RTCA, Inc.
1828 L Street, NW, Suite 805
Washington, DC 20036-5133 USA

Minimum Operational Performance Standards for Global Positioning System / Aircraft-Based Augmentation System Airborne Equipment

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Prepared by: SC-159
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Telephone: 202-833-9339
Facsimile: 202-833-9434
Internet: www.rtca.org

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Foreword

This document was prepared by RTCA Special Committee 159 (SC-159) and approved by the RTCA Program Management Committee (PMC) on April 14, 2009.

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- Developing consensus on the application of pertinent technology to fulfill user and provider requirements, including development of Minimum Operation Performance Standards (MOPS) for electronic systems and equipment that support aviation; and

- Assisting in developing the appropriate technical material upon which positions for the International Civil Aviation Organization (ICAO) and the International Telecommunication Union (ITU) and other appropriate international organizations can be based.

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1.0 PURPOSE AND SCOPE

1.1 Introduction

This document contains minimum operational performance standards (MOPS) for airborne navigation equipment using the Global Positioning System (GPS). DO-316 only provides standards for single-frequency airborne supplemental navigation sensor equipment not augmented by ground- or space-based systems. Separate standards exist for GPS augmented by ground- or space-based methods. Additionally, a separate document will be created in the future to address standards for dual frequency equipment. The basis for this MOPS is RTCA/DO-229D class beta 1 receiver without SBAS requirements.

In this document, the term "shall" is used to indicate requirements. An approved design should comply with every requirement, which can be assured by inspection, test, analysis, or demonstration. The term "must" is used to identify items that are important but are either duplicated somewhere else in the document as a "shall", or are considered to be outside the scope of this document. The term "should" is used to denote a recommendation that would improve the GPS equipment, but does not constitute a requirement.

The standards define minimum performance, functions and features for GPS sensors that provide position information to a multi-sensor system or separate navigation system. They also address Area Navigation (RNAV) equipment to be used for the en route, terminal, and Lateral Navigation (LNAV) phases of flight. These standards are based upon a nominal allocation of the aircraft-level requirements in RTCA/DO-236B, *Minimum Aviation System Performance Standards: Required Navigation Performance for Area Navigation*, accounting for the unique issues associated with GPS navigation service and minimizing the need for pilot training.

Compliance with these standards by manufacturers, installers and users is recommended as one means of assuring that the equipment will satisfactorily perform its intended functions under conditions encountered in routine aeronautical operations, and will ensure a basic compatibility with the requirements defined in RTCA/DO-236B.

The regulatory application of these standards is the responsibility of appropriate government agencies. In the United States, the Federal Aviation Administration (FAA) has published a Technical Standard Order (TSO) for GPS equipment to reference the requirements and bench test procedures in Section 2.

The word "equipment", as used in this document, includes all components or units necessary (as determined by the equipment manufacturer or installer) to properly perform its intended function. For example, the airborne "equipment" may include: sensor(s), a computer unit, an input-output unit that interfaces with existing aircraft displays/systems, a control unit, a display, shock mount(s), etc. In the case of this example, all of the foregoing components or units constitute the "equipment". It should not be inferred from this example, however, that all GPS navigation equipment will necessarily include all of the foregoing components or units. The particular components of GPS equipment will depend upon the design used by the equipment manufacturer, subject to the constraint that the equipment must meet the applicable requirements of this MOPS.

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Section 1 of this document provides information and assumptions needed to understand the rationale for equipment characteristics and requirements stated in the remaining sections. It describes typical equipment applications and operational goals and forms the basis for the standards stated in Section 2.

Section 2 contains the performance requirements. When measured values of equipment performance could be a function of the measurement method, this section also defines standard test conditions as well as testing methods. Section 2 contains the minimum performance standards for the equipment. These standards define required performance under standard operating conditions and stressed physical environmental conditions. It also details the recommended test procedures necessary to demonstrate compliance.

provides references to guidance material for installed equipment performance.

provides references to guidance material describing GPS equipment operational characteristics.

Some appendices are reserved for future use; and, are interspersed among appendices that do contain information. This was done to maintain labeling commonality with RTCA/DO-229D to facilitate any future changes needed in both documents.

Appendix A is reserved for future use.

Appendices B and C are normative. Specifically, Appendix B contains GPS assumptions, and Appendix C describes the standard interference environment.

Appendix D is reserved for future use.

Appendix E includes a description of the baseline weighted least squares algorithm. It also includes an example means of implementing the navigation system error algorithm.

Appendix F and G describe additional GPS capabilities that are not required by the MOPS. Appendix F describes a suggested method for calculating velocity data so the equipment can possibly support future ADS-B requirements. Appendix G describes the requirements and test procedures for baro-aided fault detection and exclusion (FDE) capability that is optional under this MOPS.

Note: It is not certain that equipment conforming to this MOPS is an acceptable source for all ADS-B applications because all ADS-B requirements have not yet been finalized.

Appendix H describes a recommended output standard for implementing functions required by this MOPS. But, the GPS equipment is not required to use this method.

Appendix I is reserved for future use.

Appendix J describes weights for use in an optional General Least-Squares position solution along with tropospheric and ionospheric error models.

Appendix K provides a list of references concerning the fault detection and exclusion (FDE) algorithm that can be used during the en route, terminal area, and approach phases of flight to provide integrity.

Appendix L describes an example method for making WGS-84 computations.

Appendices M through O are informative. Appendix M contains background material for bench tests. Appendix N provides guidance for determining Mean Sea Level height from WGS-84 coordinates and references to obtain the 1996 Earth Gravitational Model (EGM 96) and the Earth Gravitational Model 2008 (EGM2008). Appendix O is a glossary.

Appendices P and Q are reserved for future use.

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Appendix R contains requirements and test procedures for tightly integrated GPS/inertial systems when fault-detection and exclusion is used to provide integrity. Any equipment that uses integrated GPS/inertial must meet the requirements and accomplish the test procedures of this appendix.

Appendix S and T are reserved for future use.

Appendix U provides guidance to potentially interface equipment conforming to this MOPS with ADS-B equipment. However, it has not been determined that equipment conforming to this MOPS is an acceptable position source for ADS-B equipment. Manufacturers must consult ADS-B performance documentation to determine if their equipment provides acceptable positioning source performance.

Note: All equations in the appendices are labeled sequentially using the appendix letter identifier (e.g., [A-1], [A-2], etc.) so that the equations may be referenced.

1.2 System Overview

1.2.1 GNSS Satellite Signal Characteristics

GNSS refers to a world-wide position and time determination system that uses satellite ranging signals to determine user location. It encompasses all satellite ranging technologies and augmentation systems, including GPS, Space-Based Augmentation System (SBAS), Ground-Based Augmentation System (GBAS), Galileo, and Global Orbiting Navigation Satellite System (GLONASS). Different components of the GNSS can have different signal characteristics (e.g. GPS, Galileo, SBAS satellites, etc.).

1.2.2 GPS Signal Characteristics

The GPS ranging signal is modulated with data at 50 symbols/second that defines the satellite's position, system time, clock correction parameters, as well as the health and accuracy of the transmitted data and ranging signal. The user computes a pseudorange to the satellite by timing the arrival of the GPS signal. The user equipment uses the pseudoranges from the satellites to compute the receiver's internal clock offset and a three-dimensional position fix. A pseudo-random noise (PRN) code, known as the Coarse Acquisition (C/A) code, is generated at a rate of 1.023 MHz and modulated onto the GPS L1 frequency (1575.42 MHz). All GPS satellites transmit at the same L-band frequency. The carrier is modulated with a specific C/A code for each GPS satellite.

The GPS coordinate system provided by the signal is the Cartesian earth-centered earth-fixed (ECEF) coordinates as specified in the World Geodetic System 1984 (WGS-84). The GPS position is determined in the WGS-84 coordinate system.

The GPS Control Segment consistently manages GPS time to within one microsecond of Universal Coordinated Time (UTC) (modulo one second). For time coordination purposes, an offset between GPS time and UTC is provided in the GPS navigation message and is specified to have an SPS accuracy of 340 nanoseconds 95% of time. Detailed GPS Standard Positioning Service (SPS) information is provided in the GPS SPS Performance Standard, October 2001, and IS-GPS-200D, "Navstar GPS Space Segment / Navigation User Interfaces", December 2004.

Note: During the course of this MOPS development, a new GPS SPS version has been released. The new SPS version is not referenced because an in depth analysis has not been performed. Office of the Secretary of Defense with FAA input has ensured backward compatibility between the old standard and the new standard. Application of the previous version does not have any adverse effect from an operational standpoint.

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1.3 Operational Goals

The operational goal is to provide supplemental radionavigation equipment onboard the aircraft that meets Area Navigation (RNAV) performance requirements for oceanic, remote area and domestic en route, terminal, and Lateral Navigation (LNAV) approach phases of flight. Navigation integrity is provided by an FDE algorithm that uses redundant pseudorange measurements for all phases of flight. Aircraft using equipment conforming to this MOPS for IFR operations must also be equipped with another navigation system.

Note: Equipment compliant with Appendix 1 of AC 20-138B can provide primary navigation in oceanic/remote areas.

Additional goals for GPS are to provide:

a) flexibility for future enhancements;

b) positioning source for Required Navigation Performance (RNP) applications; and,

c) replacement of other radionavigation systems.

1.3.1 Operational Environment

The GPS equipment is intended to be a supplemental radionavigation system within the U.S. National Airspace System (NAS). As such, GPS may be used on aircraft to navigate within designated airspace, provided other operational radionavigation equipment is on the aircraft. In Oceanic and/or remote regions it may be possible to use the GPS equipment as a primary navigation system; that is, without a requirement for other operational equipment. It is anticipated that the NAS will transition to increased reliance on GNSS services and decreased emphasis on ground-based radionavigation aids. As with conventional navigation aids, operational precautions will be used to mitigate a potentially hazardous situation in the event of a failure.

GPS and its augmentation systems may result in decommissioning other radionavigation aids on the ground and the removal of other radionavigation equipment from the cockpit. Although the ultimate degree to which these reductions can be made is not yet known, it is believed that they will result in significant savings both to the aviation authority and the aeronautical community. The operating environment is expected to evolve to capture the benefits of improved RNAV capabilities, resulting in increased operational efficiency.

1.3.2 International Compatibility

The operational concept for GNSS is predicated on the combination of the different GNSS elements without pilot intervention. As GNSS is a global system, there should be no flight crew interaction based on airspace, so that the flight crew should not be involved in the selection of different GNSSs.

For LNAV approaches, it is expected that States will approve all combinations of GNSS elements provided by another State. If a State decides to approve a subset of GNSS elements for less stringent approach operations there may be serious operational restrictions depending on the capability of the equipment. While all participating States are coordinating through ICAO to ensure that GNSS provides seamless global coverage, it is important to recognize the potential ramifications should a State only approve a subset of GNSS operations, or, impose operational limits on a particular GNSS.

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1.4 Equipment Type

Equipment developed to this MOPS consists of a GPS sensor that determines position (with integrity) and provides position and integrity data to an integrated navigation system (e.g., flight management system, multi-sensor navigation system). This equipment provides integrity by using a Fault Detection and Exclusion (FDE) algorithm.

1.5 FDE with Barometric Aiding

Although it is not required, the use of barometric altitude for the fault detection and exclusion (FDE) algorithm is highly recommended. Baro-aiding can significantly improve GPS availability for the en route, terminal area, and LNAV phases of flight.

Other sensors, such as clock-aiding, eLoran or inertial, may also be used as part of the FDE algorithm. Such an algorithm would need to meet all the FDE requirements. FDE algorithms that use other navigation signals external to the aircraft, such as eLoran or VOR/DME, must satisfy the availability requirement without using the other navigation signals. The manufacturer must provide the means to test and analyze alternate FDE algorithms to demonstrate compliance.

1.6 Test Considerations

The test procedures specified in Section 2 are intended to be used as recommended means of demonstrating compliance with the minimum acceptable performance parameters specified herein. Although specific test procedures are cited, it is recognized that other methods may be suitable. These alternate procedures may be used if they provide at least equivalent information. In such cases, the procedures cited herein should be used as one criterion in evaluating the acceptability of the alternate procedures.

1.6.1 Environmental Tests

Environmental tests are specified in Section 2.2. These tests, like bench tests, are performed at the equipment level. The procedures and their associated limit requirements provide a laboratory means of determining the electrical and mechanical performance of the equipment under conditions expected to be encountered in actual aeronautical operations. Test results may be used by equipment manufacturers as design guidance, in preparation of installation instructions and, in certain cases, for obtaining formal approval of equipment design and manufacture.

1.6.2 Bench Tests

The test procedures specified in Section 2.3 provide a means to demonstrate equipment performance in a simulated environment. Test results may be used as design guidance for monitoring manufacturing compliance and, in certain cases, for obtaining formal approval of equipment design and manufacture.

Due to the number of possible sensor complements and position-fixing modes for this equipment, and the actual service to be provided, it is deemed impractical to define complete test procedures for all current and future equipment designs. Test procedures contained in Section 2.3 apply to the minimum system requirements in accordance with the minimum performance parameters specified in this standard.

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1.7 Definition of Key Terms

Appendix O provides a glossary of the terms used in this document. This section expands upon the definitions of key terms in order to increase document clarity and establish a common foundation of terminology.

1.7.1 General Terms

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

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 and was predicted to operate throughout the operation.

Horizontal Figure of Merit: The $HFOM_P$ is the radius of a circle in the horizontal plane (the local plane tangent to the WGS-84 ellipsoid), with its center being at the true position, that describes the region assured to contain the indicated horizontal position with at least a 95% probability under fault-free conditions at the time of applicability.

Misleading Information: Within this standard, misleading information is defined as any data that is output to other equipment or displayed to the pilot that has an error larger than the horizontal alert limit (HAL) or current horizontal protection level (HPL) , without an indication of the error (e.g., flag) within the time-to-alert for the applicable phase of flight. This includes all horizontal position output data.

Required Navigation Performance (RNP): A statement of the navigation performance necessary for operation within a defined airspace. See applicable requirements and advisory material (e.g., FAA AC 90-101, AC 90-105, and RTCA/DO-236B).

1.7.2 Alert Limits and Protection Levels

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

Horizontal Protection Level$_{Fault\ Detection}$: The Horizontal Protection Level$_{\text{Fault Detection}}$ (HPL_{FD}) is the radius of a circle in the horizontal plane (the local plane tangent to the WGS-84 ellipsoid), with its center being at the true position, that describes the region assured to contain the indicated horizontal position. It is a horizontal region where the missed alert and false alert requirements are met for the chosen set of satellites when autonomous fault detection is used. It is a function of the satellite and user geometry and the expected error characteristics: it is not affected by actual measurements. Its value is predictable given reasonable assumptions regarding the expected error characteristics.

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Horizontal Uncertainty Level: The Horizontal Uncertainty Level (HUL) is an estimate of horizontal position uncertainty, based on measurement inconsistency, that bounds the true error with high probability (at least 99.9 percent). This estimate will not be available if there are four or fewer measurements available (because there is no redundancy).

Horizontal Exclusion Level$_{Fault\ Detection}$: The Horizontal Exclusion Level$_{\text{Fault Detection}}$ (HEL_{FD}) is the radius of a circle in the horizontal plane, where the missed alert and failed exclusion requirements can be met when autonomous Fault Detection and Exclusion is used (i.e., exclusion is available). It is only a function of the satellite and user geometry and the expected error characteristics: it is not affected by actual measurements. Therefore, this value is predictable.

1.7.3 Fault Detection and Exclusion (FDE) Terms

Fault Detection and Exclusion (FDE): Fault detection and exclusion is a receiver processing scheme that autonomously provides integrity monitoring for the position solution, using redundant range measurements. The FDE consists of two distinct parts: fault detection and fault exclusion. The fault detection part detects the presence of an unacceptably large position error for a given mode of flight. Upon the detection, fault exclusion follows and excludes the source of the unacceptably large position error, thereby allowing navigation to return to normal performance without an interruption in service. The fault detection aspects of FDE are referred to as Receiver Autonomous Integrity Monitoring (RAIM). However, FDE also includes the capability to isolate and exclude failed ranging sources so that navigation can continue in the presence of the failure.

Figure 1-1 provides a diagram of the conditions associated with FDE. Figure 1-2 shows a Markov state diagram of the events associated with autonomous fault detection. Finally, Figure 1-3 shows several example scenarios that can lead to the FDE events defined below.

Alert: For the definitions of missed alert, false alert, and time-to-alert, an alert is defined to be an indication that is provided by the GPS equipment when the positioning performance achieved by the equipment does not meet the integrity requirements. This alert is one of the conditions that would cause a navigation alert (ref. 2.1.1.13.2, item d).

Positioning Failure: A positioning failure is defined to occur whenever the difference between the true position and the indicated position exceeds the applicable horizontal protection level.

Note 1: Additional system utility may be obtained by outputting the HUL after a positioning failure has been detected.

Missed Detection: A missed detection is defined to occur when a positioning failure is not detected.

Note 2: The term, missed detection, refers to internal processing of the FDE algorithm. It does not refer to an alert that is issued by the GPS equipment.

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