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Minimum Operational Performance Standards (MOPS) for GNSS Aided Inertial Systems

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Prepared by: SC-159
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FOREWORD

This document was prepared by Special Committee 159 (SC-159) and approved by the RTCA Program Management Committee (PMC) on December 17, 2020

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- analyzing and recommending solutions to the system technical issues that aviation faces as it continues to pursue increased safety, system capacity and efficiency;

- developing consensus on the application of pertinent technology to fulfill user and provider requirements, including development of minimum operational performance standards 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 and the International Telecommunication Union and other appropriate international organizations can be based.

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EXECUTIVE SUMMARY

RTCA DO-384 was prepared by RTCA Special Committee 159 (SC-159). It was approved by the RTCA Program Management Committee on December 17, 2020.

The purpose of this document is to provide minimum operational performance standards (MOPS) for Global Navigation Satellite System (GNSS) aided inertial systems including GNSS-aided attitude heading reference systems. Previously, Appendix R in RTCA DO-229 (any revision) and RTCA DO-316 contained the only reference material for GNSS-aided inertial systems, but only covered inertial reference systems qualified per 14 CFR Part 121 Appendix G using a tightly-coupled integration intended for long-range operations such as the oceanic environment. This document provides performance standards for an expanded range of inertial sensor technologies and integrations from short-range, loosely coupled to long-range, tightly-coupled covering a wider range of operations. Additionally, this document includes GNSS-aided performance standards used for attitude, heading and velocity information which is not covered by RTCA DO-334.

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1 PURPOSE AND SCOPE

1.1 Introduction

This document contains minimum operational performance standards (MOPS) for GNSS integrated with inertial reference systems (IRS) or attitude heading reference systems (AHRS). It is not meant to be a replacement or substitute for RTCA DO-334 (MOPS for Strapdown Attitude and Heading Reference Systems). A key assumption is that any AHRS used for compliance with the performance requirements in this MOPS first meets the performance standard described in RTCA DO-334. That is, RTCA DO-334 is the starting point for any AHRS used to comply with requirements in this MOPS.

RTCA DO-334 provides standards for strap-down AHRS equipment intended to output attitude (pitch, roll), heading, turn and slip information along with presenting this information to the pilot (see Figure 1-1) but does not provide detailed requirements for GNSS aiding. The 14 code of federal regulations (CFR) Part 121 Appendix G provides requirements for INS/IRS, but an AHRS (including those with air data computer inputs) is not presently accepted for navigation.

The 14 CFR 121 Appendix G requirements were developed in the 1970's primarily for self-contained oceanic long-range area navigation (RNAV) capability and pre-dates performance-based navigation concepts as well as GNSS. RTCA DO-229() (MOPS for GPS/SBAS Airborne Equipment) and RTCA DO-316 (MOPS for GPS/Aircraft Based Augmentation System Airborne Equipment) both include an Appendix R that describes tightly-coupled GPS/inertial requirements and tests intended for integrations with inertial sensors satisfying the 14 CFR Part 121 Appendix G requirements. This MOPS is intended to replace Appendix R in RTCA DO-316 (RTCA DO-229) and expand beyond tightly-coupled, 14 CFR Part 121 Appendix G compliant inertial integrations.

In this document, the term "shall" is used to indicate requirements. An approved design will 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 equipment, but does not constitute a requirement. The term "may" is used to denote an optional implementation at the manufacturer's discretion.

The requirements in this document define minimum performance, functions and features for both GNSS-aided inertial references systems and enhanced attitude heading reference systems. Due to the wide range of possible capabilities, it is important for manufacturers using this MOPS to characterize the equipment's intended function and expected performance. There are three performance categories and three associated Sub-categories within this MOPS. The word "equipment", as used in this document, includes all components or units necessary (as determined by the equipment manufacturer) to properly perform the intended function.

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. The regulatory application of these standards is the responsibility of appropriate government agencies. In the United States, the Federal Aviation Administration (FAA) plans to publish a Technical Standard Order (TSO) to reference the requirements and test procedures for each equipment category.

Section 1 of this document provides information and assumptions needed to understand the rationale for equipment characteristics and requirements stated in the remaining sections.

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It describes typical equipment applications and operational goals and forms the basis for the standards stated in Section 2.

Section 2 contains the performance and testing requirements. 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.

Section 3 provides references to guidance material for installed equipment performance.

Section 4 provides references to guidance material describing equipment operational characteristics.

Appendices A through P provide guidance material in support of requirements interpretation and testing. Appendix Q proposes methods to document performance of the GNSS aided inertial system to detect erroneous GNSS input based on the alternate trajectory concept.

1.2 System Overview

This MOPS addresses inertial integration with GNSS. Figure 1-1 shows an example block diagram of an inertial system aided by GNSS. The actual implementation and configuration may differ from Figure 1-1 but this MOPS addresses systems with at least one GNSS aiding source integrated with inertial systems. Additional aiding sources are possible such as magnetic sensing unit (MSU), air data computer (ADC), dual antenna-based heading aiding, etc. Recommendations regarding non-GNSS sensors are provided in Appendices J and K.

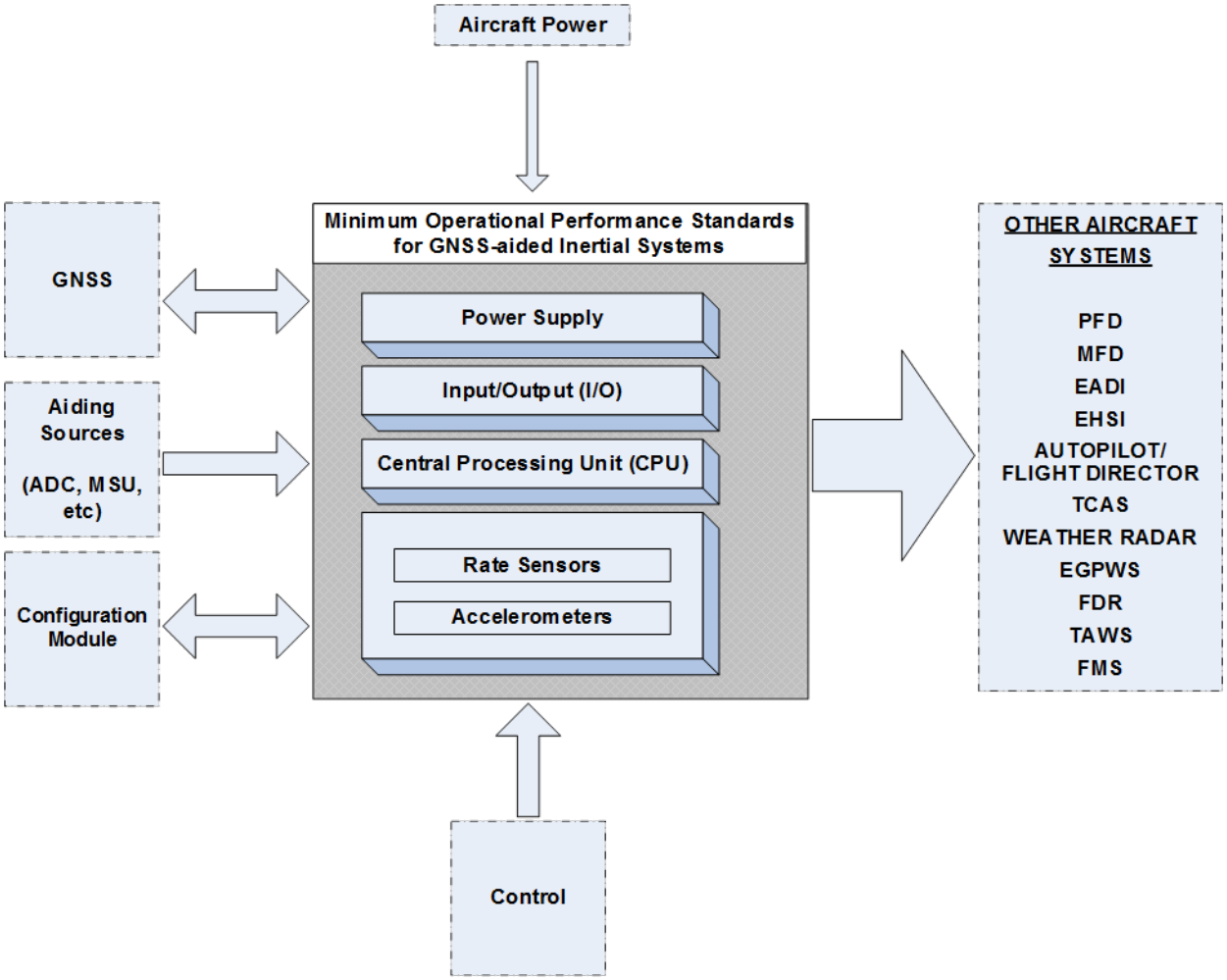


Figure 1-1: GNSS-Aided Inertial System Diagram Example

1.3 Equipment Categories

This MOPS classifies inertial performance by Equipment Category (A, B, or C) and inertially aided satellite Fault Detection and Exclusion (FDE) capability by Sub-category (0, 1, or 2)

Category A includes navigation-grade inertial components. When no GNSS is available, Category A is compliant with 14 CFR Part 121 Appendix G; that is, unaided by GNSS Category A provides inertial coasting for positioning according to Appendix G.

Category B includes gyrocompass-grade inertial components meeting the requirements for heading performance category H1 in DO-334 with no external aiding, but is not compliant with 14 CFR Part 121 Appendix G. When no GNSS is available Category B can coast for positioning over a period specified by the manufacturer.

Category C includes AHRS-grade inertial components where DO-334 category H1 gyro compassing is not possible and additional aiding for heading is typically needed. When GNSS is available, Category C can provide positioning, velocity and enhanced attitude/heading.

Note 1: During momentary GNSS disruptions, Category C systems may provide brief velocity and position coasting. Category C cannot provide position or velocity coasting for extended GNSS disruptions.

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The following Sub-categories are intended to describe the integrated fault detection capability of the GNSS-aided inertial system. The Sub-categories, zero (0), one (1) and two (2), are associated with each category (A, B, and C). These Sub-categories describe signal-in-space fault detection capabilities relative to a GNSS receiver that has been qualified to satisfy the requirements of an applicable GNSS receiver TSO. The intent for the Sub-categories is to differentiate how the equipment can support positioning operations.

Sub-category zero (0) GNSS integration provides no additional signal-in-space (SIS) fault detection-based integrity beyond what is provided by the GNSS receiver. This means the integrated system provides accuracy coasting only (i.e. horizontal figure of merit HFOM).

Note 2: The HFOM requirement is 95%. But manufacturers may claim an accuracy bound greater than 95% with additional substantiation.

Sub-category one (1) GNSS integration provides SIS fault detection-based integrity beyond what is provided by the GNSS receiver. This means that during operations where the GNSS receiver is not able to detect faulted satellites, the integrated system often maintains the satellite fault detection capability and continues to provide a horizontal protection level (HPL), a capability referred to as HPL based integrity coasting.

Sub-category two (2) GNSS integrations provide SIS fault detection-based integrity and exclusion-based continuity beyond what is provided by the GNSS receiver. This means that during operations where a faulted GNSS satellite is detected the equipment in this Sub-category maintains continuity by excluding the faulted satellite or if the satellite is no longer in use, removing the detection condition while bounding the resulting error from such a latent fault with the horizontal exclusion level (HEL). The bounding capabilities are summarized in Table 1-1.

Table 1-1: Summary of Bounding Capabilities

Sub-category	Position Bounding Capability
N/A	No position output
0	HFOM
1	HFOM & HPL
2	HFOM & HPL & HEL

Note 3: In all Sub-categories, this MOPS assumes the manufacturer is implementing good engineering practices for GNSS reasonableness checks such as step-detection, residual screening, etc.

The special case of GNSS aided inertial equipment not outputting position but providing parameters derived from integrated attitude or integrated velocity can still be covered under this MOPS based on the listed claims but the Sub-category 0, 1 or 2 would not be applicable i.e. Sub-category = N/A.

1.4 Goals

There are three goals depending upon the equipment categories described in Section 1.3:

1) providing a TSO certification path for traditional navigation grade, tightly-coupled GNSS/inertial systems compliant with 14 CFR Part 121 Appendix G;

2) defining requirements for GNSS-aided inertial systems with limited coasting capability in the absence of GNSS, that fills the gap between “traditional” AHRS with no navigation capability and “traditional” navigation grade GNSS/Inertial systems; and,

3) defining requirements for GNSS-aided inertial systems providing enhanced heading, velocity and/or attitude information.

A key operational difference for positioning within the Sub-categories is providing SIS integrity versus no SIS integrity. RNAV systems conform to the International Civil Aviation Organization (ICAO) performance-based navigation specification for total system error (TSE). Required Navigation Performance (RNP) systems as defined in DO-283 (MOPS for Required Navigation Performance for Area Navigation) conform to a performance-based navigation specification based on RNAV capability that also includes requirements for on-board performance monitoring and alerting. For further details see Section 3.

1.4.1 Goals for Category A and Category B

The intent for Category A and B equipment is to provide a certification baseline for GNSS aided inertial systems for use in performance based navigation. The goal for Category A and B equipment is to allow continued operation in the absence of sufficient GNSS aiding based on the calculated HFOM and HPL.

Category A equipment has been in existence for many years, but did not have a straight forward TSO path for certification. Typically, these tightly-coupled GNSS/inertial systems used the applicable GNSS sensor TSO requirements with the Appendix R guidance from either RTCA DO-229() or RTCA DO-316. These systems use navigation-grade components because they are intended to qualify as 14 CFR 121 Appendix G-compliant systems for long range oceanic operations. For Category A equipment, the goal is to provide an easier TSO certification path for such "traditional" systems by incorporating the Appendix R material into requirements and tests in this MOPS.

Category B equipment provides a certification path for GNSS aided inertial systems that use less expensive, less capable inertial components but still provide operationally useful coasting capabilities after loss of GNSS data. This Equipment Category bridges the gap between a DO-334 gyro-compassing AHRS with no navigation capability and the traditional 14 CFR 121 Appendix G compliant systems. Category B equipment may be able to provide inertial-only capability (without GNSS input) as well, but with higher position drift rates than Category A equipment.

For both Category A and B equipment, the position-coasting capability after loss of GNSS will be proven as part of the testing requirements contained in this document. The manufacturer will then specify the coasting limitations in their documentation package.

1.4.2 Goals for Category C

Category C equipment provides a certification path for GNSS-enhanced AHRS supplying position, velocity, and enhanced attitude and heading information. Category C uses inertial components that do not qualify for Category A or B. A key assumption for Category C equipment is sustained availability of GNSS aiding except for brief outages as specified by the manufacturer. The intent is to provide a lower-cost position, velocity and enhanced attitude/heading output to aircraft systems with sufficient short term coasting capability to bridge brief GNSS outages.

1.5 Definition of Key Terms

Refer to Appendix A for definition of key terms.

1.6 Assumptions

- Single-frequency (L1 C/A code) GPS-based sensors are the GNSS aiding source.

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- This MOPS will be updated when new standards exist for multi-frequency/multi-constellation sensors.
- GPS sensors meets the requirements of either TSO-C196(), TSO-C145() or TSO-C146().

Note 1: Manufacturers may incorporate a TSO-C206() circuit card assembly GPS sensor in their equipment provided they comply with the limitation to receive a TSO-C196() authorization on their final product.

- This MOPS does not address GNSS augmentation (i.e. SBAS or GBAS differential range corrections) under Sub-category 1 and 2.
- This MOPS assumes an external navigation performance monitor and alerting function (e.g. Required Navigation Performance (RNP) system).

Note 2: Manufacturers may use a TSO-C145()/C146() receiver in any integrated solutions as long as satellite measurement data (pseudoranges, delta ranges, etc. in standard measurement and navigation blocks) are not corrected by SBAS.

Note 3: It is acceptable to use measurement block parameters (see Appendix H) from TSO-C145() compliant GNSS receivers applying SBAS/GBAS corrections in integrated solutions for Sub-category 0 systems only. Manufacturers using such parameters will need to consider the time correlation of the GNSS outputs due to smoothing or filtering of ground-based and aircraft-based satellite measurements.

- AHRS meets the requirements of TSO-C201.

1.7 Aircraft Equipment Information Vulnerabilities

This document contains minimum performance standards for GNSS aided inertial systems and such systems rely on the correctness of the provided GNSS data which in this version of the MOPS is limited to GPS L1. Unintentional interference to GPS L1 above the standard interference mask are addressed in this MOPS but other types of disruptions, such as spoofing, are possible. Spoofing is caused by RF waveforms that mimic true signals in some ways, but deny, degrade, disrupt, or deceive a receiver's operation when they are processed. Spoofing may be unintentional, such as effects from the signals of a GPS re-radiator, or may be intentional and even malicious. There are two classes of spoofing. Measurement spoofing introduces RF waveforms that cause the target receiver to produce incorrect measurements of time of arrival or frequency of arrival or their rates of change. Data spoofing introduces incorrect digital data to the target receiver for its use in processing of signals and the calculation of Position, Navigation and Timing (PNT). Either class of spoofing can cause a range of effects, from incorrect outputs of PNT to receiver malfunction. The onset of effects can be instantaneous or delayed, and the effects can continue even after the spoofing has ended. Improperly used or installed GNSS re-radiators act like spoofers. Re-radiators replay and GNSS emulator devices can present misleading information to GNSS equipment and/or could cause lasting effects.

Equipment manufacturers should implement measures to mitigate processing of erroneous data. Cross-checks of GNSS sensor data against independent position sources and/or other detection monitors using GNSS signal metrics or data checks, can be implemented in the antenna, receiver, and/or through integration with other systems at the aircraft level. Data validity checks to recognize and reject measurement and data spoofing should be implemented in the receiver. Additional guidance and best practices related to GPS equipment can be found in the U.S. Department of Homeland Security document "Improving the Operation and Development of Global Positioning System (GPS) Equipment Used by Critical Infrastructure"[1] and IS-GPS-200 Revision H, IRN003 28 July 2016.

Aircraft equipment information vulnerabilities (such as cybersecurity risks) have been present for digital systems since the development of the personal computer (PC) in the late 1970's and even longer for RF systems, and the advent of internet connectivity has substantially increased those risks. Typically, access to navigation receivers has been controlled such that they are considered vulnerable only through RF signals and OEM and/or aircraft operator controlled processes for maintenance and update. However, it is expected that not all aircraft in the future will rely on such physical isolation for the security of avionics. Internet and Wi-Fi connectivity have become popular as a means for aircraft or equipment manufacturers to update installed avionics software, to update databases, or provide an alternate means of communicating with the flight crew or cabin (e.g. in-flight entertainment, weather, etc.).

In most countries, the State provides oversight of safety-of-flight systems (sometimes referred to as "authorized services") which provide information to aircraft, such as ILS, VOR, GNSS, and DME, to name a few. However, the State typically does not provide oversight on "non-trusted"[2] connectivity such as the internet, Wi-Fi, or manufacturer-supplied equipment interfaces which permit input of externally-supplied data into aircraft systems. A manufacturer may expose aircraft information vulnerability through equipment design, or become vulnerable as a result of being connected to a common interface. Therefore, it is important that manufacturers consider aircraft information security risk mitigation strategies in their equipment design, particularly when the equipment is responsible for an interface between the aircraft and aircraft-external systems.

Apart from any specific aircraft-information-security-related performance requirements that are contained in these MOPS, it is recommended that manufacturers look at a layered approach to aircraft information security risk mitigation that includes both technical (e.g. software, signal filtering) and physical strategies. From a technical perspective, for example, this could include signal spoofing detection capabilities or more stringent, multi-factored authentication techniques such as passwords, PINs, and digital certificates. From a physical perspective, a manufacturer could consider connectors that require special tools to remove to prevent passenger tampering; although, navigation avionics are typically located in an avionics bay inaccessible to passengers. And finally, but just as important, manufacturers should consider supply chain risk management; for example, if a manufacturer is outsourcing software code development, is the contractor and its staff properly vetted?

Civil Aviation Authorities (CAAs) have a regulatory interest when an applicant's design makes use of a non-trusted connectivity where the installation can potentially introduce aircraft information security vulnerability. This requires the applicant to address not only the information security vulnerabilities and mitigation techniques for the new installation, but to also consider how vulnerability could propagate to existing downstream systems. Therefore, it is recommended that manufacturers reference their equipment aircraft information security review and mitigation strategies in the equipment's installation manual so that the applicant can consider them in meeting the installation regulatory requirements.

[1]https://ics-cert.us-cert.gov/sites/default/files/documents/Improving_the_Operation_and_Development_of_Global_Positioning_System_(GPS)_Equipment_Used_by_Critical_Infrastructure_S508C.pdf (valid as if publication)

[2] A "non-trusted" connectivity (sometimes referred to as third-party system) is any frequency or service where an Air Navigation Service Provider (ANSP) is not providing direct monitoring/protection

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