2021 FEDERAL RADIONAVIGATION PLAN

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2021 Federal Radionavigation Plan

The Federal Radionavigation Plan (FRP) reflects the official positioning, navigation, and timing (PNT) policy and planning for the Federal Government. It is required by the National Defense Authorization Act for Fiscal Year 1998, codified at Title 10, United States Code, section 2281, paragraph (c). The FRP is prepared jointly by the Department of Defense, the Department of Transportation, and the Department of Homeland Security, with the assistance of other government agencies and published not less than every two years. This 2021 edition of the FRP reflects the policy and planning for present and future federally-provided PNT systems, covering common-use PNT systems (i.e., systems used by both civil and military sectors). Exclusively-military systems and policies are covered in the current version of the Chairman, Joint Chiefs of Staff Instruction 6130.01, the Chairman of the Joint Chiefs of Staff Master Positioning, Navigation, and Timing Plan.

The FRP contains sections covering roles and responsibilities, policy, representative PNT user requirements (while the FRP outlines the PNT performance requirements for various user groups, it is not a formal requirements document for the Federal Government), operating plans, and the National PNT Architecture, as well as appendices covering system parameters and descriptions, PNT information services, and geodetic reference systems and datums. It is updated biennially, allowing more efficient and responsive updates of policy and planning information. Suggestions for the improvement of future editions are welcomed.

Secretary of Defense Lloyd J. Austin III	Secretary of Transportation Pete Buttigieg	Secretary of Homeland Security Alejandro N. Mayorkas
Date: 5 July 2022	Date: May 17, 2022	Date: March 11, 2022

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Executive Summary

The Federal Radionavigation Plan (FRP) reflects the official positioning, navigation, and timing (PNT) policy and planning for the Federal Government. Within the construct of the National PNT Architecture, the FRP covers both terrestrial- and space-based, common-use, federally-operated PNT systems. Systems used exclusively by the military are covered in Chairman, Joint Chiefs of Staff (CJCS) Instruction 6130.01, CJCS Master Positioning, Navigation, and Timing Plan (MPNTP) (Ref. 1). The FRP does not include systems that mainly perform surveillance and communication functions. The policies and operating plans described in this document cover the following PNT systems and services:

- Global Positioning System (GPS)
- Augmentations to GPS
- Instrument Landing System (ILS)
- Very High Frequency (VHF) Omnidirectional Range (VOR)
- Distance Measuring Equipment (DME)
- Tactical Air Navigation (TACAN)
- Nondirectional Beacon (NDB)
- Internet Time Service (ITS)
- Radio Station WWVB signal
- Two-Way Satellite Time Transfer (TWSTT)
- Network Time Protocol (NTP)
- Automatic Dependent Surveillance-Broadcast (ADS-B)

The Federal Government operates PNT systems as one of the necessary elements to enable safe transportation and enable commerce within the

United States. It is a goal of the Government to provide this service in a resilient and cost-effective manner, balancing costs and needed safety, security, and efficient operational capabilities. The Department of Transportation (DOT) is responsible under Title 49, United States Code, Section 101 (49 U.S.C. 101) (Ref. 2) for ensuring safe and efficient transportation. The Department of Defense (DoD) is responsible for maintaining aids to navigation required exclusively for national defense. DoD is also required by 10 U.S.C. 2281 (Ref. 3), paragraph (b), to provide for the sustainment and operation of GPS for peaceful civil, commercial, and scientific uses on a continuous, worldwide basis, free of direct user fees. The Department of Homeland Security (DHS) is responsible, through interagency coordination, to enhance the security and resilience of the nation's critical infrastructure and the detection and mitigation of sources of GPS interference within the United States.

A major goal of DoD, DHS, and DOT is to ensure that a mix of common-use (military civil, and private sector) systems is available to meet user requirements for accuracy, reliability, availability, continuity, integrity, coverage, operational utility, and cost; to enable the capability for growth; and to eliminate unnecessary duplication of services. The National PNT Architecture is a framework to assist United States Government (USG) organizations with investment decisions. Ensuring a future PNT systems mix is a complex task because user requirements vary widely and change with time. While all users require services that are safe, trustable, readily available, and easy to use, unique requirements exist for both military and civil users. For example, military requirements include performance under intentional interference, operations in high-performance vehicles, worldwide coverage, and operational capability in severe environmental conditions. Similarly, civil users desire higher accuracy and integrity for future aviation, highway, rail, marine, and other safety-of-life applications. Increased investment in non-GPS PNT services by the owners and operators of critical infrastructure is necessary to continue to provide a robust and resilient National PNT Architecture.

Cost as well as user adoption is always a major consideration for owners and operators of critical infrastructure when contemplating non-GPS PNT investments. As the full civil potential of GPS and its augmentations are realized, the services provided by various PNT systems will be rebalanced to match demand, and demand will depend at least in part on the extent to which such services are relied upon as a part of an integrated strategy to ensure PNT resilience and availability for critical applications or safety-of-life services.

The Federal Government conducts research and development (R&D) activities relating to federally-provided PNT systems and their worldwide use by the U.S. armed forces and the civilian community. Civil R&D activities focus mainly on enhancements of GPS for civil uses, but also encompass areas such as safety, security, and resilience. Military R&D

activities mainly address military mission requirements and national security considerations – including defense of the U.S. Homeland. A detailed discussion of each agency's roles and responsibilities, user requirements, and system descriptions can be found in this edition of the FRP.

The FRP is composed of the following sections:

Section 1 – Introduction to the Federal Radionavigation Plan: Delineates the purpose, scope, and objectives of the plan, including an overview of the National PNT Architecture, and discusses PNT system selection considerations.

Section 2 – Roles and Responsibilities: Presents DoD, DHS, DOT, and other Federal agencies' roles and responsibilities for the planning, implementing, and providing of PNT services.

Section 3 – Policy: Describes the U.S. policy for providing each Federal PNT system identified in this document.

Section 4 – PNT User Requirements: Summarizes context for performance requirements of federally-provided PNT services that are available to civil users.

Section 5 – Operating Plans: Summarizes the plans of the Federal Government to provide PNT systems or services for use by the civil and military sectors. This section also presents the research and development efforts planned and conducted by DoD, DHS, DOT, and other Federal organizations.

Section 6 – PNT Architecture Assessment and Evolution: Summarizes the activities and plans of the Federal Government to implement the National PNT Architecture.

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1

Introduction to the Federal Radionavigation Plan

This section describes the background, purpose, scope, and objectives of the Federal Radionavigation Plan (FRP), identifies the statutory authority to provide positioning, navigation, and timing (PNT) services, and PNT system selection considerations. It summarizes the events leading to the preparation of this document, the national objectives for coordinating the planning of PNT services, and PNT authorities and responsibilities.

1.1 Background

A Federal Radionavigation Plan is required by Title 10 of the United States Code, Section 2281, paragraph (c) [10 U.S.C. 2281(c)] (Ref. 3). The first edition of the FRP was released in 1980 as part of a Presidential Report to Congress, prepared in response to the International Maritime Satellite Telecommunications Act of 1978 (Public Law 95–564, 92 Stat. 2392) (Ref. 4). It marked the first time that a joint Department of Defense (DoD) and Department of Transportation (DOT) plan for PNT systems had been developed. With the transfer of the United States Coast Guard (USCG) from DOT to the Department of Homeland Security (DHS) through the Homeland Security Act of 2002 (Public Law 107–296, 116 Stat. 2135) (Ref. 5), DHS was added as a signatory to the FRP. The 2008 FRP updated and merged the 2005 FRP and 2001 Federal Radionavigation Systems (FRS) documents. The 2010 FRP introduced the National PNT Architecture, which defined a PNT vision, strategy, and vectors for action in its Final Report and Implementation Plan (Ref. 6 and Ref. 7). The Architecture was intended as a framework to guide investment decisions for developing and implementing PNT capabilities and supporting infrastructure. The 2021 FRP further incorporates the National PNT Architecture to provide a construct for evaluating and advancing policy and planning for present and future federally-provided PNT systems.

The FRP addresses coordinated planning for federally-provided radionavigation systems. The Federal planning process has evolved to include other elements of positioning, navigation, and timing, now referred to as PNT.

PNT is integral to the safety and prosperity of the United States, including national and homeland security; however, in many cases its role is not obvious. PNT information is used to some extent by nearly every critical infrastructure sector, including enabling vital operational aspects of transportation, communications, energy distribution, safety-of-life, and emergency response operations. In terms of national security, PNT is integral to command, control, and communications capabilities, to all forms of precision operations, central to national economy, and to the cyber enterprise.

1.2 Purpose

The purpose of the FRP is to describe the U.S. Government's (USG) roles, responsibilities, and policies applicable to PNT systems. It describes PNT user requirements, operating plans, and a national architecture that serves as a framework to advance USG provided PNT systems.

This plan highlights the importance of ensuring PNT resilience, addressing known and emerging capability gaps, and articulating initiatives to close those gaps (or mitigating their impacts). It does this by identifying future PNT capabilities that will sustain U.S. military, civil, and scientific activities through the mid-21st century or longer; motivating studies, analyses, and assessments for the development, demonstration, implementation, and security and resilience of PNT technology; and providing a coordinated framework to inform USG investment decisions regarding PNT.

1.3 Scope

This plan encompasses terrestrial- and space-based, common-use, federally-operated PNT systems. PNT services are supported by many PNT-enabling capabilities and infrastructure and are provided in challenging spectrum, weather, fiscal, and geo-political environments. Current PNT applications are characterized by widespread use of the GPS, government-provided GPS augmentations optimized for different user groups, for-profit commercial GPS augmentations, and space-based and non-space-based systems that provide PNT services.

1.4 PNT Systems

This plan covers federally-provided systems and services used for PNT. PNT systems include radionavigation, timing, and other technologies (including network-based services) that enable PNT services and applications. While the FRP outlines the PNT performance requirements for various user groups, it is not a formal requirements document for the Federal Government.

The plan does not include electronic non-radionavigation systems that are used primarily for surveillance and communication (e.g., cell phones). Additionally, Federal agencies participating in the National PNT Architecture effort determined that federally-provided services will not satisfy the needs of all PNT users. Complementary technologies are evolving to meet those needs, and as these technologies become part of federally-provided services, this plan will address them.

The systems and services addressed in this FRP are:

- Global Positioning System (GPS)
- Augmentations to GPS
- Instrument Landing System (ILS)
- Very High Frequency (VHF) Omnidirectional Range (VOR)
- Distance Measuring Equipment (DME)
- Tactical Air Navigation (TACAN)
- Nondirectional Beacon (NDB)
- Internet Time Service (ITS)
- Radio Station WWVB signal
- Two-Way Satellite Time Transfer (TWSTT)
- Network Time Protocol (NTP)
- Precision Timing Protocol (PTP)
- Automatic Dependent Surveillance-Broadcast (ADS-B)

1.5 Objectives

The primary USG objective is to promote the responsible use of efficient, effective, and resilient PNT capabilities that support national needs.

The related objectives of USG PNT system policy are to:

- strengthen and maintain national and homeland security;
- contribute to the economic growth, trade, and productivity of the United States;
- improve safety of travel;
- promote efficient and effective transportation systems;
- promote increased transportation capacity and mobility of people and products; and
- aid in the protection of the environment.

Currently there are projected shortfalls or "gaps" in U.S. PNT capabilities that will be described in Section 1.7. Many of the plans for the programs described in this document will contribute to closing these gaps and improving PNT capabilities for the nation.

1.6 Authority to Provide PNT Services

Several departments and agencies provide PNT services. Other USG agency roles and responsibilities are described in more detail in Section 2.

DOT is responsible under 49 U.S.C. 101 (Ref. 2) for ensuring safe and efficient transportation. PNT systems play an important role in carrying out this responsibility. The two DOT operating administrations that operate PNT systems are the Federal Aviation Administration (FAA) and the Great Lakes St. Lawrence Seaway Development Corporation (GLS). The Office of the Assistant Secretary for Research and Technology (OST-R) is responsible for coordinating PNT planning within DOT and with other civil Federal elements.

The FAA is responsible for developing and implementing PNT systems to meet the needs for safe and efficient air navigation. 49 U.S.C. 44505 (Ref. 8) states that "…the Administrator of the FAA shall: develop, alter, test, and evaluate systems, procedures, facilities, and devices, and define their performance characteristics, to meet the needs for safe and efficient navigation and traffic control of civil and military aviation, except for needs of the armed forces that are particular to air warfare and primarily of military concern; and select systems, procedures, facilities, and devices that will best serve those needs and promote maximum coordination of air traffic control and air defense systems." FAA is also responsible for operating air navigation aids required by international treaties.

GLS provides maritime navigation aids in U.S. waters in the Saint Lawrence River and operates a Vessel Traffic Control System with the St. .Lawrence Seaway Management Corporation (SLSMC) of Canada.

Several additional operating administrations within DOT also participate in PNT planning. These elements include the Federal Highway Administration (FHWA), the Federal Motor Carrier Safety Administration (FMCSA), the Federal Railroad Administration (FRA), the Federal Transit Administration (FTA), the Maritime Administration (MARAD), the National Highway Traffic Safety Administration (NHTSA), and the Pipeline and Hazardous Materials Safety Administration (PHMSA).

DHS is responsible for enhancing the security and resilience of the nation's critical infrastructure, many of which depend on accurate, trustable, and reliable PNT. DHS also is responsible, through interagency coordination, for interference detection and mitigation efforts related to GPS interference within the United States. The USCG, as a component of DHS, is responsible under 14 U.S.C. 81 (Ref. 10) to provide aids to navigation for safe and efficient marine navigation to prevent disasters, collisions, and wrecks of vessels and aircraft.

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

DoD is required under 10 U.S.C. 2281 (Ref. 3), paragraph (b), to provide for the sustainment and operation of the GPS Standard Positioning Service (SPS) for peaceful civil, commercial, and scientific uses on a continuous worldwide basis free of direct user fees. DoD is also required to provide for the sustainment and operation of the GPS Protected Positioning Service (PPS).

Within the National Aeronautics and Space Act of 1958 (Public Law 85–568, 72 Stat. 426, as amended) (Ref. 11), sections 102 (d) and 103 enables the National Aeronautics and Space Administration (NASA) to provide for the operations of space transportation systems and other activities required for the exploration of space, which in addition to space vehicles also includes related equipment, devices, components, and parts.

The Secretary of Commerce, in coordination with the Secretary of the Navy, is authorized by 15 U.S.C. 261 to interpret and modify Coordinated Universal Time (UTC) for application as Standard Time in the U.S. Operational authority is vested in the National Institute of Standards and Technology (NIST) and the U.S. Naval Observatory (USNO), respectively.

The Department of Commerce (DOC) is authorized through 33 U.S.C. 883a-c (Ref. 12) to conduct various types of surveys and disseminate the resulting data.

1.7 PNT System Selection Considerations

Many factors are considered in determining the optimum mix of federally-provided PNT systems. These factors include operational, technical, economical, institutional, radio frequency spectrum allocation, homeland security and national defense needs, and international agreements and commitments. Important technical parameters include system accuracy, availability, integrity, continuity, coverage, reliability, and radio frequency spectrum usage. Certain parameters, such as anti-jamming performance, can also affect civil PNT service availability.

The current investment in service provider equipment and user equipment must also be considered. In some cases, there are international commitments that must be honored or modified in a manner mutually agreeable to all parties.

In most cases, the systems that are in place today were developed to meet different, diverse, and evolving user requirements, which has resulted in the proliferation of multiple PNT systems and was the key impetus promoting early radionavigation planning. The first edition of the FRP was published both to plan the mix of radionavigation systems and to promote an orderly life cycle for them. It also described an approach for selecting radionavigation systems to be used in the future. Early editions of the FRP, including the 1984 edition, reflected this approach with minor modifications to the timing of events. However, by 1986, it became apparent that a final recommendation on the future mix of radionavigation systems was not appropriate and that major changes to the timing of system life-cycle events were required. Consequently, it was decided that beginning with the 1986 FRP, an updated recommendation on the future mix of radionavigation systems would be issued with each subsequent edition of the FRP. Today, the FRP reflects direction from the United States, Executive Office of the President, Space Policy Directive 7 (SPD-7), U.S. Space-Based Positioning, Navigation, and Timing Policy, January 15, 2021 (Ref. 70), dynamic PNT technology, changing user profiles, budget considerations, and international activities. The National Space Policy of the United States of America, December 9, 2020 (Ref. 77) provides amplifying information to previous policy.

Starting with the 2010 edition of the FRP, the scope of user requirements has been broadened to identify PNT needs for space, aviation, surface, and subsurface applications. Provisioning of USG services to meet user requirements is subject to the budgetary process, including authorizations and appropriations by Congress, and priorities for allocations among programs by agencies.

When, after appropriate analysis and study, the need or economic justification for a particular system or capability appears to be diminishing, the department operating the system will notify the appropriate Federal agencies and the public, by publishing the proposed discontinuance of service in the Federal Register.

1.7.1 Operational Considerations

1.7.1.1 Military Selection Factors

Operational requirements determine DoD's selection of PNT systems. Precise PNT information is a key enabler for a variety of systems and missions. In conducting military operations, it is essential that PNT services be available with the highest possible availability and trust. These services must meet or exceed mission requirements. To meet these mission requirements, military operators may use a mix of independent, self-contained, and externally referenced PNT systems, provided that these systems can be traced directly to the DoD reference standards, World Geodetic System 1984 (WGS 84), and UTC (USNO). PNT applications employed by DoD forces and systems must provide resilient PNT information necessary to meet mission needs in the expected NAVWAR operations environment. Factors for military selection of PNT systems include, but are not limited to:

- flexibility to accommodate new weapon systems and technology;
- resistance to intentional or unintentional interference or degradation;
- availability of suitable capability in the supply chain;
- secure networking providing protection against unauthorized users;
- interoperability with DoD and allied systems to support coalition operations;
- position and time accuracy relative to common grid and time reference systems, to support strategic and tactical operations;
- availability of alternative/resilient means for obtaining and/or validating PNT data;
- worldwide mobility requirements; and
- compatibility with civil systems and operations, where appropriate.

Military operational requirements considerations may be found in the current version of the Chairman, Joint Chiefs of Staff (CJCS) Instruction 6130.01, DoD Master Positioning, Navigation, and Timing Plan (MPNTP) (Ref. 1).

1.7.1.2 Civil/Military Compatibility

The Federal Aviation Act of 1958 (Public Law 85–726, 72 Stat. 731 *et seq.*) (Ref. 15), requires the FAA to develop a combined civil and military aviation system. The Administrator of the FAA must "select procedures, facilities, and devices that will best serve those needs and promote maximum coordination of air traffic control and air defense systems." Appropriate PNT system standards are coordinated through the International Civil Aviation Organization (ICAO) and published for international aviation use, ensuring worldwide interoperability. Additionally, The National Interstate and Defense Highways Act of 1956 (Public Law 84–627, 84 Stat. 374) (Ref. 16), requires the FHWA to develop a combined civil and military interstate highways system.

In accordance with the Memorandum of Agreement for the Establishment and Operation of the Nationwide Differential Global Positioning System (NDGPS) (signed in February 1999 by the U.S. Air Force (USAF), the U.S. Army Corps of Engineers (USACE), the National Oceanic and Atmospheric Administration (NOAA), USCG, FRA, FHWA, and DOT,) and the Interagency Memorandum of Agreement with Respect to Support to Users of the Navstar Global Positioning System (GPS), (signed in May 2017 by DoD, DOT, and DHS) the USCG operates and coordinates PNT systems in support of civil and military traffic within the U.S. waterways.

Military aircraft, vehicles, and ships operate in civil environments. Accordingly, they may use civil PNT systems consistent with DoD policy in peacetime scenarios if the systems in use meet International Maritime Organization (IMO), ICAO, USCG, FAA, or DoD specifications and provide an equivalent level of safety and performance. DoD recognizes that PNT systems intended to only support peacetime operations may not support combat operations. In those cases, DoD may need to develop additional PNT capability to combat wartime threats.

1.7.1.3 Review and Validation

The DoD PNT system requirements review and validation process:

- identifies the unique components of PNT mission requirements;
- identifies technological deficiencies; and
- investigates system costs, user populations, and the relationship of candidate systems to other systems and functions.

1.7.2 Technical Considerations

In evaluating future PNT systems, there are a number of technical factors that must be considered:

- system:
    - accuracy;
    - precision;

    - integrity;
    - reliability;
    - availability;
- communications security;
- spectrum availability;
- signal coverage;
- received signal strength;
- signal:
    - propagation;
    - continuity;
    - acquisition and tracking continuity;
- multipath effects;
- noise effects;
- susceptibility to:
    - natural or man-made disruption, e.g., radio frequency interference (RFI);
    - cyber threats, including supply chain threats and vulnerabilities;
- environmental effects;
- platform dynamics;
- human factors engineering; and
- requirements for installation and operation (service provider and user equipment space, weight, and power considerations).

1.7.3 Vulnerabilities and Shortfalls for National PNT Services

The following are examples of capabilities and other instances where GPS alone can prove unsatisfactory for certain applications and such instances are being reviewed in this and future editions of this plan (see Section 6, PNT Architecture Assessment and Evolution, for more details on the National PNT Architecture):

- Assured and real-time PNT in physically impeded environments (e.g., indoors, multi-story buildings, urban canyons, and underground facilities).
- Sufficient accuracy and integrity in electromagnetically impeded environments including operations during spoofing, jamming, and natural and unintentional interference.
- Higher accuracy with high integrity (especially for future highway and rail applications).
- Timely notification/alarming (as short as 1 second in some situations) when PNT performance is degraded or misleading, especially for safety-of-life applications or to avoid collateral damage.
- High-altitude/space position and orientation, including real-time high accuracy position and orientation (<10 milliarcseconds).
- User access to timely geospatial information (e.g., terrain, conditions along route) for efficient and effective navigation.
- Timelier PNT modeling and simulation capabilities depicting and analyzing impeded conditions to determine impacts, as well as the capability to predict impacts in urban environments.
- Ensuring PNT services, including supporting Information Technology (IT) infrastructure, and supply chain are protected from cyber threats.
- Ability to accurately locate sources of intentional and unintentional interference in a timely manner.
- ADS-B, has become the FAA's preferred means of providing air traffic cooperative surveillance services following 2020 after the FAA's equipage mandate went into effect on January 1, 2020, requires continual PNT with assured positional accuracy and timing integrity. As ADS-B is dependent on GPS or augmented GPS for positional data from aircraft, disruptions of these PNT systems can degrade or render ADS-B surveillance unusable for air traffic control (ATC).
- National PNT Capabilities that are over-dependent on GPS provide insufficient resilience and survivability when GPS services are not available or are untrusted (e.g., spoofed).

1.7.4 Economic Considerations

The USG must continually review the costs and benefits of the PNT systems or capabilities it provides to include user adoption. Without end user adoption, the provisioning of PNT services does not change the risk associated with the loss of GPS. This continuing analysis can be used both for setting priorities for investment in new systems, and for determining the appropriate mix of systems to be retained. In some cases, systems may need to be retained for safety, security, or economic reasons, or to allow adequate time for the transition to newer systems and user equipment; however, these "legacy" systems must be periodically evaluated to determine whether their continued sustainment is justified.

In many instances, aids to air navigation that do not economically qualify for ownership and operation by the Federal Government are needed by private, corporate, or State, Tribal, Territorial, or local government organizations. While these non-federally-operated air navigation facilities do not provide sufficient economic benefit to qualify for operation by the Federal Government, they may provide significant economic benefit to specific user groups or local economies. In most cases they are also available for public use. The FAA regulates and inspects air navigation facilities in accordance with Federal Aviation Regulations (FAR), Title 14, Code of Federal Regulation, Part 171 (14 CFR 171), Non-Federal Navigation Facilities (Ref. 17), and FAA directives.

1.7.5 Institutional Considerations

1.7.5.1 Cost Recovery for PNT Services

In accordance with general policy and the User Fee Statute, 31 U.S.C. 9701 (Ref. 18), the USG recovers the costs of federally-provided services that provide benefits to specific user groups. The amount of use of present Federal PNT services by individual users or groups of users cannot be easily measured; therefore, it would be difficult to apportion direct user charges. Cost recovery for PNT services is either through general tax revenues or through transportation trust funds, which are generally financed with indirect user fees. In the case of GPS, SPD-7 (Ref. 70) states that GPS civil services and GPS augmentations shall be provided free of direct user fees. For NDGPS, Public Law 105–66 (Ref. 9) §346, 111 Stat. 1449, authorizes the Secretary of Transportation to manage and operate NDGPS and to ensure that the service is provided without the assessment of any user fee.

1.7.5.2 Signal Availability

The availability and continuity of accurate PNT signals with the appropriate means to continually determine and validate integrity is essential for safe navigation. Conversely, guaranteed availability of optimum performance may diminish national security objectives, making contingency planning necessary. The U.S. National policy is that all PNT systems operated by USG will remain available for peaceful use, subject to direction by the President in the event of a war or threat to national security.

To minimize service disruptions and prevent situations threatening safety or efficient use of GPS, any transmission on the GPS frequencies is strictly regulated through Federal regulations. These regulations require all transmissions on GPS frequencies to be coordinated with the National Telecommunications and Information Administration (NTIA) and with other potentially impacted Federal agencies.

Planned interruptions of the SPS are subject to a minimum of 48-hour advance notice provided by the Control Segment to the Coast Guard Navigation Center and the FAA Notice to Airmen (NOTAM) system (e.g., scheduled satellite maintenance). An interruption is defined as a period in which the SIS from a satellite does not comply with the standards defined in this SPS PS. A scheduled interruption is defined as a period announced at least 48 hours in advance in which the SIS from a satellite is not planned to comply with the standards defined in this SPS PS. Unscheduled interruptions resulting from system malfunctions or maintenance occurring outside the scheduled period will be announced to the Coast Guard and the FAA as soon as possible. Scheduled interruptions which are announced at least 48 hours in advance do not constitute a loss of continuity.in accordance with the GPS SPS Performance Standard (PS) (Ref. 19). Coordination of planned interference testing activities nominally begins 60 days before testing events. Users are notified by USCG as soon as an activity is approved, and by FAA typically at least 72 hours before an activity begins. DoD notice will be given to the USCG Navigation Center (NAVCEN) Navigation Information Service (NIS) and FAA Notice to Airmen (NOTAM) system. The NIS and NOTAM systems will announce unplanned system outages resulting from system malfunctions or unscheduled maintenance. DoD coordinates all interference testing with other impacted Federal agencies, and FAA coordination is a required step in this process. DHS, in coordination with DOT and DoD, and in cooperation with other departments and agencies, coordinates the use of Federal capabilities and resources to identify, locate, and mitigate interference within the U.S. that adversely affects GPS and its augmentations.

1.7.5.3 Role of the Non-Federal Sector

Radionavigation systems have historically been provided by the USG to support safety, security, and commerce. These PNT or frequency-based services have supported air, land, marine, surveying, mapping, weather forecasting, precision farming, civil engineering, and scientific applications. For certain applications, such as aircraft landing, positioning, and surveying, and in areas where Federal systems are not justified, a number of non-federally-operated systems are available to the user as alternatives, and in most all cases for a user fee required by the service provider.

Air navigation facilities, owned and operated by non-Federal service providers, are regulated by the FAA under 14 CFR 171 (Ref. 17). A non-

Federal sponsor[1] may coordinate with the FAA to acquire, install, and, in some instances, turn a qualified air navigation facility over to the FAA for operation and maintenance because waiting for a federally-provided facility would cost too much in lost business opportunity. Non-Federal facilities are operated and maintained to the same standards as federally-operated facilities under an operations and maintenance agreement with the FAA. This program includes recurrent ground and flight inspections of the facility to ensure that it continues to be operated in accordance with this agreement.

A number of factors need to be considered when examining non-Federal involvement in the provision of air navigation services:

- divestment of a federally-operated PNT service to non-Federal operation as a viable alternative to decommissioning the service;
- commercial development of air navigation equipment for both Federal and non-Federal facilities;
- impact of non-federally-operated services on usage and demand for federally-operated services;
- need for a federally-provided safety of navigation service even if commercially provided services are available;
- liability considerations for the developer, service provider, and user;
- radio frequency (RF) spectrum issues; and
- type approval of the equipment and certification of the air navigation facility, service provider, flight operator, and air traffic controller.

In addition to those services provided for air navigation, a number of commercial services exist to provide positioning for precise land and marine applications, e.g., agriculture and marine construction.

1.7.6 International Considerations

PNT services and systems are provided in a manner consistent with the standards and guidelines of international groups, including the North

[1] Non-Federal sponsor: "The owner of a non-federal facility can be a state, U.S. possession or territory, airport authority, municipality, county, company, or private interest."
REF: USDOT FAA Order 6700.20B (11/25/2015), Entitled Non-Federal Navigational Aids, Air Traffic Control Facilities, and Automated Weather Systems.
Supplement B Entitled: Definition of Terms Related to the Technical Operations Non-Federal Program (v.5/8/20)
https://my.faa.gov/content/dam/myfaa/org/linebusiness/ato/operations/technical_operations/ajw1/nas_support/nas_policy/orders/6700.20/Supplements/Supplement%20B.pdf

Atlantic Treaty Organization (NATO) and other allies, ICAO, the International Telecommunication Union (ITU), and IMO.[2]

The goals of performance, standardization, and cost minimization of user equipment influence the search for an international consensus on a selection of PNT systems. ICAO establishes standards for internationally used civil aviation PNT systems. IMO plays a similar role for the international maritime community. The International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) also develops international PNT guidelines. The International Hydrographic Organization (IHO) and IMO cooperate in the operation of a worldwide marine navigation warning system, which includes warnings of PNT system outages. IMO reviews existing and proposed PNT systems to identify systems that could meet the requirements of, and be acceptable to, members of the international maritime community.

In addition to operational, technical, and economic factors, international issues must also be considered in the determination of a system or systems to best meet civil user needs. Bilateral and multilateral negotiations and consultations related to Global Navigation Satellite Systems (GNSS) occur under the auspices of the Department of State (DoS). The primary multilateral venue for promoting use of services from global and regional systems and augmentations is the International Committee on GNSS (ICG), which held its first meeting in 2006.

1.7.7 Interoperability Considerations

The USG encourages engagement with likeminded nations on interoperability of space-based PNT systems for civil, commercial, and scientific uses worldwide. National Space Policy (Ref. 70) states that foreign space-based PNT services may be used to complement civil GPS service. Use of multiple, varied PNT services can result in better performance in terms of user accuracy, availability, and resilience. Ensuring that all foreign systems are compatible with GPS and its augmentations—and that they do not interfere with GPS military and civil signals—is a critical component of U.S. policy. A providers forum, associated with the ICG and comprised of GNSS providers, has been established to discuss compatibility and interoperability of multiple civil GNSS services. The USG has also fostered the use of interoperable augmentations through its adherence to international standards for DGPS, aircraft-based augmentation (ABAS), ground-based augmentation systems (GBAS), and space-based

[2] The FCC rules require licensing of non-Federal receive-only equipment operating with foreign satellite systems, including receive-only Earth stations operating with non-U.S.-licensed radionavigation-satellite service (RNSS) satellites. On March 15, 2011, the FCC issued a public notice regarding a licensing waiver process applicable to receivers of foreign RNSS signals. On November 15, 2018, the European Union received the first waiver of the FCC's licensing requirements using this process. The FCC waiver order permits non-Federal U.S. receive-only Earth stations to operate with specific signals of the Galileo GNSS without obtaining a license or grant of market access.

augmentation system (SBAS) services such as the Wide Area Augmentation System (WAAS).

1.7.8 Interoperable U.S. National Grid for Emergency Response Operations

Widespread public availability of location-based applications in mobile electronic devices has highlighted the need to create awareness in the USG and among the public of a standard means to identify accident and other incident locations for emergency response purposes. Lack of a uniform method for describing incident locations has been a major impediment to rapid and effective emergency response in diverse metropolitan and rural areas.

The U.S. National Grid (USNG) standard (FGDC-STD-011-2001) was adopted in 2001 by the Federal Geographic Data Committee as part of the National Spatial Data Infrastructure. Its objective is to increase the interoperability of location-based services by establishing a national, consistent, and preferred grid reference system to enable user-friendly position referencing on gridded paper and digital maps in combination with GPS receivers and Internet map portals. The USNG may be the only unambiguous way to describe locations when the end user is operating either in an area away from the established road network, or in an area impacted by a natural disaster where road signs have been destroyed. To facilitate its use in identifying accident/incident locations by the general public and emergency responders, a variety of smartphone applications are available which will provide continuous USNG geo-locations when activated.

The USNG is the civilian version of the Military Grid Reference System (MGRS) that the military uses for tactical operations. It enables geo-locating incident locations from 100 m to 1 m precision. A Chairman of the Joint Chiefs of Staff Instruction (CJCSI 3900.01D) on geo-referencing states that, "To support homeland security and homeland defense, the USNG standard is operationally equivalent to MGRS." The USNG is interoperable for civil and military first responders, facilitates and improves military support to civil authorities, and very importantly, promotes civil/military operational efficiency and facilitates crisis and disaster responses at all levels from Federal to local governments.

The USNG is designated in the National Search and Rescue (SAR) Committee manuals as the primary geo-referencing system for land SAR operations and for air-land SAR coordination. Federal Emergency Management Agency (FEMA) Urban Search and Rescue (USAR) teams adopted the USNG as a response to lessons learned during Hurricane Katrina. In October 2015, FEMA issued FEMA Directive 092-5, entitled "Use of the United States National Grid (USNG)," which states, as FEMA policy, that "FEMA will use the United States National Grid (USNG) as its standard geographic reference system for land-based operations and will encourage use of the USNG among whole community partners. FEMA will reference and employ the USNG in doctrine, relevant preparedness and grant programs, deliberate and crisis-action planning, training, exercises, operations, logistics, and other appropriate disciplines."

FEMA has also identified use of the USNG as part of its National Incident Management System, stating that, "The United States National Grid is a point and area location reference system that FEMA and other incident management organizations use as an alternative to latitude/longitude. The National Grid is simple to apply to support risk assessment, planning, response, and recovery operations. Individuals, public agencies, voluntary organizations, and commercial enterprises can use the National Grid within and across diverse geographic areas and disciplines. The use of the National Grid promotes consistent situational awareness across all levels of government, disciplines, threats, and hazards, regardless of an individual or program's role."

Additionally, the USNG is broadly useful for other purposes beyond incident location and operations management for first responders. The USNG can also provide a significant step toward encouraging improved location harmonization for many other critical infrastructure and commercial purposes. It is a useful and interoperable resource for any critical infrastructure facility or asset location reporting and referencing purpose regardless of public or private/commercial ownership. In August 2018, the USNG standard was adopted by SAE International as a systems management standard for land mobility applications and for mobilization and coordination of resources used in commerce and critical infrastructure.

1.7.9 Radio Frequency Spectrum Considerations

PNT services require a significant amount of RF spectrum to support the world's critical infrastructure, including the need to ensure safe, efficient, robust, and resilient transportation systems. PNT services require sufficient bandwidth, an appropriate level of signal availability, continuity and integrity, and protections from sources of interference – both intentional and unintentional. Spectrum engineering management is a key element of PNT system policy, implementation, and operation.

In planning for PNT systems and services, careful consideration must be given to the U.S. and international regulatory environments in terms of spectrum allocations and management. Because of the recent significant trends to share valuable spectrum, currently "protected" bands could be subjected to unintentional interference from incompatible radio services. Therefore, electromagnetic compatibility analysis remains a key requirement for planning and certification of existing and new PNT systems. Power levels, antenna heights, channel spacing, total bandwidth, spurious and out-of-band emissions, and geographic location must all be considered when implementing new systems to ensure appropriate protection for existing services. Rights and responsibilities of primary and secondary allocation incumbents and new entrants must be considered on specific, technically defined criteria.

Within the U.S., two regulatory bodies oversee the use of radio frequency spectrum. The Federal Communications Commission (FCC) is responsible for all non-Federal use of the airwaves, while NTIA manages spectrum use for the Federal Government. As part of this process, NTIA hosts the Inter-department Radio Advisory Committee (IRAC), a forum consisting of Executive Branch agencies that act as service providers and users of Government spectrum, including safety-of-life bands. FCC participates in IRAC meetings as an observer. National transportation spectrum policy is coordinated through DOT's OST-R, while spectrum for DoD is coordinated through the DoD Chief Information Officer (CIO).

The nature of PNT systems also provides a need for U.S. regulators to go beyond domestic geographic boundaries and coordinate with other nations through such forums as the ITU. ITU is a specialized technical arm of the United Nations (U.N.), charged with allocating spectrum on a global basis through the actions of the World Radiocommunication Conference (WRC), held every three to four years. As a result of the WRC process, where final resolutions hold treaty status among participating nations, spectrum allocations are relatively consistent throughout the world. This offers end users similar RF environments for their PNT equipment independent of where they operate.

The protection of PNT RF spectrum against interference is crucial. All domestic and international PNT services are dependent on the uninterrupted broadcast, reception, and processing of radio frequencies in protected radio bands. Interference-free use of these frequency bands is critical because stringent accuracy, availability, integrity, and continuity parameters must be maintained to meet service provider and end user performance requirements. Figure 1-1 presents the civil GPS signals and their relationship to the other radio services in the adjacent radio frequency spectrum environment.

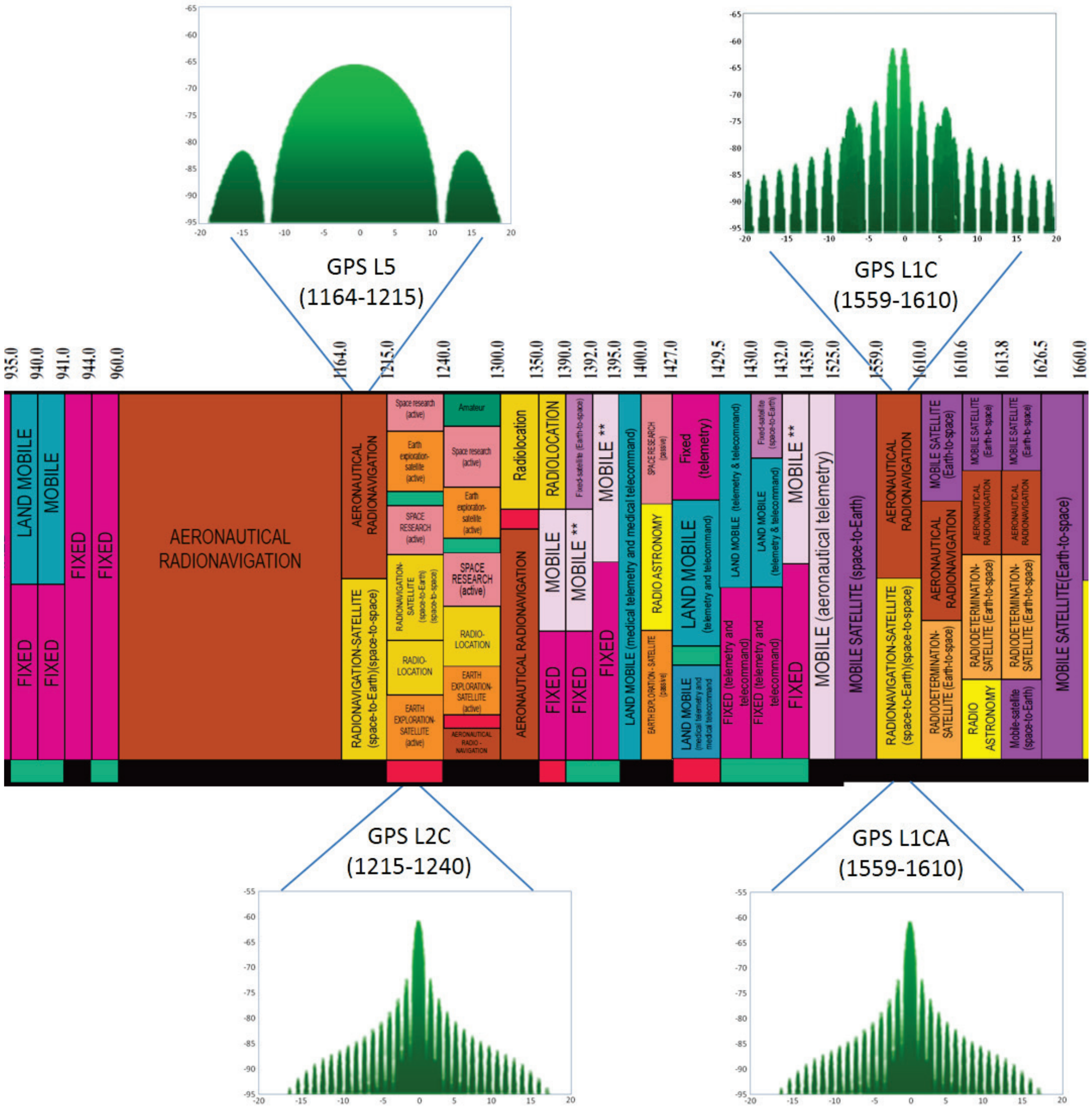

Figure 1-1: Civil GPS Signals and the Spectrum Environment

Representatives from DoD, DOT, and DHS work with other government and private sector agents as members of the U.S. delegation to jointly advocate for PNT requirements, and considerable effort is made through WRC deliberations and other international discussions to ensure that PNT services are protected. The specific ITU band designations that define U.S. PNT systems are listed below:

- Aeronautical Radionavigation Service (ARNS);
- Radionavigation Satellite Service (RNSS); and
- Radionavigation Service (RNS).

DoD, DOT, and DHS have responsibility for the certification of PNT applications and/or equipment pursuant to government responsibilities for national security and public safety[3]. DoD, DOT, and DHS are Federal users of spectrum, as well as service providers and operators of PNT systems. Within DOT, the FAA use of spectrum is primarily in support of aeronautical safety services used within the National Airspace System (NAS), and the GLS utilizes the spectrum for marine safety. Within DHS, the USCG uses internationally-protected spectrum to operate PNT systems used on waterways.

Other DOT agencies (FHWA, FRA, FTA, NHTSA, FMCSA, GLS, and OST-R) also work with the private sector, and State, Tribal, Territorial, and local governments, to use spectrum for Intelligent Transportation System (ITS) and Intelligent Railroad System applications. Many ITS applications will use GPS, GPS augmentations, and other radiodetermination systems in conjunction with vehicle sensors and systems to make roadway travel safer and more efficient by providing differential corrections and location information in an integrated systems context. Collision avoidance systems, emergency services management, and incident detection are some examples of ITS applications that require in-vehicle positioning and navigational support.

Emerging new transportation systems, such as connected vehicles and automated vehicles, as well as related safety, mobility, and environmental applications, will rely even more on PNT services. Intelligent Railroad Systems applications and research, Positive Train Control (PTC) safety systems, rail defect detection, and automated rail surveying rely on GPS and GPS augmentations, other location technologies, and rail industry telecommunications frequencies to improve safety, and economic and operating efficiency. Spectrum used for transportation, military, and homeland security applications must remain free from interference to ensure public safety and security requirements are not impaired.

In 2018, the U.S. Department of Transportation (DOT) released a report on its GPS Adjacent Band Compatibility Assessment, which evaluated the maximum transmitted power levels of adjacent band radio frequency (RF) systems that can be tolerated by GPS and Global Navigation Satellite System (GNSS) receivers with respect to the 1dB degradation in C/N0 interference protection criteria. The results of this effort advanced the Department's understanding of the extent to which such adjacent band transmitters impact GPS/GNSS devices used for transportation safety

[3] Per information in the USCG Navigation Equipment Technical Section, "Navigation equipment type approved by the U.S. Coast Guard are issued a Certificate of Approval that is valid for five years and then entered into the Coast Guard Maritime Information Exchange (CGMIX)." https://www.dco.uscg.mil/Our-Organization/Assistant-Commandant-for-Prevention-Policy-CG-5P/Commercial-Regulations-standards-CG-5PS/Design-Engineering-Standards/Systems-Engineering-Division/navigation/

purposes, among numerous other civil applications. The assessment described in that report addresses transmitters in bands adjacent to the 1559–1610 MHz radionavigation satellite service (RNSS) band used for GPS Link 1 (L1) signals that are centered at 1575.42 MHz.[4]

On December 6, 2019, the National Telecommunications and Information Administration (NTIA) sent an executive branch position to the FCC reflecting the recommendation from the National Space-Based PNT Executive Committee (EXCOM) that "proposals to operate services in bands adjacent to GPS should not be approved unless, at a minimum, they do not exceed the tolerable power transmission limits described in the DOT ABC Final Report."[5] On April 10, 2020, the NTIA sent an additional letter on behalf of the Federal agencies to the FCC supporting the PNT EXCOM recommendation.[6]

On April 20, 2020, the Federal Communications Commission (FCC) unanimously approved an application to deploy a 9.8 dBW terrestrial nationwide network in the 1526–1536 MHz, 1627.5–1637.5 MHz, and 1646.5–1656.5 MHz bands that will primarily support Internet of Things (IoT) services. These frequency bands are traditionally used for satellite operations.

In both its formal response to the FCC's ruling and its May 6, 2020, testimony before the Senate Armed Services Committee (SASC), DoD cited two primary studies that shaped its belief that the FCC Order & Authorization "would cause unacceptable operational impacts and adversely affect the military potential of GPS": the 2018 DOT GPS Adjacent Band Compatibility Assessment study and a 2016 classified study conducted by the U.S. Air Force (USAF).

The DOT concluded that base stations at the proposed frequency would have to be limited to 9.8 dBW to ensure the protection of certified avionics under the assumption that it would be operationally acceptable for these avionics to not be protected within 250 ft laterally and 30 ft in height of a base station antenna. It should be noted that the DOT study found certified avionics to be the second most robust category of GPS equipment (cellular receivers were the most robust) at the proposed base station frequency out

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[4] *Global Positioning System (GPS) Adjacent Band Compatibility Assessment, Final Report*, Washington, DC: United States Department of Transportation, April 2018, available at: https://www.transportation.gov/sites/dot.gov/files/docs/subdoc/186/dot-gps-adjacent-band-final-reportapril2018.pdf

[5] Letter to The Honorable Ajit Pai, Chairman, Federal Communications Commission, December 6, 2019, Washington, DC: National Telecommunications and Infrastructure Administration, available at https://www.ntia.doc.gov/files/ntia/publications/ntia_letter_to_fcc_chairman_re_ligado_mss_atc_applications_dec._6_2019.pdf

[6] Letter to The Honorable Ajit Pai, Chairman, Federal Communications Commission, April 10, 2020, Washington, DC: National Telecommunications and Infrastructure Administration, available at https://www.ntia.doc.gov/files/ntia/publications/ntia_letter_to_fcc_chairman_re_ligado_applications_4.10.20.pdf).

of seven categories that were assessed. Five other categories of GPS equipment were found to be less robust: non-certified aviation, general location/navigation, high precision, timing, and space-based. The study determined that base station power levels would have to be reduced to under 8 milliwatts to protect all fielded GPS receivers at distances of 100 meters and under 80 microwatts to protect all fielded GPS receivers at distances of 10 meters.

On May 22, 2020, the NTIA submitted a petition for reconsideration to the FCC requesting that FCC rescind its recent Order & Authorization.[7] In addition, NTIA has requested that FCC stay its proceedings GPS interference concerns are resolved. The petition focuses on the irreparable harm to all Federal government users of GPS resulting from the FCC's decision, as well as a myriad of public and private safety, economic, and scientific applications. On January 19, 2021, the FCC denied the petition for a stay.

In 2020, the aviation industry under the auspices of RTCA and in conjunction with the FAA, conducted a study to assess the potential interference to Radar Altimeters (RA) operating in the 4.2-4.4 GHz aeronautical band from the planned deployment of 5G networks in the 3.7-3.98 GHz band. The study concluded the deployment would cause harmful interference to RAs on all types of civil aircraft including commercial transport airplanes; business, regional, and general aviation airplanes; and both transport and general aviation helicopters. Since the RA is the only sensor onboard aircraft that provides direct measurement of the clearance height of the aircraft over the terrain or other obstacles, failure of its proper operation can lead to incidents with catastrophic results. Furthermore, the FAA requires the use of RA for many types of aircraft operations. For example, Title 14 of the Code of Federal Regulations (CFR) § 135.160 states that no person may operate a rotorcraft for compensation or hire unless that rotorcraft is equipped with an operable FAA-approved RA. In addition, operations such as Category II or Category III Instrument Landing System (ILS) approaches require the use of at least one RA.

To reduce the risk of harmful interference from 5G C-band and prevent aircraft accidents, the FAA issued a series of Airworthiness Directives (AD) that prohibit certain aircraft operations in low visibility weather. The FAA also collaborated with wireless providers and aviation stakeholders to develop Alternative Methods of Compliance to the ADs to minimize the impact to flight operations. The FAA has been engaged with NTIA and FCC and are interfacing regularly with the wireless industry, the aviation community, and the radar altimeter manufacturers to ensure that mitigations are in place to protect aviation safety.

[7] NTIA Petitions for Stay and Reconsideration in Ligado Proceedings, IB Docket No. 11-109, IB Docket No. 12-340, May 22, 2020, available at https://go.usa.gov/xwCwS.

2

Roles and Responsibilities

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

2.1 Department of Defense (DoD) Responsibilities

DoD is responsible for developing, testing, evaluating, implementing, operating, and maintaining aids to navigation and user equipment that are peculiar to warfare and primarily of military concern. DoD is also responsible for ensuring that military vehicles operating in consonance with civil vehicles have the necessary PNT capabilities. DoD is required by 10 U.S.C. 2281 (Ref. 3), paragraph (b), to provide for the sustainment and operation of the GPS SPS for peaceful civil, commercial, and scientific uses, on a continuous worldwide basis, free of direct user fees. In doing so, the Secretary [of Defense]:

a. provides for the sustainment and operation of the GPS SPS in order to meet the performance requirements of the Federal Radionavigation Plan prepared jointly by the Secretary of Defense, Secretary of Transportation, and Secretary of Homeland Security;

b. coordinates with the Secretary of Transportation regarding the development and implementation by the Government of augmentations to the basic GPS that achieve or enhance uses of the system in support of transportation;

c. coordinates with the Secretary of Homeland Security regarding GPS interference detection and mitigation efforts and how PNT enables critical infrastructure sectors;

d. coordinates with the Secretary of Commerce, the United States Trade Representative, and other appropriate officials to facilitate the development of new and expanded civil and commercial uses for the GPS; and

e. develops measures for preventing hostile use of the GPS in a particular area without hindering peaceful civil use of the system elsewhere.

In addition to the sustainment and operation of the GPS SPS, additional Secretary of Defense responsibilities include:

a. developing appropriate measures for preventing hostile use of the GPS;

b. ensuring that U.S armed forces have the capability to use the GPS effectively despite hostile attempts to prevent the use of the system by U.S. armed forces;

c. not agreeing to any restriction on the GPS proposed by the head of a department or agency of the United States outside the DoD that would adversely affect the military potential of the GPS;

d. developing an enhanced GPS involving an evolved satellite system that includes increased signal power and other improvements, such as regional-level directional signal enhancements and enhanced receivers and user equipment that are capable of providing military users with direct access to encrypted GPS signals; and

e. only purchasing user equipment after FY 2017 that is capable of receiving the M-Code from GPS, unless waived by the Secretary of Defense.

The National Geospatial-Intelligence Agency (NGA) is responsible for providing geospatial information and intelligence to DoD and the Intelligence Community (IC). This includes mapping, charting, and geodesy data and products, such as digital terrain elevation data, digital feature analysis data, digital nautical chart data, Notice to Mariners, aeronautical charts, flight information publications, global gravity and geomagnetic models, geodetic surveys, and the WGS 84. This support also includes geodetic positioning of transmitters for electronic systems and tracking stations for satellite systems, maintenance of a global GPS monitor station network, and generation and distribution of GPS precise ephemerides. NGA is also responsible for ensuring that the WGS 84 Reference Frame is interoperable with the International Terrestrial Reference Frame (ITRF). Within DoD, NGA acts as the primary point of contact with the civil community on matters relating to geodetic uses of PNT systems and provides calibration support for certain airborne navigation systems. Unclassified data prepared by NGA are available to the civil sector. The NGA Maritime Safety Office also serves as a Navigation Area (NAVAREA) Coordinator within the International Hydrographic Organization's (IHO) World-Wide Navigational Warning Service (WWNWS). NGA is the designated coordinator for NAVAREA IV and

NAVAREA XII under this international global maritime safety information broadcast service.

USNO is responsible for determining the positions and motions of celestial bodies, the motions of the Earth, and precise time; for providing the astronomical and timing data required by the United States Navy (USN) and other components of DoD and the general public for navigation, precise positioning, and command, control and communications; and for making these data available to other government agencies and to the general public. USN, through the USNO, serves as the official DoD timekeeper via its Master Clock in Washington, DC, and Alternate Master Clock at Schriever Air Force Base, Colorado.

DoD carries out its responsibilities for PNT coordination through the internal management process described in section 2.1.2. Administrative Management. The operational control of DoD PNT systems is not shown here, but is described in the CJCSI 6130.01 (Ref. 1) and other DoD documents.

2.1.1 Operational Management

The Chairman, Joint Chiefs of Staff, supported by the Joint Staff, is the principal military advisor to the President and the Secretary of Defense. The Joint Chiefs of Staff (JCS) provide guidance to the combatant commands and military departments in the preparation of their respective detailed PNT plans. The JCS are aware of operational PNT requirements and capabilities of the Unified Commands and the Services, and are responsible for the development, approval, and dissemination of the CJCSI 6130.01 (Ref. 1).

CJCSI 6130.01 (Ref. 1) is the official PNT policy and planning document of the CJCS, which addresses operational requirements and, consequently, is not publicly releasable.

The following organizations also perform PNT management functions:

2.1.1.1 Joint Staff (J-3)

Joint Staff (J-3) oversees CJCSM 3212.02E (Ref. 20), which implements guidance to request and gain approval to conduct electronic attack (EA) tests, training, and exercises (TT&E), including those involving the GPS spectrum.

2.1.1.2 Joint Staff (J-6)

The Command, Control, Communications, and Computers (C4)/Cyber Directorate, Joint Staff (J-6), is responsible for analysis, evaluation, and monitoring of PNT system planning and operations; general joint warfighter PNT matters; authoring and publishing the CJCSI 6130.01 (Ref. 1); and chairing the C4/Cyber Functional Capabilities Board (FCB) (first level of the Joint Capabilities Integration and Development System (JCIDS) review for DoD and interagency PNT requirements).

2.1.1.3 Joint Staff (J-8)

Joint Staff (J-8) validates joint PNT requirements coming from the C4/Cyber FCB through the Joint Capabilities Board and the Joint Requirements Oversight Council via the JCIDS process. J-8 identifies and assesses PNT capability needs, gaps, and risks during the JCS Capability Gap Assessment process. During the annual Planning, Programming, Budget and Execution review, J-8 advocates for Combatant Command equities with respect to PNT resource allocation decisions. The J-8 represents Joint Staff and Combatant Command equities at Acquisition Category I PNT milestone events.

2.1.1.4 Commanders of the Unified Commands

The Commanders of the Unified Commands develop PNT requirements as necessary for operational and contingency plans and JCS exercises. They are also responsible for review and compliance with the CJCSI 6130.01 (Ref. 1).

2.1.1.5 Commander of United States Space Command

Exercises command authority regarding the operational control of DoD space-based PNT assets, and advocates for joint resilient PNT requirements and capabilities supporting NAVWAR operations for the DoD.

2.1.1.6 Commander of United States Strategic Command

The Commander of United States Strategic Command reviews all DoD EA TT&E packages, coordinates first with the Joint Spectrum Center for quality assurance, and then coordinates the final package with DoD and Interagency stakeholders (e.g., FAA, USCG, etc.).

2.1.1.7 Military Departments and Combatant Commands

The Military Departments and Combatant Commands are responsible for participating in the development, dissemination, and implementation of the CJCSI 6130.01 (Ref. 1), and for managing the development, deployment, operation, and support of designated PNT systems.

2.1.2 Administrative Management

Several organizations provide PNT planning and management support to the Secretary of Defense, including the DoD PNT Oversight Council, DoD PNT Executive Management Board and the Military Departments and Combatant Commands (Figure 2-1). Brief descriptions are provided below.

The structure and responsibilities of member organizations are documented in DoD Directive 4650.05 and DoD Instruction 4650.06

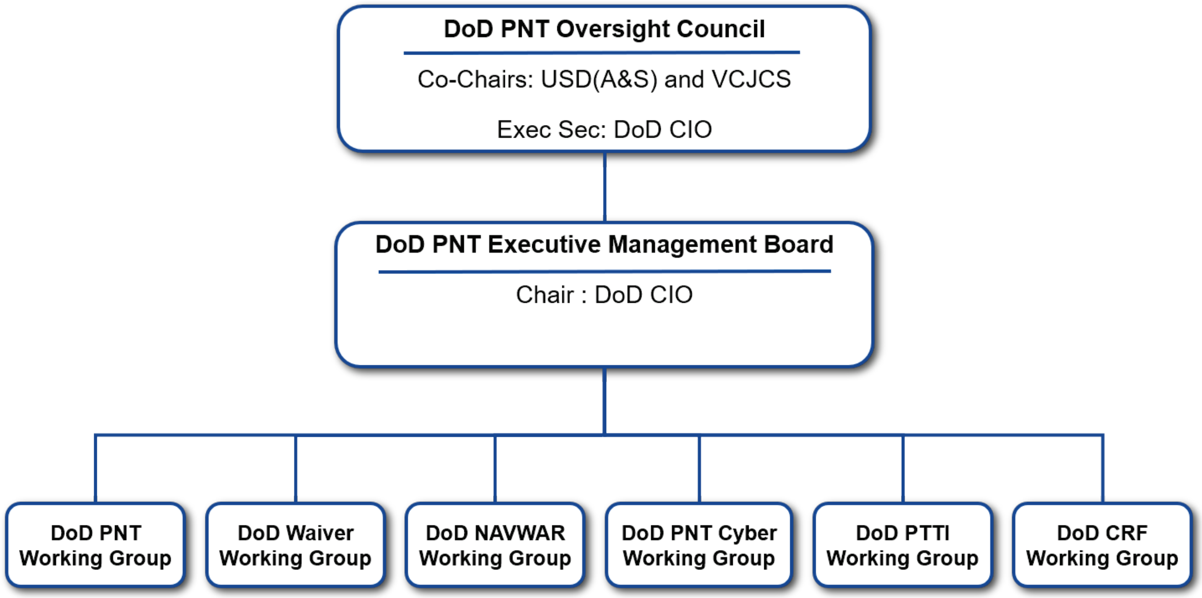

Figure 2-1: Department of Defense PNT Management Structure

2.1.2.1 DoD PNT Oversight Council

The PNT Oversight Council is co-chaired by the Under Secretary of Defense for Acquisition and Sustainment and the Vice Chairman of the Joint Chiefs of Staff. The Council serves as the principal unified and integrated DoD governance body that ensures the DoD PNT Enterprise functions meet national objectives, consistent with national policy and guidance, and that the mutually supporting systems continue to evolve to address emerging threats.

2.1.2.2 DoD PNT Executive Management Board (EMB)

The DoD PNT EMB oversees the governance process in support of the PNT Oversight Council for the DoD PNT Enterprise, functions as the primary advisory body to the DoD CIO on all DoD PNT policy matters, and advises the DoD CIO regarding the overall management, supervision, and decision-making processes for DoD PNT matters, including biennial review of the FRP and other plans requiring DoD review, (e.g., architecture products relevant to DoD PNT systems).

2.1.2.2.1 DoD PNT Working Group

The DoD PNT Working Group supports the DoD PNT EMB in carrying out its responsibilities. It is composed of representatives from the same DoD components as the EMB. The Working Group identifies and analyzes problem areas and issues, participates with the DOT PNTNT Working

Group in the revision of the FRP, and submits recommendations to the EMB.

2.1.2.2.2 DoD Waiver Working Group

To support the objectives of the DoD PNT EMB, the DoD PNT Waiver Working Group will review waiver submissions and anticipate waiver policy adjustments.

2.1.2.2.3 DoD NAVWAR Working Group

The DoD Navigation Warfare (NAVWAR) Working Group is composed of subject matter experts within DoD organizations that provide the DoD PNT EMB with support and recommendations regarding NAVWAR doctrine, policy, needs, and implementation.

2.1.2.2.4 DoD PNT Cyber Working Group

The DoD PNT Cyber Working Group is composed of subject matter experts within DoD organizations that provide the DoD PNT EMB with support and recommendations regarding PNT cyber doctrine and policy, as well as advice on existing and potential PNT cyber capabilities and capability shortfalls.

2.1.2.2.5 DoD Precise Time and Time Interval (PTTI) Working Group

The PTTI Working Group serves as the primary advisory body to the DoD PNT EMB and the DoD CIO on all PTTI matters.

2.1.2.2.6 DoD Celestial Reference Frame (CRF) Working Group

The CRF Working Group serves as the primary advisory body to the DoD PNT EMB and the DoD CIO on all CRF and Earth orientation parameters matters.

2.2 Department of Transportation (DOT) Responsibilities

DOT is responsible under 49 U.S.C. 101 (Ref. 2) for the "development of transportation policies and programs that contribute to providing fast, safe, efficient, and convenient transportation at the lowest cost consistent with those and other national objectives, including the efficient use and conservation of the resources of the United States." PNT systems play an important role in carrying out this responsibility. The two modes within DOT that operate PNT systems are the FAA and GLS. The Assistant Secretary for Research and Technology (OST-R) is responsible for coordinating PNT planning and providing overall leadership responsibility for navigation matters within DOT and with other civil Federal elements.

Specific DOT responsibilities are to:

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

b. prepare and promulgate PNT plans in the civilian sector of the U.S.;

c. represent the civil agencies in the development, acquisition, management, and operations of GPS and its augmentations and have lead responsibility for the development of requirements for civil applications from all United States Government civil agencies;

d. ensure the earliest operational availability for modernized civil signals and services on GPS and its augmentations, in coordination with the Secretary of Defense;

e. develop and validate requirements and a funding strategy to implement data and signal authentication of civil GPS and wide area augmentations for homeland security and public safety purposes in coordination with the Secretary of Defense and the Secretary of Homeland Security;

f. ensure the performance monitoring of United States civil space-based PNT services in coordination with the Secretary of Defense and the Secretary of Homeland Security and facilitate international coordination for the development of monitoring standards for space-based PNT services;

g. implement Federal and facilitate State, local and commercial capabilities to monitor, identify, locate, and attribute space-based PNT service disruption and manipulations within the United States in coordination with the Secretary of Defense and the Secretary of Homeland Security and the heads of other agencies, as appropriate;

h. facilitate international participation in the development of civil transportation applications using United States space-based PNT services in coordination with the Secretary of State; and

i. in cooperation with the heads of other agencies, as appropriate, promote the responsible use of United States and foreign civil space-based PNT services and capabilities for transportation safety as directed in Executive Order (EO) 13905 and facilitate adoption of complementary PNT technologies and/or services in the event of a disruption of GPS or other space-based positioning, navigation, and timing services, consistent with PPD-21, Critical Infrastructure Security and Resilience, dated February 12, 2013 (Ref. 31).

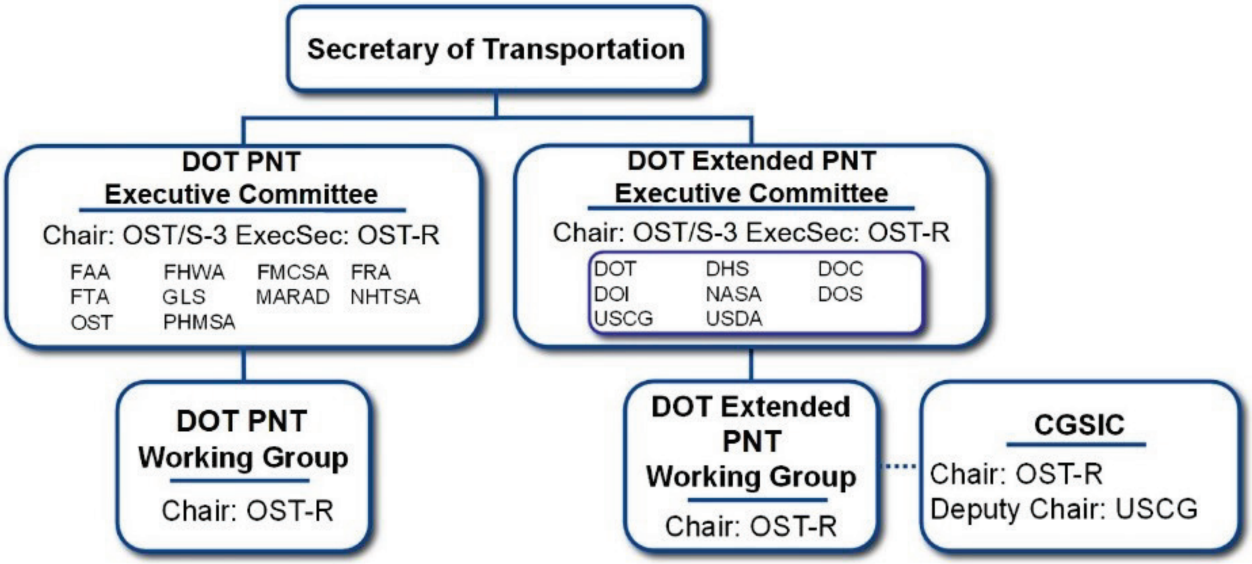

Figure 2-2: Department of Transportation PNT Management Structure

DOT carries out its responsibilities for civil PNT systems planning through the internal management structure shown in Figure 2-2. The structure was originally established by DOT Order 1120.32, April 27, 1979 (Ref. 22), later revised by DOT Order 1120.32C, October 06, 1994 (Ref. 23) and DOT Order 1120.32D, January 11, 2021 (Ref. 69):

The Secretary of Transportation, under 49 U.S.C. 301 (Ref. 24), has overall leadership responsibility for navigation matters within DOT and promulgates PNT plans. OST-R coordinates PNT issues and planning that affect multiple modes of transportation, including those that are intermodal in nature. OST-R also interfaces with agencies outside of DOT on non-transportation uses of PNT systems.

2.2.1 DOT PNT Executive Committee

The DOT PNT Executive Committee is responsible for DOT policy development and planning for civil and dual-use PNT services and systems. The Under Secretary for Transportation Policy (OST-P) chairs the DOT PNT Executive Committee. Specific policy and planning responsibilities are as follows:

1) The DOT PNT Executive Committee is comprised of one policy-level representative from each of the Office of General Counsel, the Office of the Assistant Secretary for Budget and Programs, the Federal Aviation Administration (FAA), the Federal Highway Administration (FHWA), the Federal Motor Carrier Safety Administration (FMCSA), the Federal Railroad Administration (FRA), the Federal Transit Administration (FTA), the Maritime Administration (MARAD), the National Highway Traffic Safety

Administration (NHTSA), the Pipeline and Hazardous Materials Safety Administration (PHMSA), the Great Lakes St. Lawrence Seaway Development Corporation (GLS), and the Intelligent Transportation Systems Joint Program Office (ITS JPO).

2.2.1.1 DOT PNT Working Group

The DOT PNT Working Group (WG) has representatives from each of the DOT organizations listed in section 2.2.1, as well as from the Volpe National Transportation Systems Center and other DOT representatives or advisors. The DOT PNT WG shall meet at least once each quarter and jointly with the DoD PNT WG as required, and shall facilitate coordination of PNT requirements, plans, research and development, and implementation programs developed by DOT operating administrations.

2.2.2 DOT Extended PNT Executive Committee

The DOT Extended PNT Executive Committee conducts planning with the Department of Commerce, DHS (including U.S. Coast Guard), Department of the Interior, Department of Agriculture, State Department, National Aeronautics and Space Administration, and other Federal agencies as appropriate. The Extended PNT Executive Committee shall provide a focal point for coordinating with Government agency committees; provide unified departmental comments on proposed reports and rulemakings of other governmental agencies on PNT-related matters; and provide guidance to the DOT PNT WG and DOT Extended PNT WG.

2.2.2.1 DOT Extended PNT Working Group

The DOT Extended PNT WG conducts planning with the Department of Commerce, DHS (including U.S. Coast Guard), Department of the Interior, Department of Agriculture, State Department, National Aeronautics and Space Administration, and other Federal agencies as appropriate.

The DOT PNT WG and the DOT Extended PNT WG are the working-level organizations for coordinating PNT issues being submitted for DOT PNT Executive Committee decision making. They are chaired by the Director for PNT and Spectrum Management within the Office of the Assistant Secretary for Research and Technology.

The DOT PNT WG and Extended WG shall focus on multimodal PNT issues with other governmental agencies, industry, and user groups, as directed by the DOT PNT Executive Committee.

2.2.2.2 Civil GPS Service Interface Committee (CGSIC)

The CGSIC, chaired by OST-R, along with the USCG as the deputy chair and executive secretariat, is the official DOT committee for information exchange with all GPS users, including State, Tribal, Territorial, local, international, and non-government users.

2.2.3 DOT Agencies

2.2.3.1 Federal Aviation Administration (FAA)

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

The Administrator of the FAA is required to develop a common civil and military airspace system. 49 U.S.C. 44505 (Ref. 8), paragraph (a) states the following:

"General Requirements.

(1) The Administrator of the Federal Aviation Administration shall –

> *(A) develop, alter, test, and evaluate systems, procedures, facilities, and devices, and define their performance characteristics, to meet the needs for safe and effective navigation and traffic control of civil and military aviation, except for needs of the armed forces that are peculiar to air warfare and primarily of military concern; and*
>
> *(B) select systems, procedures, facilities, and devices that will best serve those needs and promote maximum coordination of air traffic control and air defense systems.*

(2) The Administrator may make contracts to carry out this subsection without regard to section 3324(a) and (b) of Title 31 [U.S.C.].

(3) When a substantial question exists under paragraph (1) of this subsection about whether a matter is of primary concern to the armed forces, the Administrator shall decide whether the Administrator or the Secretary of the appropriate military department has responsibility. The Administrator shall be given technical information related to each research and development project of the armed forces that potentially applies to, or potentially conflicts with, the common system to ensure that potential application to the common system is considered properly and that potential conflicts with the system are eliminated."

2.2.3.2 Great Lakes St. Lawrence Seaway Development Corporation (GLS)

The GLS has responsibility for assuring safe navigation along portions of the Saint Lawrence Seaway.[8] The GLS is responsible for the navigation

[8] DOT's Saint Lawrence Seaway Development Corporation (SLSDC) was legally renamed Great Lakes St. Lawrence Seaway Development Corporation (GLS) on December 27, 2020, as part of the Consolidated Appropriations Act, 2021 (Section 512 of Division AA of Public Law 116–260), available at https://www.congress.gov/116/bills/hr133/BILLS-116hr133enr.pdf.

aids, monitoring vessel speeds, and performing hydrographic surveys and channel maintenance in U.S. waters of the St. Lawrence Seaway, and for operating and maintaining vessel traffic control and AIS systems with the with the Canadian SLSMC.

2.2.3.3 Maritime Administration (MARAD)

MARAD is the agency within DOT dealing with waterborne transportation. Its programs promote the maritime industry, including the use of waterborne transportation and its integration with other modes of the transportation system, and the viability of the U.S. merchant marine. MARAD works in many areas involving ships and shipping, shipbuilding, port operations, vessel operations, national security, environment, and safety.

MARAD is also charged with maintaining the health of the merchant marine, since commercial mariners, vessels, and intermodal facilities are vital for supporting national and economic security. MARAD's sealift programs directly support the education of mariners, commercial ship operators, ports and shipyards, and defense objectives and emergency response efforts. .

MARAD is responsible for the National Defense Reserve Fleet (NDRF), and maintains a quick-response sub-component of cargo ships in reserve, known as the Ready Reserve Force (RRF). The RRF provides immediate, surge sealift during war and national emergencies. When these and other non-combatant Government ships reach their end of service life, MARAD is responsible for disposing of ships in an environmentally sound way as they become obsolete.

MARAD is the United States representative to NATO's Transport Group (Ocean Shipping), also known as TGOS. TGOS is one of seven NATO planning boards and serves as a technical advisor to NATO on issues related to commercial shipping. TGOS also acts as a liaison between NATO military authorities and the international maritime industry and assists with NATO civil emergency and crisis management planning.

As part of the MARAD Strategic Ports Program, MARAD chairs and administers the National Port Readiness Network (NPRN). The NPRN is an organization of nine (9) Federal agencies and military commands with the mission to support the movement of military cargo through U.S. seaports. NPRN organizations coordinate the readiness of designated strategic ports to support force deployment during contingencies and other defense/national emergencies.

2.2.3.4 Other DOT Agencies and Components

FHWA, FMCSA, FRA, FTA, NHTSA, and OST-R have responsibility to conduct research, development, and demonstration projects, including projects on surface transportation uses of PNT systems used by regulated industries which depend on those systems. They also assist State, Tribal, Territorial, local, and non-governmental users in planning and implementing such systems and issue guidelines concerning their required (by law or regulation) and potential uses and applications. Due to increased emphases on safety and efficiency in surface transportation, these organizations are increasing their activities in this area.

2.3 Department of Homeland Security (DHS) Responsibilities

Following the policy requirements of HSPD 7 (Critical Infrastructure Identification, Prioritization, and Protection), SPD-7 (U.S. Space-based Positioning, Navigation, and Timing Policy), and Presidential Policy Directive (PPD) 21 (Critical Infrastructure Security and Resilience), DHS has five overarching missions:

1) preventing terrorism and enhancing security;
2) securing and managing our borders;
3) enforcing and administering our immigration laws;
4) safeguarding and securing cyberspace; and
5) ensuring resilience to disasters.

In addition to the overarching missions above, SPD-7 tasks DHS with promoting homeland security requirements, promoting responsible use of PNT, and ensuring mechanisms are in place for disruption monitoring, notification, and contingency response. DHS' specific effort for monitoring disruption of PNT services is to concentrate on operational impacts to Critical Infrastructure. Accurate PNT is necessary for the functioning of many critical infrastructure sectors. Precision timing is particularly important and is mainly provided through the Global Positioning System (GPS). In coordination with interagency efforts, private sector partners, and stakeholders, DHS manages several PNT-related programs and activities distributed across the Department.

DHS continues work towards identifying and mitigating threats and vulnerabilities, while reducing risk through efforts to increase security and resiliency. To coordinate and synchronize these efforts, the Deputy Secretary established the DHS PNT Executive Steering Committee (ESC) to organize, manage, and coordinate PNT actions and decisions across the Department. The ESC leads the Department's efforts to enhance the capabilities, security, and resilience of PNT systems and dependent U.S. critical infrastructure, including DHS mission areas and mission partners.

Additionally, to address GPS vulnerabilities in critical infrastructure, DHS Science and Technology's (S&T) PNT Program has a multi-pronged approach of conducting vulnerability and impact assessments, developing mitigations, improving PNT equipment, diversifying timing technologies, and engaging with industry through outreach events and education. Through these sustained efforts, the goal of the program is to increase the resiliency of critical infrastructure against GPS/PNT disruptions.

2.3.1 United States Coast Guard (USCG)

The USCG defines the need for, and provides, aids to navigation and facilities required for safe and efficient maritime navigation. 14 U.S.C. 541 (Ref. 10) states the following:

> *"In order to aid navigation and to prevent disasters, collisions, and wrecks of vessels and aircraft, the Coast Guard may establish, maintain, and operate:*
>
> 1) *aids to maritime navigation required to serve the needs of the armed forces or of the commerce of the United States;*
> 2) *aids to air navigation required to serve the needs of the armed forces of the United States peculiar to warfare and primarily of military concern as determined by the Secretary of Defense or the Secretary of any department within the Department of Defense and as required by any of those officials; and*
> 3) *electronic aids to navigation systems (a) required to serve the needs of the armed forces of the United States peculiar to warfare and primarily of military concern as determined by the Secretary of Defense or any department within the Department of Defense; or (b) required to serve the needs of the maritime commerce of the United States; or (c) required to serve the needs of the air commerce of the United States as requested by the Administrator of the Federal Aviation Administration.*
>
> *"These aids to navigation, other than electronic aids to navigation systems, shall be established and operated only within the United States, the waters above the Continental Shelf, the territories and possessions of the United States, the Trust Territory of the Pacific Islands, and beyond the territorial jurisdiction of the United States at places where naval or military bases of the United States are or may be located. The Coast Guard may establish, maintain, and operate aids to marine navigation under paragraph (1) of this section by contract with any person, public body, or instrumentality."*

The USCG also serves as a national coordinator within the World-Wide Navigational Warning Service (WWNWS) charged with collating and issuing coastal warnings within U.S. national waters. The USCG provides coastal Maritime Safety Information (MSI) broadcasts through VHF marine radio broadcasts on VHF simplex channel 22A and NAVTEX (navigational telex) text broadcasts on 518 kHz to meet the requirements of the WWNWS and the Global Maritime Distress and Safety System (GMDSS).

In addition, the USCG NAVCEN serves as the civil GPS point of contact for all non-aviation, non-military surface and maritime GPS users by gathering, processing, and disseminating timely GPS PNT information, as well as general maritime navigation information. NAVCEN is also a key component of the Civil GPS Service Interface Committee (CGSIC) and exchanges information between the GPS system providers and users.

2.4 Other Government Organizations Responsibilities

2.4.1 National Executive Committee for Space-Based PNT

NSPD-39 (Ref. 13) (superseded by Space Policy Directive-7, issued by President Trump on January 15, 2021) (Ref. 70) establishes guidance and implementation actions for space-based PNT programs, augmentations, and activities for U.S. national and homeland security, civil, scientific, and commercial purposes. The policy established a permanent National Space-Based PNT Executive Committee (EXCOM), co-chaired by the Deputy Secretaries of Defense and Transportation. Its membership includes representatives, at the equivalent level of the Co-chairs, from the Departments of State, Interior, Agriculture, Commerce, Homeland Security, the Joint Chiefs of Staff, the National Aeronautics and Space Administration (NASA) and any other department or agency as the chairs deem necessary. Components of the Executive Office of the President (EOP) participate as observers and the FCC Chairman participates as a liaison.

The National Space-Based PNT Executive Steering Group (ESG) performs tasks, builds consensus, and resolves issues on behalf of the National Executive Committee. The ESG is co-chaired by the Departments of Defense and Transportation at the under or assistant secretary level.

The National Space-Based PNT Coordination Office (NCO) provides day-to-day staff support to the EXCOM and ESG. It is led by a full-time Director, who functionally reports to the EXCOM co-chairs, and includes a full-time staff provided by the EXCOM departments and agencies.

The National Space-Based PNT Advisory Board provides independent advice to the EXCOM on U.S. Space-Based PNT policy, planning, program management, and funding profiles in relation to the current state of national and international space-based PNT services. The Advisory Board is composed of experts from outside the U.S. Government and is chartered through NASA as a Federal Advisory Committee.

Several working groups support the National Executive Committee through staff-level, interagency collaboration on specific topics. These include the

GPS International Working Group and the National Space-Based PNT Systems Engineering Forum.

The EXCOM management structure is shown in Figure 2-3.

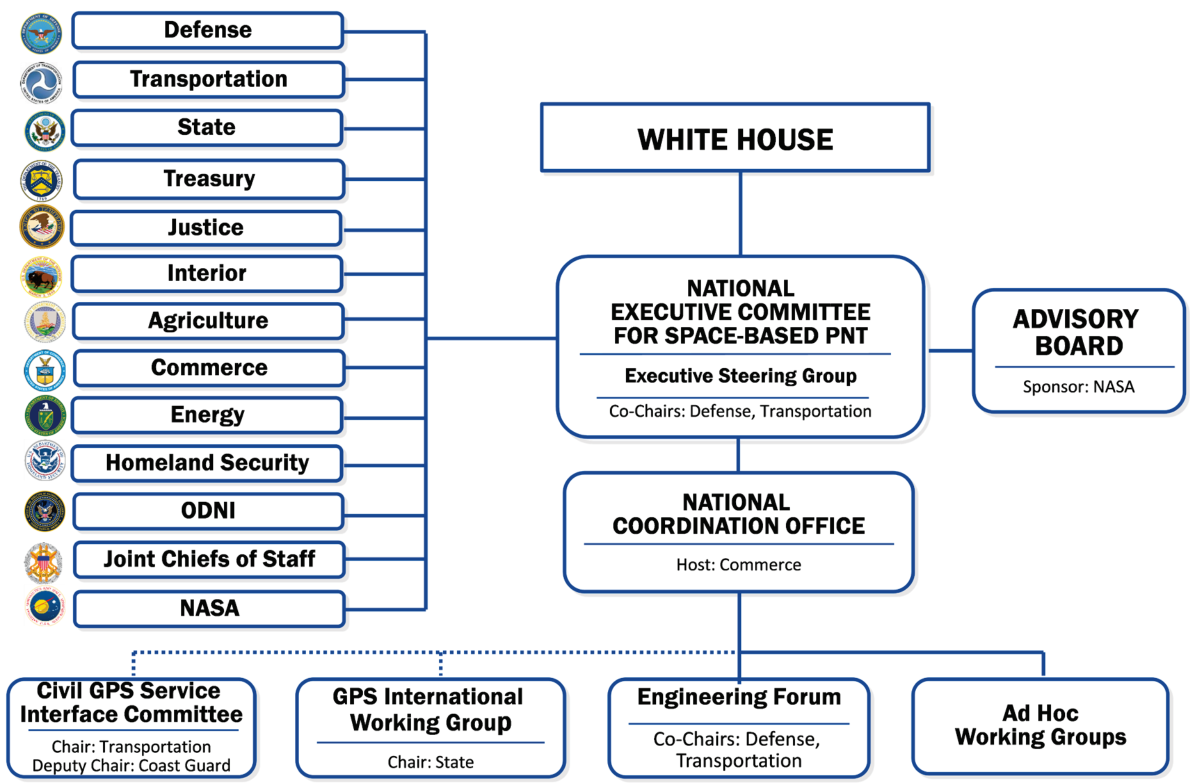

Figure 2-3: National Space-Based PNT Management Structure

The National Executive Committee makes recommendations to its member departments and agencies and to the President through the representatives of the Executive Office of the President. In addition, the National Executive Committee advises and coordinates with and among the departments and agencies responsible for the strategic decisions regarding policies, architectures, requirements, and resource allocation for maintaining and improving U.S. space-based PNT infrastructures, including GPS, its augmentations, security for these services, and relationships with foreign PNT services. Specifically, the National Executive Committee works to:

- Ensure that national security, homeland security, and civil requirements receive full and appropriate consideration in the decision-making process and facilitate the integration and deconfliction of these requirements for space-based PNT capabilities, as required;

- Coordinate individual departments' and agencies' PNT program plans, requirements, budgets, and policies, and assess the adequacy of funding and schedules to meet validated requirements in a timely manner;

- Ensure that the utility of civil services exceeds, or is at least equivalent to, those routinely provided by foreign space-based PNT services;
- Promote plans to modernize the U.S. space-based PNT infrastructure, including:
    1. development, deployment, and operation of new and/or improved national security and public safety services when required and to the maximum practical extent; and
    2. determining the apportionment of requirements between the GPS and its augmentations, including consideration of user equipment; and
- Review proposals and provide recommendations to the departments and agencies for international cooperation, as well as spectrum management and protection issues.

The National Executive Committee advises and coordinates the interdepartmental resource allocation for GPS and its augmentations on an annual basis. The details are outlined in a Five-Year National Space-Based PNT Plan approved by the National Executive Committee.

2.4.2 Department of Commerce (DOC)

Space Policy Directive-7 (Ref. 70) assigns certain roles and responsibilities to the DOC, including: promoting U.S. industry access to foreign markets for space-based PNT goods and services, while adopting a risk-management approach to U.S. national security concerns; investing in research and development on next-generation technologies that could enhance GPS applications for commercial use; representing U.S. commercial interests with other agencies in the requirements review of GPS and its related augmentations; protecting the radio frequency spectrum used by GPS and its augmentations through appropriate domestic and international spectrum management and regulatory practices; identifying mutually acceptable solutions that will preserve existing and evolving uses of space-based PNT services, while allowing for the development of other non-interfering technologies and services that depend on use of the radio frequency spectrum; developing requirements for use of GPS and its augmentations to support civil space systems; and developing guidelines to improve the cybersecurity of PNT devices, including their capability to detect and reject manipulated or counterfeit signals, and promoting the responsible use of space-based PNT services and capabilities. These roles and responsibilities complement those directed in Executive Order 13905 (Ref. 72).

DOC hosts the National Executive Committee for Space-Based PNT and NCO, providing office space, staffing, support services, and other resources. Through the National Geodetic Survey (NGS) of the National Oceanic and Atmospheric Administration (NOAA), DOC is responsible for defining, maintaining, and providing access to the National Spatial Reference System (NSRS). The NSRS is a consistent coordinate system that defines latitude, longitude, height, scale, gravity, orientation, and shoreline throughout the U.S. and is designed to meet the Nation's economic, social, and environmental needs. The NGS provides access to the NSRS through its Online Positioning User Service (OPUS), which is based on the NOAA Continuously Operating Reference Stations (CORS) Network. DOC/NOAA through the National Geodetic Survey is responsible to ensure that the NSRS is aligned to and consistent with the ITRS specified in ISO Standard 19161-1 and as agreed upon by the UN-GGIM in the Global Geodetic Reference Frame (GGRF) resolution. NGS continues to be one of the 12 currently-active orbit analysis centers contributing to the IGS GNSS orbit products.

The Secretary of Commerce, in coordination with the Secretary of the Navy, has authority to interpret and modify UTC for application as Standard Time in the U.S. Through NIST, DOC performs research and measurements to develop new high performance atomic clocks, to support the use of GNSS including GPS for precision time and frequency applications, and to develop new means of distributing precise time and frequency. NIST operates the U.S. primary frequency standard, contributes to international realization of UTC, is a provider of official U.S. time through various dissemination services, and provides a range of calibration and measurement services supporting industry and government applications.

2.4.3 Department of State (DoS)

DoS responsibilities are included in SPD-7 (Ref. 70). The policy directs that:

"The Secretary of State shall:

- *In cooperation with the Secretary of Defense, the Secretary of Transportation and the heads of other appropriate agencies, promote the use of GPS and its augmentation services and standards with foreign governments and other international organizations, and encourage the development of foreign civil PNT services and systems based on GPS;*

- *Take the lead for negotiating with foreign governments and international organizations regarding civil and, as appropriate and in coordination with the Secretary of Defense, military PNT matters, including coordinating interagency review* of*:*

- *Instructions to United States delegations for bilateral and multilateral consultations relating to the planning, management, and use of GPS, other global and regional navigation satellite systems, and their augmentation* systems*;*

- *International agreements, arrangements, and public statements with foreign governments and international organizations regarding the planning, operation, management, or use of GPS, other global and regional navigation satellite systems, and their augmentation systems; and*

- *Participate with the Secretary of Defense in PNT dialog with allies, especially NATO relations."*

2.4.4 National Aeronautics and Space Administration (NASA)

In support of the provisions of the National Aeronautics and Space Act of 1958 (Ref. 11), the operation of space activities includes providing PNT services via national assets, such as the NASA ground and space communication and tracking networks, including the broadcast of navigation signals, and the development and operation of equipment supporting PNT in NASA missions.

NASA's national policy positions on the use of GPS and its augmentations for PNT and science are developed and coordinated with the NASA Centers and Science Mission Directorate (SMD) by the Space Communications and Navigation (SCaN) Program within the Human Exploration and Operations Mission Directorate (HEOMD) at NASA Headquarters.

The NASA mission also includes pioneering the future in space exploration, scientific discovery, and aeronautics research, which includes a number of GPS application areas in the space, aeronautics, and terrestrial environments.

SPD-7 (Ref. 70) states that, consistent with Space Policy Directive-1 (SPD-1) of December 11, 2017 (Reinvigorating American's Human Space Exploration Program) and Space Policy Directive-3 (SPD-3) of June 18, 2018 (National Space Traffic Management Policy) PNT services will play an important role in space traffic management and future applications in the Cislunar Service Volume, which extends from Geosynchronous Orbit (GEO) out to and including the Moon's orbit. Under SPD-7 the roles and responsibilities of the NASA Administrator include:

- In cooperation with the Secretary of Commerce, develop and provide to the Secretary of Transportation technical requirements for the use of GPS and its augmentations to support civil and commercial space systems;

- In cooperation with the Secretary of Defense, the Secretary of Commerce, and the Secretary of Transportation, develop requirements for GPS support of space operations and science in higher orbits within the SSV and beyond to cislunar space; and
- In cooperation with the Secretary of State, the Secretary of Defense, the Secretary of Commerce, and the Secretary of Homeland Security, sustain and modernize search and rescue and distress alert and location capabilities and programs that operate as secondary payloads on GPS satellites.

2.4.5 Interagency Planning Office (IPO)

Section 709 of Vision 100—Century of Aviation Reauthorization Act (Public Law 108–176, 117 Stat. 2582) (Ref. 26) established the requirement for the FAA to coordinate and collaborate with the designated agencies (DoD, DHS, NASA, DOC, and OST-P) to establish interagency support of the Next Generation Air Transportation System (NextGen) planning and development. The interagency coordination requirement was originally carried out by the Joint Planning and Development Office (JPDO). In June of 2013, the FAA designated the Deputy Administrator as the Chief NextGen Officer and appointed a new Assistant Administrator for NextGen responsible for leading the modernization of the National Airspace System. The interagency coordination requirement became the responsibility of the FAA Assistant Administrator for NextGen.

Under the Consolidated Appropriations Act of 2014, Congress eliminated funding for the JPDO.[9] As a result of the elimination of the funding, the JPDO was dissolved, and the Interagency Planning Office for NextGen was established by the FAA Chief NextGen Officer and the Assistant Administrator for NextGen in May of 2014. The IPO was established to ensure the engagement and ongoing collaboration among the designated partner agencies to improve efficiencies in planning for research and development, and to coordinate NextGen strategic issues in collaboration with designated interagency partners. The reauthorization of 2018 eliminated the role of the Chief NextGen Officer but the IPO still exists to support the cross agency coordination.

[9] Per Congressional Record 160: 9 (January 15, 2014) p. H1188, "Joint Planning and Development Office.—The agreement does not include funding for the Joint Planning and Development Office. Funding is provided in the operations account to absorb personnel and activities from this office into the 'NextGen and operations planning' activity" (see https://www.congress.gov/113/crec/2014/01/15/CREC-2014-01-15.house-bk2).

3

Policy

This section describes the U.S. policy for providing each Federal PNT system identified in this document.

3.1 General

The Federal Government recognizes that PNT systems and related technology are integral to U.S. national security, economic growth, critical infrastructure operations, transportation safety, and homeland security, and are an essential element of the worldwide economic infrastructure. A goal of the USG is to provide reliable PNT services to the public in the most cost-effective manner possible.

Under 10 U.S.C. 2281 (Ref. 3), paragraph (b), DoD is required to provide for the sustainment and operation of the GPS SPS for peaceful civil, commercial, and scientific uses, on a continuous worldwide basis, free of direct user fees.

Under 49 U.S.C. 44505 (Ref. 8), FAA must operate a common aviation system that meets the "needs for safe and efficient navigation and traffic control of civil and military aviation, except for the needs of the armed forces that are peculiar to air warfare and primarily of military concern." To meet these aviation user requirements the "Administrator of the FAA shall…select systems…that will best serve those needs and promote maximum coordination of air traffic control and air defense systems."

Under 14 U.S.C. 541 (Ref. 10), USCG "may establish, maintain, and operate (1) aids to maritime navigation required to serve the needs of the armed forces or of the commerce of the United States." By request of the DoD, USCG can operate aids to air navigation and electronic aids to navigation systems "…required to serve the needs of the armed forces of the United States peculiar to warfare and primarily of military concern."

Title 32, CFR Part 245, "Plan for the Emergency Security Control of Air Traffic (ESCAT)" (Ref. 27) outlines the responsibilities of the DoD, DOT, and DHS in planning for ESCAT, including "the process for implementation of measures for mitigation of hostile use of navigational aid (NAVAID) signals, when required…." In accordance with paragraph 245.12 (e) of Title 32 (Ref. 27) and NSPD-39 (Ref. 13) (superseded by Space Policy Directive-7, issued by President Trump on January 15, 2021) (Ref. 70), the DoD Policy Board on Federal Aviation (PBFA), when required, will facilitate an agreement between DoD and other Departments and Agencies to mitigate the hostile use of NAVAID signals within CONUS.

PNT services have historically been provided from ground-based systems. As the full civil potential of GPS services and its augmentations are implemented, the demand for services provided by other federally-provided PNT systems is expected to decrease. The USG will rationalize non-GPS-based PNT services as needed to reduce infrastructure where appropriate while ensuring resiliency during GPS outages.

Providing a resilient navigation infrastructure may require increasing some non-GPS-based PNT systems while decreasing others to ensure safety and operational efficiency, with the exception of those systems required, in accordance with PPD-2, to maintain PNT resilience in the event of GPS interference. It is a policy objective of the USG not to be critically dependent upon a single system for PNT. Therefore, the USG will promote the commercial availability of sufficient complementary and back up PNT capabilities to meet: (1) growing national, homeland, and economic safety and security requirements, (2) civil requirements, and (3) commercial and scientific demands.

Operational, economic, safety, and security considerations will dictate the need for the required performance (accuracy, availability, integrity, continuity, and coverage) of complementary PNT systems. While some operations may be conducted safely using a single, resilient PNT system (e.g., DMEs, TACANs, oscillators), it is Federal policy to provide redundant PNT services where required. Backups to GPS for safety-of-life navigation applications, or other critical applications, can be other dissimilar PNT systems, or operational procedures, or a combination of these systems and procedures, to form a safe and effective backup. The FAA conducted a review of Alternative PNT (APNT) capabilities that support communication, navigation, and surveillance applications in the event of a loss of GPS service. Backups to GPS for timing applications can be a highly accurate crystal oscillator, atomic clock, a communications link to a resilient and trusted timing source that is traceable to UTC, or other systems that meets the requirements for redundant timing.

When the benefits (including safety benefits derived by the users of a PNT service) or additional costs to other USG agencies (including system modification costs incurred by discontinuance of PNT services) are outweighed by its sustainment cost, by policy, the Federal Government can no longer continue to provide that service or capability. Divestment criteria are established so that when usage falls below the sustainment threshold, the service or capability is offered to State, Tribal, Territorial, local, or other non-Federal service providers prior to decommissioning. The Federal Government uses rulemaking and non-rulemaking processes to establish policy decisions for discontinuation of navigation systems to ensure all interested parties are provided an opportunity to comment prior to final decisions. For example, the FAA is pursuing efforts to rationalize the conventional navigation infrastructure while providing a resilient backup to GPS, as part of an overall resilient navigation service.

In 2015, the FAA approved a program to transition the service provided by VHF omnidirectional range (VOR) to a minimum operational network (MON). The VOR MON Program supports the FAA's transition from defining airways, routes, and procedures using VORs and other legacy navigation aids to performance-based navigation (PBN). The FAA is also augmenting the distance measuring equipment (DME) network to improve coverage and availability to enable aircraft to continue PBN operations during GNSS outages in high volume airspace. A Final Policy Statement for the VOR MON was published in the Federal Register in 2016. A suitable transition period is established prior to divestment, based on factors such as user equipment availability, radio spectrum transition issues, cost, user acceptance, budgetary considerations, and the public interest. International commitments will affect certain types and levels of PNT services provided by the Federal Government to ensure interoperability with international users.

PNT systems established primarily for safety of transportation and national defense also provide significant benefits to other civil, commercial, and scientific users. In recognition of this, the USG will consider the needs of these users before making any changes to the operation of PNT systems.

The U.S. National Policy is that all PNT systems operated for public use by the USG will remain available for peaceful use subject to direction by the President in the event of a war or threat to national security. Operating agencies may cease operations or change characteristics and signal formats of PNT systems during a dire national emergency. All communications links, including those used to transmit differential GPS corrections and other GPS augmentations, are also subject to the direction of the President.

On February 12, 2020, the President signed Executive Order (EO) 13905, Strengthening National Resilience Through the Responsible Use of PNT Services (Ref. 72). To strengthen national resilience, the Federal Government must foster the responsible use of PNT services by critical infrastructure (CI) owners and operators to ensure that disruption or manipulation of PNT services does not undermine the reliable and efficient functioning of its critical infrastructure. The Federal Government must increase the Nation's awareness of the extent to which critical infrastructure depends on, or is enhanced by, PNT services, and it must ensure critical infrastructure can withstand disruption or manipulation of PNT services. Under this directive, Sector Risk Management Agencies will engage with owners and operators of CI to take a deliberate, risk-informed vulnerability assessment in their use of PNT services, including their acquisition, integration, and deployment.

3.1.1 Timing Policy

In 1975, the 15th Conférence Générale des Poids et Mesures (CGPM), composed of representatives of signatory nations to the Treaty of the Meter, including the United States, "strongly endorsed" the use of UTC, Coordinated Universal Time, as the basis of civil time throughout the world. In 2007, the United States formally adopted this recommendation. Congress passed America Creating Opportunities to Meaningfully Promote Excellence in Technology, Education, and Science (COMPETES) Act (Public Law 110–69, 121 Stat. 572 *et seq*.) (Ref. 28), which among many other things redefined Standard Time in the United States to be UTC with appropriate hour offsets for the various U.S. time zones. The COMPETES Act went on to define UTC in the U.S. as, "the time scale maintained through the [CGPM] and interpreted or modified for the United States by the Secretary of Commerce in coordination with the Secretary of the Navy." NIST and USNO provide advice and technical support to these secretaries, respectively, and act on delegated authority to maintain and disseminate UTC as official U.S. time. NIST and USNO have a Memorandum of Agreement that coordinates their programs.

In general, USNO focuses on meeting requirements of DoD systems and associated non-military systems, while NIST provides services to the private sector. In accordance with CJCSI6130.01 (Ref. 1), any DoD information that refers to time must be able to provide that time in terms of the standard temporal reference defined by UTC as maintained by the USNO Master Clock, which is the standard for military systems. Nonetheless, both organizations agree that UTC, UTC(NIST), and UTC(USNO) are equivalent at the 50 nanosecond level of accuracy. Military and civil users with timing requirements tighter than 50 nanoseconds are advised to contact USNO and NIST respectively for technical support.

3.2 Space-Based PNT Policy

3.2.1 Executive Policy

On January 15, 2021, the President issued Space Policy Directive 7, The United States Space-Based Positioning, Navigation, and Timing Policy (Ref. 70) that establishes implementation actions and guidance for United

States space-based positioning, navigation, and timing (PNT) programs and activities for United States national and homeland security, civil, commercial, and scientific purposes. This policy supersedes National Security Presidential Directive-39 (NSPD-39) of December 15, 2004 (United States Space-Based Positioning, Navigation, and Timing Policy). SPD-7 complements the guidance set forth in Executive Order 13905 of February 12, 2020 (Strengthening National Resilience through Responsible Use of Positioning, Navigation, and Timing Services), and the cross sector guidance for Global Navigation Satellite Systems (GNSS) included in the December 9, 2020, National Space Policy. In addition, Space Policy Directive 7 provides guidance for:

- sustainment and modernization of the Global Positioning System (GPS) and federally-developed, owned, and operated systems used to augment or otherwise improve GPS;
- implementation and operation of capabilities to protect United States and allied access to and use of GPS for national, homeland, and economic security, and to deny adversaries hostile applications use of United States space-based PNT services;
- develop and validate requirements and a funding strategy to implement data and signal authentication of civil GPS and wide area augmentations for homeland security and public safety purposes; and
- United States participation in international cooperative initiatives regarding foreign space-based PNT services and foreign use of GPS and its augmentations.
    - The United States will continue to encourage the development of foreign space-based PNT services based on GPS and their responsible use in non-military applications with allied and likeminded nations.
    - Use of multiple, varied PNT services can result in better performance in terms of user accuracy, availability, and resilience. However, the United States Government does not assure the reliability or authenticity of foreign PNT services.
    - Although foreign space-based PNT services may be used to complement civil GPS service, receiver manufacturers should continue to improve security, integrity, and resilience in the face of growing cyber threats.[10]

[10] FCC Title 47, Code of Federal Regulations Part 25.115 (b)(9)(i): Except as set forth in paragraph (b)(9)(ii) of this section, receive-only earth stations (i.e., all mobile and fixed receivers terrestrial and non-terrestrial)

Guidance provided in earlier policies are listed below.

The National Space Policy (Ref. 14), issued in 2010, provided high-level guidance regarding space-based PNT. The policy called for continued U.S. leadership in the service, provision, and use of GNSS. It reaffirmed existing U.S. commitments to 1) provide continuous, worldwide access to civil GPS, free of direct user fees; 2) pursue international GNSS cooperation; to operate and maintain GPS to meet published standards; and 3) take steps to detect and mitigate GPS interference. In addition, the National Space Policy provided guidance to:

- seek to protect U.S. global access to, and operation in, the radiofrequency spectrum and related orbital assignments required to support the use of space by the United States Government, its allies, and U.S. commercial users;

- identify impacts to government space systems prior to reallocating spectrum for commercial, Federal, or shared use;

- enhance capabilities and techniques, in cooperation with civil, commercial, and foreign partners, to identify, locate, and attribute sources of radio frequency interference, and take necessary measures to sustain the radiofrequency environment in which critical U.S. space systems operate.

The U.S. Space-Based PNT Policy (Ref. 13), issued in 2004, established guidance and implementation actions for space-based PNT programs, augmentations, and activities for U.S. national and homeland security, civil, scientific, and commercial purposes. This policy provided guidance for:

- development, acquisition, operation, sustainment, and modernization of GPS and U.S.-developed, owned and/or operated systems used to augment or otherwise improve the GPS and/or other space-based PNT signals;

- development, deployment, sustainment, and modernization of capabilities to protect U.S. and allied access to and use of GPS for national, homeland, and economic security, and to deny adversaries access to space-based PNT services, as required in times of conflict; and

- foreign access to the GPS and USG augmentations, and international cooperation with foreign space-based PNT services, including augmentations.

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operating (e.g., receiving and/or transmitting) with non-U.S. licensed space stations must file an FCC Form 312 requesting a license or modification to operate such station. https://www.ecfr.gov/cgi-bin/text-idx?node=se47.2.25_1115&rgn=div8

Over the past three decades, GPS has grown into a global utility providing multi-use services that are integral to U.S. national security, economic growth, transportation safety, and homeland security, and that are an essential element of the worldwide economic infrastructure. In the "Statement by the President Regarding the United States' Decision to Stop Degrading Global Positioning System Accuracy of May 1, 2000" (Ref. 29), the U.S. recognized the increasing importance of GPS to civil and commercial users by discontinuing the deliberate degradation of accuracy for non-military signals, known as selective availability (SA).

Since that time, commercial and civil applications of GPS have continued to multiply, and their importance has increased significantly. Services dependent on GPS information are now an engine for economic growth, enhancing economic development, and improving safety of life, and the system is a key component of multiple sectors of U.S. critical infrastructure. In September 2007, the USG announced its decision to procure the future generation of GPS satellites, known as GPS III, without the SA feature. In doing this, the USG made the policy decision of 2000 permanent and eliminated a source of uncertainty in GPS performance that had been of concern to civil GPS users worldwide for some time.

While the growth in civil and commercial applications continues, PNT information provided by GPS remains critical to U.S. national security. While the continuing growth of services based on the GPS presents opportunities, it can also bring risks and threats to the U.S. national, homeland, and economic security. The widespread and growing dependence on GPS of military, civil, and commercial systems and infrastructures has made many of these systems inherently vulnerable to unintentional interruption and likely targets of intentional attack on PNT services. Therefore, the U.S. must continue to improve and maintain GPS, augmentations, and backup capabilities to meet growing national, homeland, and economic, safety, and security requirements, civil requirements, and commercial and scientific demands.

The U.S. will continue to maintain space-based PNT services, and augmentation, backup, and service denial capabilities that: (1) provide uninterrupted availability of PNT services; (2) meet growing national, homeland, and economic, safety, and security requirements, civil requirements, and commercial and scientific demands; (3) remain the pre-eminent military space-based PNT service; (4) continue to provide civil services that exceed or are competitive with foreign civil space-based PNT services and augmentation systems; (5) retain essential components of internationally accepted PNT services; and (6) promote U.S. technological leadership in applications involving space-based PNT services. To achieve this goal, the USG will:

- provide uninterrupted access to U.S. space-based, global, precise PNT services for U.S. and allied national security systems and capabilities through GPS, without being dependent on foreign PNT services;

- provide civil, space-based PNT services on a continuous, worldwide basis, free of direct user fees for civil, commercial, and scientific uses, and for homeland security, through GPS and its augmentations, and provide open, free access to information necessary to develop and build equipment to use these services;
- improve capabilities to deny hostile use of any space-based PNT services, without unduly disrupting civil and commercial access to civil PNT services outside an area of military operations, or for homeland security purposes;
- train the combatant forces to effectively operate during periods of GPS denial or degradation;
- improve the performance of space-based PNT services, including more robust resistance to interference for, and consistent with, U.S. and allied national security purposes, homeland security, and civil, commercial, and scientific users worldwide;
- promote strategies to ensure resilient PNT in support of U.S. critical infrastructure operations per PPD-21 (Ref. 31);
- encourage foreign development of PNT services and systems based on GPS. Seek to ensure that foreign space-based PNT systems are interoperable with the civil services of GPS and its augmentations in order to benefit civil, commercial, and scientific users worldwide. At a minimum, seek to ensure that foreign systems are compatible with GPS and its augmentations and address mutual security concerns with foreign providers to prevent hostile use of space-based PNT services; and
- promote the use of U.S. space-based PNT services and capabilities for applications at the Federal, State, Tribal, Territorial, and local level, to the maximum practical extent.

3.2.2 GPS Service

3.2.2.1 Standard Positioning Service (SPS)

The USG has made the GPS SPS available for worldwide use by the international community. The maritime community has documented this commitment in IMO Assembly Resolution A.953(23), World-wide Radionavigation System, adopted February 26, 2004 (Ref. 30). The aviation community has documented this commitment at the ICAO Tenth Air Navigation Conference and at the 29th ICAO Assembly. The USG has made clear that it intends to make the GPS SPS available for the foreseeable future, on a continuous, worldwide basis, and free of direct user fees, subject to the availability of funds as required by U.S. law. This service is being made available on a nondiscriminatory basis to all users at the performance levels specified in the GPS SPS PS (Ref. 7474) of version April 22, 2020, which includes the first performance standards for L1 C/A, L2C, L5, and their combinations. The USG will take all necessary measures for the foreseeable future to maintain the integrity, reliability, and availability of the GPS SPS. Although the USG may examine future improvements to SPS, appropriate consideration will be provided to all civil users for transition planning.

3.2.2.2 Protected Positioning Service (PPS)

The USG has made available uninterrupted global access to the PPS of the GPS to authorized U.S. users, and authorized allied military users.

3.2.3 Navigation Warfare (NAVWAR)

With SPD-7 (Ref. 70), the President directed that the Secretary of Defense shall:

- Improve NAVWAR capabilities to deny hostile use of United States Government space-based PNT services, without unduly disrupting civil and commercial access to civil PNT services outside an area of military or homeland security operations;
- Develop, acquire, operate, realistically test, evaluate, and maintain NAVWAR capabilities and other capabilities required to:
    - Effectively utilize GPS services in the event of an adversary or other jamming, disruption, or manipulation;
    - Develop effective measures to counter adversary efforts to deny, disrupt, or manipulate PNT services;
    - Identify, locate, and mitigate, in coordination with other agencies, as appropriate, any intentional disruption or manipulation that adversely affects use of GPS for military operations;
- Ensure the earliest operational availability for modernized military and NAVWAR capabilities.

NAVWAR is defined as the deliberate defensive and offensive action to assure and prevent positioning, navigation, and timing information through coordinated employment of space, cyberspace, and electronic warfare. Desired effects are generated through the coordinated employment of components within information operations, space operations, and cyberspace operations, including electronic warfare, space control, space force enhancement, and computer network operations.

The DoD NAVWAR program exists to ensure that the U.S. retains a military advantage in the area of conflict by protecting authorized use of GPS; preventing the hostile use of GPS, its augmentations, or any other PNT service; and preserving peaceful civil GPS use outside an area of military operations. The NAVWAR program requires recurring testing, which may impact the civil use of GPS. The DoD works closely with the FAA to lessen the impact of NAVWAR testing to the NAS and maintain an acceptable level of NAS efficiency and capacity, consistent with military requirements to train and maintain effective combatant forces for the nation.

NAVWAR EA TT&E activities that could impact GPS must be coordinated within the DoD and other Federal agencies. CJCSM 3212.03 (Ref. 20) gives guidance on how to request and gain approval to conduct these EA TT&E activities.

3.2.4 GPS Time and Frequency

GPS provides global access to fully synchronized precise time and frequency. Each GPS satellite uses an atomic clock that provides a stable time and frequency reference signal that is the foundation for the GPS broadcast signal. GPS receivers process the satellite-broadcast signals and effectively synchronize themselves to GPS time. Additional data in the GPS broadcast navigation message allows receivers to relate the GPS time to UTC (USNO). This enables users to determine the UTC time to within 100 billionths of a second (100 ns) and provide a highly stable and accurate frequency reference without an atomic clock.

Precise time and frequency are crucial to a variety of economic activities around the world. Communication systems, electrical power grids, and financial networks all rely on precision timing for synchronization and operational efficiency. The free availability of GPS time and frequency services have enabled cost savings for companies that depend on precise time and has led to significant advances in capability.

USNO provides GPS with the underlying UTC timing reference. USNO operates a primary and backup Master Clock system from its headquarters in Washington, DC and the Alternate Master Clock facility co-located with the GPS Master Control Station (MCS) at Schriever Air Force Base in Colorado. The USNO Master Clock system is made up of an ensemble of more than 100 precise atomic clocks that are fully traceable to national and international standards for UTC timing. USNO uses an ensemble of specialized GPS timing monitor station receivers to continuously monitor the GPS signal and provide the GPS MCS with these precise timing data. Details about obtaining calibration of GPS timing receivers and traceability to UTC can be found at https://www.usno.navy.mil/USNO/time.

3.2.5 GPS Signal Monitoring

GPS PPS signals are continuously monitored by satellite operators at the GPS MCS at Schriever Air Force Base in near-real time, 24-hours a day. Although there is no continuous monitoring of SPS performance, the PPS monitoring is effective in detecting most anomalies in service, including user range errors, providing satellite operators the necessary information to take action and protect users from anomalous signals. To perform this monitoring, the GPS control segment maintains six monitor stations, which are currently combined with 11 NGA monitor stations, providing 100 percent global coverage of GPS satellites. NGA generates precise, post-fit GPS orbits, as well as predicted orbits, for DoD. The combined NGA-USAF GPS tracking network is also used to define the WGS 84 reference frame, the standard geodetic reference system for GPS and for all DoD positioning, navigation, and geospatial products. GPS data and products from NGA can be found at https://www.nga.mil/ProductsServices/Pages/default.aspx. https://earth-info.nga.mil/GandG/update/index.php?dir=gnss&action=gnss

The executive branch vetted the Civil Signal Monitoring Specification (CMPS, 3rd Ed.) to define the monitoring requirements for legacy and modernized GPS signals. The complete set of monitoring functions for ensuring comprehensive CMPS requirements will be implemented by a combination of the GPS control segment in the OCX program and the DOT Civil Signal Monitoring System (CSMS).

3.2.6.1 Civil Signals

In addition to the L1 coarse/acquisition (C/A) signal, the USG is introducing three additional coded signals (L1C, L2C, and L5) to support future civil applications.

The performance specifications in the current SPS PS apply to users of the L1 C/A, L2C, and L5 signals. The SPS PS states L1 C/A standards for accuracy, integrity, continuity, and availability as the L1 C/A signal is at full operational capability. The SPS PS states L2C and L5 (or any combination of those signals) standards only for accuracy and integrity as those signals are not yet at full operational capability. Also, performance standards are being developed to incorporate the modernized civil signals and future editions will be published as operational capability is achieved.

3.2.6.2 Military Signals

Currently, authorized users with keyed GPS receivers are provided access to PPS (i.e., P(Y) code) on L1 and L2. These will be supplemented in the future by M-Code, the next-generation military GPS signal. The first GPS Block IIR-M satellite began broadcasting M-Code in September 2006. M-Code will significantly improve exclusivity of access because, in addition to being encrypted, it will be spectrally separated from civilian signals and other radionavigation satellite service signals, enhancing U.S. NAVWAR operations. Military GPS receivers, when tracking the encrypted military signals, are much more resistant to interference than commercial GPS equipment. The newest generations of military GPS receivers are even more resistant to interference; however, future improvements in signal availability and receiver performance will continue to be necessary.

3.2.7 Military Use of GPS Civil Signals

DoD does not have an operational requirement to use the GPS civil signals designated L1C, L2C, and L5. Since dual equipage is not fiscally practical, type approval of military aviation receivers is required to eliminate the need for civil GPS equipage on military aircraft. This will provide an enhanced capability to span the operational environment for military aviation – from flight in civil airspace in peacetime to combat operations worldwide. Commercial operators of Civil Reserve Air Fleet (CRAF) and tactical military airframes may elect to equip with L5- and/or WAAS-capable devices where operational needs provide a demonstrated benefit.

DoD is performing a type approval of military aviation receivers for use in the NAS and in international airspace. This approval is being done in accordance with civil and/or military aviation standards to an equivalent level of safety and performance, while maintaining the capability to use military signals. DoD will also work with the military establishments of our international allies to seek approval for use of these receivers in foreign airspace.

3.2.8 Discontinuation of Codeless and Semi-Codeless GPS Access[11]

The USG commits to maintaining the existing GPS L1 C/A, L1 P(Y), L2C, and L2 P(Y) signal characteristics that enable codeless and semi-codeless GPS access until at least two years after there are 24 operational satellites meeting the following criteria: (1) Broadcasting L5 with Healthy setting as defined in the 2020 SPS PS, (2) assigned PRNs in the range 1 through 32, and (3) located in a primary orbital plane slot as defined the 2020 SPS PS. Barring a national security requirement, the USG does not intend to change these signal characteristics before then. The availability of 24 satellites broadcasting the L5 signal is estimated to occur in 2029. Maintaining the legacy signal characteristics for the stated period-of-time will allow for the orderly and systematic transition of users of semi-codeless and codeless receiving equipment to the use of equipment using modernized civil-coded signals. It is expected that 24 operational satellites broadcasting L2C will be available by 2021, with the corresponding ground segment control capability available by 2023, enabling transition to L2C by 2023. Civilian users of GPS are encouraged to start their planning for transition now.

[11] This paragraph supersedes the previously announced commitment (73 Fed. Reg. 54792) to maintain such signal characteristics through December 31, 2020.

3.2.9 GPS Augmentation

As of June 30, 2020, all NDGPS service has been discontinued in accordance with the NDGPS Federal Register Notice USCG-2018-0133. With the rollout of the new GPS III satellites combined with the permanent termination of Selective Availability, DGPS is no longer deemed a necessary augmentation.

In 2007, the FAA Administrator reaffirmed the U.S. Government's commitment to provide the GPS SPS for aviation throughout the world and to provide the WAAS service within its prescribed service volume. The U.S. Government plans to take all necessary measures for the foreseeable future to maintain the integrity, reliability, and availability of the GPS SPS and WAAS service, and expects to provide at least six 'years' notice prior to any termination of such operations or elimination of such services.

3.2.10 Vulnerability of GPS for Critical Infrastructure

PNT data derived from GPS is used throughout the U.S. economy, including in critical infrastructure operations. SPD -7 (Ref. 70) states that the continuing growth of services based on the Global Positioning System presents opportunities, as well as risks, and threats to U.S. national, homeland, and economic security. The widespread and growing dependence on GPS by military, civil, and commercial applications, systems, and infrastructure make the performance of many of these systems inherently vulnerable if disruption or manipulation of GPS signals were to occur. GPS users must plan for potential signal loss and take reasonable steps to verify or authenticate the integrity of the received GPS data and ranging signal, especially in applications where even small degradations can result in loss of life. In addition, whether designed for military capabilities or not, signals from PNT services and their augmentations provide inherent capabilities that may be used by adversaries, including enemy military forces and terrorist groups. As the coordinator of the overall Federal effort to promote critical infrastructure security and resilience, DHS will work with the Federal departments and agencies identified as Sector Risk Management Agencies (SRMAs) of the sixteen critical infrastructure sectors to promote actions to enhance the resilience of operations that rely on accurate PNT.

GPS and all GNSS signals are vulnerable to disruption or manipulation. As part of the responsible use of PNT concepts outlined in EO 13905, GPS users should consider use of GPS receivers designed to mitigate the effects of jamming and spoofing of the GPS/GNSS signals. The DHS Conformance Framework provides initial guidance to equipment manufacturers regarding expected performance parameters. Standards development organizations are expected to publish standards which describe end user equipment performance parameters by the end of 2023.

Under EO 13905, DHS in coordination with the heads of SRMAs, is working to develop plans to test the vulnerabilities of critical infrastructure systems, networks, and assets in the event of disruption and manipulation of PNT services. The results of the tests carried out under that plan will be used to inform updates to the PNT profiles. This multi-year process will be based on available resources, including funding. The PNT profiles will enable the public and private sectors to identify systems, networks, and assets dependent on PNT services; identify appropriate PNT services; detect the disruption and manipulation of PNT services; and manage the associated risks to the systems, networks, and assets dependent on PNT services.

Under EO 13905 (Ref. 72), the Secretary of Commerce, in coordination with SRMAs, must develop and make available a PNT profile for the NIST Cybersecurity Framework (https://www.nist.gov/cyberframework). This responsibility is delegated to NIST. The PNT profile assists public and private sector users to manage cybersecurity risks to systems, networks, and assets that use PNT services. It is intended to be broadly applicable, with SRMAs creating tailored profiles for specific needs. The NIST profile (NISTIR 8323 Foundational PNT Profile: Applying the Cybersecurity Framework for the Responsible Use of Positioning, Navigation and Timing (PNT) Services) will be reviewed and updated periodically (Ref. 75 and Ref. 76).

3.2.11 Interference Detection and Mitigation Plan

SPD-7 (Ref. 70) defines responsibilities for locating and resolving interference. Additionally, National Space Policy (Ref. 14) states that the U.S. shall invest in domestic capabilities and support international activities to detect, mitigate, and increase resiliency to harmful interference to GPS, and identify and implement, as necessary and appropriate, redundant and backup systems or approaches for critical infrastructure and mission-essential functions.

In support of the U.S. National Space Policy, the Purposeful Interference Response Team (PIRT) was chartered to facilitate rapid reporting, evaluation, and resolution of purposeful interference events involving USG and commercial space systems, services, capabilities, or interests. The PIRT Executive Committee established a Federal interagency working group to develop and codify mutual and individual responsibilities for real-time information sharing and support to a coordinated USG response to interference affecting GPS-provided PNT services within the homeland in order to better protect critical national infrastructure and interests.

DHS developed and published the Positioning, Navigation, and Timing, Interference Detection and Mitigation (IDM) Plan (August 20, 2007) (Ref. 32), and the Interference Detection and Mitigation (IDM) Plan Implementation Strategy (January 2008) (Ref. 33) to address these concerns. These documents provide a framework and guidance from which to execute the responsibilities required to fulfill the directives from NSPD-39 (Ref. 13) (superseded by Space Policy Directive-7, issued by President Trump on January 15, 2021) (Ref. 70).

On January 19, 2021, the FCC denied a request to stay its unanimous decision to authorize Ligado Networks LLC to deploy a low-power terrestrial nationwide network using portions of its licensed spectrum. As a result of this action, the Strategic Planning for Potential Interference (SPPI) effort will take place.

Work being planned under the Strategic Planning for Potential Interference (SPPI) from Ligado effort includes:

- Development of GPS equipment interference metrics and equipment identification;
- Validation of metrics with laboratory testing;
- Development of field monitoring capabilities and integration into test vehicles;
- Determination and dissemination of locations of active Ligado transmitters to GPS users; and
- Pre- and post-Ligado field deployments and associated data characterizations.

Planned efforts to detect and mitigate GPS interference related to SPD-7:

- Improve NAVWAR capabilities to deny hostile use of U.S. Government space-based PNT services, without unduly disrupting civil and commercial access to civil PNT services outside an area of military or homeland security operations:
  - Develop, acquire, operate, realistically test, evaluate, and maintain NAVWAR capabilities and other capabilities required to;

  - Effectively utilize GPS services in the event of an adversary or other jamming, disruption, or manipulation;
  - Develop effective measures to counter adversary efforts to deny, disrupt, or manipulate PNT services;
  - Identify, locate, and mitigate, in coordination with other agencies, as appropriate, any intentional disruption or manipulation that adversely affects use of GPS for military operations.

- Improve the performance of U.S. space-based PNT services, including developing more robust signals that are more resistant to disruptions and manipulations consistent with United States and allied national security, homeland security, and civil purposes;

- Improve the cybersecurity of GPS, its augmentations, and U.S. Government-owned GPS-enabled devices, and foster private sector adoption of cyber-secure GPS enabled systems through system upgrades and incorporation of cybersecurity principles for space systems, interface specifications, and other guidance that prescribes cybersecurity for user equipment;

- Protect the spectrum environment that is currently used by GPS and its augmentations, and work with U.S. industry to investigate additional areas of the radio spectrum which could increase GPS and PNT resilience;

- Invest in domestic capabilities and support international activities to detect, mitigate, and increase resilience to harmful disruption or manipulation of GPS, and identify and implement, as appropriate, alternative sources of PNT for critical infrastructure, key resources, and mission-essential functions;

- Maintain GPS and its augmentations for use by U.S. critical infrastructure to enhance safety of life functions and operational efficiency, consistent with PPD-21;

- Engage with international GNSS providers to ensure compatibility, encourage interoperability with likeminded nations, promote transparency in civil service provision, and enable market access for U.S. industry. Encourage foreign development of PNT services and systems based on GPS and the inclusion of GPS as an essential element in systems that integrate multiple PNT services. At a minimum, seek to ensure that all foreign systems are compatible with GPS and its augmentations, that they do not interfere with GPS military and civil signals, and that mutual security concerns are addressed to prevent hostile use of U.S. space-based PNT services;

- Promote the responsible use of U.S. space-based PNT services and capabilities for applications at the Federal, State, Tribal, Territorial, and local level, consistent with Executive Order 13905; and
- Promote U.S. technological leadership in the provision of space-based PNT services and in the development of secure and resilient end user equipment.

Due to the unique safety requirements of aviation, the FAA is implementing the interference direction finding (IDF) system to achieve faster response to interference. IDF will be integrated with DHS IDM initiatives and will help quickly reduce and mitigate the impacts of RFI on present and future NAS radio services. New capabilities, such as GPS and related augmentations, aeronautical data link systems, and ADS-B ground and airborne segments, will require enhanced agency preparedness and resolution response on radio frequency and electromagnetic interference detection capabilities. IDF program requirements include:

- developing the ability to detect, locate, and mitigate the impact of both intentional and unintentional interference on NAS elements and capacity; and
- scoping a robust but affordable program that will prevent a loss in the projected system gains achieved by the new NAS systems, while assuring that end users benefit from the significant investments being made.

Executive Order 13905 (Ref. 72) instructed the Department of Homeland Security, in coordination with the heads of SRMAs, to develop a plan to test the vulnerabilities of critical infrastructure systems, networks, and assets in the event of disruption and manipulation of PNT services. The Vulnerability Test Plan, completed in February 2021, identified the systems, networks, and assets of the critical infrastructures to be tested. The results of the tests carried out under the Vulnerability Test Plan will be used to inform updates to the PNT profiles.

3.2.12 GPS Backup/Complementary PNT

The USG recognizes the benefits of complementary PNT capabilities for critical transportation, homeland security, and other civil and commercial infrastructure applications within the United States.

Research into potential complementary PNT capabilities has included cooperative research and development agreements (CRADA) looking at technologies capable of delivering precision PNT data. This includes an examination of providing precision time over fiber optic cables and a study of alternate PNT capabilities.

Per section 1618 of the National Defense Authorization Act for Fiscal Year 2017 (Public Law 114–328) (FY18 NDAA), DHS and DOT have identified critical infrastructure needs and conducted an analysis of alternatives assessment of various GPS complementary capabilities for domestic critical infrastructure. DoD submitted its report to Congress on these issues in December 2017.

"Section 1618" of the Fiscal Year (FY) 2017 National Defense Authorization Act (NDAA) (P.L. 114-328; December 23, 2016) requires the covered Secretaries shall jointly conduct a study to assess and identify the technology-neutral requirements to backup and complement the positioning, navigation, and timing capabilities of the Global Positioning System for national security and critical infrastructure. The Homeland Security Operational Analysis Center (HSOAC) conducted an in- depth assessment of PNT systems currently used in the United States for DHS and DOT. This report[12] is a summary and analysis of that assessment and provides recommendations for the Federal Government's next steps in efforts to increase the resilience of US Critical Infrastructure to disruption of GPS services.

Per section 1606 of the National Defense Authorization Act for Fiscal Year 2018 (Public Law 115–91), DHS and DOT have conducted a GPS backup and complementary PNT demonstration. The demonstration was conducted in March 2020 and demonstrated six different technologies across eleven different commercial vendors. The demonstration report was published in January 2021 along with a set of recommended next steps for developing system requirements for PNT functions and associated standards, test procedures, and monitoring capabilities for alternative PNT services used by critical infrastructure and safety critical systems.

Based on the requirements of the FY18 NDAA, the DOT Office of the Assistant Secretary for Research and Technology (OST-R) Volpe National Transportation Systems Center (Volpe Center) conducted field demonstrations of candidate PNT technologies that could offer complementary service in the event of GPS disruptions. The purpose of the demonstration was to gather information on PNT technologies at a high

[12] Report on Positioning, Navigation, and Timing (PNT) Backup and Complementary Capabilities to the Global Positioning System (GPS) National Defense Authorization Act Fiscal Year 2017 Report to Congress: PNT Requirements, and Analysis of Alternatives April 8, 2020 https://www.cisa.gov/sites/default/files/publications/report-on-pnt-backup-complementary-capabilities-to-gps_508_0.pdf

technology readiness level (TRL) that can work in the absence of GPS, and identify alternate and complementary systems.

Ongoing input and feedback from stakeholders before, during, and after the demonstration were recognized as essential from the outset of the demonstration. DOT obtained input from external stakeholders regarding PNT technologies at a high level of technical readiness to inform the demonstration. The demonstration planning process also allowed repeated opportunities for DOT to receive input and feedback from the participating PNT industry vendors. These resulted in adjustments to the demonstration implementation that improved the conditions under which the technologies could exhibit their positioning and/or timing performance capabilities.

The Volpe Center, through a competitive acquisition process, selected 11 candidate technologies to demonstrate positioning and/or timing functions in the absence of GPS at two demonstration sites:

- Two vendors demonstrated low Earth orbit satellite PNT technologies: one L-band, one S-band.
- Two vendors demonstrated fiber-optic timing systems, both based on the White Rabbit Precision Time Protocol (PTP) technology.
- One vendor demonstrated localized database map matching database, inertial measurement unit (IMU), and ultra-wideband (UWB) technologies.
- Six vendors demonstrated terrestrial RF PNT technologies across low-frequency (LF), medium-frequency (MF), ultra-high frequency (UHF), and Wi-Fi/802.11 spectrum bands.

Five of the technologies were demonstrated at Joint Base Cape Cod (JBCC) and six were demonstrated at NASA Langley Research Center (LaRC) in March 2020. This demonstration was a scenario-based implementation consisting of a series of scenarios modeled on Critical Infrastructure use cases under various operating conditions.

Based on vendor participation in the positioning and/or timing scenarios, the results of the demonstration were analyzed to provide 14 measures of effectiveness (MoEs), structured as rubrics. “Rubric” as used in this report means a scoring guide that sets defined levels for use in assessment and scoring. The 14 MoEs, along with their respective rubrics, were:

MoE-1: Technical Readiness–System (TRL 6-9)

MoE-2: Technical Readiness–User Equipment (TRL 6-9)

MoE-3: Timing and Positioning Accuracy as residual error (m, ns)

MoE-4: Spectrum Protection (protected, owned, leased, shared)

MoE-5: Service Deployment Effort (low, medium, high)

MoE-6: Service Coverage per Unit of Infrastructure as number of transmitters per area covered (units/km2)

MoE-7: Service Synchronization (UTC, cascade, self-synchronizing)

MoE-8: PNT Signal Robustness (strong, weak)

MoE-9: Service Resilience (fail-safe, -over, -soft, -hard)

MoE-10: PNT Distribution Mode (terrestrial RF, orbital RF, fiber, database)

MoE-11: Service Interoperability (high, low)

MoE-12: PNT Information Security (high, medium, low)

MoE-13: Time to Service Implementation (short, medium, long)

MoE-14: PNT System/Service Longevity (long, medium, short)

The results from the demonstration describe the opportunities and challenges, as well as next actions determined appropriate for government, industry, owners and operators of critical infrastructure, and other stakeholders to partner in the implementation of backup and complementary PNT capabilities of GPS for national security and critical infrastructure. DOT makes two recommendations:

1) DOT should develop system requirements for PNT functions that support safety-critical services;
2) DOT should develop standards, test procedures, and monitoring capabilities to ensure that PNT services, and the equipage that utilizes them, meet the necessary levels of safety and resilience identified in Recommendation 1.

Recognizing that the transportation sector has some of the most stringent performance requirements in terms of accuracy, integrity, availability, and reliability, developing system requirements that focus on safety and resilience will allow determination of which requirements are currently met, and which requirements may require further commercial innovation. DOT supports open safety standards to promote private-sector innovation and commercial product development.

The Frank LoBiondo Coast Guard Authorization Act of 2018 (Public Law 115–282) includes section 514, "Backup National Timing System," also known as National Timing Resilience and Security Act of 2018 (NTRSA). NTRSA authorizes the Secretary of Transportation to develop, construct, and operate a land-based backup timing system within two years, with a 20-year operational life, subject to the availability of appropriations.

However, such a system would be a poor investment that would potentially undermine competitive markets for alternative PNT services. This is why the President's Budget has consistently rejected the need for such appropriations and has proposed the repeal of NTRSA.

Informed by recent federal analyses, reports, and technology demonstrations, DOT finds that 1) no single solution for the provision of back-up positioning, navigation and/or timing (PNT) services can meet the diversity of critical infrastructure application requirements, and 2) it would be inefficient and anti-competitive for the Federal Government to procure or otherwise fund a specific backup PNT solution for non-federal users.

Rather than building or otherwise procuring a new system, DOT in partnership with the Department of Homeland Security, is better positioned to enable and encourage the owners and operators of critical infrastructure to be responsible users of PNT, leveraging commercially-available PNT technologies to secure access to complementary PNT services. The private sector is then encouraged to design critical infrastructure systems in a manner that recognizes the risk associated with the use of, and potential dependence on, external PNT services.

4

PNT User Requirements

While the FRP outlines the PNT performance requirements for various user groups, it is not a formal requirements document for the Federal Government. The purpose of this section is to provide context for and technical details relating to the PNT systems provided by the USG. As used in this document, the term "requirements" encompasses a broad spectrum of user wants, needs, and "must haves." Not all agencies of the Government arrive at their requirements in the same manner. Agencies must consider the needs of civil and military users to which they provide services within their enabling statutes. DoD users need to operate worldwide with civil and NATO PNT systems while simultaneously maintaining the capability to use military PNT signals.

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

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

4.1 General PNT User Requirements

PNT requirements are determined by a process that begins with acknowledgment of a need for service in an area or for a class of users. These needs are normally identified to support commerce, national defense, or public safety. They are generated internally by a Federal agency, the user public, or as required by Congress, and defended by cost/benefit analysis throughout a system's life cycle. The requirements for an area or class of users are not absolutes; see EO 13905 (Ref. 72).

The International Civil Aviation Organization (ICAO) and the International Maritime Organization (IMO) establish standards for internationally used civil aviation and maritime PNT systems, respectively. The PNT requirements discussed here are established as technical parameters based on bodies of expertise within their community, not as standards which have been set forth legally as statutory requirements or regulations.

The process to determine requirements involves evaluation of:

- the acceptable level of safety risks to the USG, user, and general public as a function of the service provided;
- the economic needs in terms of service needed to provide cost-effective benefits to commerce and the public at large. This involves a detailed study of the service desired measured against the benefits obtained; and
- the total cost impact of any government decision on PNT system users, which includes life-cycle sustainment.

The provisioning of Government-provided PNT services is conditioned on the receipt of sufficient annual appropriations and on other applicable provisions of law.

4.2 Space PNT User Requirements

4.2.1 Space PNT Requirements

The NASA Space Communications and Navigation (SCaN) office operates as a central organization within the Human Exploration and Operations Mission Directorate (HEOMD) and its responsibilities include the management of the existing Near Earth and Space Networks and the implementation of any improvements and upgrades to those networks and associated systems. NASA has agreements with other U.S. agencies on the support provided by the Near Earth and Space Networks.

Communication channel tracking from NASA's Ground and Space Network provides the primary means for navigation in space. Measurements from the tracking networks and on-board observables are sent to a ground facility for analysis and to generate navigation products, such as trajectory analysis and orbit determination, in support of space missions. Individual missions, however, may choose to include GPS measurements as an additional observable to support navigation. As such, NASA's mission to pioneer the future in space exploration, scientific discovery, and aeronautics research, includes a number of GPS application areas in the space, aeronautics, and terrestrial environments.

This section provides examples of current and future requirements for missions that support space navigation and or space science. These are summarized in Table 4-1. These are not GPS requirements, although some are supported by the GPS capabilities available throughout the GPS Terrestrial and Space Service Volumes.

Table 4-1: Space User Requirements

REQUIREMENTS	MEASURES OF MINIMUM PERFORMANCE CRITERIA TO MEET REQUIREMENTS					
	ACCURACY	AVAILABILITY	CONTINUITY	INTEGRITY	TIME TO ALERT	COVERAGE
On-Board Processed Autonomous Navigation (1 σ) *						
	3D Position: Error not to exceed 100 m Orbital Semi-Major Axis: Error not to exceed 50 m) **Timing:** Error not to exceed 500 microseconds **Attitude Determination:** Error not to exceed 0.1º per axis	N/A	N/A	N/A	N/A	Surface to GEO altitude
Science Applications						
Earth Observation Satellites	**3D Position**: 10 cm (real-time)**, 5 cm (post-processed)** **3D Velocity**: N/A (real-time and post-processed) **Attitude Determination**: N/A (real-time and post-processed): **Time**: Real-Time: N/A Post-Processed: Time transfer stable to 0.15 ns	N/A	N/A	N/A	N/A	Surface to 3000 km altitude
Altimetry Missions	**3D Position**: 3 mm in altitude (post-processed)** **3D Velocity**: N/A **Attitude Determination**: N/A **Time**: N/A	N/A	N/A	N/A	N/A	Surface to 3000 km altitude
Occultation Measurements	**3D Position**: 10 cm level (post-processed)*** **3D Velocity**: 0.05 mm/sec (post-processed)*** 0.8 mm/sec (near real-time)*** **Attitude Determination**: N/A **Time**: N/A	N/A	N/A	N/A	N/A	Surface to 3000 km altitude

* Real-time filtered using GNSS measurements
** Real-time positioning using dual frequency GNSS measurements combined with differential corrections from NASA's Global Differential GPS (GDGPS) System network of 100+ dual frequency ground monitoring stations. Post-processing analysis incorporates additional algorithms and models.
*** Positioning and velocity needs for accurate measurement of occultation refraction of the GPS signals as they pass through the atmosphere.
N/A Not applicable

4.2.1.1 Spacecraft Navigation

Spacecraft navigation is provided by multiple sources that are processed on-board to determine the position, velocity, and time (PVT). These sources may a combination of communication channel tracking, GPS and GNSS signals, optical imagery, x-ray observations, and inertial navigation measurements.

GPS may be used in definitive (i.e., near-real-time) and predictive applications for navigation, precise time, and attitude determination. In this role, the most stringent onboard navigation and attitude accuracy requirements are typically:

- filtered three-dimensional position error not to exceed 100 m (1 sigma),
- filtered orbital (osculating) semi-major axis error not to exceed 50 m (1 sigma),
- attitude determination error not to exceed 0.1 degree in each axis (1 sigma), and
- offset between user clock and GPS time not to exceed 500 microseconds (1 sigma).

It should be noted that the accuracies listed above result from filtered (i.e. processed, either on-board or on the ground) GPS data and do not represent instantaneous solution requirements.

NASA is continuing to work with the U.S. Air Force to further define the performance parameters to support navigation services in the GPS Space Service Volume (SSV), which covers the volume in space between 3,000 km and Geosynchronous Orbit (GEO) altitude (~36,000 km). The performance of GPS, per current specifications, in combination with on-board processing and filtering, can enable a near real-time position accuracy better than 100 m. However, NASA and others already use the full capabilities available in the GPS signal for improved navigation performance within the SSV.

NASA is also leading U.S. efforts at the United Nations (U.N.) International Committee on GNSS (ICG) Working Group B (WG-B) to pursue the development of interoperable GNSS capabilities to support space users. This led to the official release on an information booklet in November 2018, "The Interoperable Global Navigation Satellite Systems Space Service Volume," an authoritative publicly-available information booklet that includes coordinated definitions, constellation-specific SSV signal performance data, and example technical data. The booklet is available in printed form at the U.N. Headquarters and online.[13]

4.2.1.2 Science Mission Support

GPS science mission support typically consists of analysis of data in a post-processing mode to accurately locate instrument position in space when measurements are taken. Typical science mission accuracy requirements are to determine three-dimensional position within 5 cm and maintain time

[13] Reference: The Interoperable Global Navigation Satellite Systems Space Service Volume, United Nations Office of Outer Space Affairs, Vienna, 2018. available at http://www.unoosa.org/res/oosadoc/data/documents/2018/stspace/stspace75_0_html/st_space_75E.pdf.

transfer stability at 0.15 ns. Some missions may require much higher accuracy levels, such as 0.3 cm accuracy in altitude measurements for altimetry missions.

There are GPS receivers aboard satellites used for atmospheric remote sensing. These receivers require dual frequency GPS measurements with sub-mm precision in order to accurately measure the refraction of the GPS signals as they pass through the atmosphere. These are also referred to as "occultation measurements."

4.2.1.3 Space-based Geodesy

NASA supports the International Laser Ranging Service (ILRS) in the tracking and orbital analysis of laser retroreflector-equipped GNSS satellites, as well as a large number of Earth observation satellites, to support the maintenance and improvement of the International Terrestrial Reference Frame (ITRF) and the advancement of precision geolocation of Earth observation. To meet NASA's space-based geodesy requirements, and to continue improving GPS capabilities, in 2013 the USAF, NASA, and the U.S. Strategic Command (USSTRATCOM) have agreed to the integration of NASA-furnished laser retro-reflector arrays onto GPS IIIF satellite vehicles, to facilitate the laser ranging of GPS satellites by the ILRS. With the establishment of USSPACECOM out of USSTRATCOM, USSPACECOM will be continuing with this agreement. The goal of this application is to provide the highest quality data and products as the standard for GNSS allows.

4.2.2 Space User Community

The Space user community includes NASA and other U.S. Government agencies, international space faring nations, and the commercial space community. Per SPD-7 and other relevant policy guidance, NASA will continue to work with the USAF, USSF, and other interagency stakeholders to ensure GPS resilience and enhance GPS interoperability when used in conjunction with other emerging GNSS constellation services for space operations and science applications.

NASA currently uses GPS to support launch range safety, search and rescue support to human space flight in the event of launch aborts and/or emergency landings, science missions, and International Space Station (ISS) operations. NASA is assessing whether GPS, and other GNSS signals, can also support throughout cislunar space. In February 2019, the NASA Magnetospheric Multiscale (MMS) mission demonstrated that GPS signals can be tracked up to approximately half of the distance to the Moon. This was the highest and fastest (over 21,000 mph, or 35,000 km/h, at perigee) successful use of GPS signals.

There are also numerous examples of GPS use by the U.S. commercial space community, such as low Earth orbit (LEO) communication satellite constellations, Earth sensing satellites, and resupply missions to the ISS under NASA's Commercial Crew and Cargo Program. On December 5, 2014, Orion's unmanned first flight test, Exploration Flight Test-1 (EFT-1) was launched on a two-orbit four-hour flight test reaching an altitude of 5,800 kilometers. This flight included inertial measurement units, barometric altimeters, and a GPS receiver with two antennae for navigation. The second unmanned flight, called Artemis-1 (previously known as Exploration Mission 1), is planned for 2020 and will send the Orion capsule around the Moon.

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

Standard GPS receivers are inadequate for certain space applications above LEO due to survivability in space issues and reduced signal power level and availability. There are specialty GPS receivers to support real-time on board navigation for space users.

Research satellites use GPS receivers for precise positioning in support of onboard science instruments, which requires precise satellite positioning at the 10 cm (1 sigma) level in real-time, and centimeter-level (1 sigma) positioning with post-processed data. This capability enables numerous scientific measurements that are not available today to support research in areas such as oceanography and geodesy.

The use of GPS signals for science observations is also the subject of continuing research. Examples of this research are the use of GPS signals for atmospheric sensing using occultation measurements through the Earth's atmosphere, and observations of GPS signals reflected off of the Earth's surface.

The latest generation of NASA GPS space-borne receivers are software programmable units and capable of tracking signals from multiple GNSS constellations. The ability to obtain multiple sets of GNSS signals will improve performance and robustness.

4.3 Aviation PNT User Requirements

Aircraft navigation includes determining position, orientation, course, and distance to the desired destination, and deviation from the desired track. Requirements for navigation performance are dictated by the phase of flight, the aircraft proximity to terrain and to other aircraft, and the air traffic control process (codified in 14 CFR), which requires aircraft to use systems that are "suitable for navigating the aircraft along the route to be flown within the degree of accuracy required for ATC" (for commercial operators) and "suitable for the route to be flown" (for private operators).

Navigation under visual flight rules (VFR) is conducted primarily by referencing features on the ground visually, but can be aided with aircraft avionics. Navigation avionics are frequently used in VFR and are required when operating under instrument flight rules (IFR).

Aircraft separation criteria consider limitations of communication, navigation and surveillance (CNS), and ATC automation services, but are strongly affected by other factors, e.g., wake turbulence, prevailing weather conditions, and air traffic control's intervention capabilities. Surveillance service normally falls into two categories:

- Cooperative: Surveillance in which the target cooperates with the process by using onboard equipment in the provision, acquisition, or derivation of surveillance information (position measurements, ID, etc. Transponder-based secondary radar and.). ADS-B both means of providing cooperative surveillance of aircraft; however, ADS-B primarily utilizes PNT information from GPS or augmented GPS to provide aircraft surveillance data to ATC for separation and or flight advisory services.

- Non-cooperative: Surveillance of a target using primary radar without depending on information provided by the target.

Surveillance Services such as ADS-B necessitate a positional and timing accuracy, as well as integrity that provides a high degree of confidence that aircraft are at the reported position at the identified time. The accuracy and integrity of the ADS-B surveillance in a defined volume of airspace must be sufficient to support the separation minima permitted in that airspace, such as 3NM terminal separation or 5 NM en route separation. Further, surveillance data must be available in identified regions of airspace when the primary PNT system supporting ADS-B is degraded or unavailable. As such, ADS-B has complementary backup cooperative surveillance (secondary to the retention of backup legacy surveillance radar) systems available in selected airspace.

Separation criteria require a high degree of confidence that an aircraft will remain within its assigned volume of airspace. The dimensions of the volume are determined, in part, by a stipulated probability that performance of the PNT system will remain within a specified error budget such that an acceptable target level of safety is achieved.

The following are basic requirements for aviation navigation systems (see Table 4-2, p. 4-17 for specific requirements). "Navigation system" means all of the elements necessary to provide navigation services throughout each phase of flight. No single set of navigation and operational requirements, even though they meet the basic requirement for safety, can adequately address the many different combinations of operating conditions encountered in various parts of the world. The requirements listed below may, therefore, apply differently by region. In general, navigation system requirements include:

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

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

c. the integrity of the navigation system, including the presentation of information in the cockpit, must be near 100 percent and provide timely alarms in the event of failure, malfunction, or interruption;

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

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

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

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

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

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

    - continuous determination of aircraft position;
    - continuous track deviation guidance;
    - continuous determination of along-track distance;
    - manual or automatic position reporting; and
    - manual or automatic flight.

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

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

l. the navigation system must permit the pilot to determine the position of the aircraft with an accuracy and frequency that will ensure that the aircraft is bounded within established protected airspace areas at all times and annunciate when the system does not satisfy the requirements for the operation;

m. the navigation system must support a defined system of routes for the appropriate phases of flight;

n. the navigation system must be cost-effective for both the Government and the users;

o. the navigation system must be designed to reduce susceptibility to interference from adjacent radio-electronic equipment and shall not cause objectionable interference to any associated or adjacent radio-electronic equipment installed in aircraft or on the ground;

p. the navigation system must compensate for signal fades or other propagation anomalies within the operating area; and

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

For any IFR route, procedure, or operation, an aircraft is required to have navigation equipment appropriate to the route to be flown. In many cases this requires carriage of a specific navigation system, such as VOR or ILS. Area Navigation (RNAV)-based routes (designated as Q, T, and TK routes) accommodate a variety of navigation systems such as GPS, GPS/WAAS, and DME navigation with and without inertial reference unit (IRU), where there is adequate infrastructure and navigation system performance. However, operations will continue to be restricted to the available and qualified systems.

The signal error characteristics of a navigation system have a direct effect on determining minimum route widths. The distribution and rate of change, as well as the magnitude of the errors, must be considered. Error distributions may contain both bias and random components. Under certain conditions, the bias component is generally easily compensated for when its characteristics are constant and known. The evaluation of errors is a complex process, and the comparison of systems based upon a single error number will be misleading or incorrect.

4.3.1 Air Navigation User Requirements and Phases of Flight

Requirements for navigation performance are codified in 14 Code of Federal Regulations, which requires aircraft to use systems that are "suitable for navigating the aircraft along the route to be flown within the degree of accuracy required for ATC" (for commercial operators) and "…suitable for the route to be flown." (for private operators).

Requirements are a function of legacy navigation system capabilities and Performance-Based Navigation (PBN) capabilities as described in section 4.3.2. FAA Advisory Circular (AC) 20-138, Airworthiness Approval of Positioning and Navigation Systems (Ref. 34), provides guidance material for the airworthiness approval of installed positioning and navigation equipment. FAA AC 90-108, Use of Suitable Area Navigation (RNAV) Systems on Conventional Routes and Procedures (Ref. 35), provides operational guidance regarding the suitability and optional use of RNAV systems while operating on or to conventional (i.e., non-RNAV) routes and procedures within the NAS; however, RNAV substitution is an optional navigation technique, and never permissible in the final approach segment.

For the purposes of this document, the phases of aerial navigation are Departure, En route (including oceanic/remote areas), Arrival, Approach, and surface operations.

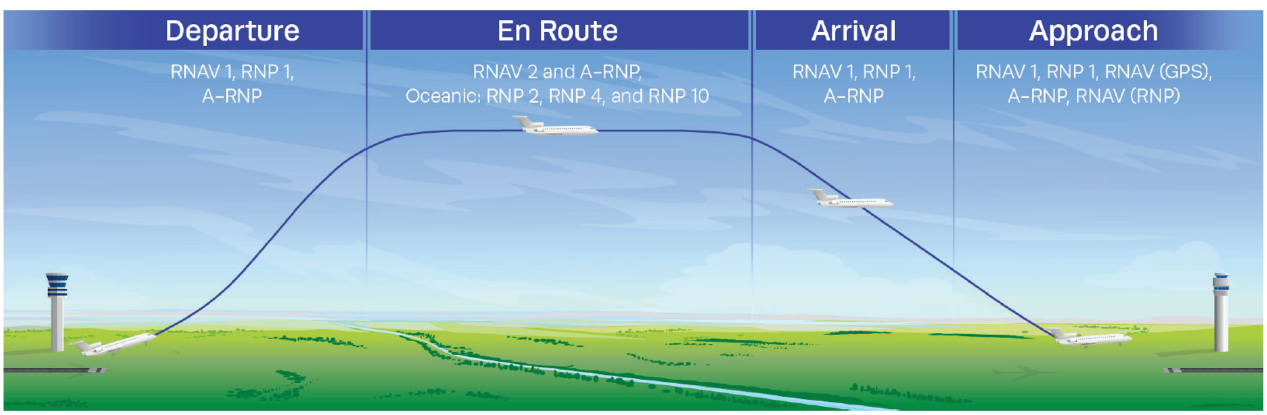

Figure 4-1: Phases of aerial navigation (Note: Various PBN procedures are used at each phase of flight)

4.3.1.1 Departure Phase

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

Instrument flight procedures provide transition from departure to the en route and en route to the approach phases of flight. Surveillance facilities, including ADS-B, primary radar, secondary radar, and wide area multilateration, provide controllers with the ability to provide radar service to IFR and VFR aircraft under their control, provide traffic and safety advisories, and sequence traffic flows into and out of airports located within the terminal area. Technological advances in aircraft navigation using RNAV and RNP specifications will reduce pilot and controller workload and facilitate more efficient airspace and procedure design. These changes will collectively result in improved access, operational efficiency, and environmental effects within these areas.

Takeoff begins with initial roll and ends at the departure end of the runway. While most takeoff operations are conducted with reliance solely on visual cues available to the pilot and accompanied by ground-based visual aids (e.g. runway lighting), at very low visibilities some takeoffs are conducted with reliance on the localizer portion of an ILS approach installation for lateral guidance. This operation requires a signal integrity and continuity of service similar to that of a CAT III ILS approach. The FAA is examining expanding the use of localizer signals during takeoff at higher visibility levels in lieu of costly ground infrastructure. Future plans may include the examination of augmented GPS signals and/or synthetic vision guidance based on GPS position to fulfil the same role.

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

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

4.3.1.2 En Route Phase

This phase is the portion of flight after departure where the aircraft cruises in en route airspace to the destination and enters the terminal arrival airspace and transition to approach and landing. The navigation services available to the aircraft must be suitable for the intended route of flight.

The general requirements in Section 4.3 are applicable. In addition, to facilitate aircraft navigation in this phase, the navigation system used must be operationally compatible with the system used for approach and landing.

A barometric measurement device is a required flight instrument to maintain vertical separation between aircraft. This is often an altimeter (altimeter information is also required for safe and efficient flight), but for some altitudes an air data computer is needed. This necessitates narrower route widths than in the oceanic en route subphase. While ADS-B is the preferred means of surveillance, independent secondary surveillance is generally available as an ADS-B backup to assist in the ground monitoring of aircraft position.

Oceanic/Remote Areas En Route

This subphase covers operations over the ocean and remote areas generally characterized by lower, but increasing, traffic density as global traffic forecasts indicate. Remote areas are special geographic or environmental areas typically characterized by challenging terrain where it has been difficult to cost-effectively implement and maintain comprehensive ground-based navigation and surveillance coverage. Typical of remote areas are mountainous terrain, oceanic areas, and large portions of the State of Alaska.

The navigation system used must provide capability commensurate with the need in specific areas to permit safe navigation and the application of lateral separation criteria. New CNS avionics and procedures have allowed reduced spacing for participating aircraft where independent surveillance (e.g., radar) is not available. New technology has reduced separation previously maintained using pilot position reports and timing, while maintaining an equivalent level of safety.

The current Minimum Navigation Performance Specification (MNPS) airspace lateral separation standard on the North Atlantic Organized Track System is nominally 60 nm. The current lateral spacing between the flex tracks, or the Pacific Organized Track System (PACOTS), in Anchorage (PAZA) and Pacific (KZAK) oceanic control areas (OCAs) is 50 nm for operators authorized for Required Navigation Performance (RNP) 10 operations. A 50 nm laterally-spaced route system has been implemented from the west coast of the United States to Hawaii, and in the New York West OCA (KZWY) between the east coast of the United States and the Caribbean region as well as in the Houston OCA (KZHU) in the Gulf of Mexico.

Anchorage, New York and Oakland also provide 30 nm lateral/30 nm longitudinal aircraft separation for operators authorized for RNP 4 navigation performance, and controller-pilot data link communications (CPDLC) Required Communications Performance (RCP) 240 and Required Surveillance Performance (RSP) 180. Starting in 2021, the FAA will implement 23 nm lateral aircraft separation minimum for operators with RNP 4 or RNP 2, and RCP 240 and RSP 180 authorizations. Future FAA plans include the implementation of 20 nm longitudinal separation for operators holding RNP 4 or RNP 2, RCP 240 and RSP 180 authorizations.

Using the Advanced Technology-Oceanic Procedures (ATOP) system, FAA oceanic air traffic controllers currently apply aircraft separation based upon the capabilities filed by operators in their flight plans. With the combination of an advanced technology ground-based system and the technological advances in aircraft navigation and communication systems, the FAA can safely clear more aircraft on individual “user-preferred” routings, which yields increased safety and efficiency benefits.

4.3.1.3 Arrival Phase

The general requirements of Section 4.3 apply to the departure and arrival phases (often called “terminal operations”). In addition, specific procedures and clearance zone requirements are specified in FAA Order 8260.3, United States Standard for Terminal Instrument Procedures (TERPS) (Ref. 36).

The minimum navigation performance criteria vary between precision and non-precision approaches (NPA).

4.3.1.4 Approach Phase

The basic classifications of approach include two-dimensional (2D) and three-dimensional (3D) operations:

- Non-precision approach procedure: A 2D instrument approach procedure without approved vertical guidance, normally to a minimum descent altitude.
- Precision approach procedure: A 3D instrument approach procedure with approved vertical guidance on a glide slope or glidepath.
- Approach with vertical guidance: an ICAO approach classification being phased out of FAA use, which allows the use of a stabilized descent, using vertical guidance, without the accuracy required for a traditional precision approach procedure. The FAA intends to reclassify all current “APV” approaches as 3D precision or 2D or 3D non-precision approach operations.

The above definitions of non-precision approach and precision approach are consistent with 14 CFR. A missed approach operation, depicted as part of a published instrument approach procedure, is conducted when a landing cannot be safely accomplished.

Non-precision and Lateral Navigation (LNAV) Approach

Non-precision approaches are based on specific navigation systems. The achieved capability for non-precision approaches varies significantly, depending on the type of navigation system used, system accuracy and integrity, and, for conventional systems, location relative to the procedure. Minimum safe altitude, obstacle clearance area, visibility minimum, final approach segment area, etc., are all functions of the navigation accuracy available and other factors.

An example of the safe non-precision approach system design includes time-to-alert requirements. The integrity time-to-alert requirement for non-precision approaches provides the pilot with either a warning or a removal of signal within ten seconds of the occurrence of an out-of-tolerance condition.

An example of a non-precision approach would be based on Required Navigation Performance (RNP) with GPS as required guidance to minima titled LNAV, LNAV/VNAV (vertical navigation), or LP (localizer performance).non-precision RNP is an area navigation (RNAV) system that includes onboard performance monitoring and alerting capability.

Approach with Vertical Guidance (LNAV/VNAV, LPV, and RNP Authorization Required (AR))

Lateral Navigation/Vertical Navigation (LNAV/VNAV) and Localizer Performance with Vertical Guidance (LPV) are RNP approach procedures that provide lateral and vertical guidance for the approach. LNAV/VNAV provides operational ceiling and visibility minima as low as 250 feet and ¾-mile visibility while LPV can provide minima as low as 200 feet and ½-mile visibility. Some flight management systems (FMS) provide LNAV/VNAV capability by incorporating lateral RNP guidance information with barometric-generated vertical guidance information and LPV using WAAS.

Barometer-generated VNAV accuracy, however, is affected by both cold and hot temperatures, requiring operational limitations on using it for LNAV/VNAV operations. WAAS LPV and LP (lateral precision without vertical guidance) operations are not affected by temperature variations. RNP Authorization Required (AR) approach procedures include three-dimensional procedures with lateral and vertical path deviation guidance. RNP AR approach procedures were formerly known as “RNP special aircraft and aircrew authorization required.” The change to AR was adopted to harmonize U.S. with ICAO PBN terminology. RNP AR vertical navigation performance is based upon barometric VNAV or GPS/WAAS. RNP AR is intended to provide specific benefits at specific locations. It is not intended for every operator or aircraft. RNP AR capability requires specific aircraft performance/design, operational processes/training, and specific procedure design criteria to achieve the required target level of safety and requires FAA Flight Standards approval.

Precision Approach-to-Landing

Precision approaches are based on specific navigation capability, including the use of approved vertical guidance. The final approach segment requires precise lateral and vertical positive course guidance/deviation information. A precision approach aid provides an aircraft with vertical and horizontal guidance information to align the aircraft to the runway touchdown zone.

The current worldwide standard for precision approach evolved from the ILS and consists of three categories: Category-I guides the aircraft to 200 feet decision altitude, Category-II 100 feet, and Category-III as low as the runway surface when coupled with an aircraft autoland system. Precision approach and landing systems must automatically detect and exclude hazardously misleading information within 6 seconds for Category-I, 2 seconds for Category-II and III or declare the service is unavailable. Ground-Based Augmentation Systems (GBAS) and WAAS also provide Category-I service. GBAS was intended to meet all three categories and has demonstrated Category-I. WAAS provides LPV approach service equivalent to Category-I at runways with appropriate precision approach infrastructure.

Examples of precision approaches include ILS, MLS, GLS, and RNP approaches using GPS and/or WAAS and/or self-contained equipment to fly to CAT I minima titled LPV, or RNP 0.30 or lower.

4.3.1.5 Surface Phase

Surface operations include navigation on the airport surface to and from the active runway. These operations are conducted visually or supplemented with Airport Surface Detection Equipment, Model X (ASDE-X), which enhances situational awareness during reduced visual conditions.

4.3.2 Evolving Aviation Navigation Requirements

The ICAO Performance-Based Navigation Study Group (formerly the Required Navigation Performance and Special Operational Requirements Study Group (RNPSORSG)) reviewed the ICAO RNP concept beginning in 2003, considering the experiences of early application, as well as current industry trends, stakeholder requirements, and existing regional implementations. It developed an agreed understanding of what is now the Performance-Based Navigation (PBN) concept and the *Performance-Based Navigation Manual*. This manual supersedes the manual on RNP (Doc 9613, Second Edition). The ICAO PBN Study Group published the Fourth Edition update to Doc 9613 in 2013 (Ref. 37) and is in the process of proposing additional changes. This affects a number of ICAO documents, including:

- Annex 11, *Air Traffic Services* (Ref. 38)
- *Procedures for Air Navigation Services, Air Traffic Management* (PANS-ATM, Doc 4444 ATM/501) (Ref. 39)
- *Procedures for Air Navigation Services, Aircraft Operations* Volumes I & II (PANS-OPS, Doc 8168) (Ref. 40)
- *Regional Supplementary Procedures* (Doc 7030) (Ref. 41)
- *Air Traffic Services Planning Manual* (Doc 9426 AN/924) (Ref. 42)
- *Manual on Airspace Planning Methodology for the Determination of Separation Minima* (Doc 9689) (Ref. 43)

Table 4-2 depicts the RNP signal-in-space performance requirements established by ICAO. Demonstrating system compliance with the signal-in-space requirements depicted below requires rigorous safety management system and safety risk management documentation processes. The following paragraphs characterize flight operations in the various phases of flight.

4.3.2.1 En Route Phase

In the United States, the RNAV 2 navigation specification supports an en route continental airspace concept. With the publication of FAA Advisory + Circular (AC) 90-100A, *U.S. Terminal and En Route Area Navigation (RNAV) Operations* (Ref. 44), RNAV en route procedures were aligned with ICAO RNAV 2 criteria. RNAV 2 applications support airspace concepts that include radar surveillance and direct controller pilot communication (voice).

Table 4-2: Aviation Performance-Based Navigation Requirements *

REQUIREMENTS	MEASURES OF MINIMUM PERFORMANCE CRITERIA TO MEET REQUIREMENTS						
	ACCURACY (95%)		AVAILABILITY	CONTINUITY	INTEGRITY	TIME TO ALERT	COVERAGE **
	Horizontal	Vertical					
Oceanic	10 or 4 NM***	N/A	0.99–0.99999		1-1x10^{-7}//hr	N/A	N/A
En route	2 NM	N/A	0.99–0.99999	1-1x10^{-4}/hr to 1-1x10^{-8}/hr	1-1x10^{-7}/hr	5 min	N/A
Terminal	1 NM	N/A	0.99–0.99999	1-1x10^{-4}/hr to 1-1x10^{-8}/hr	1-1x10^{-7}/hr	15 s	N/A
Non Precision Approach	220 m	N/A	0.99–0.99999	1-1x10^{-4}/hr to 1-1x10^{-8}/hr	1-1x10^{-7}/hr	10 s	N/A
APV-I	16 m	20 m	0.99–0.99999	1-8x10^{-6}/15 s	1-2x10^{-7} in any approach	10 s	N/A
APV-II	16 m	8 m	0.99–0.99999	1-8x10^{-6}/15 s	1-2x10^{-7} in any approach	6 s	N/A
CAT I	16 m	6–4 m	0.99–0.99999	1-8x10^{-6}/15 s	1-2x10^{-7} in any approach	6 s	N/A

* From ICAO Annex 10 Vol 1 Table 3.7.2.4-1. ICAO is in the process of changing approach definitions of the APV classification and including LPV-200 as a precision approach.

** Not Specified by ICAO, Annex 10, Vol. 1, Table 3.7.2.4-1, Signal-in-Space Performance Requirements.

*** Depends on the navigation specification (RNP 10 or RNP 4) employed in the oceanic area.

4.3.2.2 Oceanic En Route

Oceanic and remote continental airspace concepts are currently served by two navigation specifications, RNP 10 and RNP 4. Both of these navigation specifications support the navigation element of the airspace concept. In the case of RNP 10, when 50 NM longitudinal separation has been implemented, ADS-C surveillance and CPDLC is required. In the case of RNP 4, when 30 NM lateral or 30 NM longitudinal separation is applied, ADS-C surveillance and CPDLC is required.

4.3.2.3 Terminal Phase

One of the major changes for the terminal area is the increased use publication of RNAV and RNP procedures. Many existing and new terminal arrival and departure procedures can be flown by operators compliant with the RNAV 1 systems and operational approval guidance in AC 90-100A (Ref. 44). Additionally, where required, new RNP 1 arrival and departure procedures are being implemented that can be flown by operators compliant with systems and operational approval guidance in AC 90-105A (Ref. 45) for RNP 1. AC 90-105A is consistent with the ICAO PBN manual and provides operational guidance for RNP functions in both the terminal and en route phases of flight.

4.3.2.4 Takeoff and Approach-to-Landing Phases

One of the major changes for takeoff and approach-to-landing phases is the increased use of Performance Based Navigation operations (i.e. RNAV and RNP) to achieve optimum airspace utilization and noise abatement. The use of PBN for departure procedures allows increased flexibility in departure procedure design and will increase the ability of procedures to avoid noise sensitive areas.

Near-Precision and Performance-Based Approaches

With WAAS, it is possible to have aa PBN approach to LPV minima anywhere in the U.S. where exists. Current WAAS "LPV service" availability within the Conterminous United States (CONUS) and southern Alaska nominally exceeds 99 percent. In 2020, the number of approaches with LPV minima exceeded (more than the number of ILS approaches in the NAS), providing more service to appropriately equipped aviation users. Airports with appropriate infrastructure within the signal-in-space coverage area are eligible for these precision GPS-based approaches.

FAA AC 90-107, Guidance for Localizer Performance with Vertical Guidance and Localizer Performance without Vertical Guidance Approach Operations in the U.S. National Airspace System (Ref. 46) provides operational guidance for LPV and LP lines of minima. FAA AC 90-105 (Ref. 45) provides operational approval guidance for conducting LNAV and LNAV/VNAV RNP instrument approach procedures. FAA AC 90-101A, Approval Guidance for RNP Procedures with AR (Ref. 47), provides operational approval guidance and criteria for RNP AR. RNP AR approach supports minima down to 250 feet.

Approach concepts cover all segments of the instrument approach, i.e., initial, intermediate, final, and missed approach. RNP approach and RNP AR approach enable new procedures to runways never served by an instrument procedure, replaces or serves as backup to existing instrument procedures based on different technologies, and enhances airport access in demanding environments.

Precision Approach-to-Landing

Increases in navigation performance thresholds increase the safety levels for landing and rollout operations. Following considerable research and prototyping work by the FAA and International community, ICAO Annex 10 standards for CAT II/III GBAS precision approaches were accepted by the ICAO Navigation Systems Panel in December 2016. The FAA has no plan to acquire GBAS CAT II/III ground facilities; however, just like GBAS CAT I, GBAS CAT II/III may be installed by sponsors as non-Federal systems when a CAT II/III GBAS receives FAA System Design Approval.

As stated in section 1.7.9, the FAA requires the use of at least one RA to measure the height or altitude above terrain for Category II and Category III ILS approaches. RA is a sensor onboard aircraft used to measure the height or altitude above terrain. RA also provides altitude measurements to other critical onboard aircraft systems such as Automatic Flight Guidance and Control Systems (AFGCS), Predictive Wind Shear (PWS), Engine-Indicating and Crew-Alerting System (EICAS), Electronic Centralized Aircraft Monitoring (ECAM), Traffic Alerting and Warning System (TAWS) and Traffic Collision Avoidance System (TCAS). These systems have been instrumental in the reduction of fatal aviation accidents for the past 30 years.

The vast majority of RAs in civilian aircraft operate using frequency-modulated continuous wave (FMCW) radar technology; however, some RAs use unmodulated pulsed radar systems. In either case, the RA measures the altitude of the aircraft by transmitting radio frequency (RF) energy down to the ground and receiving a portion of the energy reflected off the terrain or other obstacles. Using the speed of light, the RA determines altitude above ground level based on the round-trip propagation time of the energy. Since the RA transmits with low power, typically about one watt, highly sensitive receivers are required for detection of the return signal to enable the RA to function in accordance with TSO-C87a. As such, RAs are highly susceptible to RF interference entering the receiver, from in-band and adjacent band systems, which can negatively impact their performance by either completely denying detection of the return signal or combining with the return signal to create an incorrect altitude reading that provides hazardously misleading information to the pilot.

4.3.2.5 Aviation Surface Operations

Currently, surface operations at most airports remain primarily tied to the use of visual references; however, other navigation aids will increasingly act as input sources to advanced surface movement operations in the NextGen environment.

4.3.3 Surveillance Positioning Requirements

The FAA's preferred surveillance technology has transitioned to ADS-B, which is dependent on aircraft PNT systems—primarily GNSS based on GPS. A final rule was published in 2010 to amend Title 14, CFR Part 91, General Operating and Flight Rules (Ref. 48), §91.225 and §91.227, by adding equipage requirements and performance standards for ADS–B Out avionics on aircraft operating in Classes A, B, and C airspace, as well as certain other specified classes of airspace within the NAS (such as Class E above 10,000 feet). These regulations also required aircraft to be equipped with a Positioning Source, such as GNSS, that meets the ADS-B positioning performance standards that support safe separation of aircraft. Following years of coordination with DoD, in mid-2019, the FAA published revised rulemaking under Title 14 CFR Part 91 § 91.225(f)(1) that provided for DoD relief, accommodations, and authorization to not broadcast ADS-B on equipped aircraft due to operational security concerns.

Use of ADS-B Out transitioned air traffic control surveillance from a radar-based system to a satellite-derived aircraft location system that is dependent on positioning and timing services. This rule facilitates the use of ADS-B for aircraft surveillance by FAA and DoD air traffic controllers to safely and efficiently accommodate aircraft operations, as well as the expected increase in demand for air transportation. This rule also provides aircraft operators with a platform for additional flight applications and services. The ADS-B final rule went into effect on January 1, 2020.

The required performance of the positioning source used for ADS-B Out is represented by the navigation accuracy category for position (NAC_p), the navigation accuracy category for velocity (NAC_v), the navigation integrity category (NIC), the system design assurance (SDA), and the source integrity level (SIL) parameters, as described in 14 CFR 91.227, Automatic Dependent Surveillance-Broadcast (ADS–B) Out Equipment Performance Requirements. The required positioning source performance for ADS-B Out is as follows:

- The 95% positional accuracy bound must not exceed 0.05 NM (NACp >= 8)
- The 95% velocity accuracy bound must not exceed 10 m/s (NACv >= 1)
- Positional integrity containment radius must not exceed 0.2 NM (NIC >= 7)
- System design assurance must correspond to an undetected fault probability not exceeding to 1 x 10^{-5} per hr (SDA >= 2)

- Positional integrity must correspond to a probability of the true position lying outside the containment radius without alert not exceeding 1 x 10^{-7} per hr or per sample (SIL >= 3)
- These surveillance performance requirements ensure that ADS-B meets the performance requirements for all phases of flight whether en route, terminal, or on approach so that ATC can provide requisite separation services. This performance level also provides flexibility in airspace redesign such that surveillance is not a limiting factor.

FAA AC 20-165B, *Airworthiness Approval of Automatic Dependent Surveillance-Broadcast (ADS-B) Out Systems* (Ref. 49), provides ADS-B installation guidance including a complete requirements compliance description. Appendix 4 of FAA AC 20-138D, Change 1 & 2, *Airworthiness Approval of Positioning and Navigation Systems* (Ref. 34), provides navigation sensor installation guidance and bench test procedures that can be used as an acceptable means to establish that the navigation sensor provides the required outputs described in AC 20-165B.

4.4 Surface PNT User Requirements

4.4.1 Maritime User Requirements

4.4.1.1 Phases of Marine Navigation

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

4.4.1.1.1 Inland Waterway

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

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

4.4.1.1.2 Harbor Entrance and Approach

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

From the viewpoint of establishing standards or requirements for safety of navigation and promotion of economic efficiency, there is some generic commonality in harbor entrance and approach. In each case, the nature of the waterway, the physical characteristics of the vessel, the need for frequent maneuvering of the vessel to avoid collision, and the closer proximity to grounding danger impose more stringent requirements for accuracy and for real-time guidance information than for the coastal phase.

For analytical purposes, the phase of harbor entrance and approach is built around the problems of precise navigation of large seagoing and Great Lakes ships in narrow channels between the transition zone and the intended mooring.

4.4.1.1.3 Coastal Navigation

Coastal navigation is that phase in which a ship is within 50 NM from shore or the limit of the continental shelf (200 m in depth), whichever is greater, where a safe path of water at least 1 NM wide, if a one-way path, or 2 NM wide, if a two-way path, is available. In this phase, a ship is in waters contiguous to major land masses or island groups where transoceanic traffic patterns tend to converge in approaching destination areas; where inter-port traffic exists in patterns that are essentially parallel to coastlines; and within which ships of lesser range usually confine their operations. Traffic-routing systems and scientific or industrial activity on the continental shelf are encountered frequently in this phase of navigation. Ships on the open waters of the Great Lakes also are considered to be in the coastal phase of navigation.

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

- 50 NM from land; or

- the outer limit of offshore shoals, or other hazards on the continental shelf; or
- other waters where traffic separation schemes have been established and where requirements for the accuracy of navigation are, therefore, made more rigid than the safety requirements for ocean navigation.

4.4.1.1.4 Ocean Navigation

Ocean navigation is that phase in which a ship is beyond the continental shelf (200 m in depth) and more than 50 NM from land in waters where position fixing by visual reference to land or to fixed or floating aids to navigation is not practical. Ocean navigation is sufficiently far from land masses so that the hazards of shallow water and of collision are comparatively small.

4.4.1.2 Marine Navigation Requirements

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

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

For system planning, the USG seeks to satisfy minimum safety requirements for each phase of navigation and to maximize the economic utility of the service for users. Since the vast majority of marine users are required to carry only minimal navigation equipment, and, even then, do so only if persuaded by individual cost/benefit analysis, this governmental policy helps to promote maritime safety through a simultaneous economic incentive.

Tables 4-3, 4-4, 4-5, and 4-6 identify system performance needed to satisfy maritime user requirements or to achieve special benefits. The requirements are related to safety of navigation. The USG recognizes an obligation to satisfy these requirements for the overall national interest. The benefits are specialized requirements or characteristics needed to provide special benefits to discrete classes of maritime users (and additional public benefits that may accrue from services provided by users). The USG does not recognize an absolute commitment to satisfy these requirements, but does endeavor to meet them if their cost can be justified by benefits that are in the national interest. For the purpose of comparing the performance of systems, the requirements are categorized in terms of system performance characteristics representing the minimum performance considered necessary to satisfy the requirements or achieve special benefits.

4.4.1.2.1 Inland Waterway Phase

The inland waterway system handles about 80 percent of United States flagged passenger/cargo vessels and 567 million tons of cargo annually, much of it in slow-moving, comparatively low-powered tug and barge towing combinations. Tows on the inland waterways, although comparatively shallow in draft, may be longer and wider than large seagoing ships that call at U.S. ports. Navigable channels used by this inland traffic are often narrower than the harbor access channels used by large ships. Restricted visibility and ice cover present problems in inland waterway navigation, as they do in harbor entrance and approach navigation. The long, ribbon-like nature of the typical inland waterway presents special problems to the prospective user of precise, land-based area navigation systems. Continual shifting of navigable channels in some unstable waters creates additional problems to the prospective user of any PNT system that provides position measurements in a fixed coordinate system.

Special waterways, such as the Saint Lawrence River and some Great Lakes passages, are well defined, but subject to frequent fog cover, which requires ships to anchor. This imposes a severe economic penalty in addition to the safety issues. If a fog rolls in unexpectedly, a ship may need to proceed under hazardous conditions to an anchorage clear of the channel or risk stopping in a channel. Current requirements for the inland waterway phase of navigation are provided in Table 4-3.

Table 4-3: Maritime User Requirements for Purposes of System Planning and Development - Inland Waterway Phase

REQUIREMENTS	MEASURES OF MINIMUM PERFORMANCE CRITERIA TO MEET REQUIREMENTS					
	ACCURACY (meters, 2 drms)	AVAILABILITY	CONTINUITY	INTEGRITY	TIME TO ALERT	COVERAGE
Safety of Navigation (All Ships and Tows)	2–5 m	99.9%	*	N/A	N/A	U.S. Inland Waterway Systems
Safety of Navigation (Recreational Boats and Smaller Vessels)	5–10 m	99.9%	*	N/A	N/A	U.S. Inland Waterway Systems
River Engineering and Construction Vessels	0.1**–5 m	99.0%	*	N/A	N/A	U.S. Inland Waterway Systems

* Dependent upon mission time.
** Vertical dimension.

Visual and audio aids to navigation, radar, and inter-ship communications are presently used to enable safe navigation in those areas.

4.4.1.2.2 Harbor Entrance and Approach Phase

The pilot of a vessel in restricted waters must direct the vessel's movement with great accuracy and precision to avoid grounding in shallow water, hitting submerged/partially submerged rocks, and colliding with other craft in congested waterways. Large vessels or tug and barge combinations are unable to turn around, and are severely limited in their ability to stop to address a navigation problem. Consequently, the pilot of these types of vessels or vessel combinations may find it necessary to hold the total error in navigation within limits on the order of one meter while navigating in this environment.

To navigate safely, the pilot needs highly accurate verification of position almost continuously, together with information depicting any tendency for the vessel to deviate from its intended track and a nearly continuous and instantaneous indication of the direction in which the pilot should steer. Table 4-4 presents estimates of these requirements. However, to effectively utilize the requirements stated in the table, a user must be able to relate the data to immediate positioning needs. This is not practical if one attempts to plot fixes on a chart in the traditional way. To utilize PNT information that is presented at less than 10 second intervals on a moving vessel, some form of an automatic display is required. Technology is available that presents PNT information along with other data.

Table 4-4: Maritime User Requirements/Benefits for Purposes of System Planning and Development - Harbor Entrance and Approach Phase

(a)

REQUIREMENTS	MEASURES OF MINIMUM PERFORMANCE CRITERIA TO MEET REQUIREMENTS					
	ACCURACY (meters, 2 drms)	AVAILABILITY	CONTINUITY	INTEGRITY	TIME TO ALERT	COVERAGE
Safety of Navigation (Large Ships & Tows)	8–20*** m	99.7%	**	N/A	N/A	U.S. harbor entrance and approach
Safety of Navigation (Smaller Ships)	8–20 m	99.9%	**	N/A	N/A	U.S. harbor entrance and approach
Resource Exploration	1–5* m	99%	**	N/A	N/A	U.S. harbor entrance and approach
Engineering and Construction Vessels Harbor Phase	0.1****–5 m	99%	**	N/A	N/A	Entrance channel & jetties, etc.

(b)

BENEFITS	MEASURES OF MINIMUM PERFORMANCE CRITERIA TO MEET BENEFITS					
	ACCURACY (meters, 2 drms)	AVAILABILITY	CONTINUITY	INTEGRITY	TIME TO ALERT	COVERAGE
Fishing, Recreational and Other Small Vessels	8–20	99.7%	**	N/A	N/A	U.S. harbor entrance and approach

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

Minimum Performance Criteria: The PNT system accuracy required to provide useful information in the harbor entrance and approach phase of marine navigation varies from harbor to harbor, as well as with the size of the vessel. In the more restricted channels, accuracy in the range of 8 to 20 m (2 drms) may be required for the largest vessels. A need exists to better and more accurately determine these PNT requirements for various-sized vessels while operating in such restricted confines. PNT user conferences have indicated that for many mariners, the PNT system becomes a secondary tool to visual and audio aids to navigation, radar, and inter-ship communications when entering the harbor entrance and approach environment. Continuing efforts are being directed towards verifying user requirements and desires for PNT systems in the harbor entrance and approach environment.

Navigation in the harbor entrance and approach areas is accomplished through use of fixed and floating visual aids to navigation, radar, and audible warning signals. The growing desire to reduce the incidence of accidents and to expedite movement of traffic during periods of restricted visibility and ice cover has resulted in the implementation of the Vessel Traffic Service (VTS) and the Automatic Identification System (AIS) in certain port areas and investigation of the use of radio aids to navigation.

4.4.1.2.3 Coastal Phase

There is a need for continuous, all-weather PNT service in the coastal area to provide, at the least, the position fixing accuracy to satisfy minimum safety requirements for general navigation. These requirements are delineated in Table 4-5. Furthermore, the total navigation service in the coastal area must provide service of useful quality and be within the economic reach of all classes of mariners.

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

- the need for larger vessels to navigate within the designated one-way traffic lanes at the approaches to many major ports, in fairways established through offshore oil fields, and at safe distances from shallow water; and
- the need to define accurately, for purposes of observing and enforcing U.S. laws and international agreements, the boundaries of the Fishery Conservation Zone, the U.S. Customs Zone, and the territorial waters of the U.S.

Minimum Performance Criteria: Government studies have established that a navigation system providing a capability to fix position to an accuracy of 0.25 NM (460 m) will satisfy the minimum safety requirements if a fix can be obtained at least every 15 minutes. As indicated in Table 4-5, these requirements may be relaxed slightly for the recreational boaters and other small vessels.

In activities such as marine scientific research, hydrographic surveying, commercial fishing, and petroleum or mineral exploration, as well as in USN operations, there may be a need to establish position in the coastal area with much higher accuracy than that needed for safety of general navigation. In many of these special operations that require highly accurate positions, the use of radiodetermination would be classified as radiolocation rather than PNT. Navigation service for operation within the coastal area is provided by GPS services.

Table 4-5: Maritime User Requirements/Benefits for Purposes of System Planning and Development - Coastal Phase

(a)

REQUIREMENTS	MEASURES OF MINIMUM PERFORMANCE CRITERIA TO MEET REQUIREMENTS					
	ACCURACY (meters, 2 drms)	AVAILABILITY	CONTINUITY	INTEGRITY	TIME TO ALERT	COVERAGE
Safety of Navigation (All Ships)	0.25 NM (460 m)	99.7%	**	N/A	N/A	U.S. coastal waters
Safety of Navigation (Recreation Boats and Other Small Vessels)	0.25 – 2 NM (460 – 3,700 m)	99.0%	**	N/A	N/A	U.S. coastal waters

(b)

BENEFITS	MEASURES OF MINIMUM PERFORMANCE CRITERIA TO MEET BENEFITS					
	ACCURACY (meters, 2 drms)	AVAILABILITY	CONTINUITY	INTEGRITY	TIME TO ALERT	COVERAGE
Commercial Fishing (Include Commercial Sport Fishing)	0.25 NM (460 m)	99.0%	**	N/A	N/A	U.S. coastal and U.S. fisheries areas
Resource Exploration	1.0 – 100 m*	99.0%	**	N/A	N/A	U.S. coastal areas
Search Operations, Law Enforcement	0.25 NM (460 m)	99.7%	**	N/A	N/A	U.S. coastal and U.S. fisheries areas
Recreational Sports Fishing	0.25 NM (460 m)	99.0%	**	N/A	N/A	U.S. coastal areas

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

4.4.1.2.4 Ocean Phase

The requirements for safety of navigation in the ocean phase for all ships are given in Table 4-6. These requirements must provide a ship's master with a capability to avoid hazards in the ocean (e.g., small islands, reefs) and to correctly plan the approach to land or restricted waters. For many operational purposes, repeatability is necessary to locate and return safely to the vicinity of a maritime distress, as well as for special activities, such as hydrography, research, etc. Economic efficiency in safe transit of open ocean areas depends upon the continuous availability of accurate position fixes to enable the vessel to follow the shortest safe route with precision, minimizing transit time.

The requirements for the accuracy and frequency of position fixing on the high seas for safe general navigation under normal circumstances are not very strict. As a minimum, these requirements include a predictable accuracy of 2 to 4 NM coupled with a maximum fix interval of two hours or less. These minimum requirements would permit reasonably safe oceanic navigation, provided that the navigator understands and makes allowances for the probable error in navigation, and that more accurate navigation service is available as land is approached. While these minimum requirements would permit all vessels to navigate with relative safety on the high seas, more desirable requirements would be predictable accuracy of 1 to 2 NM and a fix interval of 15 minutes or less. The navigation signal should be available 95 percent of the time. Further, in any 12-hour period, the probability of obtaining a fix from the system should be at least 99 percent.

Table 4-6: Maritime User Requirements/Benefits for Purposes of System Planning and Development - Ocean Phase

(a)

REQUIREMENTS	MEASURES OF MINIMUM PERFORMANCE CRITERIA TO MEET REQUIREMENTS					
	ACCURACY (meters, 2drms)*	AVAILABILITY	CONTINUITY	INTEGRITY	TIME TO ALERT	COVERAGE
Safety of Navigation (All Craft)	2–4 NM (3.7–7.4 km) minimum; 1–2 NM (1.8–3.7 km) desirable	Worldwide	***	N/A	N/A	99% fix at least every 12 hours

(b)

BENEFITS	MEASURES OF MINIMUM PERFORMANCE CRITERIA TO MEET BENEFITS					
	ACCURACY (meters, 2drms)*	AVAILABILITY	CONTINUITY	INTEGRITY	TIME TO ALERT	COVERAGE
Large Ships Maximum Efficiency	0.1–0.25 NM** (185–460 m)	99%	***	N/A	N/A	Worldwide, except polar regions
Resource Exploration	10–100 m*	99%	***	N/A	N/A	Worldwide
Search Operations	0.1–0.25 NM (185–460 m)	99%	***	N/A	N/A	National Maritime SAR regions

* Distance Root Mean Squared, a measure of accuracy with a range 95.4 percent to 98.2 percent probability.
** Based on stated user need.
*** Dependent upon mission time.

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

Minimum Performance Criteria: Economic efficiency in transoceanic transportation, special maritime activities, and safety in emergency situations require or benefit from navigation accuracy higher than that needed for safety in routine, point-to-point ocean voyages. These requirements are summarized in Table 4-6. The predictable accuracy benefits may be as stringent as 10 m for special maritime activities, and may range to 0.25 NM for large, economically efficient vessels, including search operations. Search operations must also have a repeatable accuracy of at least 0.25 NM.

Navigation on the high seas is accomplished by the use of dead-reckoning, celestial fixes, self-contained navigation systems (e.g., inertial systems) and GPS or other GNSS. Worldwide coverage by ground-based systems is not available or practical; therefore, GPS is now the system of choice.

4.4.1.3 Future Marine PNT Requirements

The marine PNT requirements presented in the preceding discussions and tables are based on a combination of requirement studies, user inputs, and estimates; however, they are the product of current technology and operating practices and are, therefore, subject to revision as technologies and operating techniques evolve. Trends towards expanded use of electronic charts and the changing regulatory requirements for electronic chart display and information systems increases the need for reliable, accurate, available PNT services. The principal factors that will impact future requirements are safety, technology advances and innovation, economics, environment, and energy conservation.

Special PNT requirements may arise from new environmental laws and regulations designed to reduce marine vessel casualty events. Also, the role of commercial ships in military sealift missions or in areas where the electromagnetic spectrum or PNT services are affected may require additional PNT systems capabilities.

4.4.1.3.1 Safety

4.4.1.3.1.1 Increased Risk from Collision and Grounding

Approximately 160 million tons of hazardous cargoes (petroleum, chemicals, etc.) are carried on U.S. coastal and inland waterways annually. Additionally, the ever-increasing volume of other shipping, the ability to operate at increased speed, and the increasing number of smaller vessels act to constantly increase the risk of collision and grounding. Economic constraints also cause vessels to be operated in a manner that, although not unsafe, places more stringent demands on all PNT systems.

4.4.1.3.1.2 Increased Size and Decreased Maneuverability of Marine Vessels

The desire to minimize costs and to capture economies of scale in marine transportation have led to design and construction of larger vessels and unitized tug/barge combinations, both of which are relatively less powerful and maneuverable than their predecessors. Consequently, improved PNT performance is needed.

4.4.1.3.1.3 Greater Need for Traffic Management/Navigation Surveillance Integration

The foregoing trends underlie the importance of continued governmental involvement in marine vessel traffic management to assure reasonable safety in U.S. waters. PNT systems are an essential component of traffic management systems. The Automatic Identification System (AIS) plays an increasingly important role in areas such as Vessel Traffic Services (VTS and in vessel collision avoidance.).

4.4.1.3.2 Economics

4.4.1.3.2.1 Greater Congestion in Inland Waterways and Harbor Entrances and Approaches

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

4.4.1.3.2.2 All Weather Operations

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

4.4.1.3.3 Environment

As resource exploration opportunities and exploitation capabilities allow, energy companies will move farther offshore toward the U.S. outer continental shelf and to harsher and more technically demanding environments. In addition, fishing is expected to continue in the U.S. Exclusive Economic Zone. International conventions and regulatory compliance for marine diesel engine emissions will continue to require detailed reporting. In summary, these activities will sustain greater demand for PNT services of higher quality and for broadened geographic coverage in order to allow environmentally-sound development of resources and protection of the environment.

4.4.1.3.4 Energy Conservation

The need to conserve energy resources and to reduce costs provides powerful incentives for increased transportation efficiency, some of which could come from improved PNT systems.

4.4.2 Land User Requirements

4.4.2.1 Land Transportation Requirements

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

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

The navigation accuracy, availability, integrity, continuity, and coverage needs and requirements of land modes of transportation, as well as their associated security needs and requirements (including continuity of service), has been documented in the *Capability Development Document (CDD) Update for Global Positioning System (GPS) III Space Segment Satellite Vehicles (SV) 11 through 32, 4 March 2021* (Ref. 51). Examples of land transportation positioning and navigation system accuracy needs and requirements are shown in Table 4-7. In addition, terrain factors are very important and must be considered in the final system analysis.

In conjunction with use of PNT technologies, the 5.9 GHz band of radio spectrum is of critical importance to the Department of Transportation for reducing crashes, injuries and fatalities, while mitigating congestion. It is uniquely capable of supporting safety applications that could prevent or significantly reduce the severity of vehicle crashes in a manner not available through existing vehicle technology. The 5.9 GHz band is currently being used by State departments of transportation for vehicle to vehicle (V2V) and pedestrian collision avoidance, transit priority, traffic light control, traffic monitoring, travelers' alerts, automatic toll collection, traffic congestion detection, emergency vehicle signal preemption of traffic lights, and electronic inspection of moving trucks through data transmissions with roadside inspection facilities, as well as truck platooning.

Individual railroads and the Federal Railroad Administration (FRA) conducted tests of GPS and differential GPS starting in the mid-1980s to determine the requirements for train and maintenance operations. In June 1995, FRA published a Report to the Committees on Appropriations, *Differential GPS: An Aid to Positive Train Control* (Ref. 52), which concluded that differential GPS could satisfy the Location Determination System requirements for the next generation Positive Train Control (PTC) systems. In November 1996, FRA convened a technical symposium on GPS and its Applications to Railroad Operations to continue the dialogue on accuracy, reliability, and security requirements for railroads.

Starting in the late 1990s and continuing through the late ,2000s railroads began the development and deployment of GPS-based PTC starting with the Incremental Train Control System (ITCS) and the Electronic Train

Management System (ETMS). These GPS-based technologies were designed to (1) protect against train-to-train collisions, (2) prevent protect against train derailments due to overspeed train operations, (3) protect roadway workers working along the railroad right of way within work zone limits, and (4) prevent train movement through misaligned switches.

Initially, the use of these types of systems was entirely voluntary by the railroads. However, after a series of severe rail accidents, the Congress mandated the installation of PTC under the provisions of the Rail Safety Improvement Act of 2008 (RSIA 08). Because of RSIA 08, the overwhelming majority of U.S. railroads that have been mandated by law to install PTC are implementing two main types of GPS-based PTC systems: ITCS and the Interoperable Electronic Train Management Systems (I-ETMS), a newer version of the earlier ETMS. These systems provide PTC coverage over approximately 60,000 miles of the 140,000 miles of the national rail system having PTC.

Integrity solutions for land transportation functions are dependent on specific implementation schemes. Integrity values range between 0.9 and 0.999999999, depending on the function. In order to meet this integrity value, GPS will most likely not be the sole source of positioning. It will be combined with map matching, dead reckoning, and low-rate aiding sensors (i.e., LIDAR), as well as other systems, to form an integrated approach, ensuring sufficient accuracy, availability, and integrity of the navigation and position solution to meet user needs.

Integrity needs for freight, intercity passenger, and commuter rail systems are 0.99999 for most functions, with a minimum availability requirement for rail of 99.9 percent. Those for transit rail systems are still under study by the FTA and are not available at this time. The availability requirement for highways and transit rail systems is estimated as 99.7 percent.

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

GPS, in conjunction with other systems, is used in land vehicle navigation. Government and industry have sponsored a number of projects to evaluate the feasibility of using existing and proposed PNT systems for land navigation. Operational tests have been completed that use in-vehicle navigation systems and electronic mapping systems to provide real-time route guidance information to drivers. GPS is used for automatic vehicle location for bus scheduling and fleet management. Several transit operational tests will use automatic vehicle location for automated dispatch, vehicle re-routing, schedule adherence, and traffic signal pre-emption.

Railroads and FRA have tested, and continue to test GPS and GPS augmentations as part of PTC, track defect location (TDL), automated asset mapping (AAM), automated asset tracking (AAT), roadway worker portable remote terminals, and bridge monitoring systems. PTC is in operation on all required freight and passenger route miles, with the next-generation PTC development underway. Deployment of the other systems is in progress. GPS and dead-reckoning/map-matching are being developed as systems that take advantage of PNT systems and at the same time improve safety and efficiency of land navigation. Recent research has highlighted use of low-rate aiding sensors to support vehicle positioning and to support critical PNT services essential for advanced autonomous train operations as well as next generation signal and train control systems. In terms of autonomous trains (a very long term goal) but also further automation of trains, GPS accuracy is critical. PNT is a critical function for positional accuracy (which is critical for vital train protection via PTC).

4.4.2.2 Categories of Land Transportation

4.4.2.2.1 Highways

PNT applications for highway use range from precise static and dynamic surveys (for project control before and during construction or creating as-built drawings when construction is finished) to asset tracking and route guidance. For the precise applications, geodetic accuracies, moderate integrity, and reliability are required factors. The less stringent, non-safety critical applications have commensurately reduced accuracy, integrity, and reliability.
Tables 4-7 and 4-8 identify current highway and trucking user requirements. Applications are being developed that rely on PNT as an input to an overall navigation solution for safety applications. Today, GPS observation data from the GNSS ground network of NOAA's Continuously Operating Reference Stations (CORS)) provides highway transportation agencies with the critical survey-grade solutions needed for building and maintaining our nation’s highways. In addition, having geodetic real-time networks that are aligned to the NGS National Spatial Reference System provides an opportunity for accurate positioning control on smart highways for autonomous vehicles nationwide.

Within the surface transportation system, Federal agencies are developing ways to improve the safety and efficiency of the nation’s surface transportation system. Significant effort has gone into developing approaches to address safety and efficiency to reduce the loss of life and injuries. In recent years, GPS and its augmentations, along with other PNT sources and sensors, have been a key focus and the subject of ongoing research. Use of the 5.9 GHz band for traffic safety is critical to the success of connected and automated vehicles as it ensures that automated light duty vehicles, trucks and motor coaches, rail, transit, and infrastructure and traffic devices across all surface modes can work in the safest possible way help to reduce, reducing the U.S. road deaths (37,000 in 2019) and injuries (2.7 million that occur in the U.S. each year in 2019). DOT has conducted and continues to conduct Intelligent Transportation Systems (ITS) research on both vehicle and infrastructure systems to further promote the safety and reliability of the movement of people and freight. The National ITS Architecture's systems framework, based on common user services delivered by transportation organizations, is being enhanced through further research into the Connected Vehicle Reference Implementation Architecture.

Table 4-7: Highway User Requirements

REQUIREMENTS	MEASURES OF MINIMUM PERFORMANCE CRITERIA TO MEET REQUIREMENTS					
	ACCURACY (meters, 2 drms)	AVAILABILITY	CONTINUITY	INTEGRITY (Alert Limit)	TIME TO ALERT	COVERAGE
Navigation and route guidance	1–20 m	>95.0%	*	2–20 m	5 s	Nationwide / Surface Coverage
Automated vehicle monitoring	0.1–30 m	>95.0%	*	0.2–30 m	5 s–5 min	Nationwide / Surface Coverage
Automated vehicle identification	1 m	99.7%	*	3 m	5 s	Nationwide / Surface Coverage
Public safety	0.1–30.0 m	95.0-99.7%	*	0.2–30 m	2–15 s	Nationwide / Surface Coverage
Resource management	0.005–30 m	99.7%	*	0.2–1.0 m	2–15 s	Nationwide / Surface Coverage
Collision avoidance	0.1 m	99.9%	*	0.2 m	5 s	Nationwide / Surface Coverage
Geophysical survey	1 m	**	*	***	N/A	Nationwide / Surface Coverage
Geodetic control	0.01 m	**	*	***	N/A	Nationwide / Surface Coverage
Accident Survey	0.1–4.0 m	99.7%	*	0.2–4.0 m	30 s	Nationwide / Surface Coverage
Emergency Response	0.1–4.0 m	99.7%	*	0.2–4.0 m	30 s	Nationwide / Surface Coverage
Connected Vehicle Initiative	0.1 m	99.9%	*	0.2	5 s	Nationwide / Surface Coverage

* Continuity applies to phases of operations. For highway applications, this has not been defined.
** In these instances, availability of a real-time solution is not needed, but is beneficial.
*** This is typically done using post-processing techniques. While integrity of the data is important, it is not used to directly support safety and can be provided after data is collected.

Research into developing applications that improve the safety and efficiency of the surface transportation system is helping to focus the determining of PNT systems requirements. Ongoing efforts are examining what is currently available and determining what levels of accuracy, integrity, and availability are required. Since these systems integrate the solution from GPS, GPS augmentations, inertial systems, map-matching systems, wheel rotation counters, localized beacons, etc., defining the required parameters to ensure resiliency must also examine the level of dependence and inter-dependence of each of these subsystems.

For many of safety systems, the need for sub-meter accuracies have been identified to improve safety and efficiency. Combined with other subsystems in the vehicle and the infrastructure, an accuracy in the order of as little as 10 cm horizontal (with 95 percent availability) has been suggested. Ongoing research will be needed to validate this accuracy more definitively, as well as identifying the required levels of integrity and availability and the effects of reference frame differences.

Table 4-8: Trucking User Services Requiring Use of PNT

REQUIREMENTS	MEASURES OF MINIMUM PERFORMANCE CRITERIA TO MEET REQUIREMENTS					
	ACCURACY (meters, 2 drms)	AVAILABILITY	CONTINUITY	INTEGRITY (Alert Limit)	TIME TO ALERT	COVERAGE
Truck Parking	2–20 m	95%	TBD	50 m	5 s	Nationwide / Surface Coverage
Geo-fencing / Facility Access	10–20 m	99%	TBD	10 m	5 s	Nationwide / Surface Coverage
Hazardous Materials (HAZMAT) Tracking	10–20 m	99%	TBD	10 m	5 s	Nationwide / Surface Coverage
Vehicle/Trailer Tracking	20 m	95%	TBD	50 m	5 s	Nationwide / Surface Coverage
Cabotage Violations	10–20 m	99%	TBD	10 m	5 s	Nationwide / Surface Coverage
Fleet Management	20 m	95%	TBD	50 m	5 s	Nationwide / Surface Coverage
Commercial Driver's License (CDL) Skills Test	5–20 m	99%	TBD	10 m	5 s	Nationwide / Surface Coverage

4.4.2.2.2 Transit

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

A vital link in the evolution of advancing public transit services,—including bus rapid transit (BRT), light rail, streetcars, heavy rail, and bus transit vehicles, —is the integration of GPS technologies and mobile devices (e.g., cell phones) to provide the more “interconnected traveler” information. As part of the 2009–2029 Strategic Plan, the Federal Transit Administration Intelligent Transportation System Program identified the need for more comprehensive traveler data that would complement the public’s need for ever-increased mobility.

Currently, the integrity requirements for transit PNT applications have not been determined; however, current thinking is that user requirements will be generally similar to Highway User Requirements. Therefore, Table 4-7 may be used as a reference for transit. As transit research starts to define current applications and develop newer applications for the safety and mobility that integrate GPS, DGPS, and other PNT solutions, specific requirements for accuracy, integrity, and availability will be established for the transit PNT systems. Ongoing and future research will also coordinate with FHWA, FTA, FRA, and OST-R to define and enhance these requirements.

4.4.2.2.3 Rail

The railroad industry has not identified any need for continued NDGPS based on the performance of current GPS and non-NDGPS differential systems, as well as preliminary performance results from the modernized GPS system being deployed. The GPS-dependent railroad Positive Train Control (PTC) systems currently deployed and operational are not dependent upon the availability of NDGPS. Other railroad system applications requiring accurate positioning information are using GPS or non-NDGPS differential GPS systems. However, several U.S. railroads have confirmed the need for use of non-U.S. GNSS constellations to augment the U.S. GNSS constellation to meet both PTC availability and positional accuracy requirements in high latitude, dense urban, and mountain/forested environments. Table 4-9 identifies current rail user requirements.

Table 4-9: Rail User Requirements

REQUIREMENTS	MEASURES OF MINIMUM PERFORMANCE CRITERIA TO MEET REQUIREMENTS					
	ACCURACY (meters, 2 drms)	AVAILABILITY	CONTINUITY	INTEGRITY (Alert Limit)	TIME TO ALERT	COVERAGE*
Positive Train Control (PTC)	1.0 m	99.9%	N/A	2 m	6 s	Railroad right of way in all 50 states and District of Columbia
Track Defect Location (TDL)	0.3 m	99.9%	N/A	0.6 m	30 s	Railroad right of way in all 50 states and District of Columbia
Automated Asset Mapping (AAM)	0.2 m	99.9%	N/A	0.4 m	30 s	Railroad right of way in all 50 states and District of Columbia
Surveying	0.02 m	99.7%	N/A	0.04 m	30 s	Railroad right of way in all 50 states and District of Columbia
Bridge and Tectonic Monitoring for Bridge Safety	0.002 m	99.7%	N/A	0.004 m	30 s	Railroad right of way in all 50 states and District of Columbia
Telecommunications Timing	340 nsec	99.7%	N/A	680 nsec	30 s	All 50 states and District of Columbia

* Currently there are no railroads requiring PTC in the State of Hawaii.

Railroads have an "advantage" with respect to position determination that other transportation modes do not. Train location is a one-dimensional problem, with well-defined discrete points (switches) where the potential for diverging movements exists. The most frequent interval at which successive turnouts can be located (locations at which a train may diverge from its current route over a switch) is 15 m. Since the train is constrained to be located on a track, this collapses positioning from a two- or three-dimensional problem into a one-dimensional problem. The one-dimensional nature of the problem opens up opportunities for the use of other position determination methodologies.

For example, the single most stringent requirement for the location determination system to support Positive Train Control (PTC) system operation is the ability to determine, with a probability of 0.99999 and a minimum track spacing of 3.5 m center-to-center, which parallel track a given train is occupying.[14] While GPS alone cannot always meet this requirement, GPS in conjunction with differential corrections, map matching, inertial navigation systems (INS), accelerometers, and other

[14] PTC is a computerized command control system which protects against train collision, over speed derailment, encroachments of trains into authorized track work zones, and movement through a misaligned switch. The systems are interoperable between different railroad companies and allow movements of trains between companies at track speeds without stopping.

devices and techniques can provide both the accuracy and continuity of service required.

4.4.2.2.3.2 Other Potential Rail Uses

In addition to position and timing needs for safety critical PTC system operations, railroads have a wide range of position and timing needs to support other railroad functions. These include infrastructure surveying and mapping, track defect location, weather forecasting, locomotive control, and high-capacity and trusted communications. The position and timing needs for these other non-PTC functions can also be satisfied by a variety of GPS-based and non GPS-based systems.

4.4.2.3 Other Land User Requirements

Positioning and navigation also support many civil agriculture and natural resource applications, including natural resources inventories and monitoring, conservation planning and application, wildlife and wetland management, silviculture and grasslands management, water management, fire protection, and law enforcement. GPS PNT services are interwoven into the American agricultural economy. Many natural resource applications use code range and real-time differential solutions. Some applications have greater accuracy requirements and utilize carrier-phase solutions with post processing data obtained from the CORS or from real-time differential correction networks. Requirements for signal sensitivity in compromised topography and foliage, functionality in harsh environment conditions, and processing efficiency to promote longer duration of usage are all more acute requirements considerations for individual users constrained to handheld devices. Requirements for non-transportation land users are shown in Table 4-10.

Table 4-10: Other Land User Requirements

REQUIREMENTS	MEASURES OF MINIMUM PERFORMANCE CRITERIA TO MEET REQUIREMENTS					
	ACCURACY (meters, 2 drms)	AVAILABILITY	CONTINUITY	INTEGRITY (Alert Limit)	TIME TO ALERT	COVERAGE
Resources Inventory, Soil Survey, Wetlands Monitoring, Surveying For Water Control, and Conservation Planning in an Agricultural Landscape Setting.	0.03–10 m	99%	N/A	0.09–15 m	5 s–5 min	Global/Surface Coverage
Precision Application, Harvest Mensuration, and Precision Guidance	0.3 m	99%	N/A	0.6 m	5 s	Global/Surface Coverage
Precision Irrigation Surveying and Surveying for Land Leveling	0.15 m	99%	N/A	0.25 m	5 s	Global/Surface Coverage

REQUIREMENTS	MEASURES OF MINIMUM PERFORMANCE CRITERIA TO MEET REQUIREMENTS					
	ACCURACY (meters, 2 drms)	AVAILABILITY	CONTINUITY	INTEGRITY (Alert Limit)	TIME TO ALERT	COVERAGE
Search and Rescue	1–5 m	99%	N/A	2–10 m	TBD	Global
Fire Management and Law Enforcement	1–5 m	99%	N/A	2–10 m	TBD	Global
Earthquake and volcanic hazards monitoring	1–10 mm	TBD	TBD	2–20 m	TBD	Global
Resource Management	0.5–2.0 m	TBD	TBD	1–4 m	TBD	Global
Wildlife studies and tracking	1–10 m	TBD	TBD	2–20 m	TBD	Global

4.5 Subsurface PNT User Requirements

4.5.1 Marine User Requirements

Subsurface marine PNT applications include naval submarines, offshore oil exploration, deep-sea salvage, trans-oceanic cabling, deep-sea fishing, and even recreational SCUBA diving. The positioning and timing requirements vary drastically depending on the application. Submarines use PNT for navigating the ocean floor and deployment of weapon and intelligence gathering systems. Oil exploration PNT needs include the operation of remotely operated vehicles, installation of marine structures and seabed mapping, bathymetric surveys, submarine equipment installation, well drilling location selection, pipeline installation, and spools metrology. The subsurface environment makes practical employment of traditional PNT sensors and systems, such as GPS, more of a challenge. Subsurface marine users typically rely on systems more adept to this milieu, such as sound navigation and ranging (SONAR), compasses, and water pressure sensors, but research may lead to development of systems such as underwater GPS pseudolites. Requirements for subsurface marine users are shown in Table 4-11.

Table 4-11: Subsurface Marine User Requirements

REQUIREMENTS	MEASURES OF MINIMUM PERFORMANCE CRITERIA TO MEET REQUIREMENTS					
	ACCURACY (meters, 2 drms)	AVAILABILITY	CONTINUITY	INTEGRITY (Alert Limit)	RECORDING RATE	COVERAGE
Subsurface Marine Applications	0.1–5.0 m	90–99%	N/A	0.2–10 m	1–15 s	Global

4.5.2 Land User Requirements

Subsurface land applications include mining operations, oil exploration, underground construction, utility engineering, security robotics, underground tunnel detection, and positioning of seismic activity. Subsurface applications typically require a great deal of accuracy. Requirements for subsurface land users are shown in Table 4-12.

Table 4-12: Subsurface Land User Requirements

REQUIREMENTS	MEASURES OF MINIMUM PERFORMANCE CRITERIA TO MEET REQUIREMENTS					
	ACCURACY (meters, 2 drms)	AVAILABILITY	CONTINUITY	INTEGRITY (Alert Limit)	RECORDING RATE	COVERAGE
Subsurface Land Applications	0.01–2.0 m	90–99%	N/A	0.02–4.00 m	1–15 s	Global

4.6 Other PNT Applications and Requirements

The use of PNT systems, especially GPS, for non-navigation applications is both extensive and quite diverse. Most of these applications, the nature of which is discussed in sections 4.6.1 through 4.6.7, can be grouped under the following broad headings:

- Geodesy and surveying;
- Mapping and Charting;
- Geographic information systems (GIS);
- Agriculture and natural resources applications (already addressed in 4.4.2.3);
- Geophysical applications;
- Meteorological applications;
- Timing and frequency; and
- Location-based services.

4.6.1 Geodesy and Surveying

Since the mid-1980s, the geodesy and surveying community has made extensive use of GPS for worldwide positioning. Today, GPS is used almost exclusively by the geodesy and surveying community to establish geodetic reference networks. NOAA's National Geodetic Survey (NGS) currently uses GPS to provide the geometric component of the National Spatial Reference System (NSRS) (latitude, longitude, and ellipsoid height coordinates and velocities) through the management of the NOAA CORS Network (NCN). The NCN provides users with their primary access to the NSRS and will become especially important when NGS completes a modernization of the NSRS to produce new reference frames in the U.S. and territories around 2025.

To provide the best possible access to the modernized NSRS and support the ITRF, NGS started a project, in partnership with NASA and NSF, called Foundation CORS to define and build a federally-owned "backbone" of reliable, high-quality NOAA CORS Network stations. NGS pulls together GPS observations from the NCN stations for use in post-processing applications, such as OPUS, GPS satellite orbit determination, defining the national reference frames, and supporting the ITRF. The NCN offers GPS the observation data online in the Receiver Independent Exchange (RINEX) format from ~1750 active stations, including some Network of the Americas (formerly Plate Boundary Observatory) stations belonging to the National Science Foundation, the soon-to-be-decommissioned DGPS stations belonging to the USCG, and WAAS stations belonging to the FAA. Details of the NOAA CORS Network are provided in Appendix B.6.

GPS is used extensively in a large number of surveying applications. These include positioning of points in support of reference system densification, mapping control, cadastral surveys, engineering projects, transportation projects, utility infrastructure projects, and terrain mapping. These applications involve both positioning of fixed points and after-the-fact positioning of moving receivers using kinematic methodologies.

Recently, real-time kinematic (RTK) use of GPS has become the most popular use of GPS in surveying. The RTK method relies on real-time networks (RTNs) of GPS ground stations that broadcast correctors and allow surveyors, with appropriately configured receivers, to achieve real-time positioning to several centimeters of accuracy. NGS has a project underway that will allow the numerous RTN operators in the United States to align their networks to the NSRS, ensuring accuracy and compatibility of the independent RTNs. Many other high-accuracy (i.e., within a few centimeters) geodetic and surveying activities involve post-processing differencing techniques using the dual-frequency carrier phase observables. Single-receiver positioning software can now produce sub-decimeter point positioning accuracy. The accuracy requirements for various surveying applications are shown in Table 4-13.

Table 4-13: Surveying and Mapping User Requirements

REQUIREMENTS	MEASURES OF MINIMUM PERFORMANCE CRITERIA TO MEET REQUIREMENTS						
	ACCURACY (meters, 2 drms)		AVAILABILITY	CONTINUITY	INTEGRITY (Observing Session Duration)	RECORDING INTERVAL	COVERAGE *
	Horizontal	Vertical					
Static Survey *	0.015	0.04	99%	$1–1x10^{-4}$/hr. to $1–1x10^{-8}$/hr.	4 hr	30 s	Global
Rapid Survey *	0.03	0.08	99%	$1–1x10^{-4}$/hr. to $1–1x10^{-8}$/hr.	15 min	30 s	Global
Kinematic Survey **	0.04	0.06	99%	$1–1x10^{-4}$/hr. to $1–1x10^{-8}$/hr.	Two 3-min sessions separated by 45 min	1 s	Global
Hydrographic Survey ***	3	0.15	99%	$1–8x10^{-6}$/15 s	1 s	1 s	Global
Topographic Mapping	1–10 mm	TBD	TBD	TBD	TBD	TBD	TBD
Cadastral Survey	1–10 cm	TBD	TBD	TBD	TBD	TBD	TBD
Ground Control Points	1 m	TBD	TBD	TBD	TBD	TBD	TBD

* Using OPUS-S.
** Using real-time GNSS networks.
*** IHO Standards for Hydrographic Surveys are published in IHO publication S-44, which can be obtained gratis from the publication section at www.iho.int.

4.6.2 Mapping and Charting

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

A similar application is made by hydrographic survey vessels for position and attitude determination for multi-beam survey systems. Also, three-dimensional GPS hydrographic surveys are now being conducted to relate seafloor height to the Ellipsoid Referenced Tidal Datum Model (ERTDM) and The North American Datum of 1983 (NAD 83 which uses the Geodetic Reference System (GRS80) ellipsoid). Seafloor depth locations will eventually be related to both the low water tidal datum and the Ellipsoid

Referenced Tidal Datum Model (ERTDM) / North American Datum of 1983 (NAD 83), which will allow systems to alarm for shoal waters/obstructions without application of tides.

4.6.3 Geographic Information System (GIS) Applications

GIS applications support recording, planning, analysis, and information output for diverse applications that include natural resource applications, demographics, site planning, archeology, transportation routing, and many others. GIS is supported by location-based information derived via GPS or through remote sensing. The availability of GPS, its augmentations, and other PNT services has accelerated location-based information data gathering to support dynamic and changing conditions. Most location-based information derived with PNT is generally more accurate than other geospatial layers in the GIS. The level of required accuracy for PNT solutions is usually defined by the purpose of the GIS layer. An example of accuracy variability would be the difference between representing a feature on a landscape versus the pinpoint accuracy of a city utility for asset management. This variability in required accuracy means PNT solutions for GIS vary from simple GPS code observations, with or without differential, to very accurate carrier phase observations, post-processed for centimeter-level positioning.

4.6.4 Geophysical Applications

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

The geophysical community is moving rapidly from post-processing to real-time applications. In southern California and throughout Japan, GPS station networks currently transmit data in real-time to central data facilities to support earthquake early warning systems. It is also utilized to measure the strains at the plate boundaries and has greatly contributed to the advancement of geophysics. GPS position measurements are also being used extensively to monitor the motions of glaciers and ice sheets. Crustal rebound is monitored, as well, to estimate the glacial loss due to climate changes.

The IGS Real-Time Service now provides satellite orbit information, satellite clock error, and ionospheric corrections in real-time and low-latency GPS data files. Many projects for the monitoring of ground motion are currently being supported by the National Science Foundation (NSF), the U.S. Geological Survey, and NASA, as well as State, Tribal, Territorial, regional, and local agencies.

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

4.6.5 Meteorological Applications

The international meteorological community launches three quarters of a million to a million weather radiosondes and drop-wind-sondes worldwide each year to measure such atmospheric parameters as pressure, temperature, humidity, and wind speed and direction. Radio direction finding and GPS are methods used for weather instrument tracking, wind speed and direction determination. GPS-based upper-air systems are in wide use. Measurements of refraction of the two GPS carrier phases can be used to provide continuous estimates of total precipitable water vapor. The ability to provide accurate water vapor information has been demonstrated in the research mode. Development of research meteorological GPS station networks has begun.

Radio signals travel from the satellite to the GPS antenna on the ground, passing through the Earth's ionosphere. The charged plasma of the ionosphere causes a path delay and phase advance. The amount of total electron contents (TEC) in the ionosphere is a major error source for the positioning using GPS. The anomalous energy introduced by a geomagnetic storm can cause damage to the telecommunication system and to electronics on the ground. These can be detected by monitoring GPS signals on the ground.

4.6.6 Time and Frequency Applications

GPS-provided time and frequency is a critical component of our national infrastructure, supporting innumerable applications, which continue to proliferate rapidly. GPS-provided time and frequency is also used in many DoD-specific applications.

All critical infrastructure sectors have precision timing applications, including the Communications and Energy-Electricity sectors, which are lifeline functions, "essential to the operation of most critical infrastructure sectors."[15] GPS is used extensively for communication network synchronization supporting cell phone and traditional telephone

[15] National Infrastructure Protection Plan (NIPP) 2013 (Ref. 53)

applications. Power companies use GPS for measuring phase differences between power transmission stations, for event recording, for post-disturbance analysis, and for measuring the relative frequency of power stations.

The USG recognizes the criticality of accurate timing services (time and frequency) and will continue its coordination with the critical infrastructure communities and Sector Risk Management Agencies to ensure that timing operations are secure and resilient. In addition, as part of the multi-agency working group focused on complementary capabilities to GPS, the Department of Homeland Security (DHS) is sponsoring studies to validate PNT requirements for critical infrastructure sectors. The information in Table 4-14 includes projected minimum requirement information, which will be updated and validated with critical infrastructure partners after the studies are completed. It is possible that the requirements studies may identify more stringent timing requirements than those stated below.

Table 4-14: Precision Timing Requirements found in the Life-Line Sectors (DHS Study 2017)

Critical Infrastructure (Life-Line Sectors)	Timing / Frequency Stability Requirement
Electricity	1.0 μs: Phasor Measurement Units
Communications (Wired & Wireless)	1.5 μs: 4G-LTE/Network backbone
	50–200 ppb: Frequency Stability
Emergency Services (FIRSTNET)	1.5 μs: 4G-LTE/Network backbone
	50–200 ppb: Frequency Stability
Financial Services	50 ms: Regulatory

4.6.7 Location-Based Services

Location-based services (LBS) involve the use of PNT to enable services that exploit knowledge about where an information device user is located. Examples included location-targeted advertising or allowing a user to find the nearest business of a particular type. Many of these services could involve use indoors and in urban environments. LBS includes applications that fuse various information (navigation, tracking, location of underlying infrastructure) to create a picture of the environment. With the dramatic surge in cell phone use, this technology is critical to support emergency assistance services like Enhanced 911 (E-911) and assists in tracking the location of emergency assets to help coordinate the efforts of first responders. The Next-Generation 911 (NG911) engineering architecture, aimed at updating the 911 service infrastructure in the United States and Canada, allows for emergency connections via text, images, video, and data transmission to the public safety answering point, in addition to calling 911 from any phone. Highly accurate LBS are required to affect the transition to NG911.

5

Operating Plans

This section summarizes the plans of the USG to provide PNT systems and services for use by the civil and military sectors. It focuses on three aspects of planning: (1) the efforts needed to maintain existing systems in a satisfactory operational configuration; (2) the development needed to improve existing system performance or to meet unsatisfied user requirements in the near term; and (3) the evaluation of existing and proposed PNT systems to meet future user requirements. Thus, the plan provides the framework for operation, development, and evolution of systems.

5.1 Global Positioning System

GPS is a dual-use, space-based PNT system owned by the USG, and operated by DoD, to meet defense and homeland security, civil, commercial, and scientific needs. The GPS provides two levels of service: SPS which uses the C/A code on the L1 and L5 frequencies, and PPS which uses the P(Y) code on both the L1 and L2 frequencies. Access to the PPS is restricted to U.S. Armed Forces, U.S. Federal agencies, and select allied armed forces and governments. These restrictions are based on U.S. national security considerations. The SPS is available to all users on a continuous, worldwide basis, free of any direct user charge.

The specific capabilities provided by SPS are published in the GPS SPS Performance Standard (Ref. 19) available from GPS.gov on their Performance Standards & Specifications page: http://www.gps.gov/technical/ps/.

DoD provides a 48-hour advance notice of changes in the constellation operational status, other than planned GPS interference testing, which affects the service being provided to GPS SPS users in peacetime. The USG provides notification of changes in constellation operational status that affect the service being provided to GPS users or if a problem in meeting performance standards is anticipated. In the case of a scheduled event affecting service provided to GPS users, the USG issues an appropriate Notice Advisory to Navstar Users (NANU) at least 48 hours prior to the event, in accordance with the GPS SPS PS (Ref. 19).

Coordination of planned interference testing activities nominally begins 60 days before testing events. The USCG posts approved test information on the web for all users once an activity is approved. FAA typically also posts test information not earlier than 72 hours before an activity begins. DoD notice is also given to the USCG NAVCEN Navigation Information Service (NIS) and the FAA Notice to Airmen (NOTAM) system. The NIS and NOTAM systems will announce unplanned system outages resulting from system malfunctions or unscheduled maintenance.

GPS will a primary federally-provided PNT system for the foreseeable future. GPS will be augmented and improved to satisfy future military and civil requirements for accuracy, availability, integrity, continuity, and coverage. The USG has stated that DoD will maintain a baseline 24-satellite constellation. The April 2020 SPS PS (Ref. 19) provides for an expandable 24-slot constellation that DoD has implemented. The constellation will be contracted back to the baseline 24 slots if the additional satellites are no longer available to support the specific expanded slots.

5.1.1 GPS Modernization

The GPS modernization effort focuses on improving positioning and timing accuracy, availability, integrity monitoring support capability, and modernization of the Operational Control Segment. As these system enhancements are introduced, users will be able to continue to use existing receivers that are compliant with *Navstar GPS Space Segment/Navigation User Interfaces, Interface Specification* (IS-GPS-200) (Ref. 54), as signal backward compatibility is a requirement for both the military and civil user communities. Although current GPS users will be able to operate at the same, or better, levels of performance that they enjoy today, users will need to modify existing user equipment or procure new user equipment in order to take full advantage of new signal structure enhancements. Users can participate in the modernization of the GPS enterprise through the USAF's Interface Control Working Group (ICWG), which coordinates all changes to the public GPS technical baseline prior to implementation.

GPS modernization is a multi-phase effort to be executed over the next 15 or more years. The USG is introducing three additional coded civil signals to the existing civil signal, L1 C/A, to support future civil applications:

- L1C, at a center frequency of 1575.42 MHz, to promote interoperability with other GNSS. This signal is being adopted by foreign providers and users as an international standard;

- L2C, at a center frequency of 1227.6 MHz, to support dual frequency civil PNT; and

- L5, at a center frequency of 1176.45 MHz, to support dual frequency PNT that meets the needs of critical safety-of-life applications, such as civil aviation.

In addition, a secure and spectrally-separated military M-Code will be broadcast on the L1 and L2 frequencies. The first launch of an L2C-capable satellite (GPS Block IIR-M) was in 2005, and the first satellite with operational L5 capability (GPS Block IIF) was launched in May 2010. Twenty-four L2C-capable GPS satellites are projected to be on orbit, with dependency on GPS III SV05, by July 2021, and 24 GPS L5-capable satellites are projected to be on orbit, with dependency on GPS IIIF SV11, by Q4FY27 (i.e. September 2027). These dates are current projections based on projected launch schedules and estimated satellite reliability parameters which are recomputed annually. Providing these 2nd and 3rd frequency civilian signals will allow dual-frequency civilian users to directly compensate for ionospheric effects and thus achieve greater accuracy than previous reliance on a single-frequency capability. These additional signals will also foster the development of tri-frequency GPS applications. The first L1C-capable satellite (GPS Block III) was launched December 2018. The DoD will make the L1C code available after a control segment modification (OCX Block 1) is operational to control that signal. Satellites will be launched based on constellation sustainment need and availability of launch vehicles.

The USG commits to maintaining the existing GPS L1 C/A, L1 P(Y), L2C, and L2 P(Y) signal characteristics that enable codeless and semi-codeless GPS access until at least two years after there are 24 operational satellites from primary slots broadcasting L5 with fully-functional navigation messages. Barring a national security requirement, the USG does not intend to change these signal characteristics before then. Twenty-four satellites broadcasting the L5 signal is estimated to occur in 2029 This will allow for the orderly and systematic transition of users of semi-codeless and codeless receiving equipment to the use of equipment using modernized civil-coded signals. It is expected that 24 operational satellites broadcasting L2C will be available by 2022, GPS SV06, with the corresponding ground segment control capability available by 2023, enabling transition to that signal at this earlier date. Civilian users of GPS are encouraged to start their planning for transition now.

The USAF is now transmitting continuous CNAV message-populated L2C and L5 signals prior to fielding the Next Generation Operational Control Segment. The message-populated broadcast began in April 2014. The USAF is broadcasting L2C messages with the health bit set “healthy” and with the L5 messages set “unhealthy,” but as greater experience with the L5 broadcast and implementation of signal monitoring are achieved, this status will be reviewed and revisited. Since full implementation in December 2014, CNAV user range error should meet or exceed the legacy signals. However, availability will remain low and CNAV-derived user position accuracy may be poor until more L2C and L5 capable satellites are operational. Future tests and implementation of the remaining CNAV message types will be announced. This provision of populated signals will facilitate development of compatible user equipment and a CNAV Operations Concept; however, users are reminded that they should not be used for safety-of-life or other critical applications until the L2C and L5 signals are declared fully operational.

In May 2008, the USAF awarded the development contract for ten next-generation GPS satellites, known as GPS III. The first GPS III launched in December 2018. GPS III satellites will improve the overall accuracy, availability, and integrity of the GPS constellation, as well as provide increased anti-jam performance to meet the future needs of civil and military users. These satellites will also be broadcasting the L1C signal, an interoperable signal with other GNSS.

GPS IIIF is the follow-on version of the first ten GPS III satellites which are in various stages of manufacture. GPS IIIF retains the existing capabilities and improvements built into GPS III and includes Regional Military Protection (RMP) power. RMP allows GPS IIIF satellites to focus additional power in selected regions around the globe in order to overcome interference. GPS IIIF will also host a search and rescue beacon repeater as a secondary payload.

5.1.2 Plans for Mitigating Disruptions to GPS

Like all radio-based services, GPS is subject to interference from both natural and human-made sources. For this reason, the USG strongly encourages all GPS users to be aware of the impacts of GPS interference and incorporate or integrate alternative PNT sources where needed to ensure continued operations. This section discusses sector-specific mitigation and backup capabilities. In accordance with NSPD-39 (Ref. 13) (superseded by Space Policy Directive-7, issued by President Trump on January 15, 2021) (Ref. 70), the Secretary of Transportation, in coordination with the Secretary of Homeland Security, is responsible for the development, acquisition, operation, and maintenance of backup PNT capabilities that can support critical transportation, homeland security, and other critical civil and commercial applications.

There are multiple ways to mitigate disruptions to GPS. GPS PPS receivers are less susceptible to disruptions. Alternative PNT systems can play a vital role as a backup mechanism during loss of GPS signals or as an improvement to the overall PNT application. For example, INS is an alternative PNT system, which when integrated with GPS, improves accuracy and robustness. The loss of GPS in INS-GPS coupled systems for a significant length of time can cause unacceptable error. This can be mitigated through use of improved gravitational models and attitude reference systems.

As part of wider efforts to make PNT for critical infrastructure more secure and resilient, DHS is conducting vulnerability and impact assessments on GPS receivers. DHS is also exploring ways to improve the ability to identify and mitigate disruptions to GPS signals.

While alternative back-up methods for maintaining GPS signals are crucial to users of the service, it may be necessary to employ legal remedies to investigate possible criminal activity or acts of terrorism in order to prevent long-term effects against critical infrastructure in the homeland. Interagency cooperation provides for integrated coordination of efforts to mitigate interference to GPS signals. Government agencies are coordinating to provide multiple resources to locate, track, and mitigate both unintentional and intentional interference to GPS signals. DHS, through the National Cybersecurity and Communications Integration Center, developed and published a paper titled Improving the Operation and Development of Global Positioning System (GPS) Equipment Used by Critical Infrastructure. This paper can be found at https://www.us-cert.gov/sites/default/files/documents/Improving_the_Operation_and_Development_of_Global_Positioning_System_%28GPS%29_Equipment_Used_by_Critical_Infrastructure_S508C.pdf.

This guidance document identifies 22 specific recommendations for receivers and equipment today and existing techniques that can be inserted into new products. These installation and operation strategies and development opportunities, described herein, can significantly enhance the ability of GNSS receivers and associated equipment to defend against a range of interference, jamming, and spoofing attacks. As stated in paragraph 3.2.11, DHS participates as a member in the chartered PIRT meetings. DHS works closely with Sector Risk Management Agencies (SRMAs) and their critical infrastructure (CI) owner-operator counterparts to enhance efforts to inform the CI community about potential vulnerabilities related to PNT. Finally, DHS engages in research and development activities to improve resilience of GPS user equipment. DHS S&T developed the Epsilon Algorithm Suite (found here: https://github.com/cisagov/Epsilon) which provides algorithms to end-users for basic spoofing detection capabilities (e.g., detecting inconsistencies in position, velocity, and clock observables commonly provided by GPS receivers) without any modifications to the existing GPS receiver. Additionally, DHS developed a PNT Integrity Library (found here: https://github.com/cisagov/PNT-Integrity) to provide users with a method to verify the integrity of Global Navigation Satellite System (GNSS)-based PNT sources. It provides a scalable framework for GNSS-based PNT manipulation detection that offers varying levels of protection based on the available data.

5.1.2.1 Mitigating Disruptions in Stationary Timing and other Non-Navigation Applications

Precision timing applications are especially vulnerable to disruption since they are often used in larger systemic environments where close observation is not feasible. Many of the strategies described above can be used to make precision timing applications more secure and resilient. In January 2015, DHS collaborated with interagency partners to release a best practices guide focused on timing applications. *Best Practices for Improved Robustness of Time and Frequency Sources in Fixed Locations* (Ref. 55) can be accessed at:https://www.dhs.gov/sites/default/files/publications/GPS-PNT-Best-Practices-Time-Frequency-Sources-Fixed-Locations-508.pdf. https://www.dhs.gov/sites/default/files/publications/gps-pnt-best-practices-time-frequency-sources-fixed-locations-508.pdf.This includes best practices that any user can implement to assist in mitigating disruptions, such as regular inspection of GPS antenna, denying view of the antenna from public locations, and for non-mobile uses, operating receiver in the fixed or survey mode.

As required by EO 13905, NIST (a bureau of the Department of Commerce), has made available a GNSS-independent source of Coordinated Universal Time to support the needs of public and private critical infrastructure owners and operators. For decades, NIST has offered time services at various levels of accuracy to meet a broad range of customer needs. For example, NIST's Internet Time Service receives 40 billion hits per day and provides time independent of GPS with an accuracy to about 1 millisecond—adequate for many computer networks but much less stringent than some customers require. To meet the higher requirements of some industries and to support resilient PNT, NIST has launched a service for companies, utilities or other organizations that wish to receive or disseminate U.S. civilian standard time through commercial fiber-optic cable. The service will use commercial telecommunications networks to distribute NIST's realization of the global time standard, Coordinated Universal Time [UTC(NIST)], independently of GPS. NIST's fiber-optic service aims to be 1,000 times more accurate than its Internet Time Service (fee is applied).

Additionally, DHS published Timing Guidelines for Information Technology, which can be found on the DHS CISA public web page (https://www.cisa.gov/publication/time-guidance-network-operators-cios-cisos). These documents provide information about timing being an invisible utility and the practical guidance and recommendations for network operators, chief information officers (CIOs), and chief information security officers (CISOs) on time resilience and security practices in enterprise networks and systems. The guidance attempts to address gaps in available time-testing practices, increasing awareness of time-related system issues and the linkage between time and cybersecurity.

5.1.2.2 Mitigating Disruptions in NASA Applications

Navigation for launch vehicles is provided by an INS using multiple redundant inertial measurement units (IMU) and GPS receivers. IMU measurements are considered primary, so a disruption to GPS service does not critically affect navigation.

To meet safety-of-life requirements, human spaceflight retains ground- and space-based tracking via the NASA Space and Near Earth networks and ground-in-the-loop processing. A number of GPS receivers have been tested on spacecraft for real-time navigation and attitude determination. GPS facilitates autonomous operations in Earth orbit and reduces operational costs and communications bandwidth. Should GPS service be disrupted, then ground-based tracking could be used for navigation in conjunction with on-board backup instruments such as magnetometers, Earth sensors, and directional antennas for attitude determination.

5.1.2.3 Mitigating Disruptions in Aviation Operations

The FAA will continue to operate and maintain a network of ground-based navigation aids (NAVAIDs) as part of a resilient navigation infrastructure. The FAA is committed to delivering satellite-based PNT service capable of supporting Performance-Based Navigation (PBN) operations throughout the NAS with sufficient backup to ensure continuous safe operations during GPS outages. General aviation operators can rely on WAAS as the only navigation source, but a minimum operational network of VORs will be retained as a backup during GPS outages. Commercial aircraft must carry dual independent navigation systems to ensure resiliency during GPS outages. Most commercial aircraft can rely on DME navigation or VOR during GPS outages to ensure continued operations to their planned destination. Procedural means will also be used to maintain safe operations in the event of a loss of GPS or denial or degradation of the GPS signal in support of DoD training/exercises. The resilient navigation infrastructure is described in the FAA Navigation Strategy .

Ionospheric scintillation during severe solar storms is also a concern, but is expected to have only minimal impact on en route, terminal, and precision and non-precision approach operations. Ionospheric anomalies may cause periodic outages of LPV approach capability using WAAS until an L5-capable GPS constellation is available and operators equip with dual frequency L1-L5 avionics.

A loss of GPS service, due to either intentional or unintentional interference, in the absence of any other means of navigation, would have varying negative effects on air traffic operations. These effects could range from nuisance events requiring standard restoration of capabilities to an inability to provide normal air traffic control service within one or more sectors of airspace for a significant period of time.[16]

In addition to FAA's plan for retaining a minimum network of VOR, TACAN (Tactical Air Navigation), DME, and ILS facilities to serve as an alternate means of navigation in the event of a GPS outage, several other solutions have been identified to help mitigate the effects of a GNSS service disruption:

- The FAA will continue to operate and maintain a rationalized network of ground-based navigation aids (NAVAIDs) as part of a resilient navigation infrastructure. General aviation aircraft equipped with WAAS are not required to carry any other navigation systems however, most users may elect to retain conventional NAVAIDs to ensure continued operations during GPS outages. Commercial aircraft are required to carry dual independent navigation systems if one of the sensors is GPS. Future GNSS capabilities include use of multiple GNSS constellations to improve accuracy and availability to include advanced receiver autonomous integrity monitoring (ARAIM) and multi-constellation SBAS. Even when these new capabilities become operational, operators may retain conventional navigation equipment to maintain safe operations in the event of a loss of GPS or denial or degradation of the GPS signal in support of DoD training/exercises. The FAA will update the navigation strategy as necessary to ensure safe and reliable air transportation. Critical issues to be addressed are discussed below.

- Aircraft with inertial systems may be able to continue navigating safely for a period of time after losing PNT position updating depending on the route or procedure being flown. In some cases, this capability may prove adequate to depart an area with localized interference, or alternatively the flight can proceed under visual flight rules in appropriate weather conditions. However, inertial performance without PNT updates degrades with time and will eventually fail to meet airspace requirements.

- Integrated GPS/inertial avionics, as well as improvements in antennas and algorithms, could provide increased interference resistance, effectively reducing the area affected by GPS jamming or unintentional interference. Industry research is proceeding to enhance these technologies, with an expectation that they might be marketed to a broader cross section of the aviation community at some point in the future.

[16] The NAS is divided into hundreds of air traffic control "sectors." A single air traffic controller has the responsibility to keep aircraft safely separated from one another within each sector and from other sectors. Sector dimensions vary, and are established based on predominant traffic flows, altitude, and controller workload.

- Absent a suitable onboard navigation capability, aircraft may be “vectored” by air traffic controllers, assuming that surveillance and communication capabilities continue without interruption.

- As for surveillance capabilities, the FAA has implemented plans to mitigate the potential disruption of these services due to GPS events effecting PNT by maintaining a network of secondary surveillance radars and wide area multilateration systems. These systems provide complementary cooperative surveillance services which are fused with ADS-B data to provide a seamless backup surveillance capability. Backup surveillance is available within en route and medium- to high-density terminal airspace for supporting continued operational efficiencies during potential degradation of GPS or Augmented GPS.

5.1.2.4 Mitigating Disruptions in Maritime Operations

USCG has identified two critical maritime applications:

- inland waterway and harbor entrance and approach; and

- timing and synchronization (maritime AIS standard).

For the most part, mariners practice conventional navigation and employ a variety of shipboard and external systems, such as GPS, shipboard radar, visual aids to navigation, fathometers, paper and electronic charts, VTS, and pilotage. In addition, USCG exercises a certain amount of control over the waterway, under the authority vested in the Captain of the Port, and may close waterways or restrict marine activity during adverse conditions or special operations. In the St. Lawrence Seaway, the GLS has many of the same responsibilities and authorities as the USCG has in other inland waterways, such as the authority to close or impose restrictions to commercial navigation in the St. Lawrence Seaway during adverse conditions. These combined elements facilitate safe marine navigation. Because of the extensive backup network of visual aids to navigation and independent shipboard systems, vessels operating in the harbor entrance and approach and inland waterways could continue to operate with some level of degradation to safety and efficiency during GPS disruptions.

AIS is an example of how a new technology can be designed around GPS while at the same time implementing measures that when used can mitigate the impact of the potential vulnerabilities of GPS. Specifically, the AIS design team was aware of the potential for GPS interruptions. Although AIS uses GPS for primary timing, secondary timing is provided by an external synchronization method that is based upon the reception of other AIS station broadcasts. Secondary positioning information can be utilized from an electronic navigation system other than GPS, but only if such a system is installed on the vessel. Although loss of GPS timing and positioning will not technically prevent individual AIS transceivers from operating, the system's capability to apply accurate "time tags" and accurate "vessel positions" to the data packets will be lost. This will eliminate the system's ability to serve its collision avoidance safety function unless a secondary shipboard position sensor is operational and connected to the AIS.

5.1.2.5 Mitigating Disruptions in Land Operations

Surface transportation users currently use PNT services from GPS and its augmentations to supplement other available non-space-based PNT systems. Under this operational paradigm, users seamlessly use other techniques to mitigate both the short-term loss of GPS due to obstructions and the longer-term loss due to failed on-board user equipment and adverse operating environments. In future applications, accuracy requirements are expected to become much more stringent, leading to integration of aiding technologies that will offer increased accuracy with high reliability. The loss of GPS and its augmentations will be carefully evaluated within the overall operational environment to ensure continued safe and efficient operation of the land transportation system.

Surface transportation agencies are working with industry to ensure that safety-critical systems that use GPS and its augmentations consider the loss of these PNT services and are able to mitigate its effects in order to continue safe and efficient operation of the nation's surface transportation infrastructure. This is accomplished today by outreach to user groups and local transportation agencies and defining minimum operational or functional standards. In the future, training for application developers, State, Tribal, Territorial, and local highway and transit agencies, and motor carriers on the operational capabilities of PNT solutions, as well as what to do when failures occur, may be necessary. Finally, since it is expected that signal availability from GPS may not be adequate for surface users experiencing canopy/urban obstructions, the integration of complementary and/or alternate systems that perform a verification test on the GPS navigation solution and that support continued operation in the event of degradation to the GPS signal will be employed in a system-of-systems configuration.

Positioning applications are also commonly used in applications such as surveying and mapping, precision agriculture, emergency response and law enforcement, fire services, environmental resource management, utility location and management, asset inventory and management, and logistics. These applications are variable in duration and areas of operation. Because of the flexible character of positioning applications, operations will typically be halted until the GPS or GPS augmentation 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 these operators. Users can consider use of solutions that integrate other PNT sources with GPS to improve availability where such halts in operations result in unacceptable reductions in productivity.

5.1.2.6 Mitigating Disruptions in Railroad Operations

While the Federal Government has significant safety oversight responsibility for freight, intercity, and commuter rail operations in the United States, it has an extremely limited role in the actual system operations. Daily system operations are undertaken by more than 460 railroad companies, the overwhelming majority of which are owned and operated by private-sector entities. Primary responsibility for providing mitigations in the event of GPS disruptions rests with individual railroad companies.

Because GPS is primarily used by railroads as a supporting technology to control train operations, its loss would increase the probability of train accidents, but only to pre-GPS-use levels. Railroads would simply rely on their earlier non-GPS methods of train control, such as track warrant, block signal, track-based automatic cab signal/automatic speed control, track-based automatic train stop, and track-based automatic train control. These non-GPS technologies are coupled with standardized rule sets, such as the General Code of Operating Rules (GCOR) or Northeast Operating Rules Advisory Committee (NORAC) rules. These non-GPS control methods are well established, having been in use since the early 1900s. They are also safe and effective, with train accidents rates of less than 2.4 incidents per million train miles of operation.

Although primary responsibility for implementing loss of GPS mitigations rests with the individual railroads, the Federal Government is supporting the development of alternative non-GPS-based disruption mitigations. The FRA Intelligent Railroad Systems initiative encourages an integrated approach to train control technology that incorporates systems that are interoperable, synergistic, and redundant, and that cannot be interfered with or jammed. These include not only technologies and procedures currently in use, but new technologies such as inertial navigation or advanced ground-based sensor systems.

Recognizing that satellite navigation services can be disrupted, FRA, in cooperation with individual railroads, railroad suppliers, and transportation research organizations is:

- working towards bringing anti-jam capable receivers to the railroad industry;
- encouraging the incorporation of low-cost inertial measurement units (IMU) in train control systems;
- developing disruption resistant equipment standards and architectures for use in railroad applications;

- advocating robust signal structures for satellite navigation services and their augmentation systems; and
- working with other Federal, State, Tribal, Territorial, and local agencies as well as the international community to prevent and mitigate disruptions of satellite navigation services and their augmentation systems.

5.2 Augmentations to GPS

GPS SPS does not meet all the different user performance requirements for civil PNT applications.

Various differential techniques are used to augment the GPS to meet specific user performance requirements. However, it is important to note that civil differential systems and users of civil differential systems are dependent upon being able to receive the GPS civil signal to compute a position using differential techniques. Augmentations alone provide no service if the GPS civil signal itself is unavailable.

5.2.1 Wide Area Augmentation System (WAAS)

WAAS, an SBAS operated by the FAA, provides improved navigation and positioning accuracy, availability, integrity, and continuity for aircraft navigation during departure, en route, arrival, and approach operations within the geostationary satellite footprints. WAAS supports vertically-guided instrument approach operations within the primary area of coverage, which includes significant portions of Alaska, Hawaii, Canada, and Mexico. Although designed primarily for aviation applications, WAAS is widely available in receivers manufactured for navigation use by other communities such as maritime, automotive, agriculture, and surveying.

The FAA commissioned WAAS in 2003 to enable PBN operations for departure, en route, arrival, and approach operations, including non-precision and vertically guided approach procedures. The WAAS service enables all RNAV and RNP specifications for PBN and all performance levels for ADS-B (i.e., non-precision/precision).

WAAS is being upgraded to utilize the L5 signal provided by modernized GPS satellites, in lieu of the current semi-codeless L2 signal being utilized to determine ionospheric corrections. New dual-frequency WAAS avionics using L1 and L5 will improve the resilience and coverage of RNAV approaches with an LPV line of minima.

5.2.2 Ground-Based Augmentation System (GBAS)

GBAS was developed to provide the required accuracy, availability, integrity, coverage, and continuity to initially support CAT I precision approaches and eventually CAT II and III precision approaches. Unlike current ILS, a single GBAS ground station provides precision approach capability to all runway ends at an airport. GBAS augments GPS by providing local differential corrections and integrity parameters to aircraft via a VHF data broadcast. Currently, GBAS provides straight in CAT I precision approaches only. In the future, GBAS may eventually allow suitably equipped aircraft to conduct curved approaches and segmented approaches. GBAS may also provide positioning service with high integrity to potentially support more efficient capabilities, such as parallel runway operations and airport surface operations.

A major milestone was reached by the FAA in September 2009 with the system design approval of the first non-Federal GBAS certified by the FAA for CAT I precision approaches. Newark Liberty International Airport, NJ and Houston George Bush Intercontinental Airport, TX have non-Federal GBASs in operation providing CAT I service.

Following considerable research and prototyping work by the FAA and international community, ICAO Annex 10 standards for CAT II/III GBAS precision approaches were accepted by the ICAO Navigation Systems Panel in December 2016. The FAA has no plan to acquire GBAS CAT II/III ground facilities; however, just like GBAS CAT I, GBAS CAT II/III may be installed by sponsors as non-Federal systems when a CAT II/III GBAS receives FAA System Design Approval.

5.2.3 Aircraft-Based Augmentation System (ABAS)

As the GPS constellation is populated with L1 and L5 dual frequencies, the FAA is transitioning to provide dual frequency multi-constellation (DFMC) based navigation and surveillance services in addition to maintaining legacy single frequency GPS services. DFMC includes the use of L1/L5 dual-frequency GPS and dual-frequency GPS in conjunction with dual-frequency signals from other authorized constellations.[17] The DFMC mode supports all phases of flight, including en route, terminal, Lateral Navigation (LNAV) and LPV approaches, and Automatic Dependent Surveillance Broadcast (ADS-B).

As part of the operational concept for the DFMC mode, the FAA also expects to provide aviation services based on L5 signal only augmented with aircraft-based augmentation system (ABAS). This L5-only mode augmented with ABAS will be comparable with the level of service aviation users are currently getting from L1 with RAIM, and will support existing applications. Aviation users will employ the L5 only mode when they experience loss of signal from L1 (e.g., due to interference).

[17] Foreign GNSS satellite providers must first obtain a waiver of the FCC's licensing requirements of 47 CFR 25.131 (j)(1) and/or 47 CFR 25.137 prior to reception of authorization from the FAA for aviation services in the U.S. The waiver process goes through the NTIA on behalf of the executive branch.

The signal in space characteristics and performance levels of L5 are comparable with those of L1 as specified in GPS Standard Positioning Service Performance Standard (GPS SPS PS).

5.2.4 Nationwide Differential GPS (NDGPS)

In March 2018 a Federal Register Notice was published announcing the discontinuance of the DGPS service in a phased out manner. As of June 30th, 2020, all NDGPS service has been discontinued in accordance with the stated notice. With the rollout of the new GPS III satellites combined with the permanent termination of Selective Availability, DGPS is no longer deemed a necessary augmentation.

5.3 Instrument Landing System (ILS)

An ILS is a precision approach and landing system consisting of a localizer facility, a glide slope facility, and VHF marker beacons or low-power DME (or both). A full precision approach also includes runway visual range (RVR) and approach lighting systems. An ILS provides electronic vertical and lateral navigation (guidance) information during the approach and landing phase of flight and is associated with a specific airport runway end. Distance indication is provided by the marker beacons or DME. Depending on its configuration and the other systems installed on the airport and in the aircraft, an ILS can support CAT I, II, and III approaches, as well as low visibility guided takeoff operations.

ILS is the standard precision approach system in the U.S. and abroad. The FAA operates more than 1,200 ILS systems, of which approximately 150 are CAT II or CAT III systems. In addition, the DoD operates approximately 160 ILS facilities in the U.S. Non-Federal sponsors operate fewer than 200 ILS facilities in the U.S.

As the GPS-based augmentation systems (e.g., WAAS) are integrated into the NAS, and user equipage and acceptance grows, the number of CAT I ILSs may be rationalized. The FAA does not anticipate phasing out any CAT II or III ILS systems

ILS localizers share the 108–111.975 MHz ARNS band with VOR and GBAS VDB. Substantial amounts of spectrum in the 108–111.975 MHz sub-band will continue to be needed to operate CAT II and III localizers even after many CAT I ILSs have been decommissioned.

ILS glide slope subsystems operate in the 328–335.4 MHz UHF band. The inherent physical characteristics of this band, like those of the 108–111.975 MHz VHF band, are quite favorable to long-range terrestrial line-of-sight air-ground communications and data-link applications like GBAS, ADS-B and Traffic Information Service Broadcast (TIS-B). Consequently, this band is well-suited to provide multiband diversity to such services or to serve as an overflow band for them if they cannot be accommodated entirely in other bands. Substantial amounts of spectrum in this band will continue to be needed to operate CAT II and III ILS glide slope subsystems even after many CAT I ILSs have been decommissioned.

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

5.4 VOR, DME, and TACAN

5.4.1 Very High Frequency (VHF) Omnidirectional Range (VOR)

VOR provides a bearing from an aircraft to the VOR transmitter. Current VOR services have defined airspace structures and procedures since the 1950s and are standardized internationally. The FAA plans to transition from defining airspace and procedures with VORs towards a Performance-Based Navigation (PBN) airspace system based on area navigation (RNAV) and Required Navigation Performance (RNP) meeting more stringent tolerances where needed to meet user needs for capacity, efficiency, and safety in the Next Generation Air Transportation System (NextGen) implementation.

As more airspace and procedures are transitioned to PBN, the FAA will gradually reduce the number of VOR stations to a minimum operational network (MON). The MON will provide a basic VOR navigation capability to enable aircraft to fly clear of a GNSS outage area or navigate to an airport with an ILS or VOR approach procedure during a GNSS disruption. A minimum level of VOR service will continue throughout the transition to RNAV and RNP to support IFR operations as needed. RNAV capable aircraft equipped with scanning DME will be able to continue PBN operations in high altitude airspace and at selected airports during a GNSS disruption. DME, VOR, TACAN, and ILS will provide independent navigation sources in the NAS. As the VOR portions of dual-system VOR/TACAN (i.e., VORTAC) stations are disestablished, the DME functionality will be retained and the TACAN azimuth function will be retained if needed for DoD use. Select VOR stations also broadcast weather and air traffic information, which will be provided by alternate means when VORs are discontinued.

The FAA operates approximately 1,000 VOR, VOR/DME, and VORTAC stations. DoD operates approximately 50 stations, located predominately on military installations in the U.S. and overseas, which are available to all users.

5.4.2 Distance Measuring Equipment (DME)

DME provides the slant-range distance from the aircraft to the DME transmitter. At many sites, the DME function is provided by the TACAN system that also provides azimuth guidance to military users.

FAA plans to address DME Extended Service Volume (ESV) and sustain existing DME service to support unrestricted RNAV operations in high-altitude en route airspace over CONUS. The FAA plans to expand the DME network to provide an RNAV capability for terminal area operations at major airports and to provide continuous coverage for RNAV routes and operations at en route altitudes. Continued use of the 960–1215 MHz ARNS band will be required to support DME.

The DoD Joint Tactical Information Distribution System/Multi-function Information Distribution System (JTIDS/MIDS) also operates in this band on a non-interference basis. Some aircraft operators within the civil aviation community are using 978 MHz in the DME ARNS band for ADS-B services in lieu of the 1090 MHz Mode-S extended squitter. ADS-B is a function in which aircraft transmit position and velocity data derived from onboard PNT systems to other aircraft and to the ground Air Navigation Service Provider (ANSP) network.

5.4.3 Tactical Air Navigation (TACAN)

TACAN is a tactical air navigation system for the military services. It is the military counterpart of civil VOR/DME. TACAN provides bearing and distance information through collocated azimuth and DME antennas. TACAN is primarily collocated with the civil VOR stations (VORTAC facilities) to enable military aircraft to operate in the NAS and to provide DME service to civil users.

The FAA and DoD currently operate more than 100 stand-alone TACAN stations in support of military flight operations within the NAS. DoD also operates approximately 30 fixed TACAN stations that are located on military installations overseas and maintains more than 90 mobile TACANs and two mobile VORTACs for worldwide deployment. The FAA and DoD continue to review and update requirements in support of the planned transition from land-based to space-based navigation.

There is no FAA procurement activity for TACANs at this time. All existing TACANs are 30 years old, with some components more than 50 years old. The FAA, in collaboration with the Department of Defense is performing an analysis to rationalize TACANs to establish a plan to discontinue unneeded systems. In addition, the FAA is developing a long-term sustainment plan for DME, VOR, and TACAN to ensure that these systems remain a viable part of the resilient navigation infrastructure for the foreseeable future.

5.5 Nondirectional Beacons (NDB)

NDBs serve as non-precision approach aids at some airports; as compass locators, generally collocated with the outer marker of an ILS to assist pilots in getting on the ILS course in a non-radar environment; and as en route navigation aids. The NAS includes more than 1,300 NDBs. Fewer than 300 are owned by the Federal Government; the rest are non-Federal facilities owned predominately by State, municipal, and airport authorities.

The FAA has begun decommissioning stand-alone NDBs as users equip with GPS. NDBs used as compass locators, or as other required fixes for ILS approaches (e.g., initial approach fix, missed approach holding) where no equivalent ground-based means are available may need to be maintained until the underlying ILS is phased out. Some NDBs may also need to be maintained to facilitate training and proficiency requirements.

Most NDBs that define low-frequency airways are located in Alaska or serve international gateways and certain offshore areas such as the Gulf of Mexico. Except in Alaskan airspace, no future civil aeronautical uses are envisioned for these bands after the aeronautical NDB system has been decommissioned throughout the rest of the NAS. Marine radiobeacons have been phased out.

5.6 Automatic Dependent Surveillance-Broadcast (ADS-B)

ADS-B is a safety critical service that is highly dependent on positioning and timing services primarily based on GNSS. Today's aircraft ADS-B Out avionics utilize GPS or augmented GPS to provide position and velocity information on aircraft and vehicles while providing accurate time of applicability of this data. This position and timing data contained in the surveillance messages from ADS-B are utilized to track aircraft throughout the NAS. This information is employed by air traffic controllers to safely separate aircraft and guide them to their appropriate destinations. This data is also received by aircraft with ADS-B In systems to provide pilots a traffic picture for enhanced situational awareness and conflict-alerting applications,

ADS-B equipped aircraft and vehicles periodically broadcast their state vector (horizontal position and vertical height, horizontal and vertical velocity) and other information over either a UAT (978 MHz) or a 1090-Extended Squitter (1090 MHz) data link. The ADS-B message broadcasts are received by other aircraft in within line-of-sight and by a ground-based radio stations or satellite receiver. These ADS-B messages are processed and formatted into ADS-B reports. The radio station or satellite receiver provides these reports to air traffic management (ATM) and traffic flow management automation systems for use by ATC in providing separation services, traffic flow management and other services.

ADS-B is “automatic” because no pilot action or external interrogation is required; it is “dependent” because it relies on on-board navigation and other system sources to broadcast the ADS-B information to other users. Any user—whether aircraft, ground-based or satellite-based—within range of the broadcast will receive the ADS-B information. ADS-B provides surveillance data at a higher update rate than conventional radar surveillance, with improved accuracy over today’s NAS radar systems.

5.7 Aeronautical Transition Plan

Table 5-1 summarizes the current navigation infrastructure and services in the NAS.

Table 5-1: Navigation Infrastructure Elements and Services

Operational Services		Supporting Systems/Infrastructure			
		Ground Based NAVAIDs	GNSS	Self-Contained on-Board Systems	Airport Lighting
Conventional Navigation Operations	**En Route**	VOR (Victor and Jet routes) VORTAC (Victor and Jet routes) TACAN* DME (fix definition) NDB (in Alaska and for some offshore airways)	GPS, SBAS (approved as a substitute for NDB, DME)	Inertial	N/A
	Arrival & Departure	VOR (SIDs, STARs) VORTAC (Victor and Jet routes) TACAN* (SIDs, STARs) DME (fix definition) NDB	GPS, SBAS (approved as a substitute for NDB, DME)	Inertial	N/A
	Approach & Landing				
	Instrument Approach	ILS, Localizer, LDA VOR DME NDB TACAN* Radar approaches (ASR)*	N/A	Barometric altimetry	Lighting as required for type of operation and/or minima requirements. See AC 150/5300-13
	Vertical Guidance for Instrument Approach	ILS, PAR*	See “Area Navigation Operations” below	Barometric altimetry, radar altimetry, baro-VNAV, EFVS/HUD***	Lighting as required for type of operation and/or minima requirements. See AC 150/5300-13
Performance Based Navigation (PBN) Operations	**En Route**	DME/DME**	GPS, SBAS	Inertial (as part of a multi-sensor system)	N/A
	Arrival & Departure	DME/DME**	GPS, SBAS	Inertial (as part of a multi-sensor system)	N/A
	Approach & Landing				
	RNAV and RNP Instrument Approach (horizontal guidance)	N/A	GPS, SBAS,GBAS	Inertial (as part of a multi-sensor system), barometric altimetry, baro-VNAV	Lighting as required for type of operation and/or minima requirements. See AC 150/5300-13

	RNAV and RNP Instrument Approach (with vertical guidance)	N/A	SBAS, GBAS	Barometric altimetry, baro-VNAV, EFVS/HUD***	Lighting as required for type of operation and/or minima requirements. See AC 150/5300-13

* Primarily used by DoD.
** Legacy and backup services.
*** While not a navigation system, EFVS/HUD acts to mitigate risk and credit is given for its use in operational approvals.

5.7.1 Transition to GNSS-Based PNT

The FAA is transitioning to providing GNSS services based primarily on GPS augmented by:

- aircraft-based augmentation systems (ABAS), such as receiver autonomous integrity monitoring (RAIM);
- SBAS, such as WAAS;
- GBAS, and
- ADS-B using GPS or SBAS.

As a result of this transition, the need for ground-based navigation and surveillance services will diminish, and the number of federally-provided ground-based facilities will be reduced accordingly, but with sufficient time for users to equip with GNSS avionics.

The pace and extent of the transition to GNSS will depend upon a number of factors, including:

- NAS performance;
- achievement of GPS and GPS augmentation systems program milestones; and
- user equipage and acceptance.

The specific NAVAID and surveillance radar facilities to be divested was determined based on criteria developed by the FAA with feedback from all the stakeholders, resulting in the establishment of the VOR MON. The transition plans will continue to be coordinated with airspace users and the aviation industry.

5.7.2 GNSS Transition Issues

The use of GPS represents a fundamental departure from traditional ground-based navigation systems with respect to aviation operations. Ground-based systems enable station-referenced navigation based on the fixed location of the navigation facility. VOR/DME and TACAN provide azimuth and distance relative to the facility location, which may not define the most direct path between two airports. RNAV and RNP operations, enabled by GPS, WAAS, or DME/DME, enable aircraft to fly point-to-point navigation over the shortest distance.

During transition, both types of users need to be accommodated. Discontinuing VORs can only be accomplished after all conventional instrument flight procedures have been either cancelled or replaced with PBN procedures. Most ground-based systems (such as an ILS) provide service to only a single runway. GPS-based approach operations can be made available to any existing runway in the NAS with or without ground-based PNT equipment. Required mitigations to terrain and obstructions, as well as airport improvements, are unchanged from ILS-based precision approach operations. GBAS supports precision approach operations to multiple runway ends at an airport. GBAS may eventually contribute to a higher acceptance rate than ILS, but mixed usage must be accommodated during transition.

As of January 1, 2020, the FAA transitioned to utilizing ADS-B as the preferred source of cooperative surveillance for aircraft separation services. Secondary radar systems and wide area multilateration (WAM) are being utilized as a backup capability to ADS-B and within some airspace that does not require ADS-B equipage. The FAA will continue accommodating surveillance from radar and WAM to complement ADS-B surveillance using surveillance data fusion. This fusion processing capability integrates these various surveillance technologies to provide a single track to ATC for each aircraft which is resilient to the degradation or loss of any individual surveillance source.

The FAA will continue to maintain some radar systems and provide WAM services along with ADS-B to maintain a robust and resilient surveillance capability that ensures the safe separation of aircraft even during potential GNSS disruptions. In addition, the FAA is working with industry and other partner countries in developing new positioning source standards for PNT that would be utilized by ADS-B and further mitigate disruptions to today's GNSS systems. These include dual frequency multi-constellation GNSS receivers for PNT that went into effect back in January 2020.

5.8 Timing Plan

5.8.1 NIST Timing Plan

NIST will continue to operate and maintain time dissemination services in the foreseeable future. These are summarized in Appendix A, Section A.2.7 of this document. Status and changes will be documented at http://tf.nist.gov/ and/or https://www.nist.gov/pml/time-and-frequency-division/time-services.

In addition, as specified in EO 13905 (Ref. 72), NIST will develop and provide additional GNSS-independent references of UTC(NIST), to support the needs of critical infrastructure owners and operators, and others in the public. Contacts are given on the web pages, above.

5.8.2 USNO Timing Plan

In accordance with DoD policy, USNO provides the Precise Time and Time Interval (PTTI) reference for the DoD and most U.S. Government PNT systems. USNO disseminates time via various mediums; these include GPS, two-way satellite time transfer (TWSTT), Network Time Protocol (NTP), and telephone voice announcers. The UTC(USNO) timing service broadcast by GPS is accomplished by providing to the user a correction that translates GPS time to UTC(USNO). USNO is in the process of improving its Master Clock and GPS monitoring systems to better meet future GPS III requirements. Details about the USNO timing services can be found at https://www.usno.navy.mil/USNO/time.

6

PNT Architecture Assessment and Evolution

The National PNT Architecture describes capabilities needed to meet the anticipated future requirements of a resilient PNT enterprise with expanded applications and users. A resilient PNT enterprise is one that includes the following:

- Use of multiple, diverse sources of PNT and data paths;
- Choice of architectures that minimize attack opportunities and overlapping attack vectors that could reduce protections or result in single points of failure;
- Utilization of defense-in-depth (multiple layers of protections, mitigations, and responses) and;
- Integration of modern cybersecurity principles into the greater PNT enterprise, among other key resilience-improving capabilities.

Per Executive Order 13905 ("Strengthening National Resilience through Responsible Use of Positioning, Navigation, and Timing Services"), the director of the DOT Office of Science and Technology Policy (OST-P) coordinated the development of a report/plan entitled, "The National Research and Development Plan for Positioning, Navigation, and Timing Resilience."

This report/plan:

- Is informed by existing initiatives, for the research, development, and pilot testing of additional, robust, and secure PNT services that are not dependent on global navigation satellite systems (GNSS);
- Presents a national plan of research and development (R&D) activities that promote critical infrastructure resilience against disruptions in PNT services and;

- Is consistent with the requirements of Executive Order 13905 and the strategy of the National PNT Architecture Study of 2008.

The National Research and Development Plan for Positioning, Navigation, and Timing Resilience has three overarching goals: characterize, improve, and expand resilient PNT. These goals include R&D activities that support improvements in GPS resilience and the development of complementary PNT capabilities and services. Fourteen R&D objectives are collected into the three overarching goals and span key resilience-enhancing areas of knowledge and capabilities.

Characterize and Model PNT services and their use

- Characterize PNT requirements
- Improve test capabilities and test protocols for assessing equipment and services
- Conduct modeling, simulations, and tests to assess vulnerabilities
- Develop tools to identify appropriate sources of PNT based on functional requirements

Improve and Expand PNT capabilities

- Improve PNT holdover capabilities of internal sources
- Develop and improve external sources of complementary PNT
- Establish calibration and traceability techniques
- Improve and expand disruption detection tools and methods
- Prototype and demonstrate new complementary PNT services

Integrate and Deploy Resilient PNT

- Determine concepts and techniques for securely integrating multiple sources of PNT
- Common hardware platforms
- Develop resilient PNT system architectures
- Investigate operating internal sources as primary sources of PNT
- Develop cybersecurity standards, best practices, and other guidance

The National Research and Development Plan for Positioning, Navigation, and Timing Resilience includes approaches to integrate and use multiple PNT services to enhance the resilience of critical infrastructure. The Director of OSTP shall coordinate updates to the plan every 4 years, or as appropriate.

The National PNT Architecture was developed as a forward-looking plan to help the U.S. effectively and efficiently provide government PNT systems and services. The Architecture's guiding principles represent an overarching vision of the U.S. role in PNT, an architectural strategy to fulfill that vision, and four supporting vectors to offer direction, which can be found in the PNT Architecture Final Report (Ref. 6) and its associated National PNT Architecture Implementation Plan (Ref. 7). The PNT Architecture presented an enterprise-level view of the future PNT environment to serve as a framework for individual actions by the participating USG Departments and agencies. Since the publication of the Architecture Report and Implementation Plan, the vision, strategy, and vectors are being implemented to varying degrees by individual departments and agencies – that process will continue. To the extent those various efforts result in changes to federally-provided PNT systems and services in the future, planning for those changes will be documented in subsequent editions of the Federal Radionavigation Plan.

The architectural strategy is referred to as the "greater common denominator" because it aims to make greater common-core capabilities available to an unlimited number of users, while addressing the uniquely stressing needs of specialized users through custom solutions. The architecture study found that a large number of PNT users have a common set of needs that can be more efficiently satisfied through standard solutions, rather than by multiple customized systems. Thus, a vital element of the PNT Architectural strategy is to leverage GPS modernization, which provides improved capability on a global scale to an unlimited number of users. Supporting this strategy are the four vectors summarized below.

- *Multiple Phenomenologies* – Multiple phenomenologies refer to diverse physical phenomena, such as radio frequencies, inertial sensors, and scene mapping, as well as diverse sources and data paths using those physical phenomena (e.g., multiple radio frequencies) to provide interchangeable solutions to users to ensure robust availability.
- *Interchangeable Solutions* – Interchangeable solutions, or solutions with a high degree of interoperability, implies the ability to combine signals from multiple data sources into a single PNT solution, as well as the ability to provide a solution from an alternative source when a primary source is not available or lacks required integrity.
- *Synergy of PNT and Communications* – Data communications networks can support PNT capabilities by providing PNT-aiding and augmentation data, geospatial information, etc. However, increasing connectivity to more capable communications networks also affords an opportunity to use those networks as sources of PNT, not merely as data channels for PNT aiding and augmentation data.
- *Cooperative Organizational Structures* – Promote interagency coordination and cooperation to ensure effective operations, efficient acquisition, and relevant science and technology application development. As PNT solutions rely more on the integration of multiple PNT sources, cooperation among providers becomes even more important.

The following provides a brief overview of current programs and initiatives related to and advancing the strategy and vectors of the architecture.

6.1 Strategy Implementation

The ongoing GPS modernization effort, which continues to sustain the GPS constellation through development and launch of GPS Block III satellites, is an integral part of a "greater common denominator" strategy and maintaining GPS as a cornerstone of the

National PNT Architecture. As a result of GPS modernization, GPS satellites will incorporate additional frequencies and signal structures to improve the services available to many users – in both civil and military user communities.

Following publication of the Architecture Implementation Plan, both the DoD and the FAA have undertaken analysis-of-alternative (AoA) studies to further evaluate augmentations and complements to GPS. The results of this analysis will guide the selection of candidate PNT sources and technologies that, after further development and test, will become parts of integrated PNT services and devices employed for military and civil aviation applications, respectively. Additionally, DoD implementation is guided by their *Strategy for the DoD PNT Enterprise* document to establish a DoD-specific vision, goals, objectives, responsibilities, and near-term implementation actions for DoD organizations.

6.2 Multiple Phenomenologies

Many efforts are underway to explore the integration of multiple sources of PNT information. The FAA's Alternative PNT (APNT) study is assessing alternative PNT sources and services to support flight operations and minimize impacts from GPS outages to NAS operations. Current options being considered include leveraging existing NAS system infrastructures to minimize the need to deploy more systems in the NAS and minimizing the cost of a future APNT solution. The existing system infrastructures under consideration include the DME/TACAN network, the ADS-B ground station network, and/or a combination of both.

The DoD has many ongoing and planned technology projects to develop autonomous navigation capabilities based upon diverse PNT sources and not dependent on GPS. Service research laboratories and the Defense Advanced Research Projects Agency (DARPA) are supporting projects to investigate the integration of vision aiding or imaging sensors, new inertial navigation system technologies, and use of signals of opportunity. All of these efforts offer the potential to provide more robust and resilient PNT solutions when GPS signals are physically and/or electromagnetically impeded.

DoD is also pursuing the development and implementation of modular open-system architectures in order to flexibly and affordably integrate multiple sources of PNT into platforms across the forces. These efforts include the Army's Assured PNT (APNT), the Navy's GPS PNT Service (GPNTS), and the Air Force's Resilient Embedded GPS Inertial (R-EGI) programs.

For precise timing applications (time-of-day, time difference, and frequency stability), chip-scale atomic clocks are now available from at least one company, and others have active research and development programs in the United States and abroad.

For Maritime Safety Information (MSI) broadcasts, the USCG has established a Cooperative Research and Development Agreement to develop a prototype Navigational Data maritime broadcast (NAVDAT) system as an enhancement to the existing NAVTEX system. NAVDAT is a proposed system designated by IMO and ITU as an enhanced means for transmitting coastal urgent marine safety information to ships worldwide as part of the IMO's Global Maritime Distress and Safety Systems (GMDSS) modernization effort. Spectrum allocation for the NAVDAT system was approved at the 2012 World Radio Conference and resulted in changes to the Radio Regulations.

6.3 Interchangeable Solutions

The National PNT Architecture includes recommendations regarding the use of foreign PNT systems and international cooperation to promote interoperability. Common standards and reference frames are important enablers of interchangeable solutions and PNT interoperability. The United States has advocated for such common standards and reference frames in many domestic and international venues. For many years, DOT and FAA have worked with foreign nations and international standards bodies to establish nearly identical PNT systems for transportation in other regions of the world, all based on GPS. These include space-based augmentation systems in Europe, Japan, and India and differential GPS networks in over 50 nations.

NOAA has expanded the NOAA Continuously Operating Reference Station (CORS) Network to include sites outside the United States, including Iraq and Mexico, and plans to help other nations establish CORS sites that promote United States GPS technical standards. Increasingly, the NOAA CORS Network is being integrated into global and regional networks to ensure worldwide, cross-border compatibility. The United States has participated in the AFREF (AFrica REFerence Frame) and the APREF (Asia-Pacific REFerence Frame), United Nations-supported projects to unify the many national coordinate reference frames of Africa and Asia into a single reference frame across the continents using space-based geodetic techniques. Similarly, the United States supports APREF, SIRGAS (the reference frame of the Americans and Caribbean), and the International Terrestrial Reference Frame (adopted by the United Nations).

The US NSRS will be a national densification of the SIRGAS frame, which will be a regional densification of the ITRS. They are all nested. This meets UN agreements (Global Geodetic Reference Frame) and recent US law (Geospatial Data Act) requiring US NSRS to conform to the ITRS.

Within the United States, organizations, such as the Federal Geographic Data Committee, FEMA, and several State governments have begun advocating increased use of the U.S. National Grid (USNG) as a standard for defining position locations. Use of the USNG has been slowly expanding and is becoming increasingly available in portable navigation devices and navigation software as a way of uniquely identifying locations to aid interoperability for disaster response and other applications.

6.4 Synergy of PNT and Communications

The synergy of PNT and communications envisioned by the National PNT Architecture is exemplified in a number of areas, most notably in transportation. Advancements in location-based services (LBS) and related commercial efforts provide capabilities like traffic and weather information, routing and tracking information, and personalized services to subscribers based on their current positions. Fusing communications and PNT data makes possible emergency assistance services like E-911 and assists in tracking the location of emergency assets to help coordinate the efforts of first responders.

Innovative indoor positioning systems using Wi-Fi take advantage of the rapid growth in wireless access points in urban areas. Advancements in the commercial sector will be closely monitored for possible incorporation into Federal PNT-related programs.

The FAA's implementation of Automatic Dependent Surveillance-Broadcast (ADS-B) also represents a fusion of communication and navigation. ADS-B allows an aircraft to transmit to and receive information from ground stations and other ADS-B equipped aircraft Position data is automatically shared with all appropriately equipped ADS-B aircraft. In addition to location data, the FAA's ADS-B ground stations also provide timely traffic (on 1090 and 978 MHz links) and weather (only on the 978 MHz link) information to pilots.

In the maritime domain, the Automatic Identification System (AIS) transmission system, like ADS-B, uses GPS information and a transponder system operating in the VHF maritime band capable of communicating ship-to-ship as well as ship-to-shore, which transmits information relating to ship identification, geographic location, vessel type, and cargo information – all on a real-time, automated basis.

For automobiles and other land navigation systems, Intelligent Transportation System initiatives seek to leverage the synergy of PNT and communications in areas such as connected vehicle research. As envisioned, a system of connected vehicles has the potential to transform travel through interoperable wireless communications networks. The technology will enable cars, trucks, buses, and other vehicles to "talk" to both each other and road infrastructure to continuously share important safety, mobility, and environmental information. Vehicle-to-vehicle communication systems may also factor into Positive Train Control initiatives as researchers explore ways to integrate GPS into communications systems that could warn trains and cars of potential collisions at railroad crossings.

6.5 Cooperative Organizational Structures

There are a number of existing national and international organizational structures, as well as some recent initiatives, that promote cooperation and are in line with this vector.

At the national level, the National Space-based PNT EXCOM and associated Executive Steering Group (ESG) and National Coordination Office (NCO) provide an interagency forum to address issues of interest. The NCO has expanded the content of the GPS.gov website to improve information sharing throughout the PNT community. The website offers information on wide-ranging PNT topics to a broad audience that includes the general public, PNT professionals, and congressional staffs.

One example of ongoing interagency cooperation and structures concerns interagency efforts to foster responsible use of PNT in critical infrastructure. The GPS.gov website contains various documents describing best practices for responsible use of PNT, as well as a link to Executive Order 13905, Executive Order on Strengthening National Resilience through Responsible Use of Positioning, Navigation, and Timing Services. In response to E.O. 13905, the Department of Commerce is leading an effort to develop and make available, PNT profiles that will enable the public and private sectors to identify systems, networks, and assets dependent on PNT services; identify appropriate PNT services; detect the disruption and manipulation of PNT services; and manage the associated risks to the systems, networks, and assets dependent on PNT services. These efforts will enable the combination of multiple PNT phenomena and interchangeable solutions in a manner that is safer and more effective.

At the international level, organizations like the Civil GPS Service Interface Committee (CGSIC), the International Committee on Global Navigation Satellite Systems (ICG), and the Asian-Pacific Economic Cooperation (APEC) organization promote international cooperation and coordination. The CGSIC is the recognized worldwide forum for effective interaction between all civil GPS users and the U.S. GPS authorities. The United States is a charter member of the ICG, which was established in 2005 through the U.N. Office of Outer Space Affairs. The ICG promotes worldwide applications of satellite-based PNT technology, particularly in developing nations. The United States is also a member of the ICG Providers Forum, a venue for multilateral interaction among the 'world's providers of satellite navigation services.

Some emerging cooperative initiatives include efforts to protect PNT related spectrum, especially the spectrum associated with GPS. In the area of interference detection and mitigation (IDM), the Purposeful Interference Response Team (PIRT) is an interagency effort chaired by USSPACECOM to coordinate U.S. Government resources in order to identify and mitigate intentional interference to satellite communications. Agencies involved in the PIRT include the U.S. State Department, NTIA, the National Air and Space Intelligence Center, NASA, USGS, and other agencies with responsibilities, capabilities, and/or interest in satellite interference issues.

6.6 Looking to the Future

The biennial FRP update affords the PNT community an opportunity to review progress in achieving the vision laid out in the National PNT Architecture and assess progress towards addressing the PNT capability gaps it described. Implementation activity highlighted through this process can help the PNT community focus on areas where more effort is needed.

With the modernization of GPS and the addition of other GNSS capabilities, improved common-core capabilities will be available to an unlimited number of users around the globe. Leveraging multiple global systems could improve availability and afford options to improve availability and integrity. Initiatives outlined above are also leading to improved PNT availability in urban and other physically impeded environments. Jamming and interference challenges are being addressed from multiple perspectives – developing more robust, integrated solutions at the transmitter end, while, at the same time, establishing better processes and capabilities at the receiver end to locate the offending signals. Efforts to fuse communications and PNT information give users access to timely geospatial information, for example, traffic information. As envisioned in Figure 6-1, the future will see continued growth and importance of PNT available to the Nation and the world.[18] The

[18] The National PNT Architecture vision as described and illustrated is notional and dependent on congressional funding and decisions of the U.S. Government agencies responsible for PNT services.

direction offered by the community-developed vectors and strategy remains a useful framework moving forward.

As U.S. Government departments and agencies continue to conduct analysis and development efforts, additional changes to the enterprise-level architecture will occur. Any such system-level changes affecting federally-provided PNT services will be included in future editions of this plan.

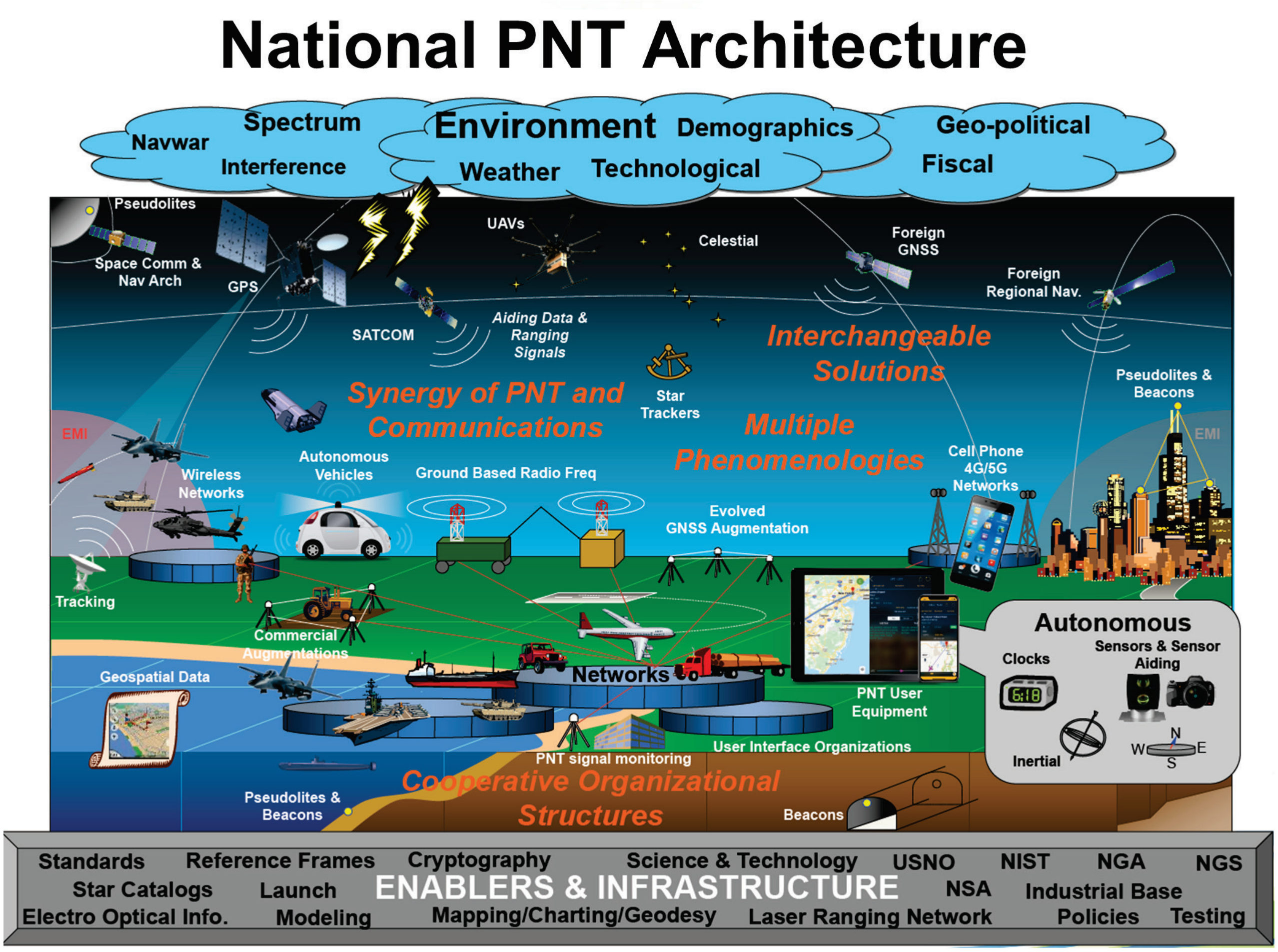

Figure 6-1: National PNT Architecture

Appendix A

System Parameters and Descriptions

A.1 System Parameters

Systems described in Section A.2 are defined below in terms of system parameters that determine the use and limitations of the individual PNT system's signal-in-space. These parameters are:

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

A.1.1 Signal Characteristics

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

A.1.2 Accuracy

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

Statistical Measure of Accuracy

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

When specifying linear accuracy, or when it is necessary to specify requirements in terms of orthogonal axes (e.g., along-track or cross-track), the 95 percent confidence level will be used. Vertical or bearing accuracies will be specified in one-dimensional terms, 95 percent confidence level (2 sigma).

When two-dimensional accuracies are used, the 2 x distance root mean square (drms) error characterization is generally used. Consider a two-dimensional plot of the error components from a collection of measured position fixes: The drms is often found by first defining an arbitrarily oriented set of perpendicular axes with the origin at the true location point. Then the variances around each axis are then found, summed, and the square root computed. When the distribution of errors is elliptical, as it often is for stationary, ground-based systems, these axes can be taken for convenience as the major and minor axes of the error ellipse. The probability of being within a circle of radius equal to 2 drms depends on the elongation of the error ellipse. As the error ellipse collapses to a line, the probability approaches 95 percent; as the error ellipse becomes circular, the probability approaches 98 percent.

Types of Accuracy

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

- Predictable accuracy: The accuracy of a PNT system's position solution with respect to the charted solution. Both the position solution and the chart must be based upon the same geodetic datum.
- Repeatable accuracy: The accuracy with which a user can return to a position whose coordinates has been measured at a previous time with the same PNT system.
- Relative accuracy: The accuracy with which a user can measure position relative to that of another user of the same PNT system at the same time.

A.1.3 Availability

The availability of a PNT 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 PNT signals transmitted from external sources are available for use. It is a function of both the physical characteristics of the environment and the technical capabilities of the transmitter facilities.

A.1.4 Continuity

Continuity is defined as the capability of the total system (comprising all elements necessary to maintain a user's position within the defined space) to perform its function without nonscheduled interruptions during the intended operation. The continuity risk is the probability that the system will be unintentionally interrupted, and not provide guidance information for the intended operation. More specifically, continuity is the probability that the system will be available for the duration of a phase of operation, presuming that the system was available at the beginning of that phase of operation.

A.1.5 Coverage

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

A.1.6 Reliability

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

A.1.7 Fix Rate

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

A.1.8 Fix Dimensions

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

A.1.9 System Capacity

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

A.1.10 Ambiguity

System ambiguity exists when the PNT system identifies two or more possible positions of the vehicle, with the same set of measurements, with no indication of which is the most nearly correct position. The potential for system ambiguities should be identified along with provision for users to identify and resolve them. Expanding further, ambiguity exists when two PNT measurements disagree or when the same PNT measurement represents different points in space or time, and the correct PNT measurement cannot be determined within a specified uncertainty tolerance without additional information. For example, during a leap second event, a device implementation may timestamp two events, one prior to the leap second, and one during the leap second, with the same timestamp of 23:59:59.

A.1.11 Integrity

Integrity is the measure of the trust that can be placed in the correctness of the information supplied by a PNT system. Integrity includes the ability of the system to provide timely warnings to users when the system should not be used for navigation.

A.1.12 Spectrum

Spectrum describes the range of operating frequencies for a given PNT system.

A.1.13 Time and Frequency

The parameters for time and frequency are

Frequency Accuracy. Maximum long-term deviation from the definition of the second without external calibration. This is measured as the frequency difference from a recognized and maintained source.

Frequency Stability. Change in frequency over a given time interval.

Timing Accuracy. Absolute offset in time from a recognized and maintained time source (NIST, USNO, BIPM, etc.).

UTC. The atomic time scale maintained by the BIPM and determined as an international average with leap seconds added for variable Earth rotation.

A.2 System Descriptions

This section describes the characteristics of those individual PNT systems currently in use or under development. These systems are described in terms of the parameters previously defined in Section A.1. All of the systems used for civil navigation are discussed. The systems that are used exclusively to meet the special applications of DoD are discussed in the CJCSI 6130.01 (Ref. 1).

A.2.1 Global Positioning System (GPS)

GPS is a space-based dual-use PNT system that is operated for the USG by the United States Space Force (USSF). The USG provides two types of GPS service. PPS is available to authorized users and SPS is available to all users.

GPS has three major segments: space, control, and user, as depicted in Figure A-1. The GPS Space Segment consists of a nominal constellation of at least 24 satellites in six orbital planes. The satellites operate in near circular Medium Earth Orbit (MEO), at an altitude of approximately 20,200 km (10,900 NM), and at an inclination angle of 55 degrees, with a period of approximately twelve hours.

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

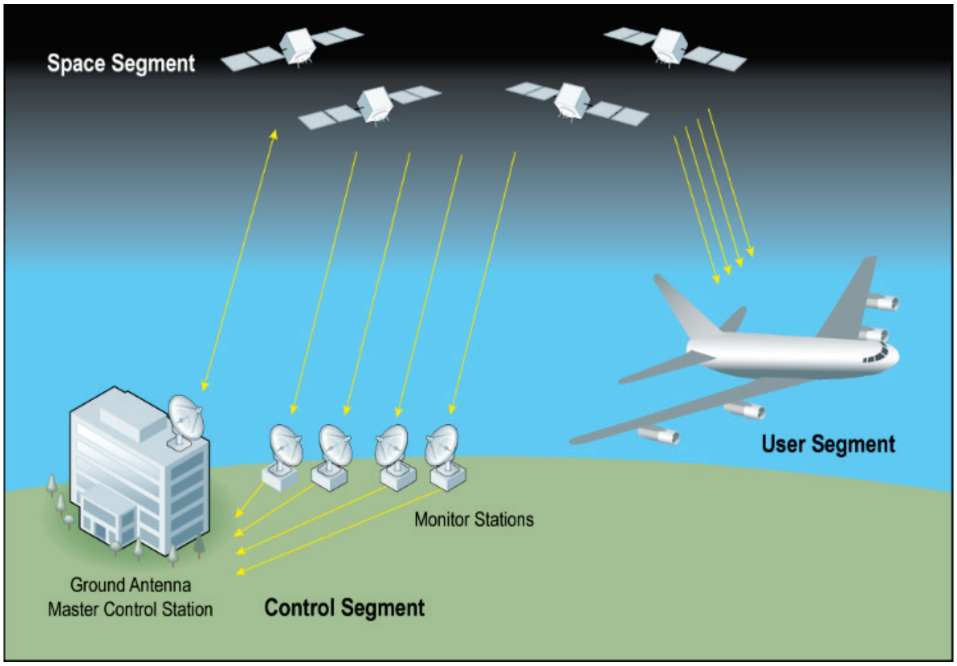

Figure A-1: GPS Architecture

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

Table A-1: GPS/SPS Characteristics

SPS ACCURACY (meters) 95%* PREDICTABLE	SERVICE AVAILABILITY	COVERAGE	SERVICE RELIABILITY**	FIX RATE	FIX DIMENSION	SYSTEM CAPACITY	AMBIGUITY POTENTIAL
Horizontal ≤ 9 Vertical ≤ 15 Time ≤ 40 ns	99%	Terrestrial Service Volume	1-1x10^{-5}/hr/SIS	1–20 per sec	3D+Time	Unlimited	None

* Accuracy and availability percentages are computed using 24-hour measurement intervals. Statistics are representative for an average location within the global service volume. Predictable horizontal 95% error can be as large as 17 m and predicted vertical 95% error as large as 37 m at the worst-case location in the terrestrial service volume. Accuracy statistics do not include contributions from the single-frequency ionospheric model, troposphere, or receiver noise. Availability statistic applies for worst-case location predicted 95% horizontal or vertical position error values.

** Reliability threshold is ±4.42 times the upper bound on the URA value corresponding to the URA index "N" currently broadcast by the satellite.

The characteristics of GPS SPS are summarized in Table A-1. Further details on the performance of GPS SPS may be found in the GPS SPS PS (Ref. 19).

A. Signal Characteristics

For PNT users, each satellite transmits three spread spectrum signals on two L-band frequencies, L1 (1575.42 MHz) and L2 (1227.6 MHz). L1 carries a Precise (P(Y)) Pseudo-Random Noise (PRN) code and a Coarse/ Acquisition (C/A) PRN code, while L2 carries the P(Y) PRN code. The

Precise code is denoted as P(Y) to signify that this PRN code can be transmitted in either a clear, unencrypted "P" or an encrypted "Y" code configuration. The PRN codes carried on the L1 and L2 frequencies are phase-synchronized to the satellite clock and modulated (using modulo two addition), with a common 50 Hz navigation data message. Modernized satellites have begun broadcasting additional signals as described in Section 3.2.7. One of these signals, L2C, can be utilized by users to reduce the ionospheric error on the L1 C/A signal received from the same satellite. The L2C signal is available starting with the Block IIRM satellites.

The SPS ranging signal received by the user is a 2.046 MHz null-to-null bandwidth signal centered about L1. The transmitted ranging signal that comprises the GPS-SPS is centered at 1575.42MHz in the 1559–1610 MHz ARNS/RNSS band. The minimum SPS received power is specified as -158.5 dBW measured at the output of a 3 dBi linearly polarized user receiving antenna (located near ground) at worst normal orientation, when the SV is above a 5-degree elevation angle. The navigation data contained in the signal are composed of satellite clock and ephemeris data for the transmitting satellite plus GPS constellation almanac data, GPS to UTC (USNO) time offset information, and ionospheric propagation delay correction parameters for use by single frequency (SPS) users. The entire navigation message repeats every 12.5 minutes. Within this 12.5-minute repeat cycle, satellite clock and ephemeris data for the transmitting satellite are sent 25 separate times so they repeat every 30 s. As long as a satellite indicates a healthy status, a receiver can continue to operate using these data for the validity period of the data (up to 4 or 6 hrs.). The receiver will update these data whenever the satellite and ephemeris information are updated—nominally once every two hours.

Conceptually, GPS position determination is based on the intersection of four separate spheres, each with a known origin and a known magnitude. Sphere centers for each satellite are computed based on satellite ephemeris. Range magnitudes are calculated based on signal propagation time delay as measured from the transmitting satellite’s PRN code phase delay. Given that the satellite signal travels at the speed of light and taking into account delays and adjustment factors such as ionospheric propagation delays, Doppler, relativity affects, and Earth rotation factors, the receiver performs ranging measurements between the individual satellite and the user by multiplying the satellite signal propagation time by the speed of light.

B. Accuracy

SPS is the standard specified level of positioning, velocity, and timing accuracy that is available, without restrictions, to any user on a continuous worldwide basis. SPS provides a global average predictable positioning accuracy of 9 m (95 percent) horizontally and 15 m (95 percent) vertically and time transfer accuracy within 40 ns (95 percent) of UTC. For more detail, refer to the GPS SPS PS (Ref. 19).

C. Availability

The SPS provides a global average availability of 99 percent. Service availability is based upon the expected horizontal error being less than 17 m (95 percent) and the expected vertical error being less than 37 m (95 percent). The expected positioning error is a predictive statistic and is based on a combination of position solution geometry and predicted satellite ranging signal errors.

D. Coverage

The coverage of the GPS SPS service is described in terms of terrestrial and space service volume. The terrestrial service volume covers the entire surface of the Earth up to an altitude of 3,000 km. The space service volume extends from 3,000 km above the surface of the Earth up to and including 36,000 km above the Earth's surface.

E. Reliability

The probability that the SPS SIS URE from a healthy satellite will not exceed ±4.42 times the upper bound on the user range accuracy (URA) value corresponding to the URA index "N" currently broadcast by the satellite without a timely alert is > $1\text{-}1 \times 10^{-5}$/hr.

F. Fix Rate

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

G. Fix Dimensions

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

H. System Capacity

The capacity is unlimited.

I. Ambiguity

There is no ambiguity.

J. Integrity

The GPS system architecture incorporates many features including redundant hardware, robust software, and rigorous operator training to minimize integrity anomalies. Resolution of an unanticipated satellite integrity anomaly may take up to 6 hr. Even the best response time may be on the order of several minutes, which is insufficient for certain applications. For such applications, augmentations, such as Receiver Autonomous Integrity Monitoring (RAIM), a built-in receiver algorithm, may be required to achieve the requisite timely alert.

K. Spectrum

GPS satellites broadcast navigation signals at three L-band frequencies: L1, centered at 1575.42 MHz in the 1559–1610 MHz ARNS/RNSS band; L2, centered at 1227.6 MHz in the 1215–1240 MHz band; and L5, centered at 1176.45 MHz in the 1164-1215 MHz ARNS/RNSS band.

A.2.2 Augmentations to GPS

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

GPS must be augmented to meet the most demanding aviation, land, and marine accuracy and integrity requirements. Differential GPS is one method to satisfy these requirements.

Differential GPS enhances GPS through the use of differential corrections to the basic satellite measurements. Differential GPS is based upon accurate knowledge of the geographic location of one or more reference stations, which is used to compute pseudorange corrections based on its measurements. These differential corrections are then transmitted to GPS users, who apply the corrections to their received GPS signals or computed position. For a civil user of SPS, differential corrections can improve navigation accuracy to better than 7 m (2 drms). A Differential GPS reference station is fixed at a geodetically surveyed position. From this position, the reference station typically tracks all satellites in view and computes corrections based on its measurements and geodetic position. These corrections are then broadcast to GPS users to improve their navigation solution. A well-developed method of handling this is by computing pseudorange corrections for each satellite, which are then broadcast to the user and applied to the user's pseudorange measurements before the GPS position is calculated by the receiver, resulting in a highly accurate navigation solution. A receiver at a fixed reference site receives signals from all visible satellites and measures the pseudorange to each. Since the satellite signal contains information on the satellite orbits and the reference receiver knows its position, the true range to each satellite can be calculated. By comparing the calculated range and the measured pseudorange, a correction term can be determined for each satellite. The pseudorange corrections are broadcast and applied to the satellite measurements at each user's location. This method is employed by the FAA's Ground Based Augmentation System (GBAS).

The FAA WAAS employs a network of GPS reference/measurement stations at surveyed locations to collect dual-frequency measurements of GPS pseudorange and pseudorange rate for all spacecraft in view. These measurements are processed to yield highly accurate ephemeris, ionospheric and tropospheric calibration maps, and corrections for the broadcast spacecraft ephemeris and clock offsets. In the WAAS, these corrections and system integrity messages are relayed to users via dedicated transponders on commercial geostationary satellites. This relay technique also supports the delivery of an additional ranging signal, thereby increasing overall navigation system availability.

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

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

A.2.2.1 Wide Area Augmentation System (WAAS)

The WAAS consists of equipment and software that augments the DoD-provided GPS SPS (see Figure A-2). 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. WAAS currently supports aviation navigation for en route through approaches equivalent to CAT I, RNAV, and RNP guided departures. In 2008 WAAS completed the Full LPV phase of the program, whereby the WAAS met the performance requirements for LPV throughout the continental U.S. and Alaska.

The GPS satellites' data are received and processed at widely dispersed sites, referred to as Wide-area Reference Stations (WRS). This data is forwarded to data processing sites, referred to as Wide-area Master Stations

(WMS), which process the data to determine the integrity, differential corrections, residual errors, and ionospheric information for each monitored satellite and generate GEO satellite navigation parameters. This information is sent to a Ground Earth Station (GES) and uplinked along with the GEO navigation message to GEO satellites. These GEO satellites then downlink these data on the GPS Link 1 (L1) frequency with a modulation similar to that used by GPS.

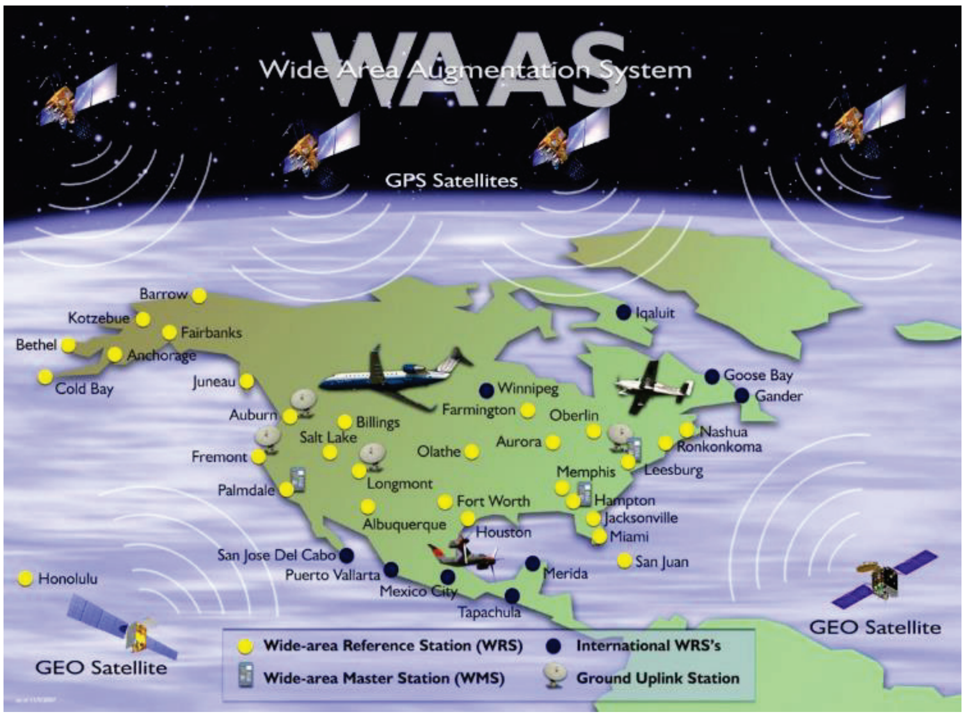

Figure A-2: WAAS Architecture

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

The WAAS user receiver processes: (1) the integrity data to ensure that the satellites being used are providing in-tolerance navigation data, (2) the differential correction and ionospheric information data to improve the accuracy of the user's position solution, and (3) the ranging data from one or more of the GEO satellites for position determination to improve availability and continuity.

A. Signal Characteristics

The WAAS collects raw data from all GPS and WAAS GEO satellites that support the navigation service. WAAS ground equipment develops messages on ranging signals and signal quality parameters of the GPS and

GEO satellites. The GEO satellites broadcast the WAAS messages to the users and provide ranging sources on the GPS L1 frequency using GPS-type modulation, including a C/A PRN code. The code-phase timing is synchronized to GPS time to provide a ranging capability.

B. Accuracy

WAAS is delivering horizontal and vertical accuracy of better than 2 m (95 percent) throughout CONUS. The accuracy requirements are based on aviation operations. For the en route through non-precision approach phases of flight, un-augmented GPS accuracy is sufficient. For LPV-200, the horizontal and vertical requirement is 1.5 m and 2 m (95 percent) respectively.[19]

C. Availability

The WAAS availability for en route through nonprecision approach operations is at least 0.9999 for CONUS and 0.999 for Alaska. For approach with vertical guidance operations in CONUS the availability is at least 0.99.

D. Coverage

WAAS coverage is defined from the surface up to 100,000 ft in separate zones for the airspace of the 48 conterminous states (CONUS), Alaska, Hawaii, and the Caribbean islands. The service level expectations for availability and continuity differ from zone to zone primarily because of the multiple levels of service and the challenge of siting reference stations to adequately monitor the ionosphere in the zones outside CONUS. Alaska is also affected by being in the northern latitudes at the edge of GEO coverage. A more complete coverage description can be found in the WAAS Performance Standard 1st edition October 2008.

E. Reliability

The WAAS provides sufficient reliability and redundancy to meet the overall NAS requirements with no single point of failure. The overall reliability of the WAAS signal-in-space approaches 99.9 percent.

F. Fix Rate

This system provides a virtually continuous position update.

G. Fix Dimensions

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

[19] LPV-200 does not meet the technical definition of Category I precision approach; however, it can provide a 200-foot decision height, equivalent to Category I.

H. System Capacity

The user capacity is unlimited.

I. Ambiguity

The system provides no ambiguity of position fixing information.

J. Integrity

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

Integrity is specified by three parameters: probability of hazardously misleading information (pHMI), time to alert, and the alert limit. For the en route through non-precision approach phases of flight the performance values are:

pHMI	10^{-7} per hr
Time to Alert	6.2 seconds
Alert Limit	Protection limits specified for each phase of flight

For LPV approach operations the performance values are:

pHMI	10^{-7} per approach
Time to Alert	6.2 seconds
Alert Limit[20]	Horizontal 40 m/vertical 50 m
Alert Limit[21]	Horizontal 40 m/vertical 35 m

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

K. Spectrum

WAAS operates as an overlay on the GPS L1 and GPS L5 links in the1559–1610 MHz and 1164–1215 MHz ARNS/RNSS frequency bands respectively.

A.2.2.2 Ground Based Augmentation System (GBAS)

The U.S. version of GBAS has traditionally been referred to as the Local Area Augmentation System (LAAS). The worldwide aviation community has adopted GBAS as the official term for this type of navigation augmentation system. To be consistent with the international community, the FAA is also adopting the term GBAS. GBAS is a safety critical

[20] For approaches with ceiling and visibility minima as low as 250 ft. and ¾ mi.
[21] For approaches with ceiling and visibility minima as low as 200 ft. and ½ mi.

precision approach navigation and landing system consisting of equipment to augment the DoD-provided GPS SPS with differential GPS pseudorange corrections, integrity parameters, and approach data (see Figure A-3). It provides a signal-in-space to GBAS-equipped users with the specific goal of supporting terminal area navigation through CAT III precision approach, including autoland. The GBAS signal-in-space provides: (1) local area differential corrections for GPS satellites and optionally for WAAS GEO satellites used as ranging sources, (2) the associated integrity parameters; and (3) precision approach final approach segment description path points.[22]

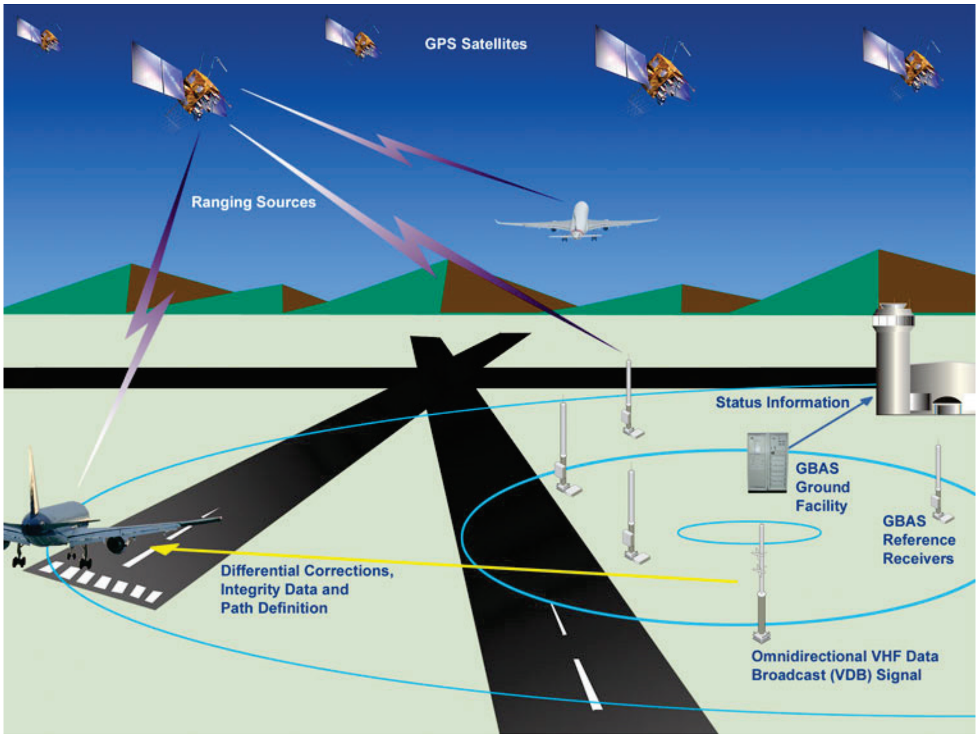

Figure A-3: GBAS Architecture

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

The individual differential range measurement corrections, integrity parameters, and final approach segment path point descriptions for each runway end being served are broadcast to aircraft operating in the local

[22] Corrections to WAAS GEO ranging sources are optional for GBAS equipment.

terminal area via an omnidirectional GBAS VHF data broadcast transmission.

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

A. Signal Characteristics

The GBAS collects raw GPS range data from all available range sources that support the navigation service.

The GBAS ground facility generates differential correction messages as well as pseudorange correction error parameters for each of the ranging measurements. The GBAS VHF data broadcast transmitter then broadcasts the GBAS correction message to users. The VHF band, 108–117.925 MHz, is used for the GBAS VHF data broadcast.

B. Accuracy

The GBAS accuracy requirements were derived from ILS accuracy requirements. For CAT I precision approach, the lateral accuracy requirement is 16.0 m, 95 percent. The GBAS CAT I vertical accuracy requirement is 4.0 m, 95 percent.

C. Availability

The availability of GBAS is location/airport dependent and ranges from 0.99 – 0.99999 (per ICAO Annex 10 SARPS). This availability range assumes fault-free GBAS aircraft equipment and is significantly dependent on the visible GPS constellation at each specific installation.

D. Coverage

The GBAS minimum service volume is defined as:

- Vertically: Beginning at the runway datum point out to 20 NM above 0.9 deg and below 10,000 ft.
- Horizontally: 450 ft either side of the runway beginning at the runway datum point and projecting out 35 deg either side of the approach path out to 20 NM (per the non-Federal LAAS specification).

E. Reliability

- The Mean-Time-Between-Failure (MTBF) for the GBAS ground facility shall be at least 2190 hours. (Paraphrased from FAA-E-3017, Specification for Non-Federal Navigation Facilities Category-I Local Area Augmentation System Ground Facility).

- Mean-Time-To-Repair (MTTR) shall be less than 30 minutes and shall account for the following (Paraphrased from FAA-E-3017, Specification for Non-Federal Navigation Facilities Category-I Local Area Augmentation System Ground Facility):
    - Diagnostic Time,
    - Removal of the failed LRU,
    - Installation of the new LRU,
    - Initialization of the new LRU,
    - All adjustments required to return the ground facility to a normal/operational mode.

F. Fix Rate

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

G. Fix Dimensions

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

H. System Capacity

There is no limit on the GBAS System Capacity.

I. Ambiguity

There is no ambiguity of position associated with the GBAS.

J. Integrity

Assurance of position integrity of the GPS SPS by the GBAS is a required capability that is both an operational characteristic and a technical characteristic. The required system performance for systems intended to support CAT I operations is specified by the following parameters:

pHMI	10^{-7} per approach
Time to Alert	6 seconds
Alert Limit	Horizontal 40 m/vertical 10 m

Requirements to support CAT III operations have been completed and are intended to fit within the operational framework of ILS CAT III operations.

K. Spectrum

GBAS broadcasts in the 108–117.975 MHz frequency band, currently populated by VORs and ILSs, either on channels interstitial to the current

VOR/ILS, or after VOR and ILS have been partially decommissioned. In the U.S., GBAS frequency assignments are limited to 112.075–117.925 MHz.

A.2.3 Instrument Landing System (ILS)

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

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

Table A-2: ILS Characteristics (Signal-in-Space)

ACCURACY AT MINIMUM APPLICABLE DECISION HEIGHT (meters - 2 Sigma)			AVAILABILITY	COVERAGE	RELIABILITY	FIX RATE*	FIX DIMENSION	SYSTEM CAPACITY	AMBIGUITY POTENTIAL
CATEGORY	AZIMUTH	ELEVATION							
I	± 9.1 m	± 4.1 m	Approaches 99%	Normal limits from center of localizer ± 10° out to 18 NM and ± 35° out to 10 NM	98.6% with positive indication when the system is out of tolerance	Continuous	Heading and Deviation in degrees	Limited only by Aircraft separation requirements	None
II	TBD**	TBD**							
III	TBD**	TBD**							

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

A. Signal Characteristics

The localizer facility and antenna are typically located 1,000 ft. beyond the stop end of the runway and provide a VHF (108–111.975 MHz ARNS band) signal. The glide slope facility is located approximately 1,000 ft. from the approach end of the runway and provides a UHF (328.6–335.4 MHz ARNS band) signal. Marker beacons are located along an extension of the runway centerline and identify particular locations on the approach. Ordinarily, two 75 MHz beacons are included as part of the ILS: an outer marker at the final approach fix (typically four to seven miles from the approach end of the runway) and a middle marker located 3,500 ft. ±250 ft. from the runway threshold.[23] The middle marker is located so as to note impending visual acquisition of the runway in conditions of minimum visibility for CAT I ILS approaches. An inner marker, located approximately 1,000 ft. from the threshold, is normally associated with CAT II and III ILS approaches.

[23] Marker beacons are no longer required for ILS approaches, if a substitute can be provided. Existing beacons are being allowed to attrit and may be taken out of service, given an acceptable substitute.

B. Accuracy

For typical air carrier operations at a 10,000-foot runway, the course alignment (localizer) at threshold is maintained within ±25 ft. Course bends during the final segment of the approach do not exceed ±0.06 deg (95 percent). Glide slope course alignment is maintained within ±7.0 ft at 100 ft (95 percent) elevation and glide path bends during the final segment of the approach do not exceed ±0.07 deg (95 percent).

C. Availability

ILS-based procedures are typically available between 98 and 99 percent of the time.

D. Coverage

Coverage for individual systems is as follows:

- Localizer: ±35 deg centered about course line out to 10 NM and ±10 deg out to 18 NM.
- Glide Slope: from 0.45 to 1.75 times the glide slope angle out to 10 NM.
- Marker Beacons: ±40 deg (approximately) on minor axis (along approach path) ±85 deg (approximately) on major axis.

E. Reliability

ILS reliability is 98.6 percent. However, terrain and other factors may impose limitations upon the use of the ILS signal. Special account must be taken of terrain factors and dynamic factors such as taxiing aircraft that can cause multipath interference.

In some cases, using localizers with aperture antenna arrays and two-frequency systems resolves ILS siting problems. For the glide slope, using wide aperture, capture effect image arrays and single-frequency arrays provides service at difficult sites.

F. Fix Rate

The glide slope and localizer provide continuous fix information, although the user receives position updates at a rate determined by receiver/display design (typically more than 5 updates per second). Marker beacons that provide an audible and visual indication to the pilot are sited at specific points along the approach path as indicated in Table A-4.

G. Fix Dimensions

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

H. System Capacity

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

Table A-3: Aircraft Marker Beacons

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

I. Ambiguity

Any potential ambiguities are resolved by imposing system limitations as described in Section A.2.3.E.

J. Integrity

ILS provides system integrity by removing a signal from use when an out-of-tolerance condition is detected by an integral monitor. The shutdown delay for each category is given in Table A-5.

Table A-4: ILS Shutdown Delay

CATEGORY	LOCALIZER	GLIDE SLOPE
I	<10 s	<6 s
II	<5 s	<2 s
III	<2 s	<2 s

K. Spectrum

ILS marker beacons operate in the 74.8–75.2 MHz VHF band. ILS localizers share the 108–111.975 MHz portion of the 108–117.975 MHz ARNS band with VOR. ILS glideslope sub-systems operate in the 328–335.4 MHz UHF band.

A.2.4 VOR, DME, and TACAN

Historically, VOR, DME, and TACAN have comprised the basic infrastructure for aviation en route and terminal navigation and non-precision approaches in the United States, but will cede their preeminence as GNSS becomes more widely implemented. Information provided to the pilot by VOR is the magnetic azimuth relative to the VOR ground station. DME provides a measurement of the slant range 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 similar to VOR/DME and is used primarily by military aircraft. When TACAN is collocated with VOR, it is designated as a VORTAC facility. DME and the distance measuring function of TACAN are functionally the same; thus, TACAN distance service is treated by civilian aircraft as a DME.

A.2.4.1 Very High Frequency (VHF) Omnidirectional Range (VOR)

A. Signal Characteristics

The signal characteristics of VOR are summarized in Table A-6. VOR are assigned frequencies in the 108–117.975 MHz (VHF) ARNS frequency band, separated by 50 kHz. A VOR transmits two 30 Hz modulations resulting in a relative electrical phase angle equal to the azimuth angle of the receiving aircraft. A cardioid field pattern is produced in the horizontal plane and rotates at 30 Hz. A nondirectional (circular) 30-Hz pattern is also transmitted during the same time in all directions and is called the reference phase signal.

Table A-5: VOR and DME System Characteristics (Signal-in-Space)

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

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

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

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

The variable phase pattern changes phase in direct relationship to azimuth. The reference phase is frequency modulated while the variable phase is amplitude modulated. The receiver detects these two signals and computes the azimuth from the relative phase difference. For difficult siting situations, a system using the Doppler effect was developed and uses 50 instead of four antennas for the variable phase. The same avionics works with either type ground station.

B. Accuracy (95 percent)

- Predictable: The ground station errors are approximately ±1.4 deg. The summation of course selection, receiver, and flight technical errors (FTE), when calculated using root-sum-squared (RSS) techniques, is ±4.5 deg.
- Relative: Although some course bending could influence position readings between aircraft, the major relative error consists of the course selection, receiver, and flight technical components. When combined using RSS techniques, the value is approximately ±4.3 deg. The VOR ground station relative error is ±0.35 deg.
- Repeatable: The major error components of the ground system and receiver will not vary appreciably in the short term. Therefore, the repeatable error will consist mainly of the flight technical error (the pilots' ability to fly the system) that is ±2.3 deg.

C. Availability

VOR availability is typically 99 percent to 99.99 percent.

D. Coverage

Most aeronautical radionavigation aids that provide positive course guidance have a designated Standard Service Volume (SSV) that defines the unrestricted reception limits usable for random or unpublished route navigation. Within the SSV, the NAVAID signal is frequency protected and is available at the altitudes and radial distances indicated in Table A-7. In addition to these SSVs, it is possible to define a non-standard service volume if siting constraints result in less coverage. Also, it is possible to define a larger service volume where siting conditions allow. SSV limitations do not apply to published IFR routes or procedures.

Table A-6: VOR/DME/TACAN Standard Service Volumes (SSV)

SSV CLASSDESIGNATOR	ALTITUDE AND RANGE BOUNDARIES
T (Terminal)	From 1,000 ft above ground level (AGL) up to and including 12,000 ft AGL at radial distances out to 25 NM.
L (Low Altitude)	From 1,000 ft AGL up to and including 18,000 ft AGL at radial distances out to 40 NM.
H (High Altitude)	From 1,000 ft AGL up to and including 14,500 ft AGL at radial distances out to 40 NM. From 14,500 ft AGL up to and including 60,000 ft AGP at radial distances out to 100 NM. From 18,000 ft AGL up to and including 45,000 ft AGL at radial distances out to 130 NM.

Reception below 1,000 ft above ground level is governed by line-of-sight considerations, and is described in Section 1-1-8 of the FAA *Aeronautical Information Manual (AIM)* (Ref. 57). Complete functional and performance characteristics are described in FAA Order 9840.1, *U.S. National Aviation Standard for the VOR/DME/TACAN Systems* (Ref. 58).

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

E. Reliability

Due to advanced solid-state construction and the use of remote maintenance monitoring techniques, the reliability of solid-state VOR approaches 99.7 percent.

F. Fix Rate

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

G. Fix Dimensions

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

H. System Capacity

The capacity of a VOR station is unlimited.

I. Ambiguity

There is no ambiguity possible for a VOR station.

J. Integrity

VOR provides system integrity by removing a signal from use within 10 s of an out-of-tolerance condition detected by an independent monitor.

K. Spectrum

VOR operates in the 108–117.975 MHz VHF band. It shares the 108–111.975 MHz portion of that band with ILS.

A.2.4.2 Distance Measuring Equipment (DME)

A. Signal Characteristics

The signal characteristics of DME have been summarized above in Table A-6. The interrogator in the aircraft generates a pulsed signal (interrogation). If the signal is of the correct frequency and pulse spacings, it is accepted by the transponder. In turn, the transponder generates pulsed signals (replies) that are sent back and accepted by the interrogator's tracking circuitry. Distance is then computed by measuring the total round trip time of the interrogation and its reply. The operation of DME is thus accomplished by paired pulse signals and the recognition of desired pulse spacings accomplished by the use of a decoder. The transponder must reply to all interrogators. The interrogator must measure elapsed time between interrogation and reply pulse pairs and translate this to distance. All signals are vertically polarized. These systems are assigned in the 962–1213 MHz (UHF) ARNS frequency band with a separation of 1 MHz.

B. Accuracy (95 percent)

- Predictable: The ground station errors are less than ±0.1 NM. The overall system error (airborne and ground RSS) is not greater than ±0.5 NM or 3 percent of the distance, whichever is greater.
- Relative: Although some errors could be introduced by reflections, the major relative error emanates from the receiver and flight technical error.
- Repeatable: Major error components of the ground system and receiver will not vary appreciably in the short term.

C. Availability

The availability of DME is considered to approach 99.7% percent, with positive indication when the system is out-of-tolerance.

D. Coverage

DME coverage is described in the preceding section on VOR and in Table A-7. Because of facility placement, almost all of the airways have coverage and most of CONUS has dual coverage, permitting DME/DME RNAV.

E. Reliability

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

F. Fix Rate

The system essentially gives a continuous update of distance to the facility. Actual update rate varies with the design of airborne equipment and system loading, with typical rates of 10 per second.

G. Fix Dimensions

The system shows slant range to the DME station in nautical miles.

H. System Capacity

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

I. Ambiguity

There is no ambiguity in the DME system.

J. Integrity

DME provides system integrity by removing a signal from use within 10 s of an out-of-tolerance condition detected by an independent monitor.

K. Spectrum

DME operates in the 960–1027, 1033–1087, and 1093–1215 MHz sub-bands of the 960–1215 MHz ARNS band. It shares those sub-bands with TACAN and with L5, the third civil frequency for GPS, located at frequency 1176.45 MHz. In addition, the 978 MHz frequency within the DME operating band is specifically reserved for exclusive use by the Universal Access Transceiver (UAT) ADS-B system. This protected ARNS band meets the needs of critical safety-of-life applications.

A.2.4.3 Tactical Air Navigation (TACAN)

A. Signal Characteristics

TACAN is a short-range UHF (962–1215 MHz ARNS band) PNT system designed primarily for military aircraft use. TACAN transmitters and responders provide the data necessary to determine magnetic bearing and slant distance[24] from an aircraft to a selected station. TACAN stations in the U.S. are frequently collocated with VOR stations. These facilities are known as VORTACs. TACAN signal characteristics are summarized in Table A-8.

[24] TACAN returns a distance, but it is referred to as Slant Range or Slant Distance.
Example: My house is 5 miles from the airport, a distance of 5 miles, a plane flies overhead at 30,000 feet (simplify to 6 miles overhead).
RADAR returns will show the aircraft at 5 miles from the airport, TACAN will report the aircraft at sqrt(5^2+6^2) away 0r 7.87 miles away.
Pythagorean Theorem, A^2 + B^2 = C^2: A = distance , B = altitude, C = Slant Range.
How TACAN returns distance to the aircrew, different from the RADAR distance.

Table A-7: TACAN System Characteristics (Signal-in-Space)

ACCURACY (2 Sigma)			AVAILABILITY	COVERAGE	RELIABILITY	FIX RATE	FIX DIMENSIONS	SYSTEM CAPACITY	AMBIGUITY POTENTIAL
PREDICTABLE	REPEATABLE	RELATIVE							
Azimuth ±1° (±63 m at 3.75 km)	Azimuth ±1° (± 63 m at 3.75 km)	Azimuth +1° (±63 m at 3.75 km)	98%	Line of sight	99%	Continuous	Slant Distance and bearing from station	110 for slant distance Unlimited in azimuth	No ambiguity in range Slight potential for ambiguity at multiples of 40°
DME: 185 m (±0.1 NM)	DME: 185 m (±0.1 NM)	DME: 185 m (±0.1 NM)							

B. Accuracy (95 percent)

- Predictable: The ground station errors are less than ±1.0 deg for azimuth for the 135 Hz element and ±4.5 deg for the 15 Hz element. Slant distance errors are the same as DME errors.
- Relative: The major relative errors emanate from course selection, receiver, and flight technical error.
- Repeatable: Major error components of the ground station and receiver will not vary greatly in the short term. The repeatable error will consist mainly of the flight technical error.

C. Availability

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

D. Coverage

TACAN coverage is described in the preceding section on VOR and in Table A-8.

E. Reliability

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

F. Fix Rate

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

G. Fix Dimensions

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

H. System Capacity

For slant distance information, 110 interrogators are considered reasonable for present traffic handling. Future traffic handling could be increased when necessary through reduced airborne interrogation rates and increased reply rates. Capacity for the azimuth function is unlimited.

I. Ambiguity

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

J. Integrity

TACAN provides system integrity by removing a signal from use within 10 s of an out-of-tolerance condition detected by an independent monitor.

K. Spectrum

TACAN operates in the 960–1027, 1033–1087, and 1093–1215 MHz sub-bands of the 960–1215 MHz ARNS band. It shares those sub-bands with DME and with L5, the third civil frequency for GPS, located at frequency 1176.45 MHz. In addition, the 978 MHz frequency within the TACAN operating band is specifically reserved for exclusive use by the UAT ADS-B system. This protected ARNS band meets the needs of critical safety-of-life applications.

A.2.5 Nondirectional Radiobeacons (NDB)

Radiobeacons are nondirectional radio transmitting stations that operate in the low- and medium-frequency bands to provide ground wave signals to a receiver. Aeronautical nondirectional beacons are used to supplement VOR-DME for transition from en route to airport precision approach facilities and as a non-precision approach aid at many airports. An automatic direction finder (ADF) is used to measure the bearing of the transmitter with respect to an aircraft or vessel. Marine radiobeacons have been phased out. NDB characteristics are summarized in Table A-9.

Table A-8: Radiobeacon System Characteristics (Signal-in-Space)

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

A. Signal Characteristics

Aeronautical NDB operate in the 190–415 kHz and 510–535 kHz ARNS bands. (Note: NDB in the 285–325 kHz band are secondary to maritime radiobeacons.) Their transmissions include a coded continuous-wave (CCW) or modulated continuous-wave (MCW) signal to identify the station. The CCW signal is generated by modulating a single carrier with either a 400 Hz or a 1,020 Hz tone for Morse code identification. The MCW signal is generated by spacing two carriers either 400 Hz or 1,020 Hz apart and keying the upper carrier to give the Morse code identification.

B. Accuracy

Positional accuracy derived from the bearing information is a function of geometry of the lines of position (LOP), the accuracy of compass heading, measurement accuracy, distance from the transmitter, stability of the signal, time of day, nature of the terrain between beacon and craft, and noise. In practice, bearing accuracy is on the order of ±3 to ±10 deg. Achievement of ±3 deg accuracy requires that the ADF be calibrated before it is used for navigation by comparing radio bearings to accurate bearings obtained visually on the transmitting antenna. Since most direction finder receivers will tune to a number of radio frequency bands, transmissions from sources of known location, such as amplitude modulation (AM) broadcast stations, are also used to obtain bearings, generally with less accuracy than obtained from radiobeacon stations. For FAA flight inspection, NDB system accuracy is stated in terms of permissible needle swing: ±5 deg on approaches and ±10 deg in the en route area.

C. Availability

Availability of aeronautical NDB is in excess of 99 percent.

D. Coverage

Extensive NDB coverage is provided by 1,260 ground stations, of which the FAA operates 605.

E. Reliability

Reliability is in excess of 99 percent.

F. Fix Rate

The beacon provides continuous bearing information.

G. Fix Dimensions

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

H. System Capacity

An unlimited number of receivers may be used simultaneously.

I. Ambiguity

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

J. Integrity

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

K. Spectrum

Aeronautical NDBs operate in the 190–435 and 510–535 kHz frequency bands, portions of which it shares with maritime NDB.

A.2.6 Automatic Dependent Surveillance-Broadcast (ADS-B)

ADS-B is an advanced surveillance technology that allows aircraft/ vehicles to broadcast pertinent information (e.g., identification, position, altitude, velocity, and other information). ADS-B is *automatic* because no external stimulus is required; it is *dependent* because it relies on an on-board navigation source to broadcast the information to other users. Since the aircraft's or vehicle's position is normally derived from the Global Positioning System (GPS) and transmitted at least once per second, the broadcasted position information is more accurate than most current radar-based position information.

Additionally, aircraft provide uniquely specific flight parameter information with the broadcast of its surveillance position. The greater positional accuracy and ability to provide parameters, in addition to position data, defines ADS-B as enhanced surveillance. These other parameters, such as directional vector, velocity, and other data are limited only by the equipment's capability, the communication data link capacity, and the receiving system's capability.

The accuracy and broadcast characteristics of ADS-B supports numerous cockpit-based and air traffic control (ATC) applications. For select ADS-B In equipped aircraft, some displays may receive ADS-B messages from other suitably equipped aircraft or vehicles within the reception range resulting in an aircraft-to-aircraft/vehicle and airport surface surveillance. ADS-B surveillance broadcasts can also be received by ground-based transceivers or space-based satellites. This provides air-to-ground, and airport surface surveillance information for ATC and traffic flow management (TFM) services and other functions such as, fleet operations management, collaborative decision making, and security functions.

In the United States, two different data links have been adopted for ADS-B, the 1090 MHz extended squitter (1090 ES) and the 978 MHz Universal Access Transceiver (978 UAT). The 1090 ES link is required for aircraft that operate in Class A airspace and the 978 UAT link is primarily intended for general aviation aircraft that operate in other controlled airspace, limited to below 18,000 feet. Vehicles have the option of equipping with either link technology. The aircraft or vehicle originating the broadcast does not have knowledge of which users are receiving its broadcast; any user, either aircraft or ground-based, within range of this broadcast, may choose to receive and process the ADS-B surveillance information. ADS-B provides surveillance data at a higher update rate and with improved accuracy over today's NAS radar systems.

Key ADS-B requirements were selected such that the performance of the system supported the ATC surveillance and defined air-to-air applications. These requirements include service availability, latency, position update rate, positional accuracy, horizontal position integrity, and coverage.

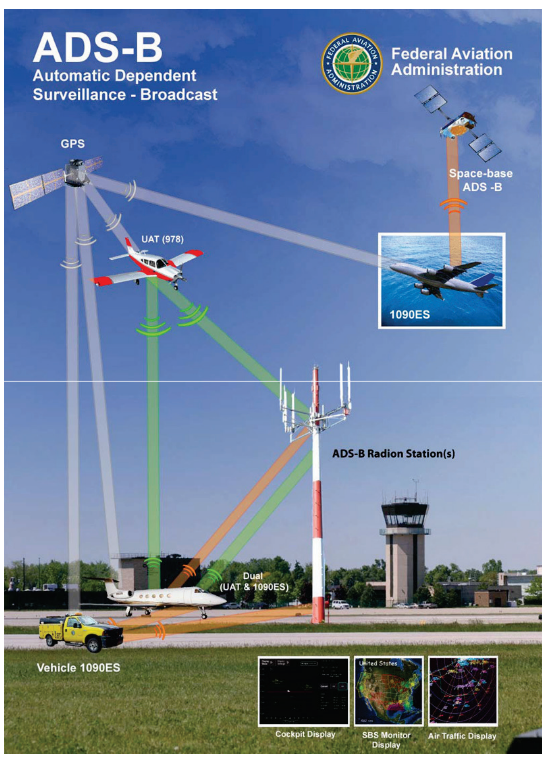

Figure A-4: ADS-B Architecture

A. Service Availability

The ADS-B service for the ATC surveillance separation applications is a safety-critical operation. As a result, the ADS-B service provides a minimum availability of 0.99999. This service availability applies to total outages in a service volume for the navigation source, back up surveillance source, the ADS-B infrastructure, and the FAA automation system. It does not apply to outages that may occur on individual aircraft.

B. Latency

The ADS-B system latency is defined as the time difference from the time of applicability of the ADS-B position data until the ADS-B report is displayed on the glass to the air traffic specialist. The latency from time of applicability of the ADS-B Message data until display by ATC automation is less than or equal to 2.7 seconds. However, with compensation of known ADS-B latencies in the aircraft and ground systems the overall latency decreases such that the total latency is less than 2.2 seconds for ATC separation services.

C. Position Update Rate

The system update rate is the rate at which the ADS-B information is delivered to the automation system for use in processing and display of data to air traffic controllers.

- For each aircraft/vehicle in motion on the surface movement area, the ADS-B Report update rate for reports containing position information is on average of at least once every 1.0 second.
- For each stationary aircraft/vehicle on the surface movement area the Surface domain, the ADS-B Report update rate for reports containing position information is at least once every 5.5 seconds (95 percent).
- For each aircraft/vehicle operating in terminal or en route airspace, the ADS-B Report update rate for reports containing position information is at least once every 3.0 seconds (95 percent).

D. Positional Accuracy

The accuracy is an estimate of the uncertainty in the position information. For ADS-B based on a GNSS positioning source, the accuracy is equivalent to the horizontal figure of merit (HFOM). The required accuracy values are defined as follows to ensure that all the baseline ADS-B portfolio applications could be performed with the ADS-B Services:

a. The aircraft/vehicle shall provide a horizontal position with a maximum error of less than or equal to 98.4 ft with a 95 percent probability for aircraft operating on the surface.

b. The aircraft/vehicle shall provide position information with a 95 percent probability of a maximum error less than or equal to 0.05 NM for airborne aircraft.

E. Horizontal Position Integrity

The horizontal position integrity is defined as the containment bound within which the reported position in the ADS-B message is assured to lie. This requirement applies to the aircraft avionics, essentially the positioning source for ADS-B. The integrity is equivalent to the Horizontal Integrity Limit (HIL) for the GNSS systems that are used as the primary source for ADS-B position determination. The aircraft/vehicle horizontal position integrity containment bound is required to be less than or equal to 0.2 NM.

F. Coverage

ADS-B coverage is provided throughout the CONUS, as well in Alaska, Hawaii, Puerto Rico, and Guam. For detailed information on ADS-B coverage at various altitudes, refer to https://www.faa.gov/nextgen/equipadsb/research/airspace/.

A.2.7 Timing Systems

NIST and USNO provide additional means to determine time (UTC) separate from systems that support positioning and navigation. NIST services are documented at https://www.nist.gov/pml/time-and-frequency-division and in NIST Special Publication 432, NIST Time and Frequency Services, January 2002 (Ref. 59), which may be downloaded from the website.

DoD Directive (DoDD) 4650.05, Positioning, Navigation, and Timing (PNT), February 19, 2008 (Ref. 59) and CJCSI 6130.01 (Ref. 1) designates the USNO responsibility to coordinate timing activities for DoD and related national defense supporting activities. DoD Instruction (DODI) 4650.06 (Ref. 61) designates the Oceanographer of the Navy as the DoD Precise Time and Time Interval (PTTI) manager. USNO is responsible for coordination of PTTI requirements and maintenance of a PTTI reference standard (astronomical and atomic) for use by all DoD Components, DoD contractors, and related laboratories. This includes programming the necessary resources to maintain the reference standard and to disseminate precise time to DoD users.

USNO historically supports U.S. PNT systems by providing the coordinating timing reference between USG navigation services, ensuring interoperability between systems. USNO disseminates time via various mediums; these include GPS, TWSTT, NTP, and voice announcers. USNO services are documented http://www.usno.navy.mil/USNO/time.

A.2.7.1 Time Measurement and Analysis Service

The NIST Time Measurement and Analysis Service (TMAS) is designed to assist laboratories maintain a high-accuracy, local time standard. The service continuously compares the customer's local time standard to the NIST time scale and reports the comparison results to the customer in near real-time.

A. Signal Characteristics

TMAS works by making simultaneous common-view measurements at NIST and at the customer's laboratory with up to eight GPS satellites. Each customer receives a time measurement system that performs the measurements and sends the results to NIST via the Internet for instant processing.

B. Accuracy

Time is measured with a combined standard uncertainty of about 10 nanoseconds, and frequency is measured with an uncertainty of near 1×10^{-14} after 1 day of averaging.

C. Availability

TMAS is available to the extent that GPS satellites are in view of the customer, and that a bidirectional Internet data path is available between the customer and NIST.

D. Coverage

TMAS is available worldwide. TMAS can process data in an all-in-view mode when satellites are not in common view.

E. Reliability

Not specified, and dependent on Internet reliability.

F. Fix Rate

Measurements are made using a time interval counter with a single shot resolution of less than 30 picoseconds.

G. Fix Dimensions

Not applicable.

H. System Capacity

The capacity is unlimited.

I. Ambiguity

There is no ambiguity.

J. Integrity

NIST personnel monitor deployed TMAS time measurement systems from Boulder, Colorado; verify and analyze the data; and quickly troubleshoot any problems that may occur.

K. Spectrum

TMAS receives the GPS L1 frequency and utilizes spectrum for Internet connectivity, as required.

A.2.7.2 Internet Time Service

The Internet Time Service (ITS) allows digital devices to obtain the time through their Internet connection. ITS supports standard Internet protocols, primarily Network Time Protocol (NTP, RFC-1305). Daytime Protocol (RFC-867) and Time Protocol (RFC-868) are also supported, but their use is strongly discouraged. NIST intends to end support for the TIME format in the future. An authenticated NTP service is also available, by request.

A. Signal Characteristics

ITS does not utilize signals in space, except as might be required to obtain an Internet connection.

B. Accuracy

The uncertainty of daytime, time, and Simple NTP (SNTP) time clients is usually <100 ms, but the results can vary due to the Internet path (e.g., asymmetry in packet travel time to/from NIST), and the type of computer, operating system, and client software. In extreme cases, the uncertainty might be 1 second or more. The uncertainty of a continuously running NTP client that polls multiple servers is often <10 ms.

C. Availability

NIST supports 17 ITS servers at 4 locations around the United States. Availability approaches 100 percent for client software with the ability to poll multiple sites.

D. Coverage

The ITS servers provide worldwide service. However, outside of the United States better results may be obtained by using a local NTP server.

E. Reliability

The reliability of ITS depends mostly on the capabilities of the client software. A completely and well-implemented NTP client will poll many servers, perform self-consistency checks, and respect status data provided by the servers. However, this is not typical for consumer-grade devices. For a sufficiently large number of servers polled, reliability is limited by that of the Internet connection.

F. Fix Rate

All users should ensure that their software never queries a server more frequently than once every 4 s. Systems that exceed this rate will be refused service. In extreme cases, systems that exceed this limit may be considered as attempting a denial-of-service attack. The normal interval between NTP requests (the “polling interval”) depends on the client software being used and the needs of the user. The most sophisticated software automatically adjusts its polling interval to between 16 s and 1024 s, depending on statistics. For many non-precision applications, a polling interval of hours or days apart would be sufficient.

G. Fix Dimensions

Not applicable.

H. System Capacity

NIST currently processes in excess of 40 billion ITS transactions daily. The system can grow with demand, as warranted.

I. Ambiguity

There is no ambiguity, with one exception. Time Protocol (RFC-868), which is now used by only about 1 percent of ITS customers, will roll back to the year 1900 in 2036.

J. Integrity

All ITS servers are monitored by NIST for integrity. A completely and well-implemented NTP client will poll many servers, perform self-consistency checks, and respect status data provided by the servers.

K. Spectrum

ITS does not utilize spectrum, except as might be required by the user to obtain an Internet connection.

A.2.7.3 Automated Computer Time Service (ACTS)

The NIST ACTS allows digital devices to obtain the time through dial-up telephone connections, using computer modems. ACTS works only with analog modems that use traditional telephone lines. Digital modems, such as digital subscriber line (DSL), cable, and wireless modems, may not work properly. For computers with Internet access, ITS should be used instead. ACTS has been provided since 1988, predating wide public use of the Internet. However, ACTS remains preferred in certain user applications with security or documentation requirements.

A. Signal Characteristics

When a digital device connects to ACTS by telephone, it receives an ASCII time code. ACTS works at speeds up to 9600 baud with 8 data bits, 1 stop bit, and no parity. To receive the full-time code, you must connect at a speed of at least 1200 baud. The full-time code is transmitted every second and contains more information than the 300-baud time code, which is transmitted every 2 s.

B. Accuracy

ACTS determines the round-trip path delay from cooperating user client software. Presuming symmetry in the path delay to and from NIST, the time can be determined with respect to UTC(NIST) with an uncertainty of <15 ms.

C. Availability

The availability of ACTS approaches 100 percent for client software with the ability to dial multiple sites.

D. Coverage

The ACTS servers provide worldwide service. However, accuracy will be degraded by long-haul telephony with asymmetric delays, which may be caused by satellite links.

E. Reliability

The reliability of ACTS depends on the capabilities of the client software. A well-implemented ACTS client will perform self-consistency checks, and, if necessary, dial into multiple servers. Reliability is limited by that of the telephone connection.

F. Fix Rate

The full-time code is transmitted every second and contains more information than the 300-baud time code, which is transmitted every 2 s.

G. Fix Dimensions

Not applicable.

H. System Capacity

The ACTS system in Colorado has eight phone lines and receives an average of more than 2,000 telephone calls per day. It can be reached by dialing (303) 494-4774. The ACTS system in Hawaii has two phone lines and receives an average of about 100 calls per day. It can be reached by dialing (808) 335-4721. Long distance charges may apply.

I. Ambiguity

There is no ambiguity.

J. Integrity

ACTS servers are monitored by NIST for integrity.

K. Spectrum

ACTS does not utilize spectrum, except as might be required by the user to obtain a telephone connection.

A.2.7.4 Radio Station WWVB

NIST radio station WWVB continuously broadcasts time and frequency signals at 60 kHz from near Fort Collins, Colorado. The carrier frequency provides a stable frequency reference traceable to the national standard. There are no voice announcements on the station, but a time code is modulated onto the carrier that enables digital devices to learn the time (UTC).

A. Signal Characteristics

A time code is synchronized with the 60 kHz carrier and is broadcast continuously at a rate of 1 symbol per second. Since late 2012, the time code has been modernized to include phase modulation in addition to the historical amplitude (pulse-width) modulation. This provides significantly improved performance in new products that are designed to receive it. Most pre-existing radio-controlled clocks and watches were only sensitive to the amplitude of the signal and not its phase, and continue to work as before. However, certain legacy products that locked to the carrier were rendered obsolete by the change.

In the historical modulation scheme the carrier power is reduced and restored to produce the time code bits. The carrier power is reduced by 17 dB at the start of each second, so that the leading edge of every negative going pulse is on time. Full power is restored 0.2 second later for a binary “0”, 0.5 second later for a binary “1”, or 0.8 second later to convey a position marker. The binary coded decimal (BCD) format is used so that binary digits are combined to represent decimal numbers. The time code contains the year, day of year, hour, minute, second, and flags that indicate the status of Daylight Saving Time, leap years, and leap seconds. (For more details, see https://www.nist.gov/pml/time-and-frequency-division/time-services/wwvb-time-code-format.)

Since 2012, the phase of the carrier may be inverted 0.1 second after the start of the second to convey an additional 0 bit (no inversion) or 1 bit (inversion). The amplitude and phase data frames contain similar, but not identical data fields. For example, the phase data includes a minute counter within a 100-year epoch, as a binary integer with an error-correcting code (rather than BCD). (For more details, see https://www.nist.gov/publications/wwvb-time-signal-broadcast-new-enhanced-broadcast-format-and-multi-mode-receiver.)

B. Accuracy

The frequency uncertainty of the WWVB signal as transmitted is less than 1 part in 10^{12}. If the path delay is removed, WWVB can provide UTC with an uncertainty of about 100 μs. The variations in path delay are minor compared to those of radio stations WWV and WWVH. The longest possible path delay in the continental United States is <15 ms.

C. Availability

Although WWVB broadcasts continuously, the propagation characteristics of LF radio waves cause the signal strength to vary diurnally and seasonally at locations remote from the transmitter. In most of the U.S., the signal is best received at night. The signal is generally easiest to receive when it is dark at both the transmitter site in Fort Collins, Colorado, and the receiving location. Such "dark path hours" vary in length from about 4 hours (Anchorage in summer) to about 14 hours (Seattle in winter). During daylight hours, the signal can be received using good antennas and more sensitive receivers.

D. Coverage

WWVB may be received in most of North America, though the fog of radio noise and other impairments make reception more difficult in the Northeast and Southeast U.S.

E. Reliability

There are three transmitters at the WWVB site. Two are in constant operation, and one serves as a standby that is activated if one of the primary transmitters fails. Occasional outages and periods of reduced power operation have occurred and are documented at https://www.nist.gov/pml/time-and-frequency-division/radio-stations/wwvb/wwvb-station-outages. Near real-time status from monitoring stations may be seen at http://tf.nist.gov/tf-cgi/wwvbmonitor_e.cgi.

F. Fix Rate

Each frame of data takes one minute to transmit. Consecutive frames can be compared for error detection and correction.

G. Fix Dimensions

Not applicable.

H. System Capacity

The capacity is unlimited.

I. Ambiguity

There is no ambiguity.

J. Integrity

The WWVB signal is monitored by NIST for integrity. In most cases, user receivers can estimate the integrity of the signal through comparison with a local "flywheel" clock. However, the integrity of the system can be compromised by purposeful interference.

K. Spectrum

WWVB uses a 60 kHz carrier frequency in the LF (low frequency) portion of the radio spectrum. This frequency is assigned for purposes of time and frequency dissemination by the World Radio Conference and is also used by radio station MSF in the United Kingdom (Anthorn) and radio station JJY in Japan (Hagane-yama Station).

A.2.7.5 Radio Stations WWV and WWVH

NIST radio stations WWV and WWVH continuously broadcast time and frequency information from near Fort Collins, Colorado, and Kekaha (Kauai Island), Hawaii, respectively. They provide time announcements, standard time intervals, standard frequencies, UT1 time corrections, a BCD time code, and geophysical alerts.

A. Signal Characteristics

WWV and WWVH operate in the high-frequency (HF) portion of the radio spectrum. WWV radiates 10,000 W on 5, 10, and 15 MHz; and 2500 W on 2.5 and 20 MHz. WWV has resumed broadcasting on 25 MHz on an experimental basis, at 2500 W. WWVH radiates 10,000 W on 5, 10, and 15 MHz, and 5000 W on 2.5 MHz. (Until further notice, the 5 MHz frequency will be transmitted at a lower power of 2.5 kW, due to a failure in the primary transmitter.) Each frequency is broadcast from a separate transmitter. Although each frequency carries the same information, multiple frequencies are used because the quality of HF reception depends on many factors such as location, time of year, time of day, the frequency being used, and atmospheric and ionospheric propagation conditions. The variety of frequencies makes it likely that at least one frequency will be usable at all times.

The signals broadcast by WWV use double sideband amplitude modulation. The modulation level is 50 percent for the steady tones, 50 percent for the BCD time code, 100 percent for the second pulses and the minute and hour markers, and 75 percent for the voice announcements. (The signal format is described at https://www.nist.gov/pml/time-and-frequency-division/time-services/wwv-and-wwvh-digital-time-code-and-broadcast-format.)

B. Accuracy

WWV and WWVH are referred to the primary NIST Frequency Standard and related NIST atomic time scales in Boulder, Colorado. The frequencies *as transmitted* are maintained within a few parts in 10^{13} for frequency and <100 ns for timing with respect to UTC(NIST). However, the received performance of WWV and WWVH is generally worse than the received performance of WWVB. This is because an HF radio path is much less stable than an LF radio path. Within the United States, the time should be delayed by less than 20 ms.

C. Availability

Although WWV and WWVH broadcast continuously, the propagation characteristics of HF radio waves cause the signal strength to vary diurnally and seasonally at locations remote from the transmitter. HF reception depends on many factors, including atmospheric and ionospheric conditions.

D. Coverage

The coverage area of the two stations is essentially worldwide on 5, 10, and 15 MHz, although reception might be difficult in some areas, since standard time and frequency stations in other parts of the world use these same frequencies.

E. Reliability

Occasional outages have occurred and are documented at https://www.nist.gov/pml/time-and-frequency-division/radio-stations/wwv/wwv-and-wwvh-broadcast-outages.

F. Fix Rate

The broadcast schedule is found at https://www.nist.gov/pml/time-and-frequency-division/time-services/wwv-and-wwvh-digital-time-code-and-broadcast-format. In general, each frame of data takes one minute to transmit. Consecutive frames can be compared for error detection and correction.

G. Fix Dimensions

Not applicable.

H. System Capacity

The capacity is unlimited.

I. Ambiguity

There is no ambiguity.

J. Integrity

The signals are monitored by NIST for integrity. In most cases, user receivers can estimate the integrity of the signal through comparison with a local "flywheel" clock. However, the integrity of the system can be compromised by purposeful interference.

K. Spectrum

WWV and WWVH use frequencies in the HF (high frequency, shortwave) portion of the radio spectrum. These frequencies are assigned for purposes of time and frequency dissemination by the World Radio Conference and are also used by such radio stations as ATA in India (New Delhi), BPM in China (Lintong), IAM in Italy (Rome), and LOL in Argentina (Buenos Aires).

A.2.7.6 NIST Telephone and Web-Based Services

For the convenience of the public, NIST provides easy-to-use time services over the telephone and Internet. The audio portions of the WWV and WWVH broadcasts can also be heard by telephone. Dial (303) 499-7111 for WWV (Colorado), and (808) 335-4363 for WWVH (Hawaii). These are not toll-free numbers; callers outside the local calling area are charged for the call at regular long-distance rates. In addition, NIST provides a web-based time service at https://time.gov/. This website provides a digital clock on the screen and a map of the world showing where it is day and where it is night.

A. Signal Characteristics

The telephone service is audio. The web-based service uses HTTP and Java.

B. Accuracy

The time announcements on the telephone service are normally delayed by less than 30 ms when using land lines from within the continental United States, and the stability (delay variation) is generally < 1 ms. When mobile phones or voice over IP networks are used, the delays can be as large as 150 ms. In the very rare instances when the telephone connection is made by satellite, the time is delayed by more than 250 ms. The Internet web page is accurate to about 200 ms within the U.S.

C. Availability

Both services operate continually.

D. Coverage

Both services are accessible worldwide.

E. Reliability

Occasional outages may occur.

F. Fix Rate

The telephone service provides a voice announcement once each minute. The web service usually responds within a few seconds, depending on the user's Internet connection.

G. Fix Dimensions

Not applicable.

H. System Capacity

The capacity is unlimited for the web page. A few telephone lines are available for the audio service. It receives about 2,000 calls per day.

I. Ambiguity

There is no ambiguity.

J. Integrity

The signals are monitored by NIST for integrity.

K. Spectrum

These services do not utilize spectrum, except as might be required by the user to obtain a telephone or Internet connection.

A.2.7.7 Time-Over-Fiber Special Calibration Service

A special calibration service can be implemented using fiber optics as a dedicated point-to-point link between a customer and a NIST time scale located in Boulder, Colorado or Gaithersburg, Maryland. The purpose is to provide a high-accuracy (1 microsecond or better), GNSS-independent time reference that is directly traceable to UTC(NIST). The link would include a commercially leased dark fiber connection between the end points and compatible end-point hardware chosen to support the required accuracy of the time signal at the user's facility. The accuracy would be validated by diagnostics that are part of the link hardware and may also be confirmed by a portable atomic clock or by similar techniques. The technical aspects may be tailored to customer requirements.

A.2.7.8 Cooperative Research and Development

As required by EO 13905 (Ref. 72), NIST will work with interested parties to develop and provide additional GNSS-independent references of UTC(NIST), to support the needs of critical infrastructure owners and operators, and others in the public.

A.2.7.9 GPS Time Distribution Service

GPS time transfer is the optimum means of globally obtaining precise time at the nanosecond level (see paragraph 3.2.5 for more info). USNO works jointly with the GPS program to supply a UTC (USNO) timing service that is used globally as the standard for timing systems.

A. Signal Characteristics

See section A.2.1.A.

B. Accuracy

See section A.2.1.B.

C. Availability

See section A.2.1.C.

D. Coverage

See section A.2.1.D.

E. Reliability

See section A.2.1.E.

F. Fix Rate

See section A.2.1.F.

G. Fix Dimensions

Not applicable.

H. System Capacity

The capacity is unlimited.

I. Ambiguity

There is no ambiguity.

J. Integrity

See section A.2.1.J.

K. Spectrum

See section A.2.1.K.

A.2.7.10 Network Time Protocol (NTP)

Network Time Protocol (NTP) is an Internet standard (RFC-1305a) which enables client computers to maintain system time synchronization to the

U.S. Naval Observatory Master Clocks in Washington, DC and Colorado Springs, Colorado, and to UTC(USNO) via GPS. USNO provides network time servers providing accurate and reliable time synchronization for computers, routers, and other hardware on the Internet, Non-classified Internet Protocol Router Network (NIPRNet) and the SIPRNet. The current (2015) NTP software daemon (ntpd), is version 4.2.8, which is compatible with all versions of NTP. NTP provides mechanisms to synchronize time and to coordinate time distribution by computer on both local and wide area networks. Network time transfer is achieved by robust estimation between remote systems of clock offset, network delays, and network dispersion.

A. Signal Characteristics

NTP messages are User Datagram Protocol/Internet Protocol (UDP/IP) datagrams (packets) generated by a daemon process and exchanged between NTP clients and their peers or higher-stratum servers. A standard NTP datagram with associated UDP, IP, and Ethernet headers uses one 90-byte Ethernet frame. NTP datagrams may be transmitted via unicast, broadcast, or multicast messaging. NTP clients obtain time stamps from one or more servers, deriving confidence intervals for time sources enabling detection of bad sources. Responses are filtered and combined to derive continuous adjustments to the local system clock.

B. Accuracy

Typical accuracy achieved is in the range 1–30 ms continuous and is highly dependent on the symmetry and speed of the Internet path between client and server. Best results are achieved using a combination of servers which are closest to the client in a network sense.

C. Availability

Public access to USNO NTP service is provided. Users are advised to check periodically for the establishment of new time servers, or for servers that change IP address due to Internet growth and reconfiguration, at http://www.usno.navy.mil/USNO/time/ntp. USNO also operates NTP services on SIPRNet. USNO offers authenticated NTP service in support of USG and DoD operations.

D. Coverage

USNO provides two NTP servers located in Washington, DC and Colorado Springs, CO. USNO NTP servers provide worldwide service. However, outside of the United States better results may be obtained by using a local NTP server.

E. Reliability

The reliability of NTP depends in part upon the proper configuration of the client software. An optimally configured NTP client will poll three or more servers, perform self-consistency checks, and respect status data provided by the servers. For a sufficiently large number of servers polled, reliability is limited by that of the Internet connections involved.

F. Fix Rate

NTP clients initially poll servers at 64 second intervals and increase this interval as their synchronization improves. The typical interval between messaging is 17 minutes (1024 s).

G. Fix Dimensions

Not applicable.

H. System Capacity

USNO currently processes approximately 550 million transactions daily (at over 6,000 packets per second). The USNO Washington NTP service can provide in excess of 40,000 packets per second.

I. Ambiguity

Network source and destination addresses are processed by the NTP protocol to eliminate ambiguity. NTP properly handles out-of-order delivery and loss of packets.

J. Integrity

USNO designs and operates NTP servers which obtain UTC(USNO) directly from the USNO Master Clocks or GPS. Servers are protected against intrusion and have operated authoritatively since 1993.

K. Spectrum

NTP does not utilize spectrum.

A.2.7.11 Two-Way Satellite Time Transfer (TWSTT)

Two-way satellite time transfer (TWSTT) allows for direct comparison of time and frequency signals over long baselines. The USNO provides TWSTT services for remote users to receive precise time and frequency referenced to UTC(USNO). TWSTT operations range from a one-time calibration service to determine the difference between the DoD Master Clock and a user’s time reference or to a full-service Earth station to provide continued monitoring of a user’s reference.

A. Signal Characteristics

TWSTT uses a code-division multiple access (CDMA) spread spectrum signal with a bandwidth ranging from 1 MHz to several MHz.

B. Accuracy

One nanosecond time transfer can be achieved using TWSTT with an associated frequency uncertainty of less than 1×10^{-14} after 1 day of averaging.

C. Availability

TWSTT is conducted on a schedule and operates continuously 24 hours a day and 7 days a week. Heavy rain may degrade performance and bi-yearly sun outages may cause signal outages that can last a few minutes.

D. Coverage

TWSTT is available under the coverage area of the geostationary satellite in use. Presently USNO Ku-band coverage is limited to the United States including Alaska and Hawaii. Defense Satellite Communications System (DSCS) X-band coverage is Global.

E. Reliability

Dependent on the Earth station system design, redundancy can be built in each system. A satellite outage while rare is a concern and would result in a long-term data outage.

F. Fix Rate

Measurements are made using a special spread spectrum time transfer modem with a single shot resolution of less than 10 ps. USNO typically schedules a time transfer experiment once an hour for 10 min.

G. Fix Dimensions

Not applicable.

H. System Capacity

The capacity is limited by satellite signal power and bandwidth.

I. Ambiguity

Absolute time transfer requires periodic time calibration, typically using a mobile TWSTT system. Accuracies of one nanosecond are possible using this calibration service.

J. Integrity

USNO personnel monitor deployed TWSTT systems from Washington, DC, verify and analyze the data, and quickly troubleshoot any problems that may occur.

K. Spectrum

TWSTT typically uses geostationary satellites run by commercial entities (Ku-band) or by the DSCS (X-band).

A.2.7.12 USNO Telephone and Web-Based Services

The USNO Telephone Time Voice Announcer produces an audible tick every second from the USNO Master Clock and announces the time every 10 seconds. The time is announced in both local time and UTC. The USNO operates two time announcers; one in Washington, DC, and one at the USNO AMC in Colorado Springs, Colorado. Time dissemination accuracy is 1 s and can be accessed worldwide. Three numbers are available: (202) 762-1401, (202) 762-1069, and (719) 567-6742.

A. Signal Characteristics

The telephone service is audio. The web-based service uses HTTP and Java.

B. Accuracy

The time announcements on the telephone service are normally delayed by less than 30 ms when using land lines from within the continental United States, and the stability (delay variation) is generally <1 ms. When mobile phones or voice over IP networks are used, the delays can be as large as 150 ms. In the very rare instances when the telephone connection is made by satellite, the time is delayed by more than 250 ms. The Internet web page is accurate to about 200 ms within the U.S.

C. Availability

Both services operate continually.

D. Coverage

Both services are accessible worldwide.

E. Reliability

Occasional outages may occur.

F. Fix Rate

The telephone service provides a voice announcement once each minute. The web service usually responds within a few seconds, depending on the users Internet connection.

G. Fix Dimensions

Not applicable.

H. System Capacity

The capacity is unlimited for the web page. A few telephone lines are available for the audio service.

I. Ambiguity

There is no ambiguity.

J. Integrity

The signals are monitored by USNO for integrity.

K. Spectrum

These services do not utilize spectrum, except as might be required by the user to obtain a telephone or Internet connection.

Appendix B

PNT Information Services

B.1 USCG NAVCEN Navigation Information Service

The USCG Navigation Center (NAVCEN) Navigation Information Service (NIS) is the operational entity of the Civil GPS Service (CGS). The mission of the NIS is to gather, process, and disseminate timely GPS PNT information, as well as general maritime navigation information. NIS serves as the civil GPS point of contact for all non-aviation, non-military surface and maritime GPS users. The NIS also works as an arm of the Civil GPS Service Interface Committee (CGSIC) in the exchange of information between the GPS system providers and the users.

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

- disseminating GPS constellation status information through the NAVCEN website and electronic mailings;
- act as the single focal point for non-aviation civil users to make inquiries or submit GPS service interruption reports;
- coordinate with other GPS authorities to identify and resolve reports of GPS service interruptions;
- collecting information from users in support of the CGSIC that provides an important link between civil GPS users and the USG;
- answer GPS-related questions submitted through the NIS website, written correspondence, telephone, or electronic mail;
- maintain a bibliography of U.S. GPS publications;
- provide information to the public on the NIS services available;
- provide instruction on the access and use of the information services available; and
- develop new user services as required.

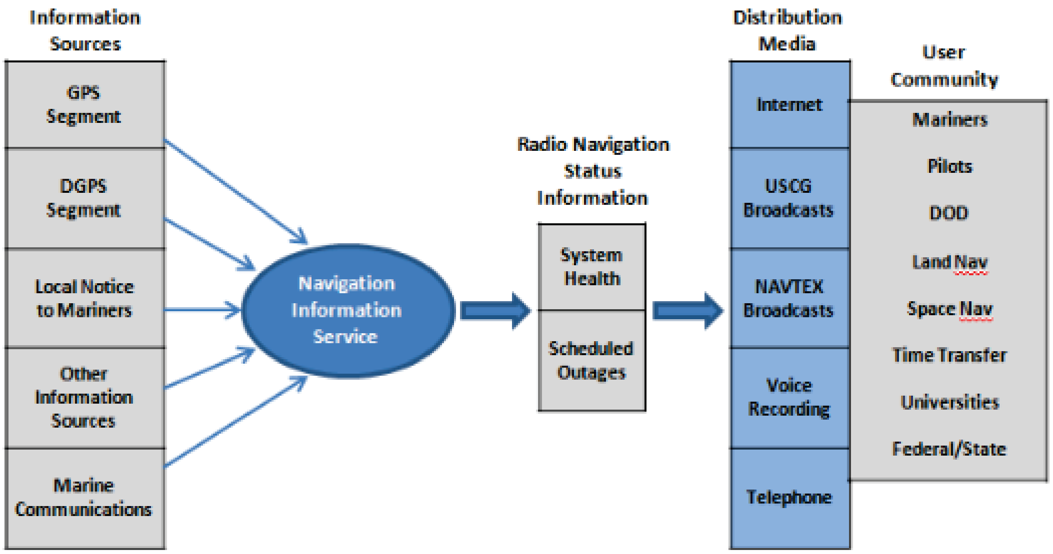

Figure B-1: NIS Information Flow to Civil GPS Users

Information on GPS and USCG-operated PNT systems can be obtained from the USCG NAVCEN as follows:

U.S. Coast Guard Navigation Center
7323 Telegraph Road (MS-7310)
Alexandria, VA 20598-7310

24-hour hotline: (703) 313-5900
email: TIS-SMB-NISWS@uscg.mil
website: https://www.navcen.uscg.gov

Table B-1: Navigation Services

SERVICE	AVAILABILITY	INFORMATION TYPE	CONTACT NUMBER
NIS Watchstander	24 hr	User Inquiries	FAX (703) 313-5920
Internet	24 hr	Status, Forecast, History, Outages, NGA Data, FRP, and Miscellaneous Information	http://www.navcen.uscg.gov
NGA Broadcast Warnings	24 hr, broadcast upon receipt	Marine Navigation Warnings	(571) 557-5455 Toll Free 1-800-362-6289 NavSafety@nga.mil
NGA Weekly Notice to Mariners	On line Notices updated weekly	Outages	(571) 557-8383 MarHelp@nga.mil
Maritime Safety Website	24 hr	Notice to Mariners, Nautical Publications	https://msi.nga.mil/ MarHelp@nga.mil (571) 557-7103
NAVTEX Data Broadcast	All stations broadcast 6 times daily at alternating times	Status Forecasts Outages	518 kHz (703) 313-5900
RAIM Prediction	24 hr	User inquiry, status forecasts for RNAV Terminal, and En route RAIM	http://www.raimprediction.net

B.2 GPS NOTAM/Aeronautical Information System

DoD provides notice of GPS satellite vehicle outages through the NOTAM system. These NOTAMs are reformatted NANU messages provided by the 2nd Space Operations Squadron (2 SOPS) at the GPS MCS. The outages are disseminated to the U.S. NOTAM Office at least 48 hours before they are scheduled to occur. Unexpected outages also are reported by the 2 SOPS to the NOTAM Office as soon as possible. Satellite NOTAMs are issued as both a domestic NOTAM under the "KGPS" identifier and as an international NOTAM under the "KNMH" identifier. This information is accessible by both civilian and military aviators. Unfortunately, the NOTAM is meaningless to a pilot unless there is a method to interpret the effects of a GPS satellite outage on the availability of the intended operation.

Use of GPS for IFR aerial navigation requires that the system have the ability to detect a satellite out-of-tolerance anomaly. This capability is currently provided by RAIM, an algorithm contained within the GPS receiver. All receivers certified for IFR navigation must have RAIM or an equivalent capability. WAAS avionics receive integrity information primarily from the WAAS message, but also have a RAIM function for times when the aircraft is outside of SBAS coverage or when messages are not available.

In order for the receiver to perform RAIM, a minimum of five satellites with satisfactory geometry must be visible. Since the GPS constellation of 24 satellites was not designed to provide this level of coverage, RAIM is not always available, even when all of the satellites are operational.

Therefore, if a satellite fails or is taken out of service for maintenance, it is not intuitively known which areas of the country are affected, if any.

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

Site-specific GPS NOTAMs are computed based on criteria in: RTCA/DO-208, *Minimum Operational Performance Standards for Airborne Supplemental Navigation Equipment Using Global Positioning System (GPS)* (Ref. 61); FAA Technical Standard Order (TSO)-C129, *Airborne Supplemental Navigation Equipment Using the Global Positioning System (GPS)* (Ref. 62); and FAA TSO-C196, *Airborne Supplemental Navigation Sensors for Global Positioning System Equipment Using Aircraft-Based Augmentation* (Ref. 63). The baseline RAIM algorithm, as specified in the Minimum Operational Performance Standards (MOPS) and TSOs, is used for computing the NOTAMs for GPS. Terminal and en route RNAV RAIM predictions to satisfy AC 90-100A preflight guidance may be obtained from the Service Availability Prediction Tool, https://sapt.faa.gov/.

The FAA provides similar GPS outage information as aeronautical information distributed through Flight Service Stations (FSS), Direct User Access Terminal System (DUATS) vendors, and other commercial vendors. The Flight Services FS-21 System in the lower 48 states plus Hawaii and Puerto Rico interfaces with a Volpe Center online RAIM prediction algorithm and provides a GPS/RAIM product to the flight service specialists. FAA Flight Services in Alaska receive GPS/RAIM information through a graphical overlay product available on the Operational and Supportability Implementation System (OASIS) briefing system. GPS availability for a non-precision approach at the destination airfield is provided to a pilot upon request from Flight Services. A pilot can request information for the estimated time of arrival or ask for the GPS availability over a window of up to 48 hours.

B.3 WAAS NOTAM/Aeronautical Information System

WAAS provides pilots with increased navigation capability throughout the NAS. The availability of WAAS is dependent on the operational status of the GPS constellation, WAAS assets and FAA infrastructure (reference stations, master stations, ground uplink, geostationary satellites, and communications network), and ionospheric interference, which is out of the control of FAA. Satellite navigation is different from ground-based navigation aids since the impact of satellites being out of service is not intuitively known and the area of degraded service is not necessarily stationary. Pilots need to know where and when WAAS is or will be unavailable.

WAAS distributes FDC NOTAMs for wide area coverage outages. The phrase "MAY NOT BE AVBL" is used in conjunction with GPS and WAAS NOTAMs as an advisory to pilots indicating that the expected level of WAAS service (LNAV/VNAV, LPV) may not be available. WAAS "MAY NOT BE AVBL" NOTAMs are published for flight planning purposes. Upon commencing an approach at locations with a WAAS "MAY NOT BE AVBL" NOTAM, if the WAAS avionics indicate LNAV/VNAV or LPV service is available, the guidance may be used to complete the approach using the displayed level of service. Should an outage occur during the approach, reversion to LNAV, a different approach procedure, or a missed approach may be required.

Outages are based on WAAS service unavailability for LNAV, LNAV/VNAV, and LPV approach minima on RNAV (GPS) approach charts, and also are designed to provide outage information for en route operations. Airfields that have been determined not to have a high enough availability (98 percent or an average of one outage per day or more) are marked with an "inverse W" (W) to indicate that WAAS service may be unreliable for short periods of time at those airfields.

The current WAAS NOTAM Generator is being overhauled and a new prediction tool is under development. With the GPS constellation operating with 27 or more satellites, the period of unavailability for LPV approaches is so low that predictive NOTAMs are generally not needed. In the future, outage information will be presented as Aeronautical Information System notices instead of NOTAMs.

Additionally, the FAA William J. Hughes Technical Center monitors and provides performance analysis reports for both GPS and WAAS in near real time and via archives: http://www.nstb.tc.faa.gov.

B.4 Maritime Information Systems

USCG provides coastal Maritime Safety Information (MSI) broadcasts through VHF Marine Radio Broadcasts on VHF simplex channel 22A and NAVTEX text broadcasts on 518 kHz to meet the requirements of the Global Maritime Distress and Safety System (GMDSS).

The NGA Maritime Safety Office is a Navigation Area (NAVAREA) Coordinator within the International Hydrographic Organization's (IHO) World-Wide Navigational Warning Service (WWNWS). NGA is the coordinator for NAVAREA IV and XII. NAVAREA IV extends from the east coast boundary of Suriname northeast to 07°00'N, then east to 035°00'W, then north to 067°00'N at the coastline of Greenland, and then following 067°00'N west to the coastline of Canada (Baffin Islands area).

NAVAREA XII extends from the coastline of South America at 03°24’S to 120°00’W, then to north to 00°00’, then west to 180°00’, then north to 50°00’N, and then following the International Date Line northward to 67°00’N.

As a NAVAREA coordinator, NGA is responsible for the satellite broadcast of MSI via enhance group (EGC) call within its two NAVAREAS. MSI includes:

- casualties to lights, fog signals, buoys, and other aids to navigation affecting main shipping lanes;
- the presence of dangerous wrecks in or near main shipping lanes;
- establishment of major new aids to navigation or significant changes to existing ones when such establishment or change, might be misleading to shipping;
- the presence of large unwieldy tows in congested waters;
- drifting hazards (including derelict ships, ice, mines, containers, other large items over 6 m in length);
- areas where search and rescue (SAR) and anti-pollution operations are being carried out (for avoidance of such areas);
- the presence of newly discovered rocks, shoals, reefs and wrecks likely to constitute a danger to shipping, and, if relevant, their marking;
- unexpected alteration or suspension of established routes;
- cable or pipe laying activities, the towing of large submerged objects for research or exploration purposes, the employment of manned or unmanned submersibles, or other underwater operations constituting potential dangers in or near shipping lanes;
- the establishment of research or scientific instruments in or near shipping lanes;
- the establishment of offshore structures in or near shipping lanes;
- significant malfunctioning of radio-navigation services and shore-based maritime safety information radio or satellite services;
- information concerning naval exercises, missile firings, space missions, nuclear tests, ordnance dumping zones;
- acts of piracy and armed robbery against ships; and
- tsunamis and other natural phenomena, such as abnormal changes to sea level.

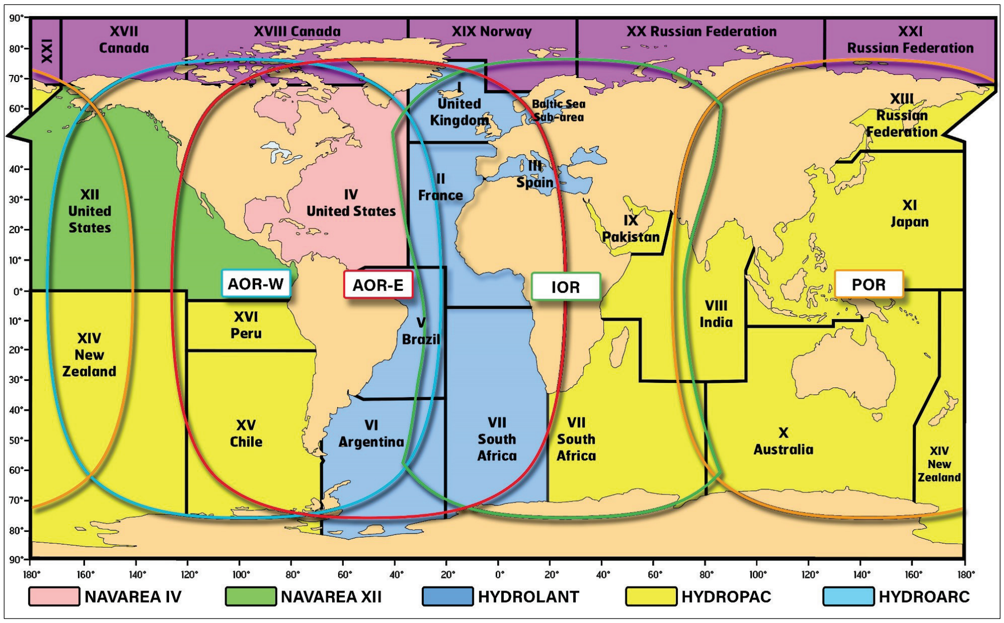

Figure B-2: NGA Navigational Warnings and SafetyNET coverage)

NAVAREA IV and NAVAREA XII promulgate EGC messages via Inmarsat SafetyNET and Iridium SafetyCast. Iridium SafetyCast is a low earth orbiting service and has global coverage. SafetyNET has four geostationary satellites and provides near global coverage. See Figure B-2 for SafetyNET coverage. All passenger ships and all cargo ships of 300 gross tonnage and upwards on international voyages are required to carry an EGC transceiver. NGA provides global broadcast service through issuance of HYDROLANT, HYDROPAC, and HYDROARC messages which are principally directed to the USN and NGA partners.

The NGA Maritime Safety Office further provides these Broadcast Warnings through its website and also provides on-line access to U.S. Notice to Mariners, Sailing Directions, List of Lights, Anti-shipping Activity Messages, mobile offshore drilling units, selected Digital Nautical Charts (DNC) and their Vector Product Format (VPF) Database Update (VDU) patches, and other miscellaneous NGA publications and brochures such as “Using Nautical Charts with Global Positioning System.”

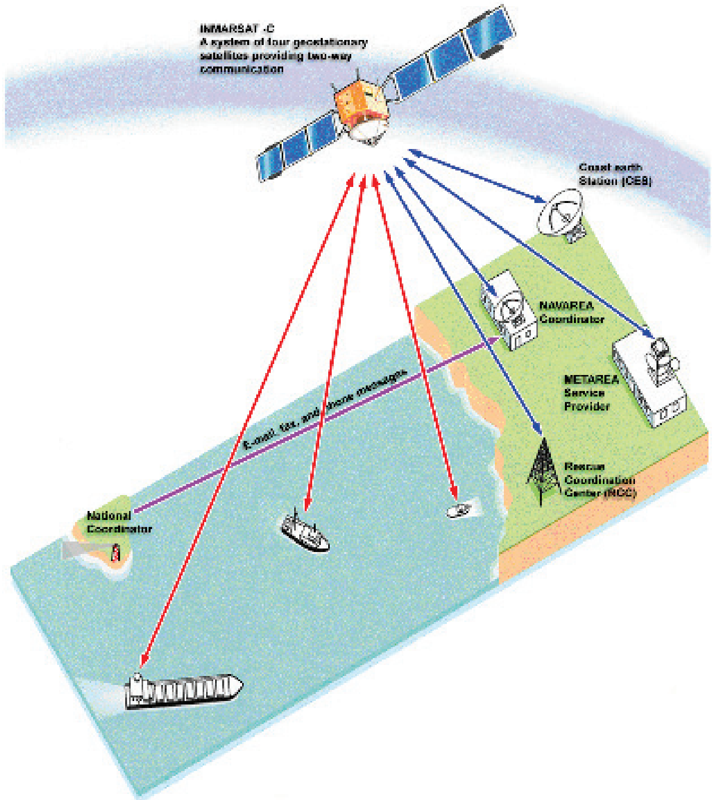

Figure B-3: IHO/IMO World-Wide Navigational Warning Service, NAVAREA Broadcast Service

B.5 NASA GPS Monitoring and Space-User Services

B.5.1 International GNSS Service (IGS)

The International GNSS Service, formerly known as International GPS Service, was formally recognized in 1993 by the International Association of Geodesy and began operations on January 1, 1994. It is recognized as an international scientific service, and it advocates an open data and equal access policy. To-date, NASA has funded the IGS Central Bureau, which is located at the California Institute of Technology Jet Propulsion Laboratory (JPL), and a global data center located at the NASA Goddard Space Flight Center (GSFC). For more than ten years, IGS has expanded to a coordinated network of over 350 GPS monitoring stations from 200 contributing organizations in 80 countries. Other contributing U.S. agencies and organizations include, among others, USNO, NGA, NSF, and the NOAA NGS. The IGS mission is to provide the highest quality data and products as the standard for GNSS in support of Earth science research, multidisciplinary applications, and education, as well as to facilitate other applications benefiting society. Approximately 100 IGS stations report with a latency of one hour. (These data, and other information, may be obtained from the IGS website at: http://www.igs.org/.)

B.5.2 GPS Metric Tracking for Space Lift Vehicles

The Eastern Range in Florida uses translator-based GPS metric tracking for some DoD launches and certification flights for receiver-based GPS on launch vehicles are underway. The Western Range in California uses both translated and receiver-based GPS operationally. NASA's Wallops Flight Facility (WFF) also uses receiver-based GPS for tracking launch vehicles on a case-by-case basis. The future will certainly see increased use of GPS for real-time tracking of space lift vehicles and other rocket tests because of its ability to provide accurate tracking anywhere in the world without the need for ground-based support equipment.

B.5.3 Global Differential GPS (GDGPS)

GDGPS is a high-accuracy GNSS augmentation system developed by JPL to support the real-time positioning, timing, and orbit determination requirements of NASA science missions. The GDGPS tracking network consists of more than 200 dual-frequency, real-time GNSS reference stations. Operational since 2000, the GDGPS real-time products are also used for civil signal monitoring, situational assessment, natural hazard monitoring, emergency geolocation (E911), and other civil and U.S. defense applications. Globally monitored GNSS include GPS, GLONASS, BeiDou, Galileo, and QZSS.

B.5.4 Next Generation Beacon Service (NGBS)

NGBS is a proposed system under development at NASA. It would provide unique signals and data to enhance user operations and enable autonomous onboard navigation. An earlier concept, known as the Tracking and Data Relay Satellite System (TDRSS) Augmentation Service for Satellites (TASS) would relay GDGPS augmentation messages to near-Earth spacecraft to decimeter-level level accuracy. TASS was demonstrated in 2006. NGBS expands on this concept and its service may consist of:

- Global coverage via TDRSS S-band multiple access forward (MAF) service;
- Unscheduled, on-demand user commanding;
- TDRS ephemerides and maneuver windows;
- Space environment/weather information;
- Earth orientation parameters;
- PRN ranging code synchronized with GPS time for time transfer, one-way forward Doppler, and ranging;
- Global differential GNSS corrections; and
- GNSS integrity

B.6 NOAA Continuously Operating Reference Station (CORS) Network

NOAA's National Geodetic Survey (NGS), an element of the Department of Commerce (DOC), established and manages the NOAA CORS Network (NCN) that provides Global Navigation Satellite System (GNSS) data, which consists of carrier phase and code range measurements. It supports satellite-based precise three-dimensional positioning, meteorology, space weather and geophysical applications throughout the United States, its territories, and a few foreign countries.

Surveyors, GIS/land information system (GIS/LIS) professionals, engineers, scientists and the public-at- large, who collect GPS data, can use the NCN to improve the precision of their positions through the NGS Online User Positioning Service (OPUS). NCN-enhanced post-processed coordinates approach a few centimeters of accuracy relative to the National Spatial Reference System (NSRS), both horizontally and vertically.

The NCN is a multi-purpose cooperative endeavor involving Federal and local government, academia, and private organizations. The sites are independently owned and operated. Each agency shares their data with NGS, and NGS in turn analyzes, distributes, and archives the data free of charge. As of June 2019, the NCN contains over 1750 active stations, contributed by over 150 different organizations. The NCN archive contains the observation data from both operational and decommissioned stations (~1900 total) back to the earliest files in

1994 to support historic projects and reprocessing of the entire network's data for definition of the ITRF and NSRS.

The NGS manages and coordinates data contributions from GPS tracking stations from all groups in the network, rather than by building an independent network of reference stations. In particular, use is being made of data from stations operated by components of DOT that support real-time navigation requirements (e.g., mostly WAAS augmentation). These two Federal real-time sources make up approximately 6 percent of all CORS stations.

While NGS does not currently conduct real-time operations, it is working toward creating a Real-Time Alignment Service for real-time networks to check their stations' coordinates accuracy against the NSRS. Other Federal stations currently contributing data to the NCN include stations operated by other Federal partners, such as NOAA, NSF, and NASA in support of global reference frame and geophysical applications, such as earthquakes and crustal motion activities. However, most NCN stations are operated by State and local governments, particularly State DOTs and State geodetic offices, in support of surveying and mapping applications. The breakdown of CORS partners is shown in Figure B-4.

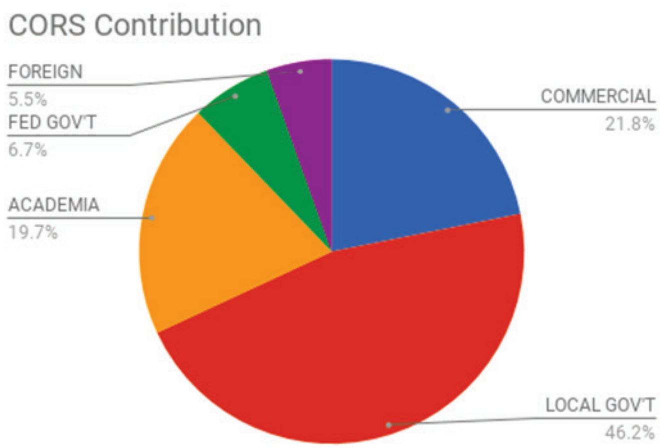

Figure B-4: Partners in the CORS System

The CORS system collects GNSS data from the contributing stations. The data are currently converted to the Receiver Independent Exchange (RINEX) 2 format, quality controlled, and placed in publicly accessible locations on the Internet. For last few years, GNSS constellations, other than GPS, became operational. An increasing number of stations have been upgraded with multi-GNSS capable equipment. In 2021, 52 percent of the NCN stations were multi-GNSS capable, although NGS currently uses only the GPS for OPUS, calculating ground station positions, and satellite orbits determination. Raw multi-GNSS data are being archived while NGS is in the process of upgrading their systems to utilize multi-GNSS.

Table B-2: NGS CORS Data Holding by Constellation

Constellation	2016	2018	2019
GPS Only	38%	30%	24%
GPS + GLONASS	61%	58%	56%
GPS + GLONASS + GALILEO	1%	12%	20%

Precise positions of the NCN are rigorously computed every day and the time-series is monitored for any errors. Using NCN data, NGS provides simplified access to high-accuracy coordinates via the Online Positioning User Service (OPUS). When a user submits GPS data collected with a survey-grade dual-frequency GPS receiver through OPUS' web interface, NGS computes the receiver's coordinates using nearby NCN data. Then, the solution report is sent to the user, via email, that provides the positional coordinates with an accuracy of a few centimeters for the location where the GPS data were collected.

The NOAA Space Weather Prediction Center uses CORS data to produce maps showing the spatial distribution of free electron content in the ionosphere above CONUS once every 15 minutes. A 1-minute ionosphere product is expected to be available in 2019.

Figure B-5 presents a map of the stations contained in the CORS network as of June 2019. GPS-only stations are shown with teardrop pinheads and GNSS capable (primarily GPS + GLONASS) stations ae shown with square pinheads.

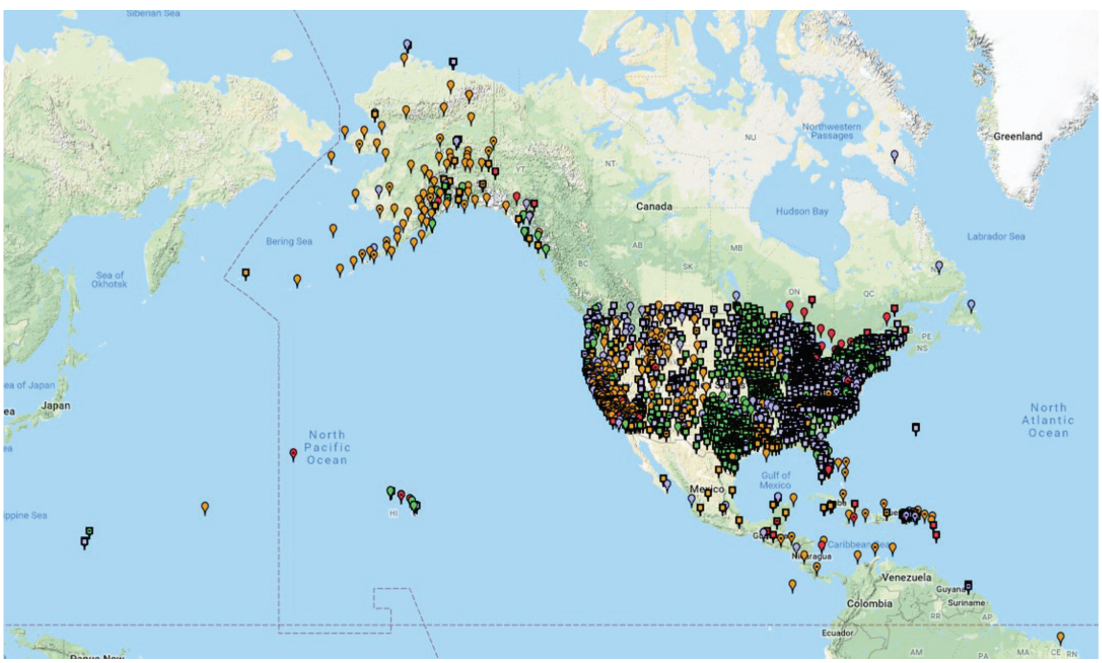

Figure B-5: Map of the NOAA CORS Network

Appendix C

Geodetic Reference Systems and Datums

C.1 Terrestrial Reference Systems

Geodetic positions referenced to the Earth are defined in the general context of a *terrestrial reference system* and with respect to a specific *terrestrial reference frame*. The reference system defines the physical constants, models, conventions, and coordinate system needed to unambiguously and consistently define the coordinates of a point. For example, the coordinate system is usually defined in an abstract sense as a 3-dimensional Cartesian (x-y-z) system with its origin at the Earth's center of mass and the three coordinate axes aligned with the equator and the rotational axis of the Earth and rotating with the Earth's crust. Constants include quantities such as the gravitational constant (GM), the semi-major axis of the Earth's best-fitting ellipsoid, and the speed of light, while models include tidal corrections, a gravitational model, and tectonic plate motion models.

The scientific standard for the terrestrial reference system is the International Terrestrial Reference System (ITRS). The ITRS embodies a set of conventions that represent the state-of-the-art for referencing geodetic positions to the Earth. These conventions are established by the International Earth Rotation and Reference Systems Service (IERS). The physical realization (or materialization) of this system is a global network of ground stations (on the Earth's crust), whose three-dimensional coordinates and linear velocities are derived from space-based observations.

These observations are collected using the techniques of very long baseline interferometry (VLBI), satellite laser ranging (SLR), GPS, and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS). The station's coordinate and velocity solutions conform to the ITRS/IERS conventions. This station set defines the International Terrestrial Reference Frame (ITRF). The ITRF is refined periodically with updated solutions for the station coordinates and velocities that define it, as well as applying any changes that have been adopted in the ITRS. The current version of the reference frame is ITRF 2014. The ITRF2020 reference frame is expected to be released in November 2021.

The terrestrial reference system used by DoD is WGS 84. WGS 84 constitutes an Earth-centered/Earth-fixed coordinate system and a prescribed set of constants, models, and conventions that are largely adopted from the ITRS. Ensuring that the WGS 84 frame is consistent with ITRF supports GPS interoperability with other GNSS. The *WGS 84 reference frame* is defined by a global network of GPS stations, whose coordinates are closely aligned with the ITRF.

As with the ITRF, the WGS 84 reference frame is periodically updated and designated by the GPS Week Number (i.e., time) at which the new reference frame became effective. WGS 84 (G2139) is the current reference frame and is aligned to ITRF2014 (IGb14) to better than 1 cm overall accuracy. The operational reference frame for GPS is WGS 84 to ensure that the broadcast satellite navigation messages are referenced to WGS 84 and that positions derived directly from the navigation message orbits are also referenced to WGS 84. (See National Geospatial-Intelligence Agency standard: NGA_STND.00036_1.0_WGS 84 World Geodetic System 1984.)

In order to express coordinates in geodetic terms as longitude, latitude, and ellipsoid height, a two-parameter oblate reference ellipsoid must be defined. For geocentric terrestrial reference systems, this ellipsoid is chosen such that its center coincides with the center of mass of the Earth, its axes oriented and fixed to the ITRS coordinate axes, and its semi-major and semi-minor axes and rotation rate approximate to those of the Earth. The semi-major axis of the ellipsoid coincides with the z-axis of the ITRF, while the x- and y-axes of the ITRF are fixed to the ellipsoid on its equatorial plane. The z-axis rotates at a rate that approximates that of the Earth.

The WGS 84 reference ellipsoid is, for most practical purposes, identical to the Geodetic Reference System 1980 (GRS 80) ellipsoid. Both ellipsoids have the same semi-major axis and orientation, but unique with respect to the ITRF, and their flattening agree to 8 significant digits. The ITRS does not directly adopt a reference ellipsoid in its definitions, but instead recommends GRS 80 to transform from ITRF Cartesian coordinates to geodetic coordinates. This relationship between the ellipsoid and the terrestrial reference system constitutes the *datum definition* as described in the next section.

In the U.S., the North American Datum 1983 (NAD 83) is the standard geodetic reference system that defines *three-dimensional control* for the country. NOAA’s National Geodetic Survey created, maintains, and provides access to NAD 83. However, NGS is replacing NAD 83 in the 2025 timeframe with a new set of plate-fixed terrestrial reference frames –—one for each tectonic plate on which the U.S. and its territories reside. These frames will be the North American, Pacific, Caribbean, and Marianas

Terrestrial Reference Frames (NATREF, PATREF, CATREF, and MATREF, respectively). The GRS 80 ellipsoid was adopted as the reference surface for NAD 83 and will remain the reference surface for each respective Terrestrial Reference Frame (*TRF). Ellipsoid heights are also associated with the traditional horizontal control points to define a rigorous set of 3-D coordinates.

The NOAA CORS Network, described in Appendix B.6, includes coordinate databases in both the NAD 83 and ITRF14.

C.2 Geodetic Datums

Since the physical shape of the Earth is closely approximated by the surface of an ellipsoid, an ellipsoid is conventionally chosen as the reference surface for geodetic coordinates. The set of parameters that defines the relationship between a specific reference ellipsoid and a terrestrial reference system is called a *geodetic datum*. A *global* geodetic datum is defined by an ellipsoid that best fits the Earth as a whole, whose origin coincides with the center of mass of the Earth, and that has a known relationship with the adopted reference frame. Both WGS 84 and NAD 83 use a global reference ellipsoid (the WGS 84 ellipsoid and the GRS 80 ellipsoid, respectively, which are nearly identical) for their datum definitions. A global geodetic datum is also essential for positioning and navigation using satellite observations. The three-dimensional geodetic coordinates (latitude, longitude, and ellipsoidal height) computed using GPS and its broadcast satellite orbits are referenced to the WGS 84 ellipsoid. Thus, the WGS 84 ellipsoid acts as a three-dimensional reference surface for satellite-derived curvilinear geodetic positions. The parameters that define the specific reference ellipsoid are also required when invoking map projections, i.e., the process of mathematically representing the surface of the 3-dimensional figure of the Earth on a plane, in effect, on a two-dimensional map.

Prior to the availability of satellite data, each nation or region established a *local* geodetic datum that was generally not geocentric and for which the reference ellipsoid was a best fit only for the "local" continental region. Many maps are still based on these local datums. In these cases, the reference ellipsoid is used only as a local *horizontal* (2-dimensional) *datum*, whose origin and orientation are defined by six topocentric parameters. The North American Datum 1927 (NAD 27) is one example. NAD 83 removed many significant local distortions in NAD 27, and changed the reference ellipsoid, making its origin as close to the geocenter as possible rather than a preselected survey point in Kansas. NAD 83 was affirmed as the official horizontal datum for the U.S. by a notice in the Federal Register (Vol. 54, No. 113 Pg. 25318) on June 14, 1989 (Ref. 64). Note that although they use nearly identical reference ellipsoids, with a difference of only 0.1 mm in their semi-minor axes, the origins of NAD 83 and WGS 84 are offset about 2 m due to the difference in the realization of the reference systems. The

2022 *TRF replacements for NAD 83 will correct that offset and be much more consistent with the latest versions of WGS 84 and ITRF at that time.

Transformation parameters have been computed in many cases to convert local datum coordinates to global datum coordinates. This involves, at a minimum, a shift (or translation) in the origin of the coordinate system from the one defined by the local datum ellipsoid to the one defined by the global datum ellipsoid. In practice, the local ellipsoids may not be exactly aligned with the geocentric terrestrial reference frame on which the global datum is based, so rotations and scaling of the local frame may be needed in addition to the origin shift to convert coordinates. The international Standards Organization Technical Committee 211 (ISO/TC 211) on Geographic Information/Geomatics has established the ISO Geodetic Registry (ISO 19111), which includes the international and regional geodetic reference systems and its transformations. ISO 19111 describes the elements necessary to define various types of spatial reference systems using parametric values or functions.

C.3 Vertical Datums and the Geoid

A *vertical datum* is conventionally defined through *orthometric* heights. Unlike ellipsoidal heights, which are purely of geometric nature, orthometric heights are related to the Earth's gravity field and are of physical nature. Orthometric heights are measured along the plumb line in the direction of local gravity. Vertical datums are traditionally associated to mean sea level (MSL) or averaged tidal observations based on low or high water (for example, mean lower low water or MLLW). Since the ocean surface, in an idealized sense, is subject only to the force of gravity, one can define an equilibrium state such that the surface represents a level surface on the Earth's gravity field. This average state is then used to effectively define zero elevation. All elevations on land are referenced to this zero value.

The North American Vertical Datum 1988 (NAVD 88) applied this concept by adopting the single tide gauge elevation at Point Rimouski, Quebec, Canada, as the continental elevation reference point and essentially referenced all other elevations in the U.S. to this. NAVD 88 was affirmed as the official vertical datum for the U.S. by a notice in the Federal Register (58 FR 34245) on June 24, 1993 (Ref. 65). By contrast, the National Geodetic Vertical Datum 1929 (NGVD 29) was fixed to a set of reference tide gauges, without correction for local variations in the sea state, as a method of defining the vertical reference. Depending on their age, U.S. topographic products and data can be referenced to either NAVD 88 or NGVD 29 (see https://www.ngs.noaa.gov/datums/vertical/).

The "best fit" approximation or realization of mean sea level at continental and global scales is a geopotential surface of the Earth's gravity field, defined as the *geoid*. Due to effects, such as atmospheric pressure, temperature, prevailing winds and currents, and salinity variations, MSL will depart from this level surface by a meter or more. Once defined, the geoid becomes the zero-elevation surface to which heights can be referenced. Note that the differences in heights referenced to the geoid versus heights referenced to the ellipsoid can be as much as 100 m.

Many national and regional vertical datums are tied to a local mean sea level (LMSL), which may differ significantly from global MSL due to local effects, such as river runoff and extremes in coastal tidal effects. Thus, national and regional vertical datums around the world, which are tied to LMSL, will differ from one another significantly when considered on a global basis. In addition, due to the ways the various vertical datums are realized, other departures at the meter level or more will be found when comparing elevations to a global geoid reference.

For the U.S., a *hybrid* geoid model, GEOID18, has been developed to directly relate ellipsoid heights from the NAD 83 datum to the NAVD 88 orthometric heights. The control data consist of benchmarks where both the GPS-derived NAD 83 ellipsoid height and leveled NAVD 88 orthometric height are known. Conversion of GPS-derived ellipsoidal height to orthometric height can generally be accomplished in the conterminous U.S. to about 2.5 cm (1-sigma); however, this is not a true measure of the accuracy of GEOID18 due to unaccounted GPS ellipsoid height errors in its original derivation (see https://geodesy.noaa.gov/geoid/index.shtml).

The U.S. vertical datum will also be updated in the 2025 timeframe. Rather than adopt the surface defined by the adjustment geopotential numbers that defined NAVD 88, a geoid model based entirely on gravity data (termed a gravimetric geoid) will be used to define the new vertical datum. Geodetic coordinates obtained using GNSS technology will be input to the model to determine the necessary transformation to orthometric heights. In this manner, orthometric heights will be consistent everywhere where the same model is used. The planned model is expected to span from Alaska to Hawaii to Puerto Rico to Greenland. Only American Samoa, Guam, and the Commonwealth of the Mariana Islands will be on a separate geoid model, which will be derived using similar techniques (e.g., they should be very similar).

On a global basis, the WGS 84 Earth Gravitational Model 2008 (EGM2008) is the latest and most accurate and complete gravitational model from which a global geoid is derived. This supersedes EGM96, the previous model. The WGS 84 (EGM2008) geoid is accurate to better than 15 cm (RMS error) over areas where high-accuracy gravity data were available for inclusion in the model. Over the conterminous U.S., EGM2008 is accurate to approximately 5 cm (1-sigma), based on comparisons with independent

GPS and leveling data; https://earth-info.nga.mil/GandG/update/index.php?action=home (Ref. 66).[25]

C.4 Land Maps

As discussed earlier, the NAD 83 and the NAVD 88 datums were adopted by the Federal Geodetic Control Subcommittee as the official datums for use by Federal civil mapping agencies, and new maps, such as U.S. Geological Survey topographic maps, are compiled on these datums. Except for the largest map scales, the horizontal components of WGS 84 and NAD 83 are equivalent. Older U.S. maps are compiled on older datums, such as the North American Datum of 1927 (NAD 27) and the National Geodetic Vertical Datum of 1929 (NGVD 29). When using coordinates and heights taken from maps created on these and other older datums, care should be taken to convert coordinates and heights between the NAD 27 and the NAD 83 datums, and the NGVD 29 and NAVD 88 datums. Datum transformations are available from the NGS NCAT and VDATUM tools, which relate the NAD 27 and NAD 83 datums.

As described in Section 1.7.8, the USNG expands the utility of topographic, street, and other large-scale maps by adding several features, e.g., it provides a grid reference system that is seamless across jurisdictional boundaries; it provides the foundation for a universal map index; and it enables user friendly position referencing on appropriately gridded paper and digital maps with Global Positioning System (GPS) receivers and Internet map portals. The USNG is a presentation standard. It does not replace data storage formats for either geographic information systems (GIS) or the State Plane Coordinate System (SPCS) for engineering and survey applications. The USNG is an alphanumeric point reference system that has been overlaid on the Universal Transverse Mercator (UTM) numerical grid. Generally, any lot-sized segment in a discrete area (city) can be described using 8-digits (e.g., 1234 5678). By including a two-letter prefix (e.g., XX 1234 5678), the location is uniquely identified within a state-wide region. To facilitate its use by the public and emergency responders, a variety of smartphone applications are available that provide continuous USNG geo-locations when activated.

C.5 Nautical Charts

As discussed earlier, the NAD 83 and NAVD 88 datums were adopted by the Federal Geodetic Control Subcommittee as the official datums for use by Federal civil mapping agencies. On a global basis, IHO designated the use of the WGS 84 as the universal datum. Since then, the horizontal

[25] Pavlis, N. K., S. A. Holmes, S. C. Kenyon and J. K. Factor (2013), Correction to “The Development and Evaluation of the Earth Gravitational Model 2008 (EGM2008),” Journal of Geophysical Research: Solid Earth, 118: 5, p. 2633-2633, doi:10.1002/jgrb.50167.

features have been based on WGS 84 or on other geodetic reference systems that are compatible, such as NAD 83. All electronic charts are required to be based upon WGS 84.

All vertical features and depths are still defined with respect to tidal surfaces, which may differ in definition from chart to chart. The IHO has agreed to lowest astronomical tide and highest astronomical tide as the preferred tidal datums for use in nautical charting.

C.6 Aeronautical Charts

As discussed earlier, the NAD 83 and the NAVD 88 datums were adopted by the Federal Geodetic Control Subcommittee as the official datums for use by Federal civil mapping agencies. On a global basis, ICAO designated the use of the WGS 84 as the universal datum. Since then, the horizontal features have been used on WGS 84 or in other geodetic reference systems that are compatible, such as the NAD 83 or the ITRF combined with the GRS 80 ellipsoid.

All vertical features and elevations are still determined relative to the local vertical datums, which may vary by a meter or more from a global geoid reference (e.g., WGS 84 (EGM08) geoid).

C.7 Map and Chart Accuracies

When comparing positions derived from GPS with positions taken from maps or charts, an understanding of factors affecting the accuracy of maps and charts is important. Several factors are directly related to the scale of the product. Map or chart production requires the application of certain mapmaking standards to the process. Because production errors are evaluated with respect to the grid of the map, the evaluation represents relative accuracy of a single feature rather than feature-to-feature relative accuracy. This is the "specified map or chart accuracy."

Another factor is the symbolization of features. This creates an error in position because of physical characteristics, e.g., what distance is represented by the width of a line symbolizing a feature. In other words, what is the dimension of the smallest object that can be portrayed true-to-scale at a map or chart? Also, a limiting factor on accuracy is the map or chart user's inability to accurately scale the map coordinates given by the grid or to plot a position. With the transition to electronic charts, the inaccuracies of manual plotting by cartographers are avoided in that the accurate position of features can be included within the electronic chart data.

Cartographic presentation or "cartographic license" is also an error source. When attempting to display two or more significant features very close together on a map or chart, the cartographer may displace one feature slightly for best presentation or clarity. Errors in the underlying survey data of features depicted on the map or chart will also affect accuracy. For example, some hazards on nautical charts have not always been accurately surveyed and, hence, are incorrectly positioned on the chart.

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

Appendix D

Abbreviations, Acronyms, Initialisms, and Units

The following is a listing of abbreviations, acronyms, and initialisms for organizations and technical terms used in this document:

AAM	automated asset mapping
ABAS	Aircraft-Based Augmentation System
AC	Advisory Circular
ACTS	Automated Computer Time Service
ADF	automatic direction finder
ADS-B	Automatic Dependent Surveillance-Broadcast
ADS-C	Automatic Dependent Surveillance-Contract
AFSPC	Air Force Space Command
AGL	above ground level
AIM	Aeronautical Information Manual
AIS	Automatic Identification System
AM	amplitude modulation
AMC	Alternate Master Clock
ANSP	air navigation service provider
AoA	analysis of alternatives
APNT	alternative positioning, navigation, and timing
APV	approach procedure with vertical guidance

ARNS	Aeronautical Radionavigation Service
ASR	airport surveillance radar
ATC	air traffic control
BCD	binary code decimal
BIPM	International Bureau of Weights and Measures
BRT	bus rapid transit
BTS	Bureau of Transportation Statistics
CAPE	cost assessment and program evaluation
C/A	coarse/acquisition
CAT	category
CCW	coded continuous wave
CDD	capability development document
CDL	commercial driver's license
CDMA	code division multiple access
CEP	circular error probable
CES	coast Earth station
CFR	Code of Federal Regulations
CGPM	Conférence Générale des Poids et Mesures
CGS	Civil GPS Service
CGSIC	Civil GPS Service Interface Committee
CI	critical infrastructure
CIO	chief information officer
CJCS	Chairman, Joint Chiefs of Staff
CNS	communication, navigation, and surveillance
COMPETES	[The] Creating Opportunities to Meaningfully Promote Excellence in Technology, Education, and Science [Act]
CONUS	conterminous United States
CORS	continuously operating reference stations

COTS	Commercial Orbital Transportation Services
CPDLC	controller-pilot data link communications
CRADA	cooperative research and development agreement
CRAF	Civil Reserve Air Fleet
DGPS	Differential Global Positioning System
DHS	Department of Homeland Security
DIA	Defense Intelligence Agency
DME	Distance measuring equipment
DNI	Director of National Intelligence
DOC	Department of Commerce
DoD	Department of Defense
DOI	Department of Interior
DORIS	Doppler Orbitography and Radiopositioning Integrated by Satellite
DoS	Department of State
DOT	Department of Transportation
drms	distance root mean square
DSCS	Defense Satellite Communications Systems
DSL	digital subscriber line
DUATS	Direct User Access Terminal System
EA	electronic attack
EFVS	enhanced flight vision system
EGM	Earth Gravitational Model
EOP	Executive Office of the President
ESG	executive steering group
ESV	Extended Service Volume
EXCOM	executive committee
FAA	Federal Aviation Administration
FAF	final approach fix

FAR	Federal Aviation Regulations
FCB	Functional Capabilities Board
FCC	Federal Communications Commission
FDC	Flight Data Center
FDE	fault detection and exclusion
FHWA	Federal Highway Administration
FL	flight level
FMCSA	Federal Motor Carrier Safety Administration
FMS	flight management systems
FR	Federal Register
FRA	Federal Railroad Administration
FRN	Federal Register Notice
FRP	Federal Radionavigation Plan
FRS	Federal Radionavigation Systems
FSS	flight service station
FTA	Federal Transit Administration
FTE	flight technical error
GBAS	Ground-Based Augmentation Systems
GDGPS	Global Differential GPS
GEO	geosynchronous Earth orbit
GES	ground Earth station
GIS	geographic information systems
GLS	Great Lakes St. Lawrence Seaway Development Corporation
GMDSS	Global Maritime Distress and Safety System
GNSS	global navigation satellite system
GPS	Global Positioning System
GRS	geodetic reference system
HAZMAT	hazardous materials

HEA	harbor entrance and approach
HEOMD	Human Exploration and Operations Mission Directorate
HSPD-7	Homeland Security Presidential Directive–7
HUD	head-up display
IALA	International Association of Marine Aids to Navigation and Lighthouse Authorities
IC	Intelligence Community
ICAO	International Civil Aviation Organization
ICG	International Committee on GNSS
IDF	interference direction finding
IDM	interference detection and mitigation
IERS	International Earth Rotation and Reference Systems Service
IFR	instrument flight rules
IGS	International GNSS Service
IHO	International Hydrographic Organization
ILS	instrument landing system
IMO	International Maritime Organization
INMARSAT	International Maritime Satellite Organization
INS	inertial navigation system
INU	inertial navigation unit
IOC	initial operational capability
IP	Internet Protocol
IRAC	Interdepartment Radio Advisory Committee
IRP	interagency requirements process
IRU	inertial reference unit
ISS	International Space Station
ITRF	International Terrestrial Reference Frame
ITRS	International Terrestrial Reference System

ITS	Intelligent Transportation Systems
ITS	Internet Time Service
ITS-JPO	Intelligent Transportation Systems Joint Program Office
ITU	International Telecommunication Union
JCB	Joint Capabilities Board
JCIDS	Joint Capabilities Integration and Development System
JCS	Joint Chiefs of Staff
JPDO	Joint Planning and Development Office
JPL	Jet Propulsion Laboratory
JPO	joint program office
JROC	Joint Requirements Oversight Council
JTIDS	Joint Tactical Information Distribution System
LAAS	Local Area Augmentation System
LBS	location-based services
LEO	low Earth orbit
LF	low frequency
LMSL	local mean sea level
LNAV	lateral navigation
LOP	line of position
LP	localizer performance
LPV	localizer performance with vertical guidance
MARAD	Maritime Administration
MCS	Master Control Station
MCW	modulated continuous wave
MDGPS	Maritime Differential GPS Service
MEO	medium Earth orbit
MIDS	multi-function information distribution system

MOA	memorandum of agreement
MON	Minimum Operating Network
MOPS	Minimum Operational Performance Standards
MPNTP	Master Positioning, Navigation, and Timing Plan
MSC	Military Sealift Command
MSK	minimum shift keying
MSL	mean sea level
N/A	not applicable
NAC_p	navigation accuracy category for position
NAC_v	navigation accuracy category for velocity
NAD	North American Datum
NANU	Notice Advisories to Navstar Users
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
NAVAID	navigation Aid
NAVCEN	Navigation Center (USCG)
NAVD	North American Vertical Datum
NAVTEX	navigational telex
NAVWAR	navigation warfare
NCIS	network-centric information sharing
NCO	National Coordination Office
NDB	nondirectional beacon
NDGPS	Nationwide Differential Global Positioning Service
NDRF	National Defense Reserve Fleet
NextGen	Next Generation Air Transportation System
NG911	Next Generation 911
NGA	National Geospatial-Intelligence Agency

NGS	National Geodetic Survey
NGVD	National Geodetic Vertical Datum
NHTSA	National Highway Traffic Safety Administration
NIC	Navigation Integrity Category
NII	networks and information integration
NIPRNet	Non-classified Internet Protocol Router Network
NIS	navigation information service
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NOTAM	Notice to Airmen
NPA	Non-precision approach
NSA	National Security Agency
NSF	National Science Foundation
NSRS	National Spatial Reference System
NTIA	National Telecommunications and Information Administration
NTM	Notice to Mariners
NTP	Network Time Protocol
OASIS	Operational and Supportability Implementation System
OCS	operational control system
OPUS	Online Positioning User Service
ORD	operational requirements document
OST	Office of the Secretary of Transportation
OST-B	DOT Assistant Secretary for Budget and Programs and Chief Financial Officer
OST-C	DOT Office of the General Counsel
OST-M	DOT Assistant Secretary for Administration
OST-P	DOT Under Secretary of Transportation for Policy

OST-R	Office of the Assistant Secretary for Research and Technology
PAR	precision approach radar
PBN	performance-based navigation
PHMI	probability of hazardously misleading information
PHMSA	Pipeline and Hazardous Materials Safety Administration
PIRT	Purposeful Interference Response Team
PNT	Positioning, Navigation, and Timing
POS/NAV	positioning and navigation
PPS	Protected Positioning Service
PRN	pseudo-random noise
PS	performance standard
PTC	positive train control
PTP	Precision Time Protocol (IEEE-1588-2019)
PTTI	Precise Time and Time Interval
R&D	research and development
RADAR	radio detecting and ranging
RAIM	receiver autonomous integrity monitoring
RCP	required communication performance
RF	radio frequency
RFI	radio frequency interference
RINEX	Receiver Independent Exchange
RNAV	area navigation
RNP	required navigation performance
RNP AR	RNP authorization required
RNPSORSG	Required Navigation Performance and Special Operational Requirements Study Group
RNS	radionavigation service
RNSS	radionavigation satellite service

RRF	Ready Reserve Force
RSP	required surveillance performance
RSS	root sum square
RTCM	Radio Technical Commission for Maritime Services
RVR	runway visual range
SA	selective availability
SAR	search and Rescue
SARPS	standards and recommended practices
SBAS	Space-Based Augmentation System
SBIR	Small Business Innovative Research
SCaN	Space Communications and Navigation
SCUBA	self-contained underwater breathing apparatus
SDA	system design assurance
SID	standard instrument departure
SIL	Source Integrity Level
SIPRNet	Secret Internet Protocol Router Network
SIS	signal-in-space
SLR	satellite laser ranging
SLSMC	St. Lawrence Seaway Management Corporation
SNTP	Simple Network Time Protocol
SONAR	sound navigation and ranging
SPC	senior policy committee
SPS	Standard Positioning Service
SRMA	Sector Risk Management Agency
SSV	Space Service Volume
STAR	standard terminal arrival route
Stat.	[Federal] Statute
TACAN	tactical air navigation

TASS	TDRSS Augmentation Service Satellites
TBD	to be determined
TBO	trajectory based operations
TDL	track defect location
TDRSS	Tracking and Data Relay Satellite System
TDWR	Terminal Doppler Weather Radar
TERPS	terminal instrument procedures
TIS	traffic information services
TMAS	Time Measurement and Analysis Service
TRSB	Time Reference Scanning Beam
TSO	technical standard order
TT&E	tests, training, and exercises
TWSTT	two-way satellite time transfer
UAT	Universal Access Transceiver
UHF	ultra high frequency
U.N.	United Nations
UNAVCO	University NAVSTAR Consortium
URA	user range accuracy
URE	user range error
USACE	U.S. Army Corps of Engineers
USAF	United States Air Force
U.S.C.	United States Code
USCG	United States Coast Guard
USDA	U.S. Department of Agriculture
USD(I)	Under Secretary of Defense for Intelligence
USD(P)	Under Secretary of Defense for Policy
UDP	User Datagram Protocol
USG	United States Government

USMC	United States Marine Corps
USN	United States Navy
USNO	United States Naval Observatory
USSF	United States Space Force
USSPACECOM	United States Space Command
USSTRATCOM	United States Strategic Command
UTC	Coordinated Universal Time
US-TEC	United States Total Electron Content
VFR	visual flight rules
VHF	very high frequency
VLBI	very long baseline interferometry
VNAV	vertical navigation
VOR	very high frequency omnidirectional range
VORTAC	collocated VOR and TACAN system
VTS	vessel traffic services
WAAS	Wide Area Augmentation System
WG	working group
WGS	World Geodetic System
WMS	Wide Area Master Station
WRC	World Radiocommunication Conference
WRS	Wide Area Reference Stations
2 SOPS	2d Space Operations Squadron
2D	two-dimensional
3D	three-dimensional

The following is a listing of units used throughout this plan:

bps	bits per second
dBW	decibel watt (decibels relative to one watt)
deg	degrees
drms	distance root mean square
ft	feet
hr	hour
Hz	Hertz (cycles per second)
GHz	Gigahertz (one billion Hertz)
kHz	kilohertz (one thousand Hertz)
MHz	Megahertz (one million Hertz)
m	meter
cm	centimeter
km	kilometer
mm	millimeter
min	minute
mi	mile
NM	nautical mile
s	second
ms	millisecond (one thousandth of a second)
µs	microsecond (one millionth of a second)
ns	nanosecond (one billionth of a second)
ps	picosecond (one trillionth of a second)
W	Watt
mW	milliwatt (one thousandth of a watt)
µW	microwatt (one millionth of a watt)

Appendix E

Glossary

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. PNT system accuracy is usually presented as a statistical measure of system error and is specified as:

- Predictable: the accuracy of a PNT system's position solution with respect to the charted solution. Both the position solution and the chart must be based upon the same geodetic datum.
- Repeatable: the accuracy with which a user can return to a position whose coordinates have been measured at a previous time with the same navigation system.
- Relative: the accuracy with which a user can measure position relative to that of another user of the same navigation system at the same time.

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

Area Navigation (RNAV): A method of navigation which permits aircraft operation on any desired flight path within the coverage of ground or space-based navigation aids or within the limits of capability of self-contained aids, or a combination of these.

Along-Track Distance: The horizontal distance between the aircraft's current position and a fix measured by an area navigation system that is not subject to slant range errors.

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

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.

Codeless or Semicodeless Processing: Techniques to obtain L2 Y code pseudorange and carrier-phase measurements without the cryptographic knowledge for full access to this signal. Codeless techniques only utilize the known 10.23 MHz chip rate of the Y code signal and the fact that the same Y code signal is broadcast on both L1 and L2. Semicodeless techniques use some known features of the Y code.

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

Conterminous United States (CONUS): 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): An atomic time scale, and the basis for civil time. UTC 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 PNT 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 PNT system accuracy by determining positioning error at a known location and subsequently transmitting the determined error, or corrective factors, to users of the same PNT system, operating in the same area.

Divestment: The transfer of a Federal PNT facility to a non-Federal service provider when it no longer meets criteria for sustainment as a Federal service. If a PNT facility cannot be transferred, the service is discontinued, and the facility is decommissioned.

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

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

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

Global Navigation Satellite System (GNSS): GNSS refers collectively to the world-wide positioning, navigation, and timing (PNT) determination capability available from one or more satellite constellations. Each GNSS system employs a constellation of satellites operating in conjunction with a network of ground stations.

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 measure of the trust that can be placed in the correctness of the information supplied by a PNT system. Integrity includes the ability of the system to provide timely warnings to users when the system should not be used for navigation.

Interagency: As used in this document, interagency refers to any PNT forum or activity involving multiple Federal departments or agencies.

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

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

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

Nanosecond (ns): One billionth of a second.

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

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

NAVDAT: A proposed Navigational Data Maritime Broadcast system designated by IMO and ITU as an enhanced means for transmitting coastal urgent marine safety information to ships worldwide as part of the IMO's Global Maritime Distress and Safety Systems (GMDSS) modernization effort.

NAVTEX: A system designated by IMO as the primary means for transmitting coastal urgent marine safety information to ships worldwide. The NAVTEX system broadcasts Marine Safety Information such as Radio Navigational Warnings, Storm/Gale Warnings, Meteorological Forecasts, Piracy Warnings, and Distress Alerts. Full details of the system can be found in IMO Publication IMO-951E – The NAVTEX Manual (Ref. 67).

Non-precision Approach (NPA): An instrument approach procedure based on a lateral path and no vertical guide path. The procedure is flown with a navigation system that provides lateral (but not vertical) path deviation guidance.

PNT Profile(s): A description of the responsible use of PNT services—aligned to standards, guidelines, and sector-specific requirements—selected for a particular system to address the potential disruption or manipulation of PNT services.

PNT Services: Any system, network, or capability that provides a reference to calculate or augment the calculation of longitude, latitude, altitude, or the process of planning, recording, and controlling the movement of a craft or vehicle from one place to another, or transmission of time or frequency data, or any combination thereof.

Precise Time: A time requirement accurate to within 10 ms.

Precision: Refers to how closely individual PNT measurements agree with each other.

Precision Approach: An instrument approach procedure, based on a lateral path and a vertical glide path, that meets specific requirements established for vertical navigation performance and airport infrastructure.

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

Radiolocation: Radiodetermination used for purposes other than those of PNT.

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

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

Required Navigation Performance (RNP): A statement of the navigation performance necessary for operation within a defined airspace, including the operating parameters of the navigation systems used within that airspace. Incorporates associated on-board performance monitoring and alerting features to notify the pilot when the RNP for a particular phase or segment of a flight is not being met.

Responsible use of PNT services: The deliberate, risk-informed use of PNT services, including their acquisition, integration, and deployment, such that disruption or manipulation of PNT services minimally affects national security, the economy, public health, and the critical functions of the Federal Government.

Sector Risk Management Agency (SRMA): The Federal executive department or agency that is responsible for providing institutional knowledge and specialized expertise as well as leading, facilitating, or supporting the security and resilience programs and associated activities of its designated critical infrastructure sector in the all-hazards environment. The SRMAs are those identified in Presidential Policy Directive 21, Critical Infrastructure Security and Resilience (February 12, 2013).

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

Surveying: The act of making observations to determine the terrestrial or three-dimensional positions of points and the distances and angles between them, including determine of 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; the length of the day, etc.

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

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

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

UT1: A time scale based on the rotation of Earth on its axis with respect to the Sun, rather than atomic clocks. UT1 takes polar motion into account. Leap seconds are used in the UTC time scale to maintain it within 0.9 s of UT1.

World Geodetic System 1984 (WGS 84): An Earth-centered, Earth-fixed terrestrial reference system and geodetic datum. WGS 84 is based on a consistent set of constants and model parameters that describe the Earth's size, shape, and gravity and geomagnetic fields. WGS 84 is the standard U.S. Department of Defense definition of a global reference system for geospatial information and is the reference system for GPS. It is consistent with ITRS.

Appendix F

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