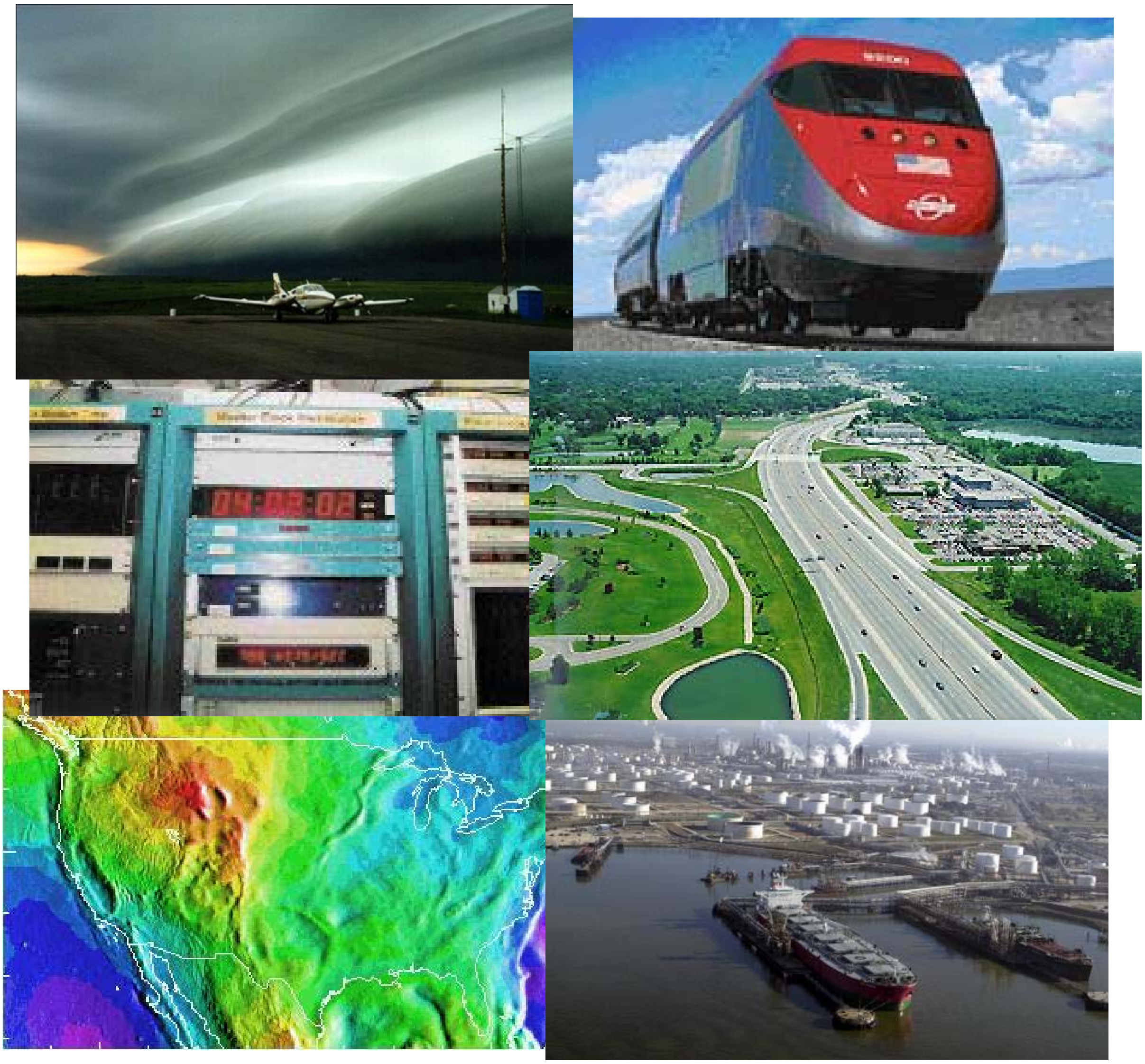
Radionavigation Systems: A Capabilities Investment Strategy



Radionavigation Systems Task Force

A Report to the Secretary of Transportation

January 2004
Overlook Systems Technologies, Inc.

Foreword

January 5, 2004

Our Nation's transportation infrastructure is the most dynamic, efficient and reliable in the world. At the same time, it is the busiest and most complex. For many years now, a key pillar of our transportation infrastructure has been the suite of radionavigation systems that have made precise and dependable position, navigation, and timing services available to land, maritime, and aviation users worldwide. As this radionavigation infrastructure begins to age and new technologies emerge, however, our ability to maintain a world-class transportation system will depend on the infrastructure investment decisions that we make today.

The continued operation, maintenance, and upgrade of our Federal navigation infrastructure must ensure a robust mix of systems based on analyses of the capabilities, requirements, benefits, costs, and risks associated with the various options. Currently, a dependable but aging array of ground-based systems and technologies exists in parallel with state of the art satellite navigation systems. As worldwide use of GPS and its augmentations has increased, so too has the need to protect our transportation infrastructure against the interruption or loss of signals from GPS.

The Radionavigation Capabilities Assessment Task Force was established to develop a multi-modal capabilities assessment and recommend to the Secretary a radionavigation investment strategy that will meet our national transportation requirements. That assessment and recommendation are set forth in this Report.

I would like to thank all study participants for their contributions to this Report. The efforts of this Task Force will ensure that our Federal radionavigation infrastructure remains the safest, most dependable, and most efficient in the world.

Sincerely

Jeffrey N. Shane
Under Secretary of Transportation for Policy

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Executive Summary

The Final Report of the President's Commission on Critical Infrastructure Protection concluded that Global Positioning System (GPS) services and applications are susceptible to various types of interference, and that the effects of these vulnerabilities on civilian transportation applications should be studied in detail. As a result of the report, Presidential Decision Directive (PDD) 63 directed that the Department of Transportation (DOT), in consultation with the Department of Defense (DoD), undertake a thorough evaluation of the vulnerability of the national transportation infrastructure that relies on the Global Positioning System.

The Volpe National Transportation Systems Center (RSPA/Volpe Center) conducted a vulnerability analysis of GPS and identified the potential impact to aviation, maritime transportation, railroads, and Intelligent Transportation Systems (ITS). The final report, *Vulnerability Assessment of the Transportation Infrastructure Relying on the Global Positioning System* was published on August 29, 2001 (Ref.1). This study contained a series of recommendations, which were reviewed and ultimately accepted by the Department's operating agencies. Recommendation sets were made relative to: overarching issues related to GPS vulnerabilities, mitigating the vulnerabilities of the GPS signal to disruption or loss, and mitigating the vulnerabilities of the transportation systems resulting from the disruption or loss of the GPS signal.

Addressing this set of Volpe recommendations started with the key question, "What type of backup systems must be in place to mitigate the disruption or loss of GPS?" The answer led to the establishment of a Capabilities Assessment Task Force to develop a recommended capabilities investment strategy for US radionavigation systems to meet transportation infrastructure requirements for the next ten years. This recommendation had to balance the plan to move toward a heavy reliance on satellite navigation with the vulnerabilities of such an approach highlighted in the Volpe Study. According to the study, "Backups for positioning and precision timing are necessary for all GPS applications involving the potential for life-threatening situations or major economic or environmental impact … The appropriate mix for a given application will result from careful analysis of benefits, costs, and risk acceptance."

To accomplish the analysis the Task Force focused on two tasks. The first task was to conduct a multi-modal capabilities assessment of all radionavigation systems, both current and planned, to satisfy the national need for radionavigation, positioning, and timing. This included looking at the possibilities of using a system designed for one operating agency as a backup for the needs of another. The output of this task was a technical and cost perspective on the five most promising alternatives for system architectures (or systems of systems). This output was the input for the second task, which was to assess a set of alternative systems considering additional factors. These factors included recommendations of the Volpe report on backups to GPS, potential impact on other US Government agencies' systems and operations, user equipage, and interagency and international agreements. The final objective was a recommendation to the Secretary on the most appropriate mix of radionavigation systems, from both a capability and cost perspective, to satisfy the national need for radionavigation, positioning and timing services for at least the next 10 years.

There are thousands of potential combinations of radionavigation systems. The Task Force initially narrowed the field to eleven potential options by focusing on four cross-cutting radionavigation systems. These systems provide potential multi-modal capabilities and have the greatest impact on the radionavigation system tradespace. These systems are Loran and the GPS augmentations: Wide Area Augmentation System (WAAS), Nationwide Differential GPS (NDGPS), and Local Area Augmentation System (LAAS). The Task Force explored the ramifications of removing individual systems. This included identifying what modal requirements could not be met and what systems enhancements might be possible to meet those requirements. As a result, the Task Force developed four alternative radionavigation mixes that could address the current user needs for primary and backup systems. This includes two baseline options derived from the 2001 Federal Radionavigation Plan (FRP) with and without Loran, and two collocation options with and without Loran. However, not all four alternative mixes may address potential future requirements. As requirements and applications continue to evolve, each operating administration must ensure that adequate backups are available. Cross-modal radionavigation systems must likewise be carefully coordinated. The current collocation and synergy of NDGPS with the Continuously Operating Reference Stations (CORS), Maritime Differential GPS Service (MDGPS), and the GPS Surface Observing System (GSOS) has already avoided significant capital construction costs. The potential for future collocation of WAAS, NDGPS, and Loran facilities should be explored in conjunction with any future expansions of those systems.

The Task Force recommends the following:

- As investment decisions are made regarding individual radionavigation systems, the Department should review the overall radionavigation system program strategy to ensure these systems meet the positioning, navigation, and timing requirements across the entire transportation infrastructure in the most cost-effective and efficient manner.

    - The current role of the Department's Investment Review Board (IRB) should be broadened to serve this function for radionavigation system programs. This would additionally require expanding the membership of the IRB to include the Under Secretary of Transportation for Policy as a voting member.

- GPS modernization, to include the implementation of the second and third civil signals, should proceed as expeditiously as feasible in order to meet a multitude of civil applications and safety-of-life missions that are critical to our transportation infrastructure.

  - Every effort should be made to meet, and accelerate if possible, the operational implementation schedule for these new GPS capabilities.

- Complete the evaluation of enhanced Loran to validate the expectation that it will provide the performance to support aviation Non precision Approach (NPA) and maritime Harbor Entrance and Approach (HEA) operations.

  - If enhanced Loran meets the aviation NPA and maritime HEA performance criteria, and is cost effective across multiple modes, the Federal Government should operate Loran as an element of the long-term US radionavigation system mix.

  - If enhanced Loran does not meet expected performance criteria, or is not cost effective across multiple modes, the Federal Government should operate the system only to the end of 2008 to allow users sufficient time to transition to alternate navigation aids.

- Complete three additional radionavigation system studies, in addition to the enhanced Loran evaluation, as follows:

  - The USCG will, in cooperation with the FAA, assess the ability of the Wide Area Augmentation System (WAAS) to meet marine requirements.

  - The FHWA will, in cooperation with the FRA and the USCG, assess the ability of the High Accuracy Nationwide Differential Global Positioning System (HA-NDGPS) to meet surface (i.e., highway, rail, and marine) requirements.

  - The FAA will assess the ability of the Local Area Augmentation System (LAAS) to meet precision approach requirements for aviation.

- The collocation of WAAS, NDGPS, and Loran facilities should be explored in conjunction with any future expansions of those systems, contingent on the results of the enhanced Loran evaluation and benefit-cost analysis.

- The Department should explore funding strategies to ensure that NDGPS is implemented in accordance with the schedule presented in the 2001 FRP.

- As requirements and applications continue to evolve, the potential for various radionavigation systems to contribute to the overall radionavigation mix should be periodically evaluated.

This document is composed of the following sections:

Section 1 - Introduction: Describes the background, purpose, and scope of the Radionavigation Systems Task Force. It summarizes events leading to the preparation of this document and tasks that were conducted under this study.

Section 2 - Current Situation: Describes Federal radionavigation planning. It also summarizes current radionavigation systems as well as future potential radionavigation systems under research & development.

Section 3 - Modal Requirements & System Capabilities Assessment: Describes the technical approach used by the Task Force. It lays out the system requirements for transportation and non-transportation users and compares them to the capabilities of each radionavigation system.

Section 4 - Selection Methodology: Describes the process of establishing a number of alternative radionavigation system mixes and how they were evaluated and down selected to 3 alternatives mixes and a baseline.

Section 5 - Backups to GPS: Describes current and future modal backups to radionavigation systems.

Section 6 - Radionavigation Systems Mix Analysis: Describes the final alternative mixes recommended by the Task Force. This includes a baseline and 3 alternative mixes.

Section 7 - Loran Decision: Describes the various options available regarding the Loran-C decision and recommendation from the Task Force.

Section 8 - Cost: Discusses the program funding for the various radionavigation systems.

Section 9 - Conclusions and Recommendations: Presents the Task Force final conclusions and recommendations.

Appendices

References

Study Team

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Introduction

1.1 Introduction

This section describes the background, purpose, and scope of the Radionavigation Systems Task Force. It summarizes the events leading to the preparation of this document and the tasks that were conducted under this study.

1.2 Background

The Final Report of the President's Commission on Critical Infrastructure Protection concluded that GPS services and applications are susceptible to various types of interference, and that the effects of these vulnerabilities on civilian transportation applications should be studied in detail. As a result of the report, PDD-63 directed that the DOT, in consultation with the DoD, undertake a thorough evaluation of the vulnerability of the national transportation infrastructure that relies on GPS.

The Volpe National Transportation Systems Center (RSPA/Volpe Center) conducted this evaluation and identified GPS vulnerabilities and their potential impacts to aviation, maritime transportation, railroads, and Intelligent Transportation Systems. The final report, *Vulnerability Assessment of the Transportation Infrastructure Relying on the Global Positioning System,* was published on August 29, 2001 (Ref.1) and is available on the US Coast Guard (USCG) website at www.navcen.uscg.gov.

With release of the report, the Secretary of Transportation requested that the administrators of each DOT operating administration thoroughly review the report and assess whether appropriate policies, plans, and activities are either in place or underway to mitigate the vulnerabilities of GPS. The Secretary stated that the assessment should also consider whether adequate backups, including multi-modal backups, are in place for each area of operations.

On December 18, 2001, operating administrations presented their assessment of the report to the Deputy Secretary and concurred with the recommendations contained in the report. As a result, the Secretary initiated an action plan on March 6, 2002, that included a capability assessment of radionavigation systems used in transportation. The action plan also called for a decision on the Loran-C system by the end of calendar year 2002. The DOT Positioning and Navigation Executive Committee (POS/NAV EC) was tasked with the responsibility to oversee implementation of the Secretary's action plan. The Secretary's memo with the attached action plan is in Appendix C.

1.3 Task Force

The Secretary directed the POS/NAV EC to establish a Task Force to conduct an assessment of radionavigation systems capabilities to support transportation. Where feasible, the Task Force would consider the requirements of non-transportation uses of Federal radionavigation systems. The Office of the Assistant Secretary for Transportation Policy was given the responsibility for chairing the Task Force. Membership included representatives from all DOT operating administrations plus the Intelligent Transportation System Joint Program Office (ITSJPO), and the Policy, Security, and Budget offices. Non-DOT Federal agencies were invited as appropriate. The GPS Interagency Advisory Council (GIAC) was an active participant throughout the assessment.

To accomplish the analysis, the Task Force focused on two tasks. The first task was to conduct a multi-modal capabilities assessment of all radionavigation systems, both current and planned, to satisfy the national need for radionavigation, positioning, and timing. This included looking at the possibilities of using a system designed for one operating agency as a backup for the needs of another. The output of this task was a technical and cost perspective that would focus on the five most promising alternatives for system architectures (or 'system of systems'). This product was the input for the second task, which was to assess the five alternatives considering additional factors. These factors included recommendations of the Volpe report on backups to GPS, potential impact on other US Government agencies' systems and operations, user equipage, and interagency and international agreements. The final objective was a recommendation to the Secretary on the most appropriate mix of radionavigation systems, from both a capability and cost perspective, to satisfy the national need for radionavigation, positioning and timing services for at least the next 10 years. The Task Force Terms of Reference are contained in Appendix C.

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Current Situation

2.1 Federal Radionavigation Planning

The Federal Government operates radionavigation systems as one of the necessary elements to enable safe transportation and encourage commerce within the United States. It is a goal of the Government to provide this service in a cost-effective manner.

As the full civil potential of GPS and its augmentations is realized, the service provided by other Federally provided radionavigation systems is expected to decrease to match the reduction in demand for those services. However, operational or safety considerations may dictate the need for complementary navigation systems to support navigation or conduct certain operations. While some operations may be conducted safely using a single radionavigation system, it is Federal policy to provide redundant radionavigation service where required. A major goal for the US Government is to select a mix of common-use civil/military radionavigation systems that meets diverse user requirements.

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

Although radionavigation systems are operated primarily for safety of transportation and national defense, they also provide significant benefits to other civil, commercial, and scientific users. In recognition of this, the Federal Government considers the needs of these non-transportation users before making any changes to the operation of radionavigation systems.

The current US policy for the provision of Federally-operated radionavigation systems is contained in the 2001 FRP (Ref. 2).

2.2 Federally-Operated Radionavigation Systems

The following are brief descriptions of each system. Detailed technical descriptions can be found in the 2001 Federal Radionavigation Systems (FRS) (Ref. 3).

2.2.1 GPS

GPS is a space-based radionavigation system developed and operated by the DoD and managed by the Interagency GPS Executive Board (IGEB). GPS will be the primary Federally provided radionavigation system for the foreseeable future. GPS will be augmented to satisfy civil requirements for accuracy, coverage, availability, continuity, and integrity.

2.2.2 Augmentations to GPS

GPS alone does not meet all the different user performance requirements for navigation, positioning, and timing applications. Various differential techniques are used to augment GPS to meet specific user performance requirements; however, it is important to note that differential systems and users of differential systems are dependent upon being able to receive the GPS signal in order to compute a position using differential techniques.

2.2.2.1 NDGPS

The USCG Maritime DGPS service (MDGPS) provides GPS users with increased accuracy and integrity using land-based reference stations that transmit correction messages. It provides coastal coverage of the conterminous US, the Great Lakes, Puerto Rico, portions of Alaska and Hawaii, and portions of the Mississippi River Basin. NDGPS is an expansion of MDGPS to cover all surface areas of the United States to meet the requirements of surface users. In this report we refer to NDGPS as including both MDGPS and this expansion.

2.2.2.2 WAAS

WAAS, a satellite-based GPS augmentation system being implemented by the Federal Aviation Administration (FAA), is expected to provide the accuracy, availability, integrity, and continuity to support lateral and vertical navigation for all phases of flight in the US through Category I approach and landing. Category I is a planned WAAS capability contingent on GPS L5 FOC. WAAS covers all of CONUS, Hawaii, Puerto Rico, and most of Alaska.

2.2.2.3 LAAS Category I

LAAS is a ground-based GPS augmentation system being developed by the FAA. LAAS is expected to provide the required accuracy, availability, integrity, and continuity to initially support Category I precision approaches and eventually for Category II and III precision approaches. Category I LAAS is currently being implemented, while Category II and III capability is under research and development.

2.2.2.4 National CORS

The National Geodetic Survey (NGS) has established a National Continuously Operated Reference Stations (CORS) system to support non-navigation, post-processing applications of GPS. As such, National CORS is an augmentation to GPS, although it is not a radionavigation system. National CORS provides code range and carrier phase data through the Internet from a nationwide network of over 330 stations. National CORS stations include NDGPS and WAAS stations, as well as numerous stations operated by the National Oceanic and Atmospheric Administration (NOAA), National Aeronautics and Space Administration (NASA), state/local governments, industry, and academia.

2.2.3 Loran-C

Loran-C was developed to provide military users with a radionavigation capability with much greater coverage and accuracy than its predecessor (Loran-A). It was subsequently selected as the radionavigation system for civil marine use in the US coastal areas. It is currently designated by the FAA as a supplemental system in the NAS for the en route and terminal phases of flight. It is also used by some users in the telecommunications community.

2.2.4 Aviation-Specific Navigation Aids

Several radionavigation systems are provided specifically to support aviation users. These systems are not usable by other modes of transportation due to their limited surface visibility.

2.2.4.1 VOR/DME/TACAN

Very High Frequency Omnidirectional Range (VOR) provides a bearing from an aircraft to the VOR transmitter. A collocated Distance Measuring Equipment (DME) provides the distance from the aircraft to the DME transmitter. At many sites, the DME function is provided by the Tactical Air Navigation (TACAN) system that also provides azimuth guidance to military users. Such combined facilities are called VORTAC stations.

2.2.4.2 NDB

Aeronautical Nondirectional Beacons (NDB) serve as non precision approach aids at some airports. They are also used as compass locators, generally collocated with the outer marker of an Instrument Landing System (ILS), and are used as en route navigation aids.

2.2.4.3 ILS & MLS

ILS is the predominant system supporting precision instrument approaches in the US. The Microwave Landing System (MLS) is installed at a few airports in the US.

2.3 Systems in R&D

2.3.1 Enhanced Loran

The FAA and USCG are conducting a joint evaluation to determine whether Loran can support non precision instrument approach operations for civil aviation and harbor entrance and approach operations for maritime users. It is envisioned that minor changes in the transmitted signal and equipage with modern all-in-view receivers will be required to achieve these levels of performance. These changes are not currently anticipated to adversely affect legacy Loran-C receivers. The resulting capability is referred to as 'enhanced Loran' in this report, and is described in further detail in Section 8.4.2. Some elements of enhanced Loran have already been implemented.

2.3.2 High Accuracy NDGPS

The DOT is collaborating with other Federal agencies, as well as state and local agencies, on a research program to assess the feasibility of improving the accuracy of NDGPS. The program goal is to enable users to compute navigation solutions at a 2-5 cm accuracy level within 50 km of the reference station, provide 10-20 cm accuracy level nationwide, and improve the integrity function to have a time-to-alarm of 2 seconds or better. High Accuracy NDGPS (HANDGPS) represents a potential solution to National non-navigation requirements for real-time kinematic navigation that includes many land based safety applications (i.e., snow plow guidance in white out conditions) and maritime applications (i.e., under keel clearance). Testing completed to date provides data supporting this accuracy claim. Long range testing has demonstrated an accuracy solution of better than 10 cm horizontal and 20 cm vertical (95%) at 150 miles from the broadcast site (Ref. 4). Modifications to the NDGPS facilities take less than 3 days and are accomplished with off-the-shelf components.

2.3.3 LAAS Category II & III

The LAAS Category II and III capability is, as mentioned above, under research and development. LAAS Cat II and III will provide improved accuracy, availability, integrity, and continuity to support these critical operations.

2.3.4 GPS III

GPS modernization is a multi-phase effort to be executed over the next 15+ years. Additional signals are planned to enhance the ability of GPS to support civil and military users. The Block III GPS satellites will include the additional signals being implemented on Block IIR and IIF satellites plus new capabilities currently being defined.

2.3.5 GDGPS

The NASA Global Differential GPS (GDGPS) is a GPS integrity monitoring and augmentation system that provides real-time positioning capability. The GDGPS processes real-time GPS data from a global network of more than 40 dual frequency GPS ground sites. The GPS data are processed to obtain real-time estimates of GPS satellite orbits and clocks, which, in turn, form differential corrections relative to GPS broadcast ephemerides. The GDGPS system is wide area, so the differential corrections are globally valid. The corrections are currently available through direct Internet connections and geosynchronous communications satellites. The user receiver must be a dual-frequency type, using codeless / semi-codeless technology. The system has demonstrated real-time Root Mean Square (RMS) positioning accuracy of 10 centimeters horizontally, 20 centimeters vertically, and 99.99% availability. The GDGPS system was developed and operated by the Jet Propulsion Laboratory (JPL) for NASA's terrestrial, airborne, and space-borne science applications. As such, the GDGPS was never designed to support safety-of-life operations. A level of research and development would be required to relate GDGPS operation to DOT navigation requirements. Detailed technical descriptions of the GDGPS can be found at: http://gipsy.jpl.nasa.gov/igdg.

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Modal Requirements & System Capabilities Assessment

3.1 Introduction and Technical Approach

As stated in Section 1, the Secretary of Transportation directed the POS/NAV EC to establish a Task Force to conduct an assessment of radionavigation systems capabilities to support transportation. To accomplish the technical assessment, the Task Force created a Technical Assessment Team (TAT) composed of technical experts from the FAA, USCG, Federal Highway Administration (FHWA), Federal Railroad Administration (FRA), Research and Special Programs Administration (RSPA/Volpe), National Highway Traffic Safety Administration (NHTSA), ITSJPO, and NGS (GIAC). The Team consulted with additional technical experts as necessary.

The TAT considered systems that are cross cutting, or have the potential to be cross cutting, that provided the most impact on the tradespace. These systems have been identified as GPS augmentations (WAAS, LAAS, NDGPS [includes Maritime DGPS]) and Loran-C. The TAT did not evaluate aviation-specific systems, i.e., VOR/DME, ILS, TACAN, and NDB. The capabilities of these systems were already known and are not capable of supporting multi-modal needs; however, the capabilities of these systems as backups to GPS and the costs of these systems were factors in paring down the combinations of system mixes during the evaluation of cost versus capability. The FAA was asked to assess these aviation-specific systems and recommend a mix that meets aviation requirements for backup. The recommendations were published in the *FAA Navigation and Landing Transition Strategy* report (Ref. 5).

Agencies provided the TAT with a set of requirements for their transportation mode or non-transportation application. Requirements came from the current edition of the FRS and Appendix F of the Air Force *GPS Operational Requirements Document* (ORD) (Ref. 6). New requirements not yet captured in the FRP or ORD were also considered. In addition, agencies that operate or plan to implement and operate a radionavigation system with multi-modal capabilities provided the TAT with the technical capabilities of those systems plus initial procurement and life-cycle costs of the systems.

Upon completion of the systems capability assessment, the TAT provided the Task Force with a baseline and 3 options for alternative mixes. The Task Force conducted further assessment of these mixes to include factors such as cost, recommendations of the Volpe Study on backups to GPS, benefits or other impacts on non-transportation users, political considerations, interagency agreements, and international commitments.

3.2 Agency Requirements

Validated radionavigation system requirements for the various modes are documented in the FRS and Appendix F of the ORD. As noted in the FRS, not all agencies arrive at their requirements in the same way. In addition, not all agencies use the same lexicon to describe their requirements. Therefore, to ensure equitable comparison across the modes this report uses a standard parameter framework of accuracy, availability, integrity, continuity, and coverage. Definitions for each of these terms are shown below.

Accuracy – The degree of conformance between the estimated or measured position and/or velocity of a platform and its true position or velocity. In this report accuracy is expressed at 95% confidence unless otherwise noted.

Availability – The availability of a navigation system is the percentage of time that the services of the system are usable within a specified coverage area.

Integrity – Integrity is the ability of a system to provide timely warnings to users when the system should not be used for navigation. Integrity has three components: probability of broadcasting Hazardously Misleading Information (HMI), alert limit, and time to alarm.

Continuity – The continuity of a system is the ability of the total system to perform its function without interruption during the intended operation. Continuity is expressed as the probability that the specified system performance will be maintained for the duration of a phase of operation, presuming that the system was available at the beginning of that phase of operation.

Coverage – The coverage provided by a radionavigation system is the surface area or space volume in which the signals are adequate to permit the user to determine position to a specified level of accuracy and integrity.

To produce a manageable framework to assess the most effective radionavigation system mix, modal requirements were viewed from the perspective of the most stringent requirements for the above five parameters. Modal requirements in terms of accuracy, availability, integrity, continuity, and coverage are summarized in Appendix D.

3.3 Transportation Requirements

Transportation requirements are based upon the technical and operational performance needed for transportation safety and economic efficiency. For civil aviation and maritime users the requirements are defined in terms of discrete “phases of navigation.” These phases are differentiated primarily by the characteristics of the navigation problem as the vehicle passes through different regions in its voyage.

3.3.1 Aviation Users

For the purpose of this report, the requirements are determined for different phases of navigation. These phases include en route / terminal, and approach & landing. Each of these phases is broken down into more detailed operations as expressed in Table D-1.

3.3.2 Marine Users

Marine navigation in the US consists of four major phases identified as inland waterway, harbor entrance and approach, coastal, and ocean navigation. Standards or requirements for safety of navigation and reasonable economic efficiency can be developed around these four phases. Each of these phases is broken down into more detailed operations as expressed in Table D-2.

3.3.3 Land Transportation Users

Phases of navigation are not as applicable to land transportation, due to the greater flexibility afforded land users to assess their position. Requirements will differ depending upon what the user intends to do, the type of transportation system used, and the user location.

Land navigation requirements are not as well defined as Aviation and Marine requirements. Radionavigation requirements are more easily categorized in terms of applications. These applications fall into three basic categories: highway, transit, and rail. Tables D-3 and D-4 contain more detailed information on these categories. Current rail and transit requirements only include accuracy, availability, and coverage. Current highway requirements include integrity but not continuity. Continuity values would require determination of phases of driving. FHWA requirements reflect potential future needs and have not yet been validated. Phases of driving have not been defined and their definition was not part of this effort.

It is important to note that land transportation applications have requirements that must be met at the surface of the Earth, where potential blockage by terrain, structures, and foliage can complicate reception of higher frequency, line-of-sight signals such as GPS.

3.4 Non-Transportation Requirements

Non-transportation uses of radionavigation systems fall into two broad categories: positioning and timing. It was recognized that there are other uses of GPS augmentations, such as for ionospheric sounding and determination of atmospheric water vapor content. The non-transportation positioning requirements were so distinct from timing requirements that they must be addressed separately.

3.4.1 Positioning Requirements

Positioning requirements were derived from both the FRS and Appendix F of the ORD. The set of applications is extremely diverse, and is best characterized by considering the methods of positioning and the 95% accuracy requirement (horizontal or vertical). Thus, Table D-5, Appendix D, divides the applications into three groups: Post-Processed Static Positioning, Post-Processed Kinematic Positioning, and Real-Time Kinematic Positioning. It is recognized that there is increased desire in the application areas to transition from post-processed and static methodologies into real-time and kinematic methodologies. This is due to the cost savings that can be obtained by having immediate results and by having results while in a mobile platform.

The 95% position accuracy requirements (as found in the FRP and Appendix F of the ORD) were so variable that they were categorized into groups that differed by orders of magnitude. Thus, non-transportation positioning can be in the range of 1 to 3 meters of accuracy for certain Geographic Information System (GIS) applications, or can be in the range of 1 to 3 millimeters for crustal motion monitoring. Just as economic benefits can be obtained by transitioning to real-time and kinematic methods; economic benefits, improved products, and new technologies are enabled by higher levels of positional accuracy.

It must be noted that non-navigation applications typically do not have quantified requirements for availability, integrity, and continuity. This is indicative of the usual conduct of survey and mapping applications. For example, temporary loss of radionavigation augmentation availability is not desirable, but can often be accommodated in survey operations.

It is important to note that positioning applications have requirements that must be met at the surface of the Earth, where potential blockage by terrain, structures, and foliage can complicate reception of higher frequency line-of-sight signals.

3.4.2 Timing Requirements

Volpe recommendations for backup apply to timing, as well as navigation, where safety, environment, and economic considerations are significant. This would include applications such as communication systems, banking, and power grids.

Timing requirements are referenced in a somewhat informal fashion. Different applications require time, time interval, or frequency at varying levels of accuracy. In keeping with the organization of Appendix F of the ORD, these distinct requirements are considered “time,” and are stated as either not-to-exceed accuracy, or 95% accuracy of time, under simplifying assumptions. In the spirit of this simplification, the term “clock” is used in place of “frequency standard.”

Timing applications are unique, extremely diverse and have a broad span of accuracy requirements ranging from microseconds to sub-nanosecond. For this reason, three categories of timing accuracy were defined that would distinguish between radionavigation system capabilities (Table D-25).

Timing applications are unique in that they do not require GPS augmentations. Rather, they can use GPS itself as a timing source. Advanced methods, such as Two Way Satellite Time Transfer (TWSTT), rely on satellite communication links that do not involve GPS satellites at all. It should be noted that WAAS has its own atomic clocks and time scale, WAAS Network Time (WNT). Investigations are underway to potentially utilize WAAS as a timing source that is independent from GPS. Timing applications that do not utilize GPS, instead, use atomic clocks or the Loran-C radionavigation system. These applications do not impose special site requirements or novel methodologies. While Loran-C is a radionavigation service, it also provides a frequency reference up to the Stratum 1 level (Table D-6). Loran-C enhancements are being considered and are described in Section 8.4.2.

Timing applications have requirements that must be met in space or on the surface of the Earth. Unlike positioning applications, timing applications generally involve fixed sites. For this reason, there can often be some flexibility in antenna mounting for signal reception. Further, only a single GPS or WAAS satellite need be in view to meet timing requirements.

As with positioning, timing applications typically do not have quantified requirements for availability, integrity, or continuity.

3.5 Systems Capabilities

The accuracy, availability, integrity, continuity, and coverage capabilities of each cross-cutting system evaluated by the Task Force are shown in Table 3-1.

Table 3-1. System Specifications and Standards

System	Accuracy (2 drms)	Availability	Integrity: robability of Broadcasting azardously Misleading Info	Integrity: Alert Limit	Integrity: Time to Alarm	Continuity (of Navigation)	Coverage
Global Positioning System (GPS) Standard Positioning Service (SPS)	13 m (H) 22 m (V)	99.0%	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Global
Nationwide Differential GPS (Includes Maritime DGPS)	10 m	99.7% (Single Coverage) 99.9% (Double Coverage)	Not Determined	10 m	6 sec	Not Applicable	(CONUS; selected areas of HI, AK, and PR)[1]
Wide Area Augmentation System (WAAS)	7.6 m (H & V)	99.9%	10^{-7} per Approach (150 sec Window)	40 m (H) [2] 50 m (V) [2]	(5.2 sec)[3]	99.9945% (150 sec Window)	(CONUS; most of AK)[4,5]
Local Area Augmentation System (LAAS) Category I Operations	9 m (H) 4.4 m (V)	99.9% to 99.999% (Airport Dependent)	10^{-7} per Approach (150 sec window)	40 m (H) 10 m (V)	(6 sec)[6]	99.9992% (15 sec Window)	Designated Terminal Areas
Legacy LORAN-C	18-90 m repeatable (H) 460 m (H)	99.7%	Not Applicable	> 100 nsec > 500 nsec	60 sec 10 sec	99.7%	CONUS, coastal areas, selected areas of Canada and AK

(H) - Horizontal, (V) - Vertical

[1] When NDGPS dual coverage FOC system is complete. NDGPS dual coverage is planned to be achieved in 2008 with the implementation of new sites.
[2] WAAS Alert Limit values reflect performance that meets aviation PHMI protection requirements.
[3] Does not include 1 sec for on-board WAAS avionics.
[4] When WAAS FOC system is complete. WAAS FOC, currently planned for December 2006, will add new WAAS monitor stations, implement pre-planned system enhancements, and an additional GEO satellite. Horizontal capability is 100% available at IOC.
[5] WAAS vertical guidance coverage is 100% of CONUS and most of Alaska. WAAS horizontal guidance coverage is 100% of CONUS and all of Alaska for enroute, terminal, non-precision approach, and airport surface operations.
[6] Includes 3 sec for the LAAS ground facility and 3 seconds for on-board LAAS avionics.

The system specifications and standards are based on the 2001 FRS (Ref. 3) and the *GPS SPS Performance Standard* (Ref. 7), with clarifications as appropriate. Some of these are based, in turn, on system specifications developed ten or more years ago. These specifications and standards set a worst-case limit on the services. Performance of these systems is typically much better than provided by the specification due to ongoing improvements in equipment and processing algorithms.

The accuracy for NDGPS was originally specified at 10 m (Table 3-1); however, FHWA and FRA data indicates the observed accuracy to be better than 1 to 3 meters (horizontal 95%) anywhere within the coverage area. Integrity broadcasts are also based on more than accuracy. The rate of change of pseudorange corrections is also monitored, providing improved integrity for GPS satellite clock errors. Furthermore, it has been shown that the future High Accuracy NDGPS can provide real-time 10 cm (95%) horizontal accuracy and 15 cm vertical accuracy (Ref. 8.).

Data collected during a 90-day test of WAAS between April 1 and June 30, 2002, indicates that its observed horizontal accuracy (95%) is better than 1 to 1.5 meters, and the vertical accuracy (95%) is better than 2 meters, measured at geographically dispersed test and monitor stations in the WAAS coverage area (Ref. 9).

3.6 Requirements vs. Systems Capabilities

The system capabilities to meet agency requirements are found in Appendix D. These matrices index capabilities against individual agency requirements for each phase of navigation or operation. Each system is scored 'yes' and 'no' based on how it meets the individual requirements. An aggregate category evaluation for each radionavigation system receives a 'yes' only if all requirements are met. A mark of 'not determined' indicates that an analysis of that parameter was not performed due to one or more of the following reasons:

1. Requires a costly and lengthy analysis to determine if the system meets the requirement because the system was not designed to meet the requirement being examined.

2. May require some enhancements to the system in order to meet the requirement, which is beyond the scope of the Task Force.

Due to the unique character of non-navigation applications, some comments are warranted regarding the requirements vs. system capabilities matrices presented in Tables D-23 through D-25. The rows only include accuracy and coverage due to the general lack of quantified requirements for integrity, availability, and continuity. The categories for accuracy (and categories of coverage for timing) were selected to distinguish between the radionavigation systems. Due to the flexible character of survey operations, NDGPS and WAAS capability was based on typical accuracy performance reported in the FRS. Since typical accuracy performance was not available for LAAS, the horizontal accuracy specification in the FRP/FRS was used to evaluate capability. The evaluation of LAAS coverage is based on the fact that it is a single frequency system and uses a short-range Very High Frequency (VHF) radio link, which limits coverage to the geographic area of interest.

Different evaluations are made of WAAS coverage between positioning and timing applications. These differences reflect the mobile character of survey and mapping applications vs. the static character of timing applications. As noted in Section 3.4.2, it is believed that timing applications will generally have some flexibility in antenna mounting for WAAS signal reception as exemplified by the proliferation of communication satellite dish antennas across the country. It should be noted that the use of the WAAS signal for timing applications is currently in the developmental phase.

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4

Selection Methodology

4.1 Introduction

This section discusses the methodology used to construct and analyze the potential radionavigation system mixes. It reviews the assumptions used in establishing the alternative mixes, the conduct of the evaluation, and the process of narrowing down to four options.

4.2 Basic Assumptions

The Task Force made a number of assumptions to limit the number of alternative radionavigation mixes. These assumptions include:

- The *2001 Federal Radionavigation Plan* was the baseline for this evaluation.

- Only GPS capabilities through modernized GPS Block IIF would be considered in the current evaluation. GPS Block III satellites will be considered in future evaluations once their capabilities have been defined.

In response to the Volpe study, augmentations to GPS (WAAS, LAAS, and NDGPS) cannot be backup radionavigation systems. All augmentations depend on receiving basic GPS position and time information. If GPS is lost the positioning and navigation capability of the augmentation is also lost.

4.3 Task Force Approach

There are thousands of potential combinations of radionavigation systems. The selection process was structured by focusing on the four cross-cutting radionavigation systems that provided the most impact on the tradespace. These systems are Loran-C and the GPS augmentations, i.e., WAAS, NDGPS, and LAAS. Even though LAAS is designed as an aviation-specific system, the Task Force studied the possibility of using its differential corrections to meet some requirements of other user groups. The Task Force explored the ramifications of removing individual systems. This included identifying what modal requirements could not be met and what systems enhancements might be possible to meet those requirements. The team also explored the possibility of collocating sites where cost effective.

The Task Force reduced the potential combinations down to an initial set of 11 *basic* options including the baseline from the 2001 FRP:

1) Baseline (2001 FRP): GPS+WAAS/LAAS/NDGPS for primary navigation while ILS and VOR/DME remain as backups and Loran-C remains as a potential backup.

2) Terminating Loran-C: This option assumes that Loran-C is terminated and enhancements halted. Loran-C would no longer be available as a potential multi-modal radionavigation backup for aviation, maritime, or timing users.

3) Terminating LAAS: This option assumes that LAAS development and implementation is halted. All ILSs would need to be retained for airport approaches.

4) Terminating NDGPS: This option assumes that deployment of NDGPS is halted. Marine and land users lose their GPS-based means of navigation and non-navigation users lose their primary means for positioning.

5) Terminating WAAS: This option assumes WAAS is terminated. All VOR/DMEs and Category I ILSs would need to be retained.

6) Terminating Loran-C & LAAS: This option assumes Loran-C is terminated and development of LAAS halted. Loran-C no longer remains as a potential backup and ILS needs to be retained at all runways for airport approaches.

7) Terminating Loran-C & NDGPS: This option assumes Loran-C is terminated and deployment of NDGPS halted. Loran-C no longer remains as a potential backup, marine and land users lose their GPS-based means of navigation, and non-navigation users lose their primary source for positioning.

8) Terminating Loran-C & WAAS: This option assumes that both Loran-C and WAAS are terminated. Loran-C no longer remains as a potential radionavigation backup and all VOR/DMEs and Category I ILSs would need to be retained.

9) Terminating LAAS & NDGPS: This option assumes that LAAS development is halted and NDGPS deployment terminated. ILS needs to be retained at all

runways, maritime, and land users lose their GPS-based means of navigation, and non-navigation users lose their primary source for positioning.

10) Terminating LAAS & WAAS. This option assumes LAAS development is halted and WAAS terminated. Aviation users lose all of their GPS-based means of area navigation and airport approaches, and would have to rely on current ground-based Navaids.

11) Collocation Option. This option explores the possibility of collocating Loran-C, NDGPS, WAAS, and LAAS sites where practical and cost effective.

One other permutation of phasing out two systems was considered: terminating both NDGPS & WAAS. This option results in all modal users losing their GPS-based means for area navigation and, in effect, precludes the use of GPS to meet civilian needs. This option was immediately dropped. A number of additional synergistic options were explored where features from one system could be incorporated into another but, for the purpose of simplicity, are not depicted here.

4.4 Evaluation

The potential radionavigation mix options were extensively evaluated – mainly on technical merits, but cost was also considered. One aspect of this evaluation was to explore the ability of one augmentation system to meet the needs of all users. In order for one system to provide service to all users, that system would need to be enhanced to meet the mode-specific accuracy, availability, integrity, continuity, and coverage requirements of those users. International standardization issues would also have to be considered. For example, the Coast Guard and FAA successfully tested the technical feasibility of broadcasting WAAS differential corrections through a data channel of an enhanced Loran system. As a result, the Task Force noted that Federal augmentation data could also be rebroadcast over other radio frequencies, such as FM and AM radio bands, but these options were not investigated further because of user and service provider cost issues.

The pros and cons for each alternative were evaluated and two important issues were identified:

1) Should systems under Research and Development (R&D) be considered in developing alternatives?

2) Can a single augmentation system meet cross-modal transportation requirements?

Considering R&D systems as part of the alternative mixes carries the risk of prejudging their outcome. The performance and lifecycle costs for systems in R&D are unknown at this time. In addition, the normal process is to consider integration into a radionavigation mix after completion of R&D.

The issue whether a single augmentation system can meet cross-modal transportation requirements was already discussed in the *1994 National Augmentation Study* (Ref. 10). The study recommended fielding both the NDGPS and WAAS systems to meet individual mode requirements. The study also recommended coordinating all Federally-operated augmented GPS systems to ensure optimal use of resources by maximizing commonality of system components.

These issues were discussed at the July 18, 2002 meeting of the DOT POS/NAV EC. The decision of the POS/NAV EC was to not consider R&D systems in the current evaluation and to retain both WAAS and NDGPS in the alternative mixes. The POS/NAV EC directed the modes to investigate cross-modal applications of all R&D systems. In addition, the POS/NAV EC directed the Task Force to review the 1994 Augmentation Study and determine if its recommendations were still valid. The Task Force concluded that the recommendations of the 1994 study are still valid and that user requirements are even more stringent now than in 1994. A report of the revalidation is found in Appendix E.

4.5 Final Mixes

Based on the guidance provided by the POS/NAV EC on July 18, 2002, the Task Force narrowed the range of options down to four (including the baseline option which is detailed in the 2001 FRP) and conducted further evaluations on each of the remaining options. The technical analysis, as well as the resultant pros and cons of the options, and requirements for backups, are discussed in more detail in Sections 5 and 6.

5

Backups to GPS

5.1 Background

There has been increasing concern over the past several years about the vulnerability of GPS to interference. In response to these concerns and to a Presidential Directive regarding the vulnerability of GPS, the DOT tasked the Volpe National Transportation Systems Center to assess the vulnerability of the transportation infrastructure relying on GPS. Volpe completed the study and provided a report to DOT published on August 29, 2001. The report included sixteen recommendations for the Department's consideration. Volpe's primary conclusion was that independent backup procedures or systems should be required where safety of life, the environment, or the economy is at stake.

5.2 DOT Response

In September 2001, the Secretary charged the administrators of each DOT operating administration to thoroughly review the Volpe report and consider the adequacy of backup systems for each area of operation in which GPS is being used for critical transportation applications.

The operating administrations completed their assessments and concurred with all of the report's recommendations as they applied to their modes. The Secretary formally endorsed the report, noting that safety-critical transportation applications that use GPS currently have adequate backups in case of GPS disruptions. Secretary Norman Mineta added that future actions would be necessary to build redundancy into critical transportation systems under development and ensure that essential radionavigation services continue. The action plan developed by DOT is intended to ensure that the vulnerabilities identified in the report do not affect the safety and security of our transportation system.

5.3 Discussion of Backups

The Radionavigation Systems Task Force Terms of Reference stipulated that the recommended mix of radionavigation systems should be evaluated on the ability to meet agency requirements such as the backup for GPS. However, the POS/NAV EC meeting in July 2002 limited the scope to the Task Force effort by excluding Research and Development systems from consideration. Systems under development cannot be adequately evaluated at this time. The POS/NAV EC also directed the Task Force to consider cross-modal implications of changes to existing radionavigation services.

A backup does not necessarily need to be a second radionavigation system. Backups can also be non-radionavigation systems such as inertial navigation or clocks. It may be that no backup system is available for new applications enabled by satellite technology. In those cases, the only option possible may be to revert to the conventional procedures that were in use prior to the advent of the new capability.

The Task Force revalidated the list of applications requiring backups, some of which are safety critical (Table 5-1).

Table 5-1. Backups

Mode	Application	Primary	Backup
Aviation	• Precision Approach • Non-Precision Approach	GPS+ WAAS & LAAS Cat I, ILS Cat II / III	Traditional Ground-Based Navigation, Procedures
Maritime	• Harbor Entrance and Approach • Constricted Waterway	GPS+NDGPS	Conventional Navigation Methods
Land	• Tracking Radioactive Items • Collision Notification	GPS+NDGPS	Conventional Procedures, Dead-Reckoning, etc.
Positioning	• Survey & Geodesy	GPS+NDGPS	Optical & Inertial Systems
Timing	• Communications, Power Grids, etc.	GPS+NDGPS	Loran-C, WAAS, Clocks

5.4 Transportation Backups

This section includes a brief discussion of current and future strategies for the various transportation modes, namely, aviation, marine, and land.

5.4.1 Aviation

FAA believes the best course of action is to maintain a navigation architecture that protects the National Airspace System (NAS) from the risk of deliberate interference. FAA intends to maintain a ground-based network of navigation aids, to continue to encourage the development of aircraft-based systems such as inertial navigation systems, and to explore the capability of radar, air traffic control procedures, and other means to ensure a safe airspace environment.

The aviation navigation backup strategy focuses on sustaining safety during GPS disruption for operations in instrument weather conditions and recovery of aircraft operating within a GPS interference area. Sufficient navigation infrastructure must also be retained for capacity and efficiency to continue commercial flight operations. FAA requirements analyses (Ref. 5) indicate that:

- Ultimately, about half the VOR systems should be retained to provide en route coverage to support general aviation and to provide landing aids at the busier airports. This notion requires extensive analyses in order to determine VOR operational coverage area, conjoined services, approach to and departure from airports, wind optimized routing, land leasing information, ownership, service life, maintenance cost, and technological obsolescence. Combining these elements with the VOR usage information could result in providing extensive information for developing the overall discontinuance criteria. The long-range NDBs in Alaska and in certain offshore areas like the Gulf of Mexico should be retained for the recovery of aircraft that are caught in an interference event.
- About half the Category I ILS, and all the Category II and III ILSs, should be retained to provide a backup precision approach capability.
- The current network of distance measuring equipment (DME) should be retained, primarily to allow transport aircraft to continue near-normal operations while flying through known areas of interference. The current network of TACAN should be retained for military aircraft.
- Radionavigation systems, such as Loran-C, could be retained to support developing technologies including Automatic Dependent Surveillance-Broadcast (ADS-B) which requires position determination and precise timing to ensure required separation assurance in the event of an interference event.

The ability to continue air transportation operations without interruption in the event of interference will provide an effective deterrent to the deliberate disruption of satellite navigation.

5.4.2 Marine

Critical maritime applications are adequately served by the existing navigation infrastructure. Mariners practice 'conventional' navigation, using 'all available means' which includes GPS/DGPS, Loran-C, radar, lights/buoys/daymarks, celestial navigation, fathometer, paper charts and dead reckoning. When combined with USCG regulatory authority (Vessels Traffic Services [VTS], Captain of the Port [COTP]) to close waterways in poor conditions of visibility and weather, safe navigation is adequately facilitated with respect to safety of life, environment and economy.

The situation, however, is less clear for future and emerging critical maritime applications. With the advent of Electronic Chart Display and Information Systems (ECDIS) and Automatic Identification Systems (AIS), mariners will begin to practice 'e-navigation' and increasingly rely upon these systems to navigate safely and efficiently. However, these electronic systems require 'e-inputs' in order to function. At present, the choices for e-input are limited, and they are installation dependent. This means that the mariner must be suitably equipped in order to use an alternative e-input. If the primary e-input is lost, and the vessel is not equipped to make use of suitable alternative e-inputs, then continued operations will have to be done the 'old fashioned way' (using conventional navigation and the all available means noted earlier). In the future, adequate backup may consist of the following:

- Requiring that mariners maintain full capability to navigate conventionally.
- Invoking regulatory procedures (temporarily closing the port/waterway or requiring pilotage).
- Identifying alternate sources of 'e-input' to these critical electronic systems (inertial, Loran-C, radar map matching, etc).
- Radionavigation systems, such as Loran-C, could be retained to support developing technologies including VTS and AIS which requires geodetic computation for position determination and precise timing to ensure required separation assurance and vessel tracking in the event of an interference event.

5.4.3 *Land - Highways*

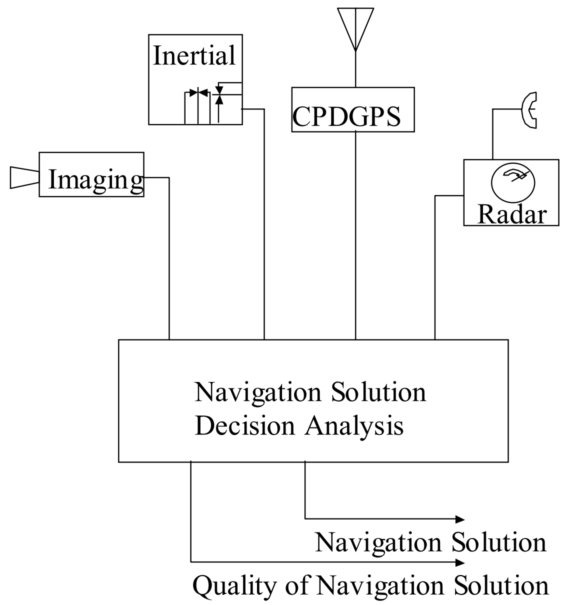
Land transportation had not made significant use of radionavigation services until the advent of GPS. In large part, this has not been due to the unavailability of a radionavigation service, but due to the complexities of incorporating that service into the vehicle environment and offering sufficient benefit to generate demand. When GPS became available, other technologies also became available that generated sufficient benefit for the land transportation modes to consider its use in various applications.

Currently, GPS has made applications such as route guidance and vehicle tracking affordable and users can see direct benefit. Transit agencies, for example, currently use GPS for Automated Vehicle Location (AVL). These agencies can revert to systems and operating procedures used prior to the use of GPS for locating vehicles. For emergency situations in which a transit vehicle needs to be located, an operator can send a priority request to talk to the dispatcher, and then describe the vehicle's location to the dispatcher via the voice radio.

As navigation systems continue to improve, applications that use position as an input for advanced safety features will become prevalent. Navigation accuracies on the order of 10 cm will be required. These systems will need to be sufficiently robust to ensure that users can depend on the safety features at all times. Thus, if a radionavigation solution is used in these systems, additional inputs will be required.

Land transportation works in an environment where terrain blockage (either man-made or natural) sometimes obstructs reception of the GPS satellites. In the case of a denial-of-service event or a complete failure, alternate systems are needed for safety-critical applications. In this environment, other technologies will be employed to fill these gaps for safety-critical applications. Some of these technologies include inertial measurement units, vehicular radar, and road imaging systems. Figure 5-1 illustrates the concept of a multi-input sensor suite that could support future safety-critical functions in highway transportation.

Figure 5-1. Conceptual System Suite for Critical Safety Applications in a Highway Environment



Each sensor functions independently but does not provide a complete solution all the time. Imaging systems work best when lane striping is clear and unobstructed. Vehicle based radars can use roadside infrastructure to determine location at points where they are available and surveyed. Inertial systems can carry through short periods when no other system is available but require a periodic navigation solution to remove drift. Carrier Phase Differential GPS (CPDGPS) will experience outages when the GPS satellites are blocked. Using a sensor suite as described here, the results of these independent sensors will be weighted and users will be offered the best possible solution, maintaining a high level of accuracy, availability, and integrity. DOT is working with research organizations to determine the performance requirements of crash warning systems and other types of driver assistance systems. Private businesses will ultimately be the suppliers to the buying public of these systems. It is expected that when manufacturers make products available to the public that they will accommodate possible disruptions of GPS signals by including measures such as backup capability or by informing users of any reduced system capability.

In this scenario, it is difficult to describe one sensor as primary and another as backup. The ability for each sensor to support the final solution is independent of the others, but a robust solution cannot be determined unless all sensors are available.

5.4.4 *Land – Railroads*

Rail operations do not currently employ GPS for safety-of-life applications so the impact of a GPS disruption would be negligible. However, the architecture for future Positive Train Control (PTC) systems will take into account potential failures of GPS. PTC Systems and train operations could continue even in the event of a severe GPS outage. PTC systems include odometers on locomotives, digital maps and map-matching algorithms in on-board computers, wayside interface units to identify passage of switches, and inertial sensors. No additional backups are required beyond those which are deemed necessary.

5.5 Non-Transportation Backups

Because of the very different characteristics of the non-transportation applications, this section is divided into two parts: positioning and timing. Review of the non-transportation requirements did show a common theme. With certain exceptions, the applications, in general, did not have a stringent need for a radionavigation backup. The lack of need must be understood in the context of a representative GPS vulnerability scenario. For the purposes of this discussion, it is assumed that the GPS signal would be lost for a period of 72 hours within a radius of 100 km. Because non-transportation applications are usually on the surface of the Earth, a signal loss situation could have a highly variable radius due to masking by terrain, structures, and foliage.

5.5.1 *Positioning*

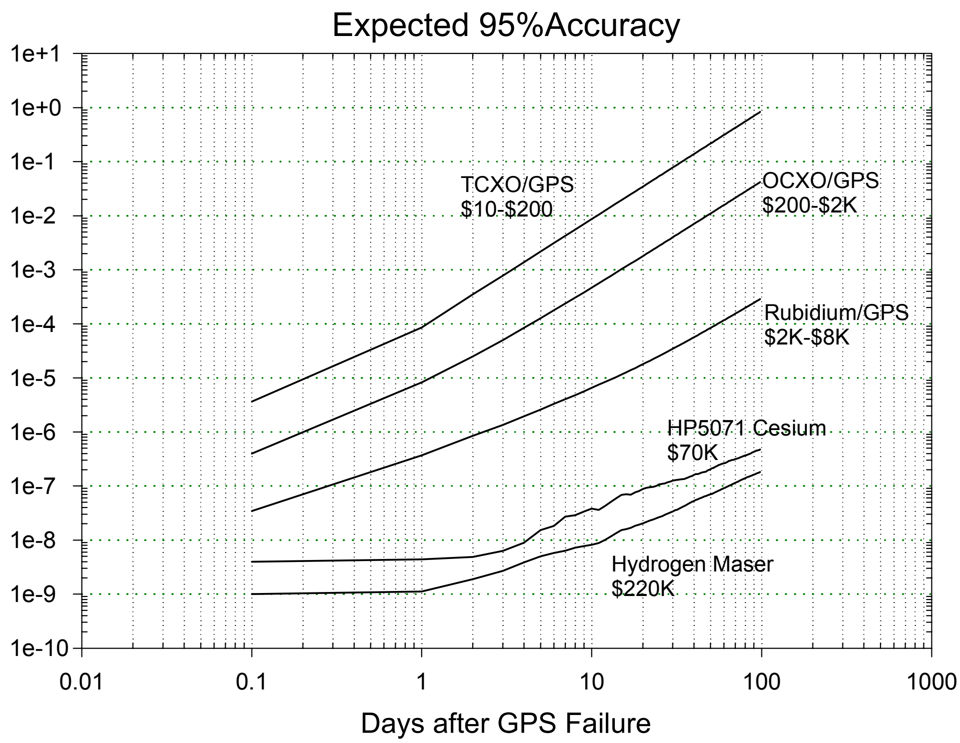
Common positioning applications include surveying and mapping. These applications have a highly variable duration and involve sporadic areas of operation. Because of the flexible character of positioning applications, operations will typically be halted until the GPS signal is restored in an area. Optical and inertial surveying equipment are backup options that could meet the accuracy requirements of these applications, depending on the capabilities and preparation of the operators.

5.5.2 *Timing*

Timing applications are more complex to characterize. Space deployments were judged insensitive to the signal loss scenario. Remaining applications can be sporadic or of continuous duration, and generally have a fixed area of operation. Certain operations, such as metrology and calibration, can be considered non-critical. Other timing applications, such as telecommunication and electrical power synchronization, were more problematic.

For non-scientific requirements such as telecommunications and electric power synchronization, clocks serve as the primary backup to GPS. However, clocks are highly variable in accuracy, stability, and expense. Examples of the relationships between clock type, clock error, and stability are found in Figure 5-2. Large telephone network carriers typically employ good rubidium clocks distributed throughout their systems. Smaller carriers use inexpensive clocks that are highly vulnerable to a 72-hour GPS outage. The weakness of particular smaller carriers represents a potential threat to the broader telecommunications network, depending upon the volume of connections. Wireless telecommunication systems have fewer options for backup clocks due to the temperature extremes that are typically encountered in a cell phone tower. Loran-C, of course, represents a backup option. However, the utilization of Loran-C as a backup to GPS varies with particular carriers

Figure 5-2. Relations between Clock Type, Error, and Stability (clock error in seconds vs. days after failure)



In general it is true that an augmentation to GPS cannot serve as a backup to GPS. Timing applications are an exception to this rule. WAAS can serve as a potential backup to GPS for timing applications. This is because WAAS has an independent clock system, as discussed in Section 3.4.2, and because only one WAAS signal needs to be received to establish timing. While it is true that the WAAS signal is transmitted on the L1 frequency, it is also true that the WAAS signals are transmitted from geosynchronous satellites. Since a geosynchronous satellite remains fixed in the sky, viewed from a fixed point on Earth, it is possible that the WAAS L1 signal can be received with a high-gain directional antenna under circumstances where the GPS signal could not be received.

5.6 Conclusions

The capabilities assessment identified which systems are capable of meeting the backup needs for each mode of transportation. The Task Force concurs that adequate backups exist today to protect current transportation and positioning requirements and applications. However, the current situation of backups for timing applications is less clear. In the future changes to cross-modal navigation systems must be carefully coordinated to assure necessary backups remain available.

Table 5-2. Future Backups

<table>
<tr><th>Mode</th><th>Applications</th><th>Primary</th><th>Backup</th></tr>
<tr><td>Aviation</td><td>All aviation uses</td><td rowspan="5">GPS
(Augmented)</td><td rowspan="6">Radionavigation & non-radionavigation systems</td></tr>
<tr><td>Maritime</td><td>• Harbor & Harbor Approach
• Constricted Waterway
• Automatic Identification System</td></tr>
<tr><td>Land – Highway</td><td>• Crash Avoidance
• Snowplow Guidance
• Tracking Radioactive Items
• Collision Notification</td></tr>
<tr><td>Land - Railroad</td><td>• Positive Train Control</td></tr>
<tr><td>Positioning</td><td>• Survey & Geodesy</td></tr>
<tr><td>Timing</td><td>• Communications, Power Grids, etc.</td><td>GPS
(Not augmented)</td></tr>
</table>

Operating Administrations are examining new radionavigation services to support enhanced transportation systems. Table 5-2 summarizes these applications for each mode. Backups are critical for these systems. However, not enough information is currently available to assess the adequacy of backups to maintain continuity should GPS be disrupted. As new services are deployed each operating administration must ensure that adequate backups are available. Once advanced transportation systems are fielded, backup procedures that severely degrade operational performance or cause significant economic costs may no longer be suitable choices.

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6

Radionavigation System Mix Analysis

6.1 Evaluation of Final Mixes

As discussed in Section 4, the Task Force, with guidance from the DOT POS/NAV EC, reduced the number of alternative mixes from 11 basic options to 4 radionavigation mix options (Table 6-1).

Table 6-1. Recommended Radionavigation System Mixes

Options		Aviation	Marine[1]	Land	Non-Navigation
Option 1: Baseline (not 2001 FRP)	Primary	GPS+WAAS/LAAS Cat I, ILS Cat II & III	GPS+NDGPS	GPS+NDGPS	GPS+NDGPS
	Backup	Reduced (VOR, ILS)[2], DME, Loran-C[3], *INS, FMS, Visual, Radar, Procedures*	Loran-C[3], *INS, Visual, Radar, Procedures*	*INS / Dead-Reckoning[4] / Digital Maps, Visual, Signaling, Procedures*	Positioning - *Optical Surveys, Inertial Surveys* Timing - Loran-C[3], WAAS[5], *Clocks*
Option 2: Drop Loran-C[3]	Primary	GPS+WAAS/LAAS Cat I, ILS Cat II & III	GPS+NDGPS	GPS+NDGPS	GPS+NDGPS
	Backup	Reduced (VOR, ILS)[2] , DME, *INS, FMS, Visual, Radar, Procedures*	*INS, Visual, Radar, Procedures*	*INS / Dead-Reckoning[4] / Digital Maps, Visual, Signaling, Procedures*	Positioning - *Optical Surveys, Inertial Surveys* Timing – WAAS[5], *Clocks*
Option 3: Collocate augmentations[6], *continue* Loran-C[3]	Primary	GPS+WAAS/LAAS Cat I, ILS Cat II & III	GPS+NDGPS	GPS+NDGPS	GPS+NDGPS
	Backup	Minimum (VOR, ILS)[2], DME, Loran-C, *INS, FMS, Visual, Radar, Procedures*	Loran-C, *INS, Visual, Radar, Procedures*	*INS / Dead-Reckoning[4] / Digital Maps, Visual, Signaling, Procedures*	Positioning - *Optical Surveys, Inertial Surveys* Timing - Loran-C, WAAS[5], *Clocks*
Option 4: Collocate augmentations[6], *discontinue* Loran-C[3]	Primary	GPS+WAAS/LAAS Cat I, ILS Cat II & III	GPS+NDGPS	GPS+NDGPS	GPS+NDGPS
	Backup	Reduced (VOR, ILS)[2], DME, *INS, FMS, Visual, Radar, Procedures*	*INS, Visual, Radar, Procedures*	*INS / Dead-Reckoning[4] / Digital Maps, Visual, Signaling, Procedures*	Positioning - *Optical Surveys, Inertial Surveys* Timing - WAAS[5], *Clocks*

[1] The US Coast Guard is initiating a study to determine if the WAAS signal can meet some maritime requirements
[2] Assumes approximately 50-60% of current network.
[3] Pending outcome of enhanced Loran studies. The Government will continue to operate the Loran-C system in the short term while evaluating the long-term need and enhancements to the system.
[4] Integrated compass, speedometer, and clock (or wheel counters), etc., to estimate position when GPS not available.
[5] WAAS has a ground based clock. High gain directional antennas may acquire WAAS L1 signals.
[6] Collocation of NDGPS, WAAS, LAAS Cat I sites, or other Federal sites, where practical. If a decision is made to continue Loran, collocation could also be, if practical, with Loran sites.

Italics: non-radionavigation systems (note: radar uses radio waves but is not assumed here to be a radionavigation system as described in the FRP)

6.1.1 Option 1: Baseline

The baseline was modified from the 2001 FRP in order to exclude R&D systems, such as LAAS Category II & III and High Accuracy NDGPS.

6.1.2 Option 2: Discontinue Loran

This option is a variation of the baseline where Loran-C is terminated and the evaluation of enhanced Loran is halted. There are cost savings to the Government with the termination of Loran but this decision would also terminate the possibility of using the system as a cross-modal radionavigation backup. The Task Force recommends completion of the evaluation of enhanced Loran before making such a decision.

Pros:

- Meets aviation requirements for primary means in North Atlantic oceanic airspace operations and for supplemental area navigation use for other oceanic areas, domestic en route, terminal area, and non precision approach using GPS only. Provides adequate accuracy, availability, continuity, coverage, and integrity with the use of Receiver Autonomous Integrity Monitoring (RAIM). For primary means of navigation over the Continental US, using GPS and WAAS for en route and terminal area, the WAAS satellite constellation must consist of at least 3 geostationary satellites in optimum positions. For primary NPA and Lateral Precision w/ Vertical guidance (LPV) precision approach use with 95% confidence over the Continental US, at least 3 geosynchronous satellites must be in optimum positions and the airborne GPS WAAS receiver must use RAIM. LAAS will initially only meet the requirements for precision instrument approach to Category I.

- Meets marine requirements for 2-5 meter horizontal accuracy for inland waterways, and 1-5 meter horizontal accuracy for resource exploration.

- Supports FHWA requirement for highway navigation & route guidance and automated vehicle identification. Enables at-speed infrastructure surveys for accurate mapping of the infrastructure, enables improved weather forecasting for land transportation, and is accepted internationally for surface applications.

- Meets FRA 1 meter requirement for automated vehicle warning, train control, and track maintenance. It ensures surface coverage of nation (currently 84%). NDGPS delivers corrected GPS position over a ground-based medium-frequency network capable of being enhanced to meet future land transportation requirements.

- Supports requirements of non-navigation users such as: GIS, cadastral, sediment, geophysical, hydrographic, and airport surveys. It supports sounding of troposphere, ionosphere, interferometric SAR. Infrastructure supports coverage of US by National CORS system. An alternative time source (WAAS) is possible if GPS is disrupted.

NDGPS is capable of being enhanced to meet numerous real-time survey applications.

- There are possible cost savings by phasing out Loran-C, but they need to be weighed against the ‘cons’. Refer to Chapter 8 for cost details.

Cons:

- General Aviation can no longer use Loran-C for en route navigation.
- Terminates any further research to determine Loran’s ability to support non precision approaches for aviation users.
- Terminates any further research to determine Loran’s ability to support the HEA phase of marine navigation.
- Denies potential future use of enhanced Loran to broadcast WAAS data under circumstances where signals from the WAAS geosynchronous satellites are not available. These include high-latitude operations, in which the WAAS geosynchronous satellites are near or below the horizon, or when these satellites are not broadcasting.
- Eliminates a potential independent multi-modal radionavigation backup.
- Negative impact to legacy equipment in power grid and metrology sectors that uses Loran-C.
- Negative impact to large telecom carriers that use Loran as one of multiple sources of synchronization for potential usage after an extended local GPS outage.
- Would incur an estimated $100M cost to decommission Loran-C.

6.1.3 *Option 3: Collocate Augmentations, Continue with Loran*

This option recommends collocating future NDGPS and WAAS sites where cost effective while retaining Loran as a radionavigation backup. This option also permits the possibility of collocating NDGPS with Loran sites. It satisfies all user requirements for primary and backup systems. However, collocation of present sites produces minimal savings. This option, nevertheless, allows for the evaluation of future synergism in radionavigation systems.

Pros:

- Preserves current radionavigation framework.
- Synergistic approach optimizes resources across all modes, potential cost savings.
- Meets aviation requirements for en route, terminal area, and non precision approach to level of Required Navigation Performance (RNP .3) if an airborne Loran receiver can be designed to satisfy compliance with enhanced Loran transmitted signal.
- Meets marine requirements for 2-5 meter horizontal accuracy for inland waterways, and 1-5 meter horizontal accuracy for resource exploration.
- Future enhancements of Loran remain a possibility as: (1) an independent backup radionavigation system for en route navigation & non precision instrument approaches; (2) an alternate means for broadcasting WAAS correction data; (3) may allow reduction to an absolute minimum VOR network; (4) an independent backup for coastal and HEA phases of marine navigation.
- WAAS-NDGPS collocation eliminates the need for two USCG GPS differential correction receivers if the WAAS Reference Stations (WRS) receivers could provide corrections to a signal processor, which could then communicate such corrections through a local area network (LAN) to a nearby USCG medium-frequency transmitter site.
- Such receiver reduction, as well as the facilities and resources necessary to house and provide power other than to the NDGPS transmitter, could be realized as savings.
- Current NDGPS near-field integrity monitor receivers presently used to measure performance of the transmitted USCG GPS differential corrections could be collocated with the WRS to sample, instead, far-field performance of the medium frequency transmitted signal, in an improved, unattenuated manner. This configuration could produce savings by eliminating two USCG receivers.
- Supports FHWA requirement for highway navigation & route guidance and automated vehicle identification. Enables at-speed infrastructure surveys for accurate mapping of the infrastructure, enables improved weather forecasting for land transportation, and is accepted internationally for surface applications.
- Meets FRA 1 meter requirement for automated vehicle warning, train control, and track maintenance. It ensures surface coverage of nation (currently 84%).

- Supports requirements of non-navigation users such as: GIS, cadastral, sediment, geophysical, hydrographic, and airport surveys. It supports sounding of troposphere, ionosphere, interferometric SAR. Infrastructure supports coverage of US by National CORS system. An alternative time source (WAAS) is possible if GPS is disrupted. NDGPS is a ground-based system capable of being enhanced to meet numerous real-time survey and land application requirements.
- Large telecom carriers want Loran as one of multiple sources of synchronization for potential usage after an extended local GPS outage.
- Savings are possible in NDGPS-WAAS collocation. More than $35M in cost savings is achieved through the collocation of NDGPS at 47 decommissioned USAF Ground Wave Emergency Network (GWEN) sites.

Cons:

- In WAAS-NDGPS collocation a signal processor and LAN would be required, as well as associated link hardware along with changes to the physical architecture of the WRSs including additional power and housing for the signal processor, and any other equipment needed to communicate the WAAS corrections to the USCG transmitter.
- Requires feasibility studies and implementation cost determination.
- Less potential for long-term cost savings because no one complete system is decommissioned.

6.1.4 *Option 4: Collocate Augmentations, Discontinue Loran*

This option recommends collocating future NDGPS and WAAS sites where cost effective while terminating Loran. There are some cost savings by terminating Loran but this option needs to be weighed against current and future requirements for a radionavigation backup. This option would terminate the possibility of using Loran as a cross-modal radionavigation system.

Pros:

- Synergistic approach optimizes resources across all modes, potential cost savings.
- Meets aviation requirements for primary means in North Atlantic oceanic airspace operations and for supplemental area navigation use for other oceanic areas, domestic en route, terminal area, and non precision approach using GPS only. Provides adequate accuracy, availability, continuity, coverage, and integrity with the use of RAIM. For primary means of navigation over the Continental US, using GPS and WAAS for en route and terminal area, the WAAS satellite constellation must consist of at least 3 geostationary satellites in optimum positions. For primary non precision and LPV precision approach use with 95% confidence over the Continental US, at least 3 geosynchronous satellites must be in optimum positions and the airborne GPS WAAS receiver must use RAIM. LAAS will initially only meet the requirements for precision instrument approach to Category I.
- Meets marine requirements for 2-5 meter horizontal accuracy for inland waterways, and 1-5 meter horizontal accuracy for resource exploration.
- WAAS-NDGPS collocation eliminates the need for two USCG GPS differential correction receivers if the WAAS WRS receivers could provide corrections to a signal processor, which could then communicate such corrections through a local area network (LAN) to a nearby USCG medium-frequency transmitter site.
- WRS receivers could provide WAAS corrections to a signal processor, which could then communicate such corrections through a local area network (LAN) to a nearby USCG medium-frequency transmitter site.
- Current NDGPS near-field integrity monitor receivers presently used to measure performance of the transmitted USCG GPS differential corrections could be collocated with the WRS to sample, instead, far-field performance of the medium frequency transmitted signal, in an improved, unattenuated manner. This configuration could produce savings by eliminating two USCG receivers.
- Supports FHWA requirement for highway navigation & route guidance and automated vehicle identification. Enables at-speed infrastructure surveys for accurate mapping of the infrastructure, enables improved weather forecasting for land transportation, and is accepted internationally for surface applications.
- Meets FRA 1 meter requirement for automated vehicle warning, train control, and track maintenance. It ensures surface coverage of nation (currently 84%). NDGPS is capable of being enhanced to meet future land transportation requirements.

- Supports requirements of non-navigation users such as: GIS, cadastral, sediment, geophysical, hydrographic, and airport surveys. It supports sounding of troposphere, ionosphere, interferometric SAR. Infrastructure supports coverage of US by National CORS system. An alternative time source (WAAS) is possible if GPS is disrupted. NDGPS is capable of being enhanced to meet numerous real-time survey applications.
- Savings are possible in NDGPS-WAAS collocation. More than $35M in cost savings is achieved through the collocation of NDGPS at 47 decommissioned USAF GWEN sites.
- There are possible cost savings by phasing out Loran-C, but they need to be weighed against the 'cons'. Refer to Chapter 8 for cost details.

Cons:

- General Aviation can no longer use Loran-C for en route navigation.
- Terminates any further research to determine Loran's ability to support non precision approaches for aviation users.
- Terminates any further research to determine Loran's ability to support harbor entrance and approach phase of marine navigation.
- Requires feasibility studies and implementation cost determination.
- Denies potential future use of enhanced Loran to broadcast WAAS data under circumstances where signals from the WAAS geosynchronous satellites are not available. These include high-latitude operations, in which the WAAS geosynchronous satellites are near or below the horizon, or when these satellites are not broadcasting,
- Eliminates a potential independent multi-modal radionavigation backup.
- Would incur an estimated $100M cost to decommission Loran-C.
- Negative impact to legacy equipment in power grid and metrology sectors that uses Loran-C.
- Negative impact to large telecom carriers that use Loran as one of multiple sources of synchronization for potential usage after an extended local GPS outage.

6.2 Conclusions

The numerous potential radionavigation mix options were extensively evaluated and reduced to four recommended mixes that satisfy current user needs for primary and backup systems. However, not all four alternative mixes may address potential future requirements. As requirements and applications continue to evolve, each operating administration must ensure that adequate backups remain available.

During the evaluation of the requirements vs. capabilities in Appendix D, the Task Force identified a number of parameters that are still under evaluation. When these evaluations are completed, it will be possible to reassess the systems mix alternatives. This iterative process will continue until an optimum future investments decision is made.

Cross-modal radionavigation systems must likewise be carefully coordinated. Future collocation of WAAS, NDGPS, and Loran facilities should continue to be pursued in conjunction with any future expansions of those systems. Close inter-modal planning and cooperation on future system developments eventually could lead to a single seamless radionavigation, positioning, and timing system that meets all primary and backup requirements.

7

Loran Decision

7.1 Background

In 1994 the DOT announced a decision to terminate Loran-C in the year 2000 in favor of GPS-based systems. However, in the FY 96 USCG Authorization Act, Congress directed the Secretary of Transportation to develop a plan for the continuation of Loran into the next century.

In fulfillment of the Congressional direction, DOT contracted with Booz-Allen, & Hamilton (BAH) to conduct an assessment of the Loran-C system. In addition, concerns were raised about the vulnerability of GPS to jamming and a continuing need for Loran-C as a backup system to GPS. Based on a number of factors, including results of the assessment, strong support from the user community to continue Loran-C, concerns about the vulnerability of GPS, and increasing Congressional interest, a senior-level Departmental meeting was held in June 1998 regarding the continuation of Loran-C.

This senior group decided that the Department needed to continue Loran-C beyond the planned phase-out date of December 31, 2000, until there was sufficient operating experience with GPS-based systems. At the same time, it was agreed that the Department should terminate Loran-C as soon as practicable after GPS systems were installed and proven. DOT established the year 2008 as the next target phase-out date. The date 2008 was chosen because Phase I of the Coast Guard's 3-phase recapitalization program would take the Loran-C system safely to 2008 before Phase 2 would need to begin. The 1999 and 2001 FRPs were published with the following policy statement:

> "The Government will continue to operate the Loran-C system in the short term while the Administration evaluates the long-term need for the system. The US Government will give users reasonable notice if it concludes that Loran-C is not needed or is not cost effective, so that users will have the opportunity to transition to alternative navigation aids."

The current Loran-C annual operating and maintenance cost is approximately $27M, which comes out of the annual appropriation for overall USCG operations. Between 1997 and 2003 additional funds were placed in the FAA budget each year for recapitalization and improvements to the system. Recapitalization funds will not only enable continued safe operation of the Loran system but will also create opportunities for potential improvements such as Loran station destaffing which are expected to decrease long-term operating costs.

7.2 Loran Options and Discussion

The Secretary of Transportation called for a decision on Loran-C by the end of CY 2002. However, to justify continuation of Loran, it must provide the performance needed to support non precision approaches for civil aviation and harbor entrance approach and navigation for maritime users. Although indications are good that these performance levels will be achieved, it has not yet been conclusively proven. The FAA / USCG / Industry / Academia evaluation team needs until March 2004 and $10M to complete the required studies to determine the performance of enhanced Loran. Phase 1 recapitalization costs may be necessary regardless of the option chosen.

The Department evaluated three options regarding the decision on Loran:

- ***Option 1: Terminate Loran-C at the end of CY 2008.*** In this option the DOT would avoid annual operating costs of $27M beginning in 2009 and would avoid $78 million for Phase 2 and 3 recapitalization costs. However, Phase 1 recapitalization would still need to be completed for safety reasons, at a cost of $113M, to maintain the system through 2008, and approximately $100M would be incurred in decommissioning costs. If Loran-C is terminated the evaluation of enhanced Loran is also terminated. However, the performance of enhanced Loran would never be determined and termination would eliminate the only cross-modal radionavigation backup to GPS.

- ***Option 2: Complete the evaluation of enhanced Loran before implementing a final decision***. In this option the Department would have a definitive answer on the ability of Loran to support non precision approaches for civil aviation and harbor entrance and approach navigation for the maritime community. This would be the most conservative approach, deferring a final decision until results of the ongoing evaluation are known. The lack of a firm commitment now could further erode the industry base to build enhanced Loran-capable receivers. Even with a firm commitment now, there is no guarantee that manufacturers will be willing to build combined GPS/Loran receivers because of the added cost to include an enhanced Loran capability.

- ***Option 3: Commit now to operate an enhanced Loran system.*** In this option the decision would provide a cross-modal radionavigation system backup or complement to GPS for civil aviation, maritime users, emergency services, and timing applications. However, without results of the evaluation, the decision would carry cost risk. Phase 2 and 3 recapitalization costs would be offset by avoiding decommissioning costs, if this option is selected

7.3 Conclusions

The Task Force concluded the following regarding Loran:

- The evaluation of enhanced Loran needs to be completed before making a firm commitment to that system.

- Some radionavigation systems (e.g., VOR) are mode specific and cannot serve other modes. Termination of Loran would eliminate the only available cross-modal radionavigation backup to GPS.

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8

Cost

8.1 Introduction

This section discusses the program cost for the radionavigation systems evaluated by the Task Force. User requirements took precedence over cost during the evaluation of the alternative mixes. Certain cost issues, however, were factored into the analysis during the technical evaluation. This included weighing whether a system designed for one user group could be enhanced to meet the requirements of another group and be cost effective. For example, completing the NDGPS network as planned was deemed a more practical option than enhancing WAAS to meet the requirements of maritime and land transportation users.

8.2 Past & Current Collocation and Synergism

The Task Force reviewed cost savings that have already been achieved during the establishment of existing radionavigation systems, including MDGPS, CORS, NDGPS, and GSOS. Future cost savings may be possible through WAAS & NDGPS collocation.

MDGPS: In the late 1980's, the USCG investigated the ability to modify the existing marine radiobeacon infrastructure to support the broadcast of differential GPS corrections. The USCG determined that a DGPS system could be deployed quickly and cost effectively using the existing infrastructure. The reuse of 42 marine radiobeacons avoided the land acquisition and construction costs that would have been required to establish the 42 sites now known as Maritime Differential GPS. On the other hand, in the early 1990's, the US Army Corps of Engineers (USACE) also investigated the implementation of their own DGPS system. This resulted in collaboration with the USCG to establish 11 facilities at existing radiobeacons. This resulted in substantial savings by avoiding the land acquisition and construction costs that would have been required to establish these sites. The final result was a single system of 53 dual-use sites that fulfill the requirements for both dredging (USACE) and maritime navigation (USCG). This avoided the costs associated with two separate overlapping systems.

CORS: In 1994, the DOT undertook a study to examine how to combine systems to meet Federal radionavigation requirements. One of the recommendations was to make all MDGPS facilities compatible with CORS standards to support non-navigation positioning applications. The collocation of CORS-compatible measuring equipment at existing MDGPS sites avoided unnecessary duplication of systems and resulted in significant savings. This enabled the NOAA's National Geodetic Survey of the Department of Commerce to implement the CORS system faster and at substantial savings based on the proposed implementation time lines.

NDGPS: The decision was made in 1998 by Congress to establish NDGPS as a means to establish a single seamless system for land-transportation users. Rather than establish a completely new service, a decision was made to reuse and expand upon existing MDGPS facilities initially established by the USCG and the USACE. Additional cost savings were realized through the reuse of existing US Air Force GWEN facilities. Reuse of MDGPS sites avoided unnecessary duplication of systems and resulted in significant savings of land acquisition and construction costs. In addition, reuse of the GWEN sites saves $750,000 at each of 47 locations for a total savings of over $35 million.

GSOS: Additional cost savings and efficiencies have been realized through the collocation of the NOAA's Forecast Systems Laboratory's GPS Surface Observing System (GSOS) for measuring integrated precipitable water vapor, and the National Science Foundation (NSF) funded Plate Boundary Observatory (PBO) at NDGPS sites. This collocation avoided significant land acquisition and construction costs.

It should be noted that the collocation of the MDGPS, NDGPS, and National CORS was highly successful and formally acknowledged by the White House.

8.3 Future Collocation Options

WAAS-NDGPS-Loran Collocation: The Task Force also evaluated the possibility of synergism by collocating future NDGPS sites at WAAS reference stations. In addition, there is also the possibility of some savings by collocating NDGPS with a Loran site in Alaska. However, while it is technically feasible for NDGPS and WAAS to share installations, retrofitting existing installations would not be cost effective. Future collocation remains a viable option that needs to be explored in conjunction with expansions or recapitalizations of current systems. Collocation could pave the way for a future single, integrated, and seamless radionavigation system.

8.4 Cost Data

The detailed cost data for GPS augmentations and radionavigation backups is presented in Table 8-1. In this evaluation, GPS and modernized GPS (IIR, IIR-M, & IIF) do not affect the decisions on augmentations to GPS and backups. Modernized GPS will not provide a civil capability within the timeframe this evaluation covers that would influence the retention or elimination of existing augmentations and radionavigation backups. Therefore, cost data for GPS and modernized GPS has been omitted. GPS-III is still in R&D, and implementation is beyond the timeframe covered by this evaluation.

The Task Force attempted to collect cost data for the purpose of establishing the total ownership cost for these systems through 2010. However, not all the data were available from the modal administrations and consequently Table 8-1 does not represent the total cost of many of the systems and does not reflect user costs. The following clarifications should be considered for the following systems:

VOR:

- Capital / R&D estimates include a systematic recapitalization of the minimum operating network sites, beginning in 2007. The selection of the specific VOR stations to be retained is subject to further analysis.
- Costs do not include potential upgrades to Doppler antenna structures at a few selected sites, which are estimated at $800,000 per station.

ILS:

- Capital / R&D estimates include a systematic recapitalization of the minimum operating network sites, beginning in 2007. The selection of the specific ILS systems to be retained is subject to further analysis.
- Does not include approach lighting arrays and runway visual range measurement equipment necessary for any new Category II or Category III installations.

WAAS:

- 1994-2001 representative costs do not include the cost associated with the 1992 cancellation of the Wilcox contract nor leasing costs of the National Satellite Test Bed (NSTB).
- Capital / R&D estimates do not include recapitalization of replacement hardware and software scheduled to begin in 2005.

DME:

- Capital / R&D estimates include a systematic recapitalization beginning in 2007.
- Estimate of costs for installing additional Low Power DME transponders to support ILS instrument approaches is not included.

TACAN:

- Capital / R&D estimates include a systematic recapitalization beginning in 2007.

Table 8-1. Estimated Cost Data (in Millions)

	Total 1994-2001	Category	2002	2003	2004	2005	2006	2007	2008	2009	2010	Total 2002-2010
VOR	217.2	O&M	86.6	87.2	83.9	83.5	80.6	78.2	68.4	56.6	48.8	673.8
		Capital/R&D	14.2	11.4	11.4	9.8	8.6	15.7	13.5	10.3	9.3	104.2
Loran	59.6	O&M	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	243.0
		Capital/R&D	20.0	23.0	25.0	25.0	25.0	21.0	16.0	6.0	0.0	161.0
ILS	297.6	O&M	78.8	79.6	80.4	82.0	83.4	78.2	72.2	69.4	62.0	686.0
		Capital/R&D	23.4	16.4	15.2	16.8	15.4	20.0	20.0	20.0	20.0	167.2
WAAS	655.3	O&M	10.4	18.6	22.5	25.5	32.2	33.3	36.5	38.7	39.7	257.4
		Capital/R&D	82.9	98.6	120.3	155.3	157.3	89.6	109.6	106.0	108.0	1027.6
LAAS	59.6	O&M	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
		Capital/R&D	45.5	55.6	34.1	43.4	41.6	43.9	38.2	50.2	NA	352.5[2]
NDGPS[1]	59.2	O&M	9.5	10.3	11.7	12.8	13.9	14.9	14.9	14.9	14.9	117.8
		Capital/R&D	3.4	6.4	4.9	4.9	4.9	4.1	0.0	0.0	0.0	28.6
DME	20.2	O&M	16.4	16.8	17.2	17.8	18.4	17.1	16.2	16.2	16.2	152.3
		Capital/R&D	7.6	3.7	4.0	5.0	10.0	13.0	15.0	3.0	3.0	64.3
TACAN	36.6	O&M	29.4	28.6	29.0	29.0	29.0	29.0	29.0	29.0	29.0	261.0
		Capital/R&D	2.0	3.2	3.3	3.5	14.0	23.1	17.6	17.6	17.6	101.9

[1]Includes MDGPS
[2]Total does NOT include cost figures which were not available
NA = Not Available

8.4.1 VOR, DME, and TACAN

VOR, DME, and TACAN provide the basic guidance for en route air and terminal navigation and non precision approach in the United States. These systems provide position determination, establishment of course and distance to the desired destination and determination of deviation from the desired track. Information provided to the aircraft pilot by VOR is the magnetic azimuth relative to the VOR ground station. DME provides a measurement of distance from the aircraft to the DME ground station. In most cases, VOR and DME are collocated as a VOR/DME facility. TACAN provides both azimuth and distance information and is used primarily by military aircraft.

8.4.1.1 VOR

The FAA *Navigation and Landing Transition Strategy* report (Ref. 5), does not identify any potential costs associated with reducing VOR services to a Minimum Operating Network (MON). "Turning off" VORs may impact air traffic management and require realignment of airspace, impose costs for disassociating local resources for DME ground-based transponders when collocated with VORs, and affect communications network and frequency reassignment.

8.4.1.2 DME

The FAA *Navigation and Landing Transition Strategy* report (Ref. 5), does not identify any potential costs associated with installing additional DME ground transponders.

8.4.1.3 TACAN

TACAN, the military counterpart of civil VOR/DME, is a tactical air navigation system for the military services ashore and afloat. TACAN is primarily collocated with the civil VOR stations (VORTAC facilities) to enable military aircraft and some civil aircraft to operate in the NAS and to provide DME information to civil users. Similar to VOR/DME, special consideration must be given to the location of ground-based TACAN facilities, especially in mountainous terrain due to line-of-sight coverage. This Report does not reflect DoD acquired, owned, and operated TACAN facilities, which are currently being budgeted for expansion within the NAS, contrary to the previously published intent by DoD to reduce land-based TACAN.

8.4.2 Loran

The fielding of an enhanced Loran consists of two basic elements: basic Loran recapitalization and Loran performance improvement. A third element, Loran Data Channel, is optional and is not an essential part of enhanced Loran and is not included in the overall cost estimates.

8.4.2.1 Basic Loran Recapitalization

Loran recapitalization is a multi-phase effort intended to sustain the existing Loran system. Some modest improvement in performance and maintainability will result from this recapitalization. Conversion from hyperbolic to Time-of-Transmission (TOT) control for better accuracy and timing is possible with basic recapitalization. The impact on legacy users from conversion to time of transmission control is expected to be minimal. Phase 1 ($113.2M) comprises that level of non-discretionary equipment modernization that is necessary to sustain Loran operations through the year 2008.

Elements of Loran Phase 1 Recapitalization include:

- Replace aging, unsupportable vacuum tube technology transmitters
- Replace aging, unsupportable timing equipment
- Extend service life of current solid-state transmitters
- Replace several antennas at the end of their service lives
- Replace other aging, unsupportable electronics
- Rehabilitate critical Alaska Loran station facilities and runways

Loran Phase 1 Recapitalization Funding (sustain operations through 2008):

Total Funds required:	$158.3M
Expended to date (through FY 2002):	($45.1M)
Remaining work (beginning FY 2003):	$113.2M

Phase 2 recapitalization ($11.5M) consists of three CONUS tower replacements in FY 06-08 and will sustain the Loran system through 2015. Phase 3 recapitalization ($67M) consists of five Alaska tower replacements in FY 13-15 and will sustain the Loran system beyond 2015. If Loran is terminated in 2008, the Phase 2 and 3 costs of $78.5M will be avoided, but will be offset by termination costs estimated to be $100M in FY 08-12.

8.4.2.2 Loran Performance Improvements

Enhanced Loran is a $58M option that will complete development of the receiver technology needed to achieve 8-20 meter maritime HEA and aviation RNP 0.3 nm NPA levels of Loran performance. Loran is already performing at a level that supports 18-90 meter repeatable accuracy. Enhanced Loran will cause the absolute accuracy (presently at 460 meters) to converge on and ultimately surpass the current repeatable accuracy of legacy Loran. The majority (90-95%) of improvement in enhanced Loran will result from advances in receiver technology (e.g., magnetic-loop antennas, all-in-view receivers, and better propagation calibration). The remaining 5-10% of performance improvement will result from changes to the transmitting station infrastructure. Implementation of a Loran differential correction may be necessary to meet maritime target accuracies. Frequency users of Loran will see minor improvement. Timing users of Loran will see significant improvement (UTC [Coordinated Universal Time] within 30-40 ns). Conversion from hyperbolic to TOT control (for better accuracy and timing) is required. Relocation of two Alaskan LORSTAs (LORSTA: Loran Station) may be needed. The impact of the station moves on legacy Loran users in Alaska will be significant, although CONUS will be largely unaffected.

Table 8-2 summarizes the performance requirements for enhanced Loran.

Table 8-2. Performance Requirements for Enhanced Loran

	Accuracy	Availability	Integrity	Continuity
Current Loran-C	**0.25 nm (460 m)**	**0.997**	**10 sec alarm (25 m error)**	**0.997**
Aviation Enhanced Loran	0.16 nm (296 m)	0.999	0.9999999	0.999 – 0.9999
Maritime Enhanced Loran	0.004 – 0.01 nm (8-20 m)	0.997	10 sec alarm (25 m error)	0.9985 – 0.9997 (3 hours)
Enhanced Loran Timing	UTC +/- 30 ns Frequency 10^{-11}	NA	NA	NA

Elements of Enhanced Loran include:

- Develop modern aviation-certifiable all-in-view Loran receivers
- Install whole-station Uninterruptible Power Supplies (UPS) to improve availability
- Develop improved propagation models to improve accuracy
- Convert to time-of-transmission control to improve accuracy and timing synchronization
- Evaluate need for differential Loran corrections
- Relocate LORSTA Attu to Prudhoe Bay[*]

- Relocate LORSTA Port Clarence to Nome*

*The $58M Enhanced Loran cost figure includes $12.3M to move LORSTA Attu, AK, to Prudhoe Bay, AK, and $5.0M to move LORSTA Port Clarence, AK, to Nome, AK. These moves may not be necessary depending on the results of ongoing development work.

Cost of Enhanced Loran:

Total Funds required:	$58.0M
Expended to date (through FY 2002):	$12.5M
Remaining work (beginning FY 2003):	$45.5M

8.4.2.3 Loran Data Channel (Optional)

A method of broadcasting FAA WAAS differential corrections on the Loran signal is under development. Initial testing, including flight trials in partnership with FAA, has yielded very promising results. The implementation of a broadcasting of WAAS corrections on a Loran Data Channel could ultimately provide an aviation-certifiable, multi-mode GPS augmentation that could also be suitable for surface and maritime use.

Cost of Loran Data Channel:

Total Funds required:	$38.3M
Expended to date (through FY 2002):	$5.3M
Remaining work (beginning FY 2003):	$33.0M

8.4.3 ILS

The Instrument Landing System (ILS) is a precision approach system normally consisting of a localizer facility, a glide slope facility, and associated VHF marker beacons and non-directional beacons. It provides vertical and horizontal navigation (guidance) information during the approach to landing at an airport runway. The costs represented in Table 8-1 for operating ILS are an aggregation of cost estimates for Capital / R&D and O&M for the components of localizer and glide slope facilities. They do not reflect the cost estimates for the associated marker beacons and non-directional beacons.

8.4.4 WAAS

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

The costs represented in Table 8-1 for operating the WAAS network including the two existing geostationary satellites are an aggregation of Capital / R&D and O&M for the components that support the existing WAAS network. They are predicated on Basis of Estimate (BOE) costs prepared for the WAAS Program Office calculated for the WAAS rebaselining activity underway at the time of the writing of this report.

The BOE costs include replacement of existing, obsolete hardware and software components used in the WRS and GUS facilities in their current configuration. There is considerable technical and cost risk associated with future WAAS development and deployment.

8.4.5 LAAS

The costs represented in Table 8-1 for operating the LAAS are uncertain since the initial implementation of only 10 facilities including 2 of which are planned for non-civil airports, is based upon an initial funding risk by both the US Government and industry. The Government and Industry Partnership (GIP) arrangement will defray considerable cost to the taxpayer; however, it is limited to the first development and deployment phase. The costs do not include any expansion or adaptation of LAAS for use beyond Category I precision instrument approaches.

8.4.6 NDGPS

Congress authorized the Secretary of Transportation to establish, operate, and manage the NDGPS service in Section 346 of Public Law 105-66, enacted on October 27, 1997. Along with this authorization, Congress provided FY 1998 appropriations for NDGPS capital expenses to accelerate the project. From this date the cost history for the non-maritime portion of NDGPS has been as follows:

- In FY 1998, Senate Amendment originated $2.4M received in US Coast Guard appropriation.
- Costs to construct and operate NDGPS in FY 1999 were estimated at $7.2M and requested in the FRA budget, and $5.5M was received in the in US Coast Guard appropriation.
- Costs to construct and operate NDGPS in FY 2000 were estimated at $10.4M and requested in the FRA budget, and $5.0M was received in the FHWA appropriation.
- Costs to construct and operate NDGPS in FY 2001 were estimated at $18.7M and requested in the FRA budget, and $6.0M was received in the FAA appropriation.
- Costs to construct and operate NDGPS in FY 2002 were estimated at $20.5M and requested in the FRA budget, and $6.0M was received in the FHWA appropriation. This includes $2.7M for capital and $3.3M for operations and maintenance (O&M). Plans called for 27 NDGPS sites operational at the end of 2002.
- Costs to construct and operate NDGPS in FY 2003 were estimated at $32.1M and requested in the FRA budget. The President's Budget requested $6M for NDGPS in the FAA budget, which includes $2.3M for capital and $3.7M for O&M. Plans call for 33 NDGPS sites operational at the end of 2003. The Senate would provide $6M for NDGPS in the FAA budget, but the House would provide $0 (zero) for NDGPS citing concerns about the movement of the budget between the various DOT modal administrations.
- Costs to construct and operate NDGPS in FY 2004 are estimated at $10M, which includes $6.0M for capital and $4.0M for O&M. Approximately 42 NDGPS sites would be operational at the end of 2004.

Once the NDGPS network is completed, the annual O&M cost is estimated to be $8.1M.

The previous cost figures reflect the non-maritime portion of NDGPS. Table 8-3 summarizes the maritime, non-maritime, and total NDGPS costs.

Table 8-3. NDGPS Estimated Costs ($M)

Maritime NDGPS	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
R & D										
Procurement										
O & M	6.9	6.9	6.9	6.9	6.9	6.9	6.9	6.9	6.9	6.9
Other										
Total	**6.9**	**6.9**	**6.9**	**6.9**	**6.9**	**6.9**	**6.9**	**6.9**	**6.9**	**6.9**
Cumulative Total	**6.9**	**13.8**	**20.7**	**27.6**	**34.5**	**41.4**	**48.3**	**55.2**	**62.1**	**69.0**

Non-Maritime NDGPS	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
R & D										
Procurement	3.9	3.4	6.4	4.9	4.9	4.9	4.1	0.0	0.0	0.0
O & M	2.1	2.6	3.4	4.8	5.9	7.0	8.0	8.0	8.0	8.0
Other										
Total	**6.0**	**6.0**	**9.8**	**9.7**	**10.8**	**11.9**	**12.1**	**8.0**	**8.0**	**8.0**
Cumulative Total	**6.0**	**12.0**	**21.8**	**31.5**	**42.3**	**54.2**	**66.3**	**74.3**	**82.3**	**90.3**

NDGPS Total	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
R & D										
Procurement	3.9	3.4	6.4	4.9	4.9	4.9	4.1	0.0	0.0	0.0
O & M	9.0	9.5	10.3	11.7	12.8	13.9	14.9	14.9	14.9	14.9
Other										
Total	**12.9**	**12.9**	**16.7**	**16.6**	**17.7**	**18.8**	**19.0**	**14.9**	**14.9**	**14.9**
Cumulative Total	**12.9**	**25.8**	**42.5**	**59.1**	**76.8**	**95.6**	**114.6**	**129.5**	**144.4**	**159.3**

As reported to Congress in the June 1998 *National Height Modernization Study,* "Every American who drives a vehicle or uses telecommunications equipment, and every farmer who uses precision farming, benefits from NDGPS. The benefit-to-cost ratio is several hundred to one even when justified solely on the basis of horizontal positioning benefits to America. The benefit-to-cost radio improves significantly when its 4-dimensional benefits (latitude, longitude, height, and time) are taken into account" (Ref. 11).

8.5 Conclusions

The current collocation and synergy of NDGPS with CORS, MDGPS, & GSOS has already avoided significant capital construction costs and has received recognition at the highest levels of government.

The collocation of WAAS, NDGPS, and Loran facilities should be explored in conjunction with any future expansions of those systems.

When investing in a major recapitalization of a radionavigation system, the Department needs to examine the multi-modal utility of the system, and the potential to combine facilities, before making a decision on the investment. For example, Loran provides increased capability to a broad sector of users whereas VOR is a mode-specific system.

Although WAAS could satisfy some land and maritime requirements, it is not designed for that purpose. Completing the NDGPS network as planned is a more practical option from a cost perspective than attempting to enhance WAAS to meet all the requirements of maritime and land transportation users or, conversely, attempting to enhance NDGPS to meet aviation requirements.

9

Conclusions and Recommendations

9.1 Conclusions

The Volpe report *Vulnerability Assessment of the Transportation Infrastructure Relying on the Global Positioning System* contained a series of recommendations which were reviewed and ultimately accepted by the Department's operating agencies. Recommendations were made relative to: overarching issues related to GPS vulnerabilities, mitigating the vulnerabilities of the GPS signal to disruption or loss, and mitigating the vulnerabilities of the transportation systems resulting from the disruption or loss of the GPS signal. This led to the establishment of a Capabilities Assessment Task Force to develop a recommended capabilities investment strategy for US radionavigation systems to meet transportation infrastructure requirements for the next ten years. This recommendation had to balance the plan to move toward a heavy reliance on satellite navigation with the vulnerabilities of such an approach highlighted in the Volpe report.

The Task Force concluded the following:

- Some radionavigation systems (e.g., VOR) are mode specific and cannot serve other modes.
- Today, adequate backups exist to protect current transportation and positioning requirements and applications. However, the situation for timing applications is less clear.
- In the future, as requirements and applications continue to evolve, each operating administration must ensure that adequate backups remain available. Cross-modal radionavigation systems must likewise be carefully coordinated.

- The evaluation of enhanced Loran needs to be completed before making a firm commitment to that system. Termination of Loran would eliminate the only available cross-modal radionavigation backup to GPS.
- The current collocation and synergy of NDGPS with CORS, MDGPS, & GSOS has already avoided significant capital construction costs.
- The collocation of WAAS, NDGPS, and Loran facilities should be explored in conjunction with any future expansions of those systems.
- Further collocation of existing systems is not cost effective at this time because only a few new WAAS sites in Alaska are available for collocation with NDGPS.
- When investing in a major recapitalization of a radionavigation system, the Department needs to examine the multi-modal utility of the system, and the potential to combine facilities, before making a decision on the investment.
- Although WAAS could satisfy some land and maritime requirements, it is not designed for that purpose. Completing the NDGPS network as planned is a more practical option from a cost perspective than attempting to enhance WAAS to meet all the requirements of maritime and land transportation users or, likewise, attempting to enhance NDGPS to meet aviation requirements.
- The final four radionavigation mixes satisfy current user needs for primary and backup systems. However, not all four alternative mixes address potential future requirements.
- Although R&D systems were not considered in the final evaluation, they would need to be considered in future evaluations once they are out of R&D.

9.2 Recommendations

The Task Force recommends the following:

- As investment decisions are made regarding individual radionavigation systems, the Department should review the overall radionavigation system program strategy to ensure these systems meet the positioning, navigation, and timing requirements across the entire transportation infrastructure in the most cost-effective and efficient manner.

  - The current role of the Department's Investment Review Board (IRB) should be broadened to serve this function for radionavigation system programs. This would additionally require expanding the membership of the IRB to include the Under Secretary of Transportation for Policy as a voting member.

- GPS modernization, to include the implementation of the second and third civil signals, should proceed as expeditiously as feasible in order to meet a multitude of civil applications and safety-of-life missions that are critical to our transportation infrastructure.

  - Every effort should be made to meet, and accelerate if possible, the operational implementation schedule for these new GPS capabilities.

- Complete the evaluation of enhanced Loran to validate the expectation that it will provide the performance to support aviation NPA and maritime HEA operations.

  - If enhanced Loran meets the NPA and HEA performance criteria, and is cost effective across multiple modes, the Federal Government should operate Loran as an element of the long-term US radionavigation system mix.

  - If enhanced Loran does not meet expected performance criteria, or is not cost effective across multiple modes, the Federal Government should operate the system only to the end of 2008 to allow users sufficient time to transition to alternate navigation aids.

- Complete three additional radionavigation system studies, in addition to the enhanced Loran evaluation, as follows:

  - The USCG will, in cooperation with the FAA, assess the ability of the Wide Area Augmentation System (WAAS) to meet marine requirements.

  - The FHWA will, in cooperation with the FRA and the USCG, assess the ability of the High Accuracy Nationwide Differential Global Positioning System (HA-NDGPS) to meet surface (i.e., highway, rail, and marine) requirements.

- The FAA will assess the ability of the Local Area Augmentation System (LAAS) to meet precision approach requirements for aviation.

▪ The collocation of WAAS, NDGPS, and Loran facilities should be explored in conjunction with any future expansions of those systems.

  - Based on the need to pursue synergism, cooperation, and collocation in future radionavigation systems, the Task Force recommends as a radionavigation mix either Option 3, ‘Collocation with Loran’, or Option 4, ‘Collocation without Loran’, contingent on the results of the enhanced Loran evaluation and benefit-cost analysis.

▪ Explore funding strategies to ensure that NDGPS is implemented in accordance with the schedule presented in the 2001 FRP.

▪ As requirements and applications continue to evolve, the potential for various radionavigation systems to contribute to the overall radionavigation mix should be periodically evaluated.

Appendix A

Glossary

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

ADS	Automatic Dependent Surveillance
AIS	Automatic Identification System
AK	Alaska
AVL	Automated Vehicle Location
C/A	Coarse/Acquisition
CG	Coast Guard (USCG)
CGSIC	Civil GPS Service Interface Committee
cm	centimeter
CONUS	Conterminous United States
CORS	Continuously Operating Reference Stations
COTP	Captain of the Port
CPDGPS	Carrier Phase Differential GPS
DGPS	Differential Global Positioning System
DME	Distance Measuring Equipment
DoD	Department of Defense
DOT	Department of Transportation
drms	distance root mean squared
ECDIS	Electronic Chart Display and Information System
FAA	Federal Aviation Administration

FHWA	Federal Highway Administration
FL	Flight Level
FMS	Flight Management Systems
FOC	Full Operational Capability
FRA	Federal Railroad Administration
FRP	Federal Radionavigation Plan
FRS	Federal Radionavigation Systems
FTA	Federal Transit Administration
FY	Fiscal Year
GDGPS	Global Differential GPS System
GEO	Geostationary Earth Orbit
GHz	Gigahertz
GIAC	GPS Interagency Advisory Council
GIP	Government and Industry Partnership
GIS	Geographic Information Systems
GPS	Global Positioning System
GSOS	GPS Surface Observing System
GUS	Geostationary Uplink Site
GWEN	Ground Wave Emergency Network
HANDGPS	High Accuracy NDGPS
HEA	Harbor Entrance Approach
HF	High Frequency
HI	Hawaii
HMI	Hazardous Misleading Information
Hz	Hertz (cycles per second)
ICAO	International Civil Aviation Organization
IGEB	Interagency GPS Executive Board
ILS	Instrument Landing System

INS	Inertial Navigation System
IOC	Initial Operational Capability
IRB	Investment Review Board
ITS	Intelligent Transportation Systems
ITS-JPO	Intelligent Transportation Systems Joint Program Office
JPL	Jet Propulsion Lab (NASA)
JPO	Joint Program Office
kHz	kilohertz
km	kilometer
LAAS	Local Area Augmentation System
LAN	Local Area Network
LEO	Low Earth Orbiting
LF	Low Frequency
LNAV	Lateral Navigation
LORSTA	Loran Station
LPV	Lateral Precision w/ Vertical Guidance
m	meter
M	Million
MARAD	Maritime Administration
MASER	Microwave Amplification by Stimulated Emission or Radiation
MCS	Master Control Station
MDGPS	Maritime Differential GPS Service
MF	Medium Frequency
MHz	Megahertz
MLS	Microwave Landing System
mm	millimeters
ms	millisecond
MOA	Memorandum of Agreement

MON	Minimum Operating Network
NASA	National Aeronautics and Space Administration
Navaids	Ground-Based Navigation Aids
NAVCEN	US Coast Guard Navigation Center
NDB	Non-Directional Beacon
NDGPS	Nationwide Differential Global Positioning Service
NGS	National Geodetic Survey
NHTSA	National Highway Traffic Safety Administration
nm	nautical mile
NOAA	National Oceanic and Atmospheric Administration
NPA	Non precision Approach
NPOESS	National Polar-Orbiting Observational Environmental Satellite System
ns	nanosecond
NSF	National Science Foundation
NSTB	National Satellite Test Bed
ORD	Operational Requirements Document
OST	Office of the Secretary of Transportation
OST/B	Assistant Secretary for Budget Programs
OST/P	Assistant Secretary for Transportation Policy
O&M	Operations and Maintenance
PBO	Plate Boundary Observatory
PBS	President's Budget Submission
PDD	Presidential Decision Directive
PHMI	Probability of Hazardously Misleading Information
POS/NAV EC	Positioning and Navigation Executive Committee (DOT)
PPS	Precise Positioning Service
PR	Puerto Rico
PRC	Pseudo Range Corrections

PTC	Positive Train Control
RAIM	Receiver Autonomous Integrity Monitoring
R&D	Research & Development
RF	Radio Frequency
RMS	Root Mean Square
RNP	Required Navigation Performance
RRC	Range-Rate Corrections
RSPA	Research and Special Programs Administration
RTCA	Radio Technical Commission for Aeronautics
RTCM	Radio Technical Commission for Maritime Services
SA	Selective Availability
SAR	Synthetic Aperture Radar
SPS	Standard Positioning Service
TACAN	Tactical Air Navigation
TAT	Technical Assessment Team
TD	Time Difference
TDMA	Time Division Multiple Access
TOT	Time of Transmission
TSARC	Transportation Systems Acquisition Review Council
TWSTT	Two Way Satellite Time Transfer
UHF	Ultra High Frequency
UPS	Uninterruptible Power Supply
US	United States of America
USACE	US Army Corps of Engineers
USCG	United States Coast Guard
USNO	United States Naval Observatory
UTC	Coordinated Universal Time
VHF	Very High Frequency

VNAV	Vertical Navigation
Volpe	Research and Special Programs Administration / Volpe National Transportation Systems Center
VOR	Very High Frequency Omnidirectional Range
VORTAC	Collocated VOR and TACAN
VTS	Vessel Traffic Service
WAAS	Wide Area Augmentation System
WGS	World Geodetic System
WMS	Wide Area Master Station
WNT	WAAS Network Time
WRS	WAAS Reference Station

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. (Note: Chapter 4 in the FRS discusses chart reference systems and the risks inherent in using charts in conjunction with radionavigation systems.)
- Repeatable - The accuracy with which a user can return to a position whose coordinates have been measured at a previous time with the same navigation system.
- Relative - The accuracy with which a user can measure position relative to that of another user of the same navigation system at the same time.

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

Alert Limit - Integrity risk is defined as the probability that the navigation sensor error exceeds either the Horizontal or Vertical Alert Limits (measured in meters) and the navigation system alert is silent beyond the time-to-alarm. The Alert Limit is sometimes also referred to as Alarm Limit.

- Horizontal Alert Limit - The Horizontal Alert Limit (HAL) is the radius of a circle in the horizontal plane (the local plane tangent to the WGS-84 ellipsoid), with its center being at the true position, which describes the region which is required to contain the indicated horizontal position with the required probability for a particular navigation mode (e.g., $1x10^{-7}$ per flight hour for en route), assuming the probability of a GPS satellite integrity failure being included in the position solution is less than or equal to 10^{-4} per hour.
- Vertical Alert Limit - The Vertical Alert Limit is half the length of a segment on the vertical axis (perpendicular to the horizontal plane of WGS-84 ellipsoid), with its center being at the true position, which describes the region which is required to contain the indicated vertical position with a probability for a particular navigation mode (e.g., of $1x10^{-7}$ per approach), assuming the probability of a GPS satellite integrity failure being included in the position solution is less than or equal to 10^{-4} per hour.

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

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

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

Clock - A device that generates periodic, accurately spaced signals used for timing applications.

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

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

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

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

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.

En Route - A phase of airborne 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 Level (FL) - A level of constant atmospheric pressure related to a reference datum of 29.92 inches of mercury. Each is stated in three digits that represent hundreds of feet. For example, flight level (FL) 250 represents a barometric altimeter indication of 25,000 feet; FL 225 represents an indication of 22,500 feet.

Frequency - The rate of a repetitive event.

Frequency Standard - An oscillator, usually atomic, that is used as a reference source for frequency measurements.

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

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

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

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

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

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

Nanosecond (ns) - One billionth of a second.

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

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.

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

Probability of Hazardously Misleading Information (PHMI) - Hazardously misleading information is defined to exist any time a properly functioning user receiver's error exceeds the protection limit and the problem is not corrected within the time to alarm requirement. PHMI is the probability this event will happen.

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

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

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

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

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

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 [observation].

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

Terminal - A phase of airborne 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 - The designation of an instant on a selected time scale.

Time Interval - The elapsed time between two events.

Time to Alarm - The time to alarm is defined as the time starting when an alarm condition occurs to the time that the last bit of the first alarm message.

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

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

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Appendix C
Documentation

C.1 Terms of Reference

TERMS OF REFERENCE

Radionavigation Systems Task Force

I. Purpose

The Secretary of Transportation has directed the Department to conduct an assessment of radionavigation systems capabilities to support transportation. To accomplish this, a Task Force is established to:

A. Conduct a multi-modal capability assessment of all radionavigation systems, current and planned, that are used in the US transportation infrastructure.
B. Provide a recommendation on a capability investment strategy for the mix of Federal radionavigation systems to meet all requirements of the US transportation infrastructure.

Where feasible, the requirements of non-transportation uses of Federal radionavigation systems will be considered.

II. Background

On September 10, 2001, the US Department of Transportation released the results of a study assessing the vulnerability of the national transportation infrastructure that relies on the Global Positioning System (GPS). The report was mandated by a Presidential Decision Directive (PDD-63) and prepared by the DOT Volpe National Transportation Systems Center.

With release of the report, the Secretary requested that the administrators of each DOT operating administration thoroughly review the report and assess whether appropriate policies, plans, and activities are either in place or underway to mitigate the vulnerabilities of GPS. The Secretary stated that the assessment should also consider whether adequate backups, including multi-modal backups, are in place for each area of operations.

On December 18, 2001, operating administrations presented their assessment of the report to the Deputy Secretary and concurred with the recommendations contained in the report. As a result, an action plan was initiated that included a capability assessment of radionavigation systems used in transportation.

III. Task Force Structure

The Office of the Assistant Secretary for Transportation Policy will chair the Task Force. Membership will include representatives from all DOT operating administrations plus ITS/JPO, OST/P, OST/S-60, and OST/B. Other Federal agencies may participate as appropriate. Administrative and technical assistance will be provided through intradepartmental staff and contract support as required.

IV. Objective

The primary objective of the Task Force is to develop a recommendation on a capability investment strategy for the most appropriate mix of radionavigation systems, from both a capability and cost perspective, to satisfy requirements across the DOT operating administrations for at least the next 10 years.

V. Tasks

To achieve its objective, the Task Force will:

a. Conduct a capability assessment of each radionavigation system, both current and planned, and the extent to which each system will meet the navigation, positioning, and timing service requirements of all modes of transportation.

- Identify additional factors to be considered, such as unit cost and life cycle cost of each system evaluated.
- Consider the navigation, positioning, and timing requirements of other US Government agencies.
- Develop 4 to 6 radionavigation system combinations that have the potential to meet agency requirements as defined in the 2001 Federal Radionavigation Plan (FRP) or the GPS Operational Requirements Document (ORD). Agency requirements not identified in the 2001 FRP or the ORD may also be considered provided they have been entered into the validation process.
- Evaluate each radionavigation system combination both in terms of technical capability and cost.

b. Assess the capability of each combination developed in Task A to meet agency requirements with respect to additional factors such as:

- Recommendations of the Volpe Report on backups to GPS
- Potential impact on other US Government agency systems and operations
- User equipage
- Interagency agreements and international commitments
- Political considerations

c. Provide a recommendation to the Secretary on the most appropriate mix of radionavigation systems, from both a capability and cost perspective, to satisfy the national need for radionavigation, positioning, and timing services for at least the next 10 years.

VI. Schedule

The Task Force will meet as necessary to complete tasking in three phases:

1. Task 'a' will be completed by the end of May 2002
2. Task 'b' will be completed by mid-August 2002
3. Task 'c' will be completed by mid-November 2002

Progress reports/briefings will be provided, as required, to the DOT Positioning and Navigation Executive Committee (POS/NAV EC) and/or the Deputy Secretary during the completion of the tasking.

VII. Oversight

The DOT POS/NAV EC will oversee completion of this effort.

______________________________Date:______________

Assistant Secretary for
Transportation Policy

C.2 Secretary's Tasking

THE SECRETARY OF TRANSPORTATION
WASHINGTON, D.C. 20590

March 6, 2002

MEMORANDUM FOR: HEADS OF OPERATING ADMINISTRATIONS

FROM: NORMAN Y. MINETA

SUBJECT: Vulnerability Assessment of the Transportation Infrastructure Relying on the Global Positioning System

I want to thank you for your organization's assessment of the Volpe Study that was provided to the Deputy Secretary on December 19, 2001. I am encouraged that all the operating administrations have concurred with the findings and recommendations of the report. As a result, the Department formally accepts the report and will now start implementing the recommendations.

I endorse the action plan presented at the December 18 meeting (Enclosure 1) and need your full support as we start on this important and ambitious effort. The DOT Positioning and Navigation Executive Committee (POS/NAV EC) will oversee the implementation of the plan. The POS/NAV EC will charter a task force in the near future to conduct a multi-modal capabilities assessment of current and planned radionavigation systems and identify the appropriate future mix of these systems. The OST Policy Office will support the POS/NAV EC in this effort.

We all need to focus on these measures to protect out critical transportation infrastructure. I look forward to periodic progress reports on these efforts. If you have any questions, please contact Mr. Michael Shaw, Director, Radionavigation and Positioning at (202) 366-0353.

Enclosure

Approved Action Plan

The DOT Positioning and Navigation Committee will oversee implementation of these approved activities by the operating administrations. The OST policy office will integrate activities and track implementation status.

- Vulnerability Mitigation
  - Ensure adequate backup systems (All)
  - Continue GPS modernization (OST)
  - Continue spectrum protection (OST/FAA/CG)
  - Enhance interference location capabilities (FAA)
- GPS Civil Receiver Enhancement
  - Facilitate transfer of DoD anti-jam technology for civil use (OST)
  - Certify safety-critical GPS receivers (FAA/CG)
  - Develop GPS receiver standards (FHWA/FRA)
- Risk Awareness
  - Emphasize education programs (All)
  - Conduct periodic Public Outreach (OST)
  - Send Letters to Industry, State/Local DOTs (FHWA)
  - Work with GPS Industry Council (OST)
- Future Direction (OST Lead, All)
  - Develop 2003 Federal Radionavigation Plan (FRP) roadmap to identify definitive mix of future radionavigation systems
  - Complete inter-modal capabilities assessment of radionavigation systems
  - Make decision on future of Loran-C by end of CY02

Enclosure (1)

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Appendix D

Modal Requirements and System Capabilities

Table D-1. Aviation Requirements

Operations Area	Accuracy (2 drms)	Availability	Integrity: Probability of Broadcasting Hazardously Misleading Info	Integrity: Alert Limit	Integrity: Time to Alarm	Continuity	Coverage	Current or Planned Primary System (s)
Oceanic	12.4 nm	99.999%	10^{-7}	4.0 nm	2 min	$1 - 10^{-5}$ per hour	Global (FL 275 to 400)	GPS
Domestic	2.0 nm	99.999%	10^{-7}	2.0 nm	1 min	$1 - 10^{-5}$ per hour	CONUS (FL180 to 600)	GPS / WAAS
Terminal	0.4 nm	99.999%	10^{-7}	1.0 nm	30 sec	$1 - 10^{-5}$ per hour	CONUS (500 ft to FL 180)	GPS / WAAS
Non-Precision Approach (NPA)	100 m (H)	99.999%	10^{-7}	0.3 nm	10 sec	$1 - 10^{-5}$ per hour	Terminal Area	WAAS
LNAV/VNAV	220 m (H) 20 m (V)	99.9%	10^{-7}	0.3 nm (H) 50 m (V)	10 sec	$1 - 8 \times 10^{-6}$ (in any 150 sec time period)	WAAS Service Volume	WAAS
Lateral Precision w/ Vertical Guidance (LPV)	16 m (H) 20 m (V)	99.9%	10^{-7}	40 m (H) 50 m (V)	6 sec	$1 - 8 \times 10^{-6}$ (in any 150 sec time period)	WAAS Service Volume	WAAS
APV II	16 m (H) 8 m (V)	99.9%	10^{-7}	40 m (H) 20 m (V)	6 sec	$1 - 8 \times 10^{-6}$ (in any 150 sec time period)	WAAS[1] Service Volume	WAAS[1]
Precision Approach CAT I	18.2 m (H) 7.6 m (V)	99.9%	10^{-7}	40 m (H) 10-15 m (V)	6 sec	$1 - 10^{-5}$ (in any 15 sec time period)	Applicable Airport	ILS / LAAS[2]
Precision Approach CAT II	6.5 m (H) 2.0 m (V)	99.9%	10^{-7}	17.3 m (H) 5.3 m (V)	1 sec	$1 - 8 \times 10^{-6}$ (in any 15 sec time period)	Applicable Airport	ILS / LAAS[2]
Precision Approach CAT III	6.2 m (H) 2.0 m (V)	99.9%	10^{-7}	15.5 m (H) 5.3 m (V)	1 sec	$1 - 6 \times 10^{-6}$ (in any 30 sec time period)	Applicable Airport	ILS / LAAS[2]

(H) - Horizontal
(V) - Vertical

[1] Future WAAS with L5

[2] LAAS expected to meet requirement

Table D-2. Marine Requirements

Operations Area		Accuracy (2 drms)	Availability	Integrity			Continuity	Coverage	Current or Planned Primary System (s)
				Probability of Broadcasting Hazardously Misleading Info	Alert Limit	Time to Alarm			
Ocean	Safety of Navigation (All Craft)	2 - 4 nm	99.0%	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Global	GPS
Coastal	Safety of Navigation (All Ships)	460 m	99.7%	Not Applicable	Not Applicable	Not Applicable	Not Applicable	U.S. Coastal Waters	GPS
	Safety of Navigation (Rec Boats & Smaller Vessels)	460 m	99.0%	Not Applicable	Not Applicable	Not Applicable	Not Applicable	U.S. Coastal Waters	GPS
Harbor Entrance & Approach	Safety of Navigation (Large Ships & Tows)	8 - 20 m	99.7%	Not Applicable	25 m	10 sec	99.97 High Risk 99.85 Low Risk	U.S. Harbor Entrance & Approach	NDGPS
	Safety of Navigation (All Ships)	8 - 20 m	99.9%	Not Applicable	25 m	10 sec	99.97 High Risk 99.85 Low Risk	U.S. Harbor Entrance & Approach	NDGPS
	Resource Exploration	1 - 5 m	99.0%	Not Applicable	25 m	10 sec	Not Applicable	U.S. Harbor Entrance & Approach	NDGPS
	Engineering & Construction Vessels	5 m (H) 0.1 m (V)	99.0%	Not Applicable	25 m	10 sec	Not Applicable	Entrance Channel & Jetties, etc.	NDGPS
Inland Waterways	Safety of Navigation (All Ships & Tows)	2 - 5 m	99.9%	Not Applicable	25 m	10 sec	99.97 High Risk 99.85 Low Risk	U.S.Inland Waterway Systems	NDGPS
	Safety of Navigation (Rec Boats & Smaller Vessels)	5 - 20 m	99.9%	Not Applicable	25 m	10 sec	99.85	U.S.Inland Waterway Systems	NDGPS
	River Engineering & Construction Vessels	5 m (H) 0.1 m (V)	99.0%	Not Applicable	25 m	10 sec	Not Applicable	U.S.Inland Waterway Systems	NDGPS

(H) - Horizontal
(V) - Vertical

Table D-3. Land Requirements[1] (Highway)

Operations Area		Accuracy (95%)	Availability	Integrity: Probability of Broadcasting Hazardously Misleading Info	Integrity: Alert Limit	Time to Alarm	Coverage	Current or Planned Primary System (s)
Highway	Navigation and Route Guidance	1 - 20 m	>95%	Not Applicable	2-20 m	>=5 sec	Nationwide/ Surface Coverage	NDGPS
	Automated Vehicle Monitoring	10 cm to 30 m	>95%	Not Applicable	20 cm to 30m	5 sec to 5 m	Nationwide/ Surface Coverage	NDGPS
	Automated Vehicle Identification	1m	99.7%	Not Applicable	3 m	>=5 sec	Nationwide/ Surface Coverage	NDGPS
	Public Safety	10cm to 30m	95 - 99.7%	Not Applicable	20 cm to 30 m	2-15 sec	Nationwide/ Surface Coverage	NDGPS
	Resource Management	5 mm to 30 m (H and V)	99.7%	Not Applicable	20 cm to 1 m	2-15 sec	Nationwide/ Surface Coverage	NDGPS[2]
	Accident Survey	.1 to 4 m	99.7%	Not Applicable	20 cm to 4 m	30 sec	Nationwide/ Surface Coverage	NDGPS[2]
	Emergency Response	30cm to 10 m	99.7%	Not Applicable	50cm to 10 m	near zero	Nationwide/ Surface Coverage	NDGPS[2]
	Collision Avoidance	0.1 m	99.9%	Not Applicable	.2m	5 sec	Nationwide/ Surface Coverage	NDGPS[2]
	Intelligent Vehicle Initiative	0.1m	99.9%	Not Applicable	.2m	5 sec	Nationwide/ Surface Coverage	NDGPS[2]

(H) - Horizontal
(V) - Vertical

There are no quantifiable requirements for continuity

[1]Reflects potential future needs and have not yet been validated.
[2]Requires High Accuracy NDGPS (HANDGPS)

Table D-4. Land Requirements (Railroad and Transit)

Operations Area		Accuracy (95%)	Availability	Integrity: Probability of Broadcasting Hazardously Misleading Info	Integrity: Alert Limit	Integrity: Time to Alarm	Coverage	Current or Planned Primary System (s)
Rail	Automated Vehicle Warning	1.0 m	99.9%	Not Applicable	10 m	5 sec	Nationwide	NDGPS
	Train Control	1.0 m	99.9%	Not Applicable	10 m	5 sec	Nationwide	NDGPS
	Track Maintenance	1.0 m	99.7%	Not Applicable	10 m	5 sec	Nationwide	NDGPS
Transit	Vehicle Command & Control	30 - 50 m	99.7%	Not Applicable	Not Available	Not Available	Nationwide	NDGPS
	Automated Voice Bus Stop Annunciation	5 m	99.7%	Not Applicable	Not Available	Not Available	Nationwide	NDGPS
	Emergency Response	75 - 100 m	99.7%	Not Applicable	Not Available	Not Available	Nationwide	NDGPS
	Data Collection	5 m	99.7%	Not Applicable	Not Available	Not Available	Nationwide	NDGPS

There are no quantifiable requirements for continuity

Table D-5. Non-Navigation Requirements (Position)

Applications Area		95% Accuracy	Coverage	Current or Planned Primary System (s)
Post-Processed Static	Geographic Information Systems (GIS) (Facilities Management)	1.0 m	Nationwide	NDGPS / CORS / Enhanced NDGPS
	Cadastral Survey, Geographic Information Systems (Facilities Management), Sediment Survey, Sounding of Troposphere, Water Vapor Determination, Ionosphere	0.1 m	Nationwide	CORS / Enhanced NDGPS[1]
	Geodetic Survey, Earthquake Research	0.01m	Nationwide	CORS
	Crustal Motion, Deformation Monitoring	0.001 m	Nationwide	CORS
Post-Processed Kinematic	Geophysical Survey, Geographic Information Systems (GIS)	1.0 m	Nationwide	NDGPS / CORS / Enhanced NDGPS
	Hydrographic Survey, Airport Survey (Runway), Interferometric Synthetic Aperture Radar	0.1 m	Nationwide	CORS / Enhanced NDGPS[1]
	Topex Altimetry, Satellite Operations, NPOESS Occultation	0.01 m	Space	NASA global tracking
Real-Time Kinematic	Track Weather Balloons	< 5 m	Nationwide	GPS and Loran-C
	GIS Land Navigation, Dredging	0.1 m	Nationwide	Enhanced NDGPS[1]
	Farming	0.01 m	Nationwide	not met

No Quantified Requirements for Availability, Integrity (HMI, Alert Limit, Time to Alarm), or continuity

[1]Requirement currently not met; in the future could be met by Enhanced NDGPS

Table D-6. Non-Navigation Requirements (Timing)

Applications Area		Accuracy (NTE)	95% Accuracy	Coverage	Current or Planned System
Timing	ADS Communications using TDMA	5 microseconds		Worldwide	GPS / Loran-C
	NPOESS Occultation	1 microsecond		Worldwide (To Geosynchronous Altitude)	GPS
	Power Grids, Metrology and Calibration	1 microsecond to 100 ns		North America	GPS / Loran-C
	Communications Networks		100 ns	Worldwide	GPS / Loran-C
	Stratum 1 Clocks		100 ns	Worldwide	GPS / Loran-C
	SPS Time Transfer from UTC		40 ns	Worldwide (To Geosynchronous Altitude)	GPS
	Satellite Operations		25 ns	Worldwide (To Geosynchronous Altitude)	GPS Common View[1]
	Metrology and Calibration		20 ns	Worldwide	GPS Common View[1]
	UTC to USNO Time Differential		10 ns	Worldwide	GPS Common View[1]
	Primary Freq. Standards Maintenance		1 ns	Worldwide	TWSTT[2]
	Advanced Clocks in Space		1 ns	Worldwide (To Geosynchronous Altitude)	TWSTT[2]
	Measure MASER Stability		0.2 ns	Worldwide (To Geosynchronous Altitude)	GPS carrier phase[3]

NTE - not to exceed
No Quantified Requirements for Integrity (HMI, Alert Limit, Time to Alarm)
See Notes for Availability/Continuity

[1] Special Technique using GPS Signal -- No Current Defined Linkage to GPS Performance Parameters

[2] Special Technique using communication satellites -- Does not use a radionavigation system or GPS augmentation

[3] Requirement currently not met, in the future could be met by GPS carrier phase

Table D-7. Aviation Requirements vs. Capabilities (Oceanic)

Characteristic	Requirement	GPS SPS	NDGPS	WAAS	LAAS	LORAN-C
Accuracy	12.4 nm	Yes	Yes	Yes	TBD	Yes
Availability	99.99%	Yes[1]	Yes[2]	Yes	TBD	TBD
Integrity	PHMI 1 x 10^{-7} 4 nm Alert Limit 2 min Time to Alarm	No[3]	No[4]	Yes	TBD	TBD
Continuity	1 – 10^{-5} per hour	Yes[1]	Yes	Yes	TBD	No
Coverage	Global (FL 275 to FL 400)	Yes	No	No	No	No
Meets Requirements		**No[5]**	**No**	**No**	**No**	**No**

[1] Requires dual equipage, clock, altimeter, and airspeed indicator; and, must meet requirements of TSO-C129a

[2] Requires dual system coverage

[3] Would require Receiver Autonomous Integrity Monitoring (RAIM)

[4] Has not been technically examined nor is there currenty an intent to do so

[5] GPS SPS alone does not meet requirement. Would require certified receiver with RAIM and other instrumentation

TBD = An evaluation is being conducted to analyze the system's capability to meet this requirement

Table D-8. Aviation Requirements vs. Capabilities (En Route)

Characteristic	Requirement	GPS SPS	NDGPS	WAAS	LAAS	LORAN-C
Accuracy	2 nm	Yes	Yes	Yes	TBD	Yes
Availability	99.999%	No	Yes[1]	Yes	TBD	TBD
Integrity	PHMI 1×10^{-7} 2 nm Alert Limit 1 Min Time to Alarm	No[2]	No[3]	Yes	TBD	TBD
Continuity	$1 - 10^{-5}$ per hour	No	Yes	Yes	TBD	TBD
Coverage	CONUS (FL 180 to FL 600)	Yes	Yes	Yes	No	Yes
Meets Requirements		**No[4]**	**No**	**Yes**	**No**	**No[4,5]**

[1] Requires dual system coverage
[2] Would require Receiver Autonomous Integrity Monitoring (RAIM)
[3] Has not been technically examined nor is there currenty an intent to do so
[4] Approved as a supplemental means of navigation
[5] Will be reevaluated as a primary means of navigation when TBD's are known

TBD = An evaluation is being conducted to analyze the system's capability to meet this requirement

Table D-9. Aviation Requirements vs. Capabilities (Terminal)

Characteristic	Requirement	GPS SPS	NDGPS	WAAS	LAAS	LORAN-C
Accuracy	0.4 nm	Yes	Yes	Yes	TBD	Yes
Availability	99.999%	No	Yes[1]	Yes	TBD	TBD
Integrity	PHMI 1×10^{-7} 1 nm Alert Limit 30 sec Time to Alarm	No[2]	No[3]	Yes	TBD	TBD
Continuity	$1 - 10^{-5}$ per hour	No	Yes	Yes	TBD	TBD
Coverage	CONUS (500 ft to FL 600)	Yes	Yes	Yes	TBD	Yes
Meets Requirements		**No[4]**	**No**	**Yes**	**No[5]**	**No[4,6]**

[1] Requires dual system coverage
[2] Would require Receiver Autonomous Integrity Monitoring (RAIM)
[3] Has not been technically examined nor is there currently an intent to do so
[4] Approved as a supplemental means of navigation
[5] Will be reevaluated when TBD's are known
[6] Will be reevaluated as a primary means of navigation when TBD's are known

TBD = An evaluation is being conducted to analyze the system's capability to meet this requirement

Table D-10. Aviation Requirements vs. Capabilities (Non Precision Approach)

Characteristic	Requirement	GPS SPS	NDGPS	WAAS	LAAS	LORAN-C
Accuracy	100 m (H)	Yes	Yes	Yes	TBD	TBD
Availability	99.999%	No	Yes[1]	Yes	TBD	TBD
Integrity	PHMI 1 x 10^{-7} 0.3 nm Alert Limit 10 sec Time to Alarm	No[2]	No[3]	Yes	TBD	TBD
Continuity	1 – 10^{-5} per hour	No	Yes[1]	Yes	TBD	TBD
Coverage	Applicable Terminal Area	Yes	Yes	Yes	TBD	Yes
Meets Requirements		**No[4]**	**No**	**Yes**	**No[5]**	**No[5]**

(H) - Horizontal

[1] Requires dual system coverage
[2] Would require Receiver Autonomous Integrity Monitoring (RAIM)
[3] Has not been technically examined nor is there currently an intent to do so
[4] Approved as a supplemental means of navigation
[5] Will be reevaluated when TBD's are known

TBD = An evaluation is being conducted to analyze the system's capability to meet this requirement

Table D-11. Aviation Requirements vs. Capabilities (LNAV/VNAV Approach)

Characteristic	Requirement	GPS SPS	NDGPS	WAAS	LAAS	LORAN-C
Accuracy	220 m (H) 20 m (V)	No	Yes	Yes	TBD	No
Availability	99.9%	No	Yes[1]	Yes	TBD	No
Integrity	PHMI 1 x 10^{-7} 0.3 nm (H)/50 m (V) Alert Limit 10 Sec Time to Alarm	No	No[2]	Yes	TBD	No
Continuity	1 – 8 x 10^{-6} (in any 150 sec time period)	No	Yes[1]	Yes	TBD	No
Coverage	Applicable Terminal Area	Yes	Yes	Yes	TBD	Yes
Meets Requirements		**No**	**No**	**Yes**	**No[3]**	**No**

(H) - Horizontal
(V) - Vertical

[1] Requires dual system coverage
[2] Has not been technically examined nor is there currently an intent to do so
[3] Will be reevaluated when TBD's are known

TBD = An evaluation is being conducted to analyze the system's capability to meet this requirement

Table D-12. Aviation Requirements vs. Capabilities (LPV Approach)

Characteristic	Requirement	GPS SPS	NDGPS	WAAS	LAAS	LORAN-C
Accuracy	16 m (H) 20 m (V)	No	Yes	Yes	TBD	No
Availability	99.9%	No	Yes[1]	Yes	TBD	No
Integrity	PHMI 1×10^{-7} 40 m(H)/50 m (V) Alert Limit 6 Sec Time to Alarm	No	No[2]	Yes	TBD	No
Continuity	$1 - 8 \times 10^{-6}$ (in any 150 sec time period)	No	Yes[1]	Yes	TBD	No
Coverage	Applicable Terminal Area	Yes	Yes	Yes	TBD	Yes
Meets Requirements		**No**	**No**	**Yes**	**No[3]**	**No**

(H) - Horizontal
(V) - Vertical

[1] Requires dual system coverage
[2] Has not been technically examined nor is there currently an intent to do so
[3] Will be reevaluated when TBD's are known

TBD = An evaluation is being conducted to analyze the system's capability to meet this requirement

Table D-13. Aviation Requirements vs. Capabilities (Category I Precision Approach)

Characteristic	Requirement	GPS SPS	NDGPS	WAAS	LAAS	LORAN-C
Accuracy	18.2 m (H) 7.6 m (V)	No	No	Yes	TBD	No
Availability	99.9%	No	Yes[1]	Yes	TBD	No
Integrity	PHMI 1×10^{-7} 40 m(H)/10-15 m (V) Alert Limit 6 Sec Time to Alarm	No	No[2]	TBD[3]	TBD	No
Continuity	$1 - 10^{-6}$ (in any 15 sec time period)	No	No	TBD[3]	TBD	No
Coverage	Applicable Terminal Area	Yes	Yes	Yes	TBD	Yes
Meets Requirements		**No**	**No**	**No[4]**	**No[5]**	**No**

(H) - Horizontal
(V) - Vertical

[1] Requires dual system coverage
[2] Has not been technically examined nor is there currently an intent to do so
[3] Planned capability using dual-frequency avionics contingent on GPS L5 FOC
[4] Expected to meet requirement with GPS L5 FOC
[5] Will be reevaluated when TBDs are known

TBD = An evaluation is being conducted to analyze the system's capability to meet this requirement

Table D-14. Aviation Requirements vs. Capabilities (Category II Precision Approach)

Characteristic	Requirement	GPS SPS	NDGPS	WAAS	LAAS	LORAN-C
Accuracy	6.5 m (H) 2 m (V)	No	No	No	TBD	No
Availability	99.9%	No	Yes[1]	Yes	TBD	No
Integrity	PHMI 1 x 10^{-9} 17.3 m(H)/5.3 m (V) Alert Limit 1 Sec Time to Alarm	No	No	No	TBD	No
Continuity	1 – 8 x 10^{-6} (in any 15 sec time period)	No	Yes[1]	Yes	TBD	No
Coverage	Applicable Terminal Area	Yes	Yes	Yes	TBD	Yes
Meets Requirements		**No**	**No**	**No**	**No[2]**	**No**

(H) - Horizontal
(V) - Vertical

[1] Requires dual system coverage
[2] Will be reevaluated when TBD's are known.

TBD = An evaluation is being conducted to analyze the system's capability to meet this requirement

Table D-15. Aviation Requirements vs. Capabilities (Category III Precision Approach)

Characteristic	Requirement	GPS SPS	NDGPS	WAAS	LAAS	LORAN-C
Accuracy	6.2 m (H) 2 m (V)	No	No	No	TBD	No
Availability	99.9%	No	Yes[1]	Yes	TBD	No
Integrity	PHMI 1×10^{-9} 15.5 m(H)/5.3 m (V) Alert Limit 1 Sec Time to Alarm	No	No	No	TBD	No
Continuity	$1 - 6 \times 10^{-6}$ (in any 30 sec time period)	No	Yes[1]	Yes	TBD	No
Coverage	Applicable Terminal Area	Yes	Yes	Yes	TBD	Yes
Meets Requirements		**No**	**No**	**No**	**No**[2]	**No**

(H) - Horizontal
(V) - Vertical

[1] Requires dual system coverage
[2] Will be reevaluated when TBD's are known

TBD = An evaluation is being conducted to analyze the system's capability to meet this requirement

Table D-16. Marine Requirements vs. Capabilities (Inland Waterway Phase)

Characteristic	Requirement	GPS SPS	NDGPS	WAAS	LAAS	LORAN-C
Accuracy	2 - 5 m (H)[1] 0.1 m (V)[2]	No	Yes(H) / No (V)	Yes(H) / No (V)	TBD (H) / No (V)	No
Availability	99.9%	No	Yes	Yes	TBD	TBD
Integrity	25m Alert Limit 10 Sec Time to Alarm	No	Yes	Yes	TBD	TBD
Continuity	99.97 High Risk 99.85 Low Risk	No	Yes	Yes	TBD	TBD
Coverage	U.S. Inland Waterway Systems	Yes	Yes	TBD	No[3]	Yes
Meets Phase Requirements		**No**	**Yes**[4]	**No**[5]	**No**	**No**

(H) - Horizontal
(V) - Vertical

[1] Safety of Navigation (Critical) - All Ships & Tows
[2] River Engineering & Construction Vessels
[3] Planned site density insufficient to cover inland waterways
[4] Except vertical requirements for engineering and construction vessels
[5] Will be reevaluated when TBD is known

TBD = An evaluation is being conducted to analyze the system's capability to meet this requirement

Table D-17. Marine Requirements vs. Capabilities (Selected Harbor Entrance & Approach Waterways)

Characteristic	Requirement	GPS SPS	NDGPS	WAAS	LAAS	LORAN-C
Accuracy	8-20 m (H)[1] 0.1 m (V)[2]	No	Yes(H) / No (V)	Yes(H) / No (V)	TBD (H) / No (V)	TBD(H) / No (V)
Availability	99.9%	No[3]	Yes	Yes	TBD	TBD
Integrity	25m Alert Limit 10 Sec Time to Alarm	No[3]	Yes	Yes	TBD	TBD
Continuity	99.97 High Risk 99.85 Low Risk	No	Yes	Yes	TBD	TBD
Coverage[8]	U.S. Selected Harbor Entrance and Approach Waterways	Yes	Yes	TBD[4]	No[5]	Yes[6]
Meets Phase Requirements		**No**	**Yes**[7]	**No**	**No**	**No**

(H) - Horizontal
(V) - Vertical

[1] Resource Exploration
[2] Engineering & Construction Vessels
[3] Insufficient constellation and no real-time integrity provided or planned.
[4] Potential masking exists in numerous HEA waterways, e.g., Prince William Sound or near large cities
[5] Planned site density insufficient to cover US HEA waterways
[6] Except in Hawaiian HEA waters.
[7] Except vertical requirements for engineering and construction vessels
[8] The Coast Guard intends to provide improved accuracy / integrity signals to HEA waters of the conterminous US including the Great Lakes and Puerto Rico, plus selected portions of Hawaii and Alaska.

TBD = An evaluation is being conducted to analyze the system's capability to meet this requirement

Table D-18. Marine Requirements vs. Capabilities (Coastal Phase)

Characteristic	Requirement	GPS SPS	NDGPS	WAAS	LAAS	LORAN-C
Accuracy	460 m	Yes	Yes	Yes	TBD	Yes
Availability	99.7%	Yes	Yes	Yes	TBD	Yes
Coverage	U.S./ Coastal Waters	Yes	Yes	Yes	No[1]	Yes[2]
Meets Phase Requirements		**Yes**	**Yes**	**Yes**	**No**	**Yes[2]**

[1] Planned site density insufficient to cover coastal US waterways
[2] Except for no coverage to Hawaiian coastal waters

Table D-19. Marine Requirements vs. Capabilities (Ocean Phase)

Characteristic	Requirement	GPS SPS	NDGPS	WAAS	LAAS	LORAN-C
Accuracy	2-4 nm	Yes	Yes	Yes	TBD	Yes
Availability	99.0%	Yes	Yes	Yes	TBD	Yes
Coverage	Global	Yes	No	No	No	No
Meets Phase Requirements		**Yes**	**No**	**No**	**No**	**No**

Table D-20. Land Requirements vs. Capabilities (Highway)

Characteristic	Requirement	GPS SPS	NDGPS	WAAS	LAAS	LORAN-C
Accuracy	Current Requirement: 5 - 30 m	No	Yes	Yes	TBD	TBD
	Future Requirement[1]: 0.1 m	No	TBD	No	No	No
Availability	Current Requirement: 99.7%	No	Yes	Yes	TBD	Yes
	Future Requirement[1,2]: 99.9%	No	Yes	Yes	TBD	TBD
Integrity	Current Requirement: 5 - 15 sec	No	Yes	Yes	TBD	Yes
	Future Requirement[1]: <5 sec	No	TBD	No	TBD	No
Coverage	Nationwide	Yes	Yes	No[3]	No	Yes
Meets Category Requirements		**No**	**Yes[4]**	**No**	**No**	**No**

[1] Future Intelligent Vehicle Initiative and Intersection Collision Avoidance requirements (not yet validated)
[2] Where dual coverage available
[3] Potential masking by man-made obstructions and natural terrain
[4] Current requirements met. Future requirements expected to be met by High Accuracy NDGPS.

TBD = An evaluation is being conducted to analyze the system's capability to meet this requirement

Table D-21. Land Requirements vs. Capabilities (Railroad)

Characteristic	Requirement	GPS SPS	NDGPS	WAAS	LAAS	LORAN-C
Accuracy	1.0 m	No	Yes[1]	No	No	No
Availability	99.7%[2] 99.9%[3]	No	Yes Yes[4]	Yes	TBD	Yes TBD
Integrity	5 sec	No	Yes	Yes	TBD	No
Coverage	Nationwide	Yes	Yes	No[5]	No[6]	Yes
Meets Category Requirements		**No**	**Yes**	**No**	**No**	**No**

[1] Within 160 km (100 miles) of NDGPS site

[2] Track Maintenance requirement

[3] Train Control / Automated Vehicle Warning requirement

[4] Where dual coverage available

[5] Potential masking by man-made obstructions and by natural terrain

[6] Designed to operate in specific areas. It is not designed to broadcast the signal over longer distances to surface users

TBD = An evaluation is being conducted to analyze the system's capability to meet this requirement

Table D-22. Land Requirements vs. Capabilities (Transit)

Characteristic	Requirement	GPS SPS	NDGPS	WAAS	LAAS	LORAN-C
Accuracy	30 - 100 m[1] 5 m [2]	Yes No	Yes Yes	Yes Yes	TBD TBD	TBD No
Availability	99.7%	No	Yes	Yes	TBD	Yes
Coverage	Nationwide	Yes	Yes	No[3]	No[4]	Yes
Meets Category Requirements		**No**	**Yes**	**No**	**No**	**No**

(H) - Horizontal
(V) - Vertical

[1] Vehicle C2/Emergency Response requirement
[2] Auto Voice Bus Stop/Data Collection requirement
[3] Potential masking by man-made obstructions and natural terrain
[4] Designed to operate in specific areas. It is not designed to broadcast the signal over longer distances to surface users

TBD = An evaluation is being conducted to analyze the system's capability to meet this requirement

Table D-23. Non-Navigation Requirements vs. Capabilities (Post-Processed)

Characteristic	Requirement	GPS SPS	NDGPS	WAAS	LAAS	LORAN-C	CORS
95% Accuracy #1	1 - 5 m	No[1]	Yes	Yes	No	No	Yes
95% Accuracy #2	0.1 - 1.0 m	No[1]	Yes[2]	Yes[2]	No	No	Yes
95% Accuracy #3	0.001 - 0.01 m	No[1]	Yes[2]	Yes[2]	No	No	Yes
Coverage	Nationwide	Yes	Yes	No	No[3]	No[4]	Yes
Meets Category Requirements		**No**	**Yes[5]**	**No**	**No**	**No**	**Yes**

[1] Modernized thru Block IIF
[2] Use of raw data collected through CORS, not the transmit signal
[3] Gaps in ground coverage
[4] Does not cover parts of Nation, not a 3-D system
[5] Meets category requirements for 5 m positioning in real-time

Table D-24. Non-Navigation Requirements vs. Capabilities (Real-Time)

Characteristic	Requirement	GPS SPS	NDGPS	WAAS	LAAS	LORAN-C	CORS
95% Accuracy #1	1 - 5 m	No[1]	Yes	Yes	No	No	No
95% Accuracy #2	0.1 - 1.0 m	No[1]	No	No	No	No	No
95% Accuracy #3	0.001 - 0.01 m	No[1]	No	No	No	No	No
Coverage	Nationwide	Yes	Yes	No[2]	No[3]	No[4]	Yes
Meets Category Requirements		**No**	**Yes[5]**	**No**	**No**	**No**	**No**

[1] Modernized thru Block IIF
[2] Ground masking issues with WAAS
[3] Gaps in ground coverage
[4] Does not cover parts of Nation, not a 3-D system
[5] Meets Category Requirement for 5 m Positioning

Table D-25. Non-Navigation Requirements vs. Capabilities (Timing)

Characteristic	Requirement	GPS SPS	NDGPS [1]	WAAS [2]	LAAS [1]	LORAN-C	GPS Carrier Phase
Accuracy (NTE)	1 microsecond to 100 ns	Yes[3]	No	Yes	No	Yes	Yes
95% Accuracy #1	40 ns to 10 ns	Yes[3]	No	Yes	No	TBD	Yes
95% Accuracy #2	0.2 ns	No[3]	No	No	No	No	Yes
Coverage #1	CONUS	Yes	Yes	Yes[4]	No[5]	Yes	Yes
Coverage #2	Worldwide	Yes	No	No	No	No	Yes
Meets Category Requirements		**Yes[6]**	**No**	**Yes[7]**	**No**	**Yes[8]**	**Yes**

[1] Do not provide an independent timing source
[2] Is under investigation as a timing source
[3] GPS Modernized thru Block IIF
[4] Do not anticipate ground masking issues
[5] Gaps in ground coverage
[6] Meets Category Requirement up to 40 nanoseconds, global
[7] Meets Category Requirement up to 40 nanoseconds, CONUS
[8] Meets Category Requirement up to 1 microsecond to 100 ns range, CONUS

TBD = An evaluation is being conducted to analyze the system's capability to meet this requirement

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Appendix E

Revalidation of 1994 Study:
A Technical Report to the Secretary of Transportation on a National Approach to Augmented GPS Services

E.1 Background

On July 18, 2002 the DOT POSNAV EC conditionally concurred with the Radionavigation Systems Task Force recommendation to continue implementation of both NDGPS and WAAS as augmentations to GPS. The Task Force recommendation was based upon recent review of modal requirements versus capabilities as well as the results of previous analyses, most notably a 1994 NTIA *Technical Report to the Secretary of Transportation on a National Approach to Augmented GPS Services*. Since the Task Force cited the 1994 report, the POS/NAV EC asked for a revalidation of the report's assumptions and findings with respect to the need for separate wide-area differential systems. This white paper addresses this request.

The 1994 study team researched existing and planned GPS augmentation systems. The team subjected 11 candidate systems to a detailed analysis using a two-stage decision matrix. In the first stage the team listed the detailed performance requirements and evaluated the ability of each candidate system to meet them. At this stage it was determined that no single existing or planned augmented GPS system was capable of meeting all user requirements. The study team then focused on six potential architectures intended to satisfy as many user requirements as possible. Highlights of the final six candidates and study recommendations are contained in section E.5.

Moving forward to 2002, the current Task Force effort to conduct a radionavigation systems assessment resulted from a 2001 Volpe Center vulnerability assessment. The primary objective of the Task Force is to develop a recommendation on a capabilities investment strategy for the nation's radionavigation systems. As part of its charter, the team revisited the possibility of cross-modal application of existing systems and augmentations. In making its most recent recommendations to the EC, a key question explored by the Task Force was, to operate effectively does the US Transportation System need both NDGPS and WAAS? Given that each system uses a different message format (Radio Technical Commission for Maritime Services [RTCM] for NDGPS vs. Radio Technical Commission for Aeronautics [RTCA] for WAAS) and each delivers that message using different frequencies (Low Frequency [LF] / Medium Frequency [MF] for NDGPS and L Band for WAAS) the issues are … can a common format as well as a common frequency band be used by all operating agencies? Without being able to answer 'yes' to acceptability of both common format and frequency band, the move to a single system was viewed as impractical.

E.2. Data Formats

E.2.1 1994 Study

Looking first at the format issue, the 1994 report contains a summary of an examination of the RTCM format performed by RTCA, Inc. to determine if the maritime format could satisfy aviation needs. RTCA concluded that the RTCM format would not work and a different format was needed for the aviation community. This RTCA-performed analysis was a central part of the report's case for maintenance of two different formats. Some of the specific concerns highlighted by RTCA were:

- RTCM format 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.

The 1994 report also makes reference to two other message types unique to RTCA and not replicated in the RTCM format. These include Message Types 5 and 6 which handle differential corrections during period of extremely large range corrections and range rate corrections. Other differences in the formats identified in 1994 are shown in Table E-1.

Table E-1. Message Format Comparison

	RTCM	**RTCA**
Station ID	10 bits	24 bits to provide compatibility with ICAO standards
Sequence Number	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 Correction	Provided by scale change in the Type 1 message	RTCA Type 5 message. In lieu of the RTCA Type 1 message for large Pseudorange Corrections (PRCs) and Range-Rate Corrections (RRCs)
Large Range Differential Corrections when Issue of Data (IOD) changes	RTCM Type 5 message specifies IOD. Delta PRCs provided by 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

E.2.2 Analysis of 1994 Data Formats

A review of current standards shows that there has been significant change in the message formats and message types over the years. For example, Message Type 6 mentioned above was associated with differential corrections during periods of large range and range-rate corrections. Now Type 6 is related to WAAS Integrity Information (RTCA/DO-229C). Although message types in the current RTCA and RTCM formats have changed, the fact remains that the formats/message types were designed based on the requirements of different users. Therefore, varied capacity to handle the demands of different messages remains an issue. Consequently, the basic arguments, especially with respect to integrity, remain. Therefore, the Task Force considers the concept of format limitations outlined by RTCA as still valid. However, the viewpoint of the 1994 analysis was an RTCA review of the RTCM format to see if the RTCM message could satisfy aviation requirements. This approach was adopted in the 1994 analysis because of the relative maturity of the two message structures. At the time of the 1994 study, the RTCM format was relatively well defined and established; the RTCA format was much less mature and still in the early stages of definition. As a result, there could be an argument that the use of RTCA format by RTCM users was not fully considered. This issue was further explored by the Task Force.

Before pursuing a full technical evaluation of using the RTCA format for RTCM applications, the Task Force considered other barriers that might prohibit (or inhibit) this path. Of primary concern to the group was the potential impact of abandoning an international standard (RTCM) promoted and fostered by the US and currently used by over 40 countries. Mandating RTCA-format equipment for operations in US ports would meet with resistance. The consensus of the group was that the anticipated international response was sufficient to remove the common format from consideration.

E.2.3 WAAS and NDGPS Data Message

Another difference between WAAS and NDGPS is the data message. This issue was not addressed in the 1994 report. NDGPS (and LAAS) transmit a correction for each satellite that provides the total range correction for that satellite to users near the ground station. This correction is the total sum of orbit errors, clock errors, tropospheric errors, and ionospheric errors for each satellite. The user receives these corrections and applies them to each satellite to improve accuracy and integrity.

WAAS, on the other hand, measures the orbit and clock errors for each satellite, and makes an estimate of the ionospheric errors in the form of a grid that overlays the WAAS service volume. WAAS then transmits the orbit/clock errors and a definition of the ionospheric error grid. The user computes a separate ionospheric correction for each satellite by interpolating the grid, and then applies the ionospheric and orbit/clock corrections to each satellite.

E.3 Frequency Bands

Next, to completely explore the issue, the Task Force turned to the question of using common frequency bands. Although the 1994 report does not delve into the issue of frequency in detail, the group felt that addressing the issue was necessary for a comprehensive answer on the question of a single system.

From the Task Force's perspective there would be several barriers to mandating LF/MF or L Band for all modal applications. Some of these include:

- *Concern over L Band masking issues in numerous inland waterways and mountain valleys.* Line-of-sight to one of the WAAS geosynchronous satellites cannot always be assured for surface users.
- *Aircraft would require separate LF/MF antenna losing the capability to receive the signal on the currently installed GPS antenna.* Industry would likely balk at the proposal to add additional equipment with no supporting business case.
- *Attempting to employ an LF/MF signal for aviation would likely erase the vision of a worldwide seamless satellite-based navigation architecture*. This parallels the concern of trying to change format standards that already have worldwide acceptance.

E.4 Conclusion

As concluded by the 1994 study team, maintaining separate augmentation systems for surface and aviation applications remains the best course of action for DOT. There is no practical argument to have all GPS differential corrections transmitted in the same format or frequency. Justification to pursue a single format or frequency would need to be linked to either improved operational performance or reduced cost. Neither of these proved probable. Both surface and aviation communities developed formats, messages, and frequencies that satisfy their specific needs and have successfully promoted these worldwide. In addition, NDGPS would require major redesigning to meet WAAS integrity requirements. A decision to levy a single system on US users would have implications beyond US borders and would not likely be embraced by the global community. The best approach for the US Transportation System is to look for synergy in the area of monitoring GPS signals, while maintaining the separate systems to deliver differential corrections to different users.

E.5 Additional Material

1994 Study Proposed Architectures

The 1994 Study researched existing and planned augmented GPS systems. Eighteen systems were identified as potential alternatives, of which the study team selected 11 systems for detailed evaluation. The study team subjected the 11 candidate systems to a more detailed analysis using a two-stage decision matrix. In the first stage the study team listed the detailed performance requirements and evaluated the ability of each candidate system to meet them. At this stage it was determined that no single existing or planned augmented GPS system was capable of meeting all user requirements. The study team then focused on six potential architectures intended to satisfy as many user requirements as possible. These are:

- Architecture 1: A 61-site Differential GPS system including the FAA WAAS to satisfy aviation requirements through Cat I precision approach, the FAA LAAS to satisfy aviation Cat II/III precision approach requirements, and the USCG Maritime-DGPS (MDGPS) for marine use. This architecture did not satisfy many land transportation and survey requirements but was included to provide a baseline against the remaining five options. All reference stations are compliant with the CORS standard across the 6 proposed architectures.

- Architecture 2: This option expands the baseline to include the USCG Maritime DGPS (renamed National DGPS) system to provide coverage for marine and land users.

- Architecture 3: An expanded version of NDGPS that, in addition to providing coverage to marine and land users, and a variant of WAAS to meet aviation requirements for en route and non precision approach. Category I, II, and II precision approach would be satisfied through the LAAS.

- Architecture 4: Same as 'Architecture 2' but with a modified version of WAAS that provides corrections at other than the GPS L1 frequency to satisfy aviation requirements for en route through Category I precision approach. Cat II and II precision approaches would be satisfied through the LAAS.

- Architecture 5: Same as 'Architecture 2' but with a modified version of WAAS that encrypts all the differential corrections. This option satisfies aviation requirements for en route through Category I precision approach. Cat II and II precision approaches would be satisfied through the LAAS.

- Architecture 6: Same as 'Architecture 3' but expanding the expanded version of NDGPS to satisfy aviation requirements for Category I precision approach, and a variation of WAAS to meet en route and non precision approach requirements. Cat II and II precision approaches would be satisfied through the LAAS.

These results are summarized in Table E-2. It is interesting to note that *none* of the architectures in the 1994 study use FAA systems for land or marine applications, whereas Architecture 6 considered the possibility of using an expanded NDGPS to meet aviation requirements for Category I Precision Approaches.

Table E-2: 1994 National Approach to Augmented GPS Service Study – 'First Cut'

Options	Aviation	Marine	Land	Non-Navigation
Architecture 1 (Baseline)	GPS+WAAS (through Cat I) + LAAS (Cat II/III)	GPS+MDGPS	none	All stations CORS compliant
Architecture 2	GPS+WAAS[1] (through Cat I) + LAAS (Cat II/III)	GPS+NDGPS	GPS+NDGPS	All stations CORS compliant
Architecture 3	GPS+WAAS[2] (En-Route + NPA) + LAAS (Cat I/II/III)	GPS+NDGPS	GPS+NDGPS	All stations CORS compliant
Architecture 4	GPS+WAAS[3] (through Cat I)* + LAAS (Cat II/III)	GPS+NDGPS	GPS+NDGPS	All stations CORS compliant
Architecture 5	GPS+WAAS[4] (through Cat I)** + LAAS (Cat II/III)	GPS+NDGPS	GPS+NDGPS	All stations CORS compliant
Architecture 6	GPS+WAAS[2] (En-Route, NPA) + NDGPS (Cat I) + LAAS (Cat II/III)	GPS+NDGPS	GPS+NDGPS	All stations CORS compliant

[1]WAAS providing integrity, availability, and differential corrections

[2]WAAS providing integrity and availability only – no differential corrections

[3]WAAS broadcasting differential corrections at frequency other than L1

[4]WAAS encrypted differential corrections

Architecture 6 was evaluated extensively as it appeared capable of meeting requirements at a lower cost than the other five architectures. It was found, however, that interference of signal reception could occur to aircraft flying through conditions conducive to the creation of precipitation static (P-Static). P-Static is radio interference caused by the impact of charged particles against an antenna. It may occur in a receiver during certain weather conditions, such as snowstorms, hailstorms, rainstorms, dust storms, or combinations thereof. This effect is more prevalent in higher latitudes. Consequently architecture 6 was dropped and the remaining five composite architectures were evaluated.

The remaining five architectures were evaluated using the second stage of the decision matrix, which consisted of a model with three major parameters: performance, cost, and security. Two viable alternatives were selected: Architectures 2 and 3 (as depicted in Table E-3). The study team concluded that the selection of one of these two viable alternatives was dependent on US Government policy regarding security. Security concerns include access control, level of influence, interdiction, post-decision response time, jamming, and vulnerability of denial. If security concerns are not the overriding consideration and do not predominate over other benefits available from an augmented GPS, Architecture 2 is the recommended National augmentation system. On the other hand, if 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.

Table E-3: 1994 National Approach to Augmented GPS Service Study – Final Selection

Options	Aviation	Marine	Land	Non-Navigation
Architecture 2	GPS+WAAS[1] (through Cat I) + LAAS (Cat II/III)	GPS+NDGPS	GPS+NDGPS	All stations CORS compliant
Architecture 3	GPS+WAAS[2] (En-Route + NPA) + LAAS (Cat I/II/III)	GPS+NDGPS	GPS+NDGPS	All stations CORS compliant

[1]WAAS providing integrity, availability, and differential corrections

[2]WAAS providing integrity and availability only – no differential corrections

Summary:

Architecture 2 recommended if Security concerns are not overriding

Architecture 3 recommended if Security concerns predominate over economic and other benefits

Security Concerns: access control, level of influence, interdiction, post-decision response time, jamming, and vulnerability of denial

Ionospheric Decorrelation

Another issue separating WAAS and NDGPS is that of Ionospheric Decorrelation. This issue was not addressed in the 1994 report. It is difficult for a signal like NDGPS (and LAAS) to provide integrity as you move away from the reference station. NDGPS extrapolates the corrections from those measurements at the ground station while WAAS interpolates corrections between points on the grid. Upgrading NDGPS to meet the WAAS integrity would essentially require redesigning the system. This includes a denser NDGPS network of stations and monitor stations, rewriting the software to DO-178B standards, and ensuring that the hardware provides adequate redundancy. However, when the second GPS civil frequency (L2C) is operational it will be possible to perform ionospheric corrections in the user receiver. In this case the ground monitor stations could perhaps transmit orbit and clock errors over longer distances and make it possible to prove integrity.

Path Data-Links

Path data-links, not to be confused with Air Traffic Control (ATC) data-links, are currently a LAAS feature, not a WAAS feature. They are used to uplink the definition of the precision approach path for every runway at the airport from the LAAS Ground Facility (LGF) to the aircraft. While this information could be stored in a navigation database, as is the case for WAAS, many Flight Management Systems (FMS) have limited storage capacity. This is the reason why airlines are reluctant to support WAAS as they would incur substantial expenses to modify their FMS. This would also require expensive recertification efforts since FMSs are flight critical systems certified to exacting standards.

The LAAS path data-link, on the other hand, was designed to send the path definitions directly to the aircraft instead of storing the path definition within the FMS. By mimicking the performance of existing ILS equipment, LAAS may be integrated with FMSs at a substantially lower cost than WAAS. The flexibility inherent in LAAS data-links allows the definition and implementation of complex procedures such as curved and segmented approach paths, as compared with the straight in ILS procedures supported by WAAS. Airlines would benefit using these complex procedures that would result in shorter approach paths that save time, fuel, and money.

The LAAS broadcast is providing the final approach segment information as a concession to the substantial number of legacy transport aircraft in the US commercial fleet with older and less capable equipment. The WAAS avionics database stores this data from a WAAS receiver and does not need to continuously receive this information.

Precipitation Static

The 1994 Study found that using NDGPS for Cat I precision approaches could result in interference of signal reception when an aircraft flies through conditions conducive to the creation of precipitation static (P-Static). This issue led to dropping this architecture from the proposed system mixes.

Subsequent to the 1994 Study, however, much progress against precipitation static has been made in the transition from electric-field (E-field) to magnetic-field (H-field) antennas. E-field antennas require a ground connection to achieve optimal performance, and for this reason are recommended for marine applications and static positioning. H-field antennas do not require a ground connection and are less susceptible to precipitation static, and may be better suited for portable applications (e.g., aviation). E-field antennas are, however, more sensitive than H-field antennas. In addition, E-field antennas in some cases provide better performance than H-field antennas, such as near the strong electromagnetic fields generated around an electric locomotive.

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