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Minimum Operational Performance Standards (MOPS) for Dual-Frequency Multi-Constellation Satellite-Based Augmentation System Airborne Equipment

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FOREWORD

This document was prepared by Special Committee 159 (SC-159) jointly with EUORCAE Working Group 62 and approved by the RTCA Program Management Committee (PMC) and the EUROCAE Council on September 21, 2023. Errata inclusion Errata inclusion was prepared by RTCA Secretariat and the content reviewed by the RTCA PMC on January 31, 2024. Coordination has been achieved with EUROCAE. This errata version only affects the DO-401 and corrects publication errors in the initial publication.

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EXECUTIVE SUMMARY

EUROCAE/ED-259 was originally prepared by EUROCAE Working Group 62. It was approved by the Council of EUROCAE on 15 February 2019.

This document ED-259A/DO-401 was prepared jointly by EUROCAE Working Group 62 "GNSS" and RTCA Special Committee 159 (SC-159) Working Group 2 "GPS/SBAS".

This document is the avionics standards for GPS/Galileo/SBAS equipment supporting Required Navigation Performance (RNP) en route and terminal operations, departure operations, RNP APCH (approach) down to Localizer Performance with vertical guidance (LPV) minima and Automatic Dependent Surveillance - Broadcast (ADS-B).

Compared to EUROCAE/ED-259, this document:

- Integrates and updates the single frequency (L1) GPS and SBAS requirements of RTCA DO-229F MOPS;
- Integrates and updates the Class Gamma and Class Delta equipment requirements of RTCA DO-229F MOPS;
- Provides robustness requirements against jamming and spoofing threats, including radio-frequency interference detection;
- Defines RNP APCH operations to Localizer Performance without vertical guidance (LP) and LPV minima accounting for the updated Final Approach Segment Data Block (FAS DB) definition;
- Defines the interference environment;
- Describes the test procedures.

This document is meant to support validation of airborne requirements supporting above mentioned operations when using Dual Frequency GPS, Galileo and SBAS signals as defined by International Civil Aviation Organization (ICAO) Standards and Recommended Practices (SARPs) (Annex 10, Volume I, Amendment 93), as well as the development of Dual-Frequency Multi-Constellation (DFMC) SBAS services. This document does not provide specifications for a production approval.

A future release of the document will provide requirements supporting production approval, typically through a new Technical Standard Order (TSO) or European Technical Standard Order (ETSO). It will address the following expected functions of future DFMC SBAS equipment:

- Navigation in degraded environment (single-frequency L5 mode);
- Horizontal Advanced Receiver Autonomous Integrity Monitoring (H-ARAIM) for new signals;
- Management of the institutional scenarios.

Additional information of this document is in supplement "DO-401_Supplement.zip".

The following items are integrated into this release to correct publication errors in the initial publication:

- Updated Table of Contents to correctly match page numbers and added to 4 levels for sections
- Updated Table of Figures to correctly match page numbers
- Updated Table of Tables to correctly match page numbers
- Corrected all “Chapter” references to “Sections”
- Restore all subscription and superscription text
- Adjusted “Note” formatting to align with EUROCAE’s formatting for referencing consistencies
- Corrected double section 1.1 number and the following subsection numbers.
- Adjusted formatting of requirement numbering to bold for designators requirements and italic for equipment class requirements.

No other content or technical content was changed.

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1 GENERAL

1.1 PURPOSE AND SCOPE

This document contains Minimum Operational Performance Standards (MOPS) for Dual-Frequency Multi-Constellation (DFMC) Satellite-Based Augmentation System (SBAS) airborne equipment. This standard specifies the minimum performance expected from airborne equipment using GPS, Galileo (GAL) and SBAS, for both single-constellation and dual-constellation modes.

This document is meant to support validation of airborne equipment requirements, as well as the development of DFMC SBAS services. This document does not provide specifications for a production approval.

A future release will provide requirements supporting production approval, typically through a new Technical Standard Order (TSO) or European Technical Standard Order (ETSO). It will address the expected functions of future DFMC SBAS equipment including navigation in degraded environment (single-frequency L5 mode), Horizontal Advanced Receiver Autonomous Integrity Monitoring (H-ARAIM) for new signals, and management of the institutional scenarios.

Compliance with this standard is recommended as one means of assuring that the equipment will perform its intended functions satisfactorily under all conditions normally encountered in routine aeronautical operation.

A future release of this document will ensure that equipment compliant to it will get the necessary regulatory approval (this is generally facilitated by the recognition of such standard by the relevant authorities as an acceptable means of compliance with the applicable regulations).

The word “equipment” as used in this document includes all components and units necessary for the system to properly perform its intended function(s).

The document is structured as follows:

Section 1 provides definitions and information required to understand the equipment characteristics and tests defined in the remaining sections. It describes typical equipment applications and operational objectives and is the basis for the performance criteria stated in Section 2 through 4.

Section 2 contains general design requirements.

Section 3 contains the minimum performance specification for the equipment, defining performance under standard operating conditions.

Section 4 prescribes the environmental test conditions, and provides a laboratory means of determining the overall performance characteristics of the equipment under conditions representative of those which can be encountered in actual operations.

Section 5 describes recommended test procedures for demonstrating compliance with Sections 3 and 4.

Section 6 specifies the performance required of the installed equipment. Ground and flight tests for the installed equipment are included when performance cannot be adequately determined through testing under laboratory test conditions.

Section 7 lists some considerations for Aircraft Operational Performance Characteristics.

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Appendix A is normative: it contains the SBAS L5 signal specification.

Appendix B is normative: it contains the SBAS L1 signal specification.

Appendix C is normative: it specifies the interference environment.

Appendix D is normative: it specifies the baseline weighted algorithm for navigation and approach when using SBAS L1 or SBAS L5-provided integrity monitoring.

Appendix E is normative: it specifies the required methods of calculating SBAS L1 and SBAS L5-based protection levels, based upon the data in the SBAS L1 or SBAS L5 messages.

Appendix F is normative: it contains GPS and Galileo assumptions. It also provides the GPS and Galileo almanacs for testing, and an example of SBAS almanac broadcast in SBAS L1 and SBAS L5 message formats.

Appendix G is normative: it specifies the parameters broadcast by GPS and Galileo satellites that cannot be used by the equipment for the determination of positioning outputs that are compliant with this MOPS.

Appendix H is normative: it specifies the data format to support straight landing approach operations.

Appendix I is normative: it specifies the tropospheric correction model to apply with SBAS L1-provided integrity monitoring for Required Navigation Performance Approach (RNP APCH) to Lateral Navigation / Vertical Navigation (LNAV/VNAV), Localizer Performance without vertical guidance (LP) and Localizer Performance with vertical guidance (LPV) minima operations, and with SBAS L5-provided integrity monitoring.

Appendix J is normative: it specifies the single-frequency ionospheric correction model that can be used as an alternative to the GPS-based model. The model is optional under this MOPS.

Appendix K is reserved for the GPS and Galileo Integrity Support Data (ISD) specifications.

Appendix L is normative: it specifies the requirements when using barometric altimeter to aid GPS Receiver Autonomous Integrity Monitoring / Fault Detection and Exclusion (RAIM/FDE), which is optional under this MOPS.

Appendix M is informative: it contains background materials for testing.

Appendix N is informative: it provides guidance for determining Mean Sea Level (MSL) height from WGS-84 coordinates.

Appendix O is informative: it contains information on the SBAS approach concept developed to handle SBAS operations in a Dual-Frequency Multi-Constellation operational environment.

Appendix P is informative: it provides a typical navigation mode switching flow diagram from the terminal area to the approach. The intent is to aid in understanding the mode switching requirements for Class Gamma equipment.

Appendix Q is informative: it contains SBAS considerations for helicopters.

Appendix R is reserved.

Appendix S is informative: it contains process flow diagrams intended to be an example of the computation and logic flow that meets requirements for the possible operational modes.

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It is not intended to show all possible implementations. Instead, a representative implementation is shown with reference to the applicable requirements.

Appendix T is normative: it specifies how to use the tool provided in Supplement 2 (see below) to determine Geostationary Satellite (GEO) bias error in receiver correlator designs. This tool is used to demonstrate receivers meet the GEO bias requirement in this MOPS.

Appendix U is reserved for additional elements on SBAS L5 signals for non-geostationary satellites.

Appendix V is informative: it provides guidance to compute velocity and velocity figure of merit, and to support Automatic Dependent Surveillance - Broadcast (ADS-B) applications.

Appendix W is informative: it describes the classifications for spoofing signals.

Appendix X is reserved for ionosphere scintillation.

Appendix Y is informative: it contains glossary and acronyms.

Appendix Z is informative: it lists substantive items resulting from the OC/FRAC for this version that need to be considered for a future release of this MOPS.

Appendix AA is informative: it lists the members of RTCA SC-159 and EUROCAE WG-62.

The supplement for this document contains six files:

- Supplement 1: “DO-229F to ED-259A DO-401 Traceability.xlsx”. It contains the cross-reference matrix between the DO-229F tagged requirements and untagged recommendations and options, and this MOPS requirements, recommendations and options.
- Supplement 2: “ED-259A DO-401 GEO Bias MATLAB Tool.zip”. It contains the MATLAB scripts to compute the GEO bias errors, as explained in Appendix T.
- Supplement 3.1: “Test_IQ_USFL100_Fc1157_Fs78MHz.mat”. It is the I/Q testing signal file in MATLAB format corresponding to the Low Altitude pulsed interference scenario.
- Supplement 3.2: “Test_IQ_USFL100_Fc1157_Fs78MHz_scaling_factor6.8806e-4.bin”. It is the I/Q testing signal file in binary format corresponding to the Low Altitude pulsed interference scenario.
- Supplement 4.1: “Test_IQ_EUFL400_Fc1157_Fs78MHz.mat”. It is the I/Q testing signal file in MATLAB format corresponding to the High Altitude pulsed interference scenario.
- Supplement 4.2: “Test_IQ_EUFL400_Fc1157_Fs78MHz_scaling_factor6.802e-4.bin”. It is the I/Q testing signal file in binary format corresponding to the High Altitude pulsed interference scenario.

Note: For Supplements 3.1, 3.2, 4.1 and 4.2, see Appendix M.5 for further details.

1.2 APPLICATIONS

Compliance with this document by manufacturers, installers and users is recommended as a means of assuring that the equipment will satisfactorily perform its intended function(s) under all conditions normally encountered in routine aircraft (A/C) operations.

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Any regulatory application of this document in whole or in part is the sole responsibility of appropriate government agencies.

As the measured values of equipment performance characteristics can be a function of the method of measurement, standard test conditions and methods of test are recommended in this document.

1.2.1 USE OF SPECIFYING TERMS AND ASSOCIATED TAGGING

The following definitions are provided for terms used in the document:

- The term “shall” is used to indicate requirements. An approvable design will satisfy every minimum requirement applicable to its equipment class. This MOPS defines both minimum requirements and requirements associated with optional capabilities. If an option is implemented, then the requirements associated with that option also apply. The design is verified by analysis, demonstration, inspection, or test (see Section 5.2).
- The term “should” is used to indicate recommendations. Contrary to requirements, the implementation of recommendations is not mandatory to comply with the minimum operational performance defined by this standard. When implemented, the verification of the design is up to the manufacturer.
- The term “will” is used to indicate assumptions, or items which 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 “may” is used to indicate options. It denotes an optional implementation at the manufacturer’s discretion.

All requirements, recommendations, options, and requirements associated with each option are designated with unique identification tags in this document as specified below. Assumptions are not tagged.

Requirement Identification Tag: Requirements are uniquely tagged as “[DMS:xxx]”. The requirement tag includes:

a) the leading and closing square brackets “[ ]”; and

b) the prefix “DMS”, which is an acronym for Dual-Frequency Multi-Constellation SBAS, to indicate that it is a requirement in this MOPS; and

c) the separator “:”; and

d) a three-digit number “xxx” that is unique for each requirement in this MOPS.

Recommendation Identification Tag: Recommendations are uniquely tagged as “[DMS-R:xxx]”. The recommendation tag includes:

a) the leading and closing square brackets "[ ]"; and

b) the prefix "DMS-R" to indicate that it is a recommendation in this MOPS; and

c) the separator ":"; and

d) a three-digit number "xxx" that is unique for each recommendation in this MOPS.

Option Identification Tag: Options are uniquely tagged as "[DMS-O:xxx]". The option tag includes:

a) the leading and closing square brackets "[ ]"; and

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b) the prefix "DMS-O" to indicate that it is an option in this MOPS; and

c) the separator ":"; and

d) a three-digit number "xxx" that is unique for each option in this MOPS.

Requirement Associated with an Option Identification Tag: Requirements associated with an option are uniquely tagged as "[DMS-O:xxx.yyy]". This tagging is used when an option defined in this MOPS includes "shall" requirements associated with implementing that specific option. The requirement associated with an option tag includes:

a) the leading and closing square brackets "[ ]"; and

b) the prefix with the separator "DMS-O:"; and

c) the option number "xxx"; and

d) the period separator "."; and

e) a three-digit number "yyy" that is unique for each requirement associated with option "xxx" as defined in this MOPS.

When implemented, these optional requirements are also verified by analysis, demonstration, inspection, or test (see Section 5.2).

1.3 DESCRIPTION OF SYSTEM

Global Navigation Satellite System (GNSS) includes sets of core satellite constellations that provide ranging signals which can be used to provide worldwide position and time determination. Four GNSS core constellations are considered for civil aviation including: the Global Positioning System (GPS), the Global Orbiting Navigation Satellite System (GLONASS), Galileo (GAL), and the BeiDou Navigation Satellite System (BDS). While GNSS potentially includes these four core constellations, this document defines requirements for aircraft equipment that is capable of receiving GPS and Galileo core constellation signals on dual centre frequencies of L1/E1 and L5/E5a.

Satellite-Based Augmentation Systems (SBAS) are regional differential systems that provide augmentation information for GNSS. This MOPS defines requirements for airborne equipment that is capable of receiving SBAS signals on both L1 and L5 centre frequencies.

Each SBAS is a safety critical system consisting of a network of ground-based reference stations, processing and control facilities, and satellites. The ground network is composed of reference receivers that monitor ranging signals from the satellites of interest. The collected data are forwarded to a central computing facility that calculates satellite orbit and clock corrections, possibly ionospheric delay corrections, and integrity information. The SBAS broadcasts the values to the airborne user equipment through a satellite link, the information being modulated on GPS-like signals. The airborne element receives GNSS ranging signals and the correction and integrity information, and applies them in the process of calculating a navigation solution. Integration of the airborne element into an airframe permits use of the navigation solution (position and protection level) for navigation, guidance, and surveillance information, enabling en route through RNP APCH to LPV minima operations while supporting surveillance applications such as Automatic Dependent Surveillance-Broadcast (ADS-B).

The SBAS can provide two different services that are independent from each other: the legacy L1 SBAS service and the DFMC SBAS service.

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The L1 SBAS service is based on the monitoring and augmentation of GPS L1 C/A signals and possibly SBAS L1 ranging signals. The satellite orbit and clock corrections, ionospheric corrections and integrity data are provided by SBAS L1 signals, which are L1 C/A-code signals broadcast by geostationary satellites. The characteristics of the L1 SBAS service and SBAS L1 signal are fully specified in the International Civil Aviation Organization (ICAO) Standards and Recommended Practices (SARPs) (Annex 10 Volume I, Amendment 93). This MOPS provides the requirements for using augmentation provided by L1 SBAS service with DFMC SBAS user equipment. Supplement 1 provides a mapping for the requirements in this MOPS and DO-229F, the Minimum Operational Performance Standards for legacy single-frequency L1 GPS/SBAS airborne equipment.

The DFMC SBAS service is based on the monitoring and augmentation of dual-frequency signals from one to four core constellations (GPS, GLONASS, GAL, and BDS) and possibly SBAS satellites. The resulting differential correction and integrity data are provided by SBAS L5 signals which are GPS L5 like signals broadcast by geostationary SBAS satellites.

DMFC SBAS service has several notable differences with legacy L1 SBAS service:

- First, the airborne equipment has to use two frequencies from the ranging sources. Together these signals permit use of an ionosphere-free pseudo-range measurement, thereby removing the largest source of uncertainty in the L1 SBAS service. Use of dual-frequency essentially shifts the responsibility of ionospheric delay mitigation from ground-based corrections to direct mitigation by the airborne user equipment. Instead of requiring both satellite corrections and ionospheric corrections as in single frequency for RNP APCH to LNAV/VNAV, LP and LPV minima, the DFMC SBAS service only needs to provide the satellite clock and orbit corrections. This design feature improves robustness against ionospheric delay and delay variation caused by space weather, but remains sensitive to ionosphere scintillation.
- Second, an inherent part of the SBAS L5 signal in space design is the capability to augment all satellites from one to four core constellations. This design feature allows augmentation of a larger number of satellites, and thus improves robustness against poor satellite geometry.

DFMC SBAS user equipment will operate in an environment with satellite-based augmentation systems providing the L1 SBAS service, both the L1 SBAS service and the DFMC SBAS service, or the DFMC SBAS service. In the case of the DFMC SBAS service, the nature and number of augmented core constellations will differ from one SBAS to the other.

DFMC SBAS user equipment will also be able to operate without SBAS augmentation, using legacy RAIM Aircraft Based Augmentation System (ABAS) with single L1 frequency ranging signals from GPS constellation.

DFMC SBAS user equipment improves robustness against abnormal radio frequency interferences:

- Regarding radio frequency interference, this MOPS introduces a detection capability to enable the downlink of the detection information to Air Navigation Service Provider (ANSP) / Air Traffic Control (ATC), and to support flight crew awareness on board the aircraft if the aircraft integrator elects to do so;

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- Regarding jamming, this MOPS introduces requirements and test procedures to prevent the output of inconsistent information when exposed to the threat, and to return to normal after the threat. A future release will introduce the capability to provide a navigation solution when only L5 signals are available;
- Regarding spoofing, when exposed to repeaters (S1), errant signals (S2), collateral spoofers (S3), and re-radiator collateral spoofers (S4), this MOPS requires and provides test procedures to prevent the output of inconsistent information and to return to normal after the threat. Regarding the robustness of the equipment against targeted spoofers (S5), re-radiator targeted spoofers (S6), and targeted sophisticated spoofers (S7), a claim table is expected to be filled with test results. The categories for spoofers are described in Appendix W.

This MOPS provides the performance requirements for DFMC SBAS user equipment that would elect to operate without SBAS augmentation, using ABAS (RAIM/FDE) augmenting GPS in L1 single frequency mode.

A future release will integrate the requirements for the advanced ABAS called Advanced Receiver Autonomous Integrity Monitoring (ARAIM)/FDE augmenting GPS or GPS and Galileo in single and dual frequency mode.

Note:

1. *The optional use of barometric altimeter aiding with RAIM/FDE is described in Appendix L*
2. *GPS L1 aided inertial systems are fully described in DO-384.*

1.4 COMPOSITION OF EQUIPMENT

The DFMC SBAS user equipment is identified with its functional and operational classes in Section 1.8.

1.5 DEFINITION AND ABBREVIATIONS

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

1.5.1 GENERAL TERMS

Accuracy: Statistical characterization of the difference between an estimated quantity (such as GNSS-estimated position, velocity, time, or track angle) and its true value over a population of independent samples and assuming fault free conditions. Statistical characterizations include the root-mean-square (RMS) and the 95^{th} percentile accuracy threshold. For example, the probability that the difference between estimated position and actual position is less than or equal to its required 95% accuracy threshold will be at least 95%.

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, assuming fault-free airborne equipment. Availability is an indication of the ability of the system to provide usable service within the specified coverage area.

Signal availability is the expected fraction of time that navigational signals transmitted from external sources are available for use: it does not assure that any given service is supported.

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Service availability is the expected fraction of time that a particular service (operation such as RNP APCH to LPV minima) is supported.

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 is available at the beginning of that phase of operation and will operate throughout the operation.

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

Vertical Figure of Merit: The VFOM or $VFOM_P$ bounds the vertical positioning error with at least a 95% probability under fault-free conditions at the time of applicability.

Horizontal Figure of Merit – Velocity: The $HFOM_V$ bounds the horizontal velocity estimation error with at least a 95% probability under fault-free conditions at the time of applicability.

Vertical Figure of Merit – Velocity: The $VFOM_V$ bounds the vertical velocity estimation error with at least a 95% probability under fault-free conditions at the time of applicability.

Integrity: Integrity is a measure of the confidence that can be placed in the correctness of the information supplied by the total system. For the purpose of this document, the integrity probabilities specified assume fault-free airborne equipment. The airborne equipment design assurance requirements in this MOPS along with the aircraft system design and certification processes control the integrity risk associated with non-fault-free airborne equipment to an acceptable level commensurate with the intended operations that the equipment is approved to support. Integrity includes the ability of a system to provide timely and valid warnings to the user (alerts) when the system cannot be used for the intended operation (or phase of flight).

Integrity Monitoring: The integrity monitoring refers to the algorithm used to provide protection levels (HPL/VPL) and/or alerts associated with the computed position. The integrity monitoring specified in this document is:

a) FDE-provided (using either RAIM algorithm with GPS L1 and SBAS L1 ranging signals or an alternate ABAS algorithm with GPS and/or Galileo ranging signals on L1 and/or L5 frequencies), providing horizontal protection level HPL_{FD}; or

b) SBAS L1-provided (using SBAS L1 augmentation and associated algorithms with GPS L1 and SBAS L1 ranging signals), providing horizontal and vertical protection levels HPL_{SBAS} and VPL_{SBAS}; or

c) SBAS L5-provided (using SBAS L5 augmentation and associated algorithms with GPS L1/L5 ranging signals and/or Galileo E1/E5a ranging signals and/or SBAS L1/L5 ranging signals), providing horizontal and vertical protection levels HPL_{DFSBAS} and VPL_{DFSBAS}.

Mask Angle: A fixed elevation angle referenced to the user's horizon below which satellites are not used in the generation of the position solution by the equipment.

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Misleading Information: Within this standard, misleading information is defined to be any data that is output to other equipment or displayed to the pilot that has an error larger than the alert limit (HAL/VAL) or current protection level (HPL/VPL), without any indication of the error (e.g., flag) within the time-to-alert for the applicable phase of flight. For equipment that is aware of the navigation mode (typically Class Gamma and Class Delta equipment), and therefore the alert limit, misleading information is defined relative to the alert limit. If the equipment is not aware of the mode (typically Class Beta equipment), then misleading information is defined relative to the protection level, since the alert limit is not known. This includes all output data, such as position, non-numeric cross-track, numeric cross-track, and distance-to-waypoint as applicable.

Navigation Mode: The navigation mode refers to the equipment operating to meet the requirements for a specific phase of flight. The navigation modes are: oceanic/remote, en route, terminal, and approach (including RNP APCH to LNAV, LNAV/VNAV, LP, and LPV minima). Departure guidance is provided by Class 1, 2, and 3 equipment in the terminal mode.

SBAS: International name used in the ICAO Navigation Systems Panel (NSP) Standards and Recommended Practices (SARPs) for a set of programs such as Wide Area Augmentation System (WAAS), European Geostationary Navigation Overlay Service (EGNOS), MTSAT Satellite based Augmentation System (MSAS), and GPS Aided GEO Augmentation Navigation (GAGAN), that use satellites to transmit GNSS integrity and correction data.

1.5.2 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 centre being at the true position, which specifies the region required to contain the indicated horizontal position with the required probability for a particular navigation mode (e.g., $1\text{-}10^{-7}$ per flight hour for en route).

Vertical Alert Limit: The Vertical Alert Limit (VAL) is half the length of a segment on the vertical axis (perpendicular to the horizontal plane of WGS-84 ellipsoid), with its centre being at the true position, which specifies the region required to contain the indicated vertical position with the required probability for a particular navigation mode. For example, for approaches to CAT-I minima, the cylinder, whose centre is at the true position, whose horizontal radius is the HAL and whose vertical extent is twice the VAL, is required to contain the indicated position with a probability of $1\text{-}2\times10^{-7}$ per approach.

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 centre being at the true position, which specifies the region assured to contain the indicated horizontal position. It is a horizontal region for which the missed alert and false alert requirements are met for the chosen set of satellites. It is 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 given reasonable assumptions regarding the expected error characteristics.

Horizontal Protection Level$_{SBAS}$: The Horizontal Protection Level$_{\text{SBAS}}$ (HPL_{SBAS}) is the radius of a circle in the horizontal plane (the local plane tangent to the WGS-84 ellipsoid), with its centre being at the true position, which specifies the region assured to contain the indicated horizontal position. It is the horizontal region for which the missed alert

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requirement can be met. It is based upon the error estimates provided by SBAS L1 using GPS L1 and GEO SBAS L1 single-frequency measurements.

Horizontal Protection Level$_{DFSBAS}$: The Horizontal Protection Level$_{\text{DFSBAS}}$ (HPL_{DFSBAS}) is the radius of a circle in the horizontal plane (the local plane tangent to the WGS-84 ellipsoid), with its centre being at the true position, which specifies the region assured to contain the indicated horizontal position. It is the horizontal region for which the missed alert requirement can be met. It is based upon the error estimates provided by SBAS L5 using a combination of GPS L1/L5, GAL E1/E5a, and/or GEO SBAS L1/L5 dual-frequency measurements.

Vertical Protection Level$_{SBAS}$: The Vertical Protection Level$_{\text{SBAS}}$ (VPL_{SBAS}) is half the length of a segment on the vertical axis (perpendicular to the WGS-84 ellipsoid), with its centre being at the true position, which specifies the region assured to contain the indicated vertical position. It defines the vertical region where the missed alert requirement can be met. It is based upon the error estimates provided by SBAS L1 using GPS L1 and GEO SBAS L1 single-frequency measurements.

Vertical Protection Level$_{DFSBAS}$: The Vertical Protection Level$_{\text{DFSBAS}}$ (VPL_{DFSBAS}) is half the length of a segment on the vertical axis (perpendicular to the WGS-84 ellipsoid), with its centre being at the true position, which specifies the region assured to contain the indicated vertical position. It defines the vertical region where the missed alert requirement can be met. It is based upon the error estimates provided by SBAS L5 using GPS L1/L5, GAL E1/E5a, and/or GEO SBAS L1/L5 dual-frequency measurements.

Horizontal Uncertainty Level: The Horizontal Uncertainty Level (HUL) is an estimate of horizontal position uncertainty, based on measurement inconsistency, which bounds the true error with high probability (at least 99.9 percent). This estimate will not be available when there is no redundancy (number of measurements less than or equal to the number of unknowns).

Horizontal Exclusion Level$_{Fault\ Detection}$: The Horizontal Exclusion Level$_{\text{Fault Detection}}$ (HEL_{FD}) is the radius of a circle in the horizontal plane, for which 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.

1.5.3 FAULT DETECTION AND EXCLUSION (FDE) TERMS

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 GNSS equipment when the positioning performance achieved by the equipment does not meet the integrity requirements.

Positioning Failure: A positioning failure is defined to occur whenever the difference between the true position and the indicated position exceeds the applicable protection level (either horizontal or vertical, as applicable). If the equipment is aware of the navigation mode/alert limit, a positioning failure is also defined to occur whenever the difference between the true position and the computed position exceeds the applicable alert limit.

Time-To-Alert: Time-to-Alert is the maximum allowable elapsed time from the onset of a positioning failure until the equipment annunciates the alert.

Fault Detection and Exclusion (FDE): Fault detection and exclusion is a receiver processing scheme that autonomously provides integrity monitoring for the position

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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.

Missed Detection: A missed detection is defined to occur when the FDE algorithm does not detect a positioning failure within the time-to-alert.

Failed Exclusion (exclusion not possible): A failed exclusion is defined to occur when a detection occurs (i.e., a detection flag is raised) but the condition leading to the detection is not excluded within the time-to-alert (from the onset of the positioning failure), leading to a navigation alert.

Wrong Exclusion: A wrong exclusion is defined to occur when detection occurs and a positioning failure exists after exclusion. A wrong exclusion can result in a missed alert when the positioning failure is undetected, or in a navigation alert when the positioning failure remains detected after exclusion.

Missed Alert: Positioning failures which are not annunciated (as an alert) within the time-to-alert are defined to be missed alerts. Both missed detection and wrong exclusion conditions can cause missed alerts after the time-to-alert expires.

False Detection: A false detection is defined as the detection of a positioning failure when a positioning failure has not occurred. It is internal to the GNSS equipment.

False Alert: A false alert is defined as the indication of a positioning failure when a positioning failure has not occurred (a result of false detection). A false alert would cause a navigation alert.

Availability of Detection: The detection function is defined to be available when the satellites provide a geometry for which the missed alert and false alert requirements can be met on all satellites being used for the applicable alert limit and time-to-alert. When the constellation is inadequate to meet these requirements, the fault detection function is defined to be unavailable. Thus the availability of detection for a specific location, time, constellation and horizontal alert limit (HAL) is defined to be:

$$Detection\ Availability\ (X, t, Const, HAL) = \prod_{i=1}^{N} D(i) \qquad (1\text{-}1)$$

where

- N = number of satellites being used in the navigation solution
- $D(i)$ = 1 if Probability(detection given error in ith satellite causing positioning error equal to HAL) ≥ the detection requirement and Probability(false alert) ≤ the false alert rate requirement, and 0 otherwise.

Note that for a given geometry and navigation mode, the detection function is either available or unavailable.

Note: The detection function is expected to operate whenever sufficient measurement redundancy exists, regardless whether or not it is "available" for the selected navigation mode by the definition above. Therefore, it can temporarily operate when the missed alert rate is greater than required for the appropriate alert limit (i.e., HPL>HAL), but the false alert rate will continue to meet requirements.

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Availability of Exclusion: The exclusion function is defined to be available when the satellites provide a geometry for which the RAIM/FDE algorithm can meet the failed exclusion requirement, and prevent the indication of a positioning failure or a loss of integrity monitoring function. Therefore, exclusion has to occur before the duration of a positioning failure exceeds the time-to-alert, and the detection function as defined above has to be available after exclusion.

Note that for a given geometry and a given failed satellite, the success of the exclusion function to prevent an alert condition (duration of positioning failure exceeds time-to-alert) can be probabilistic. For example: given a particular exclusion algorithm, a satellite geometry, and a failed satellite, the algorithm could have a 99% probability of successfully preventing an alert condition. However, the exclusion function is only defined to be available if the probability of excluding a satellite and preventing an alert (given a satellite failure has occurred and has been detected) satisfies the failed exclusion requirement. Thus the availability of exclusion for a specific location, time, constellation and HAL is defined to be:

$$Exclusion\ Availability\ (X, t, Const, HAL) = \prod_{i=1}^{N} E(i) \qquad (1\text{-}2)$$

where

- N = the number of satellites being used in the navigation solution
- $E(i) = 1$ if Probability(Failed exclusion) $\leq 10^{-3}$ and detection still available after exclusion, given i^{th} satellite failed, and 0 if Probability(Failed exclusion) $> 10^{-3}$ or detection not available given i^{th} satellite failed.

Note that for a given geometry and navigation mode, the exclusion function is either available or unavailable.

Note: The fact that the definition of exclusion availability states that detection is required to be available after exclusion occurs is only intended to be used as a comparison of algorithmic availability. There can be significant operational benefit gained by an algorithm that is designed such that it is capable of excluding even when detection is not available after exclusion. However, such an algorithm still has to meet the missed alert (including wrong exclusion) requirement on a per failure basis. In other words, there has to be a means of demonstrating that, when exclusion is attempted without subsequent detection, the equipment excludes the correct satellite with a probability of at least 0.999 (a 0.001 probability of missed alert).

1.5.4 ADDITIONAL TERMS

Arctangent: in the document, $atan2(y, x)$ function is the four-quadrant arctangent function defined as follows:

$$atan2(y,x) = \begin{cases} atan\left(\frac{y}{x}\right) & if\ x > 0 \\ atan\left(\frac{y}{x}\right) + \pi & if\ x < 0\ and\ y \geq 0 \\ atan\left(\frac{y}{x}\right) - \pi & if\ x < 0\ and\ y < 0 \\ +\frac{\pi}{2} & if\ x = 0\ and\ y > 0 \\ -\frac{\pi}{2} & if\ x = 0\ and\ y < 0 \\ undefined & if\ x = 0\ and\ y = 0 \end{cases} \quad (1\text{-}3)$$

Note: The above $atan$ *function output belongs to* $[-\frac{\pi}{2}; +\frac{\pi}{2}]$.

Default Navigation Data (DND): Default L1 LNAV data is a sequence of alternating ones and zeros in bits 61 through 298, beginning with a one, with the two trailing bits of the subframe (bits 299 and 300) set to zeros. Replacing navigation data by DND in L1 LNAV subframe 1, 2 or 3 is a signal alarm condition.

E1 I/NAV navigation message: Open Service navigation data transmitted by Galileo satellites on E1-B signals. The content and characteristics of the I/NAV data are given in GAL OS-SIS-ICD Issue 2.0.

E5a F/NAV navigation message: Open Service navigation data transmitted by Galileo satellites on E5a-I signals. The content and characteristics of the F/NAV data are given in GAL OS-SIS-ICD Issue 2.0.

Inequalities: in the document, "x strictly less than y" corresponds to notation x < y, "x less than or equal to y" corresponds to notation x ≤ y, "x strictly greater than y" corresponds to notation x > y and "x greater than or equal to y" corresponds to notation x ≥ y.

Interference: Interference arises from RF waveforms that raise the effective noise floor in the receiver processing, thus degrading or denying a receiver's ability to operate.

L1/E1 frequency band: 1575.42 MHz ± 12 MHz frequency band.

L5/E5a frequency band: 1176.45 MHz ± 12 MHz frequency band.

L1 LNAV navigation message: Legacy navigation data transmitted by GPS satellites on L1 C/A-code signals and assigned to the PRN numbers (PRN 1-63). The content and characteristics of the L1 LNAV data are given in Appendix II of IS-GPS-200K for PRN 1 to 32 and Appendix IV of IS-GPS-200K for PRN 33 to 63.

L5 CNAV navigation message: Civil navigation data transmitted by GPS satellites on L5-I5 signals. The content and characteristics of the L5 CNAV data are given in Appendix II of IS-GPS-705F.

Repetitive Message Type (MT) 0: In test mode, an SBAS signal (PRN) will transmit MT 0 at least every six seconds. When not in test mode, an SBAS signal (PRN code) will only transmit MT 0 as an alert with no specified periodicity or duration.

1.6 AIRCRAFT EQUIPMENT INFORMATION VULNERABILITIES

This document contains minimum performance standards for unintentional interference to GNSS signals in the L1 and L5 frequency bands. Other types of disruption, such as spoofing, are possible. Spoofing is caused by RF waveforms that mimic true signals in

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