS users, who apply the corrections to their received GPS signals or computed position. For a civil user of SPS, differential corrections can improve navigation accuracy to better than 7 meters (2 drms). A DGPS reference station is fixed at a geodetically surveyed position. From this position, the reference station typically tracks all satellites in view and computes corrections based on its measurements and geodetic position. These corrections are then broadcast to GPS users to improve their navigation solution. A well-developed method of handling this is by computing pseudorange corrections for each satellite, which are then broadcast to the user and applied to the user's pseudorange measurements before the GPS position is calculated by the receiver, resulting in a highly accurate navigation solution.

The commonly used method is an all-in-view receiver at a fixed reference site that receives signals from all visible satellites and measures the pseudorange to each. Since the satellite signal contains information on the satellite orbits and the reference receiver knows its position, the true range to each satellite can be calculated. By comparing the calculated range and the measured pseudorange, a correction term can be determined for each satellite. The corrections are broadcast and applied to the satellite measurements at each user's location. This method provides the best navigation solution for the user and is the preferred method. It is the method being employed by the USCG Maritime DGPS Service, the Nationwide DGPS (NDGPS) service, and the FAA LAAS.

The above method is being incorporated in the FAA's WAAS for GPS. In this system, a network of GPS reference/measurement stations at surveyed locations collects dual-frequency measurements of GPS pseudorange and pseudorange rate for all spacecraft in view, along with local meteorological conditions. These data are processed to yield highly accurate ephemeris, ionospheric and tropospheric calibration maps, and DGPS corrections for the broadcast spacecraft ephemeris and clock offsets. In the WAAS, these GPS corrections and system integrity messages are relayed to civil users via a dedicated package on geostationary satellites. This relay technique also supports the delivery of an additional ranging signal, thereby increasing overall navigation system availability.

Non-navigation users of GPS, who require accuracy within a few centimeters accuracy or employ post processing to achieve accuracies within a few decimeters to a few meters, often employ augmentation somewhat differently from navigation users. For post processing applications using C/A code range, the actual observations from a reference station (rather than correctors) are provided to users. The users then compute correctors in their reduction software. Surveyors and other users who need sub-centimeter to a few centimeter accuracy in positioning from post-processing use two-frequency (L1 and L2) carrier phase observations from reference stations, rather than range data. The national CORS system is designed to meet the needs of both of the above types of these users.

Real-time carrier phase differential positioning is increasingly employed by non-navigation users. Currently, this requires a GPS reference station within a few tens of kilometers of a user. In many cases, users are implementing their own reference stations, which they operate only for the duration of a specific project. Permanent reference stations to support real-time carrier phase positioning by multiple users are currently provided in the U.S. primarily by private industry. Some state and local government groups are moving toward providing such reference stations.

Other countries are establishing nationwide, real-time, carrier phase reference station networks at the national government level.

3.2.2.1 Maritime DGPS

The Maritime DGPS Service is a medium frequency beacon-based augmentation to GPS. The Maritime DGPS Service operated by the USCG consists of two control stations and more than 55 remote broadcast sites. The DGPS service broadcasts correction signals on marine radiobeacon frequencies to improve accuracy and integrity of the Global Positioning System.

Figure 3-1 shows the maritime DGPS architecture using pseudorange corrections. The reference station's and other mariner's pseudorange calculations are strongly correlated. Pseudorange corrections computed by the reference station, when transmitted to the mariner in a timely manner, can be directly applied to the mariner's pseudorange computation to dramatically increase the resultant accuracy of the pseudorange measurement before it is applied within the mariner's navigation solution.

A. Signal Characteristics

The datalinks for DGPS corrections are broadcast sites transmitting between 285 and 325 kHz using MSK modulation. Real-time differential GPS corrections are provided in the Radio Technical Commission for Maritime Services Special Committee 104 (RTCM SC-104) format and broadcast to all users capable of receiving the signals. The Maritime DGPS Service operated by the USCG does not use data encryption. The characteristics of the Maritime DGPS Service are summarized in Table 3-2.

B. Accuracy

The accuracy of the Maritime DGPS Service within all established coverage areas is specified 10 meters (2 drms) or better. The Maritime DGPS Service accuracy at each broadcast site is carefully controlled and is typically better than 1 meter. Achievable accuracy degrades at an approximate rate of 1 meter for each 150 km distance from the broadcast site. Accuracy is further degraded by computational and other uncertainties in user equipment and the ability of user equipment to compensate for other error sources such as multipath interference and propagation distortions. Typical user equipment should be able to achieve the stated 10-meter accuracy in all established coverage areas when the various factors that degrade accuracy are considered.

C. Availability

Availability will be 99.9 percent in selected waterways with more stringent VTS requirements and at least 99.7 percent in other parts of the coverage area.

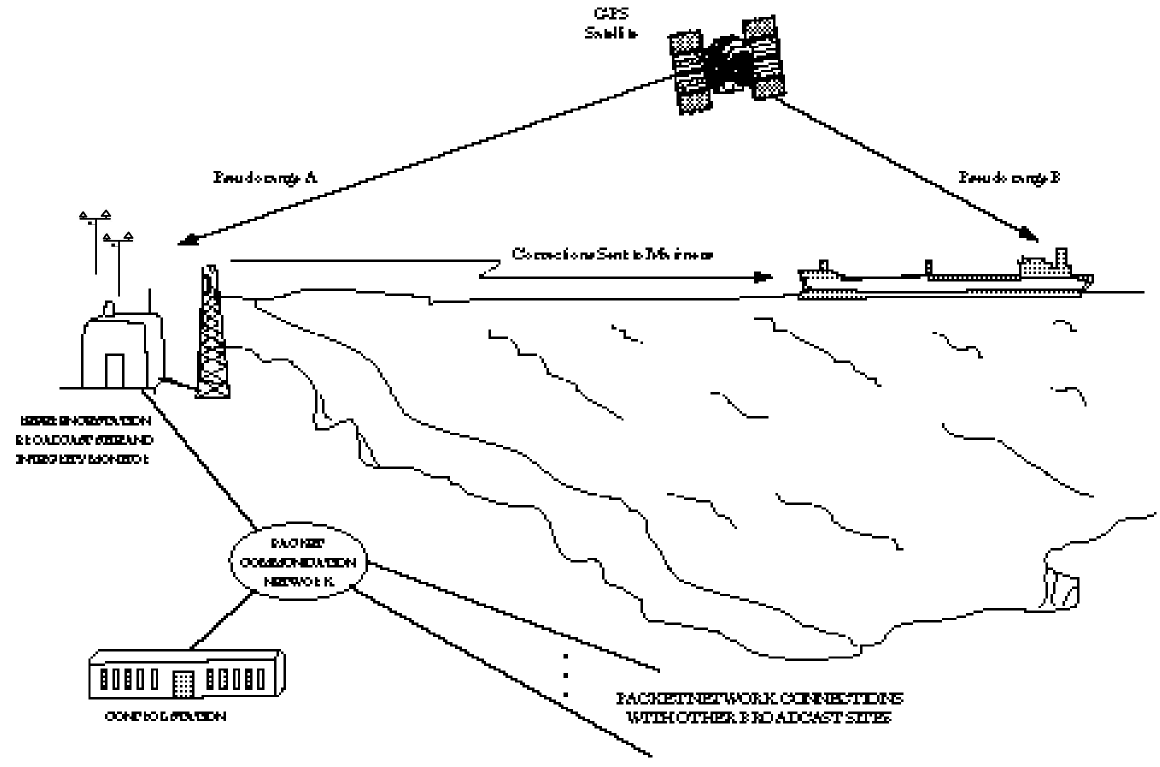

Figure 3-1. Maritime DGPS Navigation Service

Table 3-2. Maritime DGPS Service Characteristics (Signal-in-Space)

ACCURACY (2drms)	AVAILABILITY (%)	COVERAGE	RELIABILITY	FIX RATE	FIX DIMENSIONS	SYSTEM CAPACITY	AMBIGUITY POTENTIAL	INTEGRITY
<10 meters	99.9 selected areas 99.7 all other areas	U.S. coastal areas, selected areas of HI, AK, PR and major inland rivers	< 500 outages/1,000,000 hours	1-20 per second	3D	Unlimited	None	On-site integrity monitor and 24-hour DGPS control center

D. Coverage

Figure 3-2 shows the approximate coverage of the U.S. MF Radiobeacon DGPS Service operated by USCG. In accordance with the USCG's DGPS Broadcast Standard (COMDTINST M16577.1), the Maritime DGPS Service is designed to provide complete coastal DGPS coverage (to a minimum range of 20 nm from shore) of the continental U.S., selected portions of Hawaii, Alaska, and Puerto Rico, and inland coverage of the major inland rivers.

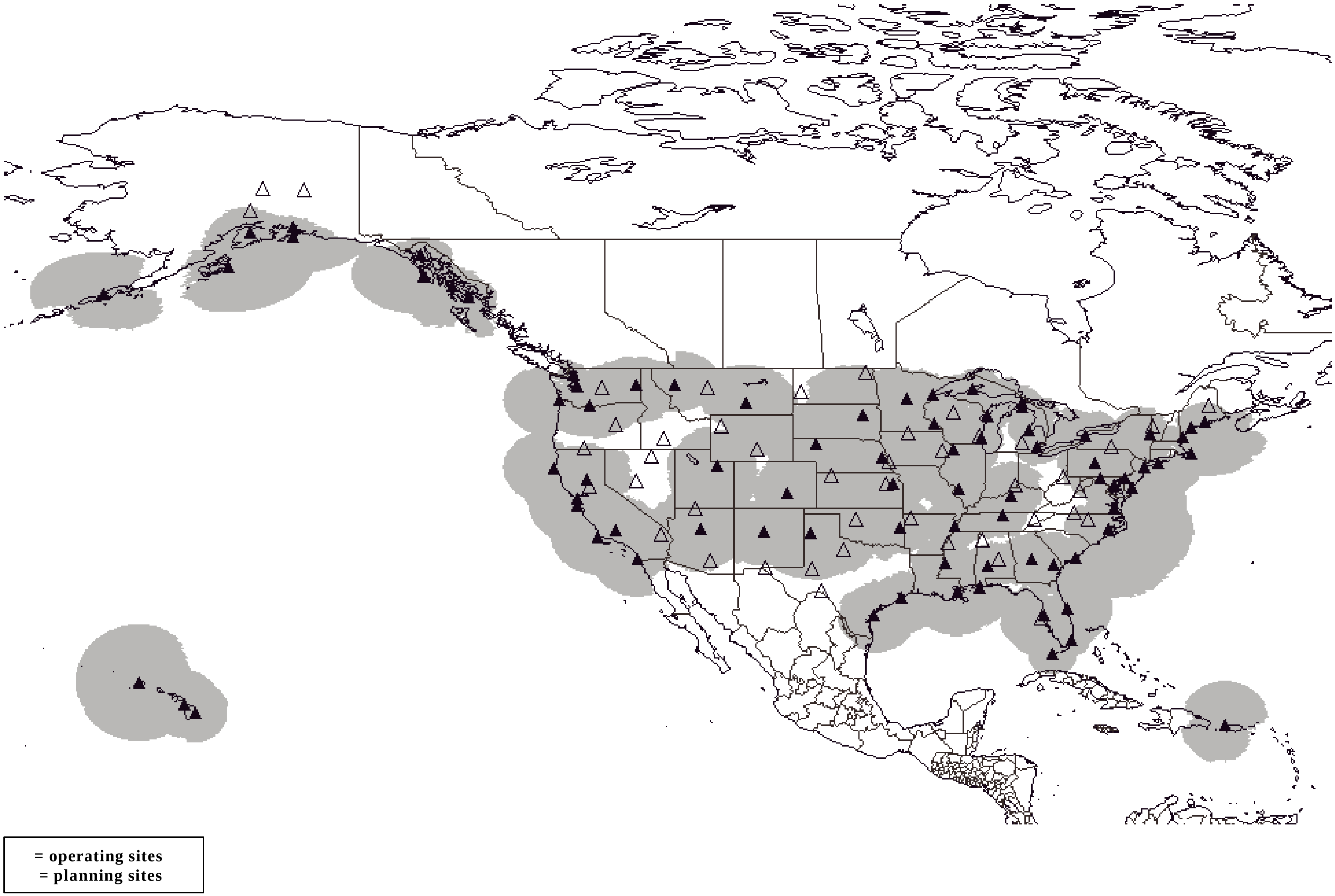

Figure 3-2. U.S. MF Radiobeacon DGPS Service Coverage

E. Reliability

The number of outages per site will be less than 500 in one million hours of operation.

F. Fix Rate

USCG DGPS Broadcast sites transmit a set of data every 2.5 seconds or better. Each set of data points includes both pseudorange and range rate corrections that permit a virtually continuous position update, but the need for receiver processing results in typical user fix rates of 1-20 per second.

G. Fix Dimensions

Through the application of pseudorange corrections, maritime DGPS provides three-dimensional positioning.

H. System Capacity

Unlimited.

I. Ambiguity

None.

J. Integrity

Integrity of the Maritime DGPS Service operated by the USCG is provided through an integrity monitor at each broadcast site. Each broadcast site is remotely monitored and controlled 24 hours a day from a DGPS control center. Users will be notified of an out-of-tolerance condition within 6 seconds.

In addition to providing a highly accurate navigation signal, maritime DGPS also provides a continuous integrity check on satellite health. System integrity is a real concern with GPS. With the design of the ground segment of GPS, a satellite can be transmitting an unhealthy signal for 2 to 6 hours before it can be detected and corrected by the Master Control Station or before users can be warned not to use the signal. Through its use of continuous, real-time messages, the Maritime DGPS Service can often extend the use of unhealthy GPS satellites by providing accurate corrections, or will direct the navigator to ignore an erroneous GPS signal.

K. Spectrum

The Maritime DGPS Service broadcasts GPS pseudorange corrections in the 285-325 kHz maritime radiobeacon band.

3.2.2.2 Nationwide DGPS

The Nationwide DGPS (NDGPS) is based on the architecture of the Maritime DGPS Service. Figure 3-3 shows the NDGPS architecture using pseudo-range corrections. Figure 3-3 and the following discussion describe the characteristics of the NDGPS system.

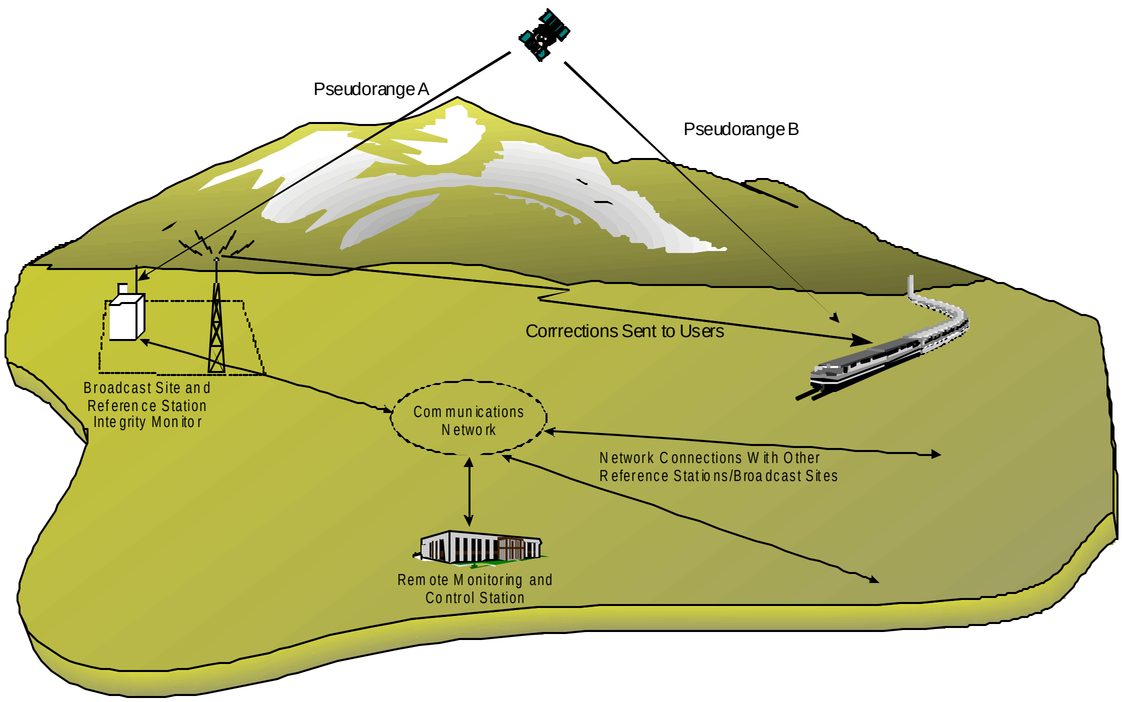

Figure 3-3. NDGPS Navigation Service

A. Signal Characteristics

The datalinks for DGPS corrections are broadcast sites transmitting between 285 and 325 kHz using MSK modulation. Real-time differential GPS corrections are provided in the Radio Technical Commission for Maritime Services Special Committee 104 (RTCM SC-104) format and broadcast to all users capable of receiving the signals. The NDGPS does not use data encryption.

B. Accuracy

The predictable accuracy of the NDGPS Service within all established coverage areas is better then 10 meters (2 drms). NDGPS accuracy at each broadcast site is carefully controlled and is typically better than 1 meter. Achievable accuracy degrades at an approximate rate of 1 meter for each 150 km distance from the broadcast site. Accuracy is further degraded by computational and other uncertainties in user equipment and the ability of user equipment to compensate for other error sources such as multipath interference and propagation distortions. High-end user equipment may achieve accuracies better than 1 meter, throughout the coverage area, by compensating for the various degrading factors.

C. Availability

Availability will be 99.9 percent for dual coverage areas and 99.7 percent for single coverage areas. Availability is calculated on a per site per month basis, generally discounting GPS anomalies.

D. Coverage

When complete, the NDGPS Service will provide uniform differential GPS coverage of the continental U.S. and selected portions of Hawaii and Alaska regardless of terrain, man made, and other surface obstructions. This is achieved by using a terrain-penetrating medium frequency signal optimized for surface application. This service, along with MDGPS, provides a highly reliable GPS integrity function to terrestrial and maritime users.

E. Reliability

The number of outages per site will be less than 500 in one million hours of operation.

F. Fix Rate

USCG DGPS Broadcast sites transmit a set of data points every 2.5 seconds or better. Each set of data points includes both pseudorange and range rate corrections that permit virtually continuous position update, but the need for receiver processing results in typical user fix rates of 1-20 per second.

G. Fix Dimensions

Through the application of pseudorange corrections, maritime DGPS improves the accuracy of GPS three-dimensional positioning and velocity.

H. System Capacity

Unlimited.

I. Ambiguity

None.

J. Integrity

NDGPS system integrity is provided through an on-site integrity monitor and 24-hour operations at a NDGPS control center. Users will be notified of an out-of-tolerance condition within 6 seconds.

In addition to proving a highly accurate navigation signal, NDGPS also provides a continuous integrity check on satellite health. System integrity is a real concern with GPS. With the design of the ground segment of GPS, a satellite can be transmitting an unhealthy signal for 2 to 6 hours before it can be detected and corrected by the Master Control Station or before users can be warned not to use the signal. Through its use of continuous, real-time messages, the NDGPS system will direct the navigator to ignore an erroneous GPS signal or may, under certain circumstances, extend the use of unhealthy GPS satellites by providing accurate corrections.

K. Spectrum

NDGPS uses fixed GPS reference stations that broadcast pseudorange corrections in the 285-325 kHz maritime radiobeacon band.

3.2.2.3 Aeronautical GPS Wide Area Augmentation System (WAAS)

The WAAS consists of equipment and software that augments the DoD-provided GPS Standard Positioning Service (see Figure 3-4). The signal-in-space provides three services: (1) integrity data on GPS and GEO satellites, (2) wide area differential corrections for GPS satellites, and (3) an additional ranging capability. After receiving an upgrade to meet strict safety-related integrity requirements, WAAS will support aviation navigation for the en route through Category 1 precision approach phases of flight.[*]

The GPS satellites' data are received and processed at widely dispersed sites, referred to as Wide-area Reference Stations (WRS). These data are forwarded to data processing sites, referred to as Wide-area Master Stations (WMS), which process the data to determine the integrity, differential corrections, residual errors, and ionospheric information for each monitored satellite and generate GEO satellite navigation parameters. This information is sent to a Ground Earth Station (GES) and uplinked along with the GEO navigation message to GEO satellites. These GEO satellites then downlink these data on the GPS Link 1 (L1) frequency with a modulation similar to that used by GPS.

In addition to providing GPS integrity, the WAAS verifies its own integrity and take any necessary action to ensure that the system meets performance requirements. The WAAS also has a system operations and maintenance function that provides information to FAA Airway Facilities personnel.

[*] The WAAS is currently under the development and test prior to FAA certification for safety-of-flight applications. The FAA has authorized the aviation use of WAAS to enhance situational awareness until the system is certified for unrestricted use. It is the user's responsibility to exercise common practice and navigational judgment while using the WAAS signal.

The WAAS user receiver processes: (1) the integrity data to ensure that the satellites being used are providing in-tolerance navigation data, (2) the differential correction and ionospheric information data to improve the accuracy of the user's position solution, and (3) the ranging data from one or more of the GEO satellites for position determination to improve availability and continuity. The WAAS user receivers are not considered part of the WAAS.

Figure 3-4. WAAS Architecture

A. Signal Characteristics

The WAAS collects raw data from all GPS and WAAS GEO satellites that support the navigation service. WAAS ground equipment will develop messages on ranging signals and signal quality parameters of the GPS and GEO satellites. The GEO satellites broadcast the WAAS messages to the users and provide ranging sources. The signals broadcast via the WAAS GEOs to the WAAS users are designed to require minimal standard GPS receiver hardware modifications.

The GPS L1 frequency and GPS-type modulation, including a C/A PRN code, are used for WAAS data transmission. In addition, the code phase timing is synchronized to GPS time to provide a ranging capability.

B. Accuracy

WAAS is delivering horizontal accuracy of 2 to 3 meters (95 percent) throughout the CONUS. The accuracy requirements are based on aviation operations. For the en route through nonprecision approach phases of flight, unaugmented GPS accuracy is sufficient. For Category I precision approach, the horizontal and vertical requirement is 7.6 meters (95 percent). These accuracy requirements are under review.

C. Availability

The WAAS availability for the en route through nonprecision approach phases of flight is at least 0.99999. For the precision approach phase of flight, the availability is at least 0.999.

D. Coverage

The WAAS full service volume is defined from the Category I decision height up to 100,000 feet for the airspace of the 48 contiguous states, Hawaii, Puerto Rico, and Alaska (except for the Alaskan peninsula west of longitude 160 degrees West or outside of the GEO satellite broadcast area).

E. Reliability

The WAAS will provide sufficient reliability and redundancy to meet the overall NAS requirements with no single point of failure. The overall reliability of the WAAS signal-in-space will approach 100 percent.

F. Fix Rate

This system provides a virtually continuous position update.

G. Fix Dimensions

The WAAS provides three-dimensional position fixing and highly accurate timing information.

H. System Capacity

The user capacity is unlimited.

I. *Ambiguity*

The system provides no ambiguity of position fixing information.

J. Integrity

Integrity augmentation of the GPS SPS by the WAAS is a required capability that is both an operational characteristic and a technical characteristic. The required system performance levels for the integrity augmentation are the levels necessary so that GPS/WAAS can be used for all phases of flight.

Integrity for the WAAS is specified by three parameters: probability of hazardously misleading information (PHMI), time to alarm, and the alarm limit. For the en route through nonprecision approach phases of flight, the performance values are:

PHMI	10^{-7} per hour
Time to Alarm	8 seconds
Alarm Limit	Protection limits specified for each phase of flight

For the precision approach phase of flight, integrity performance values are:

PHMI	10^{-7} per approach
Time to Alarm	5.2 seconds
Alarm Limit	As required for Category I operation

The WAAS will provide the information such that the user equipment can determine the integrity to these levels.

K. Spectrum

The WAAS operates as an overlay on the GPS L1 link in the 1559-1610 MHz ARNS/RNSS frequency band.

3.2.2.4 GPS Local Area Augmentation System (LAAS)

The LAAS will be a safety critical precision navigation and landing system consisting of equipment to augment the DoD-provided GPS Standard Positioning Service with differential GPS pseudorange corrections. It will provide a signal-in-space to LAAS-equipped users with the specific goal of supporting terminal area navigation through Category III precision approach, including autoland. The LAAS signal-in-space will provide: (1) local area differential corrections for GPS PRNs, WAAS/Space-Based Augmentation System (SBAS), GEOs, and Airport Pseudolites (APLs); (2) the associated integrity parameters; and (3) precision approach final approach segment description path points.

The LAAS will utilize multiple GPS reference receivers and their associated antennas, all located within the airport boundary, to receive and decode the GPS, WAAS GEO, and APL range measurements and navigation data. Data from the individual reference receivers are processed by Signal Quality Monitoring, Navigation Data Quality Monitoring, Measurement Quality Monitoring, and Integrity Monitoring algorithms. An averaging technique is used to provide optimal differential range corrections for each measurement and possessing the requisite fidelity to meet accuracy, integrity, continuity of service, and availability criteria.

The individual differential range measurement corrections, integrity parameters and final approach segment path points descriptions for each runway end being served are broadcast to aircraft operating in the local terminal area (nominally 20 nm) via a LAAS VHF data broadcast transmission.

Airborne LAAS capable receivers receive and apply the differential correction to their own satellite and pseudolite pseudorange measurements and assess error parameters against maximum allowable error bounds for the category of approach being performed.

A. Signal Characteristics

The LAAS will collect raw GPS, WAAS GEO, and APL range data from all available range sources that support the navigation service.

The LAAS ground facility will generate differential correction messages as well as pseudorange correction error parameters for each of the GPS, WAAS GEO and APL ranging measurements. The LAAS VHF data broadcast transmitter will then broadcast the LAAS DGPS data to LAAS users.

The GPS L1 frequency and a GPS-like modulation including a wideband PRN code will be used for the LAAS APL availability augmentation transmission. The VHF ARNS band, 108-117.975 MHz, is planned for the LAAS VHF data broadcast.

B. Accuracy

Accuracy for the LAAS has been derived from the aviation accuracy requirements of the ILS. For Category I precision approach the lateral accuracy is 16.0 meters, 95 percent. The LAAS Category I vertical accuracy is 4.0 meters, 95 percent (per the RTCA LAAS MASPS).

C. Availability

The availability of the LAAS is airport dependent, but ranges between 0.999 - 0.99999 (per the draft FAA LAAS specification).

D. Coverage

The LAAS full service volume is defined as:

Vertically: Beginning at the runway datum point out to 20 nm above 0.9 degrees and below 10,000 feet.

Horizontally: 450 ft. either side of the runway beginning at the RDP and projecting out ±35 degrees either side of the approach path out to 20 nm (per the draft FAA LAAS spec.).

E. Reliability

Reliability figures have not been developed.

F. Fix Rate

The LAAS broadcast fix rate is 2Hz. The fix rate from the airborne receiver is at least 5Hz.

G. Fix Dimensions

The LAAS provides three-dimensional position fixing and highly accurate timing information.

H. System Capacity

There is no limit on the LAAS System Capacity.

I. Ambiguity

There is no ambiguity of position associated with the LAAS.

J. Integrity

Assurance of position integrity of the GPS SPS by the LAAS is a required capability that is both an operational characteristic and a technical characteristic. The required system performance is defined for each of the categories of approach. Integrity is specified for two separate parameters: PHMI and Time to Alarm.

Category I		Category II/III	
PHMI	$1x10^{-7}$	PHMI	$1x10^{-9}$
Time to Alarm	6 seconds	Time to Alarm	2 seconds

K. Spectrum

LAAS will broadcast in the 108-117.975 MHz ARNS frequency band, currently populated by VORs and ILSs, either on channels interstitial to the current VOR/ILS, or after VOR and ILS have been partially decommissioned. Also, the international community supports the use of this frequency band.

3.2.2.5 National Continuously Operating Reference Stations (CORS)

The national CORS system is a GPS augmentation being established by the NGS/NOAA to support precision, non-navigation applications as described in Section 2.6. The CORS system provides code range and carrier phase data from a nationwide network of GPS stations for access through the Internet. In addition, high accuracy reference coordinates are computed to support components of the Federal Navigation System. As of October 2001, data were being provided from 232 CORS stations. National Geodetic Survey (NGS) has implemented CORS by making use of stations established by other groups, rather than by building an independent network of reference stations. About 40 percent of the stations now providing data for the CORS system are from the USCG Maritime DGPS Service and the Nationwide Differential GPS, described in Sections 3.2.2.1 and 3.2.2.2, as well as the NDGPS stations being established by DOT to support land navigation. Other stations contributing data to the CORS system include those operated by the National Oceanic and Atmospheric Administration (NOAA) and NASA in support of crustal motion activities, stations operated by state and local governments in support of surveying applications, and stations operated by NOAA's Forecast Systems Laboratory in support of meteorological applications.

The CORS system takes data to a Central Data Facility from the contributing stations using either the Internet or a telephone packet service (such as X.25). At the Central Data Facility, the data are converted to a common format, quality controlled, and placed in files on the Internet. In addition to the data, the Central Data Facility provides software to support extraction, manipulation, and interpolation of the data. The precise positions of the CORS antennas are computed and monitored. In the future, it is planned to compute and provide ancillary data, such as multipath interference models and tropospheric and ionospheric refraction models, to improve the accuracy of the CORS data.

3.2.3 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 Federally provided radionavigation system for civil marine use in the U.S. coastal areas. Loran-C is also certified as an en route supplemental navigation aid for civil aviation.

Three stations are required (master and two secondaries) to obtain a position fix in the normal mode of operation. Loran-C 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.

A. Signal Characteristics

Loran-C is a pulsed, hyperbolic system operating in the 90 to 110 kHz frequency band. The system is based upon measurement of the difference in time of arrival of pulses of radio frequency (RF) energy radiated by a chain of synchronized transmitters that 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 signal comparison early in the ground wave pulse assures that the measurement is made before the arrival of the corresponding sky waves. Precise control over the pulse shape ensures that the proper comparison point can be identified by the receiver. To aid in preventing sky waves from affecting TD measurements, the phase of the 100 kHz carrier of some of the pulses 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 3-3.

Table 3-3. Loran-C System Characteristics (Signal-in-Space)

ACCURACY (2 drms)								
PREDICTABLE	REPEATABLE	AVAILABILITY	COVERAGE	RELIABILITY	FIX RATE	FIX DIMENSIONS	SYSTEM CAPACITY	AMBIGUITY POTENTIAL
0.25nm (460m)	60-300 ft. (18-90m)	99.7%	U.S. coastal areas, continental U.S., selected overseas areas	99.7%*	10-20 fix/sec.	2D + Time	Unlimited	Yes, easily resolved

* *Triad reliability.*

B. Accuracy

Within the published coverage area, Loran-C provides the user who employs an adequate receiver with predictable accuracy of 0.25 nm (2 drms) or better. The repeatable accuracy of Loran-C is usually between 18 and 90 meters. Accuracy is dependent upon the Geometric Dilution of Precision (GDOP) factors at the user's location within the coverage area.

Loran-C navigation is predominantly accomplished using the ground wave signal. Sky wave navigation is feasible, but with considerable loss in accuracy. Ground waves and to some degree sky waves may be used for measuring time and time intervals. Loran-C was originally designed to be a hyperbolic navigation system. However, with the advent of the highly stable frequency standards, Loran-C can also 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. Because the position solution of GPS provides precise time, the interoperable use of rho-rho Loran-C with GPS appears to have merit.

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. Although this can improve Loran-C's absolute accuracy features, no investment in this approach to enhancing Loran-C's performance is anticipated by the Federal Government.

Loran-C receivers are available at a relatively low cost and achieve the 0.25 nm (2 drms) accuracy that Loran-C provides at the limits of the coverage area. A modern Loran-C receiver automatically acquires and tracks the Loran-C signal and is useful to the limits of the specified Loran-C coverage areas.

C. Availability

The Loran-C transmitting equipment is very reliable. Redundant transmitting equipment is used to reduce system downtime. Loran-C transmitting station signal availability is greater than 99.9 percent, providing 99.7 percent triad availability.

D. Coverage

The Loran-C system has been expanded over the years to meet the requirements for coverage of the U.S. coastal waters and the conterminous 48 states, the Great Lakes, the Gulf of Alaska, the Aleutians, and into the Bering Sea. The limit of coverage in a given area is determined by the lesser of: a) predictable accuracy limits of 0.25 nm; or b) signal-to-noise ratio limit of 1:3 SNR. Current Loran-C coverage is shown in Figure 3-5.

Expansion of the Loran-C system into the Caribbean Sea and the North Slope of Alaska has been investigated.

E. Reliability

Loran-C stations are constantly monitored. Stations that exceed the system tolerance are "blinked." Blink is the on-off pattern of the first two pulses of the secondary signal indicating that a baseline is unusable. System tolerance within the U.S. is $\pm$100 nanoseconds of the calibrated control value. Individual station reliability normally exceeds 99.9 percent, resulting in triad availability exceeding 99.7 percent.

F. Fix Rate

The fix rate available from Loran-C ranges from 10 to 20 fixes per second, based on the Group Repetition Interval. Receiver processing in noise results in typically 1 fix per second.

G. Fix Dimensions

Loran-C provides a two-dimensional fix plus time.

H. System Capacity

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

I. 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.

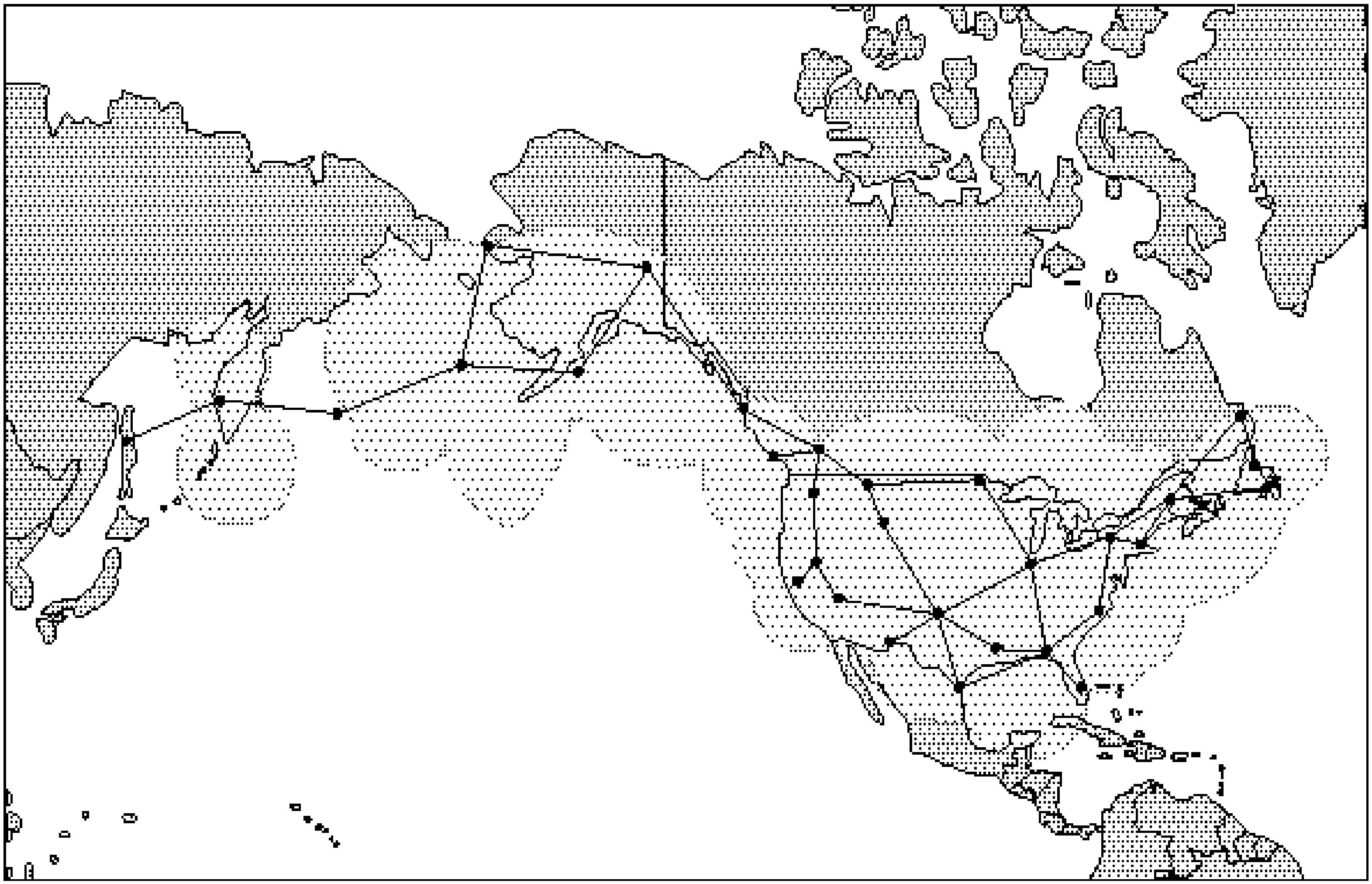

Figure 3-5. Coverage Provided by U.S. or Supported Loran-C Stations

J. Integrity

Loran-C signals are constantly monitored to detect signal abnormalities that would render the system unusable for navigation purposes. The secondary stations "blink" to notify the user that a master-secondary pair is unusable. Blink is manually initiated immediately upon detection of an abnormality and is automatically initiated within ten seconds of a timing abnormality exceeding ± 500 nanoseconds. In the case of a Master station, the signal will be taken off-air until the problem is corrected or all secondaries are blinking.

K. Spectrum

Loran-C operates in the 90-110 kHz frequency band.

3.2.4 VOR, DME, and TACAN

The three systems that provide the basic guidance for en route air and terminal navigation and nonprecision approach in the United States are VOR, DME, and TACAN. Information provided to the aircraft pilot by VOR is the magnetic 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 functionally the same.

I. VOR

A. Signal Characteristics

The signal characteristics of VOR are summarized in Table 3-4. VORs are assigned frequencies in the 108 to 117.975 MHz (UHF) ARNS frequency band, separated by 50 kHz. A VOR transmits two 30 Hz modulations resulting in 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 Hz. A nondirectional (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 and uses 50 instead of four antennas for the variable phase. The same avionics works with either type ground station.

Table 3-4. VOR and DME System Characteristics (Signal-in-Space)

ACCURACY* (2 Sigma)						FIX	FIX	SYSTEM	AMBIGUITY
PREDICTABLE	REPEATABLE	RELATIVE	AVAILABILITY	COVERAGE	RELIABILITY	RATE	DIMENSIONS	CAPACITY	POTENTIAL
VOR: 90m (±1.4°)* *	23m (±0.35°)** *	--	Approaches 99% to 99.99%	Line of Sight	Approaches 100%	Continuous	Heading in degrees or angle off course	Unlimited	None
DME: 185m (±0.1nm)	185m (±0.1nm)	--					Slant range (nm)	100 users per site, full service	

* VOR and DME accuracy do not include survey error, as they would apply to RNAV applications.

** *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 1/2nm from the VOR.*

*** *Test data shows that 99.94% of the time the error is less than ± 0.35°. These values are for ± 0.35° at 2nm from the VOR.*

B. Accuracy (2 sigma)

- 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.
- 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.
- 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) that is ±2.3 degrees.

C. Availability

VOR availability is typically 99 percent to 99.99 percent.

D. Coverage

Most aeronautical radionavigation aids that provide positive course guidance have a designated standard service volume (SSV) that defines the unrestricted reception limits usable for random or unpublished route navigation. Within the SSV, the Navaid signal is frequency protected and is available at the altitudes and radial distances indicated in Table 3-5. In addition to these SSVs, it is possible to define a non-standard service volume if siting constraints result in different coverage. SSV limitations do not apply to published IFR routes or procedures.

Table 3-5. VOR/DME/TACAN Standard Service Volumes (SSV)

SSV Class Designator	Altitude and Range Boundaries
T (Terminal)	From 1,000 feet above ground level (AGL) up to and including 12,000 feet AGL at radial distances out to 25 nm.
L (Low Altitude)	From 1,000 feet AGL up to and including 18,000 feet AGL at radial distances out to 40 nm.
H (High Altitude)	From 1,000 feet AGL up to and including 14,500 feet AGL at radial distances out to 40 nm. From 14,500 AGL up to and including 60,000 feet at radial distances out to 100 nm. From 18,000 feet AGL up to and including 45,000 feet AGL at radial distances out to 130 nm.

Reception below 1,000 feet above ground level is governed by line-of-sight considerations, and is described in Section 1-1-8 of the FAA Aeronautical Information Manual. Complete functional and performance characteristics are described in FAA Order 9840.1, U.S. National Aviation Standard for the VOR/DME/TACAN Systems.

Reception within the SSV is restricted by vertical angle coverage limitations. Distance information from DME and TACAN, and azimuth information from VOR, is normally usable from the radio horizon to elevation angles of at least 60 degrees. Azimuth information from TACAN is normally usable from the radio horizon to elevation angles of at least 40 degrees. At higher elevation angles — within the so-called cone of ambiguity — the Navaid information may not be usable.

E. Reliability

Due to advanced solid-state construction and the use of remote maintenance monitoring techniques, the reliability of solid state VOR approaches 100 percent.

F. Fix Rate

This system allows an essentially continuous update of deviation from a selected course based on internal operations at a 30-update-per-second rate. Initialization is less than one minute after turn-on and will vary as to receiver design.

G. Fix Dimensions

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

H. System Capacity

The capacity of a VOR station is unlimited.

I. Ambiguity

There is no ambiguity possible for a VOR station.

J. Integrity

VOR provides system integrity by removing a signal from use within ten seconds of an out-of-tolerance condition detected by an independent monitor.

K. Spectrum

VOR operates in the 108-117.975 MHz frequency band. It shares the 108-111.975 MHz portion of that band with ILS. The FAA and the rest of the civil aviation community are investigating several potential aeronautical applications of the 108-117.975 MHz band for possible implementation after VOR and ILS have been partially decommissioned. One of those future applications is LAAS, either on channels interstitial to the current VOR/ILS, or after VOR and ILS have been partially decommissioned. Another is the expansion of the present 117.975-137 MHz air/ground (A/G) communications band to support the transition to, and future growth of, the next-generation VHF A/G communications system for air traffic services.

II. DME

A. Signal Characteristics

The signal characteristics of DME are summarized in Table 3-4. 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) that 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 962-1215 MHz (UHF) ARNS frequency band with a separation of 1 MHz.

The capability to use Y-channel service has been developed and implemented to a very limited extent (approximately 15 DMEs paired with localizers use the Y-channel frequencies). The term "Y-channel" refers to VOR frequency spacing. Normally, X-channel frequency spacing of 100 kHz is used. Y-channel frequencies are offset from the X-channel frequencies by 50 kHz. In addition, Y-channel DMEs are identified by a wider interrogation pulse-pair time spacing of 0.036 msec versus X-channel DMEs at 0.012 msec spacing. X- and Y-channel applications are presently limited to minimize user equipment changeovers.

B. Accuracy (2 sigma)

- 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.
- Relative - Although some errors could be introduced by reflections, the major relative error emanates from the receiver and flight technical error.
- Repeatable - Major error components of the ground system and receiver will not vary appreciably in the short term.

C. Availability

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

D. Coverage

DME coverage is described in the preceding section on VOR and in Table 3-5. Because of facility placement, almost all of the airways have coverage, and most of the CONUS has dual coverage, permitting DME/DME Area Navigation (RNAV).

E. Reliability

With the use of solid-state components and remote maintenance monitoring techniques, the reliability of the DME approaches 100 percent.

F. 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, with typical rates of 10 per second.

G. Fix Dimensions

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

H. System Capacity

For present traffic capacity, 110 interrogators are considered reasonable. Future traffic capacity could be increased when necessary through reduced individual aircraft interrogation rates and removal of beacon capacity reply restrictions.

I. Ambiguity

There is no ambiguity in the DME system.

J. Integrity

DME provides system integrity by removing a signal from use within ten seconds of an out-of-tolerance condition detected by an independent monitor.

K. Spectrum

DME operates in the 960-1027, 1033-1087, and 1093-1215 MHz sub-bands of the 960-1215 MHz ARNS band. It shares those sub-bands with TACAN. The frequency 1176.45 MHz has been selected as the third civil frequency (L5) for GPS. Location of GPS L5 in this protected ARNS band meets the needs of critical safety-of-life applications. The DoD's Joint Tactical Information Distribution System/Multi-function Information Distribution System (JTIDS/MIDS) also operates in this band on a non-interference basis. The civil aviation community is investigating potential aeronautical applications of those sub-bands for implementation after DME and TACAN have been partially decommissioned. These potential future applications include:

- Automatic Dependent Surveillance, Broadcast (ADS-B), a function in which aircraft transmit position and altitude data derived from onboard navigation systems.
- Traffic Information Services (TIS), in which processed surveillance data will be reported automatically from ground stations to aircraft in flight.
- Air-to-ground transfer of voice and data traffic for CNS services.
- Potential future CNS applications to support Free Flight.

The FAA is also considering the retention of a subset of the nationwide VOR/DME network. Continued use of some of the 108-117.975 MHz band would be needed to sustain the VOR elements of such a network. A substantial portion of the 960-1215 MHz ARNS band would be required to support its DME elements.

III. TACAN

A. Signal Characteristics

TACAN is a short-range UHF (962-1215 MHz ARNS band) radionavigation system designed primarily for military aircraft use. TACAN transmitters and responders provide the data necessary to determine magnetic bearing and distance from an aircraft to a selected station. TACAN stations in the U.S. are frequently collocated with VOR stations. These facilities are known as VORTACs. The signal characteristics of TACAN are summarized in Table 3-6.

Table 3-6. TACAN System Characteristics (Signal-in-Space)

ACCURACY (2 Sigma)			AVAILABILITY	COVERAGE	RELIABILITY	FIX RATE	FIX DIMENSIONS	SYSTEM CAPACITY	AMBIGUITY POTENTIAL
PREDICTABLE	REPEATABLE	RELATIVE							
Azimuth ±1° (± 63m at 3.75km) DME: 185m (±0.1nm)	Azimuth ±1° (± 63m at 3.75km) DME: 185m (±0.1nm)	Azimuth ±1° (±63m at 3.75km) DME: 185m (±0.1nm)	98%	Line of sight	99%	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. Accuracy (2 sigma)

- 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.
- Relative - The major relative errors emanate from course selection, receiver and flight technical error.
- 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.

C. Availability

A TACAN station can be expected to be available 98 percent of the time.

D. Coverage

TACAN coverage is described in the preceding section on VOR and in Table 3-5.

E. Reliability

A TACAN station can be expected to be reliable 98 percent of the time. Unreliable stations, as determined by remote monitors, are automatically removed from service.

F. Fix Rate

TACAN 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.

G. Fix Dimensions

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

H. System 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. Capacity for the azimuth function is unlimited.

I. Ambiguity

There is no ambiguity in the TACAN range information. There is a slight probability of azimuth ambiguity at multiples of 40 degrees.

J. Integrity

TACAN provides system integrity by removing a signal from use within ten seconds of an out-of-tolerance condition detected by an independent monitor.

K. Spectrum

TACAN operates in the 960-1027, 1033-1087, and 1093-1215 MHz sub-bands of the 960-1215 MHz ARNS frequency band. It shares those sub-bands with DME. The DoD's JTIDS/MIDS also operates in this band on a non-interference basis. The civil aviation community is investigating potential aeronautical applications of those sub-bands for implementation after DME and TACAN have been partially decommissioned. Possible future applications are addressed in Section 3.2.4.

3.2.5 ILS

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

At present, ILS is one of the primary worldwide, ICAO-approved, precision landing systems. This system is presently adequate, but has limitations in siting, frequency allocation, cost, and performance. The characteristics of ILS are summarized in Table 3-7.

A. Signal Characteristics

The localizer facility and antenna are typically located 1,000 feet beyond the stop end of the runway and provide a VHF (108 to 111.975 MHz ARNS band) signal. The glide slope facility is located approximately 1,000 feet from the approach end of the runway and provides a UHF (328.6 to 335.4 MHz ARNS band) 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 final approach fix (typically four to seven miles from the approach end of the runway) and a

Table 3-7. ILS Characteristics (Signal-in-Space)

ACCURACY AT MINIMUM APPLICABLE DECISION HEIGHT (Meters - 2 Sigma)						FIX	FIX	SYSTEM	AMBIGUITY
CATEGORY	AZIMUTH	ELEVATION	AVAILABILITY	COVERAGE	RELIABILITY	RATE*	DIMENSION	CAPACITY	POTENTIAL
1	± 9.1	±4.1	Approaches 99%	Normal limits from center of localizer ±10° out to 18nm and ±35° out to 10nm	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
2	TBD**	TBD**							
3	TBD**	TBD**							

* *Signal availability in the coverage volume.*

** *Accuracy characteristics are specified by characteristics unique to ILS (e.g., beam bend tolerances, glide path alignment). Studies are underway to derive a total source accuracy (in meters).*

middle marker located 3,500 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 1,000 feet from the threshold, is normally associated with Category II and III ILS approaches.

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 ^{o} (2 sigma). Glide slope course alignment is maintained within ±7.0 feet at 100 feet (2 sigma) elevation and glide path bends during the final segment of the approach do not exceed ±0.07^{o} (2 sigma).

C. Availability

To further improve the availability of service from ILS installations, vacuum tube equipment has been replaced with solid-state equipment. Service availability is now approaching 99 percent.

D. Coverage

Coverage for individual systems is as follows:

Localizer: ±2^{o} centered about runway centerline.

Glide Slope: Nominally 3^{o} above the horizontal.

Marker Beacons: ±40^{o} (approximately) on minor axis (along approach path) ±85^{o} (approximately) on major axis.

E. Reliability

ILS reliability is 98.6 percent. 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 that can cause multipath interference.

In some cases, to resolve ILS siting problems, use has been made of localizers with aperture antenna arrays and two frequency systems. In the case of the glide slope, use has been made of wide aperture, capture effect image arrays and single-frequency infrared arrays to provide service at difficult sites.

F. Fix Rate

The glide slope and localizer provide continuous fix information, although the user will receive position updates at a rate determined by receiver/display design (typically more than 5 updates per second). Marker beacons that provide an audible and visual indication to the pilot are sited at specific points along the approach path as indicated in Table 3-8.

Table 3-8. Aircraft Marker Beacons

MARKER DESIGNATION	TYPICAL DISTANCE TO THRESHOLD	AUDIBLE SIGNAL	LIGHT COLOR
Outer	4-7nm	Continuous dashes (2/sec)	Blue
Middle	3,250-3,750 ft	Continuous alternating (dot-dash)	Amber
Inner	1,000 ft	Continuous dots (6/sec)	White

G. Fix Dimensions

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

H. System 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 3.2.5.E.

J. Integrity

ILS provides system integrity by removing a signal from use when an out-of-tolerance condition is detected by an integral monitor. The shutdown delay for each category is given below:

Shutdown Delay

	Localizer	**Glide Slope**
CAT I	<10 sec	<6 sec
CAT II	<5 sec	<2 sec
CAT III	<2 sec	<2 sec

K. Spectrum

ILS marker beacons operate in the 74.8-75.2 MHz frequency band. Since all ILS marker beacons operate on a single frequency (75 MHz), the aeronautical requirements for this band will remain unchanged unless ILS is phased out.

ILS localizers share the 108-111.975 MHz portion of the 108-117.975 MHz ARNS band with VOR. As noted in Section 3.2.4, the FAA and the rest of the civil aviation community are investigating several potential aeronautical applications of this band for possible implementation after VOR and ILS have been partially decommissioned. One of those future applications is LAAS, either on channels interstitial to the current VOR/ILS, or after VOR and ILS have been partially decommissioned. Another is the expansion of the present 117.925-137 MHz A/G communications band to support the transition to, and future growth of, the next-generation VHF A/G communications system for air traffic services. Substantial amounts of spectrum in the 108-111.975 MHz sub-band will continue to be needed to operate Category II and III localizers even after many Category I ILSs have been decommissioned.

ILS glide slope subsystems operate in the 328-335.4 MHz band. The inherent physical characteristics of this band, like those of the 108-111.975 MHz band, are quite favorable to long-range terrestrial line-of-sight A/G communications and data-link applications like LAAS, ADS-B and TIS. Consequently, this band is well suited to provide multiband diversity to such services or to serve as an overflow band for them if they cannot be accommodated entirely in other bands. Substantial amounts of spectrum in this band will continue to be needed to operate Category II and III ILS glide slope subsystems even after Category I ILS have been decommissioned.

3.2.6 MLS

MLS provides a common civil/military landing system to meet the full range of user operational requirements, as defined in the ICAO list of 38 operational requirements for precision approach and landing systems, to the year 2000 and beyond. It was originally intended to be a replacement for ILS, used by both civil and military aircraft, and the Ground Controlled Approach (GCA) system used primarily by military operators. However, augmented GPS systems are now envisioned to satisfy the majority of requirements originally earmarked for MLS. Accordingly, the FAA has terminated all R&D activity associated with MLS. The system characteristics of MLS are summarized in Table 3-9.

Table 3-9. MLS Characteristics (Signal-in-Space)

ACCURACY AT DECISION HEIGHT (Meters - 2 Sigma)									
CATEGORY	AZIMUTH	ELEVATION	AVAILABILITY	COVERAGE	RELIABILITY	FIX RATE*	FIX DIMENSION	SYSTEM CAPACITY	AMBIGUITY POTENTIAL
1	±9.1	±3.0	Expected to approach 100%	±40° from center line of runway out to 20nm in both directions*	Expected to approach 100%	6.5-39 fixes/sec depending on function	Heading and deviation in degrees Range in nm	Limited only by aircraft separation requirements	None
2	±4.6	±1.4							
3	±4.1	±0.4							

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

A. Signal Characteristics

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 to 5.25 GHz ARNS band. Ranging is provided by DME operating in the 962 - 1215 MHz ARNS band. An option is included in the signal format to permit a special purpose system to operate in the 15.4 to 15.7 GHz ARNS band.

B. Accuracy (2 sigma)

The azimuth accuracy is ±13.0 feet (+4.0m) at the runway threshold approach reference datum and the elevation accuracy is ±2.0 feet (+0.6m). 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 ±1,600 feet for the nonprecision 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 a minimum of 15° over the azimuthal coverage area, and out to 20 nm. 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. There will be simultaneous operations of ILS and MLS during the transition period.

E. Reliability

The MLS signals are generally 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.

G. Fix Dimensions

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

H. System 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 interference caused by moving reflectors.

J. Integrity

MLS integrity is provided by an integral monitor. The monitor shuts down the MLS within one second of an out-of-tolerance condition.

K. Spectrum

MLS operates in the 5000-5250 MHz frequency band. The FAA and the rest of the civil aviation community are investigating potential aeronautical applications of this band for implementation after MLS has been partially or completely decommissioned. These include:

- An extension of the tuning range of the Terminal Doppler Weather Radar (TDWR) in order to relieve spectral congestion within its present limited operating band.
- Weather functions of the planned multipurpose primary terminal radar that will become operational around the year 2013.

3.2.7 *Aeronautical Radiobeacons*

Radiobeacons are nondirectional radio transmitting stations that operate in the low- and medium frequency bands to provide ground wave signals to a receiver. Aircraft nondirectional beacons are used to supplement VOR-DME for transition from en route to airport precision approach facilities and as a nonprecision approach aid at many airports. An automatic direction finder (ADF) is used to measure the bearing of the transmitter with respect to an aircraft or vessel.

The characteristics of aeronautical NDBs are summarized in Table 3-10.

Table 3-10. Radiobeacon System Characteristics (Signal-in-Space)

ACCURACY (2 Sigma)									
PREDICTABLE	REPEATABLE	RELATIVE	AVAILABILITY	COVERAGE	RELIABILITY	FIX RATE	FIX DIMENSION	SYSTEM CAPACITY	AMBIGUITY POTENTIAL
Aeronautical ± 3 -10°	N/A	N/A	99%	Maximum service volume - 75nm	99%	Continuous	One LOP per beacon	Unlimited	Potential is high for reciprocal bearing without sense antenna
Marine ± 3°	N/A	N/A	99%	Out to 50nm or 100 fathom curve					

A. *Signal Characteristics*

Aeronautical NDBs operate in the 190 to 415 kHz and 510 to 535 kHz ARNS bands. (Note: NDBs in the 285-325 kHz band are secondary to maritime radiobeacons.) 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 1,020 Hz tone for Morse code identification. The MCW signal is generated by spacing two carriers either 400 Hz or 1,020 Hz apart and keying the upper carrier to give the Morse code identification.

B. *Accuracy*

Positional accuracy derived from the bearing information is a function of geometry of the LOPs, the accuracy of compass heading, measurement accuracy, distance from the transmitter, stability of the signal, time of day, nature of the terrain between beacon and craft, and noise. In practice, bearing accuracy is on 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. 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.

C. Availability

Availability of aeronautical NDBs is in excess of 99 percent.

D. Coverage

Extensive NDB coverage is provided by 1,575 ground stations, of which the FAA operates 728.

E. Reliability

Reliability is in excess of 99 percent.

F. Fix Rate

The beacon provides continuous bearing information.

G. Fix Dimensions

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

H. System Capacity

An unlimited number of receivers may be used simultaneously.

I. Ambiguity

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

J. Integrity

A radiobeacon is an omnidirectional navigation aid. For aviation radiobeacons, out-of-tolerance conditions are limited to output power reduction below operating minimums and loss of the transmitted station identifying tone. The radiobeacons used for nonprecision approaches are monitored and will shut down within 15 seconds of an out-of-tolerance condition.

K. Spectrum

Aeronautical NDBs operate in the 190-435 and 510-535 kHz frequency bands, portions of which it shares with maritime NDBs. Except in Alaskan airspace, no future civil aeronautical uses are envisioned for these bands after the aeronautical NBD system has been decommissioned throughout the rest of the NAS.

3.2.8 Maritime Radiobeacons

Radiobeacons are nondirectional radio transmitting stations that operate in the low- and medium frequency bands to provide ground wave signals to a receiver. These marine radiobeacons have been phased out.

3.3 Navigation Information Services

3.3.1 USCG Navigation Information Service

The U.S. Coast Guard's Navigation Information Service (NIS), formerly the GPS Information Center, is the operational entity of the Civil GPS Service (CGS) that provides GPS status information to civil users of GPS. Its input is based on data from the GPS Control Segment, Department of Defense, and other sources. The mission of the NIS is to gather, process and disseminate timely GPS, Loran-C, and DGPS radionavigation information as well as general maritime navigation information.

The NIS Website also provides the user with information on policy changes or developments about radionavigation systems, especially GPS. It works as an arm of the CGSIC in the exchange of information between the system providers and the users by:

- Automatically disseminating GPS status and outage information through a listserver.
- Collecting information from users in support of the CGSIC and the GPS managers and operators.

Specifically, the functions performed by the NIS include the following:

- Act as the single focal point for non-aviation civil users to report problems with GPS.
- Provide Operational Advisory Broadcast (OAB) Service.
- Answer questions by telephone, written correspondence, or electronic mail.
- Provide information to the public on the NIS services available.
- Provide instruction on the access and use of the information services available.
- Maintain tutorial, instructional, and other relevant handbooks and material for distribution to users.
- Maintain records of GPS broadcast information, GPS databases or relevant data for reference purposes.

- Maintain bibliography of GPS publications.
- Develop new user services as required.

Information on GPS and USCG-operated radionavigation systems can be obtained from the USCG's Navigation Center (NAVCEN), 7327 Telegraph Road, Alexandria, VA 22315-3998. Table 3-11 and Figure 3-6 show the services through which the NIS provides Operational Advisory Broadcasts. NAVCEN's 24-hour hotline: (703) 313-5900. NAVCEN's E-mail address: webmaster@smtp.navcen.uscg.mil. Internet WWW address: http://www.navcen.uscg.gov/.

3.3.2 GPS NOTAM/Aeronautical Information System

DoD provides notice of GPS satellite vehicle outages through the Notice to Airmen (NOTAM) system. These NOTAMs are reformatted Notice Advisories to NAVSTAR Users (NANUs) provided by the 2nd Space Operations Squadron (2SOPS) at the GPS Master Control Station (MCS). The outages are disseminated to the U.S. NOTAM Office, which is a joint DoD/FAA facility, at least 48 hours before they are scheduled to occur. Unexpected outages also are reported by the 2SOPS to the NOTAM Office as soon as possible.

Satellite NOTAMs are issued as both a domestic NOTAM under the KGPS identifier and as an international NOTAM under the KNMH identifier. This information is accessible by both civilian and military aviators. Unfortunately, the NOTAM is meaningless to a pilot unless there is a method to interpret the effects of a GPS satellite outage on the availability of the intended operation.

Use of GPS for Instrument Flight Rule (IFR) air navigation requires that the system have the ability to detect when a satellite is out of tolerance and should not be used in the navigation solution. This capability currently is provided by Receiver Autonomous Integrity Monitoring (RAIM), an algorithm contained within the GPS receiver. All receivers certified for IFR navigation must have RAIM or an equivalent capability.

In order for the receiver to perform RAIM, a minimum of five satellites with satisfactory geometry must be visible. Since the GPS constellation of 24 satellites was not designed to provide this level of coverage, RAIM is not always available even when all of the satellites are operational. Therefore, if a satellite fails or is taken out of service for maintenance, it is not intuitively known which areas of the country are affected, if any.

The location and duration of these outage periods can be predicted with the aid of computer analysis, and reported to pilots during the pre-flight planning process. Notification of site-specific outages provides the pilot with information regarding GPS RAIM availability for nonprecision approach at the filed destination.

Table 3-11. NIS Services

Service	Availability	Information Type	Contact Number
NIS Watchstander	24 hours	User Inquiries	(703) 313-5900 FAX (703) 313-5920
Internet	24 hours	Status Forecast, History, Outages NGS Data, FRP and Miscellaneous Information	http://www.navcen.uscg.gov ftp://ftp.navcen.uscg.gov
NIS Voice Tape Recording	24 hours	Status Forecasts Historic	(703) 313-5907
WWV	Minutes 14 & 15	Status Forecasts	2.5, 5, 10, 15, and 20 MHz
WWVH	Minutes 43 & 44	Status Forecasts	2.5, 5, 10, and 15 MHz
USCG	When broadcast	Status Forecasts	Maritime VHF Radio Band
NIMA Broadcast Warnings	When broadcast received	Status Forecasts	
NIMA Weekly Notice to Mariners	Published & mailed weekly	Status Forecasts Outages	(301) 227-3126
Navinfonet Automated Notice to Mariners system	24 hours	Status Forecasts Historic Almanacs	(301) 227-3351/ 300 baud (301) 227-5925/ 1200 baud (301) 227-4360/ 2400 baud
NAVTEX Data Broadcast	All stations broadcast 6 times daily at alternating times	Status Forecasts Outages	518kHz (301) 227-4424/ 9600 baud

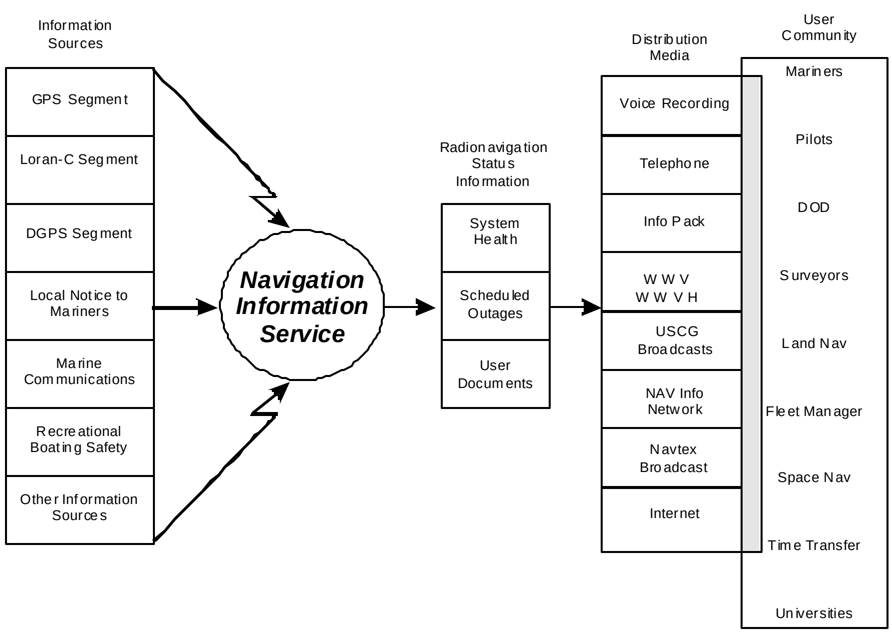

Figure 3-6. NIS Information Flow

Site-specific GPS NOTAMs are computed based on criteria in the RTCA/DO-208, "Minimum Operational Performance Standards for Airborne Supplemental Navigation Equipment Using Global Positioning System (GPS)," dated July 1991, and FAA Technical Standard Order (TSO)-C129(a), "Airborne Supplemental Navigation Equipment Using the Global Positioning System (GPS)." The baseline RAIM algorithm, as specified in the MOPS and TSO, is used for computing the NOTAMs for GPS.

GPS data are received via an antenna on the roof of the FAA Command Center. The almanac and satellite NOTAM data are input into the RAIM algorithm and processed against a database of airfields to determine location specific outages. The outage information is then distributed in the form of a NOTAM to U.S. military aviators and as aeronautical information to U.S. Flight Service Stations for civilian aviators. This occurs daily for an advance 48-hour period or whenever a change occurs in a satellite's health status. Both the military and FAA GPS RAIM outage reporting systems have been operational since 1995.

The military disseminates GPS NOTAMs through the Defense Internet NOTAM Service (DINS), a web-based distribution system. An example of GPS NOTAM is provided below:

A) KLAX
B) 0101081018
C) 0101081045
E) QXXXX GPS NON-PRECISION APPROACH NOT AVAILABLE

This NOTAM means that a GPS nonprecision approach at Los Angeles International Airport is unavailable on Jan. 8, 2001 from 10:18 to 10:45 UTC.

The FAA provides similar GPS outage information in an aeronautical information format, but not as a NOTAM. The FAA uses the same GPS NOTAM generator as the DoD to compute their aeronautical information, but it is distributed through their two Automated Weather Processors (AWPs) to the 21 Flight Service Data Processing Systems (FSDPS) and then to the 61 Automated Flight Service Stations (AFSS), as shown in Figure 3-7 GPS availability for an NPA at the destination airfield is provided to a pilot upon request from the AFSS. The pilot can request information for the estimated time of arrival or ask for the GPS availability over a window of up to 48 hours.

NOTAM information for the GPS WAAS and LAAS systems will be accommodated when they become operational. Since GPS is an area navigation system, GPS aviation outage information may be provided using a graphical display in the future, similar to that used to convey weather information.

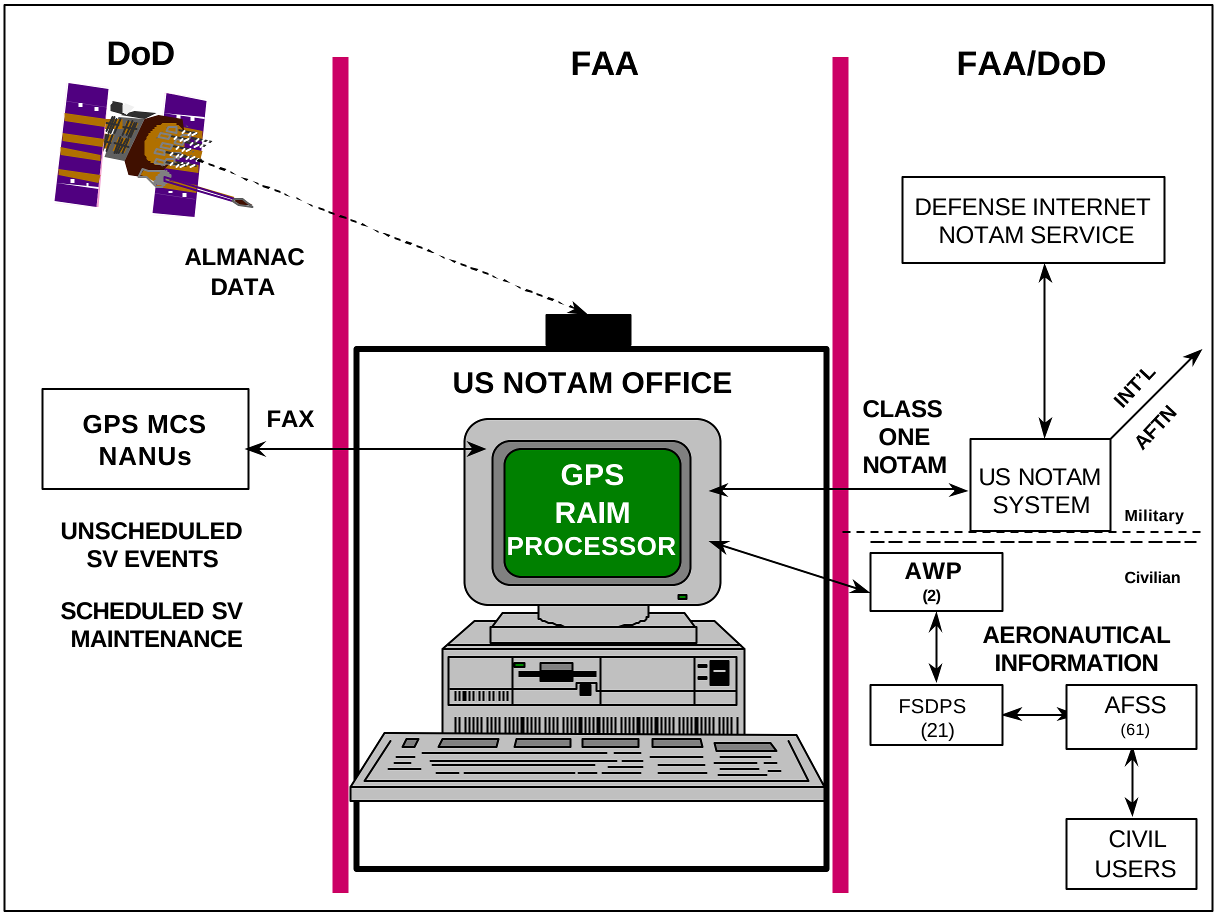

Figure 3-7. GPS NOTAM/Aeronautical Information Distribution System

4

Geodetic Datums and Reference Systems

4.1 Datums

As a general definition, a datum is a quantity or set of quantities that may serve as a referent or basis for calculation of other quantities. This broad characterization, in turn, leads to two related definitions of geodetic datum:

- A geodetic datum is a set of constants specifying the coordinate system used for geodetic control.
- A geodetic datum is defined above, together with the coordinate system and the of all points and lines whose coordinates, lengths, and directions have been determined by measurement and calculation.

The first definition is realized, for example, by specification of an ellipsoid and associated origin and orientation information. The second definition, which is prevalent in mapping and charting, is realized, for example, by specification of ellipsoid, origin, and orientation in combination with a self-consistent set of observed reference coordinates. The first definition represents an idealization of a geodetic datum, and the second definition expresses the realization of a geodetic datum.

Before the advent of manmade satellites, geodetic positions in surveying were determined separately, either horizontally in two-dimensions as latitudes and longitudes or vertically in the third dimension as heights or depths.

Horizontal datums have been defined using a reference ellipsoid and six topocentric parameters expressing origin and orientation. One example is North American Datum (NAD) 1927. Due to the constraints and requirements of the times, horizontal datums were non-geocentric in definition.

Vertical datums are expressed in some form of orthometric height, and can be clustered into two categories: those generally based on Mean Sea Level (MSL), and those based on some tidally-derived surface of an averaged high or low water. Examples of the former is the North American Vertical Datum (NAVD) 1988, and the example of the latter is Mean Lower Low Water (MLLW). Vertical datums depend upon two elements, the approximation or realization of Mean Sea Level, and the approximation or realization of orthometric height. For example, North American Vertical Datum (NAVD) 1988 is based on an adopted elevation at Point Rimouski (Father's Point), and it uses Helmert orthometric heights as an approximation to true orthometric heights. By contrast, the National Geodetic Vertical Datum (NGVD) 1929 was fixed to a set of reference tide gauges, without correction for local sea surface topography departures, and it used normal orthometric heights as an approximation to true orthometric heights.

Three-dimensional datums are defined using a reference ellipsoid and six geocentric parameters expressing origin and orientation. Unlike horizontal datum, a three dimensional datum provides the foundation for accurate determination of ellipsoid heights. Examples of three-dimensional datums are North American Datum (NAD) 1983 and World Geodetic System 1984 (WGS 84).

The North American Datum 1983 (NAD 83) was affirmed as the official horizontal datum for the United States by a notice in the Federal Register (Vol. 54, No. 113 page 25318) on June 14, 1989.

The North American Vertical Datum 1988 (NAVD 88) was affirmed as the official vertical datum for the United States by a notice in the Federal Register (Vol. 58, No. 120 page 34325) on June 24, 1993.

4.2 Geodetic Reference Systems

Using the satellites orbiting around the Earth, the determination of geodetic positions became three-dimensional, either as rectangular (X, Y, Z) coordinates or converted to geodetic (latitude, longitude, ellipsoidal height) coordinates using an Earth-centered ellipsoid. Because of this methodology, it became possible to establish positions of high accuracy in a rectangular reference frame without specification of an ellipsoid. An example of such a reference frame is the International Terrestrial Reference Frame (ITRF) 1997. A geodetic reference system is the combination of a reference frame and an ellipsoid. As seen above, a geodetic reference system is a synonym for a three dimensional datum. Examples of geodetic reference systems are North American Datum 1983 and World Geodetic System 1984.

The geodetic reference system used by unaugmented GPS is the WGS 84 (Ref. 9). The details of the models, the parameters, their uncertainties, and relationships to other systems are given in the reference. The most recent WGS 84 reference frame and the ITRF 94 system are in agreement to better than five centimeters. NAD 83 differs from WGS 84 and ITRF 94 by over 2 meters.

The geodetic reference system used by deployed GPS augmentations is the NAD 83. The Maritime Differential GPS, the Nationwide Differential GPS (NDGPS) augmentations are described in Sections 3.2.2.1 and 3.2.2.2, respectively. The DGPS corrections provided by these augmentations are referenced to NAD 83, thus allowing DGPS receivers to easily provide NAD 83 coordinates. The national CORS system, described in Section 3.2.2.5, includes coordinate databases in both the NAD 83 geodetic reference system, and in the ITRF97 reference frame combined with the GRS 1980 ellipsoid.

4.3 Geoid

The geoid is a specified equipotential surface, defined in the Earth's gravity field, which best fits, in a least square sense, global mean sea level. It should be noted that due to effects such as atmospheric pressure, temperature, prevailing winds and currents, and salinity variations, MSL will depart from an equipotential surface by a meter or more.

The geoid is a complex, physically based surface, and can vary by up to 100 meters in height from a geocentric ellipsoid. Thus, national and regional vertical datums around the world, which are locally tied to MSL, are significantly different from one another when considered on a global basis. In addition, due to the realization and orthometric height approximations of various vertical datums, other departures at the meter level or more will be found when comparing elevations to a global geoid reference.

For the United States, the GEOID99 geoid model has been developed to directly relate ellipsoid heights from the NAD 83 three-dimensional datum to the NAVD 88 vertical datum. Comparisons with GPS ellipsoid heights on leveled benchmarks show this conversion can generally be accomplished in the conterminous United States to about 2.5 cm (1 sigma).

On a global basis, the Earth Gravity Model 1996 (EGM96) was developed to produce an improved global geoid. WGS 84 (EGM96) Geoid is accurate to better than a meter in gravity surveyed areas.

4.4 Land Maps

As discussed earlier, the NAD 83 and the NGVD 88 datums were adopted by Congress as datums for United States. Depending upon the scale of mapping and the spacing of contour intervals, the older NAD 27 and NGVD 29 datums may be adequate to represent the National Spatial Data Accuracy Standard. Except for the largest map scales, the horizontal components of WGS 84 and NAD 83 are equivalent. Datum transformations are available which relate the NAD 27 and NAD 83 datums, and which relate the NGVD 29 and NAVD 88 datums.

4.5 Nautical Charts

As discussed earlier, the NAD 83 and NAVD 88 datums were adopted by Congress as datums for the United States. On a global basis, International Hydrographic Organization (IHO) designated the use of the World Geodetic System 1984 as the universal datum. Since then, the horizontal features have been based on WGS 84 or in other geodetic reference systems that are compatible, such as NAD 83.

All vertical features and depths are still defined with respect to tidal surfaces, which may differ in definition from chart to chart.

4.6 Aeronautical Charts

As discussed earlier, the NAD 83 and the NAVD 88 datums were adopted by Congress as datums for the United States. On a global basis, International Civil Aviation Organization (ICAO) designated the use of the WGS 84 as the universal datum. Since then, the horizontal features have been used on WGS 84 or in other geodetic reference systems which are compatible, such as the NAD 83 or the ITRF combined with the GRS80 ellipsoid.

All vertical features and elevations are still determined relative to the local vertical datums, which may vary by a meter or more from a global geoid reference (e.g., WGS 84 (EGM96) geoid).

4.7 Map and Chart Accuracies

When comparing positions derived from GPS with positions taken from maps or charts, an understanding of factors affecting the accuracy of maps and charts is important.

Several factors are directly related to the scale of the product. Map or chart production requires the application of certain mapmaking standards to the process. Because production errors are evaluated with respect to the grid of the map, the evaluation represents relative accuracy of a single feature rather than feature-to-feature relative accuracy. This is the “specified map or chart accuracy.” Another factor is the symbolization of features. This creates an error in position because of physical characteristics, e.g., what distance is represented by the width of a line symbolizing a feature. In other words, what is the dimension of the smallest object that can be portrayed true to scale and location on a map or chart? Also, a limiting factor on accuracy is the map or chart user’s inability to accurately scale the map coordinates given by the grid or to plot a position.

Cartographic presentation or “cartographic license” is also an error source. When attempting to display two or more significant features very close together on a map or chart, the cartographer may displace one feature slightly for best presentation or clarity.

Errors in the underlying survey data of features depicted on the map or chart will also affect accuracy. For example, some hazards on nautical charts have not always been accurately surveyed and hence are incorrectly positioned on the chart.

As a final cautionary note, realize that maps and charts have been produced on a variety of datums. The coordinates for a point in one datum will not necessarily match the coordinates from another datum for that same point. Ignoring the datum shift and not applying the appropriate datum transformation can result in significant error. This applies whether one is comparing the coordinates of a point on two different maps or charts or comparing the coordinates of a point from a GPS receiver with the coordinates from a map or chart.

Appendix A

Definitions

Accuracy - The degree of conformance between the estimated or measured position and/or velocity of a platform at a given time and its true position or velocity. Radionavigation system accuracy is usually presented as a statistical measure of system error and is specified as:

- Predictable - The accuracy of a radionavigation system's position solution with respect to the charted solution. Both the position solution and the chart must be based upon the same geodetic datum. (Note: Chapter 4 in the FRS discusses chart reference systems and the risks inherent in using charts in conjunction with radionavigation systems.)

- Repeatable - 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.

- Relative - The accuracy with which a user can measure position relative to that of another user of the same navigation system at the same time.

Air Traffic Control (ATC) - A service operated by appropriate authority to promote the safe and efficient flow of air traffic.

Approach Reference Datum - A point at a specified height above the runway centerline and the threshold. The height of the MLS approach reference datum is 15 meters (50 ft). A tolerance of plus 3 meters (10 ft) is permitted.

Area Navigation (RNAV) - Application of the navigation process providing the capability to establish and maintain a flight path on any arbitrarily chosen course that remains within the coverage area of navigation sources being used.

Automatic Dependent Surveillance (ADS) - A function in which aircraft transmit position and altitude data derived from onboard systems via a datalink for use by air traffic control, other aircraft, and certain airport surface vehicles.

Availability - The availability of a navigation system is the percentage of time that the services of the system are usable. 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 navigation signals transmitted from external sources are available for use. Availability is a function of both the physical characteristics of the environment and the technical capabilities of the transmitter facilities.

Block II/IIA - The satellites that form the initial GPS constellation at FOC.

Cellular Triangulation - A method of location determination using the cellular phone system where the control channel signals from a mobile phone are captured by two or more fixed base stations and processed according to an algorithm to determine the location of the mobile receiver.

Circular Error Probable (CEP) - In a circular normal distribution (the magnitudes of the two one-dimensional input errors are equal and the angle of cut is 90^{o}), circular error probable is the radius of the circle containing 50 percent of the individual measurements being made, or the radius of the circle inside of which there is a 50 percent probability of being located.

Coastal Confluence Zone (CCZ) - Harbor entrance to 50 nautical miles offshore or the edge of the continental shelf (100 fathom curve), whichever is greater.

Common-use Systems - Systems used by both civil and military sectors.

Conterminous U.S. - Forty-eight adjoining states and the District of Columbia.

Continuity - The continuity of a system is the ability of the total system (comprising all elements necessary to maintain aircraft position within the defined airspace) to perform its function without interruption during the intended operation. More specifically, continuity is the probability that the specified system performance will be maintained for the duration of a phase of operation, presuming that the system was available at the beginning of that phase of operation.

Coordinate Conversion - The conversion of position coordinates from one type to another within the same datum or geodetic reference system, e.g., from geodetic coordinates (latitudes and longitudes) to Universal Transverse Mercator (UTM) system (x,y).

Coordinated Universal Time (UTC) - UTC, an atomic time scale, is the basis for civil time. It is occasionally adjusted by one-second increments to ensure that the difference between the uniform time scale, defined by atomic clocks, does not differ from the earth's rotation by more than 0.9 seconds.

Coverage - The coverage provided by a radionavigation system is that surface area or space volume in which the signals are adequate to permit the user 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 that affect signal availability.

Datum Transformation - The change of position coordinates from one geodetic datum or reference system to another datum or reference system, e.g., from European Datum 1950 to WGS 84.

Deception (electromagnetic) - Deliberate radiation, reradiation, alternation, suppression, absorption, denial, enhancement, or reflection of electromagnetic spectrum in any manner intended to convey misleading information.

Differential - A technique used to improve radionavigation system accuracy by determining positioning error at a known location and subsequently transmitting the determined error, or corrective factors, to users of the same radionavigation system, operating in the same area.

Distance Root Mean Square (drms) - The root-mean-square value of the distances from the true location point of the position fixes in a collection of measurements. As used in this document, 2 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. Actually, the percentage of fixes contained within 2 drms varies between approximately 95.5 percent and 98.2 percent, depending on the degree of ellipticity of the error distribution.

En Route - A phase of navigation covering operations between a point of departure and termination of a mission. For airborne missions the en route phase of navigation has two subcategories, en route domestic and en route oceanic.

En Route Domestic - The phase of flight between departure and arrival terminal phases, with departure and arrival points within the conterminous United States.

En Route Oceanic - The phase of flight between the departure and arrival terminal phases, with an extended flight path over an ocean.

Fault Detection and Exclusion (FDE) - Fault detection and exclusion is a receiver processing scheme that autonomously provides integrity monitoring for the position solution, using redundant range measurements. The FDE consists of two distinct parts: fault detection and fault exclusion. The fault detection part detects the presence of an unacceptably large position error for a given mode of flight. Upon the detection, fault exclusion follows and excludes the source of the unacceptably large position error, thereby allowing navigation to return to normal performance without an interruption in service.

Flight Level (FL) - A level of constant atmospheric pressure related to a reference datum of 29.92 inches of mercury. Each is stated in three digits that represent hundreds of feet. For example, flight level (FL) 250 represents a barometric altimeter indication of 25,000 feet; FL 225 represents an indication of 25,500 feet.

Flight Technical Error (FTE) - The contribution of the pilot in using the presented information to control aircraft position.

Free Flight - A safe and efficient flight operating capability under instrument flight rules in which the operators have the freedom to select their path and speed in real time. Air traffic restrictions are only imposed to ensure separation, to preclude exceeding airport capacity, to prevent unauthorized flight through special use airspace, and to ensure safety of flight. Restrictions are limited in extent and duration to correct the identified problem.

Full Operational Capability (FOC) - A system dependent state that occurs when the particular system is able to provide all of the services for which it was designed.

Geocentric - Relative to the Earth as a center, measured from the center of mass of the Earth.

Geodesy - The science related to the determination of the size and shape of the Earth by such direct measurements as triangulation, GPS positioning, leveling, and gravimetric observations.

Geometric Dilution of Precision (GDOP) - All geometric factors that degrade the accuracy of position fixes derived from externally referenced navigation systems.

Global Navigation Satellite System (GNSS) - The GNSS is a world-wide position and time determination system, that includes one or more satellite constellations, aircraft receivers, and system integrity monitoring, augmented as necessary to support the required navigation performance for the actual phase of operation.

Inclination - One of the orbital elements (parameters) that specifies the orientation of an orbit. Inclination is the angle between the orbital plane and a reference plane, the plane of the celestial equator for geocentric orbits and the ecliptic for heliocentric orbits.

Initial Operational Capability (IOC) - A system dependent state that occurs when the particular system is able to provide a predetermined subset of the services for which it was designed.

Integrity - Integrity is the ability of a system to provide timely warnings to users when the system should not be used for navigation.

Interference (electromagnetic) - Any electromagnetic disturbance that interrupts, obstructs, or otherwise degrades or limits the performance of user equipment.

Intrusion (electromagnetic) - Intentional insertion of electromagnetic energy into transmission paths with the objective to deceive or confuse the user.

Jamming (electromagnetic) - The deliberate radiation, reradiation, or reflection of electromagnetic energy for the purpose of preventing or reducing the effective use of a signal.

Multipath - The propagation phenomenon that results in signals reaching the receiving antenna by two or more paths. When two or more signals arrive simultaneously, wave interference results. The received signal fades if the wave interference is time varying or if one of the terminals is in motion.

Nanosecond (ns) - One billionth of a second.

National Airspace System (NAS) - The NAS includes U.S. airspace; air navigation facilities, equipment and services; airports or landing areas; aeronautical charts, information and service; rules, regulations and procedures; technical information; and labor and material used to control and/or manage flight activities in airspace under the jurisdiction of the U.S. System components shared jointly with the military are included.

National Command Authority (NCA) - The NCA is the President or the Secretary of Defense, with the approval of the President. The term NCA is used to signify constitutional authority to direct the Armed Forces in their execution of military action. Both movement of troops and execution of military action must be directed by the NCA.

Nautical Mile (nm) - A unit of distance used principally in navigation. The International Nautical Mile is 1,852 meters long.

Navigation - The process of planning, recording, and controlling the movement of a craft or vehicle from one place to another.

Navigation System Error (NSE) - The NSE is the error attributable to the navigation system in use. It includes the navigation sensor error, receiver error, and path definition error. NSE combines with Flight Technical Error (FTE) to produce the Total System Error.

Nonprecision Approach - A standard instrument approach procedure in which no electronic glide slope is provided (e.g., VOR, TACAN, or NDB).

Position Dilution of Precision - A scalar measure representing the contribution of the GPS satellite configuration geometry to the accuracy in three-dimensional position.

Precise Time - A time requirement accurate to within 10 milliseconds.

Precision Approach - A standard instrument approach procedure using a ground-based system in which an electronic glide slope is provided (e.g., ILS).

Primary Means Air Navigation System - A navigation system approved for a given operation or phase of flight that must meet accuracy and integrity requirements, but need not meet full availability and continuity of service requirements. Safety is achieved by limiting flights to specific time periods and through appropriate procedural restrictions. There is no requirement to have a sole-means navigation system on board to support a primary means system.

Radiodetermination - The determination of position, or the obtaining of information relating to positions, by means of the propagation properties of radio waves.

Radiolocation - Radiodetermination used for purposes other than those of radionavigation.

Radionavigation - The determination of position, or the obtaining of information relating to position, for the purposes of navigation by means of the propagation properties of radio waves.

Receiver Autonomous Integrity Monitoring (RAIM) - A technique whereby a GPS receiver/processor determines the integrity of the GPS navigation signals without reference to external systems other than to the GPS satellite signals themselves or to an independent input of altitude information. This determination is achieved by a consistency check among redundant pseudorange measurements.

Reliability - The probability of performing a specified function without failure under given conditions for a specified period of time.

Required Navigation Performance - A statement of the navigation performance accuracy necessary for operation within a defined airspace, including the operating parameters of the navigation systems used within that airspace.

Rho (Ranging Mode) - A mode of operation of a radionavigation system in which the times for the radio signals to travel from each transmitting station to the receiver are measured rather than their differences (as in the hyperbolic mode).

Roadside Beacons - A system using infrared or radio waves to communicate between transceivers placed at roadsides and the in-vehicle transceivers for navigation and route guidance functions.

Sigma - See Standard Deviation.

Sole Means Air Navigation System - A sole-means navigation system approved for a given operation or phase of flight must allow the aircraft to meet, for that operation or phase of flight, all four navigation system performance requirements: accuracy, integrity, availability, and continuity of service. Note--This definition does not exclude the carriage of other navigation systems. Any sole-means navigation system could include one (stand-alone installation) or several sensors, possibly of different types (multi-sensor installation).

Spherical Error Probable (SEP) - The radius of a sphere within which there is a 50 percent probability of locating a point or being located. SEP is the three-dimensional analogue of CEP.

Standard Deviation (sigma) - A measure of the dispersion of random errors about the mean value. If a large number of measurements or observations of the same quantity are made, the standard deviation is the square root of the sum of the squares of deviations from the mean value divided by the number of observations less one.

Statute Mile - A unit of distance on land in English-speaking countries equal to 5,280 feet or 1,760 yards.

Supplemental Air Navigation System - A navigation system that may only be used in conjunction with a primary- or sole-means navigation system. Approval for supplemental means for a given phase of flight requires that a primary-means navigation system for that phase of flight must also be on board. Amongst the navigation system performance requirements for a given operation or phase of flight, a supplemental-means navigation system must meet the accuracy and integrity requirements for that operation or phase of flight; there is no requirement to meet availability and continuity requirements. Note--Operationally, while accuracy and integrity requirements are being met, a supplemental-means system can be used without any crosscheck with the primary-means system. Any navigation system approved for supplemental means could involve one (stand-alone installation) or several sensors, possibly of different types (multi-sensor installation).

Surveillance - The observation of an area or space for the purpose of determining the position and movements of craft or vehicles in that area or space.

Surveying - The act of making observations to determine the size and shape, the absolute and/or relative position of points on, above, or below the Earth’s surface, the length and direction of a line, the Earth’s gravity field, length of the day, etc.

Terminal - A phase of navigation covering operations required to initiate or terminate a planned mission or function at appropriate facilities. For airborne missions, the terminal phase is used to describe airspace in which approach control service or airport traffic control service is provided.

Terminal Area - A general term used to describe airspace in which approach control service or airport traffic control service is provided.

Theta - Bearing or direction to a fixed point to define a line of position.

Time Interval - The duration of a segment of time without reference to where the time interval begins or ends.

TOPEX/POSEIDON - TOPographic EXperiment/POSEIDON mission, a joint U.S./French oceanic mapping mission launched in August 1992.

Total System Error (TSE) - The TSE comprises both the aircraft and its navigation system tracking errors. It is the difference between true position and desired position. This error is equal to the vector sum of the path steering error, path definition error, and position estimation error.

Universal Transverse Mercator (UTM) Grid - A rectangular grid of east-west and north-south lines, with linear scale of 0.9996 along the central meridian, and based on the Transverse Mercator projection; mostly used on military maps and charts from 84oN and 80^{o}S latitudes.

User Range Error (URE) - A satellite URE is defined to be the instantaneous difference between a ranging signal measurement (neglecting user clock bias), and the true range between the satellite and a GPS user at any point within the service volume.

Vehicle Location Monitoring - A service provided to maintain the orderly and safe movement of platforms or vehicles. It encompasses the systematic observation of airspace, surface and subsurface areas by electronic, visual or other means to locate, identify, and control the movement of platforms or vehicles.

World Geodetic System (WGS) - A consistent set of constants and parameters describing the Earth's geometric and physical size and shape, gravity potential and field, and theoretical normal gravity.

Appendix B

Glossary

The following is a listing of abbreviations for organization names and technical terms used in this plan:

ADF	Automatic Direction Finder
ADS	Automatic Dependent Surveillance
ADS-B	Automatic Dependent Surveillance Broadcast
AFSS	Automated Flight Service Stations
AGL	Above Ground Level
AIRSAR	Airborne Synthetic Aperture Radar
AIS	Automatic Identification Systems
AOPA	Aircraft Owners and Pilots Association
APL	Airport Pseudolite
ARNS	Aeronautical Radionavigation Service
ATA	Air Transport Association of America
ATC	Air Traffic Control
AWP	Automated Weather Processor

BBN	Basic Backup Network
BTS	Bureau of Transportation Statistics
C/A	Coarse/Acquisition
CCW	Coded Continuous Wave
CEP	Circular Error Probable
CFR	Code of Federal Regulations
CGS	Civil GPS Service
CGSIC	Civil GPS Service Interface Committee
CJCS	Chairman, Joint Chiefs of Staff
cm	centimeter
CNS	Communication, Navigation and Surveillance
CONUS	Continental United States
CORS	Continuously Operating Reference Stations
CPDLC	Controller Pilot Data Link
CRV	Crew Return Vehicle
DGPS	Differential Global Positioning System
DIA	Defense Intelligence Agency
DME	Distance Measuring Equipment
DOC	Department of Commerce
DOD	Department of Defense
DOJ	Department of Justice
DOI	Department of the Interior
DOS	Department of State
DOT	Department of Transportation
drms	distance root mean squared
ECDIS	Electronic Chart Display Information System
FAA	Federal Aviation Administration
FAF	Final Approach Fix

FAR	Federal Aviation Regulation
FDE	Fault Detection and Exclusion
FGDC	Federal Geographic Data Committee
FHWA	Federal Highway Administration
FIR	Flight Information Region
FL	Flight Level
FM	Frequency Modulation
FMCSA	Federal Motor Carrier Safety Administration
FMS	Flight Management Systems
FOC	Full Operational Capability
FRA	Federal Railroad Administration
FRP	Federal Radionavigation Plan
FRS	Federal Radionavigation Systems
FSDPS	Flight Service Data Processing Systems
FTA	Federal Transit Administration
FTE	Flight Technical Error
GBAS	Ground Based Augmentation Systems
GCA	Ground Controlled Approach
GDOP	Geometric Dilution of Precision
GEO	Geostationary Earth Orbit
GES	Ground Earth Station
GHz	Gigahertz
GIAC	GPS Interagency Advisory Council
GIS	Geographic Information Systems
GLONASS	Global Navigation Satellite System (Russian Federation System)
GNSS	Global Navigation Satellite System (ICAO)
GPS	Global Positioning System
HF	High Frequency

HMU	Height Monitoring Unit
Hz	Hertz (cycles per second)
IAG	International Association of Geodesy
IALA	International Association of Marine Aids to Navigation and Lighthouse Authorities
ICAO	International Civil Aviation Organization
ICD	Interface Control Document
IERS	International Earth Rotation Service
IFR	Instrument Flight Rules
IGEB	Interagency GPS Executive Board
IGS	International GPS Service
ILS	Instrument Landing System
IMO	International Maritime Organization
INMARSAT	International Maritime Satellite Organization
INS	Inertial Navigation System
IOC	Initial Operational Capability
ISS	International Space Station
ITRF	IERS Terrestrial Reference Frame
ITS	Intelligent Transportation Systems
ITS-JPO	Intelligent Transportation Systems Joint Program Office
ITU	International Telecommunication Union
JPO	Joint Program Office
JTIDS	Joint Tactical Information Distribution System
kHz	kilohertz
km	kilometer
LAAS	Local Area Augmentation System
LEO	Low Earth Orbiting
LNAV	Lateral Navigation
LOP	Line of Position

m	meter
MARAD	Maritime Administration
MCS	Master Control Station
MCW	Modulated Continuous Wave
MDGPS	Maritime Differential GPS Service
MF	Medium Frequency
MHz	Megahertz
MIDS	Multi-function Information Distribution System
M-Code	Military Code
MLS	Microwave Landing System
mm	millimeters
MNPS	Minimum Navigation Performance Standard
ms	millisecond
MOA	Memorandum of Agreement
MON	Minimum Operational Network
MPNTP	Master Positioning, Navigation, and Timing Plan
NAD	North American Datum
NANU	Notice Advisories to Navstar Users
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
Navaids	Ground-Based Navigation Aids
NAVCEN	U.S. Coast Guard Navigation Center
NAVD	North American Vertical Datum
NAVWAR	Navigation Warfare
NCA	National Command Authority
NDB	Nondirectional Beacon
NDGPS	Nationwide Differential Global Positioning Service

NGS	National Geodetic Survey
NGVD	National Geodetic Vertical Datum
NHTSA	National Highway Traffic Safety Administration
NIMA	National Imagery and Mapping Agency
NIS	Navigation Information Service
nm	nautical mile
NOAA	National Oceanic and Atmospheric Administration
NOTAM	Notice to Airmen
NPA	Nonprecision Approach
NPOESS	National Polar-Orbiting Observational Environmental Satellite System
ns	nanosecond
NSA	National Security Agency
NSF	National Science Foundation
NSRS	National Spatial Reference System
OAB	Operational Advisory Broadcast
OSD	Office of the Secretary of Defense
OST	Office of the Secretary of Transportation
OST/B	Assistant Secretary for Budget Programs
OST/C	General Counsel's Office
OST/M	Assistant Secretary for Administration
OST/P	Assistant Secretary for Transportation Policy
P-code	Pseudorandom Tracking Code
PDD	Presidential Decision Directive
PHMI	Probability of Hazardously Misleading Information
POS/NAV	Positioning and Navigation
PPS	Precise Positioning Service
PRN	Pseudo-Random Noise
PTC	Positive Train Control

RACON	Radar Transponder Beacon
RAIM	Receiver Autonomous Integrity Monitoring
RBN	Radiobeacon
R&D	Research & Development
RDF	Radio Direction Finder
RF	Radio Frequency
RFI	Radio Frequency Interference
RGCSP	Review of General Concept of Separation Panel
RNAV	Area Navigation
RNP	Required Navigation Performance
RSA	Range Standardization and Automation
RSPA	Research and Special Programs Administration
RSS	Root Sum Square
RTCM	Radio Technical Commission for Maritime Services
RVSM	Reduced Vertical Separation Minima
SA	Selective Availability
SAFI	Semi-Automatic Flight Inspection
Satnav	Satellite-Based Navigation
SBAS	Space-Based Augmentation System
SCAT I	Special Category I
SLSDC	Saint Lawrence Seaway Development Corporation
SPS	Standard Positioning Service
SSV	Standard Service Volume
TACAN	Tactical Air Navigation
TD	Time Difference
TDWR	Terminal Doppler Weather Radar
TERPS	Terminal Instrument Procedures
TIA	Transportation Infrastructure Assurance

TIS	Traffic Information Services
TRSB	Time Referenced Scanning Beam
TSO	Technical Standard Order
UHF	Ultra High Frequency
USACE	U.S. Army Corps of Engineers
USAF	United States Air Force
U.S.C.	United States Code
USCG	United States Coast Guard
USDA	U.S. Department of Agriculture
USD/A&T	Under Secretary of Defense for Acquisition and Technology
USNO	United States Naval Observatory
UTC	Coordinated Universal Time
VDB	Very High Vehicle Data Broadcast
VFR	Visual Flight Rules
VHF	Very High Frequency
VLBI	Very Long Baseline Interferometry
VLF	Very Low Frequency
VNAV	Vertical Navigation
VOR	Very High Frequency Omnidirectional Range
VORTAC	Collocated VOR and TACAN
VTS	Vessel Traffic Services
WAAS	Wide Area Augmentation System
WGS	World Geodetic System
WIPP	WAAS Integrity and Performance Panel
WMS	Wide Area Master Stations
WWV/WWVH	Call Sign for the National Bureau of Standards Broadcast Notice to Airmen

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The Federal Radionavigation Systems (FRS) is a companion document to the 2001 Federal Radionavigation Plan (FRP). This edition of the FRS updates and replaces sections in the 1999 FRP relating to Government roles and responsibilities, system selection considerations user requirements, and systems descriptions.

The FRS covers common-use radionavigation systems (i.e., systems used by both civil and military sectors); describes the authorities and responsibilities of Federal agencies; and describes the management structure established to guide individual operating agencies in defining and meeting radionavigation requirements in a cost-effective manner.

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