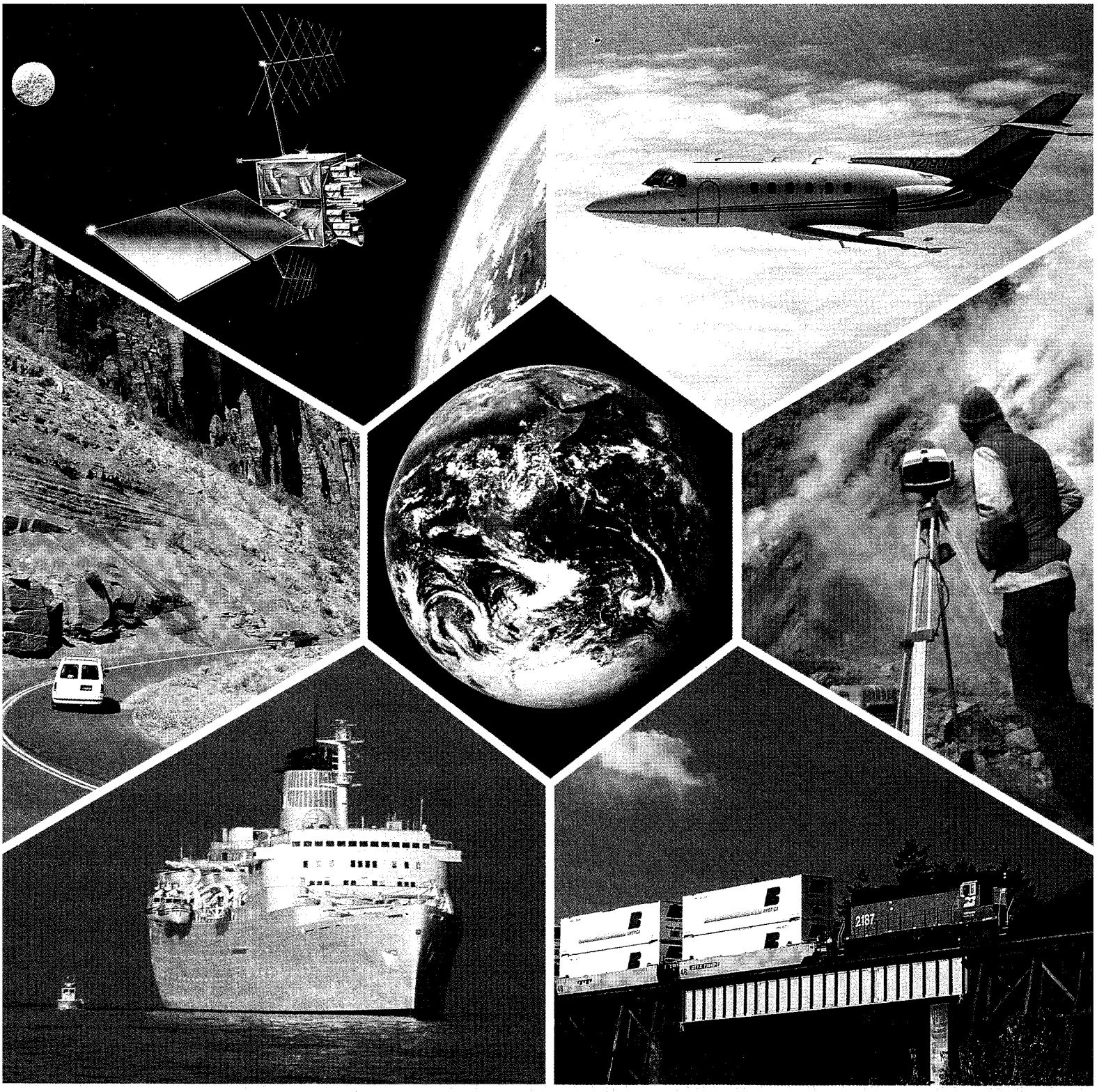

A Technical Report to the Secretary of Transportation on a National Approach to Augmented GPS Services

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PREFACE

This report is provided by the Institute for Telecommunication Sciences (ITS), National Telecommunications and Information Administration (NTIA), U.S. Department of Commerce (DOC), to the Federal Highway Administration (FHWA), U.S. Department of Transportation (DOT), in fulfillment of Interagency Agreement Number DTFH61-93-Y-00110. Personnel from ITS, the U.S. Army Topographic Engineering Center, the Volpe National Transportation Systems Center, and Overlook Systems Technologies, Inc. contributed to the writing of the report.

The recommendations contained herein are those of the authors, and should not be construed as official policy of DOT or FHWA. This document does not convey official policy of DOC, NTIA, or ITS.

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EXECUTIVE SUMMARY

Early in 1993, the Secretaries of Defense and Transportation recognized the expanding utility of the Navstar Global Positioning System (GPS) for both military and civilian applications. The Secretaries chartered a Joint Task Force to assess the growing utility of the system and make recommendations for expanding civil use. In December 1993, the Joint Task Force concluded its deliberations and reported its findings and recommendations to the Secretaries. Included in the Task Force report was a recommendation for a study of all differential GPS (DGPS) services under development or deployment to determine the optimum integrated approach to providing augmented GPS services.

In response to the Task Force recommendation, the Department of Transportation (DOT), with the support and assistance of the Department of Defense (DOD) and the Department of Commerce (DOC), undertook a study to evaluate the capabilities of various means of augmenting GPS and to determine the optimum integrated system for meeting the requirements of Federal land, marine, aviation, and space users. This report presents the findings of that study.

Study Participants

Using an existing Federal Highway Administration (FHWA) contractual relationship, the DOT engaged the services of the Institute for Telecommunication Sciences (ITS) of the National Telecommunications and Information Administration (NTIA) to conduct the study. ITS provided a broad background in communication systems, navigation systems, systems planning and analysis, standards development, and spectrum management. To augment its expertise, ITS obtained the services of additional technical specialists. The U.S. Army Topographic Engineering Center (TEC) provided technical expertise and experience with the development of GPS and positioning and navigation systems. DOT's Volpe National Transportation Systems Center added extensive overall knowledge of transportation systems. Overlook Systems Technologies, Inc. furnished expertise on aviation systems and Federal Aviation Administration (FAA) requirements. Representatives from these organizations formed a study team, led by ITS, that carried out the study. Study team meetings provided opportunity for input from other agencies. Study oversight was provided by a Study Review Board representing the Office of the Secretary of Transportation, FHWA, DOT's Research and Special Programs Administration, FAA, U.S. Coast Guard (USCG), DOD, and the National Oceanic and Atmospheric Administration (NOAA). The Study Review Board appointed a Working Group to support the efforts of the study team.

Approach

The study began with a detailed examination of the current and future navigation and positioning requirements of Federal land, marine, aviation, and space users. The primary sources of requirements information consisted of the following:

- Responses from Federal agencies to a Secretary of Transportation request for statements of intended uses for GPS.
- A workshop for Federal GPS users, conducted by ITS and TEC.
- Responses from Federal agencies to a survey generated and distributed by the study team.

The study team found that the requirements of Federal agencies vary widely, but they can be summarized as follows:

Accuracy. The range of accuracy required is from 1 mm to 1000 m. The highest accuracy is required for surveying. The FAA requires only 1000 m accuracy for en route navigation, but requires 4.1 m (13.5 ft) horizontal and 0.6 m (2 ft) vertical accuracy for Category III precision approach and landing.

Time to Alarm. Requirements for the elapsed time between a system failure and notification to the user range from 1 second for certain land transportation applications to hours for post-processing survey applications.

Availability. Most users have a need for greater than 99.7% availability. Some railroad applications require availability of 100%.

Coverage Area. Federal users require nationwide coverage both at ground level and in the volume above ground and over that part of the oceans which constitutes the National Airspace System. Worldwide coverage for a seamless transition to foreign systems is highly desirable.

Concurrent with the requirements analysis, the study team researched existing and planned augmented GPS systems. Systems examined included Federal, private, and foreign systems. Eighteen systems were identified as potential alternatives to meet Federal requirements for navigation and positioning. The study team selected 11 systems from among these alternatives for detailed evaluation. This selection was based on technical feasibility, capability of meeting user requirements, and current implementation or likely implementation in the near future.

The study team subjected the 11 candidate systems to a more detailed analysis using a specially constructed, two-stage decision matrix. In the first stage of the decision matrix, the study team listed the detailed performance requirements of Federal users and evaluated the ability of each

of the candidate systems to meet these requirements. From this stage of the decision analysis, the study team determined that no single existing or planned augmented GPS system is capable of meeting all requirements of all users. With this determination made, the study team proposed six potential composite architectures intended to satisfy as many user requirements as possible. The six composite architectures are summarized briefly in the following paragraphs:

Architecture 1. This architecture, the baseline system, consisted of the GPS augmentation systems currently planned by USCG and FAA. It included the 61-site local area differential GPS (LADGPS) system currently being implemented by USCG for marine use, FAA's Wide Area Augmentation System (WAAS) as currently planned to satisfy aviation requirements for en route through Category I precision approach, and FAA's LADGPS systems to satisfy Category II/III precision approach requirements. All of the reference stations included in this architecture would be compliant with the Continuously Operating Reference Station (CORS) standard. Such stations would have the capability of storing a standardized set of data to support the widest possible number of post-processing applications. Although Architecture 1 did not satisfy many land transportation and survey requirements, it was included to provide a benchmark against which the remaining five, more viable alternatives could be compared.

Architecture 2. This architecture consisted of an expanded version of USCG's LADGPS system to provide nationwide coverage for marine <u>and</u> land users. It also included FAA's WAAS as currently planned to satisfy aviation requirements for en route through Category I precision approach, and FAA's LADGPS systems to satisfy Category II/III precision approach requirements. All of the reference stations included in this architecture would comply with the CORS standard.

Architecture 3. This architecture consisted of an expanded version of USCG's LADGPS system to provide nationwide coverage for marine and land users and a variant of FAA's WAAS to satisfy aviation requirements for en route through nonprecision approach only. Category I, II, and III precision approach requirements would be satisfied by FAA's LADGPS systems. All of the reference stations included in this architecture would comply with the CORS standard.

Architecture 4. This architecture included an expanded version of USCG's LADGPS system to provide nationwide coverage for marine and land users. It also included a modified version of FAA's WAAS, which provided corrections at other than the GPS L1 frequency, to satisfy aviation requirements for en route through Category I precision approach. Category II/III precision approach requirements would be satisfied by FAA's LADGPS systems. All of the reference stations included in this architecture would comply with the CORS standard.

Architecture 5. This architecture included an expanded version of USCG's LADGPS system to provide nationwide coverage for marine and land users. It also included a modified version of the FAA's WAAS which would encrypt all of the corrections for

increased security. The modified WAAS would satisfy aviation requirements for en route through Category I precision approach. Category II/III precision approach requirements would be satisfied by FAA's LADGPS systems. All of the reference stations included in this architecture would comply with the CORS standard.

Architecture 6. This architecture included an expanded version of USCG's LADGPS system to provide nationwide coverage for marine and land users and to satisfy aviation accuracy requirements for Category I precision approach. It also included a variant of the FAA's WAAS to satisfy aviation requirements for en route through nonprecision approach. Category II/III precision approach requirements would be satisfied by FAA's LADGPS systems. All of the reference stations included in this architecture would comply with the CORS standard.

Architecture 6 was evaluated extensively as it appeared capable of meeting stated requirements at a lower cost than the other five architectures. In the course of the evaluation, it was found that possible interference of signal reception could occur to aircraft which were flying through conditions conducive to the creation of precipitation static (P-Static). While an extensive study had not been performed of this phenomenon, it raised significant concerns about signal availability. Consequently, Architecture 6 was not considered in the second stage of the decision matrix.

The remaining five composite architectures were evaluated using the second stage of the decision matrix, which constituted a modified version of a classic multi-attribute utility analysis. The second stage of the matrix consisted of a model with three major parameters: Performance, Cost, and Security. These major parameters were broken down into the individual factors shown below:

Performance —

- Real Time Accuracy.
- Integrity (Time to Alarm).
- Availability.
- Time Frame of Availability (Initial Operating Capability).
- Coverage.
- International Compatibility.

Cost —

- Infrastructure Cost.
- User Cost.

Security —

- Access Control.
- Level of Influence.
- Interdiction.
- Post-Decision Response Time.
- Jammability.
- Vulnerability of Denial.

Importance weights were assigned to each of the factors under each parameter. Each factor was then assigned a relative score ranging from 100 for the best architecture to 0 for the worst architecture. The second stage of the decision matrix provided a numerical score for each composite architecture for each parameter. A multi-attribute decision analysis would have assigned relative importance weights to the individual parameters themselves and, using these weights, derived a single aggregate score for each architecture. However, in this study, no attempt was made to assign relative importance weights to the parameters since to do so would have involved making value judgments that were beyond the scope of the study. Rather, the study team and Working Group concluded that the primary utility of the decision matrix was its ability to facilitate brainstorming, assist in developing a greater awareness of what the key decision factors might be, and highlight areas of uncertainty. Further, the decision matrix aided in composing and performing a series of sensitivity analyses.

Conclusions

There are two candidates that could be selected as the National augmentation architecture. The selection of one of these two viable alternatives is dependent on overall U.S. Government policy regarding augmentation systems.

- If security concerns are not the overriding consideration and do not predominate over other benefits available from an augmented GPS, composite Architecture 2 is the recommended National augmentation system.

- If, however, security concerns are of such significance as to predominate over economic and other benefits available from an augmented GPS, then Architecture 3 is the recommended National augmentation system.

Either of these architectures will meet aviation user requirements for all phases of flight, marine user requirements for all modes of operation, and most land user requirements including IVHS, railroad, and survey. However, neither architecture will satisfy highway collision avoidance because of the high degree of accuracy (1 meter) required nationwide. Neither architecture will provide the 100% availability required for railroad collision avoidance. These applications may require the development or use of other technologies either in conjunction with or independent of GPS.

Recommendations

Based on its research and evaluation, the study team recommends the following:

- FAA should continue to implement its WAAS and LADGPS systems as currently planned.

- DOT, in coordination and cooperation with DOC, should plan, install, operate, and maintain an expanded low frequency/medium frequency beacon system modeled after USCG's LADGPS system to provide nationwide coverage for land and marine users. Prior to implementing this system, a study should be performed to determine the number and optimum location of beacons necessary for nationwide coverage.

- All Federally-provided reference stations should comply with the CORS standard.

- DOT should continue to evaluate system risks and appropriate measures needed to ensure safe and reliable augmentation services. Further, DOT, with the assistance of DOD, should test and evaluate measures to mitigate the susceptibility of Federally-provided augmentation systems to all forms of interference, including jamming and spoofing.

- DOT, in conjunction with other Federal agencies, should coordinate the implementation, operation, and maintenance of all Federally-operated augmented GPS systems to ensure optimal use of resources by maximizing commonality of system components.

- Different formats for augmentation data have been developed to meet the requirements of particular user communities and to make optimum use of data links planned for augmenting GPS. For the architectures considered, there is no compelling technical or economic reason for developing a single, standardized data format for use by all Federally-operated augmentation systems. Consequently, no effort should be expended on the conversion of existing broadcast formats to a common data format in the near term. Use of the Receiver Independent Exchange (RINEX) format is recommended for post-processing applications. In addition, an international standards working group should be identified to address any future data format issues.

- A central repository for GPS augmentation information should be maintained. This information should be made available to the public via the existing USCG Navigation Information Service.

- A further study should be undertaken to investigate spectrum allocation and bandwidth requirements for any future, Federally-provided, differential GPS system.

A TECHNICAL REPORT TO THE SECRETARY OF TRANSPORTATION ON A NATIONAL APPROACH TO AUGMENTED GPS SERVICES

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ABSTRACT

This report documents the development of recommendations for a national approach to augmented Global Positioning System (GPS) services. The Institute for Telecommunication Sciences led a study team that included the U.S. Army Topographic Engineering Center, the Volpe National Transportation Systems Center, and Overlook Systems Technologies, Inc. The study team identified Federal navigation, positioning, and timing requirements for land, marine, air, and space modes of operation. The study team then evaluated numerous operating and proposed systems that augment the GPS Standard Positioning Service. The most promising systems were combined in six different architectures intended to meet the widest possible range of user requirements. One of these architectures was eliminated from consideration due to technical concerns. The study team evaluated each of the remaining architectures against a set of performance, cost, and security factors. Based on the architecture evaluations, the study team developed a set of recommendations for a coordinated, national approach to augmented GPS services that meets Federal requirements while avoiding unnecessary duplication of facilities.

Key words: Global Positioning System (GPS); differential GPS (DGPS); GPS Precise Positioning Service (PPS); GPS Standard Positioning Service (SPS)

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1
INTRODUCTION

In December of 1993, the U.S. Departments of Defense and Transportation (DOD and DOT) published a Joint Task Force report entitled *The Global Positioning System: Management and Operation of a Dual Use System* [1]. The report notes that the Federal Government is committed to selecting radionavigation systems which meet diverse user requirements for accuracy, reliability, coverage, integrity, and cost while eliminating unnecessary duplication of facilities and services. The report states that GPS is the system capable of meeting the widest range of military and civilian navigation and positioning requirements. It further notes that with the implementation of augmented GPS, several radionavigation systems currently provided and used by the U.S. Coast Guard (USCG), the Federal Aviation Administration (FAA), and the DOD could be phased out.

To satisfy many user requirements, GPS must be augmented with correction information that is applied by the user to standard civilian GPS signals. Currently, several government operating administrations, such as USCG and FAA, and private industry, including broadcasting companies and satellite service providers, are developing augmented GPS systems for various uses. The Joint Task Force report concludes:

> "Because several augmentation alternatives are under development to support multiple applications, a study of all such alternatives is required to develop an optimum integrated system to provide augmented GPS services."

This report documents the results of the recommended study of alternative augmented GPS systems.

1.1 Objective

The objective of the study was to evaluate the capabilities of augmented GPS systems and determine the optimum integrated system for meeting the navigation and positioning requirements of Federal land, marine, aviation, and space users. Augmented GPS systems may also meet most, if not all, of the positioning requirements of public and private users outside the DOT.

1.2 Scope

The recommendations of this report provide an independent expert opinion to assist DOT in determining which GPS augmentation(s) should be implemented. Factors bearing on the recommendations include:

- Ability of GPS augmentations to meet Federal user navigation and positioning requirements.
- Federal development and deployment cost.
- User cost.
- Ability of GPS augmentations to meet user safety and national security requirements.

1.3 Study Participants

Using an existing Federal Highway Administration (FHWA) contractual relationship, the DOT engaged the services of the Institute for Telecommunication Sciences (ITS) of the National Telecommunications and Information Administration (NTIA) to conduct the study. ITS provided a broad background in communication systems, navigation systems, systems planning and analysis, standards development, and spectrum management. To augment its expertise, ITS obtained the services of additional technical specialists. The U.S. Army Topographic Engineering Center (TEC) provided technical expertise and experience with the development of GPS and positioning and navigation systems. DOT's Volpe National Transportation Systems Center added extensive overall knowledge of transportation systems. Overlook Systems Technologies, Inc. furnished expertise on aviation systems and FAA requirements. Representatives from these organizations formed a study team, led by ITS, that carried out the study. Study team meetings provided opportunity for input from other agencies. Study oversight was provided by a Study Review Board representing the Office of the Secretary of Transportation, FHWA, DOT's Research and Special Programs Administration, FAA, USCG, DOD, and the National Oceanic and Atmospheric Administration. The Study Review Board appointed a Working Group to support the efforts of the study team.

1.4 Study Tasks

The study was broken down into the following tasks:

1) Identification of the requirements of Federal land, marine, aviation, and space users for navigation and positioning, including geophysical positioning, geodetic surveying, resource mapping, timing, and meteorological and ionospheric monitoring.

2) Evaluation of Federal and private GPS augmentations and examination of foreign augmentations for meeting these requirements.

3) Review of the susceptibility of GPS augmentations to malicious or hostile use.

4) Evaluation of the data formats provided by the Radio Technical Commission for Maritime Services (RTCM) and RTCA, Inc. for possible standardization.

5) Recommendation of which GPS augmentation(s) should be employed to satisfy Federal requirements without compromising national security.

The results of these tasks are described in the following sections of this report. Definitions of acronyms, abbreviations, and terms used throughout this report are contained in Appendices A and B.

1.5 Study Approach

The study began with a detailed examination of the current and future navigation and positioning requirements of Federal land, marine, aviation, and space users. The primary sources of requirements information consisted of the following:

- Responses from Federal agencies to a Secretary of Transportation request for statements of intended uses for GPS.

- A workshop for Federal GPS users, conducted by TEC and ITS.

- Responses from Federal agencies to a survey generated and distributed by the study team.

Concurrent with the requirements analysis, the study team researched existing and planned augmented GPS systems. Systems investigated included Federal, private, and foreign systems. Eighteen systems were identified as potential alternatives to meet Federal requirements for navigation and positioning. The study team selected 11 of the 18 systems for detailed evaluation. This selection was based on technical feasibility, capability of meeting user requirements, and current implementation or likely implementation in the near future.

The study team subjected the 11 candidate systems to a more detailed analysis using a specially constructed, two-stage decision matrix. In the first stage of the decision matrix, the study team listed the detailed performance requirements of Federal users and evaluated the ability of each of the candidate systems to meet these requirements. From this stage of the decision analysis, the study team determined that no single existing or planned augmented GPS system was capable of meeting all user requirements.

With this determination made, the study team proposed potential composite architectures, comprised of combinations of these 11 systems. These architectures were generated to satisfy as many user requirements as possible.

The study team evaluated these architectures using the second stage of the decision matrix, which constituted a modified version of a classic, multi-attribute, utility analysis. The second stage of the matrix consisted of a model with three major parameters: Performance, Cost, and Security. Each parameter was further subdivided into a number of factors, and weights were assigned to each of the factors. Each factor was then assigned a relative score ranging from 100 for the best architecture to 0 for the worst architecture. Scores for the potential architectures were compared to help the study team reach its conclusions.

2

FEDERAL USER REQUIREMENTS FOR NAVIGATION AND POSITIONING

This section identifies navigation and positioning requirements for Federal agencies serving transportation and non-transportation users. Information to support this effort was collected from:

- *The Global Positioning System: Management and Operation of a Dual Use System* [1].
- *1992 Federal Radionavigation Plan* [2].
- *DRAFT 1994 Federal Radionavigation Plan* [3].
- Federal GPS User's Workshop and User Survey, conducted by TEC and ITS in March 1994. Appendix C contains a list of the agencies contacted and a copy of the user survey.
- *DRAFT National Program Plan for Intelligent Vehicle-Highway Systems* [4].
- A thorough review of the literature in the field, including numerous articles, reports, and studies.
- Interviews with and field visits to Federal GPS users and GPS receiver manufacturers.
- Attendance at the XXth Congress of the International Federation of Surveyors (FIG), Melbourne, Australia, March 27–April 1, 1994; the Institute of Electrical and Electronics Engineers (IEEE) Position Location and Navigation Symposium (PLANS), Las Vegas, Nevada, April 11–15, 1994; Differential Satellite Navigation Systems 1994 (DSNS '94), London, England, April 17–21, 1994; and the Institute of Navigation (ION) 50th Annual Meeting, Colorado Springs, Colorado, June 6–8, 1994.

Although Federal users described many different requirements, the study team found that nearly all users specified requirements for accuracy, integrity (time to alarm), availability, and coverage. Requirements in these common areas provide a key means for discriminating between the various augmentation systems that are described and evaluated in Sections 3 and 4. Requirements are identified in the following sections for land, marine, air, and space transportation users and for non-transportation users.

2.1 Land Transportation Requirements

Navigation and positioning requirements for land transportation are divided into two categories:

1) Support of Intelligent Vehicle Highway Systems (IVHS).

2) Support of railroad traffic management.

IVHS. The primary goals of IVHS are improved safety and more efficient use of the existing infrastructure. Thousands of lives and billions of dollars are expected to be saved each year through the use of IVHS. In 1991, the U.S. government committed itself to IVHS by allocating $659 million over six years under the Intermodal Surface Transportation Efficiency Act [5]. There are six major IVHS program areas:

- Traffic Management — includes systems which collect and process real-time traffic information to control adaptive signals, ramps, and signs.

- Traveler Information — includes systems which provide information on location of vehicles and services, traffic conditions, and preferred routes.

- Vehicle Control — includes systems which monitor vehicle position/velocity and road conditions to avoid collisions and automate certain aspects of vehicle operation.

- Public Transportation — includes systems which optimize the movement of buses and trains through traffic and deliver location information to transit users and fleet managers.

- Rural Transportation — includes systems which provide navigation aids, deliver information on dangerous weather or road conditions, and transmit a distress alert in case of an accident or breakdown.

- Commercial Vehicle Operations — includes systems which provide automated vehicle identification/automated vehicle location (AVI/AVL) to improve dispatching, fleet management, and monitoring of hazardous materials transport.

Navigation and positioning requirements for IVHS applications within these program areas are still under study and not yet fully defined. Known requirements are summarized in Table 2-1.

Table 2-1. IVHS Navigation and Positioning Requirements

IVHS Application	Accuracy (2 drms)	Time to Alarm	Availability	Coverage Area
Navigation and Route Guidance	5-20 meters	1-15 seconds	99.7%	nationwide
Mayday/Incident Alert	5-30 meters	1-15 seconds	99.7%	nationwide
Fleet Management (AVI/AVL)	25-1500 meters	1-15 seconds	99.7%	nationwide
Automated Bus/Rail Stop Announcement	5-30 meters	1-15 seconds	99.7%	nationwide
Vehicle Command and Control	30-50 meters	1-15 seconds	99.7%	nationwide
Collision Avoidance: Control	1 meter	1-15 seconds	99.7%	critical locations
Collision Avoidance: Hazardous Situation	5 meters	1-15 seconds	99.7%	critical locations
Accident Data Collection	30 meters	1-15 seconds	99.7%	nationwide
Infrastructure Management	10 meters	1-15 seconds	99.7%	nationwide

Railroads. Most railroads manage traffic through the use of timetables, block signaling, or centralized traffic control. Block signaling involves the use of signals which are set when a section of track is occupied by a train. Centralized traffic control allows a dispatcher to control train movement from a distant location by the remote monitoring of track circuits and automatic route interlocking.

Several critical elements of advanced train control systems, including positive train control and positive train separation, have been tested or are under development by the railroad industry. These advanced systems use the knowledge of train location and speed, the input from a variety of railway sensors, and a data communication network to manage railroad traffic more effectively. These systems increase train safety and improve the operating efficiency of the railroad system.

The developing navigation and positioning requirements for railroad applications are summarized in Table 2-2. These requirements have been gathered from industry sources and have not yet been validated. "Train Position Tracking" refers to determining the position of each end of a train with respect to a block of track. Such a relatively gross tracking capability provides a primarily economic benefit to a railroad in maximizing the utilization of a section of track. "Train Control" refers to the dynamic supervision of multiple trains on a known track structure which may include parallel tracks and numerous switches. The stringent accuracy requirement for train control stems from the need to distinguish between parallel tracks that may be spaced as close as 3.8 m (12.5 ft) center-to-center. Collision avoidance, or "positive train separation," is an aspect of train control.

Table 2-2. Railroad Navigation and Positioning Requirements

Railroad Application	Accuracy (2 drms)	Time to Alarm	Availability	Coverage Area
Train Position Tracking	10-30 meters	5 seconds	99.7%*	nationwide
Speed Determination	±1 km/hour for speeds < 20 km/hour ±5% for speeds ≥ 20 km/hour	5 seconds	99.7%	nationwide
Train Control	1 meter	less than 5 seconds†	100%	nationwide
Automated Road Vehicle Warning at Railroad/Road Grade Crossings	1 meter	less than 5 seconds	100%	nationwide

*Some sources believe that this requirement can be relaxed.
†This requirement may need to be more stringent for high speed passenger rail applications.

2.2 Marine Transportation Requirements

The 1992 FRP describes four major phases of marine transportation: inland waterway, harbor/harbor approach, coastal, and ocean. Navigation and positioning requirements for inland waterways have not yet been defined by USCG or the marine community, but requirements for the other three phases are summarized in Table 2-3.

Table 2-3. Marine Navigation and Positioning Requirements

Marine Application	Accuracy (2 drms)	Time to Alarm	Availability	Coverage Area
Harbor/Harbor Approach; Large Ships and Tows	8-20 meters	6-10 seconds	99.7%	U.S. harbors and approaches
Harbor/Harbor Approach; Smaller Ships	8-20 meters	6-10 seconds	99.9%	U.S. harbors and approaches
Harbor/Harbor Approach; Resource Exploration	1-3 meters	5 seconds	99.0%	U.S. harbors and approaches
Coastal; All Ships	460 meters (0.25 nautical miles)	not specified	99.7%	U.S. coastal waters
Coastal; Recreation Boats and Other Smaller Vessels	460-3700 meters (0.25-2 nautical miles)	not specified	99.0%	U.S. coastal waters
Ocean; Safety of Navigation	3700-7400 meters (2-4 nautical miles)	not specified	99.0%	worldwide
Ocean; All Craft	1800-3700 meters (1-2 nautical miles)	not specified	99.0%	worldwide

2.3 Air Transportation Requirements

The 1992 FRP describes two basic phases of air transportation: en route/terminal and approach/landing. The en route/terminal phase includes all portions of flight to within 18,500 meters (10 nautical miles) of the runway. It includes oceanic, domestic, and terminal subphases. The approach/landing phase includes that portion of flight conducted immediately prior to touchdown. The navigation and positioning requirements for air transportation are summarized in Table 2-4. The use of aircraft for applications other than transportation, such as aerial surveying and mapping, is discussed in Section 2.5. Programs are underway to study the use of GPS for Automatic Dependent Surveillance and ground positioning and tracking on airport surfaces, but no requirements had been validated at the time of this study.

Table 2-4. Air Navigation and Positioning Requirements

Air Transport Category	Accuracy (2 drms)	Time to Alarm	Availability	Coverage Altitude
En Route Oceanic	23 km (12.6 nautical miles)	30 seconds	99.977%	8400-12,200 m (27,500-40,000 ft)
En Route Domestic	1000 m	10 seconds	99.977%	150-18,300 m (500-60,000 ft)
Terminal	500 m	10 seconds	99.977%	150-5500 m (500-18,000 ft)
Approach/Landing: Non-Precision	100 m	10 seconds	99.977%	75-900 m (250-3000 ft)
Approach/Landing: Precision Category I	horiz: 17.1 m vert: 4.1 m	6 seconds	99.999%	30-900 m (100-3000 ft)
Approach/Landing: Precision Category II	horiz: 5.2 m vert: 1.7 m	2 seconds	99.999%	15-900 m (50-3000 ft)
Approach/Landing: Precision Category III	horiz: 4.1 m vert: 0.6 m	2 seconds	99.999%	0-900 m (0-3000 ft)

2.4 Space Transportation Requirements

The 1992 FRP divides space missions into three phases: ground launch, on-orbit, and reentry and landing. Space transportation applications related to these phases include:

- Control and navigation of the U.S. Space Shuttle, other launch vehicles, automated spacecraft, and interplanetary or lunar spacecraft returning to Earth orbit.
- Determination of spacecraft position, altitude, and velocity.
- Guidance of spacecraft in the vicinity of other spacecraft or orbiting platforms (e.g. rendezvous).

Navigation and positioning requirements for space transportation remain under study and are expected to be updated in the 1994 FRP.

2.5 Non-Transportation Requirements

Federal users have several types of non-transportation applications that require precise positioning and timing information. These include:

- Remote Sensing — Space-based remote sensing techniques are commonly used to gather weather data and monitor environmental conditions.

- Search and Rescue — Fixed-wing aircraft and helicopters are routinely used in coordination with ground crews to help locate missing persons or the site of an accident.

- Aerial Surveillance — Fixed-wing aircraft and helicopters are routinely used to observe ground activity for natural resource management, emergency management, and law enforcement purposes.

- Photogrammetry — Aerial photography can be used to produce highly accurate maps. This technique depends on precise knowledge of the position of the aircraft and the camera exposure station.

- Surveying — Geodetic surveying measures the size, shape, and gravity field of the earth, and provides the control datums to which all other surveys are referenced. Surveying is also used to establish property boundaries, provide control points for large construction projects, support marine dredging operations and buoy placement, measure the physical dynamics of the earth's crust, map the relief and features of the earth's surface, and gather geospatial data (data with geographic coordinates).

- Time and Frequency Metrology — Precise time and frequency measurements are required for calibration and synchronization purposes by scientific laboratories, deep-space tracking stations and astronomical observatories, telecommunication network operators, and electrical power utilities.

Requirements for these applications are summarized in Table 2-5.

Table 2-5. Non-Transportation Positioning/Timing Requirements

Application	Accuracy (2 drms)	Time to Alarm	Availability	Coverage Area
Remote Sensing (space-based)	under study	under study	under study	worldwide
Search and Rescue	10 m	not specified	not specified	nationwide
Aerial Surveillance	1-5 m	minutes to hours	95-99%	nationwide to worldwide
Photogrammetry	2-5 cm	minutes	not specified	nationwide
Geodetic Control Surveys	horiz: 2-40 cm vert: 1 cm	hours (data post-processed)	99%	sites nationwide
Boundary Surveys	horiz: 0.02-1 m vert: none	hours (data post-processed)	99%	sites nationwide
Hydrographic Surveys:				
Offshore Dredging	horiz: 1-6 m vert: 4-10 cm	hours (data post-processed)	99%	waterways nationwide
Inshore Dredging	horiz: 1-6 m vert: none	hours (data post-processed)	99%	waterways nationwide
Channel Conditions	horiz: 1-6 m vert: 10-20 cm	hours (data post-processed)	99%	waterways nationwide
Offshore Geophysical	horiz: 2-10 m vert: 10 cm	hours (data post-processed)	99%	waterways nationwide
Deformation Surveys	horiz: 1-2 mm vert: 1 mm	hours (data post-processed)	99%	selected sites nationwide
Topographic Surveys	horiz: 2 cm vert: 1 cm	hours (data post-processed)	99%	sites nationwide
Master Plan Mapping	horiz: 0.2-5 m vert: 1-20 cm	hours (data post-processed)	99%	sites nationwide
Flood Plain Mapping	horiz: 1-5 m vert: 1-20 cm	hours (data post-processed)	99%	sites nationwide
Resources Mapping	horiz: 1-10 m vert: 0.4-1 m	hours (data post-processed)	99%	sites nationwide

Table 2-5. Non-Transportation Positioning/Timing Requirements, Continued

Hydrology Study	horiz: 1-10 m vert: 20-40 cm	hours (data post-processed)	99%	sites nationwide
Emergency Management	horiz: 8-10 m vert: 8-10 m	minutes	99%	sites nationwide
Time and Frequency Metrology	100 nanoseconds*	not specified	not specified	worldwide

*1 sigma, not a 2 drms value.

2.6 Requirements Summary

Federal navigation and positioning requirements for accuracy, time-to-alarm, availability, and coverage area are summarized below and in Table 2-6:

Accuracy. The range of accuracy required is from 1 mm to 1000 m. The highest accuracy is required for surveying. The FAA requires only 1000 m accuracy for en route navigation, but requires 4.1 m (13.5 ft) horizontal and 0.6 m (2 ft) vertical accuracy for Category III precision approach and landing.

Time-to-Alarm. Requirements range from 1 second for certain land transportation applications to hours for post-processing applications.

Availability. Most users have a need for greater than 99.7% availability. Some railroad applications require availability of 100%. Availability of 100% is not achievable with current GPS technology and may require the development and use of systems other than GPS.

Coverage Area. Federal users require nationwide coverage both at ground level and in the volume above ground and that portion over the oceans which constitute the National Airspace System (NAS). Worldwide coverage or a seamless transition to foreign systems is highly desired.

Table 2-6. Summary of Navigation and Positioning Requirements

Mode/Application	Accuracy (2 drms)	Time to Alarm	Availability	Coverage Area
Land Transportation:				
IVHS	1-100 m	1-15 seconds	99.7%	nationwide
Railroads	1-30 m	1-5 seconds	99.7-100%	nationwide
Marine Transportation:				
Harbor Navigation	8-20 m	5-10 seconds	99-99.9%	nationwide to worldwide
Air Transportation:				
Precision Approach and Landing	horiz,vert: 1000 m to horiz: 4.1 m vert: 0.6 m	2-10 seconds	99.977-99.999%	National Airspace System
Non-Transportation:				
Aerial Surveillance	1-5 m	minutes to hours	95-99%	nationwide
Search and Rescue	10 m	not specified	not specified	nationwide
Photogrammetry	2-5 cm	minutes	not specified	nationwide
Surveying/Mapping	horiz, vert: 10 m to horiz: 1 cm vert: 1 mm	hours (data post-processed)	99%	nationwide
Time and Frequency Metrology	100 nanoseconds*	not specified	not specified	worldwide

*1 sigma, not a 2 drms value.

3

DESCRIPTION OF GPS AND AUGMENTED GPS SYSTEMS

This section describes basic GPS operation and performance. It also describes existing or proposed systems which provide correction information that can be used to augment GPS performance. These descriptions are not exhaustive and all proposed augmentations to GPS are not included. The study team targeted those systems with the potential to meet the widest possible range of user requirements.

3.1 GPS Standard Positioning Service and Precise Positioning Service

GPS is a spaced-based radionavigation system which is operated for the Federal Government by DOD and jointly managed by DOD and DOT. GPS was originally developed as a military force enhancement system and will continue to function in this role. However, GPS also provides significant benefits to the civilian community. In an effort to make GPS service available to the greatest number of users while ensuring that the national security interests of the United States are protected, two GPS services are provided. The Precise Positioning Service (PPS) provides full system accuracy primarily to U.S. and allied military users. The Standard Positioning Service (SPS) provides civilian and all other users throughout the world with a less accurate positioning capability than the PPS. A more detailed description of SPS and PPS is contained in Appendix D.

3.2 The Need for Augmentation

GPS offers substantial navigation and positioning capabilities, but SPS and PPS do not meet many of the user requirements for accuracy, time to alarm, availability, and coverage that were identified in Section 2. Numerous systems have been developed or proposed to augment the performance of GPS to meet the requirements of various users. These systems provide additional data that are used to compensate for errors and enhance the capabilities of GPS. For many applications, GPS does not meet user requirements in three critical areas:

Accuracy. The requirements of many users and applications require substantially better accuracy than can be provided by SPS or even PPS. The usefulness of any GPS system, regardless of the applications, will be enhanced as accuracy is improved.

Integrity (Time to Alarm). In many applications, especially those that involve the safety of life, it is extremely important that the end user be notified of system failure

promptly. In the approach phase of aircraft flight, a failure notification time of 2 seconds or less is required to ensure safe operation.

Availability. The availability of the GPS constellation does not meet all user requirements. Availability of 99.999% is required for some aviation applications and 100% is specified for railroad collision avoidance. Safety of life is the reason for these stringent requirements.

In addition to these critical areas, other important considerations for augmented GPS systems include the following:

Coverage Area. Users require augmentation data throughout a specified coverage area, which may range from local to worldwide.

Security. Security refers to both National security and user safety. National security involves the ability to deny access to the system for hostile or unauthorized use. Security from a safety perspective involves vulnerability of the system to interference. Both aspects of security are described in more detail in Appendix E.

Cost. Cost considerations include purchase and installation of the system infrastructure, system operation and maintenance, purchase of user equipment, and any subscriber or service fees.

Data Link Characteristics. Data link characteristics describe the method and mode of transmission of augmentation data to the user. This includes radio frequency (RF) spectrum, bandwidth allocation, and modulation techniques. To date no RF spectrum has been allocated specifically for GPS augmentations, so individual providers use various portions of the spectrum. From a spectrum management perspective, there may be utility in allocating spectrum for GPS augmentation applications.

Data Format. System developers have identified four data formats for broadcast of augmented GPS data:

1) RTCM SC-104 — Radio Technical Commission for Maritime Services Special Committee 104.

2) RTCA-WAAS — RTCA, Inc., Wide Area Augmentation System (WAAS).

3) RTCA-LADGPS — RTCA, Inc., Local Area Differential GPS (LADGPS).

4) Proprietary.

An additional format standard, Receiver Independent Exchange (RINEX), is used to exchange data for post-processing. Appendix F contains an analysis and comparison of the RTCM and RTCA data formats.

Time Frame of Availability. GPS system benefits are substantial and making these benefits available as soon as possible to all potential users is of great importance. System development and deployment schedules must be examined and evaluated in light of the benefits that can be achieved by early deployment of augmentation systems.

3.3 Functional Descriptions of Augmented GPS Systems

Of the GPS augmentations developed or proposed, this study focused on those augmentations which have either been implemented, are likely to be implemented, or are system concepts that alone or in combination with other systems have a likelihood of meeting most user requirements. The augmentations studied included:

1) Low Frequency (LF)/Medium Frequency (MF) Radiobeacon System — broadcasts local augmentation data from beacons in the marine radionavigation spectrum between 283.5 and 325 kHz. USCG has begun installing beacons and associated master stations to cover coastal waters, inland waterways (in conjunction with the U.S. Army Corps of Engineers), and harbor/harbor approach areas of the U.S.

2) Commercial Frequency Modulation (FM) Subcarrier System — broadcasts local augmentation data from existing privately-owned FM broadcast radio stations.

3) Wide Area System (WAS) 1 — broadcasts augmentation data and a supplementary ranging signal from geosynchronous Earth orbit (GEO) satellites on L1 for en route navigation through Category I precision approach, and broadcasts local augmentation data for Category II/III precision approach through the LADGPS portion of the system.

4) WAS 2 — broadcasts limited augmentation data and a supplementary ranging signal from GEO satellites on L1 for en route navigation through non-precision approach, and broadcasts local augmentation data for Category I/II/III precision approach through the LADGPS portion of the system.

5) WAS 3 — broadcasts augmentation data and a supplementary ranging signal from GEO satellites on a frequency other than L1 for en route navigation through Category I precision approach and broadcasts local augmentation data for Category II/III precision approach through the LADGPS portion of the system.

6) WAS 4 — broadcasts encrypted augmentation data and an encrypted supplementary ranging signal from GEO satellites on L1 for en route navigation through

Category I precision approach, and broadcasts local augmentation data for Category II/III precision approach through the LADGPS portion of the system.

7) WAS 5 — broadcasts proprietary augmentation data from a commercial GEO satellite system.

8) WAS 6 — broadcasts proprietary augmentation data from a commercial low Earth orbit (LEO) satellite system.

9) Continuously Operating Reference Station (CORS) System — monitors GPS signals at precisely surveyed reference sites and stores the data for post-processing support of local geodetic surveying, mapping, geographic information systems (GIS), and other applications.

10) Loran-C System — broadcasts augmentation data or supplementary navigation signals from an existing network of LF transmitters that are used for military and civil radionavigation.

11) Advanced Communications Technology Satellite (ACTS) — broadcasts augmentation data from a satellite using steerable spot beams to specified geographic areas. The experimental ACTS was launched by the National Aeronautics and Space Administration (NASA) in September 1993.

12) Global Orbiting Navigation Satellite System (GLONASS) — broadcasts navigation signals from a planned 24 satellite constellation similar to GPS.

13) Expanded GPS Constellation — broadcasts navigation signals from additional GPS satellites.

14) Inertial Navigation System (INS) — provides platform attitude, position, and velocity information that can be integrated with the GPS navigation solution.

15) Sign Post System — provides position information from electronic ground-based markers that can be integrated with the GPS navigation solution.

16) Pseudolite System — broadcasts supplementary navigation signals from ground-based transmitters that imitate a GPS satellite.

17) Dead Reckoning and Map Matching System — provides position information based on measurements of distance and time and comparisons to a map database to supplement GPS navigation solutions.

18) Omega System — broadcasts data from an existing network of very low frequency (VLF) transmitters used for military and civil navigation, positioning, and timing.

The study team selected 10 augmented GPS systems from among these alternatives for detailed evaluation. An eleventh system (listed as number 2 below) was added which was an expanded version of the LF/MF radiobeacon system (listed as number 1 above). The selection was based on technical feasibility, potential for meeting user requirements, and implementation timetable. The systems selected were:

1) LF/MF Radiobeacon System (coverage over waterways).
2) LF/MF Radiobeacon System (expanded to provide complete coverage of the U.S.).
3) Commercial FM Subcarrier System.
4) WAS 1.
5) WAS 2.
6) WAS 3.
7) WAS 4.
8) WAS 5.
9) WAS 6.
10) CORS System.
11) Loran-C System.

The following systems were not considered further in this study:

1) ACTS.
2) GLONASS.
3) GPS Expanded Constellation.
4) INS.
5) Sign Post System.
6) Pseudolite System.
7) Dead Reckoning/Map Matching System.
8) Omega System.

The rationale for eliminating these systems is provided in the following paragraphs:

1) ACTS — Since ACTS has been developed for testing advanced communication concepts, it is not likely to provide a feasible augmentation scheme in a time frame considered reasonable in this study. This system is experimental and does not offer sufficient data for evaluation in the decision matrix.

2) GLONASS — This system does not offer a sufficient history of reliable operation to guarantee that integrity and availability requirements can be met by the GLONASS augmentation to GPS.

3) GPS Expanded Constellation — Insufficient data exist to verify the capabilities of this system. This expansion would also be costly and would take significant time to implement.

4) INS — As a stand-alone augmentation to GPS, INS does not satisfy the requirements of many Federal users.

5) Sign Post — As a stand-alone augmentation to GPS, sign posts do not satisfy the requirements of many Federal users.

6) Pseudolite — Research in the development of pseudolites is progressing rapidly, but at the time of this study, pseudolites had not been sufficiently developed to verify their capabilities.

7) Dead Reckoning/Map Matching — As a stand-alone augmentation to GPS, dead reckoning/map matching does not satisfy the requirements of many Federal users.

8) Omega — As a stand-alone augmentation to GPS, Omega does not satisfy the requirements of many Federal users.

For a further description of some of these systems, see Appendix G.

The 11 selected augmented GPS systems listed above are described below. The descriptions of these systems address accuracy, integrity (time to alarm), availability, and the additional considerations detailed in Section 3.2.

3.3.1 USCG LF/MF Radiobeacon System

The USCG broadcasts localized pseudorange corrections from a network of LF/MF-band marine radiobeacons. The two control centers, one for each coast of the U.S., will continuously poll the monitor and reference stations to determine the status and integrity of the broadcast. In case of technical difficulty, the control centers will resolve the problem remotely or immediately dispatch technicians to the affected site. A block diagram of the system is shown in Figure 3-1.

The system is implemented through the existing marine non-directional beacon infrastructure. The RTCM data format [6] is used for the broadcast of differential GPS (DGPS) corrections and related information. Normally, the data transmission rate will be 100 bps except along critical waterways where the transmission rate will be 200 bps.

Accuracy. A horizontal accuracy of 5 m, 2 drms, is specified by USCG for all coverage areas. However, operating beacons consistently provide horizontal accuracies of 3 m and although a horizontal system, vertical accuracy on the order of 5 m can be expected. Continuous velocity accuracy of the system (vessel speed over ground) is better than 5 cm/sec (0.1 knots).

Integrity (Time to Alarm). Based upon the Type 9 message of the RTCM format and the data rate of 200 bps, the time to alarm is 4.2 seconds.

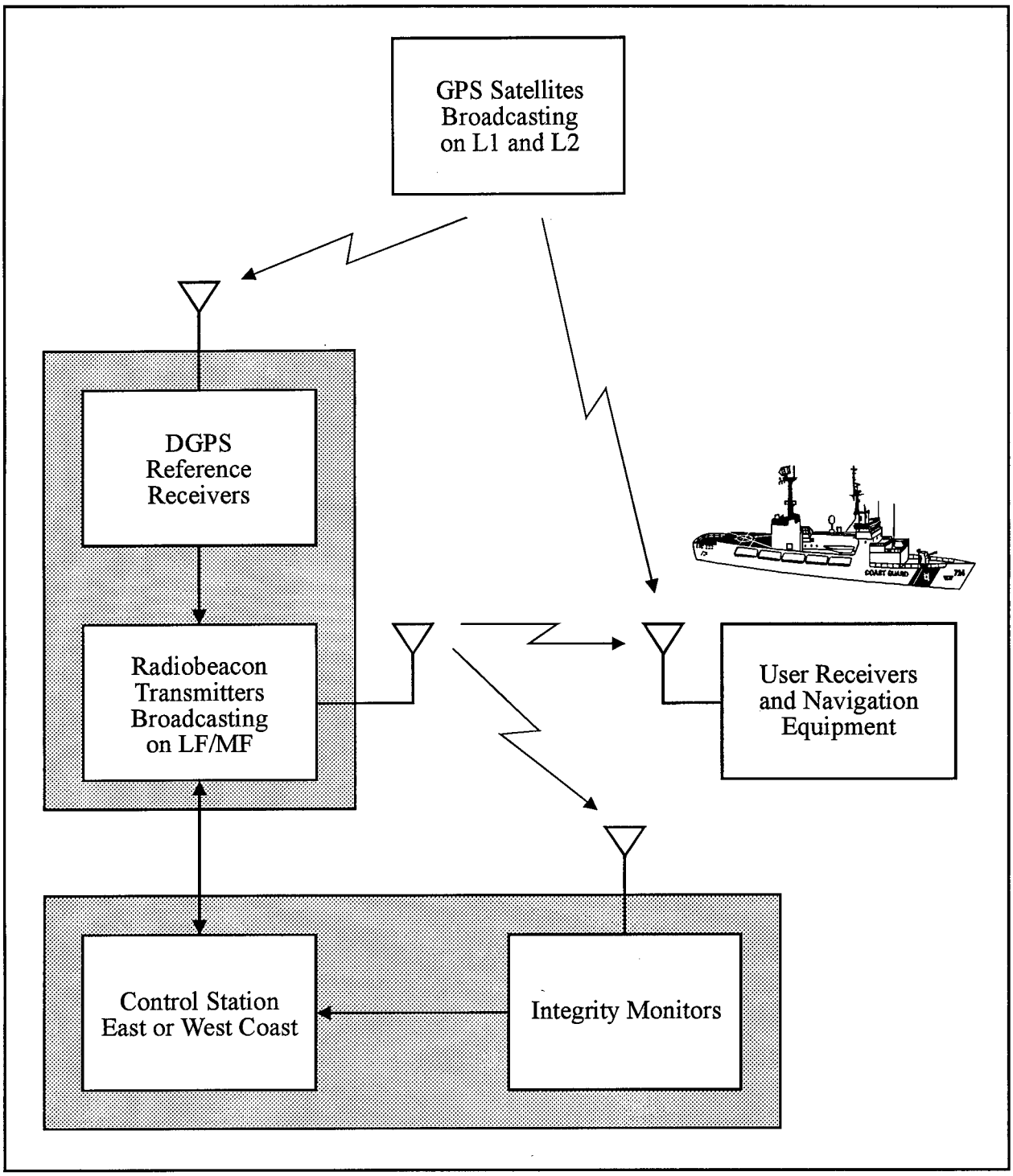

Figure 3-1. Block diagram of USCG LF/MF radiobeacon system.

Availability. Availability of 99.7% is specified in general and 99.9% is specified for critical waterways. This higher availability is achieved through redundant coverage. The availability may be further increased by decreasing the distance between reference stations.

Coverage Area. The system is designed to provide coverage for all harbor/harbor approach areas and other critical waterways for which the USCG provides aids to navigation. As a result, complete coverage of the coast line of the continental U.S. (CONUS) is provided and extends out to 37 km (20 nautical miles). It is expected that in the near future this coverage will be extended to cover the complete CONUS Coastal Navigation Zone which extends out to 93 km (50 nautical miles). Figure 3-2 shows the expected coverage area for the system as currently planned for deployment.

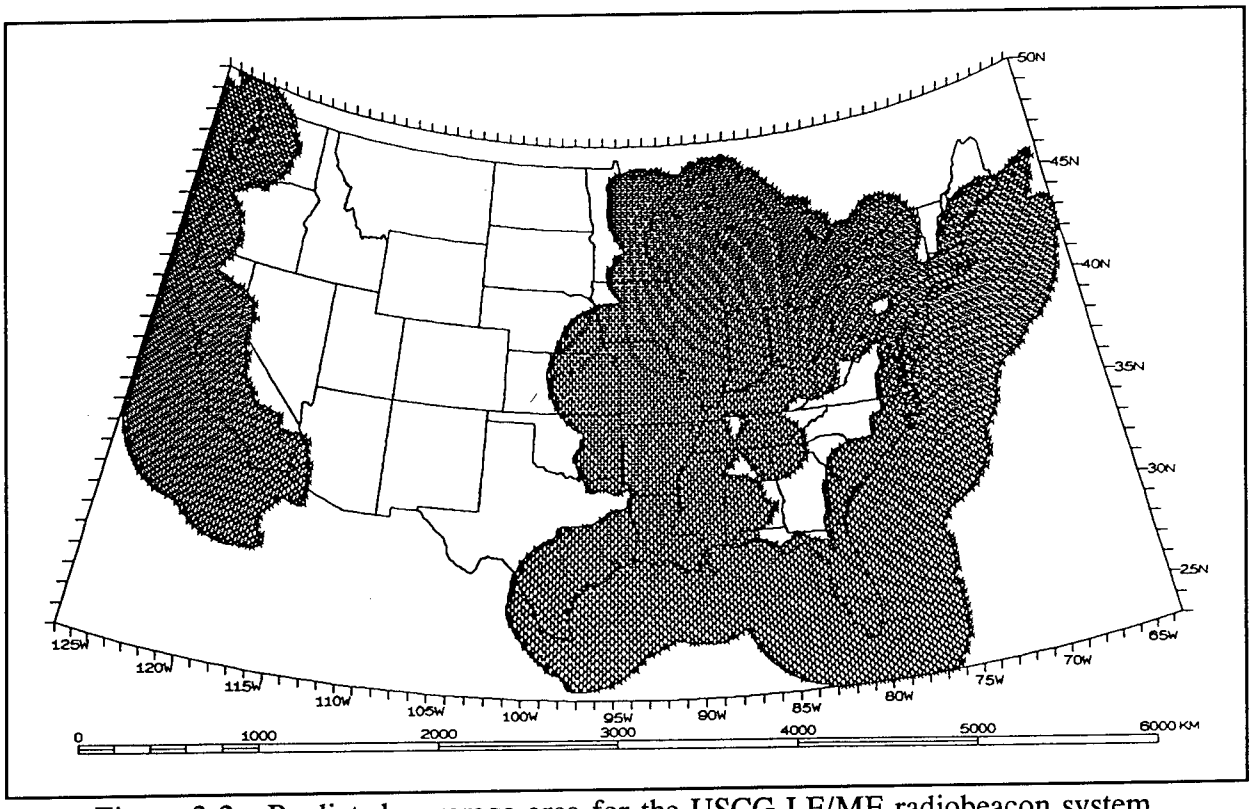

Figure 3-2. Predicted coverage area for the USCG LF/MF radiobeacon system.

Security. The system provides the same level of user safety and security as current marine radionavigation aids. The system does not employ encryption or any other user screening or security features.

Infrastructure Cost. The total cost for establishing the operational system of 61 sites is $14.2M. The annual cost for operations and maintenance (O&M) is $4.2M. The total life cycle cost over 20 years is $14.2M + 20($4.2M) = $98.2M.

User Cost. Users of the system require a LF/MF radio coupled with a DGPS-capable receiver. Current cost for low-end equipment is less than $1,000.

Data Link Characteristics. The system adds a digitally modulated minimum shift keying (MSK) subcarrier to transmissions from marine radio beacons operating in the 283.5 to 325 kHz (LF/MF) band. The LF/MF signal propagates in the groundwave mode. The signal can be received at ranges which are well beyond line of sight.

Data Format. The system broadcasts using the RTCM SC-104 format, Version 2.1. Type 9 messages are used for the GPS differential corrections. This format is supported by numerous GPS equipment manufacturers and service providers. The RTCM format has been designated for international maritime use by the International Telecommunication Union (ITU).

Time Frame of Availability. At least 12 prototype sites are operating, with a total of 61 planned to be fully operational by January 1996.

3.3.2 USCG LF/MF Radiobeacon System Expanded

With the addition of 20 to 50 beacon sites to provide nationwide coverage, this system is a nationwide expansion of the system described in Section 3.3.1. All factors described in Section 3.3.1 are identical except coverage area, infrastructure cost, and time frame of availability.

Coverage Area. The USCG Expanded (USCG(E)) System is designed to provide nationwide coverage including harbor/harbor approach areas and other critical waterways for which the USCG provides aids to navigation. Figure 3-3 shows the predicted coverage area for 41 additional beacon sites, and Figure 3-4 shows the predicted composite coverage for the original 61 beacon sites plus the 41 additional sites. Inland coverage depends on ground conductivity and the actual number of sites to achieve nationwide coverage can only be estimated at this time. Appendix H describes the expected coverage and availability of an LF/MF radiobeacon system.

Infrastructure Cost. The total cost for establishing the additional 20-50 sites is $3M to $8M. The additional annual cost for operations and maintenance (O&M) is $1M to $2M. The maximum total life cycle cost over 20 years for the USCG(E) system would be $146M.

Time Frame of Availability. It is expected that the additional 20 to 50 sites will require a total of 1 to 2 years deployment time.

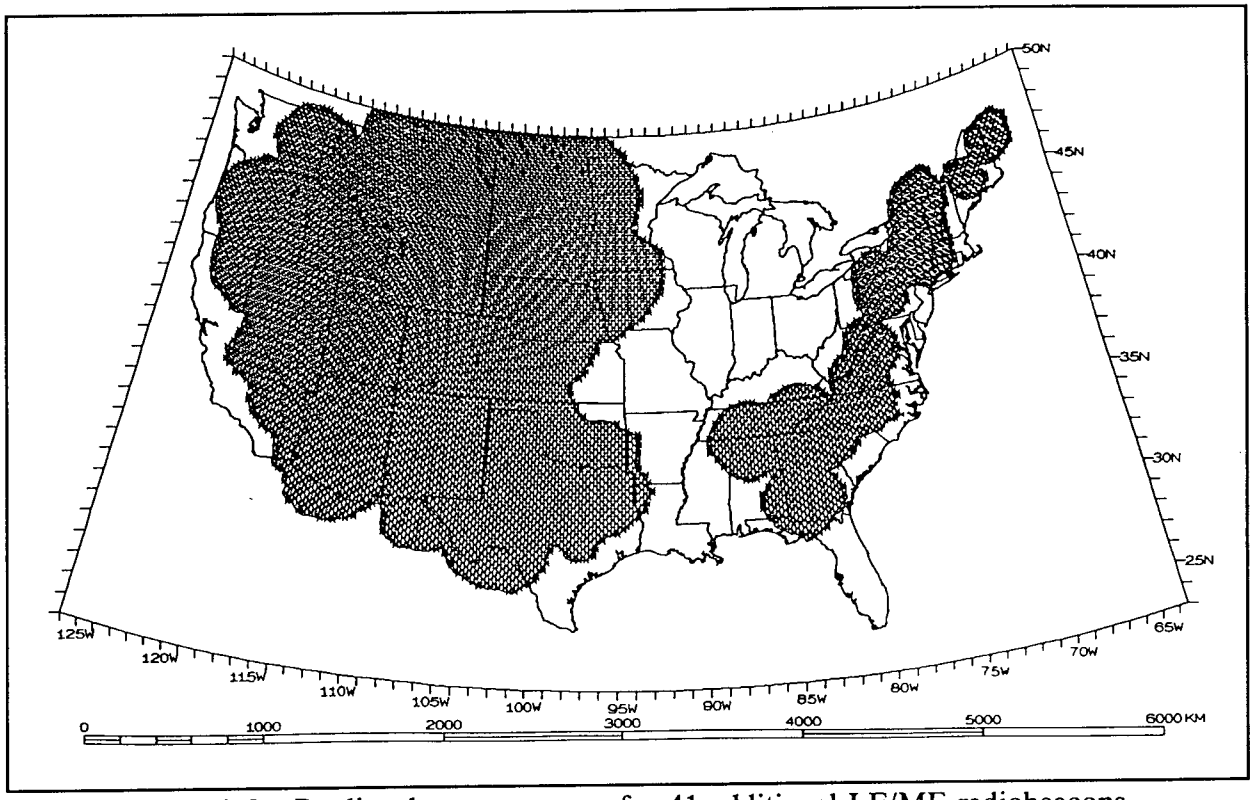

Figure 3-3. Predicted coverage area for 41 additional LF/MF radiobeacons.

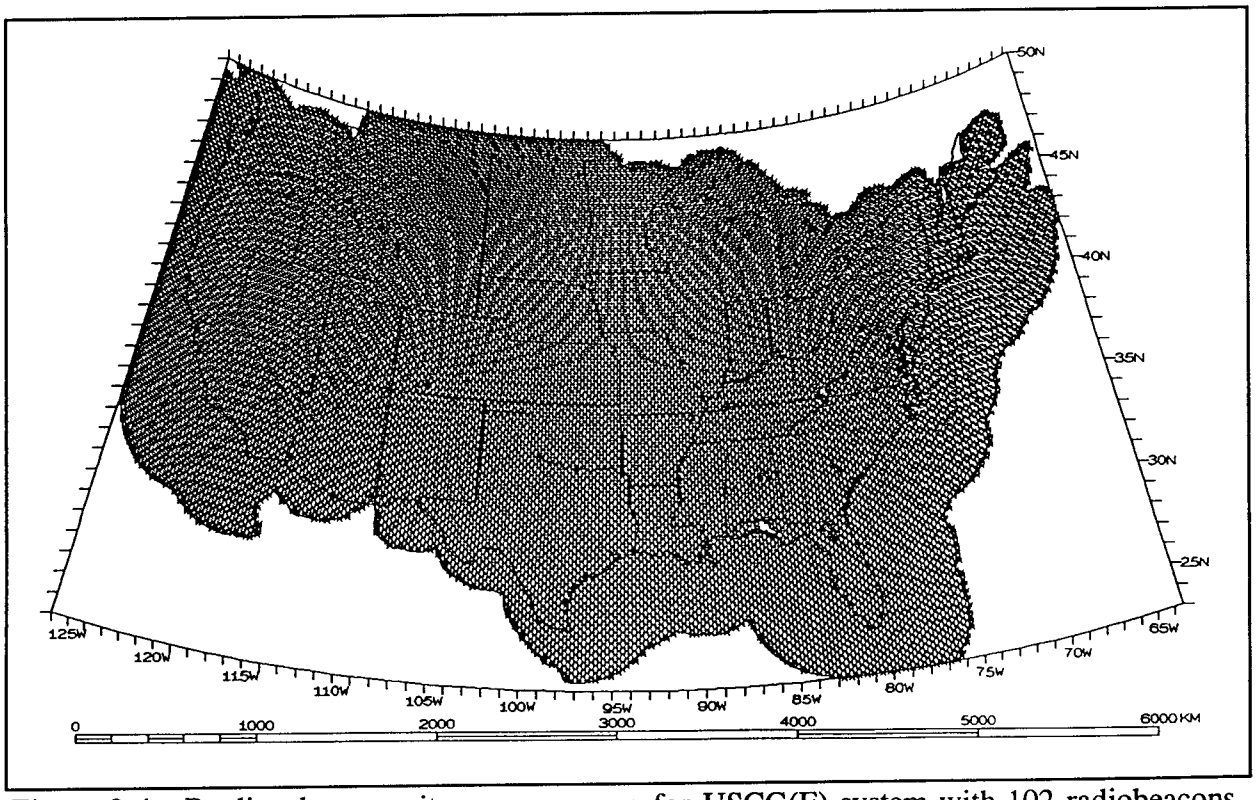

Figure 3-4. Predicted composite coverage area for USCG(E) system with 102 radiobeacons.

3.3.3 Commercial FM Subcarrier System

This system uses the existing infrastructure of FM radio station subcarriers to broadcast localized pseudorange correction factors to the user community. The system consists of a GPS reference station and one or more FM stations which broadcast the GPS corrections. A block diagram of a typical FM subcarrier system is shown in Figure 3-5. Companies providing FM subcarrier DGPS service currently contract with 300 to 400 FM stations across the Nation.

Accuracy. The accuracy provided by these types of services depends, in part, upon the level of service required and paid for by the user. Service providers offer a variety of accuracy options for the user ranging from 1 to 3 meters to several tens of meters.

Integrity (Time to Alarm). FM subcarrier systems can include integrity monitors to continuously validate that corrections remain within specified tolerances. Although current systems do not necessarily provide real-time integrity monitoring, this function is technically achievable.

Availability. Availability is a function of the maintenance schedule or the failure of independently-managed broadcast stations, the GPS reference stations, and the various data links involved. The broadcast stations used are those that operate 24 hours a day and have redundant equipment including backup power and alternate transmitters to ensure that scheduled maintenance will not generally result in an outage. The National Association of Broadcasters does not have statistics regarding FM station availability; however, it asserts that most stations do better than one hour outage per year (99.988%). FM stations have a strong financial incentive to stay operational and many stations have been on the air continuously for years. A conservative estimate predicts one day of down time every 10 years resulting in an availability of 99.97%.

Coverage Area. FM Broadcast stations cover 96% of the population and 80% of the land area of North America [7]. The coverage area of an entire subcarrier system depends upon the contractual arrangements made by the operator of the system, percent injection of the subcarrier and receiver capabilities. An example of subcarrier coverage using many Public Broadcasting System (PBS) stations for CONUS is shown in Figure 3-6.

Security. FM subcarrier systems are encrypted in order to provide a means of controlling user access to system services.

Infrastructure Cost. The infrastructure costs are borne by the service provider.

User Cost. User costs include the purchase of receiver equipment and the user service fee. User equipment for this architecture is expected to cost on the order of $500 or less and may have service fees on the order of a few dollars per day.

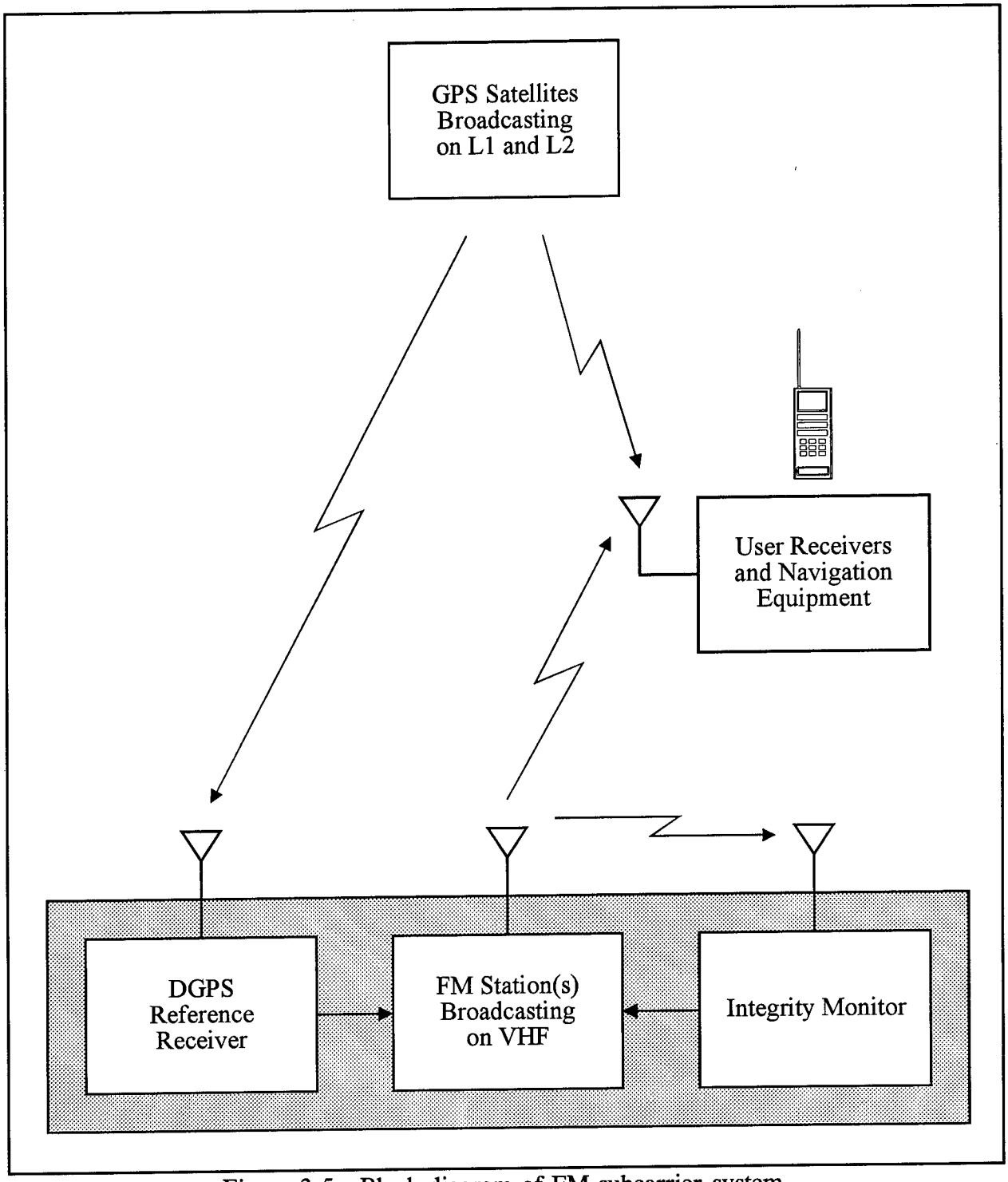

Figure 3-5. Block diagram of FM subcarrier system.

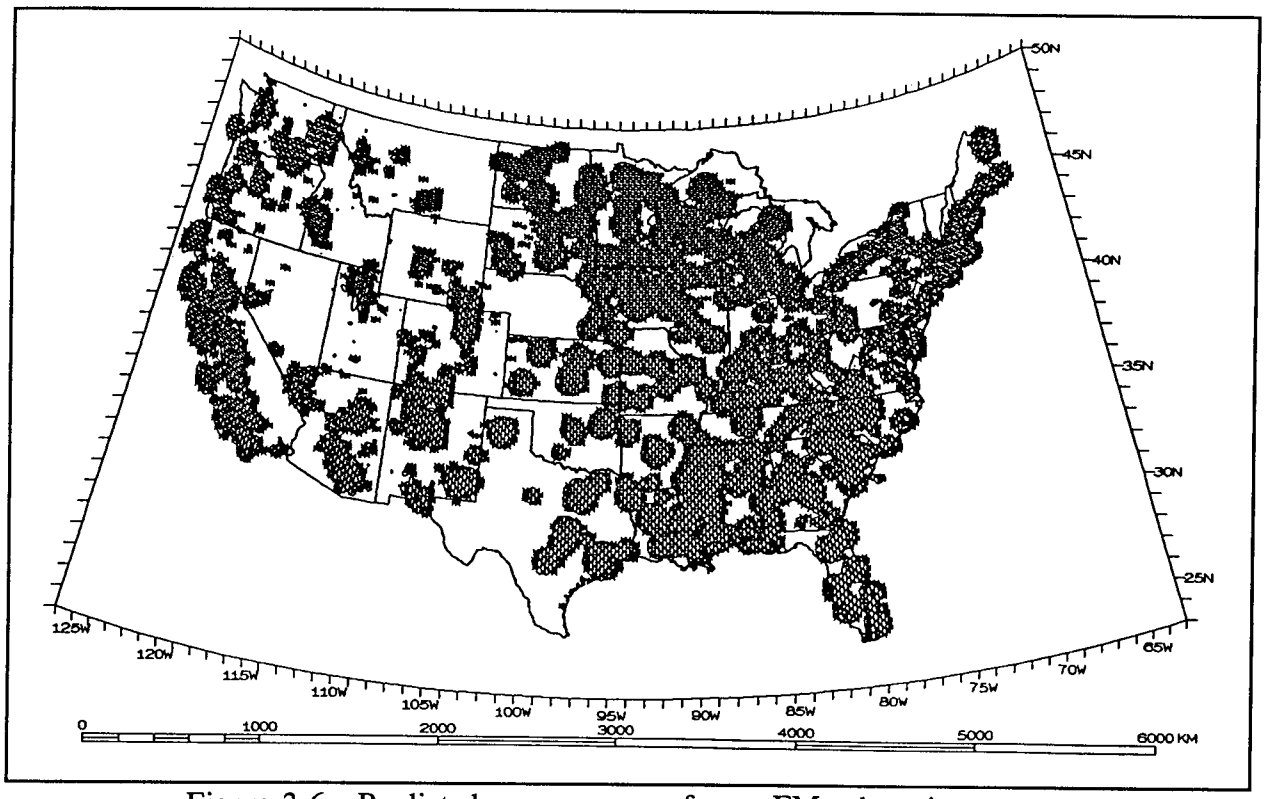

Figure 3-6. Predicted coverage area for an FM subcarrier system.

Data Link Characteristics. These systems use the Radio Data Systems (RDS) or Radio Broadcast Data Systems (RBDS-US) standard for the transmission of digital data using subcarrier modulation on broadcast FM radio stations. GPS correction data are multiplexed with other user services which are also placed on the FM subcarrier.

Data Format. A proprietary data format is used for this system. The data is translated to RTCM format to make it compatible with existing DGPS receivers. The subcarrier data structures used meet standards for FM broadcast in most countries. Other subcarrier structures can be used by these systems.

Time Frame of Availability. FM subcarrier services and systems are operational at the present time. All providers plan system and service expansions as user demands require.

3.3.4 Wide Area System 1

The Wide Area System 1 (WAS 1) has two components, FAA's Wide Area Augmentation System (WAAS) and a local area DGPS (LADGPS) system. The WAAS component satisfies accuracy, time to alarm, and availability requirements for all phases of flight down

to Category I precision approach. Category II and III precision approach requirements are satisfied by the LADGPS component of the system.

3.3.4.1 FAA WAAS

The FAA WAAS as currently planned consists of GEO communication satellites, wide area reference stations (WRSs), and wide area master stations (WMSs). The GEO satellites provide ranging signals and broadcast integrity and differential correction data. GPS satellite data are received and processed at widely dispersed WRSs. These data are forwarded to WMSs, which process the data to determine the differential corrections. GEO satellites downlink these data on the GPS L1 frequency with a modulation similar to that used by GPS.

The GEOs not only provide the WAAS information on each GPS satellite and the ionosphere, but act as additional ranging sources. Figure 3-7 is a block diagram of the FAA WAAS system.

Accuracy. The accuracy specified for the WAAS is 7.6 meters (95%) both horizontal and vertical [8].

Integrity. Integrity for the WAAS is specified in terms of probability of hazardously misleading information (HMI), time to alarm, and alarm limit. This definition of integrity is more developed than that defined for other systems since the specification for FAA applications are more demanding. For the en route through nonprecision approach operations, the WAAS specification for probability of HMI is 10^{-7} per hour; the time to alarm specified is 8 seconds; and the alarm limit is 556 meters (horizontal error) for a total system error. For the precision approach operation, the WAAS specification for probability of HMI is 4×10^{-8} per approach; the time to alarm specified is 5.2 seconds; and the alarm limit is the same as for the en route through nonprecision approach operation.

Availability. The availability of the WAAS is specified as 99.999%.

Coverage. The specified service volume is from the surface to 30,500 meters (100,000 feet) above sea level over the contiguous U.S., Alaska, Hawaii, Puerto Rico, the Pacific Ocean to Hawaii, the Atlantic Ocean off the coast of the U.S., and much of the Gulf of Mexico. This coverage is the footprint of the GEO satellite(s).

Security. This system does not use encryption methods, user access controls, or other screening.

Infrastructure Cost. The WAAS life cycle cost is estimated to be on the order of $1,139M.

User Cost. User equipment (avionics) for this architecture is expected to cost on the order of $4K for general aviation aircraft to $90K for commercial air carriers.

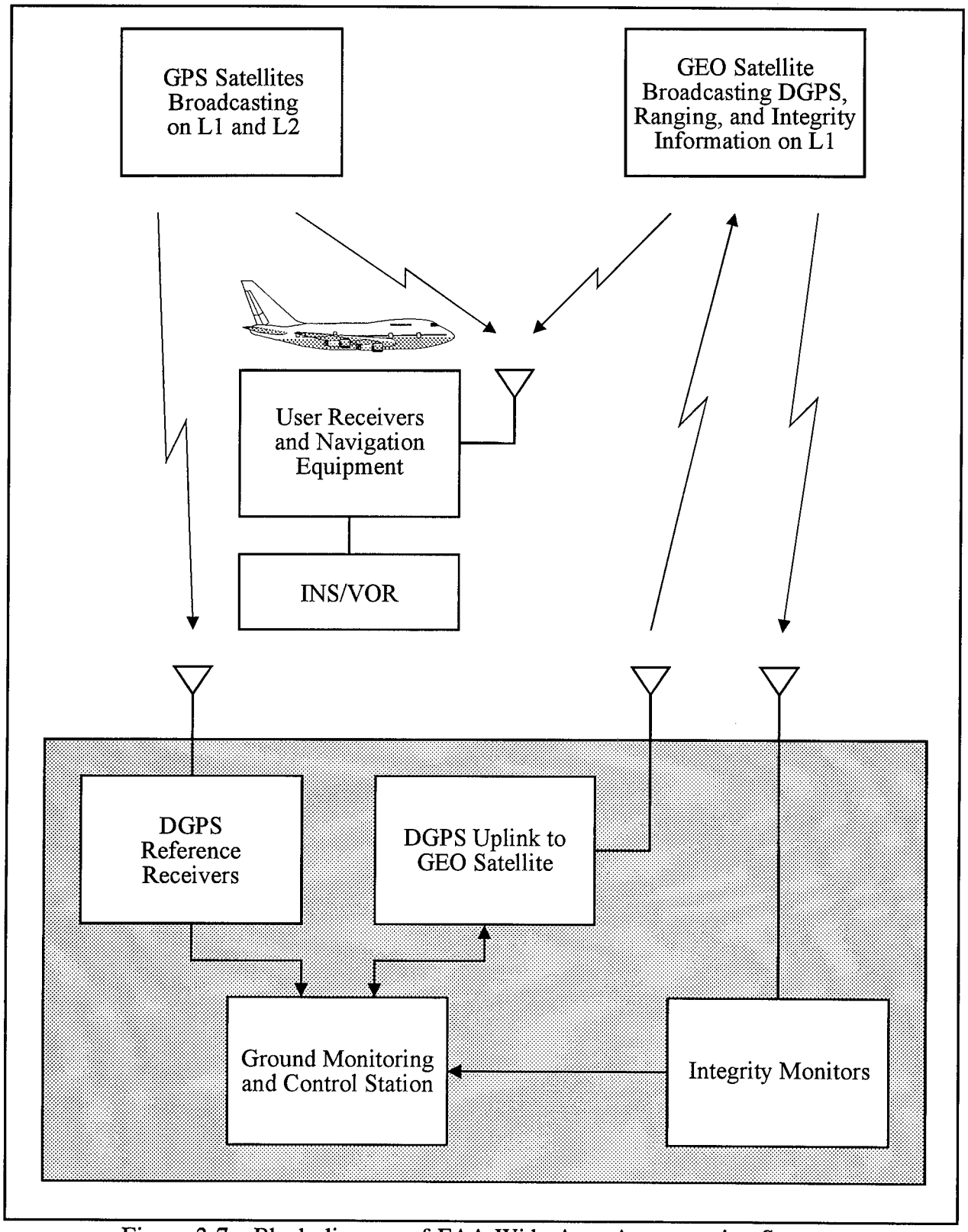

Figure 3-7. Block diagram of FAA Wide Area Augmentation System.

Data Link Characteristics. The WAAS satellites will broadcast a GPS-like spread spectrum signal on the GPS L1 frequency. The effective data rate is 250 bps versus 50 bps for GPS. The satellite navigation message will contain WAAS data (integrity data and differential corrections for accuracy), as well as navigation data so that the satellite can be a ranging source.

Data Format. The WAAS portion of the data link will use the RTCA, Inc. WAAS format [9].

Time Frame of Availability. The Phase 1 portion of WAAS, which will provide integrity and availability, is scheduled to be operational by the end of 1997. The Phase 2 portion of WAAS, the accuracy component, is scheduled to be implemented by 1998.

3.3.4.2 FAA LADGPS System

Local area systems serve airports near the reference station that gathers GPS data and determines differential corrections. A generic local area differential ground system would consist of a ground monitor system that would determine corrections and integrity, and a communications system that would transmit correction and integrity data to aircraft. FAA is conducting a feasibility program to determine if a local area DGPS system can meet the requirements for Category II/III precision approaches and landings. The results of this study are expected in fiscal year 1995. Figure 3-8 shows an example of a proposed FAA local area system. This system will be designed to meet all requirements for the Category II/III precision approach phase of flight.

3.3.5 Wide Area System 2

Wide Area System 2 (WAS 2) is a variation of WAS 1. It differs in that the WAAS portion provides enhancements to integrity and availability only. Pseudorange correction information is not transmitted from the GEO satellites. This change minimizes national security risks, but it requires additional LADGPS systems to provide the increased accuracy required for Category I precision approaches. LADGPS systems must also be implemented for the Category II and III precision approaches as in WAS 1.

LADGPS systems must be implemented to provide the increased accuracy required for Category I as well as Category II and III precision approaches supported in WAS 1. This system, therefore, includes the implementation of approximately 620 Category I LADGPS systems in addition to the 150 LADGPS systems needed to support Category II/III operations. FAA is considering two alternatives for the acquisition of the required Category I LADGPS systems: Special Category I (SCAT I) and publicly funded Category I systems.

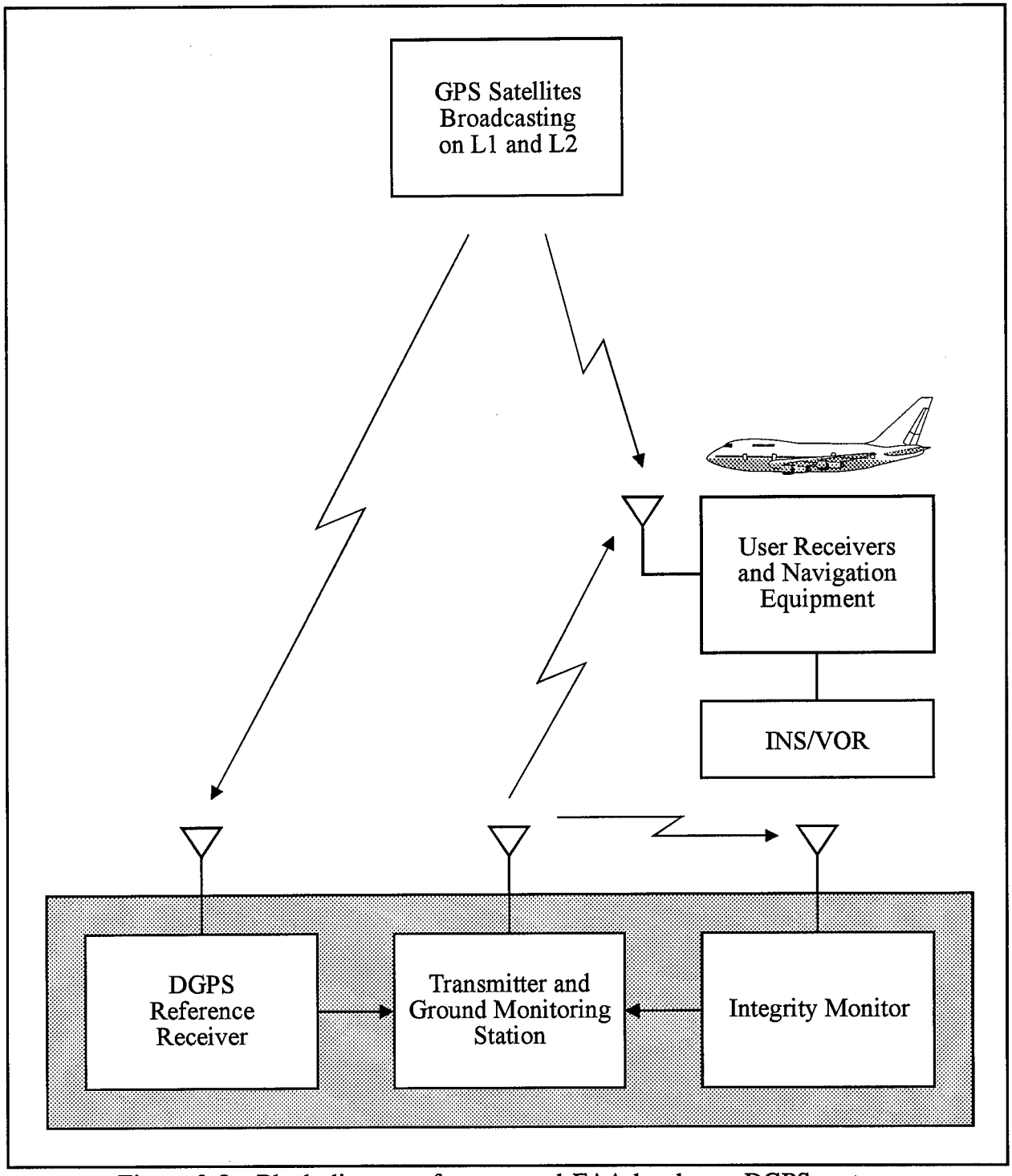

Figure 3-8. Block diagram of a proposed FAA local area DGPS system.

SCAT I systems would be developed and acquired, under FAA supervision and approval, by private industry for specific users. SCAT I systems are expected to be limited to a relatively small number of selected locations. The majority of the Category I LADGPS system requirements would be satisfied by systems developed and funded by the FAA. Both SCAT I and public Category I LADGPS systems would be specified to meet operational requirements associated with Category I precision approach operations.

Accuracy. The accuracies provided by the WAAS portion of WAS 2 are the SPS accuracies of 100 meters horizontal, 156 meters vertical. The specification for accuracy of the LADGPS system will meet the requirements defined for the precision approach phase of flight.

Integrity. The integrity enhancement provided by WAS 2 is the same as that provided by WAS 1.

Availability. The availability enhancement provided by WAS 2 is the same as that provided by WAS 1.

Coverage. The WAAS portion of WAS 2 does not provide pseudorange correction information. Integrity and availability information are provided over the footprint of the GEO satellite. The accuracy requirements for the precision approaches are provided within the coverage area of the LADGPS systems. It is expected that under WAS 2, an estimated 620 more LADGPS systems would be installed than under WAS 1 to support Category I precision approach requirements.

Security. This system does not plan to use encryption methods, user access controls, or other screening.

Infrastructure Cost. The estimated life cycle cost of the WAAS portion of WAS 2 is $670M. The estimated life cycle cost for the 620 Category I LADGPS systems is $560M. The estimated cost of the more sophisticated Category II/III LADGPS systems remains the same as in WAS 1, $195M. The total estimated life cycle cost for WAS 2 is $1,425M.

User Cost. User equipment (avionics) for this architecture is expected to cost on the order of $4.4K for general aviation aircraft to $99K for commercial air carriers.

Data Link Characteristics. The WAAS satellites will broadcast a GPS-like spread spectrum signal on the GPS L1 frequency. The effective data rate is 250 bps. The satellite navigation message will contain integrity data and navigation data so that the satellite can be a ranging source. No operational data link requirements are specified as yet for the LADGPS systems. Options for the data link include Mode-S, VHF, and L1.

Data Format. The WAAS portion of the data link will use the RTCA WAAS format. The LADGPS portion of this system will use the RTCA LADGPS format.

Time Frame of Availability. The WAAS portion of WAS 2, which includes integrity and availability components only, is expected to be available in the same time frame as the WAAS portion of WAS 1 — by 1997. The LADGPS portion of WAS 2 is expected to take an additional 2 to 3 years, predicated on the availability of funding.

3.3.6 Wide Area System 3

Wide Area System 3 (WAS 3) is another variation of WAS 1, with augmentation data transmitted from a communications satellite using a frequency other than L1.

Accuracy. The accuracy enhancement provided by the WAAS portion of WAS 3 is the same as that provided by the WAAS portion of WAS 1: 7.6 meters (95%) both horizontal and vertical. The accuracy enhancement provided by the LADGPS portion of WAS 3 is the same as that provided by the LADGPS portion of WAS 1: meets the requirements defined for the Category II/III precision approach phase of flight.

Integrity. The integrity enhancement provided by the WAAS portion of WAS 3 is the same as that provided by WAS 1: the probability of HMI is 10^{-7} per hour; the time to alarm is 8 seconds; and the alarm limit is 556 meters (horizontal error) for a total system error. For the precision approach operation, the WAAS requirements for probability of HMI is 4×10^{-8} per approach; the time to alarm is 5.2 seconds; and the alarm limit is the same as for the en route through nonprecision approach operation. The integrity enhancement provided by the LADGPS portion of WAS 3 is the same as that provided by WAS 1: meets the requirements defined for the Category II/III precision approach phase of flight.

Availability. The availability enhancement provided by the WAAS portion of WAS 3 is the same as that provided by WAS 1: 99.999%. The availability enhancement provided by the LADGPS portion of WAS 3 is the same as that provided by WAS 1: meets the requirements defined for the Category II/III precision approach phase of flight.

Coverage. The coverage provided by the WAAS portion of WAS 3 is the same as that provided by WAS 1: from the surface to 30,500 meters (100,000 feet) above sea level over the contiguous U.S., Alaska, Hawaii, Puerto Rico, the Pacific Ocean to Hawaii, the Atlantic Ocean off the coast of the U.S., and much of the Gulf of Mexico. The coverage provided by the LADGPS portion of WAS 3 is the same as that provided by WAS 1, but it has not yet been specified.

Security. This system does not plan to use encryption methods, user access controls or other screening.

Infrastructure Cost. WAS 3 design remains conceptual, but it is assumed that the life cycle cost for the WAAS portion of the system will remain the same as for WAS 1, $1,139M. The estimated life cycle cost for the Category II/III LADGPS systems also remains the same at $195M. The total life cycle cost would be approximately $1,334M.

User Cost. The cost of avionics equipment for WAS 3 is expected to be approximately $4.4K for general aviation users and $99K for commercial air carriers.

Data Link Characteristics. As in WAS 1, the WAAS portion of WAS 3 will transmit integrity, availability and accuracy information from a communications satellite, but on a frequency other than L1. The data link characteristics for the transmission of accuracy information are not yet known for WAS 3, because a specific frequency, modulation scheme, and transmitter location (satellite) have not been determined. LADGPS system data transmission will be the same as for WAS 1, and is not yet defined. Options for the data link include Mode-S, VHF, L1, or the WAS 3 WAAS frequency.

Data Format. The data format implemented in WAS 3 is the same as that implemented in WAS 1 and is based on the RTCA standard. The LADGPS portion of this system will use the RTCA LADGPS format.

Time Frame of Availability. The WAS 3 system remains conceptual, and considerable design work is required before implementation could begin. It is expected that this system could not be operational until at least 1998.

3.3.7 Wide Area System 4

In order to maximize the use of GPS without sacrificing National or user security, the GPS Joint Program Office (JPO) has proposed an Augmented GPS (AGPS) System with the following characteristics:

- One common network of systems all receiving data from the AGPS System.
- All AGPS links encrypted.
- DOT provides a master decryption key to the service providers and manages access to the AGPS System.
- Service providers licensed. Value added services could be provided to their users as seen fit. Providers distribute decryption keys to users.

Accuracy, Integrity, Availability, and Coverage. Since the service providers decrypt the AGPS signal and provide further services to the user, accuracy, integrity, availability, and coverage capabilities are largely at the control of the service provider. The augmented services can be through the infrastructure provided by the service provider. Nominally, the capabilities of the AGPS System would be similar to WAS 1 and WAS 3.

Security. This system plans to use encryption methods and user access controls.

Infrastructure Cost. The estimated cost addition to WAS 1 for WAS 4 enhancements is $300M. The total life cycle cost of WAS 4 is estimated at approximately $1,634M.

User Cost. User costs will depend upon the equipment costs and the service charges from the service provider. The U.S. government may or may not charge additional fees for providing the base AGPS System. User costs are expected to be higher for WAS 4, but exact costs are not possible to determine at this time.

Data Link Characteristics. This system is based primarily on the WAS 1 structure. Data link characteristics will be the same as those for WAS 1, with the addition that all data links will be encrypted.

Data Format. Encryption formats are not yet defined for this system. User receiver equipment provided by service providers would be able to decrypt the AGPS signal and provide any data format required by the user.

Time Frame of Availability. An estimate of system availability is 1998.

3.3.8 Wide Area System 5

A number of commercial GEO satellite systems have been developed by private industry to provide positioning services. At the present time, navigation services are not provided. These systems typically use reference stations which send data to a central control facility. The control center continuously monitors the status of the DGPS network and quality of the data.

Accuracy. Commercial systems can achieve horizontal accuracies of 0.6 m (2 drms).

Integrity. Although measures have been taken to ensure data quality, integrity has not been quantified by the commercial service providers.

Availability. Availability has been recently measured at 99.99%.

Coverage Area. The coverage area of the system depends upon the satellite(s) used. Coverage area is typical of that provided by other GEO satellite systems previously discussed.

Security. Commercial GEO satellite systems use encryption and user access controls.

Infrastructure Cost. All infrastructure costs are borne by the service provider.

User Cost. User costs involve the acquisition of receivers and user fees for service. User fees for these systems range from dollars per day to hundreds of dollars per day.

Data Link Characteristics. The commercial GEO satellite systems broadcast encrypted data on frequency bands other than L1, for example, C band.

Data Format. Standard formats, such as the RTCM format, are supported by the commercial systems; however, the signals are converted into proprietary data formats for transmission.

Time Frame of Availability. There are commercial systems currently available.

3.3.9 Wide Area System 6

Currently there are no commercial LEO satellite systems available; however, several different systems, in different stages of development, have been proposed. Depending on the system, anywhere from 36 to over 100 satellites in low earth orbit constellations have been proposed. These communications satellites would provide accuracy and integrity data to users. With these proposed systems, 100% global communications can be provided.

Some options for disseminating integrity and differential correction data from LEO satellite systems are:

- Phone access. Users make a phone call and retrieve data as required (positioning applications).
- Continuous broadcasting on a frequency in the S, L, or another band.

Accuracy. It is estimated that a LEO satellite system could provide 1 meter horizontal (2 drms) and 3 meter vertical accuracy.

Integrity. System providers estimate a 6 second time to alarm for LEO satellite systems.

Availability. LEO satellite systems should provide availability similar to GEO satellite systems (99.99%); however, since these systems are only proposed, availability cannot be measured.

Coverage Area. Proposed systems will provide global coverage.

Security. Each LEO satellite will cover a limited geographic footprint. There could be control of the coverage within each footprint. Commercial LEO satellite systems will use encryption and user access controls.

Infrastructure Cost. Infrastructure costs will be borne by the service provider.

User Cost. User costs involve the acquisition of receivers and user fees for service. Typical user fees for these systems will be slightly greater than premium phone services. Typical user equipment will cost under $1000 per unit.

Data Link Characteristics. Depending on the user service, LEO satellite systems will support a wide variety of bands, bandwidths, and multiplexing schemes.

Data Formats. Receiver equipment will be designed to provide any data format required by the user. Broadcast formats will be proprietary.

Time Frame of Availability. Since these are all proposed systems, the time frame of availability will be after 1998.

3.3.10 Continuously Operating Reference Station System

Continuously operating reference stations (CORS) provide a standardized means for recording a set of GPS observables, which includes both carrier phase and code range information. CORS have standardized GPS receivers and data storage media, and they allow remote system access. CORS serve post-processing applications and are not real time. To promote multi-agency use of existing reference stations and to preclude establishing redundant reference stations, CORS capability may be built into any reference station. A prototype CORS is operational. Appendix G contains a further description of the CORS system.

Accuracy. CORS provide observations to support two levels of accuracy: 1 cm and 1 m.

Integrity. Integrity is derived from post-mission processing.

Availability. CORS can provide 99.0% post-processing data availability.

Coverage Area. Provided both L1 and L2 data are available, CORS can provide post-processed accuracies at the 1 cm level using carrier phase and at the 1 m level using code range. These accuracies are available for locations up to hundreds of kilometers from the reference site. Note that CORS provide only a post-processing capability. Other systems have been developed that can provide real time centimeter accuracies. Currently, such systems have a range of 10 to 20 km.

Security. CORS provide post-mission capabilities and do not provide real time navigation. No encryption or limited user access is built into CORS specifications.

Infrastructure Cost. FAA WAAS reference stations will be designed to comply with the CORS standard. The USCG reference stations can be made to comply with the CORS standard at a cost estimated to be less than $10K per station. An entirely new CORS for surveying applications can cost from $70K to $150K, depending upon the quality of the equipment needed for the application.

User Cost. With CORS, survey users no longer require their own reference station, which, because of productivity gains, can result in a net savings to the user. The cost of survey

equipment can range from the low thousands to several tens of thousands of dollars. At the present time, there is no expectation that there will be a charge for access to archived data.

Data Link Characteristics. There is no direct broadcast data link to users as part of CORS.

Data Format. It is expected that a CORS will archive data in the receiver manufacturers' raw formats. The CORS central facility will provide data in the RINEX format in order to provide data to users independent of the equipment used.

Time Frame of Availability. A prototype CORS is currently operational.

3.3.11 Loran-C System

Loran-C is a low frequency radionavigation system. Loran-C chains consist of stations located several hundreds of miles apart. These chains are located in the U.S. and in various parts of the world.

Loran-C offers three possible solutions to augment GPS:

- Loran-C used as a data link to transmit DGPS corrections.
- Loran-C calibrated by DGPS. This improved Loran-C system can then be used in the event of GPS outages or in a hybrid position solution.
- Loran-C used as an additional ranging signal or pseudolite. This use results in increased availability of a navigation solution.

Accuracy. The predictable accuracy of Loran-C is 460 meters (0.25 nautical miles) 2 drms. Calibration of Loran-C with DGPS can provide a position accuracy of approximately 5 meters.

Integrity. Loran-C stations are manned and signals are monitored. Since Loran-C is a very different communications/navigation system from GPS, a disruption in either GPS or Loran-C is unlikely to disrupt the other system. Integrated GPS and Loran-C provide the user with two independent, yet cooperative, navigation capabilities which increase the overall usefulness of the mixed system. With the inclusion of monitoring equipment at Loran-C sites, users can be notified of system integrity problems within 2 seconds.

Availability. Loran-C availability is reported to be 99.75%. Results from analyses done by the Volpe National Transportation Systems Center indicate that availability from the combination of GPS with Receiver Autonomous Integrity Monitoring (RAIM) and Loran-C can exceed 99.99% [10].

Coverage Area. Loran-C provides complete coverage of CONUS and parts of Alaska, western Canada, western Europe, Japan, and parts of China. Figure 3-9 shows the coverage provided by U.S.-operated or -supported Loran-C stations.

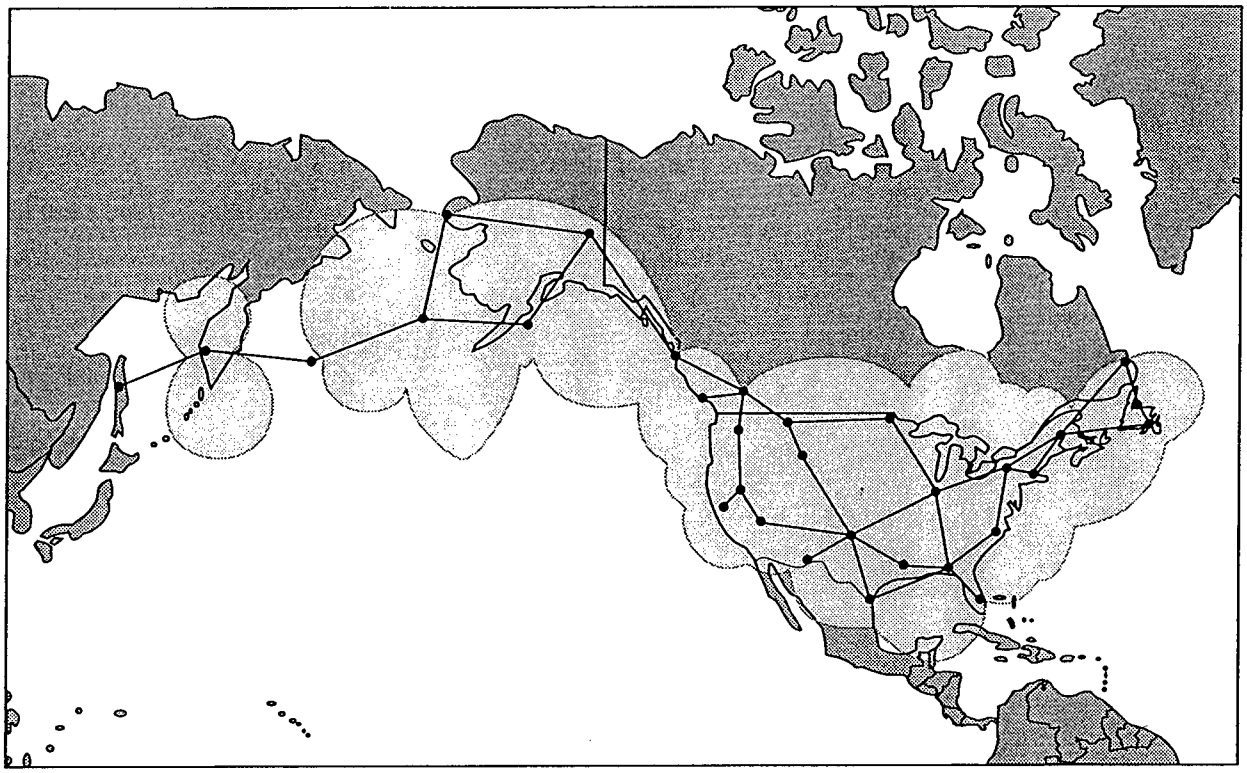

Figure 3-9. Coverage provided by U.S.-operated or -provided Loran-C stations.

Security. Loran-C does not use encryption or any methods for controlling user access.

Infrastructure Cost. Infrastructure costs to modify existing Loran-C sites to transmit differential corrections are estimated to be $100K per station. The cost of building a new Loran-C site is estimated at $8M to $10M. Loran-C sites will need upgrades within the next few years to replace aging equipment. The cost of upgrading an existing Loran site to include solid-state equipment is estimated at $5M.

User Cost. While there is an existing stock of Loran-C receivers, new receivers would be required to meet combined GPS/Loran-C capabilities. While FAA-certified equipment for air navigation could cost less than $1,000 per unit, the cost of installing and inspecting a unit in an aircraft would bring the cost to several thousand dollars per unit. However, the cost of portable GPS/Loran-C units for non-navigation uses, such as for ground vehicles, is expected to be less than $1,000.

Data Link Characteristics. The Loran-C system is centered at 100 kHz and could transmit differential GPS data by time-shifting the Loran-C bursts. This technique results in a data rate of up to 30 bps.

Data Format. To overcome the low data rates inherent in a Loran-C differential GPS system, a fully asynchronous message format is proposed. Every satellite correction would be transmitted in a single compressed message.

Time Frame of Availability. The basic Loran-C infrastructure is in place. Modifications and implementation schedules could not meet a date prior to 1998.

4

EVALUATION OF AUGMENTED GPS SYSTEMS

This section compares the technical capabilities of the 11 systems described in Section 3 with the user requirements identified in Section 2. An analytical decision matrix was developed to assist in determining the final recommendations of this study. The matrix served as a guide in evaluating the augmented GPS systems and architectures that were considered but did not provide an absolute solution to determine the most capable augmented GPS architecture. The decision matrix consisted of two stages. The first stage, the use of which is illustrated in Tables 4-1 through 4-22, is the Technical Capabilities Evaluation. During this stage, user requirements and augmented GPS system performance specifications were tabulated.

The 11 systems evaluated were:

1) U.S. Coast Guard (USCG) — This system employs LF/MF beacons and is currently being deployed by USCG and the U.S. Army Corps of Engineers to provide coverage of U.S. coasts, harbors, harbor approaches, and inland waterways.

2) U.S. Coast Guard, Expanded (USCG(E)) — This system expands the USCG LF/MF beacon system to provide nationwide coverage.

3) FM Subcarrier (FM) — The FM subcarrier system provides differential corrections using the subcarriers of FM broadcast stations.

4) Wide Area System 1 (WAS 1) — This system is composed of the FAA GEO satellite-based Wide Area Augmentation System (WAAS) to meet the integrity, availability, and accuracy requirements of aviation users for the en route through Category I precision approach phases of flight and approximately 150 local area differential GPS (LADGPS) systems for Category II/III precision approach requirements.

5) Wide Area System 2 (WAS 2) — This system is composed of the FAA WAAS to meet the requirements of aviation users for the en route through non-precision approach phases of flight. In addition to the WAAS, approximately 770 LADGPS systems are needed for Category I/II/III approach requirements. In this system, the WAAS provides integrity and availability only; it does not provide accuracy corrections.

6) Wide Area System 3 (WAS 3) — This system is the same as WAS 1 except that a frequency other than L1 is used to provide differential corrections.

7) Wide Area System 4 (WAS 4) — This system is the same as WAS 1 except that all communication links are encrypted to provide signal security.

8) Wide Area System 5 (WAS 5) — This is a GEO satellite-based system provided by private industry.

9) Wide Area System 6 (WAS 6) — This is a LEO satellite-based system provided by private industry.

10) Continuously Operating Reference Stations (CORS) — This system is designed and will be deployed throughout the country to meet the post-processing requirements of GPS users.

11) Loran-C — This system uses Loran-C as a communications link to provide differential corrections.

4.1 System Technical Capabilities

The technical capabilities of the 11 systems described in Section 3 are summarized in Table 4-1. Some of the parameters used in Section 3 to describe the systems are not included in the table. Parameters were excluded if system suppliers did not provide a specification for that parameter, system performance could not be evaluated, or the parameter did not provide discrimination between systems. A detailed justification for Table 4-1 entries is provided in Appendix I.

4.2 Capabilities Versus Requirements

Tables 4-2 through 4-17 display the degree to which each of the 11 systems satisfy user requirements. Each mode and phase of operation identified in Section 2 is compared in a separate table. Each block in these tables indicates a "YES" if the system specification meets or exceeds the required value and a "NO" if the specification does not meet the requirement. These tables provide an evaluation of the technical capabilities of each system for each mode and phase of operation.

Table 4-1. Augmented GPS System Capabilities

Characteristics	Units	USCG	USCG (E)	FM	WAS-1	WAS-2	WAS-3	WAS-4	WAS-5	WAS-6	CORS *	Loran-C
Coverage Area-Nationwide	Yes or No	NO	YES	YES	YES	NO	YES	YES	YES	YES	YES	YES
Coverage Area-Ocean	Yes or No	NO	NO	NO	YES	YES	YES	YES	YES	YES	NO	NO
Coverage Area-Coastal	Yes or No	YES	YES	NO	NO	NO	NO	NO	NO	YES	NO	YES
CoverageArea-NAS	Yes or No	NO	NO	NO	YES	YES	YES	YES	YES	YES	NO	YES
Availability	%	99.70%	99.70%	99.97%	99.999%	99.999%	99.999%	99.999%	99.99%	99.99%	99.00%	99.75%
Failure Notification Time	sec	4.2	4.2	3.0	2.0	2.0	2.0	2.0	2.0	6.0	**	2.0
Predictable Accuracy-Horizontal	meters, 2drms	3.0	3.0	1.0	4.1	4.1	4.1	4.1	0.6	1.0	0.001	5.0
Predictable Accuracy-Vertical	meters,2 Sigma	4.5	4.5	1.5	0.6	0.6	0.6	0.6	1.0	3.0	0.001	7.5
Probability of Accur. & Integ.	1/hour	**	**	**	0.0000001	0.0000001	0.0000001	0.0000001	**	**	**	**
Initial Operating Capability	Year	94	98	94	97	97	>98	>98	94	98	94	>98

* CORS is not a real time system

** Not specified for this system

Table 4-2. Augmented GPS System Evaluation, Aviation, Oceanic En Route

Characteristics	Units	Requirement	USCG	USCG (E)	FM	WAS-1	WAS-2	WAS-3	WAS-4	WAS-5	WAS-6	CORS	Loran-C
Coverage Area-Ocean	Yes or No	YES	NO	NO	NO	YES	YES	YES	YES	YES	YES	NO	NO
Availability	%	99.977%	NO	NO	NO	YES	YES	YES	YES	NO	YES	NO	NO
Failure Notification Time	sec	10	YES	YES	YES	YES	YES	YES	YES	YES	YES	NO	YES
Probability of Accur. & Integ.	1/hour	0.0000001	NO	NO	NO	YES	YES	YES	YES	NO	NO	NO	YES
Meets Requirements			NO	NO	NO	YES	YES	YES	YES	NO	NO	NO	NO

Table 4-3. Augmented GPS System Evaluation, Aviation, Domestic En Route

Characteristics	Units	Requirement	USCG	USCG (E)	FM	WAS-1	WAS-2	WAS-3	WAS-4	WAS-5	WAS-6	CORS	Loran-C
CoverageArea-NAS	Yes or No	YES	NO	NO	NO	YES	YES	YES	YES	YES	YES	NO	YES
Availability	%	99.977%	NO	NO	NO	YES	YES	YES	YES	NO	YES	NO	NO
Failure Notification Time	sec	10	YES	YES	YES	YES	YES	YES	YES	YES	YES	NO	YES
Probability of Accur. & Integ.	1/hour	0.0000001	NO	NO	NO	YES	YES	YES	YES	NO	NO	NO	YES
Meets Requirements			NO	NO	NO	YES	YES	YES	YES	NO	NO	NO	NO

Table 4-4. Augmented GPS System Evaluation, Aviation, Terminal

Characteristics	Units	Requirement	USCG	USCG (E)	FM	WAS-1	WAS-2	WAS-3	WAS-4	WAS-5	WAS-6	CORS	Loran-C
Coverage Area-Ocean	Yes or No	YES	NO	NO	NO	YES	YES	YES	YES	YES	YES	NO	NO
CoverageArea-NAS	Yes or No	YES	NO	NO	NO	YES	YES	YES	YES	YES	YES	NO	YES
Availability	%	99.977%	NO	NO	NO	YES	YES	YES	YES	NO	YES	NO	NO
Failure Notification Time	sec	10	YES	YES	YES	YES	YES	YES	YES	YES	YES	NO	YES
Probability of Accur. & Integ.	1/hour	0.0000001	NO	NO	NO	YES	YES	YES	YES	NO	NO	NO	YES
Meets Requirements			NO	NO	NO	YES	YES	YES	YES	NO	NO	NO	NO

Table 4-5. Augmented GPS System Evaluation, Aviation, Non Precision Approach and Landing

Characteristics	Units	Requirement	USCG	USCG (E)	FM	WAS-1	WAS-2	WAS-3	WAS-4	WAS-5	WAS-6	CORS	Loran-C
Coverage Area-Ocean	Yes or No	YES	NO	NO	NO	YES	YES	YES	YES	YES	YES	NO	NO
CoverageArea-NAS	Yes or No	YES	NO	NO	NO	YES	YES	YES	YES	YES	YES	NO	YES
Availability	%	99.977%	NO	NO	NO	YES	YES	YES	YES	NO	YES	NO	NO
Failure Notification Time	sec	10	YES	YES	YES	YES	YES	YES	YES	YES	YES	NO	YES
Probability of Accur. & Integ.	1/hour	0.0000001	NO	NO	NO	YES	YES	YES	YES	NO	NO	NO	YES
Meets Requirements			NO	NO	NO	YES	YES	YES	YES	NO	NO	NO	NO

Table 4-6. Augmented GPS System Evaluation, Aviation, Category 1 Approach and Landing

Characteristics	Units	Requirement	USCG	USCG (E)	FM	WAS-1	WAS-2	WAS-3	WAS-4	WAS-5	WAS-6	CORS	Loran-C
CoverageArea-NAS	Yes or No	YES	NO	NO	NO	YES	YES	YES	YES	YES	YES	NO	YES
Availability	%	99.99%	NO	NO	NO	YES	YES	YES	YES	NO	YES	NO	NO
Failure Notification Time	sec	6	YES	YES	YES	YES	YES	YES	YES	YES	YES	NO	YES
Probability of Accur. & Integ.	1/hour	0.00000004	NO	NO	NO	YES	YES	YES	YES	NO	NO	NO	YES
Predictable Accuracy-Horizontal	meters, 2drms	9	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Predictable Accuracy-Vertical	meters,2 Sigma	3	NO	NO	YES	YES	YES	YES	YES	YES	YES	YES	NO
Meets Requirements			NO	NO	NO	YES	YES	YES	YES	NO	NO	NO	NO

Table 4-7. Augmented GPS System Evaluation, Marine, Harbor/Harbor Approach

Characteristics	Units	Requirement	USCG	USCG (E)	FM	WAS-1	WAS-2	WAS-3	WAS-4	WAS-5	WAS-6	CORS	Loran-C
Coverage Area-Coastal	Yes or No	YES	YES	YES	NO	NO	NO	NO	NO	NO	YES	NO	YES
Predictable Accuracy-Horizontal	meters, 2drms	8	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Availability	%	99.7%	YES	YES	YES	YES	YES	YES	YES	YES	YES	NO	YES
Meets Requirements			YES	YES	NO	NO	NO	NO	NO	NO	YES	NO	YES

Table 4-8. Augmented GPS System Evaluation, Marine, Coastal

Characteristics	Units	Requirement	USCG	USCG (E)	FM	WAS-1	WAS-2	WAS-3	WAS-4	WAS-5	WAS-6	CORS	Loran-C
Coverage Area-Coastal	Yes or No	YES	YES	YES	NO	NO	NO	NO	NO	NO	YES	NO	YES
Predictable Accuracy-Horizontal	meters, 2drms	460	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Availability	%	99.7%	YES	YES	YES	YES	YES	YES	YES	YES	YES	NO	YES
Meets Requirements			YES	YES	NO	NO	NO	NO	NO	NO	YES	NO	YES

Table 4-9. Augmented GPS System Evaluation, Marine, Ocean

Characteristics	Units	Requirement	USCG	USCG (E)	FM	WAS-1	WAS-2	WAS-3	WAS-4	WAS-5	WAS-6	CORS	Loran-C
Coverage Area-Ocean	Yes or No	YES	YES*	YES*	YES*	YES*	YES*	YES*	YES*	YES*	YES*	YES*	YES*
Predictable Accuracy-Horizontal	meters, 2drms	1800	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Availability	%	99.0%	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Meets Requirements			YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES

* Met by SPS

Table 4-10. Augmented GPS System Evaluation, Land, Highway

Characteristics	Units	Requirement	USCG	USCG (E)	FM	WAS-1	WAS-2	WAS-3	WAS-4	WAS-5	WAS-6	CORS	Loran-C
Coverage Area-Nationwide	Yes or No	YES	NO	YES	YES	YES	NO	YES	YES	YES	YES	YES	YES
Predictable Accuracy-Horizontal	meters, 2drms	5	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Availability	%	99.70%	YES	YES	YES	YES	YES	YES	YES	YES	YES	NO	YES
Failure Notification Time	sec	15	YES	YES	YES	YES	YES	YES	YES	YES	YES	NO	YES
Meets Requirements			NO	YES	YES	YES	NO	YES	YES	YES	YES	NO	YES

Table 4-11. Augmented GPS System Evaluation, Land, Highway (Collision Avoidance)

Characteristics	Units	Requirement	USCG	USCG (E)	FM	WAS-1	WAS-2	WAS-3	WAS-4	WAS-5	WAS-6	CORS	Loran-C
Coverage Area-Nationwide	Yes or No	YES	NO	YES	YES	YES	NO	YES	YES	YES	YES	YES	YES
Predictable Accuracy-Horizontal	meters, 2drms	1	NO	NO	YES	NO	NO	NO	NO	YES	YES	YES	NO
Availability	%	99.70%	YES	YES	YES	YES	YES	YES	YES	YES	YES	NO	YES
Failure Notification Time	sec	15	YES	YES	YES	YES	YES	YES	YES	YES	YES	NO	YES
Meets Requirements			NO	NO	YES	NO	NO	NO	NO	YES	YES	NO	NO

Table 4-12. Augmented GPS System Evaluation, Land, Railroad

Characteristics	Units	Requirement	USCG	USCG (E)	FM	WAS-1	WAS-2	WAS-3	WAS-4	WAS-5	WAS-6	CORS	Loran-C
Predictable Accuracy-Horizontal	meters, 2drms	10	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Availability	%	99.70%	YES	YES	YES	YES	YES	YES	YES	YES	YES	NO	YES
Failure Notification Time	sec	5	YES	YES	YES	YES	YES	YES	YES	YES	NO	NO	YES
Coverage Area-Nationwide	Yes or No	YES	NO	YES	YES	YES	NO	YES	YES	YES	YES	YES	YES
Meets Requirements			NO	YES	YES	YES	NO	YES	YES	YES	NO	NO	YES

Table 4-13. Augmented GPS System Evaluation, Land, Railroad (Control)

Characteristics	Units	Requirement	USCG	USCG (E)	FM	WAS-1	WAS-2	WAS-3	WAS-4	WAS-5	WAS-6	CORS	Loran-C
Predictable Accuracy-Horizontal	meters, 2drms	1	NO	NO	YES	NO	NO	NO	NO	YES	YES	YES	NO
Availability	%	100%	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
Failure Notification Time	sec	5	YES	YES	YES	YES	YES	YES	YES	YES	NO	NO	YES
Coverage Area-Nationwide	Yes or No	YES	NO	YES	YES	YES	NO	YES	YES	YES	YES	YES	YES
Meets Requirements			NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO

Table 4-14. Augmented GPS System Evaluation, Survey, Land

Characteristics	Units	Requirement	USCG	USCG (E)	FM	WAS-1	WAS-2	WAS-3	WAS-4	WAS-5	WAS-6	CORS	Loran-C
Predictable Accuracy-Horizontal	meters, 2drms	0.02	NO	NO	NO	NO	NO	NO	NO	NO	NO	YES	NO
Predictable Accuracy-Vertical	meters,2 Sigma	0.01	NO	NO	NO	NO	NO	NO	NO	NO	NO	YES	NO
Coverage Area-Nationwide	Yes or No	YES	NO	YES	YES	YES	NO	YES	YES	YES	YES	YES	YES
Availability	%	99.0%	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Meets Requirements			NO	NO	NO	NO	NO	NO	NO	NO	NO	YES	NO

Table 4-15. Augmented GPS System Evaluation, Survey, Hydro

Characteristics	Units	Requirement	USCG	USCG (E)	FM	WAS-1	WAS-2	WAS-3	WAS-4	WAS-5	WAS-6	CORS	Loran-C
Coverage Area-Nationwide	Yes or No	YES	NO	YES	YES	YES	NO	YES	YES	YES	YES	YES	YES
Predictable Accuracy-Horizontal	meters, 2drms	1	NO	NO	YES	NO	NO	NO	NO	YES	YES	YES	NO
Predictable Accuracy-Vertical	meters,2 Sigma	0.04	NO	NO	NO	NO	NO	NO	NO	NO	NO	YES	NO
Availability	%	99.0%	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Meets Requirements			NO	NO	NO	NO	NO	NO	NO	NO	NO	YES	NO

Table 4-16. Augmented GPS System Evaluation, Survey, Deformation Analysis

Characteristics	Units	Requirement	USCG	USCG (E)	FM	WAS-1	WAS-2	WAS-3	WAS-4	WAS-5	WAS-6	CORS	Loran-C
Predictable Accuracy-Horizontal	meters, 2drms	0.01	NO	NO	NO	NO	NO	NO	NO	NO	NO	YES	NO
Predictable Accuracy-Vertical	meters,2 Sigma	0.001	NO	NO	NO	NO	NO	NO	NO	NO	NO	YES	NO
Coverage Area-Nationwide	Yes or No	YES	NO	YES	YES	YES	NO	YES	YES	YES	YES	YES	YES
Availability	%	99.0%	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Meets Requirements			NO	NO	NO	NO	NO	NO	NO	NO	NO	YES	NO

Table 4-17. Augmented GPS System Evaluation, Survey, Mapping

Characteristics	Units	Requirement	USCG	USCG (E)	FM	WAS-1	WAS-2	WAS-3	WAS-4	WAS-5	WAS-6	CORS	Loran-C
Predictable Accuracy-Horizontal	meters, 2drms	0.2	NO	NO	NO	NO	NO	NO	NO	NO	NO	YES	NO
Predictable Accuracy-Vertical	meters,2 Sigma	0.01	NO	NO	NO	NO	NO	NO	NO	NO	NO	YES	NO
Coverage Area-Nationwide	Yes or No	YES	NO	YES	YES	YES	NO	YES	YES	YES	YES	YES	YES
Availability	%	99.0%	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Meets Requirements			NO	NO	NO	NO	NO	NO	NO	NO	NO	YES	NO

4.3 Summary of Results

Tables 4-18 through 4-21 summarize the results of the technical capabilities evaluation for each mode of operation: aviation, marine, land, and survey. The table for each mode summarizes the evaluations for that mode and indicates whether a system meets the requirements for all phases of that mode of operation. Each entry in Tables 4-18 through 4-21 indicates a "YES" if the system meets all the requirements and a "NO" if the system does not meet all the requirements.

Table 4-18. Augmented GPS System Evaluation, Aviation, Summary

Phases	USCG	USCG (E)	FM	WAS-1	WAS-2	WAS-3	WAS-4	WAS-5	WAS-6	CORS	Loran-C
Oceanic En Route	NO	NO	NO	YES	YES	YES	YES	NO	NO	NO	NO
Domestic En Route	NO	NO	NO	YES	YES	YES	YES	NO	NO	NO	NO
Terminal	NO	NO	NO	YES	YES	YES	YES	NO	NO	NO	NO
Non precision Approach & Landing	NO	NO	NO	YES	YES	YES	YES	NO	NO	NO	NO
Category 1 Approach & Landing	NO	NO	NO	YES	YES	YES	YES	NO	NO	NO	NO
All Phases	NO	NO	NO	YES	YES	YES	YES	NO	NO	NO	NO

Table 4-19. Augmented GPS System Evaluation, Marine, Summary

Phases	USCG	USCG (E)	FM	WAS-1	WAS-2	WAS-3	WAS-4	WAS-5	WAS-6	CORS	Loran-C
Harbor/Harbor Approach	YES	YES	NO	NO	NO	NO	NO	NO	YES	NO	YES
Coastal	YES	YES	NO	NO	NO	NO	NO	NO	YES	NO	YES
Ocean	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
All Phases	YES	YES	NO	NO	NO	NO	NO	NO	YES	NO	YES

Table 4-20. Augmented GPS System Evaluation, Land, Summary

Phases	USCG	USCG (E)	FM	WAS-1	WAS-2	WAS-3	WAS-4	WAS-5	WAS-6	CORS	Loran-C
Highway	NO	YES	YES	YES	NO	YES	YES	YES	YES	NO	YES
Highway (Collision Avoidance)	NO	NO	YES	NO	NO	NO	NO	YES	YES	NO	NO
Railroad (Control)	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
Railroad	NO	YES	YES	YES	NO	YES	YES	YES	NO	NO	YES
All Phases	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO

Table 4-21. Augmented GPS System Evaluation, Survey, Summary

Phases	USCG	USCG (E)	FM	WAS-1	WAS-2	WAS-3	WAS-4	WAS-5	WAS-6	CORS	Loran-C
Land Survey	NO	NO	NO	NO	NO	NO	NO	NO	NO	YES	NO
Hydro Survey	NO	NO	NO	NO	NO	NO	NO	NO	NO	YES	NO
Deformation Survey	NO	NO	NO	NO	NO	NO	NO	NO	NO	YES	NO
Mapping	NO	NO	NO	NO	NO	NO	NO	NO	NO	YES	NO
All Phases	NO	NO	NO	NO	NO	NO	NO	NO	NO	YES	NO

4.4 Conclusions

Table 4-22 summarizes the system evaluation for all modes of operation. It illustrates that no single augmentation system meets the requirements of all modes of operation. For the land mode, no system evaluated can meet the collision avoidance requirements of land users because of the high availability requirements of railroads (100%) or the high accuracy requirements nationwide (1 meter).

Table 4-22. Augmented GPS System Evaluation, Mode, Summary

Mode	USCG	USCG (E)	FM	WAS-1	WAS-2	WAS-3	WAS-4	WAS-5	WAS-6	CORS	Loran-C
Aviation	NO	NO	NO	YES	YES	YES	YES	NO	NO	NO	NO
Marine	YES	YES	NO	NO	NO	NO	NO	NO	YES	NO	YES
Land	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
Surveying & Other	NO	NO	NO	NO	NO	NO	NO	NO	NO	YES	NO

5

EVALUATION OF AUGMENTED GPS ARCHITECTURES

The results of Section 4 indicate that no single proposed system meets all Federal user requirements. Further, no system evaluated can meet the collision avoidance requirements of land users because of the high availability requirements of railroads (100%) or the high accuracy requirements nationwide (1 meter). All other user requirements can be met through a combination of systems, referred to as an architecture. Architectures include systems which individually meet the Federal user requirements for one or more modes: aviation, marine, land, and/or survey.

5.1 Eliminating Systems

Four systems were not considered for the development of composite architectures:

1) FM.
2) WAS 5.
3) WAS 6.
4) Loran-C.

The reasons for excluding these systems are explained in the following paragraphs:

1) FM — FM subcarrier systems do not provide the integrity, availability, and coverage required by aviation and marine users. FM subcarriers may not provide coverage for marine and land users in rugged or remote areas. FM stations cover approximately 80% of the area of North America. Subcarriers broadcast over a smaller area than the complete coverage provided by the FM station. Some FM stations in remote areas do not operate 24 hours a day, and are the only stations available in that area.

2) WAS 5 — Private, GEO satellite-based systems do not meet the integrity and availability requirements of aviation.

3) WAS 6 — Because of the premium that the study team attached to early realization of the benefits available from augmentation systems, LEO satellite-based systems were excluded because of their uncertain time frame of availability and a lack of data concerning the systems.

Overall, private systems such as FM, WAS 5, and WAS 6 have not been designed or developed as navigation aids supporting safety of life operations. Futher, private system

providers are not willing to accept liability inherent with navigation systems use. If private systems were to be chosen as part of a navigation architecture, Federal cooperation, support, and regulation would be necessary to ensure integrity, availability, and continuity of service.

4) Loran-C — A Loran-C system cannot meet aviation integrity and availability requirements. Additionally, the role of Loran-C in a satellite-based navigation system is under study at this time. Use of Loran-C as an additional ranging signal in an integrated navigation system has been proposed, but to date, no empirical data is available. Research on the use of Loran-C in a GPS-based system continues.

Combinations of the remaining systems were used to develop composite architectures.

5.2 Composite Architectures

To meet the requirements of the various Federal users, any architecture will require at least two augmentation systems: one primarily focused on the requirements of users operating on the earth's surface, i.e. land, marine, and survey users; and one primarily addressing the requirements of aviation users. It is recognized that some aviation users might employ the surface/marine local area system, and some land-based users might employ the wide area aviation system.

While any architecture requires at least two separate systems, there should be maximum commonality and sharing of resources between all elements to eliminate duplication of effort and resources. The study team proposed six potential architectures, each intended to satisfy as many user requirements as possible:

Architecture 1. This architecture, the baseline system, consisted of the GPS augmentation systems currently planned by USCG and FAA. It included the 61-site local area differential GPS (LADGPS) system currently being implemented by USCG for marine use, the FAA's Wide Area Augmentation System (WAAS) as currently planned to satisfy aviation requirements for en route through Category I precision approach, and FAA's LADGPS systems to satisfy Category II/III precision approach requirements. All of the reference stations included in this architecture would be compliant with the Continuously Operating Reference Station (CORS) standard. Such stations would have the capability of storing a standardized set of data to support the widest possible number of post-processing applications. Although Architecture 1 did not satisfy many land transportation and survey requirements, it was included to provide a benchmark against which the remaining five, more viable, alternatives could be compared.

Architecture 2. This architecture consisted of an expanded version of USCG's LADGPS system to provide nationwide coverage for marine <u>and</u> land users. It also included FAA's WAAS as currently planned to satisfy aviation requirements for en route through

Category I precision approach, and FAA's LADGPS systems to satisfy Category II/III precision approach requirements. All of the reference stations included in this architecture would comply with the CORS standard.

Architecture 3. This architecture consisted of an expanded version of USCG's LADGPS system to provide nationwide coverage for marine and land users and a variant of FAA's WAAS to satisfy aviation requirements for en route through nonprecision approach only. Category I, II, and III precision approach requirements would be satisfied by FAA's LADGPS systems. All of the reference stations included in this architecture would comply with the CORS standard.

Architecture 4. This architecture included an expanded version of USCG's LADGPS system to provide nationwide coverage for marine and land users. It also included a modified version of FAA's WAAS, which provided corrections at other than the GPS L1 frequency, to satisfy aviation requirements for en route through Category I precision approach. Category II/III precision approach requirements would be satisfied by FAA's LADGPS systems. All of the reference stations included in this architecture would comply with the CORS standard.

Architecture 5. This architecture included an expanded version of USCG's LADGPS system to provide nationwide coverage for marine and land users. It also included a modified version of the FAA's WAAS which would encrypt all of the corrections for increased security. The modified WAAS would satisfy aviation requirements for en route through Category I precision approach. Category II/III precision approach requirements would be satisfied by FAA's LADGPS systems. All of the reference stations included in this architecture would comply with the CORS standard.

Architecture 6. This architecture included an expanded version of USCG's LADGPS system to provide nationwide coverage for marine and land users and to satisfy aviation accuracy requirements for Category I precision approach. It also included a variant of the FAA's WAAS to satisfy aviation requirements for en route through nonprecision approach. Category II/III precision approach requirements would be satisfied by FAA's LADGPS systems. All of the reference stations included in this architecture would comply with the CORS standard.

Architecture 6 was evaluated extensively as it appeared capable of meeting stated requirements at a lower cost than the other five architectures. In the course of the evaluation, it was found that possible interference of signal reception could occur to aircraft which were flying through conditions conducive to the creation of precipitation static (P-Static). While an extensive study had not been performed of this phenomenon, it raised significant concerns about signal availability. Consequently, Architecture 6 was not considered in the second stage of the decision matrix.

5.3 Architecture Evaluation

Each of the five remaining architectures were evaluated using the second stage of the decision matrix, which constituted a modified version of a classic multi-attribute utility analysis. The development of the decision matrix is described in detail in Appendix J. The second stage of the matrix consisted of a model with three major parameters: Performance, Cost, and Security. These parameters were broken down into several different factors, and each architecture was scored for each factor. A brief description of each of the factors and their scoring is provided below.

Performance Factors:

- Real Time Accuracy — This score reflects how well an architecture meets the real time accuracy requirements.

- Integrity (Time to Alarm) — The time to alarm score reflects how well a system provides timely warnings to users when the system or parts of the system should not be used.

- Availability — The availability score reflects architecture performance, without failure, over a one-year period. Availability is the probability that service, meeting the coverage constraints, will be available to the user.

- Time Frame of Availability — The score for time frame of availability reflects the ability of a system to meet an initial operating capability between 1996 and 1998.

- Coverage — The coverage score reflects the architecture's ability to provide service in a geographic area.

- International Compatibility — This score reflects how compatible and acceptable this architecture is to the international community. It includes compatibility with international standards and agreements, as well as ease of use in a seamless worldwide infrastructure.

Cost Factors (estimated in FY 94 dollars):

- Infrastructure Cost — This cost score reflects the cost of initial implementation and the 20 year life cycle cost for the architecture.

- User Equipment Cost — This score reflects the cost of equipment to the user.

Security Factors:

- Access Control — This score reflects the capability to selectively deny unauthorized use through command and control features of the architecture.

- Level of Influence — This score reflects the level of political influence and managerial control the U.S. has over denying use of the architecture.

- Interdiction — The interdiction score reflects the U.S. and allied military forces' ability to deny any adversary's military use of an architecture's enhanced performance, through a nonelectronic physical means, within a theater of operations.

- Post-Decision Response Time — The post-decision response time score reflects the time required to implement denial once the decision to deny access to the architecture has been made.

- Jammability — The jammability score reflects the ability of U.S. and Allied forces to electronically deny an adversary's use of an architecture.

- Vulnerability of Denial — The vulnerability of denial score reflects an assessment of how easily the access control features of the architecture can be circumvented by unauthorized users.

Weights were assigned to each factor in the matrix as an indication of that factor's relative importance to the overall goals of this study. The weights for evaluation factors were developed in an iterative process by the study team and the Working Group.

The scores for the evaluation factor were multiplied by the weight assigned to the factor to obtain a weighted score. Overall Performance, Cost, and Security scores for each architecture were obtained by summing the weighted score column.

Scores, weights, weighted scores, and total scores for the various architectures are shown in Tables 5-1 through 5-3. Detailed explanations for the scores assigned to each architecture are contained in Appendix K.

Table 5-1. Weighted Analytical Decision Matrix - Performance

		ARCHITECTURES									
		1		2		3		4		5	
		USCG+WAS-1		USCG(E)+WAS-1		USCG(E)+WAS-2		USCG(E)+WAS-3		USCG(E)+WAS-4	
Evaluation Parameters	Weight	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
PERFORMANCE											
Real Time Accuracy	23.5	80	1880	80	1880	80	1880	80	1880	80	1880
Integrity (Time to Alarm)	21.5	100	2150	100	2150	100	2150	100	2150	100	2150
Availability	19.5	90	1755	90	1755	90	1755	90	1755	90	1755
Time Frame of Availability (IOC)	15.5	95	1472.5	90	1395	90	1395	0	0	0	0
Coverage	14.5	0	0	90	1305	90	1305	90	1305	90	1305
International Compatibility	5.5	95	522.5	95	522.5	85	467.5	88	484	30	165
Total Performance Score			7780		9007.5		8952.5		7574		7255

Table 5-2. Weighted Analytical Decision Matrix - Cost

		ARCHITECTURES									
		1		2		3		4		5	
		USCG+WAS-1		USCG(E)+WAS-1		USCG(E)+WAS-2		USCG(E)+WAS-3		USCG(E)+WAS-4	
Evaluation Parameters	Weight	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
COST											
Infrastructure Cost	50	20	1000	17	850	12	600	17	850	0	0
User Equipment Cost	50	14	700	14	700	9	450	9	450	0	0
Total Cost Score			1700		1550		1050		1300		0

Table 5-3. Weighted Analytical Decision Matrix - Security

		ARCHITECTURES									
		1		2		3		4		5	
		USCG+WAS-1		USCG(E)+WAS-1		USCG(E)+WAS-2		USCG(E)+WAS-3		USCG(E)+WAS-4	
Evaluation Parameters	Weight	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
SECURITY											
Access Control	37	0	0	0	0	50	1850	0	0	75	2775
Level of Influence	19	80	1520	80	1520	80	1520	80	1520	90	1710
Interdiction	14	0	0	0	0	100	1400	0	0	100	1400
Post-Decision Response Time	13	80	1040	80	1040	80	1040	80	1040	80	1040
Jammability	11	5	55	5	55	100	1100	30	330	100	1100
Vulnerability of Denial	6	50	300	50	300	50	300	50	300	50	300
Total Security Score			2915		2915		7210		3190		8325

The five architectures are compared on the basis of performance vs. cost, performance vs. security, and security vs. cost in Figures 5-1 through 5-3. The upper right quandrant of each chart represents the location for the most desirable architectures. The numbers that label the data points on the charts correspond to the architectures referred to in Tables 5-1 through 5-3. The figures indicate that Architecture 2 provides the best performance vs. cost, Architecture 3 provides the best performance vs. security, and Architecture 3 provides an intermediate level of security at an intermediate cost.

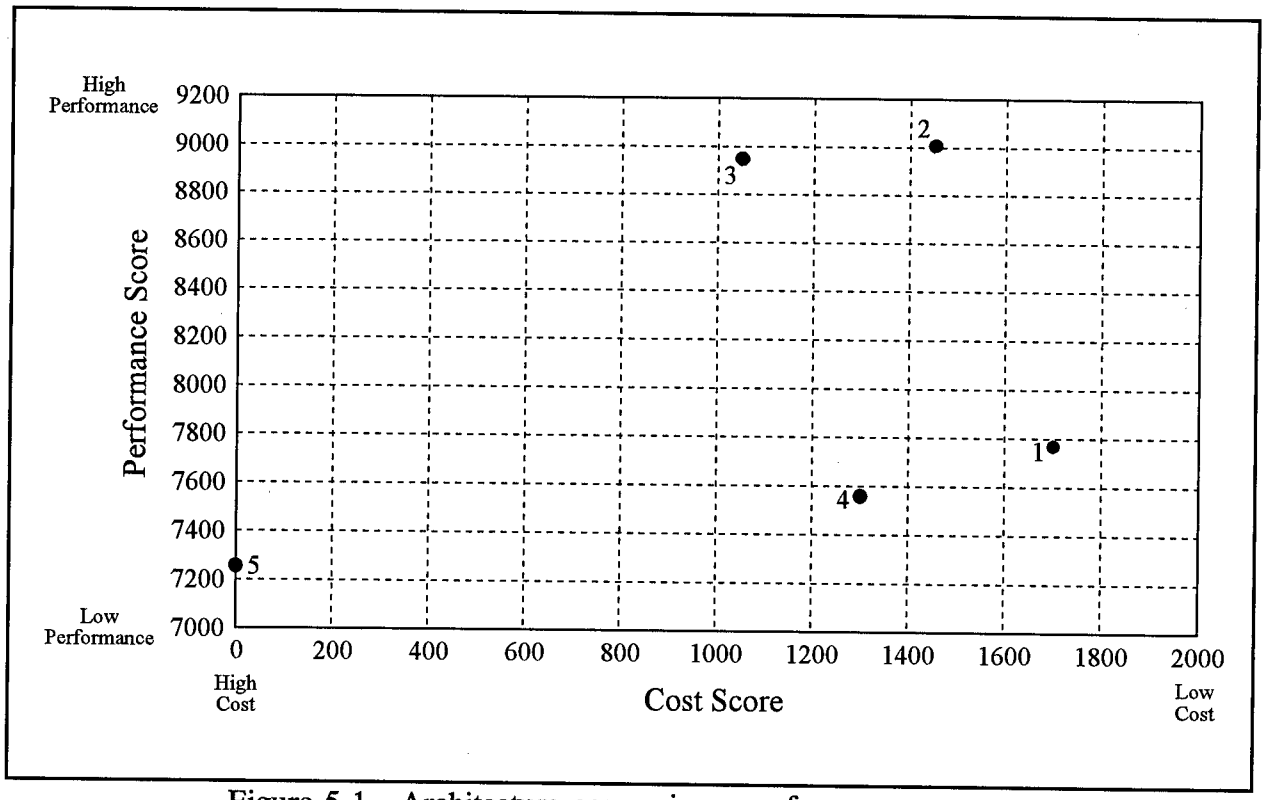

Figure 5-1. Architecture comparison, performance vs. cost.

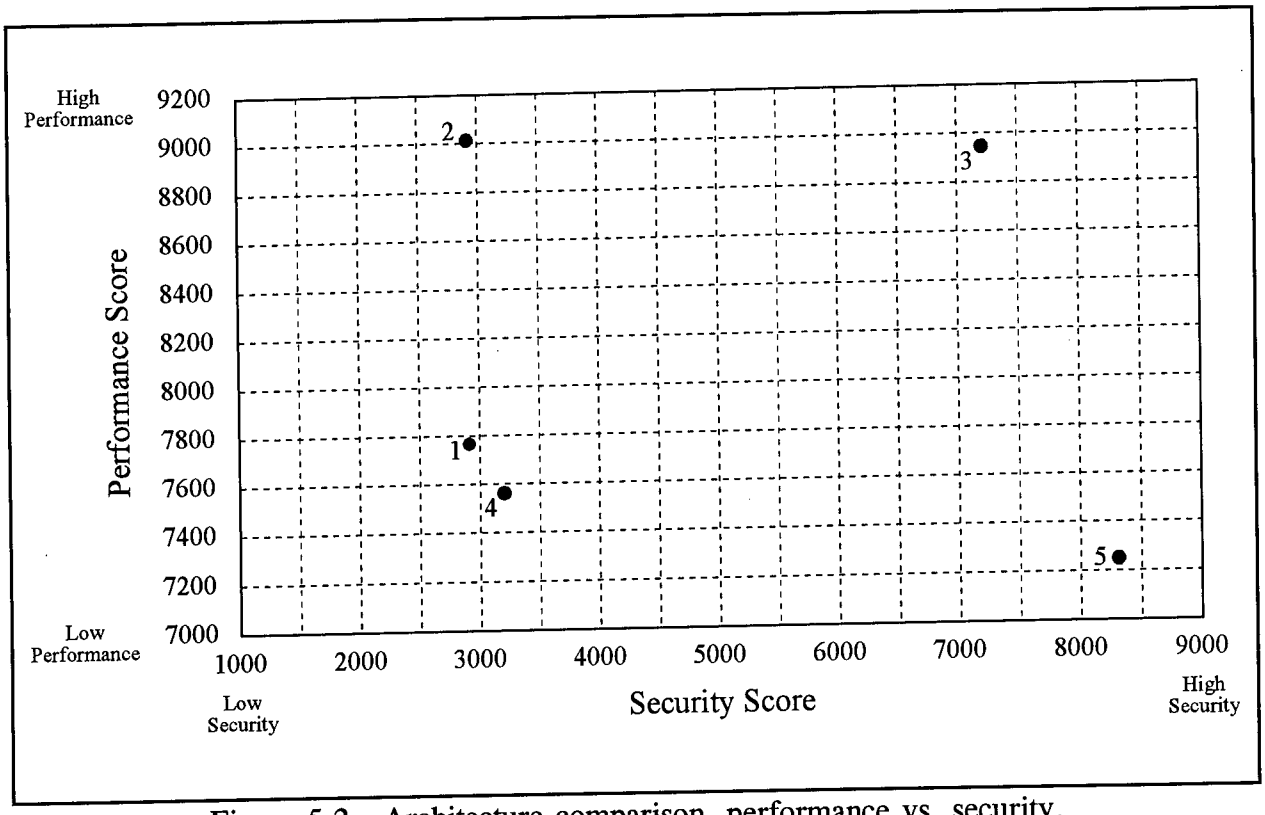

Figure 5-2. Architecture comparison, performance vs. security.

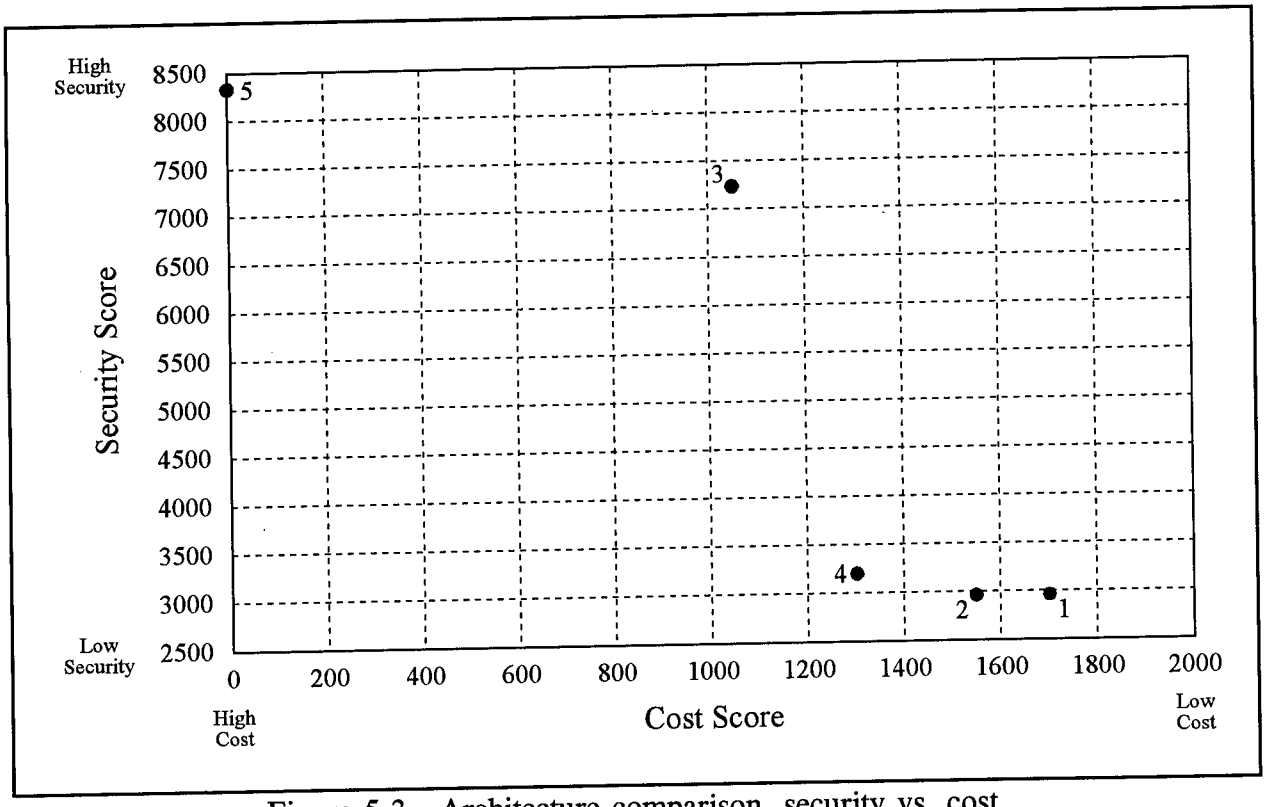

Figure 5-3. Architecture comparison, security vs. cost.

5.4 Summary of Results

Architecture 1, USCG/WAS 1/CORS — This architecture is included as a baseline architecture for comparative purposes. This is the default architecture which would be in place if no actions are taken. It does not meet the minimum requirements for Federal users and cannot serve as the Federal augmentation system. This architecture ranked third in overall performance because its does not meet the minimum requirements for coverage. As the least expensive architecture, it ranked first for cost. It ranked last for security because of the wide area broadcast of differential corrections on the L1 frequency.

Architecture 2, USCG(E)/WAS 1/CORS — This architecture ranked first in performance because it had the earliest IOC and scored highest for international compatibility. It ranked second for cost since the increase in cost for the expansion of the USCG system is minor when compared to the cost of the accuracy component of the WAAS. It ranked last for security because of the wide area broadcast of differential corrections on the L1 frequency.

Architecture 3, USCG(E)/WAS 2/CORS — This architecture ranked second in performance because it had a later IOC and a lower international compatibility score than Architecture 2. It ranked fourth for cost because it required an additional 620 LADGPS systems for Category I precision approach requirements. It ranked second for security because it does not provide wide area broadcast of differential corrections.

Architecture 4, USCG(E)/WAS 3/CORS — This architecture ranked fourth in performance because it had a later IOC date and a lower international compatibility score than other architectures. It ranked third for cost because of the relocation of the WAAS downlink to a frequency other than L1, resulting in higher infrastructure and user equipment costs. It ranked third for security because of the wide area broadcast of differential corrections.

Architecture 5, USCG(E)/WAS 4/CORS — This architecture ranked fifth in performance because of the late IOC date and low international compatibility score. It ranked fifth for cost because of the addition of encrypted WAAS data links. It ranked first for security because of the addition of encrypted WAAS data links.

6
RECOMMENDATIONS

This section presents the study conclusions and recommendations based upon the requirements of users, available technologies, and the evaluation contained in this report. The recommendations are subdivided into two categories, architecture recommendations and architecture independent recommendations.

6.1 Recommended Architecture

There are two candidates that could be selected as the National augmentation architecture. The selection of one of these two viable alternatives is dependent on overall U.S. Government policy regarding augmentation systems.

- If security concerns are not the overriding consideration and do not predominate over other benefits available from an augmented GPS, composite Architecture 2 is the recommended National augmentation system.

- If, however, security concerns are of such significance as to predominate over economic and other benefits available from an augmented GPS, then Architecture 3 is the recommended National augmentation system.

Either of these architectures will meet aviation user requirements for all phases of flight, marine user requirements for all modes of operation, and most land user requirements including IVHS, railroad, and survey. However, neither architecture will satisfy highway collision avoidance because of the high degree of accuracy (1 meter) required nationwide. Neither architecture will provide the 100% availability required for railroad collision avoidance. These applications may require the development or use of other technologies either in conjunction with GPS or independent of GPS.

6.2 Architecture Independent Recommendations

Based on its research and evaluation, the study team also recommends the following:

- FAA should continue to implement its WAAS and LADGPS systems as currently planned.

- DOT, in coordination and cooperation with DOC, should plan, install, operate, and maintain an expanded low frequency/medium frequency beacon system modeled after

USCG's LADGPS system to provide nationwide coverage for land and marine users. Prior to implementing this system, a study should be performed to determine the number and optimum location of beacons necessary for nationwide coverage.

- All Federally-provided reference stations should comply with the CORS standard.

- DOT should continue to evaluate system risks and appropriate measures needed to ensure safe and reliable augmentation services. Further, DOT, with the assistance of DOD, should test and evaluate measures to mitigate the susceptibility of Federally-provided augmentation systems to all forms of interference, including jamming and spoofing.

- DOT, in conjunction with other Federal agencies, should coordinate the implementation, operation, and maintenance of all Federally-operated augmented GPS systems to ensure optimal use of resources by maximizing commonality of system components.

- Different formats for augmentation data have been developed to meet the requirements of particular user communities and to make optimum use of data links planned for augmenting GPS. For the architectures considered, there is no compelling technical or economic reason for developing a single, standardized data format for use by all Federally-operated augmentation systems. Consequently, no effort should be expended on the conversion of existing broadcast formats to a common data format in the near term. Use of the Receiver Independent Exchange (RINEX) format is recommended for post-processing applications. In addition, an international standards working group should be identified to address any future data format issues.

- A central repository for GPS augmentation information should be maintained. This information should be made available to the public via the existing USCG Navigation Information Service.

- A further study should be undertaken to investigate spectrum allocation and bandwidth requirements for any future, Federally-provided, differential GPS system.

7

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APPENDIX A

ACRONYMS AND ABBREVIATIONS

The following is a listing of acronyms and abbreviations pertinent to the subject of radionavigation in general and the Global Positioning System in particular:

AGPS	Augmented Global Positioning System
A-S	Anti-Spoofing
ASD/C3I	Assistant Secretary of Defense for Command, Control, Communications and Intelligence
ASR	Airport Surveillance Radar
ATC	Air Traffic Control
ATCS	Advanced Train Control Systems
ATCRBS	Air Traffic Control Radar Beacon System
ATIS	Advanced Traveler Information System
ATS	Air Traffic Service
ATMS	Advanced Traffic Management System
AVCS	Advanced Vehicle Control System
AVI	Automatic Vehicle Identification
AVL	Automatic Vehicle Location
AVM	Automatic Vehicle Monitoring
CAT	category
C/A Code	Course/Acquisition Code (GPS)
CCZ	Coastal Confluence Zone
CEP	Circular Error Probable
CGS	Civil GPS Service
CGSIC	Civil GPS Service Interface Committee
CONUS	Continental United States
CORS	Continuously Operating Reference Station
CVO	Commercial Vehicle Operations
DGPS	Differential Global Positioning System
DH	Decision Height
DME	Distance Measuring Equipment
DME/P	Precision Distance Measuring Equipment
DMSP	Defense Meteorological Satellite Program
DOC	Department of Commerce
DOD	Department of Defense
DOI	Department of the Interior
DOP	Dilution of Precision
DOT	Department of Transportation
DR	Dead Reckoning

drms	Distance Root Mean Squared
ECEF	Earth Centered Earth Fixed
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
FAA	Federal Aviation Administration
FAF	Final Approach Fix
FCC	Federal Communications Commission
FEMA	Federal Emergency Management Agency
FHWA	Federal Highway Administration
FL	Flight Level
FM	Frequency Modulation
FMS	Flight Management System
FOC	Full Operational Capability
FRA	Federal Railroad Administration
FRP	Federal Radionavigation Plan
FTE	Flight Technical Error
GA	General Aviation
GDOP	Geometric Dilution of Precision
GHz	Gigahertz
GLONASS	Global Orbiting Navigation Satellite System
GNSS	Global Navigation Satellite System
GOES	Geosynchronous Operational Environmental Satellite
GPS	Global Positioning System
HDOP	Horizontal Dilution of Precision
HF	High Frequency
HHA	Harbor/Harbor Approach
Hz	Hertz (cycles per second)
IALA	International Association of Lighthouse Authorities
ICAO	International Civil Aviation Organization
IFR	Instrument Flight Rules
ILS	Instrument Landing System
IMO	International Maritime Organization
INMARSAT	International Maritime Satellite Organization
INS	Inertial Navigation System
IOC	Initial Operational Capability
ITS	Intelligent Transportation System
ITU	International Telecommunication Union
IVHS	Intelligent Vehicle Highway Systems
JPO	Joint Program Office
kHz	Kilohertz
km	Kilometer
LADGPS	Local Area Differential GPS
LEO	Low Earth Orbiting
LF	Low Frequency

Loran-C	Long-Range Navigation, Version C
MCS	GPS Master Control Station
MARAD	Maritime Administration
MF	Medium Frequency
MHz	Megahertz
MLS	Microwave Landing System
mm	Millimeter
MOA	Memorandum of Agreement
MOPS	Minimum Operational Performance Standard
MSK	Minimum Shift Keying
MTBF	Mean Time Between Failures
NAD	North American Datum
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NCA	National Command Authority
NDB	Non directional Beacon
NGS	National Geodetic Survey
NHTSA	National Highway Traffic Safety Administration
nm	Nautical Mile
NOAA	National Oceanic and Atmospheric Administration
NOS	National Ocean Service
NOTAM	Notice to Airmen
ns	Nanosecond
NSF	National Science Foundation
NTIA	National Telecommunications and Information Administration
NWS	National Weather Service
O&M	Operation & Maintenance
OCS	Operational Control Segment
OMB	Office of Management and Budget
OSD	Office of the Secretary of Defense
OTP	Office of Telecommunications Policy
P-code	Pseudorandom Tracking Code
PDOP	Position Dilution of Precision
POS/NAV	Positioning and Navigation
PPS	Precise Positioning Service
PRC	Pseudorange Correction
PRN	Pseudo Random Noise
PTC	Positive Train Control
PTS	Positive Train Separation
RAIM	Receiver Autonomous Integrity Monitoring
R&D	Research & Development
RF	Radio Frequency
RFI	Radio Frequency Interference
RINEX	Receiver Independent Exchange

RNP	Required Navigation Performance
RRC	Range-Rate Corrections
RSPA	Research and Special Programs Administration
RTCM	Radio Technical Commission for Maritime Services
SA	Selective Availability
SAR	Search and Rescue
SEP	Spherical Error Probable
SIS	Signal in space
SLSDC	Saint Lawrence Seaway Development Corporation
SPS	Standard Positioning Service
SV	Space Vehicle
TMC	Traffic Management Center
TOC	Traffic Operations Center
TVA	Tennessee Valley Authority
UHF	Ultra High Frequency
URE	User Range Error
USAF	United States Air Force
USCG	United States Coast Guard
USDA	United States Department of Agriculture
USGS	United States Geological Survey
USNO	United States Naval Observatory
UTC	Coordinated Universal Time
VFR	Visual Flight Rules
VHF	Very High Frequency
VLF	Very Low Frequency
VOR	Very High Frequency Omnidirectional Range
VSAT	Very-Small Aperture Terminals
VTS	Vessel Traffic Services
WAAS	Wide Area Augmentation System
WADGPS	Wide Area Differential GPS
WAS	Wide Area System
WDGPS	Wide Area Differential GPS
WGS	World Geodetic System
WRC	World Radio Conference

APPENDIX B

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.

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, orderly, and expeditious 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) — A method of navigation that permits aircraft operations on any desired course within the coverage of station-referenced navigation signals or within the limits of self-contained system capability.

Automatic Dependent Surveillance — A function in which aircraft automatically transmit navigation data derived from onboard navigation systems via a datalink for use by air traffic control.

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 navigational 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.

It is important to realize that the term "availability" has different meanings for different systems. For example, the U.S. Coast Guard defines availability as the percentage of time in a one month

period during which a DGPS Broadcast transmits healthy PRC's at its specified output level (e.g., exceeding 75 uV/m for 100 bps broadcast). The specification indicates HDOP < 2.3 is assumed. This definition is also called "broadcast availability" while other sub-definitions include "signal availability" and "user availability." Broadcast and signal availabilities primarily refer to healthy PRC's at the specified output level while user availability takes into account environmental effects such as noise.

The FAA has a much broader definition of availability which is applied to the WAAS. Availability is defined as the probability that the navigation and fault detection functions are operational and that the GPS/WAAS signal in space accuracy, integrity, and continuity of function requirements are met.

For the purposes of this report, the FAA definition of availability applies to aviation requirements and systems designed to meet aviation requirements while the concept of broadcast availability applies to the USCG and other systems. In some cases, the estimated availability may be relative to a year instead of a month.

Block II/IIA — The satellites that will form the GPS constellation at FOC.

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°), circular error probable is the radius of the circle containing 50% of the individual measurements being made, or the radius of the circle inside of which there is a 50% probability of being located.

Coastal Confluence Zone (CCZ) — Harbor entrance to 93 km (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.

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 which affect signal availability.

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% 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% and 98.2%, 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.

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

Full Operational Capability (FOC) — For GPS, this is defined as the capability that will occur when 24 operational (Block II/IIA) satellites are operating in their assigned orbits and have been tested for military functionality and meet military requirements.

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 (geoid) by such direct measurements as triangulation, leveling, and gravimetric observations; which determines the external gravitational field of the Earth and, to a limited degree, the internal structure.

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

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) — For GPS, this is defined as the capability that occurred when 24 GPS satellites (Block I/II/IIA) were first operating in their assigned orbits and were available for navigation use (December 1993).

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

Meaconing — A technique of manipulating radio frequency signals to provide false navigation information.

Mode S — An enhanced mode of secondary surveillance radar (SSR) that permits the two-way exchange of digital data between ground facilities and aircraft. Ground-to-air Mode S signals are transmitted on the 1030 MHz interrogation frequency channel. Air-to-ground Mode S signals are transmitted on the 1090 MHz reply frequency channel.

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 U.S. jurisdiction. System components shared 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; by law, no one else in the chain of command has the authority to take such action.

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.

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

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

Precision Approach — A standard instrument approach procedure in which an electronic glide scope is provided; e.g., the Instrument Landing System (ILS).

ILS Category I (CAT I) — An ILS approach procedure that provides for approach to a height above touchdown of not less than 200 feet and with runway visual range of not less than 1,800 feet.

ILS Category II (CAT II) — An ILS approach procedure that provides for approach to a height above touchdown of not less than 100 feet and a runway visual range of not less than 1,200 feet.

ILS Category III (CAT III) —

IIIA — An ILS approach procedure that provides for approach without a decision height minimum and with runway visual range of not less than 700 feet.

IIIB — An ILS approach procedure that provides for approach without a decision height minimum and with runway visual range of not less than 150 feet.

IIIC — An ILS approach procedure that provides for approach without a decision height minimum and without runway visual range minimum.

GPS Special Category I — A special issuance instrument approach procedure with minima not lower than 200 feet height above touchdown zone or runway visual range of not less than 1,800 feet. Special instrument approach procedures are approved by the FAA for individual operators, but are not published in Federal aviation regulations for public use.

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.

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).

RINEX (Receiver-Independent Exchange) — RINEX is a data format based upon a set of standard definitions for GPS observables (time, phase, range). Use of RINEX allows appropriate software to process RINEX formatted GPS data, even though it is collected using different vendor receivers. Most GPS manufacturers use their own proprietary formats for the data collected using their equipment. Before the advent of RINEX, users had no way to post-process GPS data collected using different vendor equipment, unless they had access to the restricted knowledge about the manufacturer's proprietary format. RINEX removes this

restriction on the user community by providing a standard format which can be used for the post-processing and analysis of GPS data.

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.

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.

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

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.

Survey — The act of making measurements to determine the relative position of points on, above, or beneath the earth's surface.

Surveying — That branch of applied mathematics which teaches the art of accurately determining the area of any part of the earth's surface, the lengths and directions of the bounding lines, the contour of the surface, etc., and accurately delineating the whole on a map or chart for a specified datum.

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.

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

Universal Transverse Mercator (UTM) Grid — A military grid system based on the Transverse Mercator projection applied to maps of the Earth's surface extending to 84°N and 80°S latitudes.

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 parameters describing the size and shape of the earth, the positions of a network of points with respect to the center of mass of the earth, transformations from major geodetic datums, and the potential of the earth (usually in terms of harmonic coefficients).

APPENDIX C

GPS USER'S WORKSHOP AND USER SURVEY

Listed below are the Federal agencies and organizations invited to attend the GPS User's Workshop conducted in March 1994 by the U.S. Army Topographic Engineering Center and the Institute for Telecommunication Sciences:

Advisory Commission on Intergovernmental Relations
Agency for International Development
Arms Control & Disarmament Agency
Bureau of Census
Bureau of Indian Affairs
Central Intelligence Agency
Defense Mapping Agency
Department of Agriculture
Department of Energy
Department of Housing & Urban Development
Department of Justice
Department of Labor
Department of State
Environmental Photographic Interpretation Center
Federal Aviation Administration
Federal Bureau of Investigation
Federal Communications Commission
Federal Emergency Management Agency
Federal Highway Administration
Federal Railroad Administration
Federal Transit Administration
Fish and Wildlife Service
General Services Administration
Geographic Data Service Center
Immigration and Naturalization Service
International Boundary Commission
International Boundary and Water Commission, U.S. & Mexico
Internal Revenue Service
Interstate Commerce Commission
Marine Corps Operational Test and Evaluation Activity
Maritime Administration
Minerals Management Service
National Park Service/National Biological Survey
National Aeronautics and Space Administration

National Geodetic Survey
National Institute of Standards and Technology
National Capital Planning Commission
National Railroad Passenger Corp.(AMTRAK)
National Oceanic and Atmospheric Administration
National Science Foundation
National Marine Fisheries Service
National Transportation Safety Board
National Telecommunications and Information Administration
Naval Oceanographic & Meteorological Command
Naval Operational Test and Evaluation Force
Nuclear Regulatory Commission
Office of Engineering and Technology
Office of Technology Management
Office of Management and Budget
Office of Science & Technology
Office of the Federal Coordinator for Meteorological Service and Support in Research
Panama Canal Commission
Peace Corps
St. Lawrence Seaway Development Corporation
Soil Conservation Service
Tennessee Valley Authority
U.S. Customs
U.S. Geological Survey
U.S. Air Force Operational Test and Evaluation Command
U.S. Army Corps of Engineers
U.S. Army Test and Evaluation Command
U.S. Army Transportation School
U.S. Environmental Protection Agency
U.S. Coast Guard
U.S. Postal Service
U.S. Naval Observatory
U.S.D.A. Forest Service

These agencies and organizations were also asked to complete a survey intended to help the study team identify requirements for augmented GPS services. A copy of the survey begins on the following page.

FEDERAL REQUIREMENTS SURVEY FOR AUGMENTED GPS SERVICES

1. **INTRODUCTION**: A survey is being performed to determine the requirements for augmented Global Positioning System (GPS) services. Many Federal Organizations have requirements to provide or use augmented GPS services and/or support state and local governments or private citizens needing augmented GPS services. It is requested that organizations having or projecting needs to provide or use augmented GPS services for the next 20 years, or which have constituents having such needs, complete the following questionnaire.

   If there are multiple classes or phases of service required, please identify the differing requirements for each. If an organization is cognizant of widely divergent requirements, a separate questionnaire should be completed for each.

   Definitions for minimum performance requirements are consistent with those in the Global Positioning System Standard Positioning Service Signal Specification. Unless otherwise requested, please provide requirements for the service, not individual user equipments.

2. **ORGANIZATION DATA**:

   a. Organization:
   b. Address:
   c. Point of Contact/Title:
   d. Voice Phone: FAX:
   e. Electronic mail address:

3. **DESCRIPTION**: Provide a brief description of your functional requirements for augmented GPS service.

4. **COVERAGE AREA**: Specify the geographic area(s) which must be covered by the augmented GPS service. If there are requirements for different levels of service (e.g. en route navigation and landing approach), provide the coverage areas for each. If multiple, specific sites must be covered, indicate the number of sites as well as coverage area. Stand-alone GPS provides global coverage.

5. **COVERAGE**: Coverage is the probability the system will provide adequate signal coverage of the coverage area assuming the complete system is operating within specification limits. The GPS coverage standards are predicated on having 4 or more satellites in view, above a 5 degree elevation mask, with no local obscura, with 4 satellites providing a Position Dilution of Precision (PDOP) $\leq$ 6, and the constellation having 24 operational satellites located in accordance with the almanac. The standard is that coverage will be $\geq$ 99.9% over any 24 hour period when averaged over the globe. Coverage may be $\geq$ 96.9% at the worst location over any 24 hour period. Systems requiring greater levels of coverage must be augmented. Augmented systems may have different constraints (e.g. redundant satellites, different geometric limits, etc.) and coverage requirements than GPS.

   Specify coverage requirements and constraints.

6. **LOCAL COVERAGE LIMITATIONS**: GPS coverage is predicated on having a clear view of the satellites, with no local signal degradation, and optimal operation of the user's receiver. Specify the spatial and temporal characteristics of local conditions, such as obstructions and heavy foliage, which may reduce coverage of the augmented system. Include conditions which may affect other segments of the system (e.g. terrestrial communications) as well as GPS.

7. **AVAILABILITY**: Availability is the probability that service, meeting the coverage constraints, will be available to the user. Availability is reduced when some portion of the system is removed from service for maintenance or through malfunction. GPS service availability standards are: $\geq$ 99.85% for a typical 24 hour period, averaged over the globe; $\geq$ 99.16% for a typical 24 hour period, at the worst case point on the globe; $\geq$ 95.87% for the worst case 24 hour period, averaged over the globe; and $\geq$ 83.92% for the worst case 24 hour period, at the worst case point on the globe.

   Specify service availability requirements and constraints.

8. **RELIABILITY**: Reliability is the probability that the service error is less than or equal to a threshold value, assuming the coverage and availability criteria are satisfied. The GPS SPS service reliability threshold is not to exceed 500 meters horizontal error. The service reliability standards are: $\geq$ 99.7%, based on a measurement interval of a year and average of daily values over the globe; and $\geq$ 99.79% based on the yearly average of daily values for the worst case point on the globe.

   Specify service reliability requirements and constraints.

9. **FAILURE NOTIFICATION RESPONSE TIME**: Failure notification response time is the time between the time a service element fails (becomes unreliable) and the time a user is notified the element has failed (i.e. made unavailable). GPS failure notification response time may be several hours.

   Specify maximum allowable and statistical failure notification response times.

10. **OTHER INTEGRITY REQUIREMENTS**: Specify any service integrity requirements not covered above.

11. **ACCURACY**: Accuracy is a statistical measure of how consistently the solution conforms to the expected value. Different users may view accuracy in different ways. GPS SPS accuracy standards have been established for predictable accuracy, repeatable accuracy, relative accuracy, and time transfer accuracy. Accuracy standards are predicated on the coverage, availability and reliability constraints having been met. The GPS accuracy standards also assume optimum user receiver operation with no signal degradation by local multipath, foliage attenuation, etc.

    Predictable accuracy represents how well the position solution conforms to "truth." Truth is defined as any location accurately surveyed with respect to the WGS 84 coordinate system. GPS SPS predictable accuracy standards are: $\leq$ 100 meters horizontal error, 95% of the time; $\leq$ 156 meters vertical error, 95% of the time; $\leq$ 300 meters horizontal error, 99.9% of the time; and $\leq$ 500 meters vertical error, 99.9% of the time.

    Repeatable accuracy represents how well a user can return to a position previously established with the same system. GPS SPS repeatable accuracy standards are: $\leq$ 141 meters horizontal error, 95% of the time: and $\leq$ 221 meters vertical error, 95% of the time.

    Relative accuracy represents how well a user position solution relates to a position solution obtained at another location using the same system at approximately the same time. For GPS, an additional constraint is that the solutions at both locations employ the same signals from the same set of satellites. The GPS SPS relative accuracy standards are: $\leq$ 1.0 meter horizontal error, 95% of the time; and $\leq$ 1.5 meters vertical error, 95% of the time.

    Time transfer accuracy represents how well a service user can relate receiver time to Universal Coordinated Time (UTC) as disseminated by the U.S. Naval Observatory. The GPS SPS time transfer accuracy standard is $\leq$ 340 nanoseconds time transfer error (95%).

    Specify type(s) of accuracy required (for position, velocity and time), quantitative accuracy requirements, and statistical basis for the requirements. (NOTE: The GPS SPS Signal Specification does not specify velocity performance standards.)

12. **PROCESSING TIMELINESS (POST-PROCESSING, NEAR-REAL-TIME, OR REAL-TIME):** Describe how long after measurements are made that the positional result is required by the application.

13. **GPS METHOD:** GPS methods include absolute point positioning, kinematic, real-time On-The-Fly, etc. What GPS method is involved in meeting this application?

14. **OBSERVATIONS TYPES:** Describe whether this application requires carrier or code observations.

15. **FREQUENCY of OBSERVATIONS:** Describe whether this application requires single or dual frequency (i.e., L1, L1/ L2).

16. **OTHER MEASUREMENT CRITERIA:** For example, is full wavelength L2 required or is L2 squaring sufficient?

17. **DATA TYPES**: Specify the data types which must be provided by the augmented GPS service. Include data requirements for ancillary functions as well as for the primary service.

18. **DATA ARCHIVING**: Specify any requirements for data archiving. Include: purpose (e.g. post-processing survey, liability records, system performance evaluation, etc.); types of data required; frequency of data recording; and retention time.

19. **DATA COMMUNICATIONS**: Specify any preferred communications methods, frequency bands, modulation methods, etc. for communicating augmented GPS service data. Provide the rationale for any preferences. Include requirements for communication of auxiliary data as well as primary positioning service data. Identify any unacceptable communications methods. Include any requirements for allowable error rates which aren't covered by the service reliability requirements.

20. **UPDATE RATE AND LATENCY**: Update rate is the frequency of transmission of similar sets of data (e.g. pseudo-range corrections for nominally the same set of satellites) needed to provide the minimal acceptable level of service. It is not necessarily the required solution output rate for the user equipment. Latency is the time between the time of

applicability of the data and the time the data is actually received by the user and is available for use. Specify any requirements for data update rates and latency.

21. **SAMPLING RATE:** What is the time period between raw measurement recordings that is required for this application? (Not to be confused with the output rate of position fixes).

22. **COMMAND AND CONTROL**: Specify any system command and control requirements.

23. **SECURITY/LIMITED ACCESS**: Identify and provide rationale for any security requirements or needs to limit access.

24. **COST RECOVERY:** Identify any cost recovery requirements or funding constraints for providing augmented GPS services.

25. **USER EQUIPMENT CONSTRAINTS**: Identify and provide rationale for any user equipment constraints, such as size, weight, power consumption, cost, performance certification, specific integration requirements, etc.

26. **STANDARDS/INTEROPERABILITY**: Identify and provide rationale for any Government and/or industry standards with which the augmented GPS service must comply or be compatible or other systems with which it must be interoperable.

27. **DEPLOYMENT SCHEDULE**: Provide the desired deployment schedule for the augmented GPS service. Identify any legal or regulatory requirements which impose schedule constraints.

28. **ADDITIONAL USERS**: The potential user base for the augmented GPS service is large and varied. This study is focusing on the Federal users. List Federal user(s) that your organization interfaces with that is not represented today but should be contacted to be surveyed. Due to the limitations of time, this study is limited to focus on the Federal user. If your organization interfaces with state and/or local government(s) that would be affected by or benefit by the implementation of an augmented service, list those. Given time, these may also be surveyed.

29. **ADDITIONAL COMMENTS:**

APPENDIX D

GPS BACKGROUND

The Global Positioning System (GPS) is a spaced-based radionavigation system which is managed for the Government of the United States by the U.S. Air Force, the system operator. GPS was originally developed as a military force enhancement system and will continue to play this role. However, GPS also has significant potential to benefit the civilian community in an increasingly large number and variety of applications. In an effort to make GPS service available to the greatest number of users while ensuring that national security interests of the United States are protected, two GPS services are provided. The Precise Positioning Service (PPS) provides full system accuracy primarily to U.S. and allied military users. The Standard Positioning Service (SPS) is designed to provide a less accurate positioning capability than the PPS for civilian and all other users throughout the world.

D.1 System Description

GPS has three major segments: Space, Control, and User.

The GPS Space Segment is composed of 24 satellites in six orbital planes. The satellites operate in circular 20,200 km (10,900 nautical mile) orbits at an inclination angle of 55 degrees and with a 12-hour period. The satellites are arranged in orbit so that a minimum of 5 satellites are in view at any point on the earth's surface.

The GPS Control Segment has five monitor stations and three ground antennas with uplink capabilities. The monitor stations use a GPS receiver 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 user equipment which can be applied in a variety of configurations and integration architectures. User equipment includes an antenna and receiver-processor to receive and compute navigation solutions to provide positioning, velocity, and precise timing to the user.

D.2 Data Link Characteristics

Each satellite transmits three separate spread spectrum signals on two L-band frequencies, Ll (1575.42 MHz) and L2 (1227.6 MHz). Ll 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 identify that this PRN code can be operated as either an 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 containing satellite clock and ephemeris information. Bandwidth and received power characteristics for each of the signals are summarized in Table D-1 below.

Table D-1. Bandwidth and Received Power Characteristics for GPS Signals

Channel	Center Frequency	Bandwidth	Minimum Received Power
L1 C/A*	1575.42 MHz	2.046 MHz	-160.0 dBW
L1 P(Y)	1575.42 MHz	20.46 MHz	-163.0 dBW
L2 P(Y)	1227.6 MHz	20.46 MHz	-166.0 dBW

*SPS signal

In order to support civilian GPS applications, the SPS user is guaranteed system access through the use of the L1 C/A signal while the P(Y) code on L1 and L2 is reserved for PPS requirements. System accuracy for the SPS user is maintained through the use of Selective Availability (SA). SA is the means by which the U.S. intentionally degrades full system accuracy to an unauthorized user (i.e., SPS users) by corrupting satellite clock and ephemeris data. SA was developed by the U.S. to ensure that an adversary does not use GPS as a military force enhancer against the U.S. and its allies.

The navigation data contained in the signal is composed of satellite clock and ephemeris data for the transmitting satellite plus GPS constellation almanac data, GPS to UTC time offset information, and ionospheric propagation delay correction parameters for single frequency 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 is sent 25 separate times so that the minimal data required to perform navigation fixes repeats every 30 seconds.

D.3 Acquisition Time

Receiver acquisition time from a cold start varies between receiver manufacture designs and surrounding environmental conditions (i.e., dynamics, terrain masking). Nominally, a receiver's

time to first fix is 1 to 3 minutes. Once a position fix is established, the receiver fix rate is continuous with nominal 1 Hz update rates.

D.4 Computational Requirements

The concept of 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 data that are continuously transmitted by the satellite (every 30 seconds). 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, the receiver is able to perform ranging measurements between the individual satellite and the user by multiplying the satellite signal propagation time by the speed of light.

These measurements are combined to yield system time and the user's three-dimensional position and velocity with respect to World Geodetic System, 1984 (WGS-84) Earth Centered-Earth Fixed (ECEF) coordinates. Standard coordinate transformations are then performed within the receiver to provide user position and velocity in local coordinates (e.g., North American Datum 1987 latitude, longitude, and altitude coordinates).

A receiver requires four simultaneous measurements from four separate satellites to determine position in three dimensions and time. The receiver uses the four simultaneous measurements to yield four mathematically linearized equations with four unknowns from which the four unknowns can be solved (e.g., latitude, longitude, altitude, and time). If the user needs only two-dimensional positioning and time determination, only three simultaneous satellite measurements are required for three equations and three unknowns (latitude, longitude, and time). If the user needs only time determination, only one satellite measurement is required for one equation and one unknown (time).

D.5 GPS SPS Performance

SPS is the standard specified level of positioning and timing accuracy that is available, without restrictions, to any user on a continuous worldwide basis. The accuracy of this service is established by the DOD and DOT based on U.S. security interests. SPS performance levels are documented in the *Global Positioning System Standard Positioning Service Signal Specification* [1]. This specification states that at a minimum, the SPS user is guaranteed performance as follows:

> **Coverage:** The probability that four or more GPS satellites are in view over any 24-hour interval, with a PDOP of 6 or less, with at least a 5 degree elevation mask angle is at least 99.9% (global average).

Availability: Provided there is coverage as defined above, the SPS will be available at least 99.85% of the time (global average). Availability of the GPS signals is subject to accidental failure of one of the satellites and to regularly scheduled maintenance periods. It is estimated that there will be an average of 1 accidental failure per year with a maximum of perhaps 3. Resolution might be a simple remote reprogramming of the system, but it also might require replacement by spare satellites that have been parked in orbit or that must be newly launched. Clearly such replacements could take quite a lot of time, but the purpose of having 24 satellites in the first place is that even with one or two out of service the remainder should still supply adequate signals. When a failure occurs, the satellite software will usually respond immediately to take that signal out of service. On occasion, however, this may require manual operation and that in turn may require as much as 6 hours. Regular maintenance should take one satellite out of service about every 10 days. Maintenance operations may require up to 24 hours.

Reliability: Conditioned on coverage and service availability, the probability that the horizontal positioning error will not exceed 500 meters at any time is at least 99.97% (global average).

Accuracy: SPS provides a predictable positioning accuracy of 100 meters (95%) horizontally and 156 meters (95%) vertically and time transfer accuracy to UTC within 340 nanoseconds (95%).In reality, however, accuracy is partially dependent on the design of the GPS receiver and some manufacturers have achieved considerably better results through the use of predictive filters, carrier-phase reception, and (L1/L2) comparisons. Such steps make the receivers more complicated (and more expensive) but they point out the fact that their development is an ongoing process with a promising future.

D.6 GPS PPS Performance

PPS is the most accurate direct positioning, velocity, and timing information continuously available, worldwide, from the basic GPS. This service is limited to users specifically authorized by the U.S. PPS coverage, availability, and reliability performance is identical to the SPS. PPS provides a predictable positioning accuracy of at least 22 meters (95%) horizontally and 27.7 meters (95%) vertically with a time transfer accuracy to UTC within 200 nanoseconds (95%).

D.7 References

[1] U.S. Department of Defense, *Global Positioning System Standard Positioning Service Signal Specification*, Washington, DC, November 1993.

APPENDIX E

JAMMING AND SPOOFING OF AUGMENTED GPS

The inherent precision, coverage, and availability provided by a Federally-operated Augmented GPS (AGPS) architecture will potentially make it a national asset that is quickly embedded into the U.S. infrastructure. Since GPS Augmentations will provide accuracies of 1-5 meters (95%), versus GPS SPS accuracies of 100 meters (95%), applications employing GPS augmentations will be much more sensitive to system perturbations than those applications using the basic GPS SPS.

Currently identified AGPS applications encompass very large and diverse user populations such as precision landing systems, air traffic control, railway management, inland waterway navigation, harbor/harbor approach navigation, and telecommunication systems. Service disruptions or undetected errors in such applications can result in risk to life, property, and/or U.S. commerce. Consequently, consideration needs to be afforded the following in fielding and operation of Federal augmentations:

- Service Disruption: What risk is there to disruptions to the U.S. infrastructure and its ability to conduct normal commerce as a result of a service failure or interruption? How severe and what additional risks are incurred due to service failures or interruptions?

- Environmental Impact: What risk is there for ecological disasters occurring due to a service failure or interruption?

- Property Damage: What risk is there for property damage occurring due to a service failure or interruption?

- Human Life: What risk is there to human life due to a service failure or interruption?

- Liability: What are the liability implications for providing a radionavigation and positioning service?

Vulnerabilities must be recognized and quantified so that appropriate countermeasures can be developed. Foremost of these is the vulnerability of GPS and its augmentations to jamming and spoofing.

E.1 Jamming and Spoofing

The term "jamming" refers to intentional and unintentional radio frequency (RF) interference of transmitted signals received by a user. The term "spoofing" refers to the transmission of counterfeit signals to provide undetectable falsification of service.

Unintentional jamming includes known RF sources that coincidentally interfere with the GPS or AGPS signal. Typical sources that can unintentionally interfere with GPS or AGPS systems include mobile communication systems and television station transmitters.

Intentional jamming and spoofing sources include signals deliberately transmitted to interfere with the GPS or AGPS signal. The objective of an intentional jammer or spoofer is to cause havoc in system applications resulting in total denial or mistrust of the system. Jamming and spoofing can be accomplished using information from open literature which defines signal format and data structure and off-the-shelf hardware and software. Persons or groups who might want to intentionally jam or spoof GPS or AGPS systems would include hackers, extortionists, and terrorists.

E.1.1 GPS Jamming

The GPS uses a spread spectrum signal design which provides some inherent resistance to jamming. Spread spectrum signals provide a means for a receiver to enhance the power of a GPS signal spread over a given frequency band, while conversely dispersing a high power jamming signal transmitted at a given frequency. Several GPS augmentations have identified a spread spectrum signal structure transmitted on L1 similar to that used by GPS.

However, the GPS signal is vulnerable to jamming. The ability to jam a GPS signal is predominately a function of a jammer's radiated power and the distance between the receiver and jamming source. Since GPS received power levels are very low, radiated power from the jamming source can be fairly low and still affect fairly large areas.

Upon entering a jammer's sphere of influence, a typical GPS receiver will initially loose carrier lock, but maintain code lock, which may result in aberrant position solutions. Once a receiver is totally within a jammer's sphere of influence, the GPS receiver will loose code lock resulting in total loss of GPS positioning capability. Even if an AGPS system is not using GPS's L1 frequency, all AGPS services will be disrupted since they all rely on GPS signal availability.

As GPS receivers become more numerous, concerns over identifying and mitigating RF interference sources continue to increase. Tests conducted in England have demonstrated that GPS users can be jammed to a range of 95 kilometers by a 1 Watt jammer. Field tests have demonstrated that FCC-compliant television transmitters output signal harmonics that can unintentionally jam GPS signals. Test results indicate that, depending on the television channel

and emitted power, a television station can interfere with GPS receivers within a 16 kilometer radius for land users and even greater distances for airborne users.

E.1.2 GPS SPS Spoofing

A spoofer must emulate a GPS signal and "capture" users within a specific target area. To "capture" a user, the spoofer must manage signal levels received at the user location. Spoofer power must be high enough to ensure that the receiver will lock and track on the spoofed signal and yet low enough so as not to be detectable as a spoofer or act like a jammer. Additionally, "capturing" a GPS receiver requires that the spoofer's code phase coincide with the time of arrival of the code phase of the real GPS satellite at the user location. Due to this time-of-arrival constraint, normal expectations are that a spoofer would spoof only one satellite at a time rather than managing complicated time-of-arrival constraints for two or more satellites.

Once "captured," the spoofer introduces errors into the user receiver with either falsified data contained within the spoofer's navigation message, slewing of the code phase, or both. Slewing the code phase also increases the number of potential "captured" user sets as the signal's code phase is swept back and forth to coincide with GPS signals over a given area.

Provided that a spoofer is able to "capture" a user receiver, errors introduced by the spoofer may or may not affect the receiver's navigation solution. A spoofer's ability to introduce errors in the user navigation processing is dependent on whether the spoofed satellite was selected within the receiver as one of the satellites used in computing the navigation solution. Since most receiver manufacturers use common logic for satellite selection, a spoofer using the same satellite selection logic has a high probability of selecting a satellite being used in the GPS receiver's navigation solution. However, assuming that a spoofer is transmitting corrupted data for one satellite at a time, GPS receivers using integrity checking algorithms, such as Receiver Autonomous Integrity Monitoring (RAIM), would most likely detect the spoofed signal as a satellite integrity failure and reject it from inclusion in the navigation solution.

E.1.3 AGPS Spoofing

Since GPS Augmentations rely on some type of a Differential GPS (DGPS) link, spoofing GPS Augmentations may be more effective than spoofing GPS SPS. For local area DGPS (LADGPS) systems, the spoofer would replicate and transmit a "LADGPS" signal with falsified data to users in the surrounding area. "Capturing" LADGPS sets would entail that the spoofing signal be at high enough power to mask out and override the true LADGPS signal level at the receiver. Unlike GPS SPS, no time-of-arrival complexities are involved since the LADGPS signal used does not require code phase synchronization. For GPS Augmentations that provide a ranging capability (e.g., pseudolites and WAAS), the same time-of-arrival constraints as those identified for GPS SPS would apply.

The spoofer introduces errors into the AGPS receiver by transmitting false pseudorange corrections for all satellites in view using the appropriate AGPS format and signal structure. Unlike a GPS SPS spoofer that imitates only one GPS satellite, an AGPS spoofer can corrupt data for every satellite visible. Doing so ensures that corrupt navigation solutions will result regardless of which satellites the receiver uses in its navigation solution. In addition, spoofing all satellites in view may bypass commonly used integrity detection algorithms used within AGPS receivers, hence the spoofer is able to falsify service and remain undetected.

E.2 Conclusion

DOT's January 1994 Strategic Plan has established the goal to "Promote Safe and Secure Transportation." To meet this objective, the plan specifies that DOT will "Identify and implement new measures to enhance security on all modes of transportation to achieve personal security and national security goals."

DOT should continue to evaluate system risks and appropriate measures needed to ensure safe and reliable augmentation services. Further, DOT, with the assistance of DOD, should test and evaluate measures to mitigate the susceptibility of Federally provided augmentation systems to all forms of interference including jamming and spoofing.

APPENDIX F

EVALUATION OF DGPS DATA FORMATS

The purpose of this appendix is to examine existing Radio Technical Commission for Maritime Services (RTCM) and RTCA, Inc. data formats and determine if a common data format can and should be developed which would meet the requirements of users as well as provide an efficient means of transmitting augmented GPS data.

Differential GPS service providers must address four issues regarding the transmission of differential corrections:

1) Select an appropriate communications link.
2) Interface the link with the GPS receivers at the reference and user stations.
3) Choose a modulation technique.
4) Choose the signal and data format.

The following discussion addresses the fourth issue of this list.

F.1 Background

In selecting a data format, several factors must be considered. These include limitations imposed upon the format by the data link chosen, such as:

1) Bandwidth — Information rate and data content define the bandwidth required.

2) Range of coverage — Correction data required varies as a function of the size of the area covered. A local area system usually has a single reference station and reports on all satellites it can view. Typically such systems assume that ephemeris and atmospheric errors in their service area are effectively the same for the user and reference station. A wide area system, however, will have to report on those satellites that can be seen by any user within its wide service area. This may be all GPS satellites plus geostationary satellites. In addition, since some error components are spatially and temporally decorrelated, a wide area system will need to provide corrections for error components such as ionospheric decorrelation, ephemeris error, and clock errors.

3) Update rate — Update rate is a function of the length of time that correction data is considered valid, the dynamics of the user platform, and the level of accuracy the user requires.

4) Noise characteristics — Noise characteristics and effects are a function of frequency. A low frequency transmission (say below 30 MHz) requires a different message structure to accommodate lower data rates and noise characteristics. For communication frequencies above 30 MHz, the noise is relatively low and is white Gaussian in nature. At the lower frequencies the noise, such as that caused by lightning, is impulsive and non-Gaussian. The effects of noise are an important consideration in developing coding techniques to optimize reception.

F.2 Current Standards

There are currently two primary data format standards available for the transmission of differential corrections, RTCM SC-104 and RTCA, Inc. SC-159.

F.2.1 RTCM

RTCM historically has taken the lead in developing standards for use in the maritime community. RTCM developed the initial draft of the RTCM SC-104 format in 1985 to meet marine user requirements for augmentation of GPS. Version 1.0 was published in 1988. The most recent revision, version 2.1, was published in January 1994 [1]. Major factors in the development and ongoing evolution of RTCM have been the desire to maintain a "GPS-like" format data structure and to capitalize on the existing radiobeacon infrastructure.

F.2.2 RTCA, Inc.

RTCA, Inc. performs a similar function for the aviation community that RTCM does for the marine community. RTCA, Inc. is developing formats for FAA's planned Wide Area Augmentation System (WAAS) and FAA LADGPS systems. A draft specification for the WAAS format was published in 1994 [2]. The RTCA, Inc. Special Category (SCAT) I format for LADGPS systems was published in April 1993 [3].

In contrast with LADGPS systems which primarily provide pseudorange corrections from a single reference station, the WAAS also contains information from an integrity and reference monitoring and processing network. Data is collected from reference and integrity monitor sites which are widely dispersed geographically. Measured data is processed to determine integrity, differential corrections, residual errors, and ionospheric delay information for each monitored satellite. The stations also provide timing references for the establishment of WAAS system time. This information is superimposed on a GPS-like signal and broadcast over a wide area from geostationary satellites.

The WAAS Minimum Operational Performance Standard (MOPS) specifies a 250 bit block which is transmitted in one second. Each block contains an 8-bit part of a distributed preamble,

a 6-bit message type, a 212-bit data field and 24-bit Cyclic Redundancy Check (CRC) parity. The block length is consistent with the required time to alarm and any message type can occur in any given one-second interval. The start of the first 8-bit part of every other 24-bit distributed preamble will be synchronous with the 6-second GPS subframe epoch to within the overall WAAS performance requirements. The minimum message set to be decoded by the WAAS receiver for en route and terminal operations is shown in Table F-1 below. Each message type occupies an integral number of 250 bit blocks.

Table F-1. Minimum Message Set Based on RTCA, Inc. MOPS

Type	Contents
0	Don't use this GEO for anything; for WAAS testing.
1	PRN mask assignments, set up to 52 of 210 bits.
2	Fast corrections (clock corrections).
9	GEO ephemeris message (X, Y, Z, time, etc.).
12	WAAS network/UTC offset parameters.
17	GEO satellite almanacs.
18 to 23	Ionospheric grid point mask numbers 1 to 5.
24	Mixed fast corrections/long-term satellite error corrections (clock/ephemeris corrections).
25	Long-term satellite error corrections.
26	Ionospheric error corrections.

An important difference between the WAAS and LADGPS is the fact that the WAAS must provide information on all navigation satellites in the footprint of the geostationary satellite broadcast. This could be most all GPS and GLONASS satellites plus geostationary satellites; there are 52 slots provided for this, 32 for GPS PRNs. To reduce the overhead required, a Type 1 message (PRN Mask assignments) is used to define the "position" of the corrections for each satellite in the following Type 2, 24, and 25 messages. Although this mask assignment requires a full block, it is only broadcast as needed, which is every two to five minutes or after changes. This reduces the overhead required for message headers, since satellite ID's need not be given for pseudorange and ephemeris corrections. Message blocks are timed so that the

correction time stamp used in LADGPS formats is not needed, thus reducing the required data by 13 bits.

Another important difference is that errors resulting from spatial decorrelation become significant, necessitating the broadcast of "slow" corrections for atmospheric delays and ephemeris errors. Ionospheric delay corrections are broadcast as vertical delay estimates at specified ionospheric grid points. The Message Types 18 through 23 are masks for predefined grid points. Message Type 26 contains ionospheric delays at the Ionospheric Grid points. Using this scheme, ionospheric corrections require 7 blocks. Ephemeris corrections (Type 24 or 25) require 1 block for 2 satellites. The messages are designed so that error corrections for satellites with faster changing long term errors can be repeated at a higher rate than ones with slower changing long term errors. Corrections for spatial decorrelation require a significant amount of information, however these are slow corrections and it is anticipated that they will be broadcast at the rate of once per 2 to 5 minutes. RTCA, Inc. proposed rules are that long term satellite error corrections, which are ionospheric delay corrections and GEO navigation messages shall all be broadcast at a rate sufficient not to degrade the user's first fix capability. It should also be noted that broadcast messages will not include any explicit tropospheric corrections.

F.3 Comparison of RTCM and RTCA-LADGPS Data Formats

RTCA, Inc. examined the RTCM format several years ago to determine if the RTCM format could be used to support aviation applications. RTCA, Inc. determined that the RTCM format could not satisfy all aviation requirements and that aviation applications would be better served by a different message format. Specifically, the following information required by aviation users is not supported by the RTCM format:

- RTCM does not support an estimator for Selective Availability (SA).
- RTCM was incompatible with ICAO airport identification standards.
- RTCM did not support aviation integrity requirements. RTCM had only a 30 bit word for integrity, which was considered insufficient given the noise environment on-board an aircraft.
- The RTCM format did not support waypoints for the final approach path.

Two other message types unique to RTCA and not represented by the RTCM format are message types that handle differential corrections during periods of extremely large range corrections and range-rate corrections (Message Types 5 and 6).

Other data format differences between RTCM and RTCA, Inc. are shown in Table F-2.

Table F-2. RTCM/RTCA, Inc. Specifications

	RTCM	RTCA
Station ID	10 bits.	24 bits to provide compatibility with ICAO stds.
Sequence No.	3 bits.	Not used.
Acceleration Error Bound	Not used.	Replaces RTCM Station Health and can be used by avionics to estimate error growth (3 bits).
Station Health	3 bits.	Not used.
Scale Factor	1 bit.	Replaced by Type 5 message.
Large Range Differential Corrections	Provided by scale change in the Type 1 message.	RTCA Type 5 message. In lieu of RTCA Type 1 message for large PRC's and RRC's.
Large Range Differential Corrections when IOD changes	RTCM Type 5 message specifies IOD. Delta PRCs provided by a Type 2 message.	RTCA Type 6 message. Used for delta PRC and RRC during periods of large scale corrections.
SCAT I Waypoint message	Not used.	Replaces RTCM Type 4 message.

F.4 Summary and Conclusions

GPS differential corrections, both local and wide area, are broadcast at many frequencies. The question addressed here has been whether the RTCA, Inc. SC-159 format and the RTCM SC-104 format could move towards one single format that could be used by both user communities. Overall, there seems to be no compelling reasons why in the near term this should occur. It must be mentioned, however, that due to the similarity between RTCM SC-104 and the RTCA SC-159 LADGPS formats, there may be some utility for both user and vendor communities, in devising a single format at some point in the future. If the systems that transmit a particular format are used by those outside the community for which that format was created, there may be cause to revisit this subject. If there is a move towards a single format, it will most likely come from the user community.

F.5 Recommendations

The development of a data link format is a technically challenging effort and requires coordination of users and policy makers. This effort may require several years to complete. For this reason, this study does not recommend that a common data link format be developed for the augmented GPS architecture recommended in this study. The time required for such an effort would significantly impact the scheduled development and deployment of the recommended architecture, thereby delaying the delivery of benefits to users.

This study recommends that a working group within an existing international committee be assigned the responsibility of providing a forum for any future data link format discussions that may arise in the user communities.

This working group should address the following three issues:

1) the information content needed to meet user requirements.
2) the amount of parity protection to be provided.
3) the interface required between the DGPS receivers and the GPS receivers.

F.6 References

[1] Radio Technical Commission for Maritime Services (RTCM) Special Committee No. 104, *RTCM Recommended Standards for Differential Navstar GPS Service, Version 2.1*, Washington, DC, January 1994.

[2] RTCA Inc., *Minimum Operation Performance Standards for Sensors Using Global Positioning System/Wide Area Augmentation System, Draft 1*, Washington, DC, July 1994.

[3] RTCA, Inc. Special Committee No. 159, *Minimum Aviation System Performance Standards DGNSS Instrument Approach System: Special Category I (SCAT-I)*, Document No. RTCA/DO-217, Washington, DC, August 1993.

APPENDIX G

AUGMENTATION DESCRIPTIONS

G.1 Advanced Communications Technology Satellite (ACTS)

The Advanced Communications Technology Satellite (ACTS) is an experimental telecommunications satellite which was built for NASA and launched in 1993. The satellite is a test bed for high gain hopping spot beams, on-board processing, and Ka-band technologies. These technologies provide many different capabilities, including the ability to transmit digital data with a data latency of less than one second at rates up to hundreds of megabytes per second. The major technology developments of ACTS include the use of Ka-band frequencies, multiple spot beams, on-board switching and processing, time division multiple access, and adaptive forward error correction coding.

G.1.1 Ka-band

As data transmission requirements have grown and the geosynchronous arc has begun to fill with C- and Ka-band satellites, it has become apparent there is a need for satellite transmissions to move to higher frequency bands, where more bandwidth is available. The Ka-band (30/20 Ghz) is a candidate for future use. The Ka-band's allotted frequency bandwidth is twice the size of the combined bandwidths of the C- and Ka-bands presently used by commercial satellites. It has been predicted that use of the Ka-band, combined with other technologies used in ACTS could increase the communications capacity of future commercial satellites by as much as five times over current technology.

The Ka-band also has the advantages of smaller antenna size for the same gain and smaller electronic components in general. A drawback of Ka-band for communications systems has been the high susceptibility to fading in rain or snow. ACTS dynamically compensates for this fading with Forward Error Correction coding. Testing underway will show the effectiveness of this method.

G.1.2 Spot Beams

Conventional satellites have antenna patterns which make a footprint on the surface of the earth which concentrates the satellite power on the desired area of coverage, for example the Continental United States (CONUS). However, this beam contouring spreads the satellite signal over the entire continent, while users may actually be concentrated in a few densely populated areas. The ACTS uses high gain spot beams, which focus the satellite signal power only in

those areas where it is required, on demand. The high gain provided by the spot beams allows smaller earth terminals and frequency reuse, in the manner of cellular systems.

G.1.3 On-board Processing

Unlike conventional communications satellites, ACTS has the ability to downconvert and demodulate the uplink signal down to baseband digital, then remodulate and upconvert it to 20 Ghz before retransmission down to earth. This means that the satellite performs as a *regenerative* repeater, isolating the uplink from the downlink. Thus a degradation on the uplink may appear as bit errors in the satellite and be retransmitted, but it does not appear as a weak signal-to-noise ratio which can be further degraded on the downlink. On a link in which uplink and downlink carrier to noise ratios are equal, for example, this results in a 3 dB improvement in the overall link.

Compared to alternative commercial satellite frequency allocations, Ka-band's larger bandwidth allows for higher data transmission rates. In addition to DGPS data, the anticipated capacity of the ACTS will support additional data without any negative impact on the performance of the DGPS. Some examples of additional data that could be supported include corrections and data from multiple DGPS reference stations, digital mapping and terrain data, voice communications, FAX, etc. The satellite's on-board processing and on-board switching should reduce the data latency from the satellite link to a level competing with digital RF radios, resulting in a higher message update rate than conventional satellites. True mobile satellite antennas are also possible through the combined gains of a higher operating frequency and the higher received signal power achieved by focusing the radiated signal into the smaller footprints of the hopping spot beams.

G.2 Global Orbiting Navigation Satellite System (GLONASS)

The Russian Federation is in the process of developing and implementing GLONASS to provide signals from space for accurate determination of position, velocity, and time for properly equipped users. GLONASS will provide high accuracy and availability to users. Navigation coverage will be continuous, worldwide, and all-weather. Three-dimensional position and velocity determinations are based upon the measurement of transit time and Doppler shift of RF signals transmitted by GLONASS satellites.

When fully operational, the GLONASS space segment will consist of 24 satellites (21 operational and 3 spares). GLONASS satellites will orbit at an altitude of 19,100 kilometers with an orbital period of 11 hours and 15 minutes. Eight evenly spaced satellites are to be arranged in each of three orbital planes, inclined 64.8 degrees and spaced 120 degrees apart.

The GLONASS ground segment performs satellite monitoring and control functions and determines the navigation data to be modulated on the coded satellite navigation signals. The ground segment includes monitoring stations, a Master Control Station, and an upload station.

Measurement data from each monitoring station is processed at the Master Control Station and used to compute the navigation data that is uploaded to the satellites via the upload station. Operation of the system requires precise synchronization of satellite clocks with GLONASS system time. To accomplish the necessary synchronization, clock correction parameters are provided by the Master Control Station.

A navigation message transmitted from each satellite consists of satellite coordinates, velocity vector components, corrections to GLONASS system time, and satellite health information. To obtain a system fix, a user's receiver tracks at least four satellite signals, either simultaneously or sequentially, and solves four simultaneous equations for the three components of position and time. A position solution may be derived from three satellites if an external source of time or altitude is provided.

GLONASS satellites broadcast in two L-band portions of the RF spectrum and have two binary codes, the C/A code and the P code, and the data message. GLONASS is based upon a frequency division multiple access concept. GLONASS satellites transmit carrier signals in different L-band channels, i.e., at different frequencies. A GLONASS receiver separates the total incoming signal from all visible satellites by assigning different frequencies to its tracking channels. The use of frequency division permits each GLONASS satellite to transmit identical P and C/A codes.

In GLONASS, the C/A code is modulated onto the L1 carrier only. The P code is transmitted on both L1 and L2. Receivers designed to operate with only the C/A code can use only the L1 signal for ranging. P-code-capable receivers can use both frequencies to measure range. The use of both frequencies provides a means of correcting for ionospheric refraction.

The frequency of the GLONASS P code, 5.11 Mhz, is ten times higher than the frequency of the C/A code, 0.511 Mhz. Since the higher code frequencies generally provide a better range measuring accuracy than lower frequencies, GLONASS has a precise mode of operation with the P code and a less accurate mode using the C/A code. GLONASS is expected to provide accuracies of 100 meters in horizontal position, 150 meters in vertical position, 15 centimeters per second in velocity, and 1 microsecond in time.

Each GLONASS satellite transmits navigation data at a rate of 50 bits per second. The navigation data message provides information regarding the status of the individual transmitting satellite along with information on the remainder of the satellite constellation. From a user's perspective, the primary elements of information in a GLONASS satellite transmission are the clock correction parameters and the satellite position (ephemeris). GLONASS clock corrections provide data detailing the difference between the individual satellite's time and GLONASS system time, which is related to UTC.

To provide ephemeris information, GLONASS satellites broadcast their three-dimensional Earth Centered Earth Fixed (ECEF) position, velocity, and acceleration for every half-hour epoch. For a measurement time somewhere between the half-hour epochs, a user interpolates the

satellites's coordinates using position, velocity, and acceleration from the half-hour marks before and after the measurement time. The resulting ECEF coordinates are referenced to the Soviet Geocentric System 1985.

G.3 Inertial Navigation Systems (INS)

Inertial Navigation Systems (INS) determine change in position by double-integration of specific-force measured by accelerometers. Gyroscopes are used to track changes in the orientation of the INS coordinate frame relative to a fixed, non-rotating coordinate system known as the inertial coordinate frame. The INS reference frame can be aligned to local level and north by sensing the direction of gravity and the earth's spin vector or by comparing inertial velocities to external sources of velocity.

A typical, 3-axis, INS consists of a cluster of three accelerometers and three gyroscopes, orthogonally mounted on a stable element, and associated electronics. There are two generic INS implementations: gimballed and strapdown. In gimballed systems, the inertial sensor assembly (ISA) is isolated from vehicle rotations by a set of motor driven gimbals. The gyroscopically sensed rotation (rate) information is fed back to the gimbal drive motors to maintain a constant ISA orientation in space. Additional gimbal torquing may be applied to orient the ISA in some other desired reference frame (e.g. local level, north pointing.) In strapdown systems, the ISA is mounted directly to the vehicle. Changes in orientation of the ISA, sensed by the gyroscopes, are used to computationally rotate the accelerometer reference frame to the desired output frame.

While the concept of strapdown INS has been understood for a long time, advances in computer and gyro technology were required before strapdown systems became practical. For most applications, modern strapdown systems are mechanically simpler, lighter weight, smaller, more reliable, and less expensive than gimballed systems. Gimballed systems have performance advantages for a few, high accuracy applications because the gyros must track only the gimbal servo-loop errors rather than the total dynamic range of vehicle rotation rates. Angular accelerations, sensed by the accelerometers, also are minimized by a gimballed implementation.

An INS may be mechanized with more than three gyros and accelerometers for redundancy and error checking. Non-orthogonal mounting or incomplete implementations (e.g. 2-axis systems) may be used to meet specific requirements.

Inertial navigation error sources include: instrument biases, instrument noise, instrument and platform misalignments, initial position and velocity errors, and unmodeled gravitational disturbances. Inertial sensor errors vary greatly depending on instrument quality and basic technology. Often, external data sources (e.g. altimeters, doppler radars, and radio navigation aids in aircraft, and odometers and zero-velocity stops in ground vehicles) are used to aid INS. Unaided INS position errors tend to grow with time. High quality INS positions typically have

low latency and small high-frequency error components. The low INS high-frequency and bounded GPS low-frequency error characteristics complement each other.

There are two basic approaches for integrating GPS and INS which are known as loosely-coupled and tightly-coupled. In the loosely-coupled mechanization, the GPS receiver and the INS maintain separate position and velocity solutions. Here, GPS positions and velocities are sent to the INS's Kalman filter for error bounding and instrument calibration (cascading the two navigation filters). Alternately, the outputs of GPS and INS filters can be combined in a third filter. INS positions and velocities can be sent to the GPS receiver to aid tracking loops and satellite acquisition. In a tightly-coupled system, GPS receiver raw data are used directly as measurements in a Kalman integration filter for controlling error in the inertial navigation process, and the compensated INS velocity is used in the receiver to allow narrower tracking loops. Estimated system errors include: errors in the INS nominal position and velocity solution, INS misalignments, gyroscope and accelerometer errors, GPS receiver clock bias and drift, and, possibly, external sensor errors such as barometric altimeter bias.

The loosely coupled approach is, in general, less robust under conditions of multiple satellite obscurations and when high dynamics occur during periods of jamming. Careful tuning of cascaded filters is required to prevent stability problems when INS data is fed back to the GPS receiver. Data latency must be carefully handled when integrating separate boxes. The industry trend seems to be tightly coupling GPS and INS within the same box.

GPS provides several benefits to INS:

- Three-dimensional position and velocity information for position initialization, dynamic alignment, and initializing velocities.

- Bounds on INS position error growth.

- Estimation of residual accelerometer and gyroscope instrument biases (assuming sufficient satellite availability). During subsequent periods of reduced satellite availability, the calibrated performance of the INS will be superior to its nominal performance characteristics until such time as the random errors and bias drifts exceed the nominal bias errors. This may reduce costs by allowing use of instruments with less stable bias errors.

INS also provides several benefits to GPS:

- In cases of total loss of lock (GPS signal) followed by a high-dynamic maneuver, the frequency uncertainty (due to Doppler shift) can be large which may preclude timely signal reacquisition. INS velocity-aiding data can reduce the frequency uncertainty thus increasing the probability of a timely reacquisition.

- The autonomy and rapid response characteristics of INS should enable detection and isolation of many classes of signal-in-space failures that could not otherwise be corrected in a timely fashion by the control segment, RAIM or other receiver processing techniques. In addition, the integration of GPS/INS should prove useful in combatting spoofing.

- The GPS receiver tracking loops must have sufficient bandwidth to account for phase and frequency changes induced by vehicle maneuvers. At the same time, they must be narrow enough to limit the level of interfering noise (e.g. jamming) seen by the phase detector. INS velocities can be used to "steer" the tracking loops for frequency changes caused by vehicle maneuvers, allowing tracking loop bandwidth reductions.

- INS can be used to reduce GPS velocity errors resulting from tracking loop bandwidth limitations and other effects.

The DOD has several embedded GPS/INS systems under development or in procurement. Commercial GPS/INS integrations are still in a relatively early stage of development. Recent advances in inertial component and GPS circuit technology will provide cost reductions currently limiting this expansion.

G.4 Sign Posts

Sign posts are electronic check points at known positions which dynamically update a moving platform's position whenever a sign post is passed. The updated position can be used either by the user or by a remote tracking facility. The sign post transmits a signal which is a formatted message containing the sign post's position and other pertinent information. It is not a ranging signal.

G.5 Dead Reckoning Systems

There are many instances where GPS signals will be blocked or become unusable for the automobile user. This is especially true in the urban environment or where there is a canopy of trees or in tunnels. In these cases, dead reckoning can help maintain a continuous fix for the user. Examples of devices used for dead reckoning include: solid state gyro, differential odometry, magnetic compasses, magnetic flux gates, and accelerometers. Dead reckoning has the problem of accumulated distance error. GPS and dead reckoning can work synergistically to provide a low-cost navigation system particularly suited for land-based vehicles. Map matching could be added to both systems which would be integrated using algorithms which implement Kalman filtering.

The dead reckoning system helps to provide real-time to near real-time solutions in cases where stand-alone GPS may not be usable for periods lasting several minutes in "canyons" due to

terrain, vegetation, and urban environments. With these two systems, integrity of the navigation solution is improved because they can check each other for gross errors.

G.6 Map Matching

Positions refer to actual mathematical coordinates in some reference system. Locations refer to a reference relative to land features such as roads and intersections. Map matching refers to matching the position or path of a vehicle derived by positioning sensors to a corresponding position of path in a digital database. The database must be positionally accurate, geometrically correct, topologically correct, current, and complete.

G.6.1 Horizontal Features

For land vehicles, horizontal features would comprise a digital road network. With a dead reckoning system, map matching would use previous position and heading and current position and heading to match its computed position with the most likely location on the digital road network. Map matching ensures that if a vehicle is physically on a road network, it is displayed on the corresponding digital road network.

G.6.2 Vertical Features

Map matching using vertical features matches vertical profiles obtained from sensors with a vertical profile from a database. Sensors measure the actual terrain profile; a processor "compares" what is being measured with what is stored in the digital database and then makes any necessary steering adjustments to maintain the proper course.

G.7 Continuously Operating Reference Stations (CORS)

G.7.1 Purpose of CORS

The purpose of the GPS Continuously Operating Reference Station(s) (CORS) is to provide code range and carrier phase measurements from reference stations to users to support after-the-fact (often called post-processing or post-mission) differential positioning of both stationary receivers and receivers on moving platforms. Currently, after-the-fact differential positioning is the primary operating mode in the survey and positioning communities. This section summarizes CORS compatibility requirements. An approved standard defining CORS requirements will be available in 1995.

GPS range observations from reference stations are used to compute corrections that allow positioning of stationary receivers at the 1 to 10 meter accuracy level. This is the dominant

mode of positioning of objects and events for input to Geographic Information Systems (GIS). Almost all high-accuracy GPS geodetic positioning at the subdecimeter level is differential positioning relative to permanent or temporary reference stations using GPS carrier phase measurements and after-the-fact computation of positions. With respect to moving vehicles, after-the-fact differential positioning at the meter level using code ranges and at the subdecimeter level using carrier phase ranges are currently employed in such applications as positioning aircraft in aerial photogrammetry, remote sensing, positioning of ships in support of bathymetric and geophysical surveys and positioning of land vehicles to determine road location or the location of objects in digital imagery.

The CORS network is designed to provide a single network of GPS reference stations to overcome problems of duplication, inefficiency, availability, and access. CORS will provide all GPS data types to all positioning users in a single common format, Receiver Independent Exchange (RINEX), with continuous monitoring of station position. Furthermore, sampling rates will be sufficient to satisfy essentially all users.

G.7.2 Definition of CORS — Standards

The CORS concept includes individual GPS reference stations, located nationwide. A standardized set of observations are made at these stations. Included is centralized administration, management, storage, and distribution of GPS observations. CORS supply these reference station measurements for all private, academic, and government users in support of moving and static forms of survey.

The standardized observation set is characterized by:

- Permanent: 24 hours per day; every day.
- L1 C/A code and carrier measurements.
- Full-wavelength L2 carrier when L2 available.
- L2 code when L2 available.
- "All-in-View" GPS satellite tracking.
- 10.0-degree horizon visibility.
- 5 second sample rate or faster; 1 second desirable.
- Receiver manufacturers' raw formats.
- 1-meter L1 code range double differences at epoch.
- GPS observations and Broadcast Message Parameters.
- Weather data desired (Pressure, Temperature, Humidity).
- 15-days on-site data holding or central facility transfer.
- 95% hourly measurement sets received (availability).
- 95% hourly sets received have 95% of data (continuity).

The standardized station is characterized by the following parameters:

- L1 phase center location is official position.
- L2 phase center is desirable.
- NAD-83 geodetic coordinates (latitude, longitude, ellipsoidal height).
- NAVD-88 orthometric height.
- Accuracies (95%):
  latitude - 2 cm.
  longitude - 2 cm.
  ellipsoidal height - 5 cm.
  orthometric height - 10 cm.
- Physical antenna meets wind load guidelines.

G.7.3 The CORS Central Facility (CCF)

The CORS Central Facility will accept the data, actively or passively, from the many CORS facilities. These data will be stored, converted to additional formats, processed, archived, and distributed.

The observations would be placed online for 20 days, nominally within one hour of the observations, on direct access hard disk storage. The original provided data would be in manufacturers' raw formats. The data will be converted to RINEX for distribution. Possibly RTCM and RTCA messages will also be provided, but not in real time. The present method of user access is via the Internet.

These data will be post-processed by NOAA/NGS. In this way definitive geodetic vectors will be computed. These daily vectors will be stored and compared. Should an individual CORS antenna location significantly change for whatever reason this should be quickly detected. Daily processing of these vectors will provide an important baseline for repeatability.

These observational data will be archived in off-line storage (CD-ROM) for a period of time which has not been finalized; one year has been proposed. After one year, these data may be reduced, filtered, and/or compressed for long-term storage. Post-processing solutions will be stored indefinitely.

G.7.4 Status and Plans

The National Geodetic Survey currently operates five prototype CORS which meet the standards presented here. The differential reference stations being installed by the U.S. Coast Guard and the U.S. Army Corps of Engineers will have a CORS capability. The FAA plans to install a Wide Area Augmentation System (WAAS); the WAAS reference stations are planned to comply with the CORS standard.

APPENDIX H

COVERAGE AND AVAILABILITY OF LF/MF RADIOBEACONS

It has been suggested that the U.S. Coast Guard LF/MF Radiobeacon system be expanded to provide DGPS corrections for CONUS. An important question to be considered is how many radiobeacons will be required to provide adequate coverage for DGPS users. To answer this question, from a technical standpoint, four important issues must be considered:

1) Atmospheric (and man-made) radio noise.

2) The ability of minimum shift keying (MSK) receivers to mitigate the effects of the noise (i.e., signal to noise ratio required to achieve an acceptable bit error ratio).

3) LF/MF propagation over ground with varying conductivities.

4) Skywave self interference.

In the LF/MF band, the background noise is primarily due to distant lightning and can be predicted using the methods specified in CCIR Report 332-3 [1]. This does not include effects of nearby electrical storms (which may add perhaps 20 dB to the noise power) and man-made impulsive noise which may be expected in large urban areas.

Issues regarding the ability of MSK receivers to mitigate the effects of impulsive noise are more difficult to quantify. In addition, advances in MSK receivers will likely reduce bit error ratios (BER) for a given signal to noise ratio (SNR). Several authors have published measured and simulated results. For example, data collected at a test bed in Durham, New Hampshire indicate that for a receiver using "hard limiting," an SNR exceeding 10 dB is required to provide a 10^{-3} probability of a "channel error" [2]. It is further reported that forward error correction can reduce the required SNR by one half. Published results of receiver simulations using combinations of nonlinear receiver front ends (hole puncher, floating envelope clipper) and filters indicate that BER's of less than 10^{-3} may be achieved for SNR's near 0 dB [3]. Currently, the Broadcast Standard for the USCG DGPS Navigation Service [4] specifies that an MSK Beacon Receiver should achieve a bit error rate of less than 10^{-3} for an SNR of 7 dB in the 99% power containment bandwidth of the MSK signal.

Table H-1 shows atmospheric radio noise levels exceeded 5%, 1.0%, and 0.1% of the year at a variety of locations throughout CONUS. Major cities are used as a convenient method to specify the geographic region (it should be noted that these values do not include urban noise). For the purposes of this analysis a receiver bandwidth of 120 Hz is assumed, which corresponds

to the bandwidth containing 99% of the modulation spectrum for MSK at 100 bps. The actual noise bandwidth to be considered will, of course, depend on receiver design.

Table H-1. Atmospheric Noise Levels Near Various Cities in CONUS

	E (dB μV/m) exceeded 0.1% of the year	E (dB μV/m) exceeded 1.0% of the year	E (dB μV/m) exceeded 5% of the year
Albuquerque	53.8	41.3	30.8
Atlanta	52	40.6	31.9
Boise	43.2	31.9	22
Chicago	51.5	40.8	32
Denver	53.9	41.1	30.1
Fargo	52.6	41.3	30.3
Houston	52.3	40.3	30.3
Los Angeles	40.5	39.1	20.2
Miami	51.5	40.1	30.8
New York City	40	31	24
Oklahoma City	55	42.5	31.6
Phoenix	44.9	32.9	23.2
Pittsburgh	45	38	28.3
San Francisco	38.1	27	18.6
Seattle	37.5	25.6	16.2
Washington D.C.	42.9	34.2	26.8

The values in the table clearly show that the coastal regions of the northeast and west are significantly quieter than the southeast and central/mountain areas. Currently, the USCG standards specify that radiobeacon coverage extends to the point that the electric field strength drops to 37.5 dB μV/m (for 100 bps transmission). From the predicted levels in Table H-1, we can conclude that this does not provide the required SNR (7 dB) at the fringe of the coverage area if the desired availability exceeds 99%.

Ideally, we would like to estimate the number of radiobeacons required to provide satisfactory DGPS service to users in CONUS. This of course would require an engineering/administrative analysis to determine optimal beacon locations (tempered by relevant legal and practical considerations). Such an analysis needs to address the fact that beacons should be located such that they provide the "best" service (in terms of availability, accuracy, and integrity) to the largest population of users. In the absence of such an analysis, only very crude estimates can be made. Such estimates, however, are useful to planners as they indicate potential problem areas which must be considered and allow one to get at least a loose grip on potential costs.

Signal levels as a function of range from a given radiobeacon may be predicted using groundwave propagation models developed by ITS. The signal level depends on the ground conductivity and radiated antenna power. For the purposes of this study it is assumed that the radiated power for a 1 kilowatt transmitter is 150 watts. Using the results of Table H-1, and ITS LF/MF propagation models, the ranges for a single beacon in the vicinity of various cities as a function of the annual availability of a 0 or 7 dB SNR are tabulated in Table H-2. An alternative view of the situation is shown in Figures H-1 and H-2. From these plots one can find how SNR requirements affect availability or, more generally, how signal quality will vary with time at various distances from the transmitter.

The conductivities specified for a given city are estimates based on conductivities in the region surrounding the city (FCC § 73.190 Figure R3). The conductivities used are shown (in parenthesis by the city) in units of mS/m. The calculations indicate that atmospheric noise dominates range predictions when a high annual availability is desired (i.e., 99.9%), while ground conductivity becomes more important as the desired annual availability decreases.

Table H-2. Range of Individual Beacons (in km) Near Various Cities for 99.9%, 99%, and 95% Annual Availability

	SNR > 7 99.9% of the year	SNR > 0 99.9% of the year	SNR > 7 99% of the year	SNR > 0 99% of the year	SNR > 7 95% of the year	SNR > 0 95% of the year
Albuquerque (10 mS/m)	82	148	219	329	391	525
Atlanta (4)	77	127	166	239	259	349
Boise (6)	166	250	310	418	466	587
Chicago (8)	97	166	212	314	344	465
Denver (10)	82	147	222	332	404	539
Fargo (18)	99	181	248	379	463	620
Houston (10)	94	166	233	346	400	535
Los Angeles (6)	196	287	213	307	496	619
Miami (5)	86	143	187	271	302	403
New York City (3)	150	214	234	313	313	403
Oklahoma City (22)	80	153	235	367	451	612
Phoenix (10)	171	270	353	484	537	680
Pittsburgh (10)	169	268	268	387	438	575
San Francisco (10)	267	386	462	601	630	777
Seattle (3)	172	240	294	381	414	513
Washington D.C. (3)	128	186	202	276	280	366

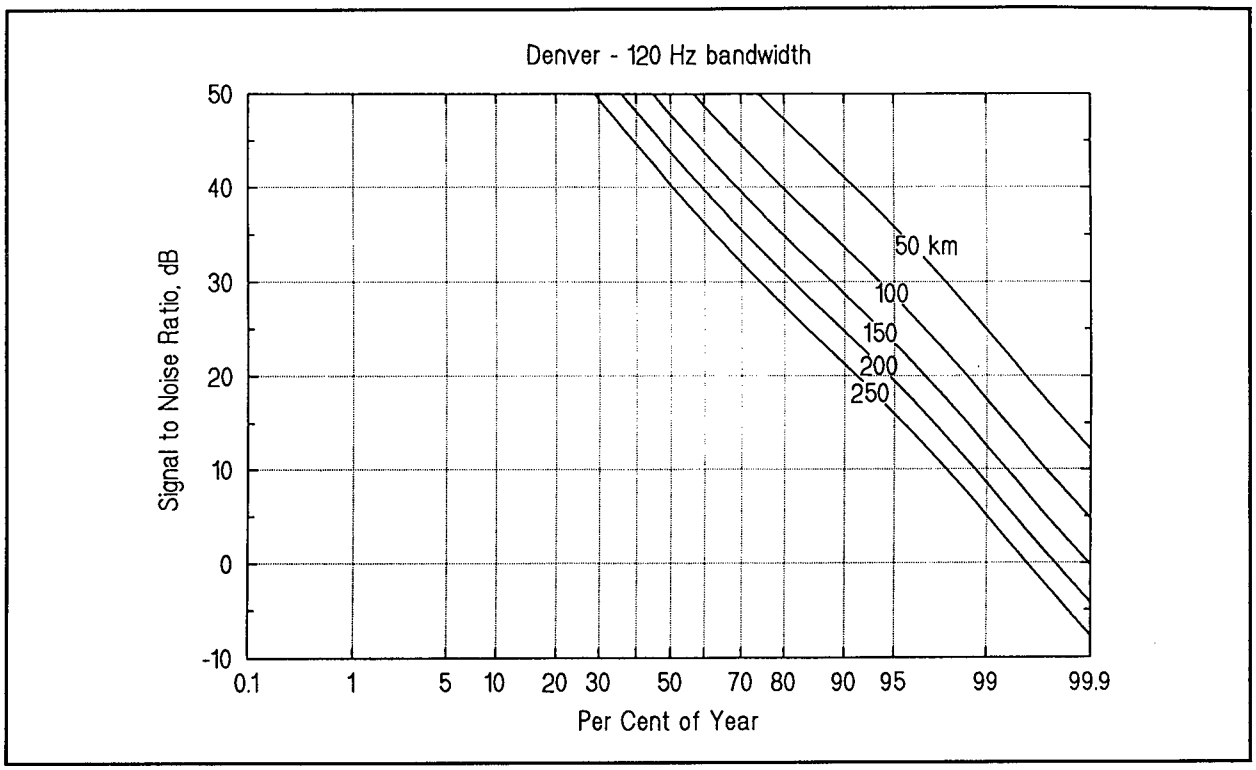

Figure H-1. Cumulative distributions at the indicated ranges of Signal to Noise Ratios as they might appear in the relatively noisy region near Denver. The frequency is 300 kHz, and the radiated power is 150 W.

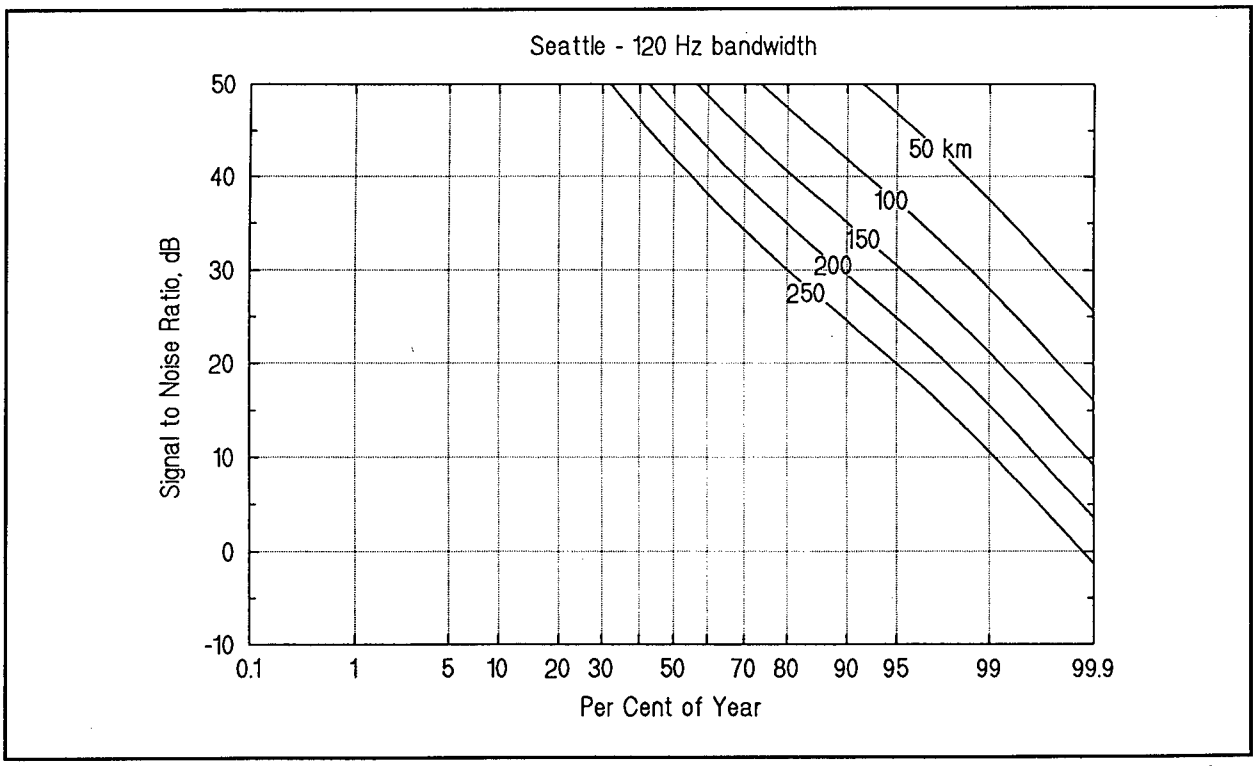

Figure H-2. Cumulative distributions at the indicated ranges of Signal to Noise Ratios as they might appear in the relatively quiet region near Seattle. The frequency is 300 kHz, and the radiated power is 150 W.

One way of predicting the necessary number of radiobeacons (when atmospheric noise dominates) is to assume:

1) Due to overlap, each beacon has a coverage area of 70% of a circle.
2) The mountain/central/southeast noise statistics are relevant to 66% of the total area of the U.S. — ($0.66 \times 8 \times 10^6$ km^2).

Using these assumptions, a very rough prediction based on Table H-2 is:

1) For 99.9% availability and 7 dB SNR, 66% of CONUS would be covered by beacons with a range of roughly 87 km and 34% of CONUS would be covered by beacons with a range of roughly 177 km resulting in an estimated 354 beacons (for 0 dB only 118 beacons are required).

2) For 99% availability and 7 dB SNR, 66 % of CONUS would be covered by beacons with a range of roughly 215 km and 34% of CONUS would be covered by beacons with a range of roughly 292 km resulting in an estimated 65 beacons (for 0 dB only 31 beacons are required).

3) For 95% availability and 7 dB SNR, 66% of CONUS would be covered by beacons with a range of roughly 325 km and 34% of CONUS would be covered by beacons with a range of roughly 402 km resulting in an estimated 23 beacons (for 0 dB only 13 beacons are required).

While the estimates provided above may vary significantly from the results of a detailed analysis, the predictions do show some important trends, namely that increasing the availability throughout the coverage area (particularly on the fringe) has a serious impact on the number of beacons required, and the more beacons, the more the potential for interference problems. Also, improvements in receiver technology which lower the required SNR have a significant impact on the coverage. It would seem that a judicious placement of beacons would be to have them relatively close to large population centers (i.e., largest number of users) where availability is greater at the expense of the fringes where the number of users is expected to be small.

It should be noted that these results are based on the following assumptions:

1) a 100 bps broadcast.
2) an antenna efficiency of 15%.
3) the desired availability is annual availability (vs. worst case 6 hour time block).

The effects resulting from changes in any of these factors can easily be estimated by shifting the distance curves in Figures H-1 and H-2. For example, referring to Figure H-1, in Denver, a 3 dB increase in bandwidth which corresponds to a 200 bps broadcast reduces the range by 18% (7 dB SNR, 99% availability). The noise field strength statistics during the worst case time block can exceed annual estimates by 10 dB or more which in Denver reduces the range by

40% (7 dB SNR, 95% availability). In both cases, the number of beacons required would increase substantially.

Another important consideration is the effect skywave propagation might have on the received signal. If the skywave and the ground wave have approximately equal amplitudes, then one might easily observe a classic example of multipath fading in which the signal strength varies between wide limits. In such a situation, the signal from a radiobeacon would probably be unreadable. During the daytime the skywave is heavily attenuated in the lower part of the ionosphere and one does not expect to observe it. But during the night the absorbing layer disappears and the skywave can become important. Figure H-3 shows field strengths for both the ground wave and the skywave — the ground wave varies with ground conductivity but is otherwise fairly constant, while the skywave varies in time and can only be represented here in statistical form. We note that over land, the two waves are approximately equal at distances between 200 and 300 km. It therefore follows that it is probably inadvisable to expect ranges of more than about 200 or 250 km.

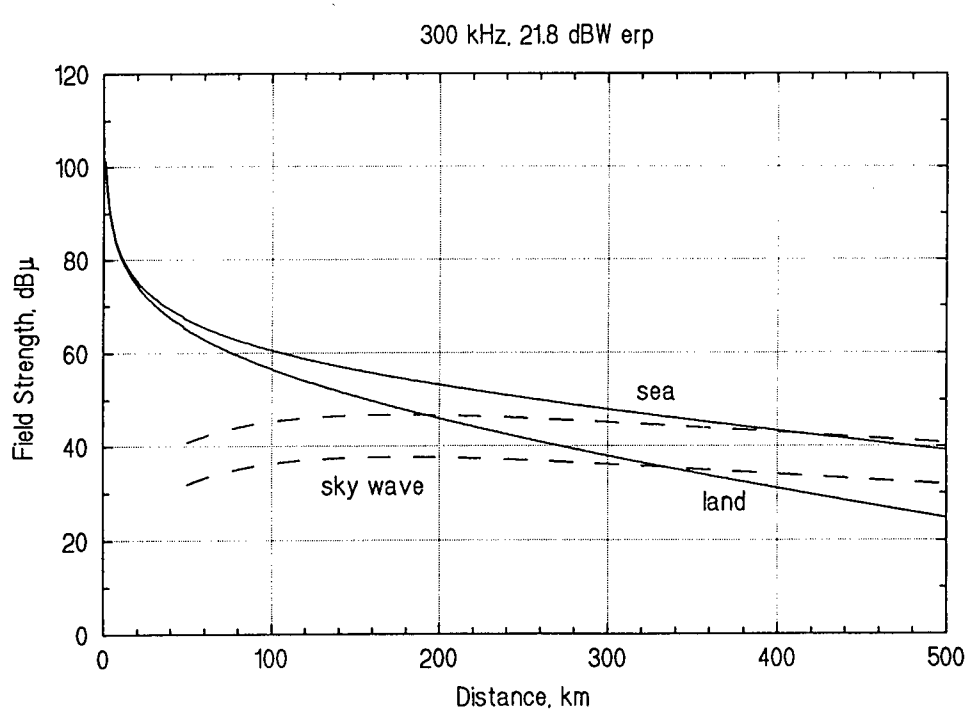

Figure H-3. A plot of electric field strength versus distance for a typical radiobeacon broadcast. Pictured are the ground wave over both sea and land (σ = 5 mS/m), and deciles (10% and 90% of an average year) of an estimated nighttime sky wave. The frequency is 300 kHz, and the radiated power 150 W.

Essentially, self interference produces an additional limit on the useful range of a radiobeacon. For example, if 95% availability is acceptable at the fringe of coverage, the range, based on noise calculations alone, will exceed 300 km; however, skywave interference will limit the useful range to say 200-250 km. Assuming a 200 km range and using the methods described previously, 91 beacons are required to provide coverage of CONUS which effectively provides a lower bound for the number of beacons required. Even if 99% availability is acceptable on the fringes of coverage for each beacon, it appears that skywave interference would be a limiting factor in many cases. It is interesting to note that the skywave places a practical limit on the use of increased power to increase the range (or availability).

It is apparent that the factors described above will have an impact on the successful extension of the USCG system to cover CONUS. It is important that planning include a careful analysis of the numbers and locations of beacons so that users will be provided with the information they require. Other important issues which should be examined are the effect of man-made impulsive noise in urban areas and effects of nearby electrical storms. Ignition noise may have a pronounced effect on the use of radiobeacon broadcast of DGPS on crowded highways. Data losses due to nearby electrical storms will likely increase latency and exacerbate bit synchronization problems which have been recently reported by Gloeckler (private communication). Beacon placement will also require that close attention be paid to the issue of skywave interference from other beacons.

H.1 References

[1] CCIR XVIth Penary Assembly, *Characteristics and Applications of Atmospheric Radio Noise Data*, Dubrovnik, 1986.

[2] P.K. Enge and K.E. Olson, "Medium Frequency Broadcast of Differential GPS," *IEEE Transactions on Aerospace and Electronic Systems*, Vol. 26, No.4, July 1990.

[3] T.A. Schonhoff, "A Differential GPS Receiver System Using Atmospheric Noise Mitigation Techniques," in *Proc. Institute of Navigation (ION) GPS '91*, Albuquerque, NM, Sept. 1991.

[4] U.S. Coast Guard, U.S. Department of Transportation, *Broadcast Standard for the USCG DGPS Navigation Service, COMDTINST M16577.1*, Washington, DC, April 1993.

APPENDIX I

CAPABILITIES TABLE VALUES

This appendix is provided in support of Table 4-1, "Capabilities Table," and provides the rationale for the assignments of system capabilities.

I.1 USCG LF/MF Radiobeacon System

Coverage Area, Nationwide: No — the Coast Guard System has been designed and is currently planned for installation as primarily a coastal system. Coverage will also include Midwestern rivers and the Great Lakes. Analysis shows that this system covers approximately 30% of the contiguous land area of CONUS and the coastal regions of Alaska, Hawaii, and the U.S. protectorates and territories.

Coverage Area, Ocean: No — this system does not provide augmented coverage in the ocean.

Coverage Area, Coastal: Yes — this system is designed to provide coverage in coastal areas of the United States and protectorates and territories. Radiobeacons have a maximum range of approximately 250 nautical miles. This implies by definition that the system also covers harbor and harbor approach areas of the country.

Coverage Area, NAS: No — this system is not designed to provide a specified capability throughout the National Airspace System.

Availability: The USCG reports that the beacon system currently achieves 99.97% availability.

Failure Notification Time: Based upon the RTCM format, Type 9 messages, and the data rate of 200 bps, failure notification time is 4.2 seconds.

Predictable Accuracy, Horizontal: USCG reports that achievable accuracy for users with "high end equipment" within 300 km of the radiobeacon is better than 3.0 meters.

Predictable Accuracy, Vertical: Data shows that achievable vertical accuracies are 1.5 times horizontal accuracies. Thus, vertical accuracy is expected to be 4.5 meters.

Probability of Accuracy and Integrity: Not defined for this system.

Time Frame of Availability, Initial Operating Capability: The USCG beacon system will be fully installed in 1995. A number of beacons will be installed in 1994. The time frame for availability is, therefore, 1994.

I.2 USCG Expanded LF/MF Radiobeacon System

Coverage Area, Nationwide: Yes — the USCG System can be expanded to provide nationwide coverage with the addition of between 20 to 50 stations.

Time Frame of Availability, Initial Operating Capability: Nationwide deployment of USCG beacons could begin in 1997 and be completed by 1998. The Time Frame for Availability is therefore 1997.

All other capabilities are identical to System I.1 above.

I.3 FM Subcarrier System

Coverage Area, Nationwide: Yes — these systems can provide nationwide coverage with an adequate number of FM stations under contract. The owners/managers do intend to provide nationwide coverage. It should be understood that FM subcarrier systems provide limited coverage in mountainous areas where terrain shadowing can impact coverage.

Coverage Area, Ocean: No — this system is not designed or intended to provide coverage in ocean areas. Many FM stations incorporate directional antennas to avoid coverage in areas of low population density such as oceans.

Coverage Area, Coastal: No — this system is not designed or intended to provide coverage in coastal areas (as defined in the FRP). FM station coverage has not been demonstrated to cover coastal and harbor/harbor approach areas of the country with any consistency.

Coverage Area, NAS: No — this system is not designed to provide a specified capability in the National Airspace System. It may be capable of doing so with additional stations, but there is no intention to do so at this time. FM stations generally design their antennas so as not to waste energy in the direction above the horizon.

Availability: These systems contract with well established, full service, FM broadcast stations. Availability then concerns the maintenance schedule or the failure of these stations, the reference stations, and the various data links involved. The broadcast stations used are those that operate 24 hours a day and have redundant equipment including backup power/generators and alternate transmitters in which case scheduled maintenance does not in general result in an outage.

The National Association of Broadcasters does not have statistics regarding FM station availability, however, they believe that most stations do much better than a one hour outage per year (99.988%). FM stations have a strong financial incentive to remain up and many stations are on the air continuously for years. A conservative estimate would have the system down for one day every 10 years, resulting in an availability of 99.97%.

Failure Notification Time: Message data comprises an update for a single satellite, and therefore may be very short. These updates are assembled at the user's receiver and passed on in an RTCM message. Type 1 messages can be supplied every 3 seconds depending upon the amount of data sharing the subcarrier with DGPS. Thus the time to alarm should be within 3 seconds but can be much less.

Predictable Accuracy, Horizontal: Industry reports that given the correct GPS receiver, constellation and environment, FM systems provide horizontal accuracy in the range of 1 meter 95% of the time. The value of 1 meter is assigned.

Predictable Accuracy, Vertical: 1.5 meters is assumed if horizontal accuracy of 1 meter is achievable.

Probability of Accuracy and Integrity: Not defined for this system.

Time Frame of Availability, Initial Operating Capability: FM subcarrier systems are currently operating and therefore have a time frame of availability of 1994.

I.4 WAS-1 (WAAS for Integrity, Availability and Accuracy; LADGPS Systems for Category II/III Approach)

Coverage Area, Nationwide: Yes — this system will provide nationwide augmented coverage. It should be understood that geosynchronous satellite-based systems provide limited coverage in mountainous areas or urban canyons where terrain shadowing can impact coverage. This is particularly true in high latitudes.

Coverage Area, Ocean: Yes — this system is designed and intended for use in ocean en route navigation.

Coverage Area, Coastal: No — geosynchronous satellites will not cover all coastal areas due to terrain shadowing. There are many coastal and harbor areas that will be covered by the geosynchronous WAAS system, however, no geostationary satellite system can ensure complete coastal coverage.

Coverage Area, NAS: Yes — this system is designed and intended for use throughout the National Airspace System.

Availability: This system is specified to provide 99.999 percent availability.

Failure Notification Time: This system is specified to provide a 2 second failure notification time.

Predictable Accuracy, Horizontal: This system is specified to meet FAA requirements for all phases of flight. The WAAS portion is specified to provide an accuracy of 7.6 meters nationwide. The LADGPS portion will be specified to provide an accuracy of 4.1 meters, depending upon the type of precision approach.

Predictable Accuracy, Vertical: This system is specified to meet FAA requirements for all phases of flight. The WAAS portion is specified to provide an accuracy of 7.6 meters nationwide. The LADGPS portion will be specified to provide an accuracy of 0.6 meters, depending upon the type of precision approach.

Probability of Accuracy and Integrity: This system is specified to provide a probability of accuracy and integrity of 1×10^{-8} failures per hour during Category III approaches as defined in FAA requirements.

Time Frame of Availability, Initial Operating Capability: This system is specified to have a time frame of availability of 1997.

I.5 WAS-2 (WAAS for Integrity and Availability; LADGPS Systems for All Accuracy Requirements for Category I/II/III Approaches)

Coverage Area, Nationwide: No — this system will provide integrity and availability augmentation only. Accuracy augmentation will not be provided nationwide. LADGPS systems will provide coverage only in areas around the LADGPS stations.

Time Frame of Availability, Initial Operating Capability: This system is specified to have a time frame of availability of 1997, although more time will be required to install additional LADGPS stations for Category I precision approach requirements.

All other capabilities are identical to System I.4 above.

I.6 WAS-3 (WAAS for Integrity and Availability, Frequency Other Than L1; LADGPS Systems for all accuracy requirements for Category II/III approaches)

Time Frame of Availability, Initial Operating Capability: This system is a conceptual system only. It could not be implemented sooner than 1999.

All other capabilities are identical to System I.4 above.

I.7 WAS-4 (Encrypted Data Link System)

Time Frame of Availability, Initial Operating Capability: This system is a conceptual system only. It could not be implemented sooner than 1999.

All other capabilities are identical to System I.4 above.

I.8 WAS-5 (Private GEO Satellite System)

Coverage Area, Nationwide: Yes — this system will provide nationwide augmented coverage. It should be understood that geosynchronous satellite-based systems provide limited coverage in mountainous areas or urban canyons where terrain shadowing can impact coverage. This is particularly true in high latitudes.

Coverage Area, Ocean: Yes — this system is capable of providing ocean coverage.

Coverage Area, Coastal: No — Geosynchronous satellites will not cover all coastal areas due to terrain shadowing. There are many coastal and harbor areas that will be covered by geosynchronous systems, however, no geostationary satellite system can ensure complete coastal coverage.

Coverage Area, NAS: Yes — this system is capable of providing coverage in the National Airspace System, but is not intended for use as a navigation system.

Availability: Private systems of this type have been in operation for several years and have demonstrated an availability of up to 99.99 percent.

Failure Notification Time: These systems are capable of providing a 2 second time to alarm depending upon system implementation characteristics.

Predictable Accuracy, Horizontal: These systems are capable of providing a horizontal accuracy of 0.6 m (2 drms).

Predictable Accuracy, Vertical: Data shows that achievable vertical accuracies are 1.5 times horizontal accuracies. Therefore, these systems can provide 1.0 meter vertical accuracy based upon a horizontal accuracy of 0.6 meter.

Probability of Accuracy and Integrity: Not defined for this system.

Time Frame of Availability, Initial Operating Capability: These systems are currently in operation. Therefore, their time frame of availability is 1994.

I.9 WAS-6 (Private LEO Systems)

Coverage Area, Nationwide: Yes — this system will provide nationwide augmented coverage. It should be understood that low earth orbit satellite-based systems are not subject to the same coverage limitations as geosynchronous systems.

Coverage Area, Ocean: Yes — this system can provide ocean coverage.

Coverage Area, Coastal: Yes — LEO satellites can cover all coastal areas.

Coverage Area, NAS: Yes — this type of system can provide coverage throughout the National Airspace System, but is not intended for use as a navigation system.

Availability: Analyses have shown that with a sufficient number of satellites, an availability of 99.999 percent can be achieved.

Failure Notification Time: Potential system providers have indicated that a 6 second time to alarm is achievable.

Predictable Accuracy, Horizontal: Potential system providers have indicated that 1 meter accuracy will be possible with this system.

Predictable Accuracy, Vertical: Potential system providers have indicated that 3 meter vertical accuracy will be possible with this system.

Probability of Accuracy and Integrity: Not defined for this system.

Time Frame of Availability, Initial Operating Capability: This type of system will not be available before 1999.

I.10 Continuously Operating Reference Station (CORS) System

This system is intended to meet post-processing requirements for survey and other applications and to provide a cost effective means of developing and maintaining a national spacial reference system.

Coverage Area, Nationwide: Yes — this system will be designed to provide a nationwide post-processing capability.

Coverage Area, Ocean: No — this system will not provide oceanic augmented coverage.

Coverage Area, Coastal: No — CORS does not meet any real time augmentation requirement. Post-processing coastal requirements would be met by CORS.

Coverage Area, NAS: No — this system is not planned to provide service in the National Airspace System since it is not a real time system.

Availability: CORS stations will be designed to provide better than 99.0 percent availability. A greater availability is possible but not planned at this time.

Failure Notification Time: Only real time systems define Failure Notification Time.

Predictable Accuracy, Horizontal: This system will provide 1 centimeter accuracy to survey users. The accuracy is not provided in real time.

Predictable Accuracy, Vertical: This system will provide 1 centimeter accuracy to survey users. The accuracy is not provided in real time.

Probability of Accuracy and Integrity: Not defined for this system.

Time Frame of Availability, Initial Operating Capability: Some CORS sites are currently operational. Therefore, the time frame of availability is 1994.

I.11 Loran-C System

Coverage Area, Nationwide: Yes — this system could provide nationwide augmented coverage.

Coverage Area, Ocean: No — this system could not provide complete oceanic augmented coverage.

Coverage Area, Coastal: Yes — Loran-C could provide augmented coverage for all coastal areas.

Coverage Area, NAS: No — this system could not provide augmented coverage throughout the National Airspace System since the coverage does not include a portion of the NAS which extends over the ocean.

Availability: The availability of Loran-C is 99.9%.

Failure Notification Time: Using an asynchronous message structure, a failure notification time of 2 seconds is possible.

Predictable Accuracy, Horizontal: Using Loran-C as a data link to carry DGPS messages and re-calibrating the Loran-C system can provide accuracies of 5 meters.

Predictable Accuracy, Vertical: 7.5 meters is assumed if horizontal accuracy of 5.0 meters is achievable.

Time Frame of Availability, Initial Operating Capability: A Loran-C augmentation could not be available before 1999.

APPENDIX J

DEVELOPMENT OF THE WEIGHTED ANALYTICAL DECISION MATRIX

The weighted analytical decision matrix was developed for use as a tool that would assist in determining the final recommendations of this study. The matrix serves as a guide in evaluating the augmented GPS architectures that were considered, and does not provide an absolute solution to determining the most capable augmented GPS architecture.

J.1 Matrix Organization

The decision matrix consists of two stages. The first stage contains spreadsheets that provide a method of organizing and presenting the large amount of data collected for user requirements and augmented GPS system performance specifications. This stage is where the Technical Capabilities Evaluation is performed. The second stage is the Weighted Analytical Decision Matrix that is used to apply weights to each evaluation factor and arrive at a weighted score for each architecture evaluated.

J.2 Technical Capabilities Evaluation

Under subtask one of this study, a Federal workshop was conducted which developed a list of user requirements. Some of these requirements were removed from further consideration because the suppliers of systems did not provide performance specifications in terms of these requirements. Other requirements were not included because performance specifications were common to all systems and therefore did not provide discrimination between systems. The remaining requirements provided the basis for the capabilities depicted in Table 4-1, entitled "Augmented GPS System Capabilities."

Tables 4-2 through 4-17, entitled "Augmented GPS System Evaluation," display the results of comparing requirements to system specifications. There is a separate table for each mode and phase of operation that was identified. Each block on these spreadsheets indicates a "YES" if the architecture specification meets or exceeds the required value, and a "NO" if the specification does not meet the requirement. These tables provide an evaluation of the technical capabilities of each system, for each mode and phase of operation.

Tables 4-18 through 4-21, entitled "Augmented GPS System Evaluation Summary," display a summary of the results obtained in the technical capabilities evaluation for each mode of operation.

Table 4-22, entitled "Augmented GPS System Mode Summary," summarizes the technical capability evaluation results for all modes of operation. Any system that receives a "NO" indication in the technical evaluation, indicating that it does not meet a stated requirement, is not eliminated from further consideration in the final stage of evaluation, the Weighted Analytical Decision Matrix. This technical capabilities evaluation is used as a tool in the selection of systems for evaluation in the Weighted Analytical Decision Matrix.

J.3 Weighted Analytical Decision Matrix

The second stage of the decision matrix is the "Weighted Analytical Decision Matrix," Table 5-1. This table evaluates the architectures selected against three important parameters: Performance, Cost, and Security. Each of these parameters was scored separately. No weights were assigned to the Performance, Cost, and Security parameters to obtain a total score for each architecture. The assignment of weights to these parameters would have required value judgements that were beyond the scope of this study.

J.4 Scoring Guidelines

Through a series of meetings, the study team identified evaluation factors for each parameter. A scoring scale which ranged between 0 and 100 was developed for each factor. The minimum acceptable level was scored zero. The maximum useful capability was scored 100. Intermediate levels were established to provide the evaluator guidance on relative importance of architecture capabilities.

Ground rules for selecting the evaluation factors were:

Quantifiable. The factor had to be quantifiable.

Discrimination. The factor must provide meaningful discrimination between architectures.

Adequate Data. Sufficient data had to be available to permit evaluation of the factor.

Independence. To prevent redundant weighing, evaluation factors and criteria had to be considered only once.

J.5 Evaluation Parameters

The scoring factors identified for each Performance, Cost, and Security parameter were generated to achieve consistency in scoring. The stated scoring levels were a consensus of the study team and the Working Group.

J.6 Performance Factors

The working group considered a number of factors. Several were discarded because they did not comply with established ground rules. The remaining factors that were included as part of the performance evaluation are described in the following sections.

J.6.1 Real Time Accuracy

Real time accuracy includes predictable, repeatable, and relative accuracy. Predictable accuracy is 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. Repeatable accuracy is 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 accuracy is the accuracy with which a user can measure position relative to that of another user of the same navigation system at the same time.

Table J-1. Real Time Accuracy Scoring Scale

LEVEL		SCORING SCALE
Deformation analysis	1 mm*	100
Surveyors	1 cm	99
FAA Category III	.6 m	90
Railroad	1 m	85
General requirements	3 m	80
General requirements	5 m	70
USCG	10 m	60
SPS	100 m	0

*Real Time Accuracy scores are based on 2 drms accuracy, at 95% confidence level.

J.6.2 Integrity (Time to Alarm)

Integrity is the ability of a system to provide timely warnings to users when the system should not be used for navigation. Each architecture's integrity was determined considering methods of integrity determination, system dynamics, data latency, data update rate, failure notification time, and criteria for rejection of specific satellite correction data.

Table J-2. Integrity (Time to Alarm) Scores

CHARACTERISTIC	SCORE
2 seconds notification time	100
6 seconds notification time	80
10 seconds notification time	0

J.6.3 Time Frame of Availability, Initial Operating Capability (IOC)

These scores were determined with the assumption that 1996 was the earliest that IOC could be obtained, and 1998 was the latest acceptable IOC. IOC is defined as when the architecture is sufficiently deployed to permit beneficial use.

Table J-3. Time Frame of Availability (IOC) Scores

CHARACTERISTIC	SCORE
1996 IOC	100
1997 IOC	90
1998 IOC or later	0

J.6.4 Availability

Availability is the probability that service, meeting the coverage constraints, will be available to the user. Availability is reduced when some portion of the architecture is removed from service for maintenance or through malfunction.

Table J-4. Availability Scores

CHARACTERISTIC	SCORE
100%	100
99.999%	90
99.7%	85
95%	0

J.6.5 Coverage

Coverage is a measure of the geographic area where the augmented GPS service is available assuming the complete architecture is operating within specification limits. Architecture coverage takes into consideration signal blockage due to man-made and natural terrain obstructions as well as meteorological and man-made electrical noise.

Table J-5. Coverage Scores

CHARACTERISTIC	SCORE
Worldwide coverage, total	100
Minimum+ Continental U.S. + U.S. territories, Hawaii, Alaska	90
Minimum+ Continental U.S. (all roads), adjacent waters, ground up	75
Minimum: All major interstates, U.S. highways and state routes, all cities, all U.S.-controlled airspace, all harbors and harbor approaches, all inland waterways	0

J.6.6 International Compatibility

Internationally compatibility is a measure of the ability of an architecture to conform to international standards and the ease with which it can be incorporated into a seamless worldwide infrastructure.

Table J-6. International Compatibility Scores

CHARACTERISTIC	SCORE
Conforms to international standards	100
Does not conform or conflicts with international standards	80
Major technical obstacle	0

J.7 Cost Factors

The cost parameters considered infrastructure cost and user equipment cost.

J.7.1 Infrastructure Cost

Infrastructure cost included initial acquisition cost and a 20 year life cycle cost expressed in 1994 dollars. A score of 100 is defined as being a architecture with zero cost to the Federal Government. The highest cost architecture receives a 0 score. The other architectures are scored as a percentage of this scale.

Table J-7. Infrastructure Cost Scores

CHARACTERISTIC	SCORE
Zero Cost	100
Highest Cost Architecture	0

J.7.2 User Equipment Cost

User equipment costs were estimated considering current cost and excursions from this cost due to architectural variations. A score of 100 is defined as being a architecture with zero cost. The highest cost architecture receives a 0 score. The other architectures are scored as a percentage of this scale.

Table J-8. User Equipment Cost Scores

CHARACTERISTIC	SCORE
Zero Cost	100
Highest Cost Architecture	0

J.8 Security Factors

The two major National security concerns are susceptibility to exploitation and deniability. An additional user concern is susceptibility to disruption through jamming and spoofing.

J.8.1 Susceptibility to Exploitation

Susceptibility to exploitation is a measure of the desirability and cost for a hostile user to exploit a U.S. provided AGPS service. The following susceptibility factors were examined:

Accuracy. All viable AGPS architectures are expected to contain a differential GPS (DGPS) component providing levels of accuracy having hostile utility. Furthermore, civil users require as high accuracy DGPS service as can be economically supported. The trend is to provide more accurate performance. It was felt that accuracy doesn't provide significant discrimination for security.

Update Rate. The update rate affects DGPS accuracy, response time, and warning time. DGPS architectures, which meet civil requirements, will provide update rates having hostile utility. While differences in update rates can be qualified, no significant discrimination factors for security were identified.

Cost, Size, & Complexity. An architecture which is too expensive. too large, or difficult to integrate may have limited hostile utility. However, the civil thrust is towards low cost, small size and easy integration. The history of GPS technology indicates cost, size and integration complexity will reduce over time. It is felt that AGPS user equipment meeting civil needs will be affordable for hostile use. With the expected

technology growth, cost discrimination criteria for security couldn't be accurately projected.

Temporal Restrictions. An architecture which is available only part of the time may have less hostile utility than one available full time. Civil navigation requires coverage 24 hours per day. Therefore, it was felt that there would be no temporal discrimination between viable AGPS architectures.

Applicant Screening. If access to the architecture could be restricted to friendly users, it would be less subject to hostile exploitation. However, it may be required that anyone legitimately operating in U.S. airspace or waters use the AGPS, regardless of our political relationships. Political relationships change over time. Discriminating evaluation criteria for applicant screening were not identified. The converse of applicant screening is covered in the "Access Control" evaluation factor for "Deniability."

Geographic Restrictions. An architecture which has limited geographic coverage is less subject to hostile exploitation. The trend is expected to be towards greater coverage. Near global coverage, by AGPS architectures meeting international standards, is likely to evolve, even though the architectures probably will be operated by different service providers. Also, geographic restrictions are considered in the "Access Control" evaluation factor for "Deniability." Because of likely global application of the selected AGPS architecture and to prevent double weighing, a "Geographic Restrictions" evaluation factor was not included for "Susceptibility to Exploitation."

Even though a number of evaluation factors were identified for "Susceptibility to Exploitation," none were retained for the decision matrix. Either they didn't provide significant discrimination between competing architectures or equivalents were covered under "Deniability."

J.8.2 Susceptibility to Disruption

From a user's perspective, the AGPS service should have a high immunity to disruption from jamming, spoofing, atmospheric interference, and radio frequency interference (RFI). These characteristics should be addressed in the evaluation of the AGPS service data links. Depending on AGPS architecture implementation, user desires for resistance to jamming and spoofing may be inverse deniability requirements. This factor was not retained for the decision matrix.

J.8.3 Deniability

Evaluation of the characteristics of the architecture that affect the potential to deny access, including signal structure, message content, transmission frequency, and the area coverage of DGPS transmissions. Evaluation of any features provided by the architecture to deny access. The factors defined below were retained for the decision matrix.

J.8.3.1 Access Control

Access control is the technical capability to deny use of the AGPS architecture to hostile users. A architecture which does not permit denial of access is unacceptable. Architectures which allow denial to be pinpointed to specific hostile users are rated higher than those which negatively impact groups of friendly users.

Table J-9. Access Control Scores

CHARACTERISTIC	SCORE
Deny by individual subscriber	100
Deny by subscriber group	80
Deny by geographic area	50
Turn off entire system	0

J.8.3.2 Level of Influence

The level of influence is a measure of the political and managerial control the U.S. has over denying use of the AGPS architecture. It is assumed the selected AGPS architecture will proliferate globally. This will be considered under the "International Acceptability" factor elsewhere in the decision matrix. Unimpeded U.S. control is the most desirable from a security viewpoint. Even though no U.S. control of a globally used AGPS architecture is not acceptable to some, the political reality is that the U.S. may not have control of some portion of a globally implemented AGPS architecture. Therefore, the minimal acceptable level was established at "No U.S. Control."

Table J-10. Level of Influence Scores

CHARACTERISTIC	SCORE
Total U.S. control	100
Shared control with friendly nations	80
Shared control with both friendly and unfriendly nations	10
No U.S. control	0

J.8.3.3 Interdiction

Should the U.S. military be required to engage hostile forces in regional conflict, any DGPS operating as a threat is assumed to be operated by the adversary and contained within the region. Interdiction by U.S. and allied military forces would be to deny adversary military advantage of precise positioning capability within the region.

Table J-11. Interdiction Scores

CHARACTERISTIC	SCORE
Interdictable, no impact on friendly use of architecture or other valued services by authorized users	100
Interdictable, but impacts other valued services	30
Interdictable, but interferes with authorized users	0

J.8.3.4 Post-Decision Response Time

Post-decision response time is the time required to implement denial once the decision to deny access to the AGPS service has been made by the appropriate authority. If denial activation is delayed, hostile users may have use of the AGPS service for a militarily significant period of time.

Table J-12. Post-Decision Response Time Scores

CHARACTERISTIC	SCORE
Seconds	100
Minutes	95
Hours	80
Days	0

J.8.3.5 Jammability

Jammability is a measure of the ease of denying use of the AGPS service and impact on other desirable services using jamming. Jamming is a technique available to deny use of the AGPS service when the U.S. level of influence and/or the technical access control features are inadequate to provide security. The evaluation criteria address jamming from the perspective of preventing hostile use of the AGPS architecture. The desire is to be able to use jamming to prevent hostile use without disrupting friendly use of the AGPS architecture or other services in the same frequency band. Having the capability to deny use of the AGPS architecture using jamming may conflict with users desires to minimize the possibility of service disruption by intentional or unintentional jamming.

Table J-13. Jammability Scores

CHARACTERISTIC	SCORE
Jammable, no impact on friendly use of architecture or other valued services by authorized users	100
Jammable, but impacts other valued services	30
Jammable, but interferes with authorized users	5
Cannot be jammed	0

J.8.3.6 Vulnerability of Denial

Vulnerability of the denial capability is an assessment of how easily the access control features of the AGPS architecture can be circumvented. If access control can be easily circumvented, it is almost the same as having no access control. No redundancy or security of access control features is unacceptable.

Table J-14. Vulnerability of Denial Scores

CHARACTERISTIC	SCORE
Secure facilities and data links on U.S. soil	100
Encrypted data links or secure facilities	50
Redundant, but unsecured command and control facilities and data links	0

J.9 Factor Weighting

The study team and Working Group assigned weights to the factors associated with each parameter. Factor weights were determined by the application of two decision analysis guidelines: "swing weights" and "additive weights." "Swing weights" reflect the relative importance of the difference between scores of 0 and 100 on one factor as compared with 0 to 100 on each of the other factors. "Additive weights" reflect the fact that the weights are on a ratio scale; a single factor with a weight of 100 is equally important as the sum of any two other factors that each have weights of 50.

J.10 Scoring

The study team and Working Group assigned scores to each architecture for all the factors included in the decision matrix. The assigned scores were based upon the scoring scales described above and reflected the collective subjective judgment of the study team and working group.

Factor scores for each architecture were then multiplied by the relative importance weights assigned to the respective factor to arrive at a weighted score. Individual weighted scores for each factor contained within each parameter were summed to provide an aggregate score for that parameter for each architecture.

APPENDIX K

ARCHITECTURE EVALUATION

This appendix is provided in support of Tables 5-1, 5-2, and 5-3, and provides the rationale for the assignments of architecture scores.

K.1 ARCHITECTURE 1 — USCG system deployed as currently planned, WAS-1 (FAA WAAS for integrity, availability, and accuracy; LADGPS systems for Category II/III precision approach requirements), all stations compliant with CORS standard.

K.1.1 Performance Factor Scores

Accuracy: 80. The accuracy of this architecture is based upon extensive testing by USCG and independent test results by USACE, NOAA and others. Based on the testing that has been performed, the accuracy of the system is 3 meters 2 drms within the coverage area (based on the USCG system). Because this accuracy dominates, the architecture receives a score of 80.

Integrity (Time to Alarm): 100. The time to alarm for the USCG system is 4.2 seconds, the time to alarm for the WAAS is 6 seconds, and the time to alarm for the LADGPS portion of the FAA system is 2 seconds. This meets all user requirements for time to alarm and receives a 100 score.

Availability: 90. This system will meet FAA availability requirements (99.999%) as well as all other user requirements for availability except the railroad control requirement of 100% in the coverage region.

Time Frame of Availability, Initial Operating Capability: 95. IOC for the USCG system will be December, 1995. The WAS-1 portion of the architecture has an IOC of 1997.

Coverage: 0. This system does not meet the minimum requirements as specified. The minimum requirements are all major interstates, U.S. highways and state routes, all cities, all U.S. controlled air space, all harbors and harbor approaches, and all inland waterways. The USCG system does not provide inland coverage and the WAS-1 system does not provide coverage in higher latitudes and many harbor and harbor approaches or inland waterways.

International Compatibility: 95. The USCG system conforms to International Telecommunication Union (ITU) Standard 823, "Recommended Standard for Maritime Differential Global Navigation Satellite Systems."

At the present time, there are no international aviation standards for augmented GPS. Ongoing discussions within the international aviation community indicate that the WAAS, as currently specified by FAA, will be accepted internationally. Various nations throughout the world are currently experimenting with LADGPS systems to support precision approach and landing. There is also reason to expect, therefore, that LADGPS systems as ultimately specified and adopted by FAA will also be accepted internationally.

The score is 95 since it can be said that this system would meet or likely meet international standards when they are developed.

K.1.2 Cost Factor Scores

Infrastructure Cost: 24.[1] The 20 year life cycle cost for the existing USCG system of 61 stations will be: \$14.2M +20(\$4.2M) = \$98.2M.

The cost of 61 USCG CORS-compliant sites is estimated at \$0.6M. The FAA WAAS sites are already specified to be CORS-compliant and require no additional funding. The cost to establish the central facility is \$1.0M. Thus, the total CORS system will cost an estimated \$1.6M.

The WAAS life cycle cost is estimated to be on the order of \$1,139M. The LADGPS systems life cycle cost is estimated to be on the order of \$195M. These costs include the cost of airport lighting and procedures for use of the WAAS and LADGPS systems within the NAS. The total life cycle cost of this portion of the architecture, therefore, is estimated at approximately \$1,334M.

The total life cycle cost of this architecture is estimated to be:

$$\$98.2M + \$1.6M + \$1,334M = \$1,433.8M.$$

Therefore, the infrastructure cost score for this architecture is 20.

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[1]Infrastructure cost was scaled relative to the most costly system. The most costly system received a zero score and the other systems received a scaled score according to the following equation:

$$Score = (100)(1 - a/b)$$

where

a = cost of architecture
b = cost of most expensive architecture.

The most costly architecture is the encrypted architecture option (Architecture 5). This cost is \$1,782.1M. This is the value of b in the equation above.

User Equipment Cost: 14.[2] Marine user equipment costs range from $2,000 for general marine equipment to $22,500 for high precision on-the-fly kinematic navigation.

Aviation user equipment costs range from $4,000 for general aviation equipment to $90,000 for more sophisticated commercial aircraft.

Land user equipment costs range from $500 for recreational user equipment to $22,500 for high precision geodetic survey equipment.

The maximum total user cost for this architecture is estimated to be:

$$\$22,500 + \$90,000 + \$22,500 = \$135,000.$$

Therefore, the user equipment cost score for this architecture is 14.

K.1.3 Security Factor Scores

If adopted by the U.S. and replicated worldwide, this architecture would present a potential threat to U.S. and allied forces in combat areas. Precise position, time, and velocity data transmitted on the GPS Ll frequency from geosynchronous satellites could provide military utility. It negates selective availability, the basic GPS security protection; impairs U.S. efforts to restrict the export of precise guidance systems; and limits countermeasure efforts. The countermeasures that are available could disrupt the peaceful use of GPS on a worldwide basis or at the least on a near-hemispheric basis.

Access Control: 0. The WAAS differential broadcast coverage from a geosynchronous satellite is nearly hemispheric. Should the U.S. be required to deny GPS augmentation within a particular region covered by the WAAS, the WAAS must be turned off. In effect, this may not be a realistic option since significantly more non-combatants than combatants would be denied service.

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[2]User cost was scaled relative to the system with the most costly user equipment. The system with the most costly user equipment received a zero score and the other systems received a scaled score according to the following equation:

$$Score = (100)(1 - a/b)$$

where

a = cost of user equipment
b = cost of most expensive user equipment suite.

The most costly user equipment suite is that for the encrypted architecture option (Architecture 5). This cost is $157,500. This is the value of b in the equation above.

Level of Influence: 80. It is assumed that in a seamless WAAS architecture, some level of U.S. control would be maintained as a result of U.S. technology transfer and required configuration control. In addition, nations with the economic infrastructure capable of sustaining a WAAS are assumed to be friendly to U.S. interests.

Interdictability: 0. It is assumed that future U.S. military conflicts will be limited to a region. Any WAAS operation considered a threat is assumed to be operated by another country outside the region and not involved with hostilities. Therefore, military interdiction of the WAAS is not considered as a viable option.

Post-Decision Response Time: 80. If the DGPS control station is in a country cooperative to the U.S. and the decision is made to exercise access control, it could require hours to identify and select appropriate transmission sites, coordinate operations, and terminate service.

Jammability: 5. The designated RF downlink for the WAAS is L1. Jamming of the WAAS L1 will also jam the GPS Ll, thereby jamming all GPS users within the vicinity.

Vulnerability of Denial: 50. It is assumed that WAAS and DGPS stations would be operated and maintained within secure facilities.

K.2 ARCHITECTURE 2 — USCG(E) system deployed nationwide, WAS-1 (FAA WAAS for integrity, availability, accuracy; LADGPS systems for Category II/III precision approach requirements), all stations compliant with the CORS standard.

K.2.1 Performance Factor Scores

Accuracy: 80. The accuracy of this architecture is based upon extensive testing by USCG and independent test results by USACE, NOAA and others. Based on the testing that has been performed, the accuracy of the system is 3 meters 2 drms within the coverage area (based on the USCG system). This accuracy dominates and the architecture receives a score of 80.

Integrity (Time to Alarm): 100. The time to alarm for the USCG system is 4.2 seconds, the time to alarm for the WAAS is 6 seconds, and the time to alarm for the LADGPS portion of the FAA system is 2 seconds. All user requirements are met, therefore this architecture receives a score of 100.

Availability: 90. This system will meet FAA availability requirements (99.999%) as well as all other user requirements for availability except the railroad control requirement of 100% in the coverage region. It therefore receives a score of 90.

Time Frame of Availability, Initial Operating Capability: 90. IOC for the USCG(E) system could be December, 1997. The WAS-1 portion of the architecture also has an IOC of 1997. The architecture therefore receives a score of 90.

Coverage: 90. The USCG(E) portion of this architecture provides coverage for all major interstates, all highways and state routes, all cities, all harbor and harbor approaches and inland waterways in the U.S. and its territories. The WAS-1 portion of this architecture provides coverage for the NAS. Therefore this architecture receives a score of 90.

International Compatibility: 95. The USCG(E) system conforms to International Telecommunication Union (ITU) Standard 823, "Recommended Standard for Maritime Differential Global Navigation Satellite Systems."

At the present time, there are no international aviation standards for augmented GPS. Ongoing discussions within the international aviation community indicate that the WAAS, as currently specified by FAA will be accepted internationally. Various nations throughout the world are currently experimenting with LADGPS systems to support precision approach and landing. There is also reason to expect, therefore, that LADGPS systems as ultimately specified and adopted by FAA will also be accepted internationally.

The score is 95 since it can be said that this system would meet or likely meet international standards when they are developed.

K.2.2 Cost Factor Scores

Infrastructure Cost: 23. The total life cycle cost over 20 years for the existing USCG system of 61 stations will be: $14.2M +20($4.2M) = $98.2M. The additional 20-50 stations required for CONUS coverage would cost $3-8 million. The annual operating cost would be $1-2 million for the additional stations. The maximum total life cycle cost over 20 years for the USCG(E) system would be $146M.

The cost of 110 USCG(E) CORS-compliant sites is estimated at $1.1M. The FAA WAAS sites are already specified to be CORS-compliant and require no additional funding. The cost to establish the central facility is $1.0M. Thus, the total nationwide CORS system will cost an estimated $2.1M. It is anticipated that the USCG(E) and WAAS sites will provide adequate coverage.

The WAAS life cycle cost is estimated to be on the order of $1139M. The LADGPS systems life cycle cost is estimated to be on the order of $195M. These costs include the cost of airport lighting and procedures for use of the WAAS and LADGPS systems within the NAS. The total life cycle cost of this portion of the architecture, therefore, is estimated at approximately $1,334M.

The total life cycle cost of this architecture is estimated to be:

$$\$146M + \$2.1M + \$1,334M = \$1,482.1M.$$

Therefore, the infrastructure cost score for this architecture is 17.

User Equipment Cost: 14. Marine user equipment costs range from $2,000 for general marine equipment to $22,500 for high precision on-the-fly kinematic navigation.

Aviation user equipment costs range from $4,000 for general aviation equipment to $90,000 for more sophisticated commercial aircraft.

Land user equipment costs range from $500 for recreational user equipment to $22,500 for high precision geodetic survey equipment.

The maximum total user cost for this architecture is estimated to be:

$$\$22,500 + \$90,000 + \$22,500 = \$135,000.$$

Therefore, the user equipment cost score for this architecture is 14.

K.2.3 Security Factor Scores

If adopted by the U.S. and replicated worldwide, this architecture would present a potential threat to U.S. and allied forces in combat areas. Precise position, time, and velocity data transmitted on the GPS L-1 frequency from geosynchronous satellites could provide military utility. It negates selective availability, the basic GPS security protection; impairs U.S. efforts to restrict the export of precise guidance systems; and limits countermeasure efforts. The countermeasures that are available could disrupt the peaceful use of GPS on a worldwide basis or at the least on a hemispheric basis.

Access Control: 0. The WAAS differential broadcast coverage from a geosynchronous satellite is nearly hemispheric. Should the U.S. be required to deny GPS augmentation within a particular region covered by the WAAS, the WAAS must be turned off. In effect, this may not be a realistic option since significantly more non-combatants than combatants would be denied service.

Level of Influence: 80. It is assumed that in a seamless WAAS architecture, some level of U.S. control would be maintained as a result of U.S. technology transfer and required configuration control. In addition, nations with the economic infrastructure capable of sustaining a WAAS are assumed to be friendly to U.S. interests.

Interdictability: 0. It is assumed that future U.S. military conflicts will be limited to a region. Any WAAS operation considered a threat is assumed to be operated by another country outside the region and not involved with hostilities. Therefore, military interdiction of the WAAS is not considered as a viable option.

Post-Decision Response Time: 80. If the DGPS control station is in a country cooperative to the U.S. and the decision is made to exercise access control, it could require hours to identify and select appropriate transmission sites, coordinate operations, and terminate service.

Jammability: 5. The designated RF downlink for the WAAS is L1. Jamming of the WAAS L1 will also jam the GPS Ll, thereby jamming all GPS users within the vicinity.

Vulnerability of Denial: 50. It is assumed that WAAS and DGPS stations would be operated and maintained within secure facilities.

K.3 ARCHITECTURE 3 — USCG(E) system deployed nationwide, WAS-2 (WAAS for integrity and availability only; LADGPS systems for Category I/II/III precision approach requirements), all stations compliant with the CORS standard.

K.3.1 Performance Factor Scores

Accuracy: 80. The accuracy of this architecture is based upon extensive testing by USCG and independent test results by USACE, NOAA and others. Based on the testing that has been performed, the accuracy of the system is 3 meters 2 drms within the coverage area (based on the USCG system). This accuracy dominates and the architecture receives a score of 80.

Integrity (Time to Alarm): 100. The time to alarm for the USCG system is 4.2 seconds, the time to alarm for the WAAS is 6 seconds, and the time to alarm for the LADGPS portion of the FAA system is 2 seconds. All user requirements are met, therefore this architecture receives a score of 100.

Availability: 90. This system will meet FAA availability requirements (99.999%) as well as all other user requirements for availability except the railroad control requirement of 100% in the coverage region. It therefore receives a score of 90.

Time Frame of Availability, Initial Operating Capability: 90. IOC for the USCG(E) system could be December, 1997. The WAS-2 portion of the architecture also has an IOC of 1997. The architecture therefore receives a score of 90.

Coverage: 90. The USCG(E) portion of this architecture provides coverage for all major interstates, all highways and state routes, all cities, all harbor and harbor approaches and inland waterways in the U.S. and its territories. The WAS-2 portion of this architecture provides coverage for the NAS. Therefore this architecture receives a score of 90.

International Compatibility: 85. The USCG(E) system conforms to International Telecommunication Union (ITU) Standard 823, "Recommended Standard for Maritime Differential Global Navigation Satellite Systems."

At the present time, there are no international aviation standards for augmented GPS. Ongoing discussions within the international aviation community seem to indicate that the WAAS, as currently specified by FAA will be accepted internationally. Various nations throughout the world are currently experimenting with LADGPS systems to support precision approach and landing. There is also reason to expect, therefore, that LADGPS systems as ultimately specified and adopted by FAA will also be accepted internationally. Since the international community does not appear to share the U.S. reservations concerning the accuracy (Phase II) component of the WAAS, a U.S. WAAS with only Phase I (integrity and availability) components may be less acceptable internationally than the full (Phase I and II) WAAS. The score is, therefore, 85.

K.3.2 Cost Factor Scores

Infrastructure Cost: 17. The 20 year life cycle cost for the existing USCG system of 61 stations will be: $14.2M +20($4.2M) = $98.2M. The additional 20-50 stations required for CONUS coverage would cost $3-8 million. The annual operating cost would be $1-2 million for the additional stations. The maximum total life cycle cost over 20 years for the USCG(E) system would be $146M.

The cost of 110 USCG(E) CORS-compliant sites is estimated at $1.1M. The FAA WAAS sites are already specified to be CORS-compliant and require no additional funding. The cost to establish the central facility is $1.0M. Thus, the total nationwide CORS system will cost an estimated $2.1M. It is anticipated that the USCG(E) and WAAS sites will provide adequate coverage.

The WAAS component of this architecture will satisfy aviation requirements for all phases of flight through non-precision approach, WAAS Phase I as briefed at the TSARC. The WAAS Phase I life cycle cost is estimated to be on the order of $670M. Since the WAAS Phase I will not satisfy Category I requirements, 620 Category I LADGPS systems will be required under this architecture. The Category I LADGPS systems life cycle cost is estimated to be on the order of $560M. The Category II/III LADGPS systems life cycle cost is estimated to be on the order of $195M. The total life cycle cost of this portion of the architecture, therefore, is estimated at $1,425M.

The total life cycle cost of this architecture is estimated to be:

$$\$146M + \$2.1M + \$1,425M = 1,573.1M.$$

Therefore the infrastructure cost score for this system is 12.

User Equipment Cost: 8. Marine user equipment costs range from $2,000 for general marine equipment to $22,500 for high precision on-the-fly kinematic navigation.

Aviation user equipment costs range from $4,400 for general aviation equipment to $99,000 for more sophisticated commercial aircraft.

Land user equipment costs range from $500 for recreational user equipment to $22,500 for high precision geodetic survey equipment.

The maximum total user cost for this architecture is estimated to be:

$$\$22,500 + \$99,000 + \$22,500 = \$144,000.$$

Therefor, the user equipment cost score for this architecture is 9.

K.3.3 Security Factor Scores

The use of a geosynchronous satellite to transmit integrity data and provide additional ranging is not considered a military threat. As in other architectures, short range transmitters such as LADGPS stations used to transmit accuracy corrections can be mitigated by conventional means.

Access Control: 50. Access control is achieved by terminating correction transmissions at specified locations. This constitutes access control by geographic location.

Level of Influence: 80. It is assumed that in a seamless architecture, some level of U.S. control would be maintained as a result of U.S. technology transfer and required configuration control. In addition, nations with the economic infrastructure capable of sustaining such an architecture are assumed to be friendly to U.S. interests.

Interdictability: 100. It is assumed that future U.S. military conflicts will be limited to a region. Any DGPS not being operated by U.S. or allied forces will be deemed hostile. Interdiction by U.S. and allied forces would negate this threat.

Post-Decision Response Time: 80. If the DGPS control station is in a country cooperative to the U.S. and the decision is made to exercise access control, it could require hours to identify and select appropriate transmission sites, coordinate operations, and terminate service.

Jammability: 100. It is assumed that DGPS stations will have RF links which will not interfere with other RF systems, including GPS L1. Therefore, jamming the correction portion of the architecture does not impact friendly use of the overall architecture.

Vulnerability of Denial: 50. It is assumed that WAAS and DGPS stations would be operated and maintained within secure facilities.

K.4 ARCHITECTURE 4 — USCG(E) system deployed nationwide, WAS-3 (WAAS for integrity and availability, accuracy at a frequency other than L1; LADGPS systems for Category II/III precision approach requirements), all stations compliant with CORS standard.

K.4.1 Performance Factor Scores

Accuracy: 80. The accuracy of this architecture is based upon extensive testing by USCG and independent test results by USACE, NOAA and others. Based on the testing that has been performed, the accuracy of the system is 3 meters 2 drms within the coverage area (based on the USCG system). This accuracy dominates and the architecture receives a score of 80.

Integrity (Time to Alarm): 100. The time to alarm for the USCG system is 4.2 seconds, the time to alarm for the WAAS is 6 seconds, and the time to alarm for the LADGPS portion of the FAA system is 2 seconds. All user requirements are met, therefore this architecture receives a score of 100.

Availability: 90. This system will meet FAA availability requirements (99.999%) as well as all other user requirements for availability except the railroad control requirement of 100% in the coverage region. Therefore, it receives a score of 90.

Time Frame of Availability, Initial Operating Capability: 0. This architecture exists only in conceptual form. Suitable alternative communications satellites with the capability to provide correction messages at other than the GPS L1 frequency are not readily available. The current lack of definition virtually assures that this architecture could not be operational prior to 1998. Consequently, this architecture receives a score of 0.

Coverage: 90. The USCG(E) portion of this architecture provides coverage for all major interstates, all highways and state routes, all cities, all harbor and harbor approaches and inland waterways in the U.S. and its territories. The WAS-3 portion of this architecture provides coverage for the NAS. Therefore, this architecture receives a score of 90.

International Compatibility: 88. The USCG system conforms to International Telecommunication Union (ITU) Standard 823, "Recommended Standard for Maritime Differential Global Navigation Satellite Systems."

At the present time, there are no international aviation standards for augmented GPS. Ongoing discussions within the international aviation community seem to indicate that the WAAS, as currently specified by FAA will be accepted internationally. Various nations throughout the world are currently experimenting with LADGPS systems to support precision approach and landing. There is also reason to expect, therefore, that LADGPS systems as ultimately specified and adopted by FAA will also be accepted internationally. The international community does not appear to share the U.S. reservations with the accuracy (Phase II) component of the WAAS. A WAAS providing error corrections on the GPS L1 frequency permits the use of a relatively

simple avionics suite to receive transmissions from the GPS satellites themselves as well as from the differential station. Consequently, a U.S. WAAS providing differential corrections, i.e., accuracy enhancements, at a completely different frequency will likely be less acceptable internationally than the full (Phase I and II) WAAS with accuracy corrections at the GPS L1 frequency, but more acceptable than no accuracy component at all. Therefore, this architecture receives a score of 88.

K.4.2 Cost Factor Scores

Infrastructure Cost: 23. The 20 year life cycle cost for the existing USCG system of 61 stations will be: $14.2M +20($4.2M) = $98.2M. The additional 20-50 stations required for CONUS coverage would cost $3-8 million. The annual operating cost would be $1-2 million for the additional stations. The maximum total life cycle cost over 20 years for the USCG(E) system would be $146M.

The cost of 110 USCG(E) CORS-compliant sites is estimated at $1.1M. The FAA WAAS sites are already specified to be CORS-compliant and require no additional funding. The cost to establish the central facility is $1.0M. Thus, the total nationwide CORS system will cost an estimated $2.1M. It is anticipated that the USCG(E) and WAAS sites will provide adequate coverage.

The WAAS life cycle cost is estimated to be on the order of $1139M. The LADGPS systems life cycle cost is estimated to be on the order of $195M. The total life cycle cost of this portion of the architecture, therefore, is estimated at approximately $1,334M.

The total life cycle cost of this architecture is estimated to be:

$$\$146M + \$2.1M + \$1,334M = \$1,482.1M.$$

Therefore, the infrastructure cost score for this architecture is 17.

User Equipment Cost: 8. Marine user equipment costs range from $2,000 for general marine equipment to $22,500 for high precision on-the-fly kinematic navigation.

Aviation user equipment costs range from $4,400 for general aviation equipment to $99,000 for more sophisticated commercial aircraft.

Land user equipment costs range from $500 for recreational user equipment to $22,500 for high precision geodetic survey equipment.

The maximum total user cost for this architecture is estimated to be:

$$\$22,500 + \$99,000 + \$22,500 = \$144,000.$$

Therefor, the user equipment cost score for this architecture is 9.

K.4.3 Security Factor Scores

Transmitted data from geosynchronous satellites on frequencies other than Ll will permit jamming that does not interfere with friendly GPS use. The wide availability of the data, however, will increase the countermeasure requirements. LADGPS stations, which transmit accuracy corrections, can be mitigated by conventional means.

Access Control: 0. The WAAS differential broadcast coverage from a geosynchronous satellite is nearly hemispheric. Should the U.S. be required to deny GPS augmentation within a particular region covered by the WAAS, the WAAS must be turned off. In effect, this may not be a realistic option since significantly more non-combatants than combatants would be denied service.

Level of Influence: 80. It is assumed that in a seamless WAAS architecture, some level of U.S. control would be maintained as a result of U.S. technology transfer and required configuration control. In addition, nations (or group of nations) with the economic infrastructure capable of sustaining a WAAS are assumed to be friendly to U.S. interests.

Interdictability: 0. It is assumed that future U.S. military conflicts will be limited to a region. Any WAAS operation considered a threat is assumed to be operated by another country outside the region and not involved with hostilities. Therefore, military interdiction of the WAAS is not considered as a viable option.

Post-Decision Response Time: 80. If the DGPS control station is in a country cooperative to the U.S. and the decision is made to exercise access control, it could require hours to identify and select appropriate transmission sites, coordinate operations, and terminate service.

Jammability: 30. Jamming the differential correction frequency will likely impact other valued services, but will not preclude the continued use of integrity and availability capabilities on L1.

Vulnerability of Denial: 50. It is assumed that WAAS and DGPS stations would be operated and maintained within secure facilities.

K.5 ARCHITECTURE 5 — USCG(E) system deployed nationwide, WAS-4 (WAAS encrypted for integrity, availability, and accuracy; LADGPS systems for Category II/III precision approach requirements), all stations compliant with CORS standard.

K.5.1 Performance Factor Scores

Accuracy: 80. The accuracy of this architecture is based upon extensive testing by USCG and independent test results by USACE, NOAA and others. Based on the testing that has been performed, the accuracy of the system is 3 meters 2 drms within the coverage area (based on the USCG system). This accuracy dominates and the architecture receives a score of 80.

Integrity (Time to Alarm): 100. The time to alarm for the USCG system is 4.2 seconds, the time to alarm for the WAAS is 6 seconds, and the time to alarm for the LADGPS portion of the FAA system is 2 seconds. All user requirements are met, therefore this architecture receives a score of 100.

Availability: 90. This system will meet FAA availability requirements (99.999%) as well as all other user requirements for availability except the railroad control requirement of 100% in the coverage region. Therefore, it receives a score of 90.

Time Frame of Availability, Initial Operating Capability (IOC): 0. IOC for the USCG(E) system could be December, 1997. IOC for the WAS-4 portion of the architecture has the potential, from a technical perspective, to meet a 1997 IOC date if the encryption concepts in this architecture are incorporated into the currently planned FAA WAAS. However, this would require an engineering change to the current WAAS specifications. Based on procurement regulations, funding, and the level of coordination required, it is unlikely that an IOC date of earlier than 1999 could be achieved. The architecture, therefore, receives a score of 0.

Coverage: 90. The USCG(E) portion of this architecture provides coverage for all major interstates, all highways and state routes, all cities, all harbor and harbor approaches and inland waterways in the U.S. and its territories. The WAS-4 portion of this architecture provides coverage for the NAS. Therefore, this architecture receives a score of 90.

International Compatibility: 30. The USCG(E) system conforms to International Telecommunication Union (ITU) Standard 823, "Recommended Standard for Maritime Differential Global Navigation Satellite Systems."

At the present time, there are no international aviation standards for augmented GPS. Various nations throughout the world are currently experimenting with LADGPS systems to support precision approach and landing. There is also reason to expect, therefore, that LADGPS systems as ultimately specified and adopted by FAA will also be accepted internationally.

To date there is no precedent in the international community for an encrypted aviation navigation aid. Therefore, this architecture receives a score of 30.

K.5.2 Cost Factor Scores

Infrastructure Cost: 0. The 20 year life cycle cost for the existing USCG system of 61 stations will be: $14.2M +20($4.2M) = $98.2M. The additional 20-50 stations required for CONUS coverage would cost $3-8 million. The annual operating cost would be $1-2 million for the additional stations. The maximum total life cycle cost over 20 years for the USCG(E) system would be $146M.

The cost of 110 USCG(E) CORS-compliant sites is estimated at $1.1M. The FAA WAAS sites are already specified to be CORS-compliant and require no additional funding. The cost to establish the central facility is $1.0M. Thus, the total nationwide CORS system will cost an estimated $2.1M. It is anticipated that the USCG(E) and WAAS sites will provide adequate coverage.

The WAAS life cycle cost is estimated to be on the order of $1139M. The estimated cost addition for the WAS-4 system enhancements is $300M. The LADGPS systems life cycle cost is estimated to be on the order of $195M. The total life cycle cost of this portion of the architecture, therefore, is estimated at approximately $1,634M.

The total life cycle cost of this architecture is estimated to be:

$$\$146M + \$2.1M + \$1,634M = \$1,782.1M.$$

This makes this architecture the most costly one proposed and it receives an infrastructure cost score of 0.

User Equipment Cost: 0. Marine user equipment costs range from $2,000 for general marine equipment to $22,500 for high precision on-the-fly kinematic navigation.

Aviation user equipment costs range from $5,000 for general aviation equipment to $112,500 for more sophisticated commercial aircraft.

Land user equipment costs range from $500 for recreational user equipment to $22,500 for high precision geodetic survey equipment.

The maximum total user cost for this architecture is estimated to be:

$$\$22,500 + \$112,500 + \$22,500 = \$157,500.$$

This makes this architecture the most costly one proposed and it receives a user equipment cost score of 0.

K.5.3 Security Factor Scores

The WAAS portion of this architecture is an encrypted version of Architecture K.2. If adopted by the U.S. and deployed worldwide, this architecture would help mitigate the potential threats to U.S. and allied forces in combat areas.

Access Control: 75. Access to the USCG(E) portion of the architecture would be denied by geographic region. The security factors of the WAAS portion greatly improve the overall security of the architecture since access control can be denied by subscriber groups or possibly

even by individual subscriber. The USCG(E) portion of this architecture is not encrypted, resulting in a score of less than 100.

Level of Influence: 90. It is assumed that the WAAS portion of this architecture is under U.S. control. However, LADGPS systems could exist outside direct U.S. control. Therefore, it can not be assumed that the U.S. would be able to exert influence over the entire architecture.

Interdictability: 100. The U.S. would have no need to interdict a U.S. controlled system. As in other architectures, short range transmitters such as LADGPS stations used to transmit accuracy corrections can be mitigated by conventional means.

Post-Decision Response Time: 80. If the DGPS control station is in a country cooperative with the U.S. and the decision is made to exercise access control, it could require hours to identify and select appropriate transmission sites, coordinate operations, and terminate service. A similar time would be required for control of the WAAS portion of the architecture.

Jammability: 100. The WAAS portion of this architecture is under U.S. control and would not require jamming to deny service. For the LADGPS portions, it is assumed that they will have RF links which will not interfere with other RF systems, including GPS L1. Therefore, jamming this portion of the architecture does not impact friendly use of the overall architecture.

Vulnerability of Denial: 50. It is assumed that WAAS and DGPS stations would be operated and maintained within secure facilities.

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15. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)* This report documents the development of recommendations for a national approach to augmented Global Positioning System (GPS) services. The Institute for Telecommunication Sciences led a study team that included the U.S. Army Topographic Engineering Center, the Volpe National Transportation Systems Center, and Overlook Systems Technologies, Inc. The study team identified Federal navigation, positioning, and timing requirements for land, marine, air, and space modes of operation. The study team then evaluated numerous operating and proposed systems that augment the GPS Standard Positioning Service. The most promising systems were combined in six different architectures intended to meet the widest possible range of user requirements. One of these architectures was eliminated from consideration due to technical concerns. The study team evaluated each of the remaining architectures against a set of performance, cost, and security factors. Based on the architecture evaluations, the study team developed a set of recommendations for a coordinated, national approach to augmented GPS services that meets Federal requirements while avoiding unnecessary duplication of facilities.

16. Key Words *(Alphabetical order, separated by semicolons)*

Global Positioning System (GPS); differential GPS (DGPS); GPS Precise Positioning Service (PPS); GPS Standard Positioning Service (SPS)

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