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MINIMUM OPERATIONAL PERFORMANCE STANDARDS FOR GLOBAL POSITIONING SYSTEM/AIRCRAFT BASED AUGMENTATION SYSTEM AIRBORNE EQUIPMENT

RTCA DO-316
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Prepared by: SC-159

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Foreward

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

RTCA, Incorporated is a not-for-profit corporation formed to advance the art and science of aviation and aviation electronic systems for the benefit of the public. The organization functions as a Federal Advisory Committee and develops consensus-based recommendations on contemporary aviation issues. RTCA's objectives include but are not limited to:

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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 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.

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.

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.

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.

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.

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.

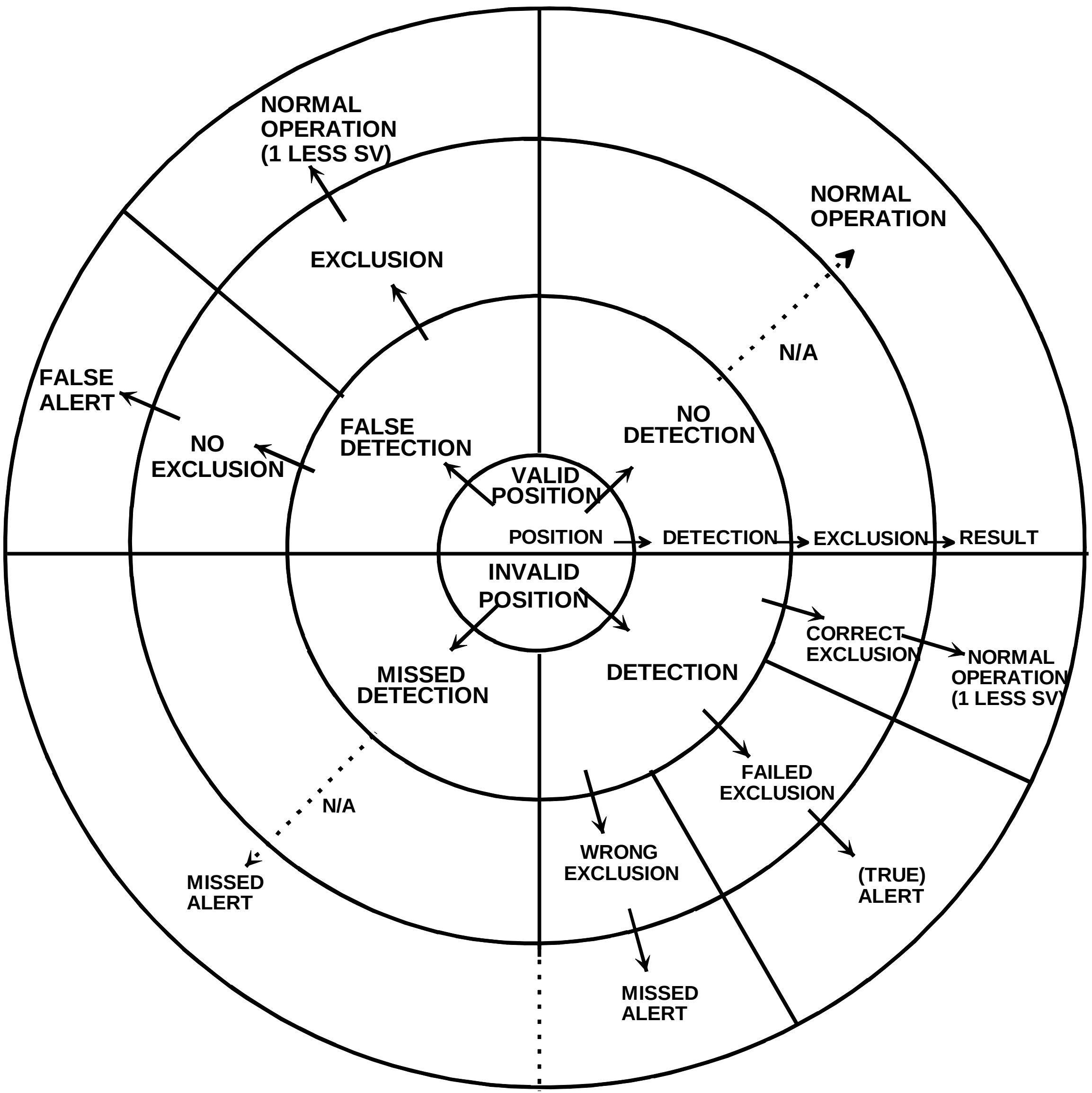
Alert: For the definitions of missed alert, false alert, and time-to-alert, an alert is defined to be an indication that is provided by the GPS equipment when the positioning performance achieved by the equipment does not meet the integrity requirements. This alert is one of the conditions that would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



<u>FIGURE 1-1</u> DIAGRAM OF FDE CONDITIONS

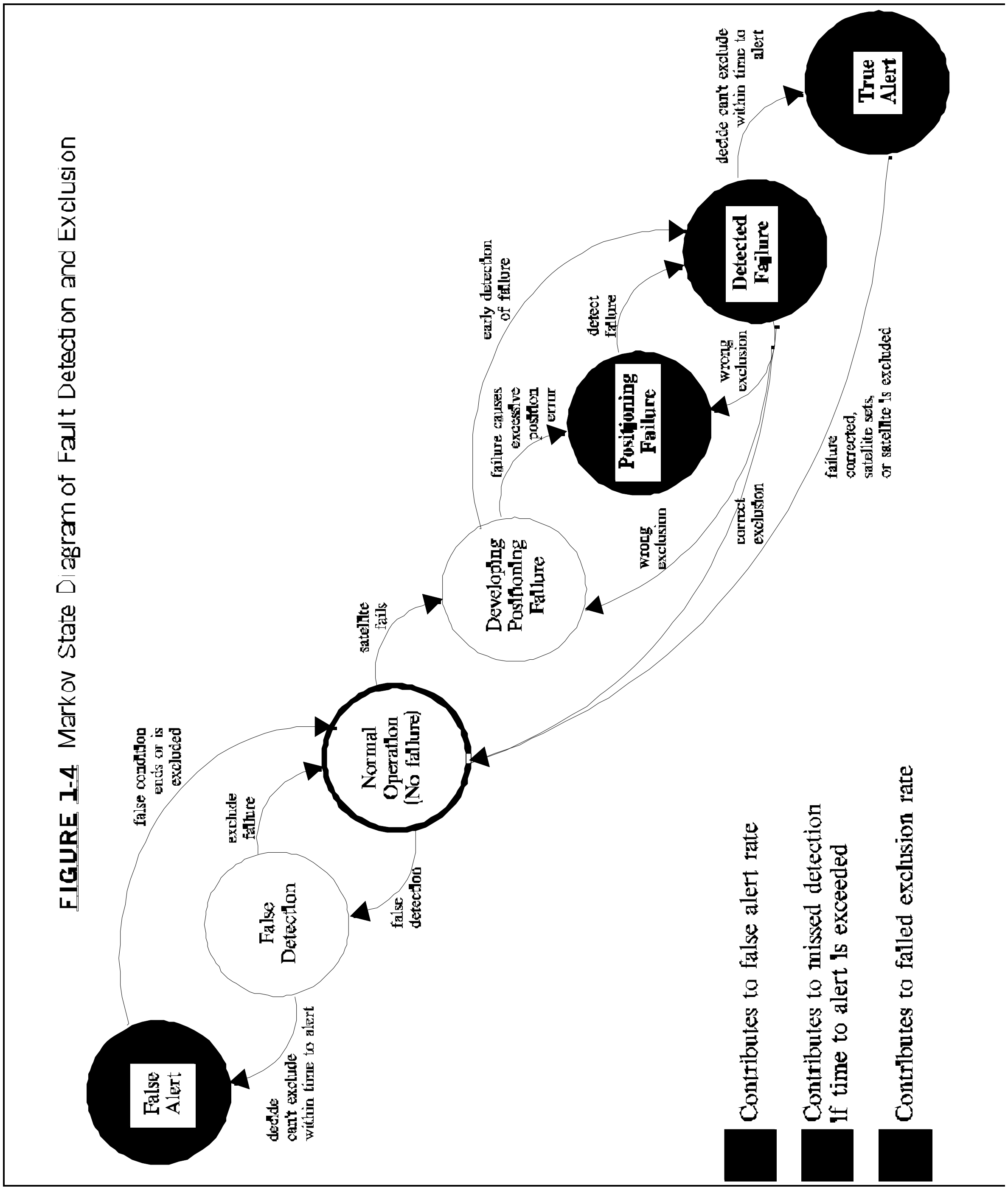
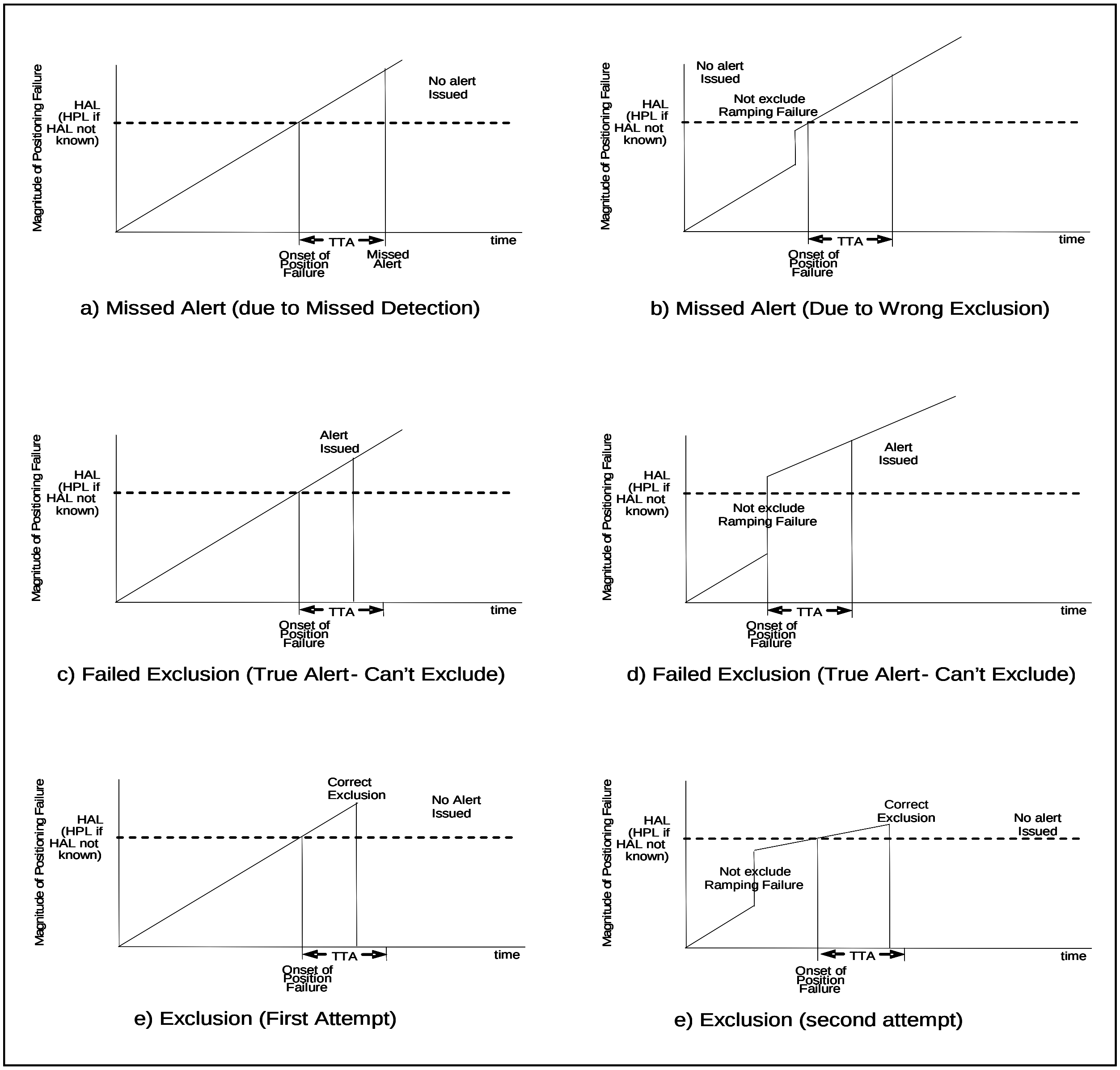


FIGURE 1-2 MARKOV CHAIN FOR FDE



<u>FIGURE 1-3</u> EXAMPLE FDE EVENTS

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.

Failed Exclusion (exclusion not possible): A failed exclusion is defined to occur when a true positioning failure is detected and the detection condition is not eliminated within the time-to-alert (from the onset of the positioning failure). A failed exclusion would cause a navigation alert.

Wrong Exclusion: A wrong exclusion is defined to occur when a detection occurs, and a positioning failure exists but is undetected after exclusion, resulting in a missed alert.

Missed Alert: Positioning failures that 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 GPS 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.

Note 3: The exclusion function may exclude a false detection internal to the GPS equipment, which does not contribute to the false alert rate (if an alert is not issued by the GPS equipment).

Availability of Detection: The detection function is defined to be available when the constellation of satellites provides 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 (Sections 2.1.2.2.2 and 2.1.3.2.2), 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:

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

where N = number of satellites being used by the GPS equipment

D(i) = 1, if Pr(detection given error in ith satellite causing positioning error equal to HAL) ≥ the detection requirement and Pr (false alert) ≤ the false alert rate requirement.

0, otherwise.

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

Note 4: The detection function is expected to operate whenever sufficient measurement redundancy exists, regardless of whether or not it is "available" for the selected navigation mode by the definition above. Therefore, it may 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 must continue to meet requirements.

Availability of Exclusion: The exclusion function is defined to be available when the constellation of satellites provides a geometry for which the 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 must occur before the duration of a positioning failure exceeds the time-to-alert, and the detection function as defined above must 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) may 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 a warning 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:

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

where N = the number of satellites being used by the GPS/WAAS equipment

E(i) = 1, if Pr(Failed exclusion) $\leq 10^{-3}$ and detection still available after exclusion, given i^{th} satellite failed,

0, if Pr(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 5: 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 may 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 must still meet the missed alert (including wrong exclusion) requirement on a per failure basis. In other words, there must 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).

1.8 Assumptions and Approach to Selected Issues

1.8.1 General

1.8.1.1 GPS Constellation

It is assumed that the GPS constellation provides the accuracy and availability specified in the 2005 Federal Radionavigation Plan and GPS SPS Performance Standard, October 2001. It is also assumed that the GPS signals being transmitted are in conformance with IS-GPS-200D, "Navstar GPS Space Segment / Navigation User Interfaces", December 2004; and, that Selective Availability (SA) is inactive per U.S. government policy.

Note: In the absence of SA, the availability of GPS FDE integrity is dramatically increased. The GPS Signal Specification has been replaced by GPS SPS Performance Standard, October 2001, and IS-GPS-200D, "Navstar GPS Space Segment / Navigation User Interfaces", December 2004. SA was turned off on 1 May 2000.

1.8.1.2 GPS Performance

Initially, it is envisioned that aircraft using the GPS signal will maintain conformance to current airway or other airspace separation requirements and to available/applicable approach and terminal instrument procedures. Over time, it is anticipated that these requirements and procedures will be revised and/or extended to take advantage of GPS capabilities.

Note: RTCA Special Committee 181 defined Required Navigation Performance (RNP) standards in RTCA/DO-236B, Minimum Aviation System Performance Standards (MASPS): Required Navigation Performance (RNP) for Area Navigation (RNAV). The requirements of this document satisfy many of the requirements specified in RTCA/DO-236B.

1.8.1.3 Navigational Waypoints

It is assumed that appropriate waypoints are provided to the aircraft's navigation system with sufficient accuracy and integrity for the GPS-supported phases of operation. This document uses the term "waypoints" as a generic term to refer to navigation fixes regardless of whether they are coincident with existing navigation aids or are used as part of a published procedure.

Note: Waypoints are stored by the navigation computer that the GPS sensor supplies position information to and are not part of the sensor requirements in this document. RTCA/DO-200A addresses the processing of aeronautical data. RTCA Special Committee 181 is developing a revision of RTCA/DO-201A that will address waypoint generation and distribution for all phases of operation.

1.8.1.4 RF Interference

It is assumed that this document's specification of the RF interference environment specified in Appendix C in which GPS sensors must operate successfully will be consistent with the real environment.

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2.0 EQUIPMENT PERFORMANCE AND TEST PROCEDURES

2.1 General Requirements

Section 2.1.12.1.1 applies to all navigation modes, while Sections 2.1.2 through 2.1.3 define the additional requirements for en route/terminal mode, and LNAV approach mode. The equipment must meet all of the requirements for the applicable navigation modes.

2.1.1 Requirements Applicable to GPS Equipment

2.1.1.1 General Requirements for All Navigation Modes

2.1.1.1.1 Airworthiness

When installed, the equipment's design and manufacture shall [GPS 1] not impair the airworthiness of the aircraft.

2.1.1.1.2 General Performance

The equipment shall [GPS 2] perform its intended function, as defined by this MOPS and the manufacturer.

2.1.1.1.3 Fire Resistance

All materials used shall [GPS 3] be self-extinguishing except for small parts (such as knobs, fasteners, seals, grommets and small electrical parts) that would not significantly contribute to propagating a fire.

2.1.1.1.4 Equipment Interfaces

The interfaces with other aircraft equipment shall [GPS 4] be designed so that normal or abnormal GPS equipment operation does not adversely affect the operation of other equipment. Conversely, normal or abnormal operation of other equipment shall [GPS 5] not adversely affect the GPS equipment except as specifically allowed.

Note: These requirements assume that the GPS equipment is properly installed and the equipment it is interfacing with is both adequately designed and properly installed.

2.1.1.1.5 Effects of Test

The equipment shall [GPS 6] be designed so that applying the specified test procedures does not produce a condition detrimental to the equipment's performance, except as specifically allowed in this MOPS.

2.1.1.2 GPS Signal Processing Requirements

The equipment shall [GPS 7] be designed to process the GPS signals and necessary data described in the latest GPS SPS Performance Standard, October 2001, and IS-GPS-200D, "Navstar GPS Space Segment / Navigation User Interfaces", December 2004, under interference conditions described in Appendix C and under the minimum signal conditions defined in Section 2.1.1.8. The equipment shall [GPS 8] decode the ionospheric coefficients in the GPS navigation message and apply the ionospheric corrections described in the IS-GPS-200D, "Navstar GPS Space Segment / Navigation

User Interfaces", December 2004. A tropospheric correction shall [GPS 9] also be applied (an acceptable algorithm is described in Appendix J, Section J.4).

GPS satellite navigation data shall [GPS 10] be continuously decoded. Except for "not healthy" information (as defined in Section2.1.1.3.2), new clock and ephemeris data (subframes 1, 2 and 3 of the GPS navigation message) shall [GPS 11] only be used when the data is verified by reception of a second message containing the same data with a broadcast IODE that matches the 8 least-significant bits of broadcast IODC. Ionospheric data (subframe 4) shall [GPS 12] not be used until the data is verified by reception of a second message, potentially from a different satellite, containing the same data. The equipment shall [GPS 13] apply the satellite clock correction (including relativistic corrections) derived from the clock parameters in subframe 1 of the GPS navigation message after smoothing the pseudorange measurement (if applicable).

Note: GPS navigation data in subframes 1, 2, and 3 may not always be updated in the same frame.

In addition, the equipment shall [GPS 14] not mistake one GPS satellite for another due to cross-correlation during acquisition or reacquisition. An acceptable means of preventing cross-correlation effects during acquisition is to reject GPS satellite ranging data if there is a 3000 km separation between satellite positions derived from the almanac and broadcast ephemerides.

Note: Equipment should be able to track satellites under conditions of ionospheric scintillation that could occur during solar maximum at auroral and equatorial latitudes. There is insufficient information to characterize scintillation and define appropriate requirements and tests for inclusion in this MOPS. However, equipment should be able to track satellites through phase jitter and amplitude fading that can result from scintillation. New requirements may be defined when ionospheric effects can be adequately characterized.

2.1.1.3 Satellite Integrity Status

The equipment shall [GPS 15] designate each satellite as GPS UNHEALTHY or GPS HEALTHY, as defined in Sections 2.1.1.3.2 and 2.1.1.3.3 respectively. The latency of this designation must be consistent with the requirements of Sections 2.1.1.11.

2.1.1.3.1 Step Detector

The equipment shall [GPS 16] detect a pseudorange step greater than 700 meters on any satellite used in the position solution, including steps that cause loss of lock for less than 10 seconds. A pseudorange step can be caused by:

a) A change in navigation data; or

b) A sudden change in the code phase.

The equipment shall [GPS 17] falsely declare a pseudorange step less frequently than or equal to 3.33×10^{-7} per sample. If the equipment is capable of recovering a satellite after a step error has been declared, the declaration of a pseudorange step shall [GPS 18] only be cleared if it is verified through autonomous fault detection.

Note: The manufacturer is free to choose any method to detect step errors. However, any method used should properly take into account satellite movement and aircraft dynamics.

2.1.1.3.2 GPS UNHEALTHY Designation

The equipment shall [GPS 19] designate any GPS satellite as GPS UNHEALTHY if the GPS satellite navigation message meets any of the following conditions:

a) 6 bit health word in subframe 1: all cases where MSB=”1” (ref. 20.3.3.3.1.4 and 20.3.3.5.1.3 of IS-GPS-200D, “Navstar GPS Space Segment / Navigation User Interfaces”, December 2004;

b) Failure of parity on 5 successive words (3 seconds);

c) User range accuracy index of 8 or more;

d) Bit 18 of the HOW set to 1(Ref. 20.3.2 of IS-GPS-200D, “Navstar GPS Space Segment / Navigation User Interfaces”, December 2004.);

e) All bits in subframe 1, 2, or 3 are 0’s;

f) Default navigation data [alternating ones and zeros] is being transmitted in subframes 1, 2, or 3 (ref. 20.3.2 of IS-GPS-200D, “Navstar GPS Space Segment / Navigation User Interfaces”, December 2004); or

g) The preamble does not equal 8B (hexadecimal) or 139 (decimal).

The GPS UNHEALTHY status for a satellite shall [GPS 20] be changed only after the condition has cleared.

Note: The condition of failure of parity on 5 successive words is intended to avoid processing an interfering signal by mistake.

2.1.1.3.3 GPS HEALTHY Designation

The equipment shall [GPS 21] designate any GPS satellite as GPS HEALTHY if it does not satisfy any of the criteria listed under Section 2.1.1.3.2 (if not designated as GPS UNHEALTHY).

2.1.1.4 Satellite Selection

The equipment shall [GPS 22] automatically select satellites for use in the position solution computation and for use in the FDE algorithm. The equipment shall [GPS 23] use the same set of satellites in the position solution and for integrity. The equipment shall [GPS 24] not use the range measurement from any satellite designated GPS UNHEALTHY in the position solution.

Note: Selecting the satellites has a significant impact on the availability and reliability of the position with integrity. If possible, an all-in-view receiver should be used and compute HPL based on all satellites useable for each HPL to determine which set of satellites and HPL provides the best performance (i.e., smallest HPL).

When a change to the selected set of satellites is necessary, the equipment shall [GPS 25] accomplish this change within the time-to-alert as specified in section 2.1.2.2.2.1 or 2.1.3.2.2.1.

It is recommended that the equipment does not provide manual de-selection of satellites to avoid situations where the pilot incorrectly de-selects satellites or fails to re-select them. In a GPS environment, it is highly unlikely that the pilot is aware of a satellite failure that the GPS system has not flagged. If manual de-selection is implemented, the manufacturer shall [GPS 26] address these issues. Consideration should be given to: 1) annunciations to remind the pilot that satellites have been de-selected; 2) the capability to readily re-select satellites; and, 3) the appropriate training to ensure proper equipment operation. The equipment shall [GPS 27] clear all previous manual de-selections at power-up.

Manual selection of satellites that have been designated GPS UNHEALTHY shall [GPS 28] be prohibited.

2.1.1.5 Initial Acquisition Time

The equipment shall [GPS 29] be capable of acquiring satellites and determining a position without any initialization information, including time, position, and GPS almanac data.

The time from power application to first valid position fix shall [GPS 30] be less than 5 minutes with 95% confidence given the following:

a) Latitude and longitude initialized within 60 nautical miles;

b) Time and date within 1 minute;

c) Valid almanac data and unobstructed satellite visibility;

d) Under interference conditions of Appendix C;

e) Under the signal conditions defined in Section 2.1.1.8.

In this context, valid position fix means all of the following conditions are met:

a) The determined position meets the accuracy requirements of Section 2.1.2.1, and continues to meet the requirement after the first valid position fix;

b) Integrity monitoring is provided as defined in Section 2.1.2.2.2.

2.1.1.6 GPS Satellite Acquisition Time

After steady state accuracy has been established, i.e., at least one minute of accurate navigation, the equipment shall [GPS 31] be capable of incorporating a new GPS satellite signal into the position within 80 seconds. This requirement applies to a satellite with the minimum signal power in the presence of interfering signals described in Appendix C, and assumes valid almanac data is available.

Note: 66 seconds is required to ensure that a new ephemeris message is received twice, plus 14 seconds for Doppler and range bin search. The 80 seconds begins when a satellite becomes available.

2.1.1.7 Satellite Reacquisition Time

For satellite signal outages of 30 seconds or less when the remaining satellites provide a GDOP of 6 or less, the equipment shall [GPS 32] reacquire the satellite within 20 seconds from the time the signal is reintroduced. This requirement applies to a satellite with the minimum signal power in the presence of interfering signals as described in Appendix C.

2.1.1.8 Sensitivity and Dynamic Range

All antennas shall [GPS 33] comply with either RTCA/DO-301; or, RTCA/DO-228, Change 1. To the extent non-standard antenna performance is used to define the GPS equipment requirements, that performance shall [GPS 34] be validated in accordance with the tests and methods described in RTCA/DO-301.

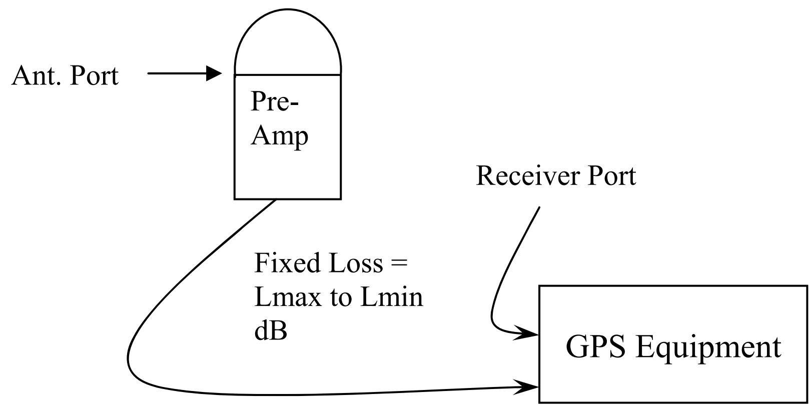
This MOPS defines architectures for an active antenna that includes a preamplifier and for a passive antenna without a preamplifier as shown in Figure 2-1. Minimum requirements for a standard active antenna are defined in RTCA/DO-301; and, manufacturers are highly encouraged to use one of these antennas because of their superior performance. Minimum requirements for a passive antenna are defined in RTCA/DO-228, Change 1. Manufacturers that restrict their sensor interoperability to a specific antenna can use the unique characteristics of their antenna in defining the sensitivity and dynamic range (and associated test conditions) as described in this document.

Throughout this section (and the test procedures), signal and interference power levels are specified at the input to the preamplifier (antenna port in Figure 2-1) unless otherwise stated. If an active antenna is used, the manufacturer must specify the minimum and maximum preamplifier gain (minimum gain is specified in RTCA/DO-301 but the maximum gain is not) and the corresponding minimum and maximum installation loss (L_{min} and L_{max} in Figure 2-1). These limits should be defined in the installation instructions.

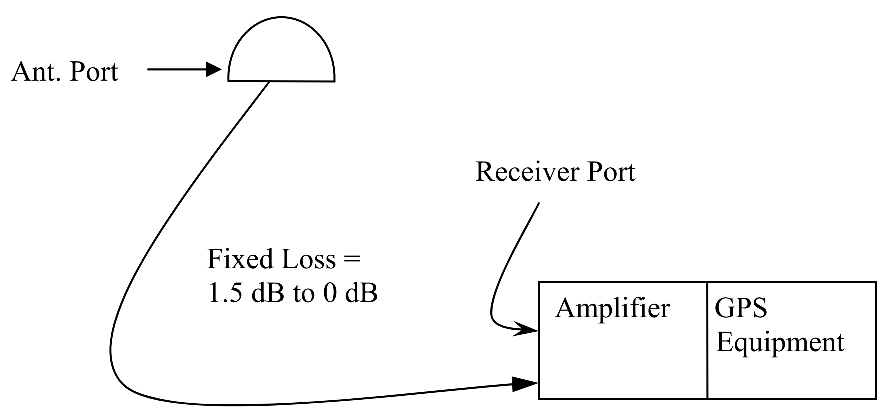
a) Equipment compatible with a minimum standard RTCA/DO-301-compliant or minimum standard RTCA/DO-228, Change 1-compliant active antenna: The equipment shall [GPS 35] accommodate GPS signals with a minimum input signal power of –136.5 dBm and a maximum input signal power of –115.5 dBm (although acceptable acquisition and tracking performance may not be achievable throughout this entire range). The equipment shall [GPS 36] have the capability of tracking GPS satellites with a minimum input signal power of -134 dBm in the presence of sky and antenna thermal noise density ($N_{sky,antenna}$) of -172.5 dBm/Hz and the Appendix C interference conditions. The equipment shall [GPS 37] have the capability of tracking GPS satellites with a maximum power of at least -121 dBm in the presence of SBAS satellites with a maximum power of at least -115.5 dBm.

b) Equipment compatible with a specific RTCA/DO-301-compliant or RTCA/DO-228, Change 1-compliant passive antenna: All signal-in-space power levels in this paragraph are referenced to the output of a 0 dBi circularly polarized antenna. The equipment shall [GPS 38] accommodate GPS signals with a minimum signal-in-space power of -131 dBm and a maximum signal-in-space power of –119.5 dBm (although acceptable acquisition and tracking performance may not be achievable throughout this entire range). The equipment shall [GPS 39] have the capability of tracking GPS satellites with a minimum signal-in-space power of -128.5 dBm in the presence of sky and antenna thermal noise density ($N_{sky,antenna}$) for a specific antenna and the Appendix C interference conditions. The equipment shall [GPS 40] have the capability of tracking GPS satellites with a maximum signal-in-space power of at least -123 dBm in the presence of SBAS satellites with a maximum signal-in-space power of at least –119.5 dBm.

   The manufacturer must specify any unique antenna requirements (e.g., minimum gain at 5 degree elevation angle, G/T ratio). Manufacturers using a passive antenna shall [GPS 41] account for the frequency selectivity for the total system as specified in Appendix C. The manufacturer must determine the minimum and maximum signal power levels at the antenna port, accounting for the antenna radiation pattern. The maximum signal power level may account for the combined satellite antenna and specific antenna radiation patterns. For the minimum standard antenna, this effect results in a 2 dB reduction in the maximum GPS signal power level with respect to the sum of the maximum signal in space and the maximum gain of the antenna radiation pattern. The GNSS Noise and external interference are not adjusted by the antenna radiation pattern.



Active Antenna



Passive Antenna

FIGURE 2-1 SENSITIVITY AND DYNAMIC RANGE CONFIGURATION

Note 1: RTCA/DO-301 is the current standard for active antennas implemented by TSO-C190. However, it is acceptable to use a previously certified active antenna that complies with RTCA/DO-228, Change 1 implemented by TSO-C144. It is also acceptable to use a passive antenna that complies with RTCA/DO-228, Change 1 implemented by TSO-C144 or TSO-C144a.

Note 2: If a specific antenna is to be used, or the manufacturer elects to demonstrate tracking at a lower mask angle (< 5 degrees), then gain values must be adjusted, and sensitivity and dynamic range specified.

Note 3: $N_{sky,antenna}$ is determined by the antenna G/T for 1575.42 ±2MHz, as the correlation of the noise density outside ±2 MHz with the C/A code spectrum has a negligible effect. RTCA/DO-301 provides the method to determine sky and antenna thermal noise density ($N_{sky,antenna}$) from G/T. RTCA/DO-301 also provides for guidance on the preamplifier gain (for active antennas) to support the test procedures.

Note 4: Acceptable acquisition and tracking performance may not be achievable for the minimum signal-in-space levels of -136.5 dBm depending on the external interference environment and actual level of inter- and intra-system interference. For GPS signal, the minimum signal-in-space power is -128.5 dBm.

Note 5: The requirements contained in this section are based on a minimum antenna gain of -5.5 dBic and a maximum antenna gain of +4.0 dBic.

2.1.1.9 Equipment Burnout Protection

Equipment using an active antenna shall [GPS 42] withstand, without damage, an in-band CW signal of +20 dBm as seen at the output of the preamplifier.

Equipment using a passive antenna shall [GPS 43] withstand, without damage, an in-band CW signal of +20 dBm input at the antenna port.

Note: For receivers using passive antennas, the burnout protection of +20dBm may not guarantee compatibility with all aircraft or all operations. Some contemporary commercial airborne installations require +30dBm burnout protection.

2.1.1.10 Integrity in the Presence of Interference

The equipment shall [GPS 44] satisfy the applicable integrity requirement within the time-to-alert (See sections 2.1.2.2.2.1, 2.1.3.2.2.1) for the output of misleading information in the presence of interfering signals higher in power than the values specified in Appendix C. Under these extreme conditions, it is acceptable to output a navigation alert, but not to output misleading information. The equipment shall [GPS 45] autonomously return to steady state accuracy (according to the conditions in Section 2.1.1.5) within 5 minutes after the interference conditions return to those specified in Appendix C for initial acquisition.

Note 1: This requirement is comprehensive in nature in that it is intended to prevent the output of misleading information under any unintentional interference scenario that could arise and specify the recovery time. It is not intended to address the potential effects of intentional interference. While it is recognized that this requirement is impossible to completely verify through testing, an acceptable means of compliance can be found in Section 2.3.3 (Scenario #2 Initial Acquisition Time after abnormal interference Test) and Section 2.3.5.

Note 2: To support problem investigations and maintenance, it is recommended that the equipment output the signal-to-noise ratio for each satellite. This data can be useful when determining if a particular outage is caused by the environment or by receiver anomalies.

2.1.1.11 Alerts/Outputs

The equipment provides data outputs when significant conditions occur that affect flight decisions, in particular loss of integrity monitoring or navigation.

Note: The requirements in this section apply to the output of position and integrity to other equipment. For example, the time to alert for the position output is 8.0 seconds since the use of that data is not defined.

2.1.1.11.1 Protection Level

The equipment shall [GPS 46] output the Horizontal Protection Level as described in Sections 2.1.2.2.2 and 2.1.3.2.2. The equipment shall [GPS 47] indicate if the HPL cannot be calculated (insufficient number of GPS HEALTHY satellites/ fault detection is not available).

Note 1: In addition to the HPL, the equipment may output the HUL.

Note 2: When no HPL can be calculated, integrity monitoring is not provided.

2.1.1.11.2 Navigation Alert

The equipment shall [GPS 48] provide an indication or output of the loss of navigation capability within one second of the onset of any of the following conditions:

a) The absence of power (loss of function is an acceptable indicator);

b) Equipment malfunction or failure;

c) The presence of a condition lasting five seconds or more where there are an inadequate number of usable satellites to compute a position solution (i.e., no computed data);

d) The presence of a condition where fault detection detects a position failure that cannot be excluded within the 8.0 second time-to-alert.

The alert shall [GPS 49] be returned to its normal state immediately upon termination of the responsible condition.

Note: These requirements do not preclude the implementation of a dead reckoning mode that would allow continued display of navigation information even under condition c), together with a clear indication that the equipment is using the dead reckoning mode.

2.1.2 Requirements for En Route and Terminal Mode

2.1.2.1 Accuracy

The horizontal radial position fixing error shall [GPS 50] not exceed 32m, 95th percentile, when HDOP is normalized to 1.5. This requirement shall [GPS 51] be met under the minimum signal conditions defined in Section 2.1.1.8 and interference conditions defined in Appendix C.

Note 1: The assumptions are as follows:

signal-in-space pseudorange error of 6m;

avionics pseudorange error has a conservative upper bound of 5m (rms);

a 7 m (rms) ionospheric delay model error; and,

a 0.25m (rms) residual tropospheric delay error.

The dominant pseudo-range error for users of the GPS Standard Positioning Service is the ionospheric error that remains after application of the ionospheric corrections. This error is also highly variable and depends on conditions such as user geomagnetic latitude, level of solar activity (i.e., point of the solar cycle that applies), level of ionospheric activity (i.e., whether there is a magnetic storm, or not), elevation angle of the pseudo-range measurement, season of the year, and time of day. The ionospheric delay model error assumption reflected in the position fixing error is generally conservative; however, conditions can be found under which the assumed 7 m (1 s) error during solar maximum would be inadequate. Flight Technical Error (FTE), waypoint error, and RNAV path computation error are not included in this error.

A receiver that uses pseudoranges smoothed using the algorithm in 2.1.2.6.4 will have significantly better avionics pseudorange error than the 5 m (rms) assumption above.

Note 2:The signal-in-space error model above is applicable only to an airborne receiver. Models for these errors, particularly multipath, may be considerably different for an aircraft that is stationary or taxiing.

Note 3: Section 2.3.6 describes the test for this requirement. Section 2.3.6 uses a sensor pseudorange accuracy threshold of 5 meters minus the manufacturers' allocation to multipath error. The manufacturer should determine the allocation between thermal noise and multipath error and adjust the threshold in section 2.3.6 appropriately.

If a time output is provided, it shall [GPS 52] be within 1 second of coordinated universal time (UTC).

2.1.2.2 Integrity Requirements

2.1.2.2.1 Development Assurance

The hardware and software shall [GPS 53] be designed such that the output of misleading information, considered to be a major failure condition, shall [GPS 54] be improbable. To demonstrate compliance it will be necessary to conduct a safety assessment to evaluate the system's implementation against known failure conditions.

Note 1: The design requirements applicable to this hazard classification depend upon the aircraft type. The following two paragraphs define acceptable means of compliance for the most stringent application of this hazard classification.

Note 2: In addition to showing compliance with the above requirement, for equipment that supports approach, arrival and departure phases of flight, the European Aviation Safety Agency requires that for electronic display systems, displaying hazardously misleading navigational or position information simultaneously on both pilots' displays must be "Extremely Remote" (reference- CS 25.1309 and AMC 25.1309).

2.1.2.2.1.1 Hardware Compliance

An acceptable means of compliance for the equipment (oceanic/en route/terminal modes) is to show that failures resulting in misleading information are not more probable than 10^{-5}/flight hour. For complex firmware implementations such as application-specific integrated circuits (ASIC's), processes similar to those described in RTCA/DO-178B or RTCA/DO-254 provide an acceptable means of compliance with applicable airworthiness requirements.

2.1.2.2.1.2 Software Compliance

AC 20-115B, which references RTCA/DO-178B, provides an acceptable means for showing that software complies with applicable airworthiness requirements. One acceptable approach to software development is to develop all software that affects navigation and integrity functions to at least the Level C criteria, as defined in RTCA/DO-178B. Another acceptable approach is to substantiate software levels in the safety assessment.

2.1.2.2.2 FDE-Provided Integrity Monitoring

The equipment shall [GPS 55] have a fault detection and exclusion (FDE) capability that uses redundant GPS ranging measurements to provide independent integrity monitoring. The detection function refers to the capability to detect a positioning failure that affects navigation, while the exclusion function refers to the capability to exclude one or more satellites from the solution to prevent a positioning failure from affecting navigation. The equipment shall [GPS 56] compute a horizontal protection level using a weighted FDE algorithm.

An acceptable value for the weight is the reciprocal of the estimated variance of range error. The weight shall [GPS 57] account for clock/ephemeris, ionospheric, tropospheric, and airborne contributions to range error. An acceptable value for the standard deviation of clock/ephemeris error is the URA. An acceptable value for tropospheric error is given in Appendix J, sections J.4 and J.5. An acceptable value of ionospheric error is $\sigma_{i,UIRE}$ given in Appendix J, section J.2 for single-frequency GPS ionospheric corrections. An acceptable value for airborne contribution to range error is $\sigma_{i,air}$ given in Appendix J, section J.3.

Note 1: The nominal URA index in IS-GPS-200D, "Navstar GPS Space Segment / Navigation User Interfaces", December 2004, paragraph 20.3.3.3.1.3 can be used to determine range-domain uncertainty by assuming the URA maps into the near-Gaussian distribution. For convenience, Table 2-1 shows the mapping from URA index to URA value.

TABLE 2-1 URA VALUES

URA Index	URA value (m)
0	2
1	2.8
2	4
3	5.7
4	8
5	11.3
6	16
7	32
8	64

URA Index	URA value (m)
9	128
10	256
11	512
12	1024
13	2048
14	4096
15	Do not use

Note 2: The URA does not include the tropospheric or ionospheric uncertainties. These uncertainties are included in Appendix J.

Note 3: The position solution and the FDE algorithms should use the same variance weights to maintain the same statistical characterization of the measurements used.

If the manufacturer chooses to use different weights for the position solution and HPL_{FD} then the manufacturer shall [GPS 58] substantiate that HPL_{FD} bounds the horizontal position error with a conditional probability of 0.999.

Equipment that uses barometric altitude to improve the performance of this algorithm shall [GPS 59] meet the requirements specified in Appendix G. Equipment that uses inertial information to improve the performance of this algorithm shall [GPS 60] meet the requirements specified in Appendix R. Equipment that uses other measurements (besides GPS, barometric altitude or inertial) must demonstrate that equivalent safety and performance are obtained. FDE algorithms that use other navigation signals external to the aircraft such as eLORAN or VOR/DME must be shown to satisfy the availability requirement without the use of the other navigation signals. The manufacturer must provide the means to test and analyze alternate FDE algorithms to demonstrate compliance.

2.1.2.2.2.1 Time-to-Alert

The equipment shall [GPS 61] alert within 8 seconds for FDE-provided integrity monitoring.

2.1.2.2.2.2 Missed Alert Probability

The probability of missed alert shall [GPS 62] be less than or equal to 0.001 for every geometry and every navigation mode, regardless of which satellite is causing the positioning failure. If this requirement is not met for a given geometry, then the detection function is defined to be unavailable for that geometry (See Section 1.7.3).

Note 1: This requirement is on the missed alert rate generated by the GPS equipment. The missed alert probability is a function of missed detection and wrong exclusion.

Note 2: The testing paragraph defines specific constellations to be used to evaluate this requirement.

2.1.2.2.2.3 False Alert Probability

The probability of false alert shall [GPS 63] be less than or equal to 3.33×10^{-7} per sample. This requirement shall [GPS 64] be met for every geometry.

Note: The testing paragraph defines specific constellations to be used to evaluate this requirement.

2.1.2.2.2.4 Failed Exclusion Probability

The probability of failed exclusion shall [GPS 65] be less than or equal to 10^{-3} for every geometry and every navigation mode, regardless of which satellite is causing the positioning failure. If this requirement is not met for a given geometry, then the exclusion function is defined to be unavailable for that geometry (See Section 1.7.3).

Note: This requirement is on the alert rate generated by the GPS equipment due to failed exclusion. It is equivalent to the probability that a positioning failure is annunciated when a GPS satellite failure occurs and is detected internally. For some algorithms, this probability may be 0 in that exclusion is conducted whenever a failure is detected, if at least 6 measurements are available. However, such an algorithm could only be used if it also meets the missed alert requirement.

2.1.2.2.2.5 Availability

The availability of the FDE algorithm to meet the above requirements with a HAL of 2 nm, when evaluated over the constellations and grids specified in the test procedures (Section 2.3.7), using the same satellite selection algorithm used by the equipment, and using a mask angle of 5 degrees, shall [GPS 66] be greater than or equal to the following:

Availability of detection:	99.95%
Availability of exclusion:	99.30%

The availability of the FDE algorithm to meet the above requirements with a HAL of 1 nm, when evaluated over the constellations and grids specified in the test procedures (Section 2.3.7), using the same satellite selection algorithm used by the equipment, and using a mask angle of 5 degrees, shall [GPS 67] be greater than or equal to the following:

Availability of detection:	99.90%
Availability of exclusion:	98.45%

Note: This requirement is intended to provide a means to assess the adequacy of FDE algorithms. These numbers are based upon simulation and analysis of the practical availability. These numbers are intended to ensure a consistent minimum capability that can be used by airspace system designers. This availability has not been determined to meet all operational requirements.

2.1.2.3 Equipment Reliability

The equipment should be designed for reliable operation.

2.1.2.4 Satellite Tracking Capability

The equipment shall [GPS 68] be capable of simultaneously tracking a minimum of 8 GPS satellites.

2.1.2.5 Dynamic Tracking

When the aircraft has dynamics within normal maneuvers defined by the maximum ground speeds and accelerations shown below, the equipment shall [GPS 69] meet the accuracy requirements of 2.1.2.1 and the satellite acquisition time requirements of 2.1.1.6 and the satellite reacquisition requirements of 2.1.1.7. Note that g = acceleration of gravity = 9.8 m/s^2.

Ground Speed	**Horiz. Accel.**	**Vertical Accel.**	**Total Jerk**
800 kt	0.58 g	0.5 g	0.25 g/s

Abnormal maneuvers are defined to be maneuvers whose accelerations/jerks exceed these values, up to the maximum ground speeds and accelerations shown below.

Ground Speed	**Horiz. Accel.**	**Vertical Accel.**	**Total Jerk**
800 kt	2 g	1.5 g	0.74 g/s

During abnormal maneuvers, the equipment shall [GPS 70] not output misleading information. When the aircraft returns to normal maneuvers from abnormal maneuvers, the equipment shall [GPS 71] meet the steady-state reacquisition requirements of Section 2.1.1.7. During the abnormal maneuver period, loss-of-navigation capability and loss-of-integrity monitoring alerts and outputs shall [GPS 72] function as specified.

2.1.2.6 Position Output

The equipment shall [GPS 73] determine a position for navigation. This position shall [GPS 74] represent the WGS-84 position of the aircraft antenna (or center of navigation) at the time of applicability.

The equipment shall [GPS 75] output (via electronic data interface) "position output data." The "position output data" shall [GPS 76] consist of at least the position, velocity, horizontal position figure of merit ($HFOM_P$), and HPL.

Optional postion output data:

"position output data" includes the vertical position figure of merit ($VFOM_P$), and the velocity figures of merit which consist of both the horizontal velocity figure of merit ($HFOM_V$) and the vertical velocity figure of merit ($VFOM_V$).

If the $VFOM_P$ is output by the equipment, then it shall [GPS 77] be considered to be part of the receiver "position output data".

If the velocity figures of merit ($HFOM_V$ and $VFOM_V$) are output by the receiver, then they shall [GPS 78] be considered to be part of the receiver "position output data".

Note 1: The position, velocity, $HFOM_P$, HPL, $VFOM_P$ (if output), and $HFOM_V$ and $VFOM_V$ (if output) are collectively referred to as the "position output data" in the following subsections. Appendix H provides guidance concerning an electronic data interface and Appendix F provides an example velocity algorithm.

Note 2: Manufacturers who wish to have their equipment support ADS-B functions should refer to Appendix U. Compliance with this MOPS does not guarantee the equipment meets all ADS-B position sensor requirements.

2.1.2.6.1 Position Output Data Update Rate

The minimum update rate of position output data shall [GPS 79] be once per second.

2.1.2.6.2 Position Output Data Latency

The latency of the position, velocity, and $HFOM_P$ output, defined as the interval between the time of the measurement and the time of applicability of the position and velocity, shall [GPS 80] be less than or equal to 500 milliseconds.

Note: Latency of the HPL is defined in Section 2.1.1.11.1.

The position output data shall [GPS 81] be output prior to 200 milliseconds after the time of applicability.

2.1.2.6.3 Position Solution

The equipment shall [GPS 82] use a weighted position solution (see Appendix J, Section J.1). Manufacturers should consider implementing a three-dimensional position using a linearized, weighted least-squares solution as defined in Appendix E.

Note: It is unlikely that user equipment will meet both availability and integrity requirements if equal weights are used.

2.1.2.6.4 Smoothing

Manufacturers should consider implementing carrier smoothing. If carrier smoothing is implemented, the smoothing filter output shall [GPS 83] achieve an error less than 0.25 m within 200 seconds after initialization in the presence of a code-carrier divergence rate of up to 0.018 m/s relative to the steady-state response of the following filter:

$$P_{proj} = P_{n-1} + \frac{\lambda}{2\pi}\left(\phi_n - \phi_{n-1}\right)$$

$$P_n = \alpha\rho_n + (1-\alpha)P_{proj}$$

where

P_n is the carrier-smoothed pseudorange in meters,

P_{n-1} is the previous carrier-smoothed pseudorange in meters,

P_{proj} is the projected pseudorange in meters,

ρ_n is the raw pseudorange measurement in meters (code loop carrier driven, 1st order or higher and with a one sided noise bandwidth greater than or equal to 0.125 Hz),

λ is the wavelength in meters,

ϕ_n is the accumulated carrier phase measurement in radians,

ϕ_{n-1} is the previous accumulated carrier phase measurement in radians, and

α is the filter weighting function (a unit less parameter), equal to the sample interval in seconds divided by the time constant of 100 seconds.

Note 1: The difference between the steady-state response of the smoothing filter implemented in the equipment and the steady-state response of the filter defined above is included in the accuracy requirements.

Note 2: The code-carrier divergence rate is assumed to be a Normal distribution with zero mean and a standard deviation of 0.012 m/s. Steady-state operation is defined to be following 360 seconds of continuous operation of the smoothing filter.

Note 3: One acceptable implementation of the airborne smoothing filter is the filter specified above. Smoothing can be done in parallel with other acquisition processes, making the smoothed pseudoranges available as quickly as possible.

2.1.2.6.4.1 Smoothing Pseudorange Accuracy

This requirement only applies to manufacturers that elect to perform carrier smoothing. The RMS of the total steady-state equipment contribution to the error in the corrected pseudorange for a GPS satellite ($RMS_{pr\_air,GPS}$) at the minimum signal level (Section 2.1.1.8) shall [GPS 84] be as follows:

Minimum signal level:

$RMS_{pr\_air,GPS} \leq 0.36$ meters.

2.1.2.6.5 Velocity Accuracy

The requirements in this section are optional. If the manufacturer elects to support ADS-B, the following requirements for velocity accuracy apply. However, including these velocity accuracy requirements in the equipment design does not ensure the equipment is suitable for all ADS-B applications.

The equipment's horizontal velocity output shall [GPS 85] have an error that is less than 10 m/s, (95th percentile), when the HDOP is normalized to 1.5 and the vertical velocity output shall [GPS 86] have an error that is less than 50 ft/s, (95th percentile), when the VDOP is normalized to 3.0. These requirements shall [GPS 87] be met under the minimum signal conditions defined in Section 2.1.1.8.

Note 1: *These velocity accuracy requirements are design requirements. These requirements do not imply that if the velocity FOMs at the time of applicability are equal to or greater than 10 m/s and 50 ft/s for the horizontal and vertical velocities respectively that the velocity should stop being output or flagged invalid. Rather, the velocities should continue to be output and the velocity FOMs (if provided as outputs) should continue to appropriately* characterize the velocity accuracy.

Note 2: The tests in Section 2.3.6.4 *define an acceptable means of determining the 95th percentile velocity accuracy and figure of merit.*

Note 3: The tests in section 2.3.6.4.3 *may be accomplished to demonstrate velocity accuracies less than 3 m/s horizontal and 15 ft/s vertical. Both of these accuracies are 95th percentile values.*

2.1.3 Requirements for LNAV

2.1.3.1 Accuracy

See Section 2.1.2.1.

2.1.3.2 Integrity Requirements

2.1.3.2.1 Development Assurance

See Section 2.1.2.2.1.

2.1.3.2.1.1 Hardware Compliance

See Section 2.1.2.2.1.1

2.1.3.2.1.2 Software Compliance

See Section 2.1.2.2.1.2

2.1.3.2.2 FDE-Provided Integrity Monitoring

See Section 2.1.2.2.2.

2.1.3.2.2.1 Time-to-Alert

See Section 2.1.2.2.2.1.

2.1.3.2.2.2 Missed Alert Probability

See Section 2.1.2.2.2.2.

2.1.3.2.2.3 False Alert Probability

See Section 2.1.2.2.2.3.

2.1.3.2.2.4 Failed Exclusion Probability

See Section 2.1.2.2.2.4.

2.1.3.2.2.5 Availability

The availability of the FDE algorithm to meet the above requirements with an horizontal alert limit (HAL) of 0.3 nm, when evaluated over the constellations and grids specified in the test procedures (Section 2.3.7), using the same satellite selection algorithm used by the equipment, and using a mask angle of 5 degrees, shall [GPS 88] be greater than or equal to the following:

Availability of detection:	99.80%
Availability of exclusion:	93.10%

Note 1: This requirement is intended to provide a means to assess the adequacy of FDE algorithms. These numbers are based upon simulation and analysis of the practical availability. These numbers are intended to ensure a consistent minimum capability that can be used by airspace system designers. This availability has not been determined to meet all operational requirements.

2.1.3.2.2.6 FD Prediction

The equipment shall [GPS 89] provide an FD prediction algorithm to enable LNAV approach operations. If the equipment uses barometric altitude to improve availability, the availability of corrected barometric altitude (either by automatic or manual altimeter setting input) may be assumed for this purpose. For the purpose of this calculation an acceptable value of the standard deviation of pressure altitude error is 50 meters.

A means to manually identify a satellite that is expected to be unavailable at the destination (for scheduled maintenance as identified in an FAA Notice to Airmen) may be provided. Identification of such a satellite for FD prediction purposes shall [GPS 90] not affect the satellite selection process or deselect that satellite from use in the navigation solution.

When making FD predictions within 30 NM of the destination, current weights may be used. For FD predictions, an acceptable value of the URA index for GPS satellites is 3. Acceptable values of ionospheric, tropospheric, and multipath error are the values associated with the satellite elevation angle at the estimated location and time of arrival. See Appendix J.3 for the $RMS_{pr\_air,GPS}$ ($\sigma_{i,air}$ term) for the minimum GPS signal level.

2.1.3.3 Equipment Reliability

See Section 2.1.2.3.

2.1.3.4 Satellite Tracking Capability

See Section 2.1.2.4.

2.1.3.5 Dynamic Tracking

When the aircraft has dynamics within normal maneuvers defined by the maximum ground speeds and accelerations shown below, the equipment shall [GPS 91] meet the accuracy requirements of 2.1.2.1 and the satellite acquisition time requirements of 2.1.1.6 and the satellite reacquisition requirements of 2.1.1.7. Note that g = acceleration of gravity = 9.8 m/s^2.

Ground Speed	Horiz. Accel.	Vertical Accel.	Total Jerk
250 kt	0.58 g	0.5 g	0.25 g/s

Abnormal maneuvers are defined to be maneuvers whose accelerations/jerks exceed these values, up to the maximum ground speeds and accelerations shown below.

Ground Speed	Horiz. Accel.	Vertical Accel.	Total Jerk
250 kt	2 g	1.5 g	0.74 g/s

During abnormal maneuvers, the equipment shall [GPS 92] not output misleading information. When the aircraft returns to normal maneuvers from abnormal maneuvers, the equipment shall [GPS 93] meet the steady-state reacquisition requirements of Section 2.1.1.7. During the abnormal maneuver period, loss-of-navigation capability and loss-of-integrity monitoring alerts and outputs shall [GPS 94] function as specified.

2.1.3.6 Position Output

See Section 2.1.2.6.

2.1.3.6.1 Position Output Update Rate

See Section 2.1.2.6.1.

2.1.3.6.2 Position Output Latency

See Section 2.1.2.6.2

2.1.3.6.3 Position Solution

See Section 2.1.2.6.3.

2.1.3.6.4 Smoothing

See Section 2.1.2.6.4.

2.1.3.6.5 Velocity Accuracy

See Section 2.1.2.6.5.

2.2 Airborne Equipment Performance - Environmental Conditions

The environmental tests and performance requirements described in this subsection are intended to provide a laboratory means of determining the overall performance characteristics of the equipment under conditions representative of those that may be encountered in actual operations.

The environmental performance requirements identified in this section must be met for all components in the airborne GPS equipment .

Some of the environmental tests contained in this subsection need not be performed unless the manufacturer wishes to qualify the equipment for the particular environmental condition. The unshaded columns of

TABLE 2-2 identifies the environmental tests that are required to qualify the equipment. The shaded columns identify the optional environmental tests that are to be performed if the manufacturer wishes to qualify the equipment for these additional environmental conditions. An “X” in the rows of

TABLE 2-2 identifies the GPS requirements that must be met while the equipment is subjected to the environmental test condition specified in the columns.

Unless otherwise specified, the pass/fail criteria are those specified in the test procedures applicable to the requirements listed in

TABLE 2-2 , as modified by Section 2.2.1.1. The test procedures applicable to a determination of equipment performance under environmental test conditions are set forth in RTCA document DO-160F, Environmental Conditions and Test Procedures for Airborne Equipment.

Some of the performance requirements in Section 2.1 of this document do not need to be tested to all of the conditions contained in RTCA/DO-160F; these requirements/conditions are not listed in Table 2-2 . Judgment and experience have indicated that these particular performance parameters are not susceptible to certain environmental conditions and that the level of performance specified in Section 2.1 will not be measurably degraded by exposure to these particular environmental conditions.

2.2.1 Environmental Tests

TABLE 2-2 shows the matrix chart that defines the tests required for the equipment. It shows the paragraph numbers in RTCA/DO-160F that describe the individual environmental tests. These tests must be performed on the test article as specified in the table.

RTCA/DO-160F contains equipment categories for each environmental condition with different environmental test limits for each category. The equipment manufacturer is allowed to choose to which environmental category the article is to be qualified, except for Lightning and Radio Frequency Susceptibility tests, for which a minimum test level is

.

specified. The manufacturer's certification must specifically state the environmental categories for which the article is qualified.

2.2.1.1 Required Performance

The following paragraphs state procedure requirements for demonstrating performance requirements stated in Table 2-2.

2.2.1.1.1 Accuracy

The demonstration of accuracy while subjecting the equipment to environmental tests described in RTCA/DO-160F must be done in accordance with Section 2.3.6.1 of this MOPS only for the test case with a broadband external interference noise. For all environmental tests except for temperature tests (RTCA/DO-160F, Sections 4.5.1 and 4.5.3) the procedure will not need to last longer than the minimum duration of the particular test as specified in RTCA/DO-160F. The test threshold is the 125% PASS THRESHOLD column in TABLE 2-6 and has been defined to yield an 80% probability of failing equipment with a true accuracy of 125% of the required accuracy.

Accuracy demonstrations must be performed to the LNAV requirement for all navigation modes capable by the equipment.

Note 1: For all environmental tests except temperature, only the broadband external interference noise test case using minimum satellite power will be executed unless the minimum duration of the particular test as specified in RTCA/DO-160F allows enough time to also execute the maximum satellite power case. In particular, the RF and induced signal susceptibility tests per section 2.2.1.2.3 only use the minimum satellite power.

Note 2: A simpler test procedure may be used to demonstrate accuracy under environmental conditions.

2.2.1.1.2 Loss of Navigation Indication

While demonstrating this performance requirement any of the sources that generate this indication may be used.

2.2.1.1.3 Loss of Integrity Indication

While demonstrating this performance requirement any of the sources that generate this indication may be used.

2.2.1.1.4 Initial Acquisition Test

The Initial Acquisition Time after abnormal interference test included within the Initial Acquisition test does not need to be performed during environmental testing.

2.2.1.1.5 Sensitivity and Dynamic Range

Demonstration of this requirement should be done in conjunction with demonstration of accuracy.

2.2.1.1.6 System Operating

The "System Operating" row in Table 2-2 exists for the environmental tests that require the system to simply be powered and operational while the environmental test is being performed.

2.2.1.2 Clarification of Environmental Tests

The following paragraphs provide additional guidance for the environmental tests described in RTCA/DO-160F.

2.2.1.2.1 Power Input Tests

When Normal Operating Conditions Tests, outlined in RTCA/DO-160F par. 16.5.1 & 16.6.1, (excluding 16.6.1.3.d “Double interrupt Requirement” tests 1 & 2, and 16.6.1.5 “Engine starting under-voltage operation) are being performed, the equipment shall [GPS 95] operate during the tests without interruption, so that the accuracy requirement shall [GPS 96] continue to be met. When Abnormal Operating Conditions Tests, par. 16.5.2 & 16.6.2, are being performed, the equipment is not required to operate normally during the specified minimum voltage period, but must not provide misleading information during and after the test, and must meet the initial acquisition time requirement after the minimum voltage period.

2.2.1.2.2 Icing Tests

Icing tests are required primarily for the antenna and only if the manufacturer wants to qualify the antenna as part of the GPS equipment. If an antenna is used that already has been qualified in this area, this environmental test is not required.

2.2.1.2.3 RF and Induced Signal Susceptibility Tests

The equipment shall [GPS 97] be qualified to at least equipment Category T of Section 20 of RTCA/DO-160F for conducted and radiated radio frequency susceptibility, and provide the required accuracy during the test. The high level radiated susceptibility does not apply between 1500 MHz and 1640 MHz.

To limit test time during the frequency scans of Sections 19.3.2 and 20 (RTCA/DO-160F), the accuracy test can be run on the aggregate data and repeated only at the frequencies of greatest susceptibility. The frequencies of greatest susceptibility should be determined by at least the following two methods. First, by inspection of the receiver design, the most susceptible frequencies are identified. Second, the value of pseudo-range error during the test will be compared to the standard deviation (not RMS) of the error during the scan and the frequencies with errors that deviate significantly from the aggregate are identified. The identification of frequencies can be made over sub-regions of the full frequency range as convenient given the set-up changes required when switching frequency bands; in this case, the aggregate data will be evaluated over each sub-region. Full accuracy tests are run at each of the specific frequencies identified by both methods for each type of test (conduction, radiated, and induced susceptibility).

Alternatively, the C/No (or the σ_{noise}) can be monitored to determine susceptibility as long as frequency dwell time is sufficient to detect the effect.

In addition, the GPS equipment shall [GPS 98] provide the required tracking when subjected to a radiated signal with continuous wave modulation at a frequency of 1.57542 GHz and an electric field strength of 20mv/meter measured at the exterior case of the GPS receiver. The radiated susceptibility test procedures of RTCA/DO-160F, Section 20, should be followed when conducting this test. The test should be conducted with simulated satellite inputs and should not result in the loss of track of any satellite used for navigation. The duration of the test must be sufficient to determine if tracking has been lost (20 seconds should normally be long enough, depending on the coasting features used by the GPS equipment).

2.2.1.2.4 Lightning Induced Transient Susceptibility Tests

The equipment should at least be qualified with an appropriate wave form set and test level from Section 22 of RTCA/ DO-160F for lightning induced transient susceptibility which is compatible with the GPS antenna(s) specified to be used with the equipment by the manufacturer. The equipment is not required to operate normally during the lightning transient test, and must automatically become operational within the specified acquisition time requirement.

2.2.1.2.5 Lightning Direct Effects Tests

Lightning Direct Effects Tests outlined in Section 23 of RTCA/ DO-160F are required for the antenna. The antenna(s) should function normally after the lightning direct effects tests have been conducted.

Note: Because of GPS antenna mounting requirements, the antenna should be qualified for mounting in at least Lightning Zone 2A.

2.2.1.2.6 Crash Safety Shock

All equipment shall [GPS 99] pass the crash safety shock test as specified in of RTCA/ DO-160F, Section 7.3. Applicants shall [GPS 100] select the aircraft type and the appropriate shock levels to which they wish to qualify their equipment.

TABLE 2-2 GPS ENVIRONMENTAL TEST REQUIREMENTS

MOPS Section	Requirement	DO-160F Requirement	Low Operating Temp. Test	High Short-Time Temp. Test	High Operating Temp. Test	In-Flight Loss of Cooling	Altitude Test	Decompression Test	Overpressure Test	Temperature Variation Test	Humidity Test	Operational Shocks	Crash Safety Shocks	Vibration Test	Explosion Proofness Test	Condensation Drip Proof Test	Drip Proof Test	Spray Proof Test	Cont. Stream Proof Test	Spray Test	Immersion Test	Sand and Dust Test	Fungus Resistance Test	Salt Fog Test	Magnetic Effect Test	Norm/Abnorm Op Conditions (AC)	Norm/Abnorm Op Conditions (DC)	Volt. Spike Cond. Test	Audio Freq. Cond. Susc. Test	Induced Signal Susc. Test	RF Susceptibility Test	Emission of RF Energy Test	Lightning Ind. Trans. Susc.	Lightning Direct Effects	Icing	Electrostatic Discharge	Fire, Flammability Test
	Environmental	Section	4.5.2	4.5.3	4.5.4	4.5.5	4.6.1	4.6.2	4.6.3	5	6	7.2	7.3	8	9	10.3.1	10.3.2	10.3.3	10.3.4	11.4.1	11.4.2	12	13	14	15	16.5.1,2	16.6.1,2	17	18	19	20	21	22	23	24	25	26
2.1.3.1	Accuracy		X	X	X	X	X	X	X	X	X	X		X		X	X	X	X	X	X	X	X	X		X	X	X	X	X	X		X	X	X	X	
2.1.1.13.2	Loss of Nav.		X		X																																
2.1.1.13.1	Loss of Integrity		X		X																																
2.1.1.10	Sensitivity		X	X	X	X	X	X	X	X	X	X		X		X	X	X	X	X	X	X	X	X		X	X	X	X	X	X		X	X	X	X	
2.1.1.7	Acquisition Time																										X						X	X			
2.1.1.9	Reacquisition Time																									X									X		
NA	Sys. Operating																								X							X					

2.3 Test Methods and Procedures

The following definitions of terms and conditions of tests are applicable to equipment tests specified herein:

a. Power Input Voltage

Unless otherwise specified, all tests shall [GPS 101] be conducted with the power input voltage adjusted to design voltage ±2 percent. The input voltage shall [GPS 102] be measured at the input terminals of the equipment under test.

b. Power Input Frequency

(1) In the case of equipment designed for operation from an AC power source of essentially constant frequency (e.g. 400 Hz), the input frequency shall [GPS 103] be adjusted to design frequency ±2 percent.

(2) In the case of equipment designed for operation from an AC power source of variable frequency (e.g. 300-1000 Hz), unless otherwise specified, tests shall [GPS 104] be conducted with the input frequency adjusted to within ±5 percent of a selected frequency and within the range for which the equipment is designed.

c. Standard Test Signals and Simulator Requirements

(1) The GPS simulator shall [GPS 105] operate in accordance with the GPS SPS Performance Standard, Navstar GPS Interface Specification (IS-GPS-200D).

Note: The development of software to RTCA/DO-178B includes tool qualification of the GPS simulator.

(2) Unless otherwise specified, all GPS signals will not indicate UNHEALTHY, erroneous, failed, abnormal, or marginal conditions. The signals will contain ranging errors as calculated by approved models of the troposphere, ionosphere, satellite clock, and satellite ephemeris.

(3) The broadband noise used to simulate sky and antenna thermal noise density ($N_{sky,antenna}$), GNSS test noise ($I_{GNSS,Test}$) and external interference ($I_{Ext,Test}$) shall [GPS 106] have a bandwidth greater than the RF bandwidth of the equipment under test. $I_{GNSS,Test}$ is defined as the broadband noise needed to ensure that the total effective noise (including the intra-system noise produced by the interfering satellites actually simulated during the test procedure) equals the values specified in Appendix C. The pulsed interference source requires an on/off ratio of 154 dB in order to achieve the necessary isolation. The CWI interference generator shall [GPS 107] be accurate to within 1 kHz.

(4) The signal and interference levels cited in the following test procedures are defined with respect to the input of the antenna preamplifier (active antenna). The test set-up must include a test amplifier that has the same gain as the active portion of the antenna. If any interference is inserted after the test amplifier, the interference level must be adjusted to reflect the expected interference at the insertion point. The minimum or maximum installation loss (as appropriate for the test case) must be included in the test setup, using passive devices. This accounts for the noise generated by the aircraft cabling. When using a specific antenna, the satellite signal levels at the test preamplifier input are adjusted based on the minimum antenna radiation pattern above five degrees; the maximum antenna radiation pattern (taking into account the satellite gain characteristics); and the CW interference levels, adjusted by the minimum frequency selectivity of the specific antenna/preamplifier. The test signals presented to the equipment

under test, unless otherwise specified, shall [GPS 108] account for the minimum preamplifier gain and maximum loss ($_{Lmax}$) between the antenna port and the receiver port**.** Unless otherwise specified, the interference tests are conducted with one GPS satellite at maximum power (-121 dBm which includes maximum combined satellite and antenna radiation pattern gain), one satellite at minimum power (-134 dBm which includes minimum radiation pattern gain), and remaining satellites 3 dB above the satellite at minimum power.

(5) For interference tests conducted with all satellites at maximum power, the test signals presented to the equipment under test shall [GPS 109] be the maximum input signal at the receiver port accounting for the maximum preamplifier gain and minimum fixed loss (L_{min}) between the antenna port and the receiver port.

(6) The test setup must provide the total specified broadband noise at the input to the test amplifier. This total noise comes from the simulator, a noise generator (as appropriate), and the test amplifier. The simulator noise ($I_{Simulator}$) includes all noise generated by the test equipment up to the input to the test amplifier. The test amplifier noise figure is NF_{Amp}, and broadband noise from the noise generator is I_{NG}. The test setup must ensure that:

$$[10^{I_{Simulator}/10} + 10^{I_{NG}/10} + 290k(10^{NF_{Amp}/10} - 1)] \geq$$

$$[10^{N_{sky,antenna}/10} + 10^{I_{GNSS,Test}/10} + 10^{I_{Ext,Test}/10}]$$

Note that additional noise is included in the test from the GNSS signals that are simulated and from the noise contribution of the loss block.

Note 1: The specified test procedures provide a representative level of self-interference when acquiring, re-acquiring, and tracking the minimum signal. The test represents a reasonable baseline scenario with respect to self-interference caused by C/A code GPS and SBAS signals, P(Y), and Earth Coverage M code GPS signals, Galileo signals, and QZSS signals.

Note 2: Authorized emissions are regulated to a level below the external interference levels (as described in Appendix C) to provide a safety margin.

Note 3: RTCA is updating RTCA/DO-235 to address complete GNSS inter/intra system interference environment. The GNSS Noise specified herein represents the current state of this work at time of publication and includes a safety margin.

Note 4: Refer to Appendix M for examples of the broadband noise calibration.

d. Adjustment of Equipment

The circuits of the equipment under test shall [GPS 110] be aligned and adjusted in accordance with the manufacturers' recommended practices prior to the application of the specified tests.

e. Test Instrument Precautions

Due precautions shall [GPS 111] be taken during the tests to prevent the introduction of errors or misleading data resulting from the connection of voltmeters, oscilloscopes and other test instruments across the input and output impedance of the equipment under test.

f. Ambient Conditions

Unless otherwise specified, all tests shall [GPS 112] be conducted under the conditions of ambient room temperature, pressure and humidity. However, room temperature shall [GPS 113] not be lower than 10 degrees Celsius.

g. Warm-up

Unless otherwise specified, all tests shall [GPS 114] be conducted after the manufacturers' specified warm-up period.

h. Connected Loads

Unless otherwise specified, all tests shall [GPS 115] be conducted with the equipment connected to loads having the impedance values for which it is designed.

i. Analysis

Analysis is the method of verification which consists of comparing hardware or software design with known scientific and technical principles, technical data, or procedures and practices to validate that the proposed design will meet the specified functional or performance requirements

j. Demonstration

Demonstration is the method of verification where qualitative versus quantitative validation of a requirement is made during a dynamic test of the equipment. Additional definition applied to this term includes:

(1) In general, software functional requirements are validated by demonstration since the functionality must be observed through some secondary media.

k. Inspection

Inspection is the method of verification to determine compliance with specification requirements and consists primarily of visual observations or mechanical measurements of the equipment, physical location, or technical examination of engineering support documentation.

l. Test

Test is the method of verification that will measure equipment performance under specific configuration load conditions and after the controlled application of known stimuli. Quantitative values are measured, compared against previous predicated success criteria and then evaluated to determine the degree of compliance.

The following subsections define the minimum test procedures required to substantiate the minimum operation performance required for sensors using GPS. Alternative procedures may be used if they provide an equivalent evaluation of the GPS equipment. These test procedures assume the GPS equipment is compliant with the minimum standard, and no additional augmentations (e.g., barometric aiding) are incorporated.

2.3.1 Reserved

2.3.2 Step Detector Test

The step detector is tested under four scenarios. If the manufacturer can show by inspection that its equipment's step detection mechanism is insensitive to the type of step (a change in navigation data or a sudden change in code phase), only one type of step need be tested. Typical satellite signal power may be used during these tests.

2.3.2.1 Verification of Step Detector Operation Without Exclusion Capability

Simulate a satellite scenario as follows:

1) Only five satellites in view and used in the positioning solution.

After the equipment reaches steady-state operation (i.e. navigates with integrity using all of the applied satellite signals), simulate a 750 meter step error on the hardest-to-detect satellite being used in the position solution by changing the navigation message. Repeat the test with a step change in code phase to simulate the 750 meter step error.

In order to pass, the equipment must do the following:

2) The satellite with the step error should be removed from the positioning solution within 10 seconds of introducing the pseudorange step;

3) The positioning error is not to exceed 200 meters throughout the entire test; and,

4) The HPL will be unavailable and the loss of integrity monitoring will be indicated.

Note: When a step is introduced by changing the broadcast ephemeris data, the pseudorange step does not occur until after receipt of a second set of the broadcast ephemeris (per Section 2.1.1.2).

2.3.2.2 Verification of No Interference with Fault Detection Algorithm

Simulate a satellite scenario as follows:

1) Only five satellites in view and used in the positioning solution; and,

2) HPL less than 0.3 nm.

After the equipment reaches steady-state operation, simulate a ramp error in the hardest-to-detect satellite being used in the position solution (10 meters/second).

In order to pass, the equipment must do the following:

3) At no time is there to be an exclusion of any satellite; and,

4) The FD algorithm shall [GPS 116] indicate a positioning failure within the time-to-alert after the onset of the positioning failure;

2.3.2.3 Verification of Step Detector Operation with Exclusion Capability

Simulate a satellite scenario as follows:

1) Six or more satellites in view and used in the positioning solution; and,

2) Detection and exclusion capability are available for an alert limit of 0.3 nm.

After the equipment reaches steady-state operation (i.e. navigates with integrity using all of the applied satellite signals), simulate a 750 meter step error on the hardest-to-detect satellite being used in the position solution by changing the navigation message. Repeat the test with a step change in code phase to simulate the 750 meter step error.

To pass, the equipment must do the following:

3) The satellite with the step error shall [GPS 117] be removed from the position solution within 10 seconds of introducing the step error;

4) The positioning error is not to exceed 200 meters throughout the entire test, before and after the introduction of the step error; and

5) HPL will change.

Note: When a step is introduced by changing the broadcast ephemeris data, the pseudorange step does not occur until after receipt of a second set of the broadcast ephemeris (per Section 2.1.1.2).

2.3.2.4 Verification of No Interference with Exclusion of the FDE Algorithm

Simulate a satellite scenario as follows:

1) Six or more satellites in view and used in the positioning solution; and,
2) Detection and exclusion capability are available for an alert limit of 0.3 nm.

After the equipment reaches steady-state operation, simulate a ramp error in the hardest-to-detect satellite being used in the position solution (10 meters/second).

In order to pass, the equipment must do the following:

3) The exclusion function should operate normally, eliminating the error as a positioning failure develops.

2.3.3 Initial Acquisition Test Procedures

2.3.3.1 Simulator and Interference Conditions

The tests to verify initial acquisition performance shall [GPS 118] be run for each of the GPS signal generator (simulator) scenarios described below. It is not intended to verify the accuracy of the atmospheric corrections; these corrections need not be included in the test.

Scenario #1: Initial Acquisition Time Test

1) Exactly 5 GPS satellites with C/A code only.
2) Broadband GNSS test noise ($I_{GNSS,Test}$) of spectral density equal to -172.7 dBm/Hz at the antenna port (the contribution of simulated satellites has been removed for the specified noise density).
3) Broadband external interference ($I_{Ext,Test}$) of spectral density equal to -176.5 dBm/Hz at the antenna port.
4) Thermal noise contribution from the sky and from the antenna (See $N_{sky,antenna}$ in 2.1.1.8).
5) One satellite at maximum power (including maximum combined satellite and aircraft antenna gain), one satellite at minimum power (including minimum antenna gain), and other satellites 3 dB above the one satellite at minimum power (see 2.1.1.8).
6) Platform dynamics: Constant velocity of 800 kt beginning at 5,000 ft (MSL) and performing a 3° climb.

The test to verify initial acquisition performance after abnormal interference shall [GPS 119] be run for the GPS signal generator (simulator) scenario described below:

Scenario #2: Initial Acquisition Time after abnormal interference Test

1) Exactly 5 GPS satellites with C/A code only.
2) Broadband GNSS test noise ($I_{GNSS,Test}$) of spectral density equal to -172.7 dBm/Hz at the antenna port (the contribution of simulated satellites has been removed for the specified noise density).
3) Broadband external interference ($I_{Ext,Test}$) of spectral density equal to -176.5 dBm/Hz at the antenna port.
4) Thermal noise contribution from the sky and from the antenna (See $N_{sky,antenna}$ in 2.1.1.8).

5) One satellite at maximum power (including maximum combined satellite and aircraft antenna gain), one satellite at minimum power (including minimum antenna gain), and other satellites 3 dB above the one satellite at minimum power (See 2.1.1.8).

6) Platform dynamics: Constant velocity of 800 kt and constant altitude.

The GNSS and external interference is to be applied to the receiver before it is powered on or the simulator is engaged.

2.3.3.2 Test Procedures (Initial Acquisition)

1) The broadband GNSS test noise, the broadband external interference noise, and $N_{sky,antenna}$ shall [GPS 120] be simulated.

2) The simulator scenario shall [GPS 121] be engaged and the satellites RF shall [GPS 122] be turned on.

3) The airborne equipment shall [GPS 123] be powered and initialized to a position with total radial error equal to 60 nautical miles, and one minute (60 seconds) of error in time with respect to the starting position and time reference in the simulator. It is assumed that the receiver has obtained a valid almanac for the simulator scenario to be tested prior to conducting these tests.

4) The time to first valid position fix (TTFF), defined as the time from when the equipment is powered on until the first valid position (with integrity, i.e. HPL is available) is output, shall [GPS 124] be observed. Integrity shall [GPS 125] be provided by the sensor's FDE algorithm. Along with the TTFF, at least the next 60 seconds of continuous position fixes (a minimum of 60 data points) after the initial fix shall [GPS 126] also be recorded in order to verify the accuracy requirement.

5) Precise ephemeris shall [GPS 127] be purged or rendered invalid at the end of each acquisition attempt.

6) Go to Step 2 and repeat as required.

2.3.3.3 Pass/Fail Determination

The accuracy statistic that will be compared with the 15 m (95%) horizontal accuracy requirement stated in section 2.1.2.1 shall [GPS 128] be computed using the 2drms formula shown below.

$$2drms = 2\sqrt{\frac{\sum_{i=1}^{N}\left(\frac{1.5(d_i)}{HDOP_i}\right)^2}{N}}$$

where:

2drms=Twice the distance, root-mean-square

d_i = Instantaneous 2-D horizontal position error (meters)

N = Number of points considered

HDOP = Instantaneous Horizontal Dilution of Precision

The use of the 2drms formula provides a conservative estimate of the 95% error and effectively weights large position errors that may be caused by unwanted interference. A failure by the sensor to produce a position output after 5 minutes indicates a failure mode, and results in declaring the test a failure.

Scaling the instantaneous 2-dimensional position error (d_i) by 1.5/$HDOP_i$ provides a means of normalizing the tests to a constant HDOP = 1.5 and accounts for fluctuations in the satellite coverage due to changing geometries. $HDOP_i$ may be obtained from the receiver under test or calculated separately. Only those satellites used in the position solution shall [GPS 129] be included in the $HDOP_i$ calculation. The manufacturer shall [GPS 130] demonstrate the validity of the values chosen for $HDOP_i$.

To determine the initial acquisition pass/fail criteria, consider a single trial where the sensor under test provides a valid position fix within the required time (5 minutes) and maintains the required accuracy (15 m, 95%) for at least the next 60 seconds. This sensor is considered to have passed one (1) trial. Table 2-3 shows the total test disposition and represents a quit-while-ahead testing approach designed to keep testing times at a reasonable length.

TABLE 2-3 GRADUATED SAMPLING PASS/FAIL CRITERIA

Trials	Cumulative Failures within Specified Time	Test Disposition
First Ten (10)Trials	Zero (0) One (1) Two (2) or More	Pass Run Ten (10) More Fail
Second Ten (10) Trials	Zero (0) One (1) or Two (2) Three (3) or More	Pass Run Ten (10) More Fail
Third Ten (10) Trials	Zero (0) One (1) or More	Pass Fail

For example, if no failures occur in the first ten trials, success for that simulator and interference case would be declared and the current test terminated. A single failure in the first set of ten trials necessitates running the next set of ten trials. Two or more failures during the first ten trials indicate that the sensor has failed that particular test, and so on. Justification for the above-stated criteria is shown in Appendix M.

2.3.3.4 Test Procedures (Initial Acquisition After Abnormal Interference)

The abnormal CW interference frequency is at 1575.42 MHz and the power level is selected to ensure that no GPS satellites can be tracked at that power. The test procedure is the same as the initial acquisition test, with the following exceptions:

1) Before the equipment has output a valid position for one minute, the signal power may be set to a higher level, or, the broadband noise to a lower level to facilitate acquisition.
2) After the equipment has output a valid position for one minute, apply the abnormal CW interference. Remove the abnormal interference after 1 minute in the first trial, 2 minutes in the second trial, and so on up to 10 minutes in the tenth trial.
3) The time to first valid position fix (TTFF) for this test is defined as the time from when the abnormal CW interference is removed until the first valid position (with integrity, i.e. HPL is available) is output.

4) When reinitializing between trials, it is not necessary to purge the precise ephemeris data.

2.3.4 Satellite Reacquisition Time Test

2.3.4.1 Simulator and Interference Conditions

The tests to verify reacquisition performance shall [GPS 131] be run for each of the GPS signal generator (simulator) scenarios described below:

Steady-State Reacquisition Time Test (GPS C/A code)

1) Broadband GNSS test noise (IGNSS,Test) of spectral density equal to -172.4 dBm/Hz at the antenna port (the contribution of simulated satellites has been removed for the specified noise density).
2) Thermal noise contribution from the sky and from the antenna (See $N_{sky,antenna}$ in 2.1.1.8).
3) Broadband external interference noise (IExt,Test) of spectral density equal to -170.5 dBm/Hz at the antenna port.
4) Platform dynamics: Constant velocity of 800 kt beginning at 5,000 ft (MSL) and performing a 3° climb.
5) Any number of GPS satellites at any power until the sensor reaches steady state navigation.
6) Then one satellite at maximum power (including maximum combined satellite and aircraft antenna gain), one satellite at minimum power (including minimum antenna gain), and other satellites 3 dB above the one satellite at minimum power (See 2.1.1.8).
7) Then, turn off the minimum power satellite to retain exactly 4 GPS satellites providing a GDOP of 6 or less, preparing to reacquire the lost GPS satellite, which is just above the mask angle and whose RF state (on or off) shall [GPS 132] be controlled by the simulator.
8) Finally, the signal from the fifth GPS satellite to be acquired is turned on at minimum power.

2.3.4.2 Test Procedures

1) The broadband GNSS test noise, the broadband external interference noise, and $N_{sky,antenna}$ shall [GPS 133] be simulated.
2) The simulator scenario shall [GPS 134] be engaged and the satellites RF shall [GPS 135] be turned on.
3) The airborne equipment shall [GPS 136] be powered. It is assumed that the receiver has obtained a valid almanac for the simulator scenario to be tested prior to conducting these tests.
4) The sensor shall [GPS 137] be allowed to reach steady state accuracy before the satellite to be reacquired is cycled off and on. Once in steady state navigation, the simulated satellites and the broadband noise shall [GPS 138] be set to the appropriate steady state power levels.
5) The satellite whose reacquisition is being tested shall [GPS 139] be removed from the sensor, at least until the sensor has lost lock on the satellite and removed

the satellite from the position solution, and then reapplied to the sensor within 30 seconds.

6) The reacquisition time, or time to satellite inclusion, defined as the time from when the satellite under test is reapplied to the sensor until the first valid position which includes that satellite is output, shall [GPS 140] be observed. In addition, at least the next 60 seconds of position fixes (sampled at the minimum of once per second) after the inclusion of the reacquired satellite, shall [GPS 141] also be recorded in order to verify the 15 m (95%) requirement.

7) Reset the scenario (including signal and noise power levels), go to Step 2 and repeat as required.

2.3.4.3 Pass/Fail Determination

The accuracy statistic shall [GPS 142] be computed using the 2drms formula as shown in Section 2.3.3.3.

To determine the reacquisition time pass/fail criteria, the graduated sampling pass/fail criteria of Table 2-3 shall be used. A single trial success occurs when the sensor under test includes the reacquired satellite into the position solution within the required time (20 seconds) and maintains the required accuracy, 15 m (95%), for the following 60 seconds.

The statistical justification for the reacquisition time test follows that for initial acquisition and can be found in Appendix M.

2.3.5 Interference Rejection Test

2.3.5.1 Simulator and Interference Conditions

These tests are intended to verify the performance of the sensor in the presence of in-band continuous-wave interference conditions at and above the levels of Appendix C. Tests shall [GPS 143] be run for the GPS signal generator (simulator) scenario described below.

The simulation and interference conditions shall [GPS 144] conform to the following two requirements:

1) Simulated GPS RF for PRN 6 shall [GPS 145] be at the minimum power level for the equipment (as described in Section 2.1.1.8). Other satellites shall [GPS 146] be at a high power level to minimize the effect of interference on their pseudorange.

2) The CWI frequency tested shall [GPS 147] be 20 Hz ±5 Hz offset below the 3rd spectral line below the received carrier frequency of PRN 6 (i.e., 3020 Hz offset from the carrier frequency). The initial CW power shall [GPS 148] be -120.5 dBm (may be reduced during initial acquisition). The I/S ratio will be varied according to the test procedures. The exact frequency relationship must be maintained throughout the test. The scenario shall [GPS 149] include PRN 6 because it is used in the definition of the CWI frequency.

Note: *This evaluation method is based on the assumption that a weighted least-squares position algorithm is implemented, and that the baseline integrity algorithms are used. If a different form of positioning or integrity method is used, this evaluation method may not be appropriate.*

2.3.5.2 Test Procedures

1) The CW interference to be applied shall [GPS 150] be turned on and connected to the sensor. Note that the power of the CW interference during initial acquisition is lower than that for steady-state operation. Broadband external interference and GNSS test noise do not need to be simulated for this test.
2) The simulator scenario shall [GPS 151] be engaged and the satellites RF shall [GPS 152] be turned on.
3) The airborne equipment shall [GPS 153] be powered and initialized. It is assumed that the receiver has obtained a valid almanac for the simulator scenario to be tested prior to conducting these tests.
4) The sensor shall [GPS 154] be allowed to reach steady state. When the sensor has reached steady state, the power of the CW interference shall [GPS 155] be adjusted to -120.5 dBm.
5) The CW interference power shall [GPS 156] be maintained until the accuracy has reached steady-state. Pseudorange measurements and pseudorange validity indications (e.g., isolation bit) for all satellites shall [GPS 157] be recorded during this interval.
6) The power of the CW interfering signal shall [GPS 158] be increased by 1 dB and maintained for 200 seconds. Pseudorange measurements and pseudorange validity indications (e.g., isolation bit) for all satellites shall [GPS 159] be recorded during this interval.
7) Go to Step 6 and repeat until PRN 6 has been excluded from the navigation solution. Increase the CW interfering signal another 3 dB and verify that PRN 6 is still excluded.

2.3.5.3 Pass/Fail Determination

For each sample when the PRN 6 pseudorange is declared valid, the following error criterion shall [GPS 160] be evaluated:

$$Z_j \le 5.33\left[\frac{N_j - 1}{N_j}\right]\sigma_{noise,PRN6,j}$$

where:

$$Z_j \equiv PR_{PRN6,j} - R_{PRN6,j} - (c\Delta t)_j$$

$$(c\Delta t)_j \equiv \frac{1}{N_j}\sum_{i=1}^{N_j}\left(PR_{ij} - R_{ij}\right)$$

PR_{ij} = pseudo-range, channel i, time j

R_{ij} = true range, satellite i, time j (includes extrapolation)

N_j = number of satellites at time j

$\sigma_{noise,ij}$ = receiver output or equivalent, satellite i, time j (refer to Appendix J.2.4)

If the error criterion is exceeded for more than the appropriate time to alert, the test fails.

2.3.6 Accuracy Tests

2.3.6.1 Measurement Accuracy Test

The purpose of the Accuracy Test is to validate that the equipment meets the accuracy requirements of Section 2.1.2.1 and 2.1.3.1 under the specified interference conditions. It is also intended to verify that the σ_{noise} used in the protection level equations is an appropriate bound on the residual errors allocated to the receiver tracking performance. It is not intended to verify the accuracy of the atmospheric corrections; these corrections need not be included in the test.

Note: *This evaluation method is based on the assumption that a least-squares position algorithm is implemented. If a different form of positioning is used, this evaluation method may not be appropriate.*

2.3.6.2 Simulator and Interference Conditions

The simulation and interference conditions shall [GPS 161] conform to the following requirements:

1) For all test scenarios, the broadband GNSS test noise and $N_{sky,antenna}$ shall [GPS 162] be simulated. There are three sets of interference test scenarios: broadband external interference noise, Continuous Wave Interference, and pulsed interference.

   a) The broadband external interference noise ($I_{Ext,Test}$) has a spectral density equal to -170.5 dBm/Hz as seen at the antenna port.

   b) The CW power and frequencies are listed in Table 2-4.

   c) For the pulsed interference tests, a pulse modulated carrier at 1575.42 MHz with a signal bandwidth of 1 MHz, with peak carrier level of +10 dBm, pulse width of 125 usec, and duty cycle of 1% shall [GPS 163] be used. This corresponds to an I/S ratio of +144 dB for GPS satellites.

2) The GNSS test noise depends on the number, power, and type of satellites simulated during the test. The power spectral density of the total GNSS Noise (I_{GNSS}) is -171.9 dBm/Hz (See Appendix C.2.3). The effective noise power spectral density (I_{Test}) of the satellites present in the simulator scenario may be removed from the total GNSS Noise; to do so, the satellite equivalent power spectral density specified in Table 2-5 (I_{GH}, I_{GL}, I_{SH}, and I_{SL}) is removed for each satellite present. The number of maximum power GPS satellites is N_{GH}, the number of minimum power GPS satellites is N_{GL}, the number of maximum power SBAS satellites is N_{SH}, and the number of minimum power SBAS satellites is N_{SL}. The GNSS test noise is determined by removing I_{Test} from I_{GNSS} as follows:

$$I_{GNSS,Test} = 10\log10[10^{-171.9//10} - 10^{I_{Test}/10}]$$

where:

$$I_{Test} = 10\log10[(N_{GL})10^{I_{GL}/10} + (N_{GH})10^{I_{GH}/10} + (N_{SL})10^{I_{SL}/10} + (N_{SH})10^{I_{SH}/10}]$$

Note: *The indicated power levels (both signal and noise) are for the steady-state portion of the tests; power levels are set to the required values once steady state navigation has been achieved. Refer to Appendix M for an explanation of how I_{Test} is derived and examples of the computation of $I_{GNSS,Test}$ and how it may be applied.*

3) Simulated GPS and SBAS RF shall [GPS 164] be at the minimum power level for the equipment, except for the broadband external interference noise case that shall [GPS 165] be tested at the maximum power level as well as the minimum power level. For test cases that require the minimum power level, one GPS satellite shall [GPS 166] be set to the maximum power level (including maximum transmit power and maximum combined satellite and aircraft antenna gain). For these cases the pseudorange samples of the satellite at maximum power are not used in the evaluation. The scenario shall [GPS 167] include PRN 6 because it is used in the definition of the CWI frequency. For all conditions, during the portion of the test where accuracy is evaluated, at least two SBAS satellites shall [GPS 168] be used.

Note 1: The steady-state accuracy test will include a total of nine cases (ten when installed on aircraft with SATCOM).

4) The total duration of each test case test shall [GPS 169] be based upon sampling intervals required to obtain samples that are statistically independent. Independent samples collected during the initial acquisition and before steady-state operation are used for the validation of σ_{noise} overbounding. The samples collected prior to steady-state operation should not be used for the steady-state RMS accuracy evaluation and the steady-state evaluation of $\left(\sigma_{noise}^2[i]+\sigma_{divg}^2[i]\right)^{1/2}$.

TABLE 2-4 STEADY STATE ACCURACY TEST CWI VALUES*

Frequency (MHz)	Power (dBm)	I/S (dB)
1525.0	-12.0	122.0
1555.42	-89.5	44.5
1575.42**	-120.5	13.5
1595.42	-89.5	44.5
1610.0	-30.0	104.0
1618.0	-12.0	122.0
1626.0***	+8.0	142.0

* The CWI power is specified at the antenna port. The actual level used during testing is reduced by the minimum frequency selectivity of the active antenna adjusted for any filtering in the test set-up itself. When demonstrating compatibility with a minimum standard active antenna, the frequency selectivity is specified in Appendix C.3 (derived from RTCA/DO-301). When using a passive antenna, the interference levels specified in Appendix C.2.1 and the total frequency selectivity of the user equipment should be taken into account. When using a specific antenna, its minimum frequency selectivity can be used when determined in accordance with RTCA/DO-301.

** The CWI frequency tested shall [GPS 170] be 20 Hz ± 5 Hz offset below the 3rd spectral line below the carrier frequency of PRN 6 (i.e., 3020 Hz offset from the carrier frequency). The CWI must be synchronized to the satellite signal provided. The exact frequency relationship must be maintained throughout the test.

*** Only Required for Aircraft with SATCOM

Note: Care should be taken when applying non-L1 CW frequencies so that the L1 CW and broadband specifications are not exceeded.

TABLE 2-5 SATELLITE EQUIVALENT POWER SPECTRAL DENSITY

Satellite Type	Maximum Power Satellite	Minimum Power Satellite
GPS	I_{GH} = -183.5 dBm/Hz	I_{GL} = -196.5 dBm/Hz
SBAS	I_{SH} = -179.8 dBm/Hz	I_{SL} = -198.3 dBm/Hz

Note: *These values of equivalent power spectral density were computed using the same assumptions as were used to determine the total GNSS Noise in Appendix C.*

2.3.6.2.1 Test Procedures

1) The test unit is connected to the RF signal and interference source.
2) The simulator scenario shall [GPS 171] be engaged and the satellites RF shall [GPS 172] be turned on.
3) The equipment under test shall [GPS 173] be powered and initialized. It is assumed that the receiver has obtained a valid almanac for the simulator scenario to be tested prior to conducting these tests.
4) When the unit is navigating, the interference to be applied shall [GPS 174] be applied to the equipment under test, and the power of the signal and interference shall [GPS 175] be adjusted to the required level. Sampling should begin for each satellite immediately after it is included in the navigation solution for the σ_{noise} overbounding evaluation described in paragraph 8) below.
5) When steady-state accuracy is reached, data are recorded as follows:
6) Initially, 50 independent samples of pseudorange data are recorded at the required sampling interval (see note below).

Note: *The sampling interval will be two times the integration interval used for carrier phase smoothing of pseudoranges. For example, if the integration interval used for carrier smoothing of the pseudoranges is 100 second, the sampling interval will be 200 seconds. If pseudorange measurements for ten satellites are collected per sampling interval, this results in 9 independent samples, as the equivalent of one measurement must be used to estimate the receiver clock bias cΔt for this interval. The duration of the initial data collection period will then be approximately 18.5 minutes [computed as follows: (50 independent samples) × (1 sampling interval / 9 independent samples) × (200 seconds / 1 sampling interval) × (1 minute / 60 seconds)].If unsmoothed pseudoranges are used for this test the time interval between independent samples is typically 1 second.*

7) The normalized RMS range error statistic, RMS_PR, is computed according to the following formula, using all collected samples (including those prior to steady-state operation):

$$RMS\_PR(M) \equiv \sqrt{\frac{\sum_{j=1}^{M}\left\{\sum_{i=1}^{N_j}\frac{Z_{ij}^2}{\left[\sigma_{norm,ij}^2 N_j\right]}\right\}}{M}}$$

where:

$$Z_{ij} \equiv PR_{ij} - R_{ij} - (c\Delta t)_j$$

$$(c\Delta t)_j \equiv \frac{1}{N_j}\sum_{i=1}^{N_j}\left(PR_{ij} - R_{ij}\right)$$

$$\sigma^2_{norm,ij} = \frac{\left[\left(N_j - 1\right)^2 \sigma^2_{noise,ij} + \sum_{\substack{k=1 \\ k \neq i}}^{N_j} \sigma^2_{noise,kj}\right]}{N_j^2}$$

where:

PR_{ij} = pseudo-range, channel i, time j

R_{ij} = true range, satellite i, time j (includes extrapolation)

N_j = number of satellites at time j

M = number of sampling intervals

$\sigma_{noise,ij}$ = satellite i, time j (refer to Appendix J.3)

Note 1: Interchannel biases on the simulator may impede the accuracy test specified herein. It may be necessary to determine this bias and inflate the test threshold based upon equipment calibration. If two receivers are used to remove this bias (via double-differencing), the test must account for potential interchannel biases in the receivers themselves and cannot simply remove all bias components.

Note 2: Since code-carrier divergence is not simulated in this test, the σ_{divg} term is not used in this normalization. Validation of σ_{divg} should be accomplished by analysis.

8) Verification of σ_{noise} overbounding: The error statistic is compared to the 110% Pass Threshold of Table 2-6 based on the Number of Independent Samples (NIS), where NIS is given by:

$$NIS(M) \equiv \sum_{j=1}^{M}\left(N_j - 1\right)$$

If RMS_PR is below the pass threshold, the result is a pass. If the RMS_PR is not below the pass threshold, additional data may be collected. In this case, the RMS_PR shall [GPS 176] include the initial independent samples plus all additional data, and the formulas and pass criteria of this section (which apply for an arbitrary number of samples) shall [GPS 177] be used.

Note: It is expected that the pass criteria will not be met with the initial data collection (only the initial acquisition and 50 steady-state operation independent samples due to the limited sample size. Development of the test criteria, and the associated pass probabilities are described in Appendix M.

9) Steady-state value of $\left(\sigma^2_{noise}[i] + \sigma^2_{divg}[i]\right)^{1/2}$: Using only those samples collected during steady-state, the average $\left(\sigma^2_{noise}[i] + \sigma^2_{divg}[i]\right)^{1/2}$ output values for each satellite are compared to the requirements of J.3. The output values must be less than or equal to the required accuracy values for the designator of the equipment.

10) Verification of RMS accuracy: The steps defined in paragraph 6 and 7 are repeated using only those samples collected during steady-state operation and using the required RMS accuracy (section 2.1.2.1 minus any steady-state value of σ_{divg} and minus the manufacturer's allocation to multipath) instead of the output $\sigma_{noise,i,j}$ in the computation of $\sigma_{norm,i,j}$. The pass criteria defined in paragraph 8 applies.

TABLE 2-6 PASS THRESHOLD TABLE

NIS	110% Pass Threshold	125% Pass Threshold
25-50	N/A	1.084
50-75	0.954	1.137
75-100	0.981	1.159
100-150	0.998	1.172
150-200	1.017	1.187
200-300	1.028	1.196
300-400	1.042	1.206
400-500	1.050	1.212
500-750	1.055	1.216
750-1000	1.063	1.222
1000-1250	1.068	1.226
1250-1500	1.072	1.229
1500-2000	1.074	1.231
> 2000	1.078	1.233

Note 1: The 110% pass threshold yields a 10% probability of passing equipment with a true accuracy of 110% of the required accuracy. The 125% pass threshold yields an 80% probability of failing equipment with a true accuracy of 125% of the required accuracy.

Note 2: The requirements of section 2.1.2.1 include both thermal noise and multipath errors in the allocation to the airborne equipment. Manufacturers must allocate a portion of this requirement to the multipath errors that may occur as a result of the design choices. While it is not required to simulate multipath errors for this test, it is necessary to reduce the threshold used in the computation of $\sigma_{norm,i,j}$.For example, a manufacturer that chooses to smooth the pseudoranges used in the position solution may expect to see a $\sigma_{multipath}$ less than or equal to 0.45 meters. The value used in the computation of $\sigma_{no\ rm,i,j}$ would then be $\sqrt{5^2 - 0.45^2} = 4.98$ m. (The multipath experienced by receivers that do not smooth pseudoranges for satellites at low elevations can be up to 10 times greater.)

2.3.6.3 24-Hour Actual Satellite Accuracy Test

2.3.6.3.1 Test Procedure

The equipment shall [GPS 178] be tested over a 24-hour period using actual (live) GPS satellites. The horizontal position errors shall [GPS 179] be normalized by $1.1d_{major}$ as defined below. The RMS of the normalized errors is compared to the pass threshold in Table 2-6.

For the purpose of this test, d_{major} is defined as follows:

$$d_{major} \equiv \sqrt{\frac{d_{east}^2 + d_{north}^2}{2} + \sqrt{\left(\frac{d_{east}^2 - d_{north}^2}{2}\right)^2 + d_{EN}^2}}$$

where

$$\begin{bmatrix} d_{east}^2 & d_{EN} & d_{EU} & d_{ET} \\ d_{EN} & d_{north}^2 & d_{NU} & d_{NT} \\ d_{EU} & d_{NU} & d_U^2 & d_{UT} \\ d_{ET} & d_{NT} & d_{UT} & d_T^2 \end{bmatrix} = \left(G^T W G\right)^{-1}$$

The i^{th} row of the geometry matrix G is defined as follows:

$$G_i = \begin{bmatrix} -\cos El_i \sin Az_i & -\cos El_i \cos Az_i & -\sin El_i & 1 \end{bmatrix}$$

when positive azimuth is defined clockwise from north.

Note: The sign and coordinate frame convention used is different from the one adopted for GBAS in RTCA/DO-253 and for ICAO standards; however, the definitions of the G-matrix adopted by these standards are all mathematically equivalent.

$$W = \begin{bmatrix} w_1 & 0 & \cdots & 0 \\ 0 & w_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & w_N \end{bmatrix}$$ is the weighting matrix.

Acceptable values of the weights $w_i = 1/\sigma_i^2$ are defined in Appendix J, Section J.1, with the following two exceptions:

- The multipath contribution to $\sigma_{i,air}$ is replaced by a term representative of multipath error in the ground test environment.
- The ionospheric contribution to $\sigma_{i,UIRE}$ is replaced by a term representative of ionospheric error at the test location.

If alternate error model contributions are used, they shall [GPS 180] be substantiated by data or analysis.

2.3.6.3.2 Pass/Fail Criteria

Equipment shall [GPS 181] be considered pass if accuracy and integrity requirements are maintained throughout the 24-hour test (i.e. the RMS condition is met and the error never exceeds the HPL).

2.3.6.4 Velocity Accuracy and Velocity Figure of Merit Tests (Optional)

The following velocity tests are only required if manufacturers choose to have their equipment provide inputs to ADS-B equipment.

The ADS-B Out Draft Advisory Circular (Paragraph 7d) states that installations with a position source capable of providing velocity accuracy should have the NAC_V derived from the position source, and the velocity accuracy should be validated during the position source manufacturer's certification testing. The following procedures, developed by RTCA SC-159, are one means of accomplishing this testing.

The purpose of GNSS velocity accuracy test is to characterize the 95% horizontal and 95% vertical velocity accuracies during normal maneuvers as specified in RTCA/DO-229D and RTCA/DO-253B receiver MOPS for equipment intended to support either NAC_V =1 or NAC_V = 2. Test procedures for higher levels are expected to be developed as more demanding ADS-B applications mature.

The tests to verify velocity accuracy performance shall [GPS 182] be run for each of the scenarios described below for all operating modes of the receiver where a valid position and/or velocity could be output by the receiver.

Note: It is not required to repeat the test for different sub-modes of a mode where the inputs, velocity algorithm and outputs are the same.

2.3.6.4.1 Horizontal Velocity Accuracy Test Conditions Commensurate with NAC_V = 1

1) Ensure the simulator scenario has enough GPS satellites to provide a HDOP of 1.5 or less.

2) One satellite shall [GPS 183] be set at maximum power (including maximum combined satellite and aircraft antenna gain), and the other satellites shall [GPS 184] be set at minimum power (including minimum antenna gain).

3) Broadband GNSS test noise ($I_{GNSS,Test}$) of spectral density as defined in section 2.3.6, broadband external interference ($I_{ext,test}$) and thermal noise contribution from the sky and the antenna ($N_{sky,antenna}$) shall [GPS 185] be simulated.

4) The airborne equipment shall [GPS 186] be initialized with the appropriate position and time. It is assumed that the receiver has obtained a valid almanac for the simulator scenario to be tested prior to conducting the test.

5) Platform dynamics for the horizontal velocity accuracy test shall [GPS 187] be as defined in TABLE 2-7.

TABLE 2-7 PLATFORM DYNAMICS FOR HORIZONTAL VELOCITY ACCURACY TEST

Time (s)		Dynamics	Start Jerk (g/s)				End Jerk (g/s)			
From	To		North	East	Down	Total	North	East	Down	Total
0	T	Static	0	0	0	0	0	0	0	0
T+1	T+71	0.58g longitudinal acceleration to 411 m/s	0.xx *Note 1*	0.xx *Note 1*	0	0.25	0.xx *Note 1*	0.xx *Note 1*	0	0.25
T+72	T+129	Straight un-accelerated flight	0	0	0	0	0	0	0	0
T+130	T+194	-0.45g longitudinal acceleration to 125 m/s	0.xx *Note 1*	0.xx *Note 1*	0	0.2	0.xx *Note 1*	0.xx *Note 1*	0	0.2
T+195	T+254	Straight un-accelerated flight	0	0	0	0	0	0	0	0
T+255	T+325	turn 180° with 0.58g lateral acceleration	0.xx *Note 1*	0.xx *Note 1*	0	0.25	0.xx *Note 1*	0.xx *Note 1*	0	0.25
T+326	T+420	Straight un-accelerated flight	0	0	0	0	0	0	0	0

Note 1: The components of the jerk in the North and East direction depend on the heading chosen in the scenario. The total jerk is not to exceed the vector combination of north, east, and down jerk components. The maximum total jerk to quickly achieve the desired dynamics should be used, but the jerk should not exceed the normal maneuver total jerk requirement of 0.25 g/s.

Note 2: The actual times may vary based on the simulator scenario control settings.

6) Signal and RF interference conditions can be modified during static period to aid acquisition. Ensure the receiver enters the desired operation mode before dynamics and appropriate signal and interference conditions are applied.

7) Use the simulator velocity truth data ($V_i^{east\_truth}$, $V_i^{north\_truth}$) and the GNSS receiver velocity data (V_i^{east}, V_i^{north}) to determine the horizontal velocity error h_i after the GNSS receiver has entered the desired Navigation mode with the specified signal and RF Interference conditions:

$$h_i = \sqrt{(V_i^{east\_truth} - V_i^{east})^2 + (V_i^{north\_truth} - V_i^{north})^2}$$

2.3.6.4.1.1 Horizontal Accuracy Pass/Fail Determination

The 95% Horizontal Velocity accuracy statistic shall [GPS 188] be computed using the formula given below. The equipment shall [GPS 189] pass if the statistic is less than 10 m/s (10-LSB m/s).

Note: The notation "10-LSB m/s" specifies that the pass threshold is 10 m/s minus the magnitude of the least significant bit of the output data fields representing the horizontal velocity components. The intent is to ensure that quantization error in the velocity output does not degrade the accuracy below the threshold.

$$2*\sqrt{\frac{\sum_{i=1}^{N}\left(\frac{1.5(h_i)}{HDOP_i}\right)^2}{N}}$$

Where:

h_i - is the horizontal velocity error (m/sec)

$HDOP_i$ – Horizontal Dilution Of Precision at epoch i

N – Number of sample points used

For this test, the number of samples shall [GPS 190] include all samples where the receiver is in the desired Navigation mode and when in motion.

Note: *The minimum number of samples is 420 for a 1 Hz solution and 2100 for a 5 Hz solution (i.e., 5* 420).*

2.3.6.4.1.2 Horizontal Velocity Figure of Merit Pass/Fail Determination

The receiver velocity data and the $HFOM_V$ data shall [GPS 191] be used to determine the percentage of samples bounded by the $HFOM_V$ as shown below. The test passes if $TS_{h,b}$ is greater than or equal to 0.95.

$$TS_{h,b} = \frac{1}{N}\sum_{i=1}^{N} b_{h,i}$$

$$N = \text{number of samples}$$

$$b_{h,i} = \begin{cases} 1 & h_i \le HFOM_V \\ 0 & h_i > HFOM_V \end{cases}$$

2.3.6.4.2 Vertical Velocity Accuracy Test Conditions Commensurate with NAC_V = 1

1) Ensure the simulator scenario has enough GPS satellites to provide a VDOP of 3.0 or less.

2) One satellite shall [GPS 192] be set at maximum power (including maximum combined satellite and aircraft antenna gain), and the other satellites shall [GPS 193] be set at minimum power (including minimum antenna gain).

3) Broadband GNSS test noise ($I_{GNSS,Test}$) of spectral density as defined in section 2.3.6, broadband external interference ($I_{ext,test}$) and thermal noise contribution from the sky and the antenna ($N_{sky,antenna}$) shall [GPS 194] be simulated.

4) The airborne equipment shall [GPS 195] be initialized with the appropriate position and time. It is assumed that the receiver has obtained a valid almanac for the simulator scenario to be tested prior to conducting the test.

5) Platform Dynamics for the vertical velocity accuracy test shall [GPS 196] be as defined in Table 2-8 below.

<u>TABLE 2-8</u> PLATFORM DYNAMICS FOR VERTICAL VELOCITY ACCURACY TEST

Time (s)		Dynamics	Start Jerk (g/s)				End Jerk (g/s)			
From	To		North	East	Down	Total	North	East	Down	Total
0	T	Static	0	0	0	0	0	0	0	0
T+1	T+71	0.58g longitudinal acceleration to 411 m/s	0.xx *Note 1*	0.xx *Note 1*	0	0.25	0.xx *Note 1*	0.xx *Note 1*	0	0.25
T+72	T+130	Straight and level un-accelerated flight	0	0	0	0	0	0	0	0
T+131	T+131+X	Climb, increasing the vertical climb rate from 0 to 21 m/s, then decrease the rate back to 0 m/s and repeat this increasing and decreasing pattern until the time out.	0	0	0.xx *Note 1*	0.25	0	0	0.xx *Note 1*	0.25
T+132+X	T+192+X	Straight and level un-accelerated flight	0	0	0	0	0	0	0	0
T+193+X	T+193+2X	Descend, increasing the vertical descent rate from 0 to 21 m/s, then decrease the rate back to 0 m/s and repeat this increasing and decreasing pattern until the time out.	0	0	0.xx *Note 1*	0.25	0	0	0.xx *Note 1*	0.25
T+194+2X	T+274+2X	Straight and level un-accelerated flight	0	0	0	0	0	0	0	0

Note 1: The components of the jerk in the North and East direction depend on the heading chosen in the scenario. The total jerk is not to exceed the vector combination of north, east, and down jerk components. The maximum total jerk to quickly achieve the desired dynamics should be used, but the jerk should not exceed the normal maneuver total jerk requirement of 0.25 g/s.

Note 2: The actual times may vary based on the simulator scenario control settings.

Note 3: The value of X must be at least 63 seconds to have enough samples during vertical acceleration.

6) Signal and RF Interference conditions can be modified during the static period to aid acquisition. Ensure the receiver enters the desired Operation mode before dynamics and appropriate signal and interference conditions are applied.

7) Use the simulator velocity truth data ($V_i^{vertical\_truth}$) and the GNSS receiver velocity data ($V_i^{vertical}$) to determine the vertical velocity error (v_i) after the GNSS receiver has entered the desired Navigation mode with the specified signal and RF Interference conditions:

$$v_i = \left| V_i^{vertical\_truth} - V_i^{vertical} \right|.$$

2.3.6.4.2.1 Vertical Velocity Accuracy Pass/Fail Determination

The 95% Vertical Velocity accuracy statistic shall [GPS 197] be computed using the formula given below. The equipment shall [GPS 198] be considered pass only if the statistic is less than 50 ft/s (50-LSB ft/s).

$$2 * \sqrt{\frac{\sum_{i=1}^{N} \left(\frac{3(v_i)}{VDOP_i} \right)^2}{N}}$$

Where:

v_i - is the vertical velocity error (ft/sec)

$VDOP_i$ – Vertical Dilution Of Precision at epoch i.

N – Number of sample points used

For this test, the number of samples shall [GPS 199] include all samples where the receiver is in the desired navigation mode.

Note: The minimum number of samples is 420 for a 1 Hz solution and 2100 for a 5 Hz solution.

2.3.6.4.2.2 Vertical Velocity Figure of Merit Pass/Fail Determination

The receiver velocity data and the $VFOM_V$ data shall [GPS 200] be used to determine the percentage of samples bounded by the $VFOM_V$ as shown below. The test passes if $TS_{v,b}$ is greater than or equal to 0.95.

$$TS_{v,b} = \frac{1}{N} \sum_{i=1}^{N} b_{v,i}$$

$$N = \text{number of samples}$$

$$b_{v,i} = \begin{cases} 1 & v_i \le VFOM_V \\ 0 & v_i > VFOM_V \end{cases}$$

2.3.6.4.3 Additional Tests to Demonstrate Accuracy Commensurate with NAC_V = 2

The following procedure is one acceptable means for equipment capable of better accuracy performance to demonstrate compliance with the horizontal velocity error requirement of less than 3 m/s (3-LSB m/s).

1) Run the scenario in Table 2-7 with all satellites set at high power and no RF interference.
2) This accuracy evaluation shall [GPS 201] only include those data samples collected during the acceleration period.
3) Find the particular h_i (noted as T_{acc}) so that 95% of h_i samples are less than or equal to T_{acc}.
4) Re-run the scenario in Table 2-7 with the same satellite and RF interference conditions as the 10-LSB m/s (NAC_V=1) test.
5) This time only the data samples during the non-acceleration period with the specified signal and RF Interference conditions are used.
6) Compute

$$T_{non\_acc} = 2 * \sqrt{\frac{\sum_{i=1}^{N_{non\_acc}} \left(\frac{1.5(h_{i\_non\_acc})}{HDOP_{i\_non\_acc}} \right)^2}{N_{non\_acc}}}$$

where $HDOP_{i\_non\_acc}$ and N_{non_acc} are the HDOP values for each sample i and the total number of samples (non-acceleration period), respectively.

7) The test passes only if $T_{acc} + T_{non\_acc}$ is 3-LSB m/s.
8) The velocity FOM is evaluated in the same way as for the 10-LSB m/s test, i.e. the samples during acceleration and non-acceleration periods of the above 2 runs are evaluated together against the 0.95 threshold.

The vertical velocity requirement of less than 15 ft/s (15-LSB ft/s) should be tested using the exact same philosophy as the test of 3-LSB m/s above but with the scenario in Table 2-8.

2.3.7 Integrity Monitoring Test Procedures

The verification of the FDE algorithm for the equipment shall [GPS 202] consist of four tests. The first test (Section 2.3.7.2) shall [GPS 203] demonstrate that the FDE algorithm provides proper fault detection and fault exclusion availability, and will be performed off-line. The second test (Section 2.3.7.3) is an off-line test to verify that the missed alert and failed exclusion requirements are satisfied. The third test (Section 2.3.7.4) is an off-line test to verify the false alert rate. The final test (Section 2.3.7.5) is an on-line test to verify that the algorithm that is implemented in the equipment is identical to the algorithm used during the off-line tests. Note that the on-line test specifies several additional off-line scenarios for comparison to on-line results.

2.3.7.1 General Test Conditions

2.3.7.1.1 Test Philosophy

These tests specify the procedures and pass/fail criteria for equipment demonstrating compliance with the FDE requirements in Section 2.1.2.2.2 and 2.1.3.2.2. With the exception of the first test for availability, the test is independent of the navigation mode and does not have to be repeated for different modes.

2.3.7.1.2 GPS Constellation

The GPS satellite constellation to be used in the simulations shall [GPS 204] be the 24 satellite constellation defined in Appendix B. In all tests, the satellite selection algorithm and number of channels shall [GPS 205] be the same as that used by the equipment. The mask angle shall [GPS 206] be 5 degrees, regardless of the mask angle of the particular equipment under test.

2.3.7.1.3 Applicability of RTCA/DO-178B

The off-line FDE software used for testing compliance with the FDE requirements shall [GPS 207] at least be compliant to RTCA/DO-178B Level D or equivalent. The software shall [GPS 208] be designed such that the implementations of the position solution, FDE, and satellite selection algorithms are functionally identical in both the GPS equipment and the off-line software.

The proof of equivalence to RTCA/DO-178B and functional identity depends upon the methods, platforms, code, and tools used. In the simplest case, the platforms, code, and tools are identical. It is recognized that these elements are variable. The proof of equivalence and identity lies on the developer and is dependent upon circumstance. The RTCA/DO-178B level will also vary dependent upon the criticality of the equipment. The particular method to be used must be negotiated with the relevant regulatory agencies. RTCA/DO-178B Level D has been determined to be acceptable for the off-line tests.

2.3.7.1.4 Test Repetition

If the equipment fails two successive tests defined in Section 2.3.7.3 or 2.3.7.4 with different sets of numbers for the random processes, the integrity algorithm must be modified to correct the problem before re-testing. Re-testing must be done for all FDE tests.

2.3.7.1.5 Protection Level/Alert Limit

In order to reduce the amount of test time, these tests are based upon the HPL_{FD} used internal to the equipment. By predicating these tests upon the HPL_{FD}, the navigation mode is irrelevant and the tests can be conducted only once. In addition, the satellite geometry should not be a dominant factor since the equipment is tested to the worst-case satellite. The off-line HPL_{FD} used for this test shall [GPS 209] not include any additional margin that is a function of the navigation mode. For example, if the HPL_{FD} is 0.2 nm, but the equipment inflates this value to the approach (LNAV) HAL of 0.3 nm to improve the false alert rate, the equipment must be tested to a HPL_{FD} = 0.2 nm. Therefore, for the purposes of these tests a positioning failure is referenced to the HPL_{FD}, not the HAL. Similarly, the tests conducted when exclusion is available are referenced to the HEL_{FD}, not the HAL.

2.3.7.1.6 Time-to-Alert

These tests shall [GPS 210] use the appropriate time-to-alert for the equipment under test. Recall that the total time-to-alert for the position output is 8 seconds, regardless of the value of HPL_{FD}.

The time-to-alert used in these tests shall [GPS 211] accommodate the equipment latencies after fault detection and provides time to attempt exclusion before indicating the fault. For example, if a sensor has a 200 ms delay in issuing a navigation alert due to a positioning failure, then the time-to-alert for these tests would be (8 seconds - 0.2 seconds) = 7.8 seconds.

2.3.7.2 Availability Tests

The off-line test described in this paragraph shall [GPS 212] be used to demonstrate compliance with the availability requirements of Sections 2.1.2.2.2.5 and 2.1.3.2.2.5. Availability of fault detection and fault exclusion shall [GPS 213] be determined for each of the space-time points in the following analysis grid sampled every 5 minutes for 12 hours from 00:00:00 to 12:00:00 UTC (144 time points). Since SA is currently turned off and will remain off per U.S. Government policy, the availability of FDE without SA shall [GPS 214] be determined with the error model described below:

Note: *Because section 2.3.7.5 requires identical performance between on-line and off-line algorithms; and, section 2.3.7.2 requires using specific weights to compute HPL, this implies user equipment should use the weights below to compute HPL.*

Gaussian Error Models: The residual errors for GPS pseudorange measurements for non-failed GPS satellites shall [GPS 215] be modeled by RSSing the error components per Appendix J:

$\sigma_i^2 = URA_i^2 + \sigma_{i,UIRE}^2 + \sigma_{i,air}^2 + \sigma_{i,tropo}^2$ where σ_i is the standard deviation of satellite i's pseudorange measurement. The 4 terms are specified below.

The first term URA_i, is set to 5.7 m.

The term $\sigma_{i,UIRE}$ is the modeled standard deviation of ionospheric slant delay estimation error of F_{pp} x τ_{vert} m where F_{pp} is the ionospheric obliquity factor and τ_{vert} is the modeled standard deviation of ionospheric vertical delay error. From Appendix J.2, F_{pp} is given by:

$$F_{pp} = \left[1 - \left(\frac{R_e \cos\theta_{ir}}{R_e + h_I}\right)^2\right]^{-\frac{1}{2}}$$

where θ_{ir} is satellite i's elevation angle in radians. The terms R_e and h_I are defined to be R_e = 6378136.0 m, h_I = 350000.0 m. The term τ_{vert} is obtained using information from IS-GPS-200D and its derivation is repeated below:

$$\psi = \frac{0.0137}{(E_i + 0.11)} - 0.022 \quad \text{with } E_i \text{ and } \psi \text{ in semi circles}$$

$$\phi_i = \phi_U + \psi\cos(\alpha_i) \quad \text{in semi circles}$$

$$IF(\phi_i > 0.416), \phi_i = 0.416$$

$$IF(\phi_i < -0.416), \phi_i = -0.416$$

$$\lambda_i = \lambda_U + \frac{\psi\sin(\alpha_i)}{\cos(\phi_i)} \quad \text{in semi circles}$$

$$\phi_m = \phi_i + 0.064\cos(\lambda_i - 1.617) \quad \text{in semi circles}$$

$$\phi_{md} = \phi_m \cdot 180 \quad \text{in degrees}$$

$$IF(\,|\phi_{md}|\ \le\ 20\,),\ \tau_{vert}^2 = 81\,\mathrm{m}^2$$

$$IF(\,20 <\ |\phi_{md}|\ <\ 55\,),\ \tau_{vert}^2 = 20.25\,\mathrm{m}^2$$

$$IF(\,55 \le\ |\phi_{md}|\ \,),\ \tau_{vert}^2 = 36\ \mathrm{m}^2$$

The new terms are defined as follows:

ϕ_U user latitude

λ_U user longitude

α_i satellite i azimuth

The third term is the multipath and receiver noise modeled as a Gaussian white sequence with samples that are uncorrelated in time and a standard deviation of $\sigma_{i,air}$. The standard deviation of the airborne segment's contribution is given by (see Appendix J.3):

$$\sigma_{i,air} = \left(\sigma_{noise,GPS}^2[i] + \sigma_{multipath}^2[i] + \sigma_{divg}^2[i]\right)^{1/2}$$

These first and third terms are specified as constants defined in Appendix J.3 for a receiver under minimum power conditions. For a GPS satellite, the root-sum-square of the first and third terms must be less than or equal to 0.36 meters; for the purposes of modeling, the worst case is set as:

$$\left(\sigma_{noise,GPS}^2[i] + \sigma_{divg}^2[i]\right)^{1/2} = 0.36 \text{ meters}$$

This second term is specified in Appendix J.3, as:

$$\sigma_{multipath}[i] = 0.13 + 0.53e^{(-\theta_i/10\deg)} \text{ meters}$$

where, θ_i is the elevation angle for the i'th satellite in units of degrees.

Note: *The multipath formula above is only valid for smoothed pseudoranges. The value of $\sigma_{i,air}$ assumed for this test corresponds to the use of smoothed pseudoranges. The purpose of this test is to verify the availability of the FDE algorithm under a standard set of assumptions. The fielded availability of the user equipment may differ because the equipment will use error models that reflect its actual performance.*

The last term, $\sigma_{i,tropo}$ is the tropospheric delay estimation error. It is modeled as a zero-mean gaussian random variable with a standard deviation of $\sigma_{i,tropo}$ as specified in Appendix J, section J.5

$$m(\theta_{ir}) = \frac{1.001}{\sqrt{0.002001 + \sin^2(\theta_{ir})}}$$

and

$$\sigma_{i,tropo} = \left(\sigma_{TVE} \cdot m(\theta_{ir})\right) \text{ meters}$$

with $\sigma_{TVE} = 0.12$ meters and θ_{ir} is satellite i's elevation angle in radians.

This completes the total sigma model for the satellite pseudo range measurement.

Analysis grid: Points are sampled every three degrees in latitude from zero to ninety degrees north. Each latitude circle will have points separated evenly in longitude, defined as:

$$long.step = \frac{360}{ROUND\left(\frac{360}{MIN(3\ \ \deg rees/\cos(latitude),360)}\right)}$$

This grid yields 2353 points.

Note that the total number of space-time points is 2353*144 = 338,832 points.

The availability of fault detection for each space-time point shall [GPS 216] be determined as defined in Section 1.7.3. The availability of detection shall [GPS 217] be determined for the terminal and LNAV HALs.

Similarly, the availability of exclusion shall [GPS 218] be calculated for each space-time point as defined in Section 1.7.3. The availability of exclusion shall [GPS 219] be determined for the terminal and LNAV HALs.

The availability calculations for each space-time point shall [GPS 220] be based upon the same set of satellites that would be used by the equipment. This requires that the satellite selection algorithm be used to select the satellites for use in the FDE algorithm. In addition, the mask angle shall [GPS 221] be 5 degrees.

The total number of space-time points for which the detection function is available shall [GPS 222] be determined (N_d). The total number of space-time points for which the exclusion function is available shall [GPS 223] be determined (N_a). The availability is then determined as:

$$Availability\ of\ Detection = \frac{N_d}{338832} \qquad Availability\ of\ Exclusion = \frac{N_a}{338832}$$

If additional augmentations are used to improve system availability, the effects of those augmentations must be completely simulated. In particular, equipment logic that affects when the augmentation is applied shall [GPS 224] be simulated. For augmentations that do not result in predictable HPL_{FD}'s for a given geometry, location, and time, the statistical nature of the HPL_{FD} must be taken into consideration and the total number of samples taken increased accordingly.

FDE algorithms that use other navigation signals external to the aircraft, such as Loran or VOR/DME, must satisfy the availability requirement without the use of the other navigation signals. The manufacturer must provide the means to test and analyze alternate FDE algorithms to demonstrate compliance. Note that these algorithms must also be demonstrated to satisfy the missed alert, false alert, and failed exclusion requirements when the external navigation signals are used.

2.3.7.3 Off-Line FDE Tests

2.3.7.3.1 Off-Line Test Setup

For GPS signals, the noise models specified above shall [GPS 225] apply to the pseudo range measurements. The effect of equipment tracking-loop noise shall [GPS 226] be modeled with a single white noise term with an RMS value representative of the equipment under test at the minimum signal-to-noise ratio (C/N_0). Such noise shall [GPS 227] be generated as Gaussian white sequence with samples that are uncorrelated in time.

The sampling interval used in the simulation tests shall [GPS 228] not exceed 1 second. A GPS satellite malfunction shall [GPS 229] be simulated as a ramp error in measured pseudorange with a slope of 5 m/s.

Different noise samples shall [GPS 230] be used for each satellite being used in the FDE algorithm, and new sets of noise samples are to be generated and used for each run.

During all runs in the off-line simulation tests, satellite velocities are to be set to zero, and the satellite positions are to be frozen at the values for the selected geometry. This ensures that HPL will not change during the run.

All tests in this section are based upon the assumption that all satellite range measurements have identical error models, the equipment shall [GPS 231] de-weight each range measurement based upon the expected error residual. In this case, the equipment must demonstrate that it satisfies all FDE requirements with a combination of expected error characteristics. Appendix J discusses the performance bounds on the measurement residuals for a variety of correction scenarios.

2.3.7.3.2 Selection of Geometries

The space-time points analyzed under Section 2.3.7.2 shall [GPS 232] be reviewed to yield the following sets of points. If the geometries cannot be found for any set, deselect satellites in order to find acceptable geometries.

Set 1: Twenty geometries shall [GPS 233] be selected to provide an approximately uniform range of HPL_{FD} from 0.1 nm to the maximum HAL supported by the equipment (e.g., 4 nm). Note that only the missed alert and false alert probabilities are required to be satisfied under this condition.

Set 2: Twenty geometries shall [GPS 234] be selected to provide an approximately uniform range of HEL_{FD} from 0.1 nm to the maximum HAL supported by the equipment (e.g., 4 nm). Note that all requirements (missed alert, false alert, failed exclusion) must be satisfied for this set.

2.3.7.3.3 Test Procedure

One of the most difficult issues to test is the integration of the exclusion and detection functions. In particular, the exclusion requirements state that the equipment must exclude the failure prior to the radial error becoming unacceptable and without alerting the user.

Because the equipment that does not know the HAL, the decision of when to indicate a failure to the user can, in this situation, be made by the navigation management unit (typically a flight management system). Therefore, it is acceptable for the equipment to indicate an alert as soon as a detection occurs together with an output of the HUL. In this case, the navigation management unit must decide when the error becomes unacceptable and must be annunciated.

The integrated system (receiver and the navigation management unit) would be expected to withhold indication of the failure until it becomes unacceptable if exclusion is available.

In addition to the data recorded specifically for this test, the position trace and alert status shall [GPS 235] be recorded for several runs in support of the on-line test procedures. See Section 2.3.7.5 for a discussion of which runs should be retained.

For each of the 40 geometries selected above, a ramp-type failure with a velocity of 5 m/s shall [GPS 236] be introduced. For Set 1, the failure shall [GPS 237] be introduced in the most difficult to detect satellite. For Set 2, the failure shall [GPS 238] be introduced in the most difficult to exclude satellite. A Monte-Carlo (random) trial run shall [GPS 239] then be made with the ramp initiated at the time of the chosen geometry (defined as t=0).

For Set 1, the run is to be continued until one of the following three events occur (1-3):

1) Correct Exclusion: The right satellite is excluded before the position error exceeds the HAL (HPL_{FD} in this test) for longer than the time to alert;

2) Failed Exclusion: A navigation alert is output due to detected positioning failure; or

3) Missed Alert: The position error exceeds the HAL (HPL_{FD} in this test) for longer than the time-to-alert without a navigation alert (this could be due to missed detection or wrong exclusion).

For Set 2, the run is to be continued until one of the following three events occur (4-6):

4) Correct Exclusion: The right satellite is excluded before the position error exceeds the HAL (HEL_{FD} in this test) for longer than the time to alert;

5) Failed Exclusion: A navigation alert is output when the position error exceeds the HEL_{FD} for longer than the time to alert; or

6) Missed Alert: The position error exceeds the HAL (HEL_{FD} in this test) for longer than the time-to-alert without a navigation alert (this could be due to missed detection or wrong exclusion).

Since the receiver equipment may not be aware of the HAL, it is acceptable for a navigation alert to be output prior to exclusion. The run should be continued until the occurrence of one of the three outcomes listed above (4-6).

A total of 1650 trials shall [GPS 240] be run for each of the 20 geometries in Set 1 and the 20 geometries in Set 2. The number of occurrences of each outcome shall [GPS 241] be recorded for each geometry set defined in Section 2.3.7.3.2.

2.3.7.3.4 Pass/Fail Criteria

For the equipment to pass, the total number of events for each satellite set shall [GPS 242] be less than or equal to the numbers shown in Table 2-9.

TABLE 2-9 MAXIMUM NUMBER OF OUTCOMES TO OFF-LINE FDE TEST

Outcome	SET 1	SET 2
a. Failed Exclusion (True alert)	N/A	47
b. Missed Alert (Missed Detection or Wrong Exclusion)	47	47

Note: *The number of test runs is designed to ensure a high probability of passing the test properly, and a low probability of falsely passing the test. The probability that properly designed equipment passes the missed alert and failed exclusion tests is 99%, while the probability that equipment with a missed alert or wrong exclusion probability of 0.002 is only 1% likely to pass the test.*

2.3.7.4 False Alert Rate Test

The false alert rate is the rate with which the equipment flags the outside world that its position is outside the HPL, with the actual position still being inside the HPL (no positioning failure occurred). The false alert rate does not depend on the geometry of the visible satellites, false alerts will be driven either by ionospheric error or receiver noise. These tests use the same 40 geometries that are used in Section 2.3.7.3.

The tests are classified in two categories, depending upon the algorithm implementation. The test for snapshot algorithms takes advantage of the fact that single samples of ionospheric error, or receiver noise can be modeled as a simple Gaussian distribution. The test for non-snapshot algorithms must model the correlated effect of the error source over the correlation time.

2.3.7.4.1 False Alert Rate Simulations for Snapshot Algorithms

For each of the geometries defined in Section 2.3.7.3, a total of N=2,475,000 independent samples are simulated. The number N is determined by dividing the required total number of samples (99,000,000) by 40 geometries, yielding 2,475,000 sample points per geometry. For each sample, the satellites used for positioning are selected, the pseudoranges to the selected satellites are calculated, the FDE algorithm is executed and the result is logged. The number of geometries must be higher if the alert threshold is not set based upon the geometry. In this case, the number of geometries should be selected such that an algorithm with a true false alert rate of or equal to 6.66 $x10^{-7}$ per sample has a 0.01 chance of passing.

For each geometry, the number of false alerts is counted. To pass the false alert test, the following criteria shall [GPS 243] be met:

1) The total number of alerts over all admissible geometries shall [GPS 244] be equal to or less than 47.
2) For each geometry, there shall [GPS 245] be no more than 3 alerts.

The first criterion ensures compliance with the overall false alert rate requirement. The second criterion ensures that there will be no unusual bunching of alerts at any position.

Note: To test the false alert probability with statistical confidence, a total number of 99,000,000 statistically independent samples have to be taken. Of these, a maximum of 47 samples may be allowed to have a false alert.

2.3.7.4.2 False Alert Rate Simulations for Non-Snapshot Algorithms

For each of the geometries defined in Section 2.3.7.3, a total of N=82,500 hours of operation is to be simulated. The number N is determined by dividing the required total number of simulation hours (3,300,000) by 40 geometries, yielding 82,500 hours per geometry. During each simulation run of 82,500 hours, the satellite velocities are to be set to zero, and the satellite positions are to be frozen at the values for the selected marginal geometry. This ensures that the HAL/HPL will not change during the run.

For the purpose of this test, a false alert is defined as the occurrence of an alert indication in the absence of a real positioning failure, regardless of how long the alert indication is provided. The total number of alerts shall [GPS 246] be counted. Only the number of indication occurrences will be counted, not the duration of the indication. To pass the false alert test, the following criteria shall [GPS 247] be met:

1) The total number of alerts over all admissible geometries shall [GPS 248] be less than or equal to 47.
2) There shall [GPS 249] be no more than 3 alerts for each admissible geometry.

The first criterion ensures compliance with the overall false alert rate requirement. The second criterion ensures that there will be no unusual clustering of alerts at any one position.

Note: The false alert rate for non-snapshot algorithms cannot be easily converted into a false alert probability. For these algorithms, a total number of 3,300,000 hours of operation has to be simulated to gain statistical confidence. During this simulation, no more than 47 false alerts can be allowed for the equipment to pass the test.

2.3.7.5 On-Line Verification Test

The purpose of the on-line verification tests is to ensure that the off-line algorithms and the on-line implemented algorithms are identical in function, performance, and computational (logical and arithmetic) results. This requirement is derived from the fact that all statistical performance results are determined by the off-lines tests.

Because the off-line and on-line tests use fundamentally different data generators, it is not possible to ensure that any off-line and on-line tests, under identical scenarios, will produce identical results. Therefore, there shall [GPS 250] be two separate tests: an on-target computational test; and, an on-line behavioral test.

2.3.7.5.1 On-Target Computational Test

The purpose of the on-target test is to ensure that software on the target processor (in the GPS equipment) produces equivalent output data as the off-line algorithm, for identical input data. This test does not have to be conducted if the off-line tests described in Sections 2.3.7.3 and 2.3.7.4 are performed on the target processor using the same FDE software and parameter values (other than URA) used in the GPS equipment.

For the purpose of this test, equivalent means that arithmetic variables are within 0.1 meter of the off-line values and all logical variables are strictly identical (including logical counters, etc.).

The on-target test requires that the target software be exercised by forty satellite scenarios; one from each constellation in Set 1 and Set 2 as defined in Section 2.3.7.3.2. A ramp failure shall [GPS 251] be generated as defined in Section 2.3.7.3.2 in each case.

1) For each satellite static scenario, the input data to the off-line navigation/FDE algorithm shall [GPS 252] be recorded with its computational results. At a minimum, the computational results shall [GPS 253] include the HPL_{FD}, horizontal radial position error, alert flag, and loss of integrity flag. Any additional variables internal to the navigation/FDE algorithm may also be recorded.

2) This input data will be duplicated in the on-target software and the input data will exercise the on-target navigation/FDE software. The computational results of the on-target software will be recorded and compared to the off-line results. The strict meaning of equivalent is defined above. The computational results for the on-line and on-target implementations are required to be equivalent.

2.3.7.5.2 On-Line Behavioral Test

The test shall be run using five constellations selected from the forty used under Section 2.3.7.5.1 that have a relatively constant HPL_{FD} and HEL_{FD} for the duration of the test. A ramp failure shall [GPS 254] be generated as defined in Section 2.3.7.3.3 in each case. All test scenarios will be conducted with the equipment stationary (non-dynamic).

To pass the behavioral test:

1) The equipment position fixing difference shall [GPS 255] only exceed 5 meters for periods of 2 seconds or less.

2) The equipment HPL_{FD} difference shall [GPS 256] only exceed 50 meters for periods of 10 seconds or less.

If these thresholds are exceeded, the cause of the difference shall [GPS 257] be identified and that cause must be within the expected characteristics of the algorithm.

3.0 INSTALLED EQUIPMENT PERFORMANCE

Installation material for the equipment can be found in AC 20-130A Airworthiness approval of Navigation or Flight Management Systems Integrating Multiple Navigation Sensors; and, 20-138A Airworthiness Approval of Global Navigation Satellite System (GNSS) Equipment. Related guidance material for installation includes Advisory Circulars:

- AC 20-129, Airworthiness Approval of Vertical Navigation (VNAV) Systems for Use in the U.S. National Airspace System and Alaska;
- AC 23.1309-1C, Equipment, Systems, and Installations in Part 23 Aircraft;
- AC 25.1309-1A, System Design and Analysis;
- AC 43.13-1B, Acceptable Methods, Techniques, and Practices – Aircraft Inspection and Repair; and,
- AC 43.13-2A, Acceptable Methods, Techniques, and Practices – Aircraft Alterations.

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4.0 OPERATIONAL CHARACTERISTICS

Information on GPS operational characteristics can be found in the Aeronautical Information Manual (AIM). Specific information for a particular installed product will typically be found in a flight manual supplement, or, the manufacturer's literature. Related guidance material on GPS operations can be found in the following Advisory Circulars:

- AC 90-79, Recommended Practices and Procedures for the Use of Electronic Long-Range Navigation Equipment;
- AC 90-94, Guidelines for Using GPS Equipment for IFR En route and Terminal Operations & for Nonprecision Instrument Approaches;
- AC 90-96, Approval of U.S. Operators and Aircraft to Operate under Instrument Flight Rules (IFR) in European Airspace Designated for Basic Area Navigation (BRNAV/RNP-5); and,
- AC 91-49, General Aviation Procedures for Flight in North Atlantic Minimum Navigation Performance Specification Airspace

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APPENDIX A

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APPENDIX B

STANDARD GPS ASSUMPTIONS

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B.1 GPS Constellation

The following parameters describe the target location orbital elements of the Optimized 24 GPS Constellation (Table B-1).

TABLE B-1 OPTIMIZED 24 GPS CONSTELLATION

	Orbital Plane	Semimajor Axis (a)	Eccentricity (e)	Inclination Angle (i)	Rt. Ascension of Ascending Node (Ω)	Arg. of Perigee (ω)	Mean Anomaly (M)
1.	A1	26559800	0.0	55.0	272.847	0.0	268.126
2.	A2	26559800	0.0	55.0	272.847	0.0	161.786
3.	A3	26559800	0.0	55.0	272.847	0.0	11.676
4.	A4	26559800	0.0	55.0	272.847	0.0	41.806
5.	B1	26559800	0.0	55.0	332.847	0.0	80.956
6.	B2	26559800	0.0	55.0	332.847	0.0	173.336
7.	B3	26559800	0.0	55.0	332.847	0.0	309.976
8.	B4	26559800	0.0	55.0	332.847	0.0	204.376
9.	C1	26559800	0.0	55.0	32.847	0.0	111.876
10.	C2	26559800	0.0	55.0	32.847	0.0	11.796
11.	C3	26559800	0.0	55.0	32.847	0.0	339.666
12.	C4	26559800	0.0	55.0	32.847	0.0	241.556
13.	D1	26559800	0.0	55.0	92.847	0.0	135.226
14.	D2	26559800	0.0	55.0	92.847	0.0	265.446
15.	D3	26559800	0.0	55.0	92.847	0.0	35.156
16.	D4	26559800	0.0	55.0	92.847	0.0	167.356
17.	E1	26559800	0.0	55.0	152.847	0.0	197.046
18.	E2	26559800	0.0	55.0	152.847	0.0	302.596
19.	E3	26559800	0.0	55.0	152.847	0.0	333.686
20.	E4	26559800	0.0	55.0	152.847	0.0	66.066
21.	F1	26559800	0.0	55.0	212.847	0.0	238.886
22.	F2	26559800	0.0	55.0	212.847	0.0	345.226
23.	F3	26559800	0.0	55.0	212.847	0.0	105.206
24.	F4	26559800	0.0	55.0	212.847	0.0	135.346

The epoch date for this constellation is June 30, 1993 at 23:34:24 (1993, 6, 30, 23 hr, 34 min, 24 sec UTC, or GPS Week 703, 344064 seconds).

B.2 GPS Satellite Failure

The probability of a satellite integrity failure is 10^{-4} per hour for the GPS position solution (based on 3 satellite major service failures/year/constellation, assuming 8 satellites in view). A satellite integrity failure is defined to be an insidious failure that contributes to a hazardously misleading situation.

B.3 GPS Constellation for Availability Analysis

Table B-2 contains the location of the GPS satellites on December 1, 1995 at 0000UTC. These locations can be used for the FDE availability analysis, and may also be used to test simulation orbit software.

TABLE B-2 GPS CONSTELLATION ON DECEMBER 1, 1995 AT 00:00 UTC

(GPS Week: 829 GPS Seconds: 00432000)

SVID	MEAN ANOMALY	OMEGA_O	X-Position	Y-Position	Z-Position
1	268.126	-2.253	-14870571.94	8899797.75	-20126665.56
2	161.786	-2.253	23589887.94	11991875.55	-2266072.27
3	11.676	-2.253	-16176102.35	-16770562.96	12747741.24
4	41.806	-2.253	-4355434.09	-17071145.97	19875340.13
5	80.956	57.747	15395084.60	5233826.18	21000509.74
6	173.336	57.747	-1695661.81	25682884.00	-6552646.52
7	309.976	57.747	-9297858.71	-23002281.98	-9479864.10
8	204.376	57.747	-9361634.66	18753790.62	-16311900.87
9	111.876	-242.253	-9092026.91	19872361.08	15094611.22
10	11.796	-242.253	22600908.12	-5583452.08	12784638.87
11	339.666	-242.253	21913985.95	-14935082.68	1464070.04
12	241.556	-242.253	-10617702.92	-11042774.34	-21696647.11
13	135.226	-182.253	-24936980.94	-5007408.16	7648256.07
14	265.446	-182.253	13908721.33	-9596379.71	-20490972.24
15	35.156	-182.253	7188942.92	17419062.74	18716792.70
16	167.356	-182.253	-22645671.90	-13176689.83	-4355613.11
17	197.046	-122.253	7720020.91	-20979445.69	-14341795.98
18	302.596	-122.253	10802779.38	21135634.15	-11916706.88
19	333.686	-122.253	3560816.01	26307697.10	-805381.07
20	66.066	-122.253	-15149811.05	1603096.34	21756292.96
21	238.886	-62.253	11566835.96	10254727.75	-21597959.17
22	345.226	-62.253	-22547453.11	13577895.19	3560350.61
23	105.206	-62.253	6551951.60	-19489487.66	16812340.02
24	135.346	-62.253	16838480.90	-19079928.60	7605580.96

All semi-major axes are 26559800 meters.

All eccentricities are 0.0

All orbital planes are inclined at 55 degrees.

OMEGA_0 = omega - 275.1.

B.4 Signal Quality Monitoring

The signal effects that might cause a Double Delta (DD) Delay Lock Loop (DLL) discriminator to track the wrong peak can be categorized into three different effects on the correlation function as follows:

B.4.1 Dead Zones

If the correlation function loses its peak, then the receiver's discriminator function will include a flat spot or dead zone. If the airborne receiver settles on incorrect portions of this dead zone, then Misleading Information (MI) can result.

B.4.2 False Peaks

If the airborne receiver locks on to an incorrect correlation peak, then MI could exist.

B.4.3 Distortions

If the correlation peak is misshapen, then an airborne receiver may track the misshaped peak and could suffer MI.

B.4.4 Threat Models

The GPS threat model has three parts that can create the three correlation peak pathologies listed above.

B.4.4.1 Threat Model A

Threat Model A consists of the normal C/A code signal except that all positive chips have a falling edge that leads or lags relative to the correct end time for that chip. This threat model is associated with a failure in the Navigation Data Unit (NDU), the digital partition of a GPS satellite. Threat Model A has a single parameter Δ, which is the lead $(\Delta < 0)$ or lag $(\Delta > 0)$ expressed in fractions of a chip. The range for this parameter is $-0.12 < \Delta \leq 0.12$. Within these ranges, Threat Model A generates the dead zones described above. (Note that waveforms with lead need not be tested, because their correlation functions are simply advances of the correlation functions for lag. Hence the MI threat is identical.)

B.4.4.2 Threat Model B

Threat Model B introduces amplitude modulation and models degradations in the analog section of the GPS satellite. More specifically, it consists of the output from a second order system when the nominal C/A code baseband signal is the input. Threat Model B assumes that the degraded satellite subsystem can be described as a linear system dominated by a pair of complex conjugate poles. These poles are located at $\sigma \pm j2\pi f_d$, where σ is the damping factor in nepers/second and f_d is the resonant frequency with units of cycles/second. They can also be used to specify the impulse response $h_{2nd}(t)$ or the unit step response e(t). The unit step response of a second order system is given by

$$e(t) = \begin{Bmatrix} 0 & t \leq 0 \\ 1 - \exp(-\sigma t)\left[\cos \omega_d t + \dfrac{\sigma}{\omega_d} \sin \omega_d t\right] & t > 0 \end{Bmatrix}$$

Threat Model B corresponding to 2^{nd} order anomalies uses the following ranges for the parameters defined above :

$\Delta=0$; $4 \leq f_d \leq 17$ and $0.8 \leq \sigma \leq 8.8$.

Within these parameter ranges, Threat Model B generates distortions of the correlation peak as well as false peaks.

B.4.4.3 Threat Model C

Threat Model C introduces both lead/lag and amplitude modulation. More specifically, it consists of outputs from a second order system when the C/A code signal at the input suffers from lead or lag. This waveform is a combination of the two effects described above. Threat Model C includes all three parameters described above with the following ranges:

$-0.12 \leq \Delta \leq 0.12$; $7.3 \leq f_d \leq 13$ and $0.8 \leq \sigma \leq 8.8$.

Within these parameter ranges, Threat Model C generates dead zones, distortions of the correlation peak, and false peaks.

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APPENDIX C

STANDARD RECEIVED SIGNAL AND INTERFERENCE ENVIRONMENT

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C.1 Introduction

This appendix specifies the RF Interference environment at and around L-band frequencies for GPS receivers. It also describes the frequency selectivity of the minimum standard antenna.

All signal levels in this appendix are specified in dBm measured at the antenna port.

C.2 Operating Interference Environment

Interference levels specified in this appendix are defined at the antenna port regardless of antenna radiation pattern.

Figure C-1 represents the operating interference environment. The regions of this figure indicated as having interference with bandwidths other than CW are considered to represent in-band and near-band interference with received power levels defined in Figure C-2 as a function of bandwidth. Figure C-3 represents the frequency selectivity of the minimum standard antenna in order to define the operating environment of equipment using such an antenna.

C.2.1 Out-of-Band Interference

The out-of-band continuous wave (CW) interfering signals can be as high as the levels shown in Figure C-1, measured at the antenna port. The CW interference level below 1500 MHz increases linearly to 25.5 dBm at 1315 MHz. The CW level increases linearly above 1640 MHz, to 21.5 dBm at 2 GHz, accounting for High Intensity Radiation Fields (HIRF).

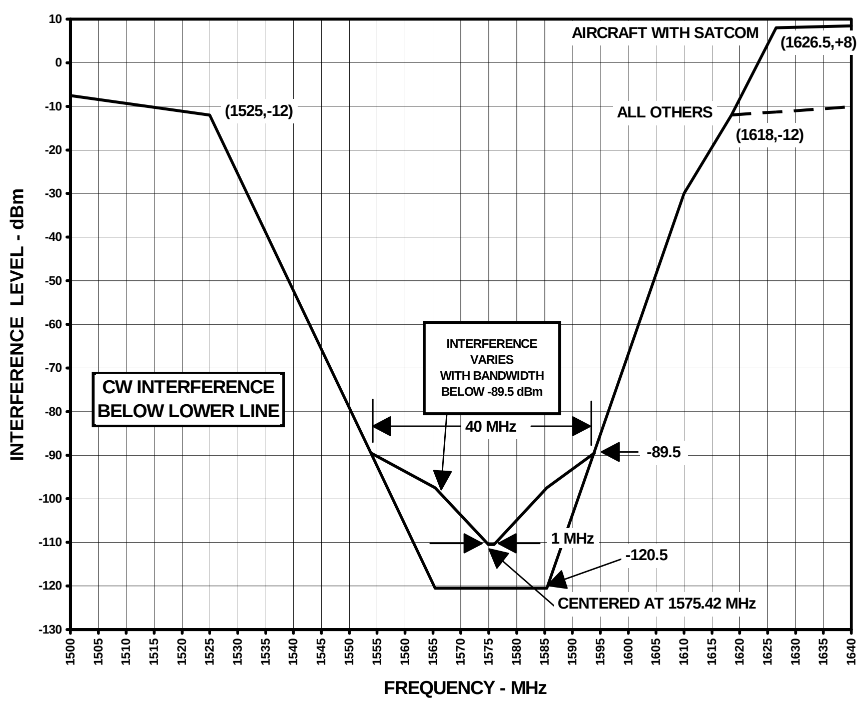

FIGURE C-1 INTERFERENCE LEVELS AT THE ANTENNA PORT

C.2.1.1 Out-of-Band Pulse Interference

After steady state navigation has been established, equipment operating in all flight phases could receive pulsed interference in the out-of-band frequency ranges specified above having the characteristics described in Table C-1.

TABLE C-1 OUT-OF-BAND PULSE INTERFERENCE

	GPS
Peak Power	+30 dBm
Pulse Width	125 μsec
Pulse Duty Cycle	1%

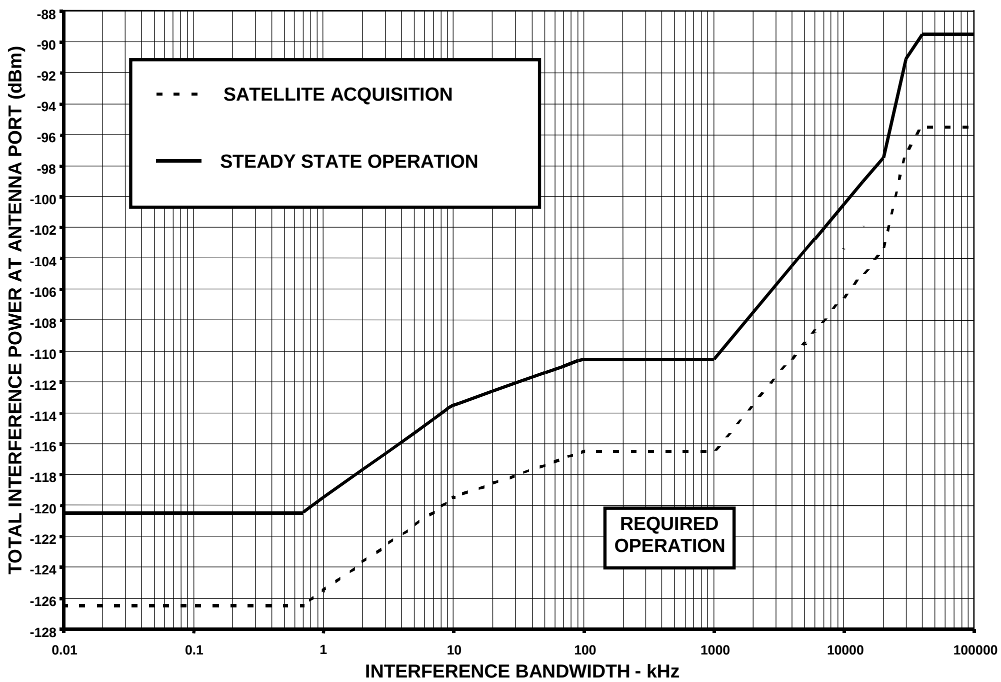

FIGURE C-2 IN-BAND AND NEAR-BAND INTERFERENCE ENVIRONMENTS

C.2.2 In-Band and Near-Band Interference

The baseline in-band and near-band interference environments apply to steady-state operation. For initial acquisition of the GPS signals prior to steady-state navigation, the in-band and near-band interference levels are 6 dB less than those for steady-state operation. The interference bandwidth is the 3 dB bandwidth.

Figure C-1 and Figure C-2 are related as follows: The upper mask of Figure C-1 (the mask that varies with bandwidth) at 1575.42 MHz ±0.5 MHz relates to the level in Figure C-2 between the bandwidths of 100 and 1000 kHz. For interference bandwidths outside of that range, the level of the mask in Figure C-1 is adjusted up or down according to the levels of Figure C-2. For example, for the upper curve of Figure C-2, interference with a bandwidth of 0.1 kHz lowers the mask to the CW interference mask at 1575.42 MHz (-

120.5 dBm), while interference with a bandwidth of 20 MHz raises the mask at 1575.42 MHz at a level of -97.5 dBm. In addition, if the center of the interference moves away from 1575.42 MHz, the levels of Figure C-2 for bandwidths not greater than 20 MHz are raised according to the mask of Figure C-1. For example, for the upper curve of Figure C-2, for interference centered at 1565.42 MHz, the curve of Figure C-2 is increased by 13 dB.

After steady state navigation has been established, the equipment could receive an interfering signal in the frequency range of 1575.42 $\pm BW_I/2$ MHz that is as high as the levels defined in Table C-2 as a function of interfering signal bandwidth BW_I:

TABLE C-2 IN-BAND AND NEAR-BAND INTERFERENCE BANDWIDTH DEFINITIONS

BANDWIDTH	INTERFERENCE LEVEL
$0 \leq BW_I \leq 700$ Hz	-120.5 dBm
700 Hz $< BW_I \leq$ 10 kHz	Linearly increasing[1] from -120.5 dBm to -113.5 dBm
10 kHz $< BW_I \leq$ 100 kHz	Linearly increasing[1] from -113.5 dBm to -110.5 dBm
100 kHz $< BW_I \leq$ 1 MHz	-110.5 dBm
1 MHz $< BW_I \leq$ 20 MHz	Linearly increasing[1] from -110.5 to -97.5 dBm[2]
20 MHz $< BW_I \leq$ 30 MHz	Linearly increasing[1] from -97.5 to -91.1 dBm[2]
30 MHz $< BW_I \leq$ 40 MHz	Linearly increasing[1] from -91.1 to -89.5 dBm[2]
40 MHz $< BW_I$	-89.5 dBm[2]

[1] Increase in interference power is linear for the units shown in Figure C-2.

[2]Interference levels will not exceed –110.5 dBm/MHz in the frequency range of 1575.42 ± 10 MHz.

These interfering levels as a function of bandwidth are shown in Figure C-2.

C.2.2.1 In-Band and Near-Band Pulsed Interference

After steady state navigation has been established, equipment operating in all flight phases could receive pulsed interference in the in-band and near-band frequency ranges specified above having the characteristics described in Table C-3.

TABLE C-3 IN-BAND AND NEAR-BAND PULSE INTERFERENCE

	GPS
Peak Power	+10 dBm
Pulse Width	125 μsec
Pulse Duty Cycle	1%
Signal Bandwidth	1 MHz

C.2.3 GNSS Noise

The GNSS Noise is a broadband noise with spectral density that has an equivalent effect on the equipment than the aggregate power from the anticipated future GNSS environment, including GPS C/A, P/Y, and M-code signals from a full GPS constellation, SBAS C/A code signals from the anticipated SBAS providers, QZSS and Galileo. Values are specified in Table C-4 for different receiver functions due to different signal coupling and operational requirements.

TABLE C-4 EFFECTIVE NOISE DENSITY FOR ALL GNSS SOURCES

Receiver Function	Effective Noise Density (dBm/Hz)
Initial Acquisition (GPS Only)	-172.2
GPS Tracking and Re-acquisition	-171.9

C.3 Minimum Standard Antenna Frequency Selectivity

When received by a minimum standard antenna, interfering signals are attenuated, at minimum, in accordance with the frequency selectivity shown in Table C-5 and Figure C-3.

TABLE C-5 FREQUENCY SELECTIVITY

Frequency (MHz)	Selectivity (dB)
1315 ≤ f < 1504.42	-50 dB
1504.42 ≤ f < 1554.42	Linearly increasing from -50 dB to -5 dB
1554.42 ≤ f < 1558.42	Linearly increasing from -5 dB
1558.42 ≤ f ≤ 1591.92	0 dB
1591.92 < f ≤ 1605.42	Linearly decreasing to -25.35 dB
1605.42 < f ≤ 1625.42	Linearly decreasing from -25.35 dB to -50 dB
1625.42 < f ≤ 2000	-50 dB

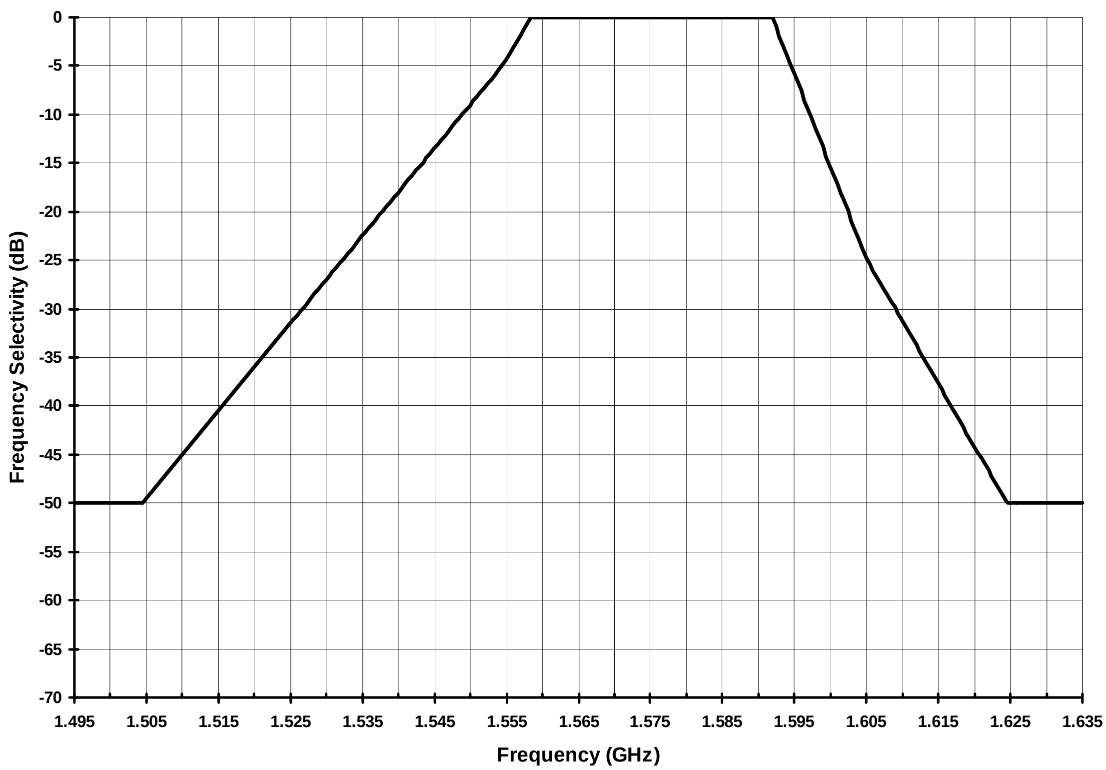

FIGURE C-3 FREQUENCY SELECTIVITY

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APPENDIX D

RESERVED

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APPENDIX E

BASELINE WEIGHTED NAVIGATION SOLUTION AND NAVIGATION SYSTEM ERROR ALGORITHMS

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E.1 Introduction

This appendix describes an algorithm for computing the navigation solution where, this algorithm makes use of a weighted least squares method to solve the navigation equations.

The equipment must realize navigation solutions which perform at least as well as the algorithm described in Section E.2.

E.2 Baseline Navigation Solution

The basic linearized GPS measurement equation is: [1]

$$y = G \bullet x + \varepsilon$$

where x is the four dimensional position vector (north, east, up and clock) about which the linearization has been made, y is an *N* dimensional vector containing the raw pseudorange measurements minus the expected ranging values based on the location of the satellites and the location of the user (x), G is the observation matrix and ε is an *N* dimensional vector containing the errors in y. The expected pseudoranges from the linearization point to the satellites are determined from the linearization point. The observation matrix consists of *N* rows of line of sight vectors from x to each satellite, augmented by a 1 for the clock. Thus the i^{th} row corresponds to the i^{th} satellite in view and can be written in terms of the elevation angle El_i and the azimuth angle Az_i

$$\mathbf{G_i} = \left[-\cos El_i \sin Az_i \quad -\cos El_i \cos Az_i \quad -\sin El_i \quad 1\right] = i^{th} \text{ row of } \mathbf{G}$$

when positive azimuth is defined clockwise from North.

Note: The sign and coordinate frame convention used is different from the one adopted for LAAS in RTCA/DO-253 and for the ICAO standards; however, the definitions of the G-matrix adopted by these standards are all mathematically equivalent.

The weighted least squares solution for x is the solution (found by iteration) to: [2]

$$\hat{\mathbf{x}} = \left(\mathbf{G}^{\mathbf{T}} \cdot \mathbf{W} \cdot \mathbf{G}\right)^{\mathbf{-1}} \cdot \mathbf{G}^{\mathbf{T}} \cdot \mathbf{W} \cdot \mathbf{y} \equiv \mathbf{S} \cdot \mathbf{y}$$

where the definition has been made:

$$\mathbf{S} \equiv \left(\mathbf{G}^{\mathbf{T}} \cdot \mathbf{W} \cdot \mathbf{G}\right)^{\mathbf{-1}} \cdot \mathbf{G}^{\mathbf{T}} \cdot \mathbf{W}$$

and where W is the weighting matrix (see below). In this case, the weighted least squares solution is also a minimum variance solution. This baseline algorithm assumes that the error sources for each satellite are uncorrelated with the error sources for any other satellite. The weighting matrix will be diagonal and its inverse will look like:

$$W = \begin{bmatrix} w_1 & 0 & \cdots & 0 \\ 0 & w_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & w_N \end{bmatrix}, \qquad w_i = 1/\sigma_i^2$$

While this assumption may not be strictly true, it should be a reasonably good approximation. For the baseline weighting algorithm, the variances are described in Appendix J.

E.3 References

1. Milliken, R. J. and Zoller, C. J., Principle of Operation of NAVSTAR and System Characteristics, Global Positioning System Vol I, published by the Institute of Navigation, 1980, pp 3-14.
2. Strang, G., Introduction to Applied Mathematics, Wellesley-Cambridge Pub., 1986.

APPENDIX F

EXAMPLE VELOCITY AND VELOCITY FIGURE OF MERIT COMPUTATION

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F.1 Introduction

This appendix describes an example processing technique manufacturers may consider for computing velocity and velocity FOMs (collectively referred to as velocity solution).

Pseudorange data is derived from the received signal code phase and that the delta range data is derived from the received signal integrated carrier phase. It is well known that a finite difference velocity with respect to the navigation frame may be derived from the integrated carrier phase (or delta range). A simple example algorithm is presented below. However, it is understood there are numerous techniques to produce a velocity solution.

Only GPS delta-range data will be considered for use in the velocity solution unless there are an insufficient amount of GPS satellites to support the computation.

The integrity of this velocity solution is provided by:

a) The receiver GPS data integrity (all broadcast data is validated),

b) The receiver GPS measurement integrity (all measurement data is validated); and,

c) GPS receiver signal processing (carrier to noise estimates are validated)

Integrity is available from GPS augmented by RAIM. If RAIM is not available or indicates an integrity alert, integrity is understood to be unavailable. If receiver integrity is unavailable, then the integrity of the velocity solution will be unavailable as well. Furthermore, additional integrity is provided by the step detector, the GPS receiver signal processing stages such as those found in the code and carrier tracking loops, and their respective signal-to-noise estimators. The velocity solution derives its integrity from the receiver's integrity mechanisms. No further integrity data processing is required to validate the velocity solution integrity. It is assumed that whenever the receiver determines it has complete integrity, then the velocity solution can be produced.

The velocity solution presented below is qualified by a figure of merit. This figure of merit can be used by the ADS-B system as the velocity uncertainty.

F.2 Velocity Solution with Figure of Merit

The solution is based on the model:

$$\rho_1 = [\ (X_u - X_S)_1^{\,2} + (Y_u - Y_S)_1^{\,2} + (Z_u - Z_S)_1^{\,2} + R_1\ ]^2$$

$$\rho_0 = [\ (X_u - X_S)_0^{\,2} + (Y_u - Y_S)_0^{\,2} + (Z_u - Z_S)_0^{\,2} + R_0\ ]^2$$

$$\Delta\rho = \rho_1 - \rho_0$$

Where the pseudo range at time t_1 is ρ_1 and the pseudo range at time t_0 is ρ_0 and the ideal delta range measurement between the two instantaneous pseudo ranges ρ_1 and ρ_0 is $\Delta\rho$ for each satellite. The pseudo range measurements are made using ideal code tracking loops and the delta measurement is made using an ideal carrier tracking loop. Let the measured delta range be denoted by: $\mathit{\Delta\rho}$. The user position is the vector $[X_u\ Y_u\ Z_u\ R\ ]$ in WGS-84 coordinates with X_u, Y_u, and Z_u as position and R is the clock uncertainty in the same units as position. The vector $[X_s\ Y_s\ Z_s\ ]$ is the satellite position in WGS-84 coordinates.

Assume the position solutions have been determined from the code phase measurements according to the weighted least squares solution provided in appendix E for time instances t_0 and t_1. We desire a delta position solution in the local level navigation frame corresponding to the delta range measurements at time t_1. This delta position measurement, divided by the time difference $\Delta t = t_1 - t_0$ will yield the linear velocity.

Velocity Algorithm:

Let $\underline{P}_1$ denote the solved-for position in the local navigation frame with clock uncertainty in the same units as position (there is no need to scale clock uncertainty into time) at t_1 using $\underline{\rho}_1$ and the weighted least squares solution as in Appendix E. Assume the point $\underline{P}_1$ is known and there is no uncertainty with respect to $\underline{P}_1$.

Now form the fictitious measurement $\underline{\mathit{\rho}}_0 = (\underline{\rho}_1 - \underline{\mathit{\Delta\rho}})$ and solve for $\underline{\mathit{P}}_0$ using the same Appendix E algorithm, but with the differences described below. Note that $\underline{\mathit{P}}_0$ is not the same solution as $\underline{P}_0$ that would result from the Appendix E weighted least squares using $\underline{\rho}_0$. $\underline{\mathit{P}}_0$ is derived from $\underline{\mathit{\rho}}_0 = (\underline{\rho}_1 - \underline{\mathit{\Delta\rho}})$ and with the algorithmic differences described below. Once $\underline{\mathit{P}}_0$ has been obtained, the finite difference is:

$$\Delta\underline{P} = \underline{P}_1 - \underline{\mathit{P}}_0$$

Note that another means to determine $\Delta\underline{P}$ is to use $\underline{P}_0$ as the linearization point instead. The above equation becomes $\Delta\underline{P} = \underline{\mathit{P}}_1 - \underline{P}_0$ where $\underline{\mathit{P}}_1$ is solved for using the corresponding fictitious measurement: $\underline{\mathit{\rho}}_1 = (\underline{\rho}_0 + \underline{\mathit{\Delta\rho}})$, given $\underline{P}_0$. The results will be nearly identical and well within the FOM limit. The finite difference velocity vector is determined from:

$$\underline{V} = \Delta\underline{P}/\Delta t$$

The vector $\underline{V}$ contains velocity north, east, up, and the clock rate in the same units as the velocity components.

With respect to Appendix E, the basic linearized GPS measurement equation is:

$$\underline{y} = G \bullet \underline{x} + \underline{\varepsilon}$$

where $\underline{x}$ is the four dimensional position vector (north, east, up and clock) about which the linearization has been made, $\underline{y}$ is an N dimensional vector containing the fictitious pseudorange measurements minus the expected ranging values based on the location of the satellites and the location of the user ($\underline{x}$), G is the observation matrix and $\underline{\varepsilon}$ is an N dimensional vector containing the errors in $\underline{y}$. The expected fictitious pseudoranges from the linearization point to the satellites are determined from the linearization point P. The observation matrix consists of N rows of line of sight vectors from $\underline{x}$ to each satellite, augmented by a 1 for the clock. Thus the i^{th} row corresponds to the i^{th} satellite in view and can be written in terms of the elevation angle El_i and the azimuth angle Az_i

$$\mathbf{G_i} = \left[-\cos El_i \sin Az_i \quad -\cos El_i \cos Az_i \quad -\sin El_i \quad 1\right] = i^{th} \text{ row of } \mathbf{G}$$

when positive azimuth is defined clockwise from North.

Note: The sign and coordinate frame convention used is different from the one adopted for LAAS in RTCA/DO-253 and for the ICAO standards; however, the definitions of the G-matrix adopted by these standards are all mathematically equivalent.

The weighted least squares solution for x is the solution (found by iteration) to

$$\underline{\hat{\mathbf{x}}} = \left(\mathbf{G}^{\mathbf{T}} \cdot \mathbf{W} \cdot \mathbf{G}\right)^{\mathbf{-1}} \cdot \mathbf{G}^{\mathbf{T}} \cdot \mathbf{W} \cdot \underline{\mathbf{y}} \equiv \mathbf{S} \cdot \underline{\mathbf{y}}$$

where the definition has been made

$$\mathbf{S} \equiv \left(\mathbf{G}^{\mathbf{T}} \cdot \mathbf{W} \cdot \mathbf{G}\right)^{\mathbf{-1}} \cdot \mathbf{G}^{\mathbf{T}} \cdot \mathbf{W}$$

and where W is the weighting matrix corresponding to the noise variance of the delta range measurements. In this case, the weighted least squares solution is also a minimum variance solution. This baseline algorithm assumes that the error sources for each satellite are uncorrelated with the error sources for any other satellite. The weighting matrix will be diagonal and its inverse will look like

$$W = \begin{bmatrix} w_1 & 0 & \cdots & 0 \\ 0 & w_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & w_N \end{bmatrix}, \qquad w_i = 1/\sigma_i^2$$

While this assumption may not be strictly true, it should be a good approximation. For the baseline weighting algorithm, the delta range variances are determined from the carrier-to-noise estimators for each integrated carrier phase measurement.

The Figure of Merit is derived from the co-variance of the solution. The co-variance matrix is:

$$\mathrm{Var(V)} = \left(\mathbf{G}^{\mathbf{T}} \cdot \mathbf{W} \cdot \mathbf{G}\right)^{\mathbf{-1}} / \Delta t^2$$

a 4 x 4 matrix. The diagonal elements correspond to the variance of finite difference velocity components in the north, east, up, and clock range-rate coordinates. The 95% probability Figures of Merit are given by:

Velocity Horizontal FOM = $2\ [\ \mathrm{diag}_{11}\{\mathrm{Var}(\underline{V})\} + \mathrm{diag}_{22}\{\mathrm{Var}(\underline{V})\}\ ]^{1/2}$

Velocity Vertical FOM = $2\ [\ \mathrm{diag}_{33}\{\mathrm{Var}(\underline{V})\}\ ]^{1/2}$

This completes the algorithm and outputs for ADS-B.

F.3 References

1. Milliken, R. J. and Zoller, C. J., Principle of Operation of NAVSTAR and System Characteristics, Global Positioning System Vol I, published by the Institute of Navigation, 1980, pp 3-14.
2. Strang, G., Introduction to Applied Mathematics, Wellesley-Cambridge Pub., 1986

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APPENDIX G

REQUIREMENTS FOR BAROMETRIC ALTIMETER AIDING

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G.1 General

Barometric altimeter data may be used to augment GNSS. There are two different methods of obtaining barometric altimeter data and deweighting it before the data gets incorporated in the GNSS position solution: one uses altimeter data calibrated with GNSS derived altitude data and the other uses pressure altitude data corrected for the local barometric pressure setting. The incorporation of pressure altitude data calibrated by GNSS significantly improves the availability of detection and exclusion for en route and terminal modes. The use of local barometric pressure setting increases the availability of detection and exclusion for LNAV approach. This appendix specifies the requirements for equipment that incorporates barometric altimeter data using either method, as defined below.

In both methods, a weighted linearized equation shall [GPS 258] be used:

$$\mathbf{wy} = \mathbf{wGx} \qquad (1)$$

where

$$W = \begin{bmatrix} \sigma_1^{-1} & 0 & \ldots & 0 \\ 0 & \sigma_2^{-1} & \ldots & 0 \\ \ldots & \ldots & \ldots & \ldots \\ 0 & 0 & \ldots & \sigma_{baro}^{-1} \end{bmatrix}$$

where σ_i is the standard deviation of the pseudorange measurement error for the i^{th} satellite and σ_{baro} is standard deviation of the barometric altitude error estimated as described in this appendix.

Note: Consideration should be given to the selection of when to incorporate altitude aiding to improve availability and minimize HPL_{FD}. If baro-corrected pressure altitude is used, altitude aiding should only be used when necessary, in order to reduce the pilot workload associated with entering the barometric correction.

G.2 Altimeter Aiding with GNSS Calibration

This method involves two steps: calibration of the altimeter data with GNSS data when the integrity of GNSS data can be assured with good user-to-satellite geometry, and actual use of the data.

G.2.1 Requirements for Calibration

a) The equipment shall [GPS 259] use altimeter data with the same altimeter setting. This requirement can be met by consistently using pressure altitude without local barometric altitude correction.

b) Prior to calibration, the vertical calibration error, σ_{VC}, shall [GPS 260] be calculated using fault detection only with GNSS satellites in a manner similar to the calculation of a Vertical Protection $\text{Limit}_{\text{Fault Detection}}$ (VPL_{FD}) with the following requirements:

   1) A false alarm probability (P_{fa}) shall [GPS 261] be no more than 0.05 and

   2) Missed detection probability (P_{md}) shall [GPS 262] be no more than 0.32

Calibration shall [GPS 263] not be performed if a detection condition exists relative to this detection threshold.

Note: P_{md} of 0.32 is the probability of a normally distributed variable having a value larger than 1σ. (See [1] for the rationale.)

c) Upon calculation of σ_{VC}, recalibration shall [GPS 264] be done (i.e., the most recent calibration shall [GPS 265] be replaced with the new calibration) when and only when all the following conditions are met:

1) Both navigation and FD functions exist and no fault has been detected with the FD algorithm.

2) The test statistic for FD is less than a threshold that corresponds to the 95th percentile given that no other errors are present.

3) The σ_{VC} calculated in 2 above is less than σ_{baro} calculated on the basis of the most recent calibration, using the growth model described below.

d) For calibration (or recalibration), the following shall [GPS 266] be recorded:

1) The offset between the pressure altitude and the GNSS-derived altitude

2) σ_{VC}

3) The time of calibration

G.2.2 Calculation of σ_{baro}

The parameter σ_{baro} is used to deweight the pressure altitude data before it is incorporated in the position solution equation. When σ_{baro} is determined using a GNSS vertical calibration, it shall [GPS 267] be calculated as follows:

σ_{baro}= RSS (σ_{VC}, σ_h, σ_t, σ_V), where

σ_{VC} = GNSS vertical calibration error (at the time of the most recent calibration)

At the time of each new GNSS vertical calibration, the following errors are zero. Otherwise,

σ_h = k_h * d_h, where

k_h = horizontal error growth rate = 0.5 m/nmi
d_h = horizontal distance between current position and the position of most recent GNSS vertical calibration

σ_t = k_t * t, where

k_t = time error growth rate = 15 m/hr
t = time elapsed since the most recent GNSS vertical calibration

σ_V = Algebraic sum of the errors obtained for each of the applicable pressure gradient regions in Table G-1 or G-2, for the aircraft altitude change since the most recent GNSS calibration.

Table G-1 may be used if local ground level (GL) is known or can be estimated as follows. If local GL is not explicitly known, and if the nearest flight plan "TO" or "FROM" waypoint is within 30 nmi (horizontal) of the estimated present position, GL may be estimated as the GL associated with the waypoint (e.g., published elevation of a Navaid or airport). If both waypoints are more than 30 nmi, but less than 100 nmi from the present position, and both have an associated GL, then local GL may be estimated as the HIGHER of the GLs associated with the "TO" or "FROM" waypoint.

Table G-2 shall [GPS 268] be used If GL is not known and cannot be estimated using these methods. In this case, GL is assumed to be 6,000 ft MSL and the surface effects causing the largest pressure gradient error are assumed to be present between 6,000 ft and 12,000 ft MSL. If GL is below 6,000 MSL, table may result in a small to moderate overestimation of the altimeter error.

Table G-2 may always be used in lieu of Table G-1 to simplify calculations.

TABLE G-1 PRESSURE GRADIENT ERRORS (KNOWN GL)

Indicated (Geometric) Altitude	**Pressure Gradient Error (1 σ)**
Above 18,000 ft, MSL	13 m per 1000 ft altitude change
6,000 ft AGL to 18,000 ft, MSL	23 m per 1000 ft. altitude change
Below 6000 ft, AGL	32.5 m per 1000 ft. altitude change

TABLE G-2 PRESSURE GRADIENT ERRORS (UNKNOWN GL)

Indicated (Geometric) Altitude	**Minimum Pressure Gradient Error (1σ)**
Above 18,000 ft, MSL	13 m per 1000 ft altitude change
12,000 ft MSL to 18,000 ft MSL	23 m per 1000 ft. altitude change
Below 12,000 ft MSL:	
First, 6,000 ft of change	32.5 m per 1000 ft. altitude change
Remainder of change	23m per 1000 ft. altitude change

For example, suppose that σ_{vc} = 200 m, d_h = 40 nmi, t = 30 min = 0.5 hr, and

altitude at the time of the last calibration = 12,000 ft, MSL
current aircraft altitude = 5,000 ft, MSL

i) If it is known or estimated that local ground level is at 2,000 ft, MSL, then:

$$\sigma_v = 23 \times (12000 - 8000) / 1000 + 32.5 (8000 - 5000) / 1000 = 189.5 \text{ m, and}$$

$$\sigma_{baro} = \text{RSS} (200, 40 \times 0.5, 189.5, 0.5 \times 15) = 276.3 \text{ m.}$$

ii) If local ground level is unknown or cannot be estimated, then:

$$\sigma_v = 32.5 \times (12000 - 6000) / 1000 + 23 (6000 - 5000) / 1000 = 218 \text{ m, and}$$

$$\sigma_{baro} = \text{RSS} (200, 40 \times 0.5, 218, 0.5 \times 15) = 296.6 \text{ m}$$

G.2.3 Actual Use of the Altitude Measurement to Augment GNSS

Pressure data can only be incorporated into the position solution after calibration. The pressure altitude, properly scaled as shown above, should be used to augment GNSS when the navigation and/or the necessary FDE functions cannot be provided by GNSS alone. This method can be used in any of the en route, terminal, and LNAV approach operations as long as it maintains the consistency of data between the time of calibration and the time of actual use of the data. This consistency requirement is met if pressure altitude is consistently used.

G.3 Barometric Altimeter Aiding Using Baro-corrected Pressure Altitude

This method is to use pressure altitude data corrected for the local barometric pressure setting and the difference between the WGS-84 ellipsoid altitude and mean sea level altitude at the present position. Although this method can achieve the most benefit in the LNAV approach operations, it may also be used for en route and terminal operations as long as it consistently uses the properly corrected the pressure altitude.

Note: Consideration must be given to the pilot workload associated with baro-corrected pressure altitude. The necessity for the pilot to double-enter the local pressure setting into the barometer and the GPS equipment should be avoided. The possible lack of integrity associated with the manual entry of the setting should also be considered.

G.3.1 Requirements for calibration

The correction for the pressure altitude data shall [GPS 269] meet the following requirements:

a) This correction may be provided by automatic or manual input.

b) The pressure altitude data corrected for the local barometric pressure setting shall [GPS 270] be corrected with the difference between the WGS-84 ellipsoid altitude and mean sea level altitude at the present position with sufficient accuracy. This requirement can be met with a table that stores the ellipsoid bounded by 10 deg of latitude and longitude.

G.3.2 Calculation of σ_{baro}

In the method of using baro-corrected pressure altitude, σ_{baro} shall [GPS 271] be calculated as follows:

$$\sigma_{baro} = RSS(\sigma_{ht}, \sigma_a, \sigma_v)$$

where:

σ_{ht}= 33 m, representing errors due to horizontal and temporal separation between the aircraft and baro correction (See [2] for its derivation)

σ_a= Altimeter accuracy error = 10 m

σ_v = Algebraic sum of the errors obtained for each of the applicable pressure gradient regions in Table G-1, for the difference between the aircraft altitude and the altitude of the reference station

For this calculation, GL is the lower of the reference station GL or local GL. If local GL is not explicitly known, and if the nearest flight plan "TO" or "FROM" waypoint is within 30 nmi of the estimated present (horizontal) position, GL may be estimated as the GL associated with the waypoint (e.g., published elevation of a Navaid or airport). If both waypoints are more than 30 nmi, but less than 100 nmi from the present position, and both have an associated GL, then local GL may be estimated as the LOWER of the GLs associated with the "TO" or "FROM" waypoint. If either the reference station GL or an estimate of the local GL is not available or if both waypoints are not within 100 nmi from the present location, GL should be estimated as MSL. To simplify calculations, GL may always be estimated as MSL.

For example, suppose that:

altitude of the reference station = 1000 ft, MSL
= 0 ft, AGL
current aircraft altitude = 6,000 ft, MSL

Then,

σ_V = 32.5 x (5000 - 0) / 1000
= 162.5 m

and thus

σ_{baro} = RSS (162.5, 33, 10)
= 166.12 m.

G.3.3 Actual Use of the Barometric Altitude Measurement to Augment GNSS

When navigation and/or FDE functions cannot be provided by GNSS alone, properly corrected pressure altitude data and scaled as shown above, may be used to augment GNSS. This method can be used in any of the en route, terminal, and LNAV approach operations as long as properly corrected and scaled data is used.

G.3.4 Requirements for Pilot Interaction

If the system has a capability to accept an automatic input of barometric corrected altitude data, then this method of barometric altimeter aiding may be used with no requirements for pilot interaction.

However, if the equipment is to use this method only for the LNAV approach, and if there is no automatic barometric input capability, then the equipment shall [GPS 272] provide the following:

Concurrent with the approach alert, a suitable means to alert the pilot of the need to manually insert the barometric pressure setting shall [GPS 273] be provided. This alert will be followed by the pilot's insertion of the barometric pressure setting and then a pilot's input with a single action indicating to the receiver that the insertion has been made. Upon receipt of this indication, the receiver shall [GPS 274] incorporate the altitude measurement in the navigation solution and the FDE algorithm according to the procedure outlined above. If such an insertion is not made, pressure altitude shall [GPS 275] continue to be used with GNSS calibration.

G.4 Test Procedures

It is recognized that equipment manufacturers will have different implementations of FDE algorithms and barometric aiding in these algorithms. Differences in implementation will greatly influence any test procedures. It is therefore left to the manufacturer to define tests that show compliance with the requirements listed in this appendix. However, such tests shall [GPS 276] cover all applicable requirements and cases (e.g., when testing compliance with Table G-2, all cases in the table have to be tested - at altitudes between 0 and 6000 ft, between 6000 and 12000 ft, between 12000 and 18000 ft, and above 18000 ft).

G.5 References

1. John Studenny, "Baro-Altimeter Calibration for GPS Integrity", RTCA Paper No. 235-95/SC159-639, April, 1995.

2. John Dobyne, "Barometric Altimeter Aiding of GPS", Proceedings of the International Technical Meeting of the Satellite Division of the Institute of Navigation, September, 1989.

APPENDIX H

STANDARD OUTPUT FORMAT

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H.1 Introduction

It is anticipated that the GPS position output will be made available for other on-board and external applications. On-board examples include: ground navigation moving map displays, cockpit displays of traffic information, and weather mapping systems. Users of GPS position which are external to the aircraft include: Traffic Alert and Collision Avoidance System (TCAS) [e.g.,RTCA/DO-185], Automatic Dependent Surveillance (ADS) [e.g., RTCA/DO-212], and Automatic Dependent Surveillance - Broadcast (ADS-B) [RTCA/SC-186]. It is important that the GPS position outputs sent to these applications convey the accuracy and integrity provided by the certified GPS receiver. This appendix therefore recommends a minimum output standard for GPS equipment that can provide reliable position data to these applications.

Particularly for external applications used to separate aircraft, it is essential that there be no ambiguity in comparing aircraft positions and velocities. For this reason, not only the aircraft position but its time of applicability must meet a common definition.

H.2 GPS Minimum Output and Output Timing

This section describes the recommended minimum output as well as output timing.

H.2.1 Minimum GPS Output

The equipment outputs recommended here are based on the data items specified in the ADS MOPS (RTCA/DO-212) as well as the industry standards (e.g., ARINC 743A). The parameters listed in Table H-1 represent a minimum set of parameters that should be available from equipment meeting this MOPS. Clearly, additional data may be provided and provisions to request specific data at various rates may be desirable options. While the intent is not to require a specific output interface, it is recommended that industry standards (e.g., ARINC 743A, 429) be adhered to in the interest of avionics interoperability.

Table H-1 summarizes key characteristics of the twelve basic parameters that are recommended for a minimum GPS output. The first column is provided for reference to the ARINC 743A field labels used to identify each parameter as it is output on the ARINC 429 output bus. The output formats are typically two's complement binary numbers (BNR) except for the date that is in binary coded decimal (BCD). The units for each parameter are listed. The positive sense is indicated but many are magnitudes only. The range or maximum is given for each variable. The size in bytes and number of significant bits (excluding sign) are also shown. The resolution of the least significant bit is given for the number of significant bits shown, though some implementations may provide greater accuracy.

TABLE H-1 MINIMUM GPS OUTPUT

743A Label	Parameter	Fmt	Units	pos+	Range**	Sig Bits	Resolut. LSB
110, 120	GNSS Latitude*	BNR	degrees	N	±180	31	8.38E-8
111, 121	GNSS Longitude*	BNR	degrees	E	±180	31	8.38E-8
247	Horiz. Figure of Merit	BNR	nm	***	16	15	4.88E-4
130	Horiz. Protection Level	BNR	nm	***	16	15	4.88E-4
076	GNSS Altitude (MSL)	BNR	ft	up	±131,072	20	0.125
136	Vert. Figure of Merit	BNR	ft	***	32,768	15	1.0
133	Vertical Protection Level	BNR	ft	***	32,768	15	1.0
103	GNSS True Track Angle	BNR	degrees	cw-	±180	15	0.0055
112	GNSS Ground Speed	BNR	knots	***	4,096	15	0.125
165	Vertical GNSS Velocity	BNR	ft/min	up	±32,768	15	1.0
150,140	Time (UTC, UTC Fine)	BNR	seconds	***	86,400	31	61.035µs
260	Date	BCD	ddmmyy	***	N/A	6	1 day
370	GNSS Height	BNR	ft	up	±131,072	20	0.125

*** Always Positive

** When no value is available or the value is invalid, the default will be all "ones".

* When either latitude or longitude for a position are invalid, both set to -180E.

The resolution of the least significant bit for latitude and longitude is 8.38E-8, which is less than 9.4 centimeters. This should be sufficient accuracy for even the most accurate modes of operation. The GNSS Height field gives the geodetic height above the WGS-84 ellipsoid and is not corrected for geoidal or barometric variations. The difference between label 076 and label 370 is defined within ARINC-743A-4. The applicable geoid model is EGM96, a joint NASA/NGA (formerly NIMA) model that can be found at http://cddisa.gsfc.nasa.gov/926/egm96/egm96.html. EGM-96 has been updated to EGM2008 (http://earth-info.nga.mil/GandG/wgs84/gravitymod/egm2008/index.html). Both EGM-96 and EGM2008 may be used as an acceptable geoid model; and, EGM-96 continues to be available on the website listed above. Appendix N contains guidance information on altimetry and Mean Sea Level conversion relative to WGS-84.

The Horizontal and Vertical Figure of Merit are the current assessment of the 95% accuracy (i.e., 2drms) of the reported position in these dimensions. The Horizontal and Vertical Protection Levels are the current assessment of the integrity bounds on the reported position in each dimension. It is recognized that the GPS solution may incorporate various levels of augmentation from sources such as inertial navigation, altitude aiding, or clock coasting. In each case the equipment is expected to assess its accuracy (i.e., Figure of Merit) as well as its integrity (i.e., Protection Level) in both the horizontal and vertical dimensions. Reporting these parameters should, therefore, replace the need for discrete information about the equipment configuration or status. These parameters are expected to be valid at the time of the report and any delay in recognizing a change in them should be commensurate with the required integrity warning time for that mode.

The GPS True Track Angle is the bearing from true north of the velocity vector of the aircraft's GPS antenna. Likewise, the GPS Ground Speed is the speed of the GPS antenna relative to the ground. Vertical Velocity is a signed binary integer in units of feet per minute.

The time parameter is the UTC (universal coordinated time) time of day in seconds. The time of day (contained in the first 17 bits) advances to 86,399 and then starts over at zero. The remainder of the field (14 bits) allow time to be specified to a precision of 61µs. The interpretation of the time field is discussed under Section H.2.2. Finally, the date is given in three two-digit BCD fields of day, month, and year.

H.2.2 Timing

In producing an output of GPS position there are four times of interest: a) the time the measurement is made, b) the time the output is available to external applications, c) the time for which the position solution is valid (i.e., User Time Epoch), and d) the UTC Epoch (i.e., the start of a new UTC second). Figure H-1 depicts these events with the lower line representing the measurement of the satellite (SV) data by the tracking loops in the GPS receiver signal processor. Once the measurement has been made, the receiver's data processor can compute a solution including the correction for the receiver clock bias as depicted on the middle line. This solution is computed to be valid at the User Time Epoch which in general may differ from the UTC Epoch. In most GPS receivers (e.g., ARINC 743A) the receiver hardware also generates a pulse at the User Time Epoch as shown on the top line. In some receivers this time pulse is also aligned with the UTC epoch. The actual output of the GPS parameters may precede this time. It is desirable that the time between the measurement and the time of output be as small as possible so that the position can be used before the estimate gets stale.

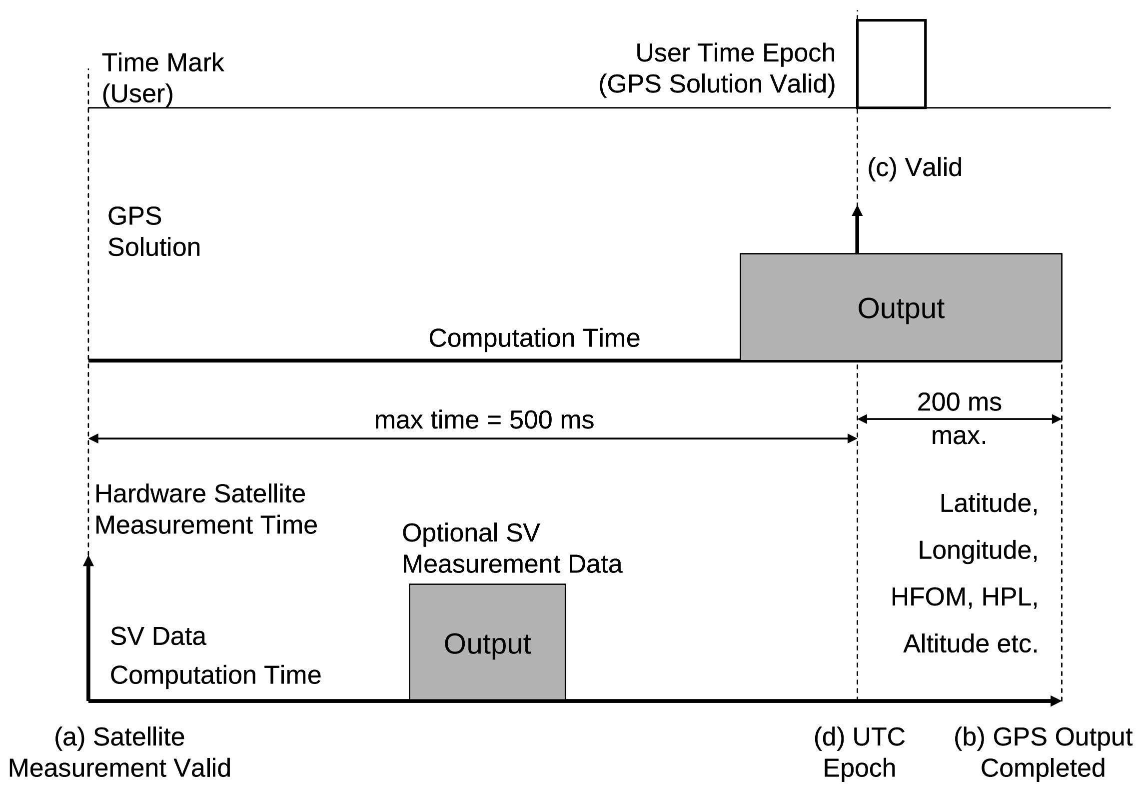

FIGURE H-1 GPS TIMING RELATIONSHIPS

In addition to the above, there is a very good reason for asking that the time of validity (User Time Epoch) be made as close to the UTC Epoch as possible. When external users such as Air Traffic surveillance or TCAS units on other aircraft want to compute the distance between aircraft, they need to compute positions at a common time such as the UTC Epoch. In order to minimize the extrapolation errors, it is desirable to have the GPS output time and valid time (User Time Epoch) as close to the UTC Epoch as possible. It is therefore recommended that the User Time Epoch be aligned with the UTC Epoch as close as possible. This will have the benefit of not only reducing the extrapolation and latency errors, but will also cause the lower order time bits to be zero. If the receiver is unable to align the User Time Epoch and the UTC Epoch then the external application would have to extrapolate the solution to the nearest UTC Epoch using the velocity data, with the attendant degradation in position accuracy.

In order to keep the total time between the SV measurement and the GPS output/ User/UTC Time Epoch as short as possible it is desirable that the time required for the GPS output to take place be small. Typical output data rates (e.g., ARINC 429) are 100,000 bps. Thus it takes only 5.1 ms to output fifteen ARINC 429 data words, which is not very significant compared to the total time available.

It is required that the GPS output period be once per UTC second (Section 2.1.2.6.1).

H.3 Other Desirable GPS Outputs

The above basic set of parameters is a recommended minimum that will assure that the GPS set provides at least a minimal level of interoperability with other avionics applications. In addition to this basic data, some applications (e.g., inertial navigation system) may need to have access to the underlying satellite measurements (e.g., ARINC 743A).

H.4 Summary

This appendix recommends that basic GPS outputs be provided for use by on-board and external systems. Basic position and velocity data should be provided with a one second period aligned to the UTC Epoch. Associated accuracy and integrity assessments will allow the position data to be properly used regardless of the details of the equipment configuration or mode of operation.

H.5 References

1. The Development of the Joint NASA GSFC and NIMA Geopotential Model EGM96, NASA Goddard Space Flight Center, Greenbelt, Maryland, 20771 USA, July 1998.
2. Technical Characteristics of the NAVSTAR GPS, June 1991, Appendix 6, Section 1.

APPENDIX I

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APPENDIX J

WEIGHTS FOR USE IN GENERAL LEAST SQUARES SOLUTIONS AND TROPOSPHERIC CORRECTION ALGORITHM

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J.1 Weights

The following weights are acceptable for GPS range measurements for a weighted-least-squares position solution and FDE. (See Appendix E for a description of the baseline weighted-least-squares position solution.).

$$\sigma_i^2 = URA_i^2 + \sigma_{i,UIRE}^2 + \sigma_{i,air}^2 + \sigma_{i,tropo}^2$$

$$w_i = 1/\sigma_i^2$$

Note: URAs are defined in Table 2-1.

J.2 Variance of Ionospheric Delay

The following model characterizes ionospheric error associated with the use of GPS-based ionospheric corrections:

$$\sigma_{i,UIRE}^2 = MAX\left\{\left(\frac{cT_{iono}}{5}\right)^2, \left(F_{pp}\cdot\tau_{vert}\right)^2\right\}$$ (see note 4)

c = the speed of light in a vacuum (2.99792458×10^8 meters/sec, see IS-GPS-200D pg 89)

T_{iono} = ionospheric correction (seconds, see Section 20.3.3.5.2.5 of IS-GPS-200D)

F_{pp} = obliquity factor $F_{pp} = \left[1-\left(\frac{R_e\cos E}{R_e+h_I}\right)^2\right]^{-\frac{1}{2}}$

R_e = 6378136.0 m

h_I = 350000.0 m

$$\tau_{vert} = \begin{cases} 9\,m, & 0 \le |\phi_m| \le 20 \\ 4.5\,m, & 20 < |\phi_m| \le 55 \\ 6\,m, & 55 < |\phi_m| \end{cases}$$

ϕ_m is the geomagnetic latitude as defined in Section 20.3.3.5.2.5 of IS-GPS-200D.

Note 1: User equipment must convert ϕ_m from semicircles to degrees. One semicircle is defined as 180 degrees or π radians.

Note 2: The GPS-based ionospheric model is valid for satellite elevation angles not less than 2 degrees.

Note 3: The above ionospheric error model has only been validated for HALs down to approximately 0.1 nautical miles.

Note 4: The purpose of selecting $\sigma_{i,UIRE}$ as the maximum of $cT_{iono}/5$ and $F_{pp}\cdot\tau_{vert}$ is to cause $\sigma_{i,UIRE}$ to be large if for some reason the GPS ionospheric correction T_{iono} is erroneously large. The largest value of vertical ionospheric delay ever observed is on the order of 50 meters. However, if an unintended combination of GPS ionospheric parameters is sent, T_{iono} could have a value of approximately 900 meters. Such an erroneously large ionospheric correction has never been sent, but cannot be ruled out.

J.3 Variance of Airborne Receiver Errors

The parameter, $\sigma_{i,air}$, shall [GPS 277] be one of the following two models:

Error Model 1 (equipment that does not do carrier-smoothing of pseudorange measurements):

$$\sigma^2_{i,air} = 25m^2$$

Note: The multipath error sigma contribution to error model 1's σi,air is based upon data collected during enroute, approach and landing operations. This data collection does not include surface taxi operations.

Error Model 2 (equipment that does carrier-smoothing of pseudorange measurements as defined in Section 2.1.2.6.4):

$$\sigma_{air}[i] = \left(\sigma^2_{noise}[i] + \sigma^2_{multipath}[i] + \sigma^2_{divg}[i]\right)^{1/2}$$

The installed multipath error for the airborne equipment is described by the distribution, $N(0,\sigma^2_{\mathrm{multipath}})$ where:

$$\sigma_{\mathrm{multipath}}[\mathrm{i}] = 0.13 + 0.53\mathrm{e}^{(-\theta[\mathrm{i}]/10\,\mathrm{deg})} \text{ (in meters)}$$

$\theta[i]$ = elevation angle of satellite (in degrees)

Note 1: The multipath error sigma is valid down to 2 degrees.

Note 2: DO-229D included a term "$\sigma_{divg}[i]$" (in meters) which accounts for the steady-state effects of the airborne smoothing filter relative to the steady-state response of the filter defined in Section 2.1.2.6.4, given an ionospheric divergence. For a HAL of >=556 m the error induced by carrier smoothing of code measurements is negligible and may be assumed to be zero. If the manufacturer chooses to use equipment that performs carrier smoothing for applications with a HAL of less than 556m, the manufacturer should account for the error induced due to carrier smoothing.

Note 3: If the airborne smoothing filter converges to a different steady-state bias than the standard filter, a steady-state error will remain which must be accounted for in σ_{divg}.

$\sigma_{\mathrm{noise}}[i]$ (in meters) shall [GPS 278] be the standard deviation of a normal distribution that bounds the errors in the tails of the distribution associated with the GNSS receiver for satellite i, including receiver noise, thermal noise, interference, inter-channel biases, extrapolation, time since smoothing filter initialization, and processing errors.

The parameter σ_{noise} must change to reflect current signal conditions. For example, degradation to system accuracy due to interference must be accounted for in the value of RMS_{pr_air} that is used in the protection level computations, within the time to alert.

Note: The test procedures of Section 2.3.6.1 *are sufficient to show compliance with the both the accuracy requirement in Section* 2.1.2.1 *and the* σ_{noise} *requirement for integrity. The* σ_{noise} *validated through those tests can be used as the standard deviation of a normal distribution that bounds the tails of the error distribution associated with the receiver tracking performance.*

J.4 Tropospheric Correction Model

Because tropospheric refraction is a local phenomenon, all users will compute their own tropospheric delay correction. A suggested tropospheric correction model is described below.

The tropospheric delay correction [TC_i] for satellite i takes the form:

$$TC_i = -\left(d_{hyd} + d_{wet}\right) \cdot m(El_i)$$

where [d_{hyd} , d_{wet} (m)] are the estimated range delays for a satellite at 90° elevation angle, caused by atmospheric gases in hydrostatic equilibrium and by water vapor respectively, and [$m(El_i)$ (dimensionless)] is a mapping function to scale the delays to the actual satellite elevation angle [El_i].

[d_{hyd}, d_{wet}] are calculated from the receiver's height and estimates of five meteorological parameters: pressure [P (mbar)], temperature [T (K)], water vapor pressure [e (mbar)], temperature lapse rate [β (K/m)] and water vapor "lapse rate" [λ (dimensionless)].

Values of each of the five meteorological parameters, applicable to the receiver latitude [ϕ] and day-of-year [D] (starting with 1 January), are computed from the average and seasonal variation values given in Table J-1. Each parameter value [ξ] is computed as:

$$\xi(\phi, D) = \xi_0(\phi) - \Delta\xi(\phi) \cdot \cos\left(\frac{2\pi(D - D_{\min})}{365.25}\right)$$

where D_{min}=28 for northern latitudes, D_{min}=211 for southern latitudes, and ξ_0, $\Delta\xi$ are the average and seasonal variation values for the particular parameter at the receiver's latitude. For latitudes $|\phi| \le 15°$ and $|\phi| \ge 75°$, values for ξ_0 and $\Delta\xi$ are taken directly from Table J-1. For latitudes in the range $15° < |\phi| < 75°$, values for ξ_0 and $\Delta\xi$ at the receiver's latitude are each pre-calculated by linear interpolation between values for the two closest latitudes [ϕ_i, ϕ_{i+1}] in Table J-1:

$$\xi_0(\phi) = \xi_0(\phi_i) + \left[\xi_0(\phi_{i+1}) - \xi_0(\phi_i)\right] \cdot \frac{(\phi - \phi_i)}{(\phi_{i+1} - \phi_i)}$$

$$\Delta\xi(\phi) = \Delta\xi(\phi_i) + \left[\Delta\xi(\phi_{i+1}) - \Delta\xi(\phi_i)\right] \cdot \frac{(\phi - \phi_i)}{(\phi_{i+1} - \phi_i)}$$

TABLE J-1 METEOROLOGICAL PARAMETERS FOR TROPOSPHERIC DELAY

	Average				
Latitude (°)	P_0 *(mbar)*	T_0 *(K)*	e_0 *(mbar)*	β_0 *(K/m)*	λ_0
15° or less	1013.25	299.65	26.31	6.30e-3	2.77
30	1017.25	294.15	21.79	6.05e-3	3.15
45	1015.75	283.15	11.66	5.58e-3	2.57
60	1011.75	272.15	6.78	5.39e-3	1.81
75° or greater	1013.00	263.65	4.11	4.53e-3	1.55
	Seasonal Variation				
Latitude (°)	ΔP *(mbar)*	ΔT *(K)*	Δe *(mbar)*	$\Delta\beta$ *(K/m)*	$\Delta\lambda$
15° or less	0.00	0.00	0.00	0.00e-3	0.00
30	-3.75	7.00	8.85	0.25e-3	0.33
45	-2.25	11.00	7.24	0.32e-3	0.46
60	-1.75	15.00	5.36	0.81e-3	0.74
75° or greater	-0.50	14.50	3.39	0.62e-3	0.30

Zero-altitude zenith delay terms [z_{hyd}, z_{wet} (m)] are calculated as:

$$z_{hyd} = \frac{10^{-6} k_1 R_d P}{g_m}$$

$$z_{wet} = \frac{10^{-6} k_2 R_d}{g_m(\lambda+1) - \beta R_d} \cdot \frac{e}{T}$$

where k_1 = 77.604 K/mbar, k_2 = 382000 K^2/mbar, R_d = 287.054 J/(kg·K), and g_m = 9.784 m/s^2.

[d_{hyd}, d_{wet}] are calculated as:

$$d_{hyd} = \left(1 - \frac{\beta H}{T}\right)^{\frac{g}{R_d \beta}} \cdot z_{hyd}$$

$$d_{wet} = \left(1 - \frac{\beta H}{T}\right)^{\frac{(\lambda+1)g}{R_d \beta} - 1} \cdot z_{wet}$$

where g = 9.80665 m/s^2 and the receiver's height, [H] is expressed in units of meters above mean-sea-level.

The tropospheric correction mapping function for satellite elevation, [m(Eli)], is calculated in one of two ways:

A simplified calculation of [m] is valid f or satellite elevation angles [El_i] of not less than 4°: $m(El_i) = \frac{1.001}{\sqrt{0.002001 + \sin^2(El_i)}}$

An alternate calculation of [m] is valid for satellite elevation angles [El_i] of not less than 2°:

$$m(El_i) = \left(\frac{1.001}{\sqrt{0.002001 + \sin^2(El_i)}} \right) \cdot \left(1 + 0.015 \cdot \left(MAX \begin{bmatrix} 0 \\ (4° - El_i) \end{bmatrix} \right)^2 \right)$$

For equipment that does not apply the tropospheric model described above, the equipment shall [GPS 279] include a model of the residual error that overbounds the rare tropospheric delays.

J.5 Model Standard Deviation for Tropospheric Error

The tropospheric delay residual has been based on an assessment of tropospheric errors. The residual error parameter $\sigma_{i,tropo}$ for the tropospheric delay correction for satellite i, based on the model of J.1.3 above, is:

$$\sigma_{i,tropo} = \left(\sigma_{TVE} \cdot m(El_i) \right) \quad \text{(units are in meters)}$$

where the tropospheric vertical error is σ_{TVE} = 0.12 meters.

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APPENDIX K

FAULT DETECTION AND EXCLUSION REFERENCES

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The following references provide additional information concerning fault detection and exclusion.

1. Brown, G., RTCA Paper No. 491-94/SC-159-584, November 7, 1994.
2. Brenner, M., "Implementation of a RAIM Monitor in a GPS Receiver and an Integration GPS/IRS", Proceedings of ION GPS-90, Colorado Springs, CO, September 9-21, 1990.
3. Farrell, J., "Extended RAIM (ERAIM) - Estimation of SV Clock Offset", Proceedings of ION GPS-92.
4. Kelly, R. J., "Hypothesis Testing as Applied to GPS Receiver Autonomous Integrity Monitoring", Ohio University Lectures, October 1997.
5. Kelly, R. J., "Derivation of the RAIM Algorithm from First Principles with Performance Comparisons Between Published Algorithms", Proceedings of ION Technical Meeting, January, 1996.
6. Lee, Y., "Example Fault Detection and Exclusion Algorithm, RTCA Paper No. 595-95/SC159-683.
7. Parkinson, B., Axelrad, P., "Autonomous GPS Integrity Monitoring Using the Pseudorange Residual", ION, Vol. 35, No. 2, Summer, 1988.
8. Sturza, M., "Navigation System Integrity Monitoring Using Redundant Measurements", Navigation, ION, Vol. 35, No. 4, Winter 1988-89.
9. Van Dyke, K., et al, Summary of RTCA SC-159 GPS Integrity Working Group Activities, Proceedings of ION Technical Meeting, January, 1996.

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APPENDIX L

THE DIRECT AND INDIRECT GEODETIC PROBLEMS FOR GREAT CIRCLE NAVIGATION

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L.1 General

One of the most important considerations as the NAS evolves from a station-referenced navigation system to an earth-referenced navigation system is the earth model (datum) used for Aviation Information Publications (AIPs) and air navigation systems. This appendix describes the geometry of the WGS-84 ellipsoid, and defines the geodetic latitude and longitude of a point on that ellipsoid. An example algorithm is then given for solving the following, which is called the inverse problem of geodesy:

Given the geodetic latitude and longitude of two points on the WGS-84 ellipsoid, find the range and bearing of the shortest path between them.

This path is called a geodesic.

A related problem is the direct problem of geodesy:

Given the departure geodetic latitude and longitude, the geodesic path length, and the departure bearing on the WGS-84 ellipsoid, find the arrival latitude, longitude and bearing.

The corresponding problem on the surface of a sphere has the following well-known and elementary solution. Suppose that one is given a pair of distinct, nonantipodal points on the surface of a sphere. (Recall that two (distinct) points on the surface of an ellipsoid are said to be antipodal if they are located symmetrically with respect to the center of the ellipsoid). Then these two points, together with the center of the sphere, determine a plane. This plane intersects the surface of the sphere in two circular arcs which together form a circle called a great circle. The shorter of these two circular arcs is the shortest path on the surface of the sphere that joins the prescribed points.

For two antipodal points on the surface of a sphere, there are infinitely many planes that contain both of those points and which also contain, the center of the sphere. Any of the circular arcs determined by the intersection of one of these planes with the surface of the sphere will be a geodesic. Hence, the problem does not have a unique solution in this case.

On a nonspherical, ellipsoid, the situation is considerably different. (It is therefore inappropriate to refer to geodesics on a nonspherical ellipsoid as "great circles"). In particular, the only geodesics that are plane curves are those that lie along a meridian or along the equator [1]. Furthermore, the geodesic can in general be computed to an arbitrary level of accuracy only iteratively. The iterative algorithms presented here were published in [2], and will yield accuracy to within fractions of a millimeter if the termination criterion ε is taken to be 10^{-12} (unless the two points are antipodal, or nearly antipodal. The geodesic is nonunique or highly sensitive to small changes in the problem data, respectively, in that case). This accuracy is generally obtained in no more than six iterations. Compared to "closed-form" approximate solutions, such as that in [3], the algorithm presented here is simpler to implement in software. Further discussion of various algorithms may be found in [4].

L.2 Definitions of Terms

Throughout this appendix, the term ellipsoid will specifically refer to an ellipsoid of revolution, obtained by rotating an ellipse about its minor axis. The points at which the minor axis intersects the surface of the ellipsoid are called the North and South poles. The plane which passes through the center of the ellipsoid and which is normal to the minor axis is called the equatorial plane. The equatorial plane intersects the surface of the ellipsoid in a circle, called the equator.

The geodetic latitude of a point on an ellipsoid is the angle between the equatorial plane and the outward normal vector at that point on the ellipsoid. This angle is taken to be positive in the Northern Hemisphere and negative in the Southern Hemisphere.

Any plane that is orthogonal to the equatorial plane and that passes through the center of the ellipsoid intersects the surface of the ellipsoid in an ellipse, called a meridian. One of these meridians is arbitrarily selected as a reference, and is called the Greenwich meridian. The longitude of a point on the ellipsoid is determined by the angle between the plane that contains the meridian passing through that point, and the plane which contains the Greenwich meridian. (The longitude of either pole is undefined). Longitude is customarily expressed in degrees, measured Eastward from the Greenwich meridian.

A curve that is traversed in a specified direction is said to be oriented. The bearing of an oriented smooth curve on an ellipsoid describes the direction of the tangent vector to that curve, at a particular point on that curve. Bearing is usually expressed in degrees, measured clockwise from local North. (Local (true) North at a point on an ellipsoid is defined as the direction of the tangent vector to the meridian at that point, where the meridian is oriented toward the North Pole. Note that local North is undefined at either pole, so this description of bearing does not apply there).

L.3 Nomenclature

B_1 = Geodetic latitude of departure point, in degrees.

L_1 = Longitude of departure point, in degrees.

B_2 = Geodetic latitude of arrival point, in degrees.

L_2 = Longitude of arrival point, in degrees.

α_1 = Bearing of the geodesic, at the departure point, in radians

α_2 = Bearing of the geodesic, at the arrival point, in radians

s = Range (arclength along the geodesic) from departure point to arrival point, in meters.

L.4 WGS-84 Parameters (from [5])

a = 6378137 m (WGS-84 semimajor axis).

b = 6356752.3142 m (WGS-84 semiminor axis).

e^2 = $6.694379991013 \times 10^{-3}$ (square of WGS-84 first eccentricity)

= $(a^2 - b^2)/a^2$

$(e')^2$ = $6.73949674227 \times 10^{-3}$ (square of WGS-84 second eccentricity)

= $(a^2 - b^2)/b^2$

f = $3.35281066474 \times 10^{-3}$ (WGS-84 flattening)

= $(a - b)/a$

L.5 The Indirect Problem

The inputs are:

B_1 = Departure geodetic latitude in degrees

L_1 = Departure geodetic longitude in degrees

B_2 = Arrival geodetic latitude in degrees

L_2 = Arrival geodetic longitude in degrees

(B_1, L_1) and (B_2, L_2) are with respect to the WGS-84 ellipsoid.

The outputs are:

s = Geodesic path length on the WGS-84 ellipsoid

α_1 = Departure bearing at (B_1, L_1) in radians

α_2 = Arrival bearing at (B_2, L_2) in radians

The algorithm is specified as follows:

a) Convert geodetic latitude from degrees to radians.

$\Phi_1 = \pi B_1/180$

$\Phi_2 = \pi B_2/180$

b) Compute the difference in longitude, in radians.

$\Delta L = (\pi/180)\ (L_2 - L_1)$

c) Compute the "reduced latitudes", in radians.

$\beta_1 = \tan^{-1}\ [(1 - f)\tan(\Phi_1)]$

$\beta_2 = \tan^{-1}\ [(1 - f)\tan(\Phi_2)]$

d) Initialize the iteration.

$\lambda_k = \Delta L$

e) Perform the following iteration, until

$|\lambda_{k+1} - \lambda_k| < \varepsilon$,

where ε is the termination criterion:

$$\sin\sigma = \sqrt{(\cos\beta_2 \sin\lambda_{k+1})^2 + (\cos\beta_1 \sin\beta_2 - \sin\beta_1 \cos\beta_2 \cos\lambda_{k+1})^2}\ ,0$$

$$\cos\sigma = \sin\beta_1 \sin\beta_2 + \cos\beta_1 \cos\beta_2 \cos\lambda_{k+1}$$

σ = atan2 (sinσ, cosσ),

$$\sin\alpha_e = \frac{\cos\beta_1 \cos\beta_2 \sin\lambda_{k+1}}{\sin\sigma}\ ,0$$

$\cos^2\alpha_e$ = $1 - \sin^2\alpha_e$,

$$\cos 2\sigma_m = \begin{cases} \cos\sigma - \dfrac{2 \cdot \sin(\beta_1) \cdot \sin(\beta_2)}{\cos^2\alpha_e}, if\ \cos^2\alpha_e \neq 0; \\ 0, otherwise \end{cases}\quad 0$$

C = $(f/16)\cos^2\alpha_e\ [\,4 + f\ (\,4 - 3\ \cos^2\alpha_e\,)\,]$,

λ_{k+1} = $\Delta L + (1 - C)\ f \sin\alpha_e\ \{\,\sigma + C\sin\sigma\ [\,\cos 2\sigma_m + C\cos\sigma\ (\,-1 + 2\cos^2 2\sigma_m\,)\,]\,\}$

where the function atan2 has following definition, as in FORTRAN:

$$atan2(Y,X) = \begin{cases} \tan^{-1}(Y/X), & \text{if } X > 0; \\ \tan^{-1}(Y/X) + \pi, & \text{if } X < 0; \\ \pi/2, & \text{if } X = 0 \wedge Y > 0; \\ -\pi/2, & \text{if } X = 0 \wedge Y < 0. \end{cases}$$

f) The range s, and the bearings α_1 and α_2 at the departure point and arrival point, respectively, may now be computed as follows:

$u^2 = (e')^2 \cos^2\alpha$,

$A = 1 + (u^2/16384) \{4096 + u^2 [-768 + u^2 (320 - 175 u^2)]\}$,

$B = (u^2/1024) \{256 + u^2 [-128 + u^2 (74 - 47 u^2)]\}$,

$\Delta\sigma = B \sin\sigma \{\cos 2\sigma_m + (1/4) B [(-1 + 2 \cos^2 2\sigma_m) \cos \sigma - (1/6) B (-3 + 4 \sin^2 \sigma) (-3 + 4 \cos^2 2\sigma_m) \cos 2\sigma_m]\}$,

$s = bA (\sigma - \Delta\sigma)$,

$\alpha_1 = (180/\pi)\, atan2(\cos\beta_2 \sin\lambda_{k+1}, \cos\beta_1 \sin\beta_2 - \sin\beta_1 \cos\beta_2 \cos\lambda_{k+1})$,

$\alpha_2 = (180/\pi)\, atan2(\cos\beta_1 \sin\lambda_{k+1}, -\sin\beta_1 \cos\beta_2 + \cos\beta_1 \sin\beta_2 \cos\lambda_{k+1})$,

Note that α_2 is the bearing at the destination point, of the arriving geodesic which originated at the departure point. The so-called back azimuth, or initial bearing of the geodesic that departs from the arrival point and returns to the departure point, is

$\alpha_2 \pm \pi$

L.6 The Direct Problem

The inputs are:

B_1	Departure geodetic latitude in degrees
L_1	Departure geodetic longitude in degrees
s	Geodesic path length
α_1	Departure bearing at (B_1, L_1) in radians

The outputs are:

B_2	Arrival geodetic latitude in degrees
L_2	Arrival geodetic longitude in degrees
α_2	Arrival bearing at (B_2, L_2)

The algorithm is specified as follows:

a) Convert geodetic latitude and longitude to radians

$\Phi_1 = \pi B_1/180$

$\lambda_1 = \pi L_1/180$ positive east, negative west

b) Compute the reduced latitude

$\beta_1 = \text{atan} [(1 - f) \tan (\Phi_1)]$ ... 2 quadrant arctan

c) Compute equatorial geodesic angular distance and azimuth

$\tan \sigma_e = \tan\beta_1 / \cos\alpha_1$

$\sin \alpha_e = \cos\beta_1 \sin\alpha_1$

$\cos^2\alpha_e = 1 - \sin^2\alpha_e$

d) Initialize the iteration

$u^2 = (e')^2 \cos^2 \alpha_e$

$A = 1 + (u^2/16384) \{4096 + u^2 [- 768 + u^2 (320 - 175 u^2)]\},$

$B \quad = (u^2/1024) \{256 + u^2 [-128 + u^2 (74 - 47 u^2)]\},$

$\sigma_i \quad = s/bA$

e) Perform the following iteration, until

$| \sigma_{i+1} - \sigma_i | \leq \varepsilon$

where ε is the termination criterion:

$$2\sigma_m = 2\sigma_e + \sigma_{i+1}$$

$\Delta\sigma = B \{\cos 2\sigma_m + 1/4\, B [(-1 + 2 \cos^2 2\sigma_m) \cos \sigma_{i+1} - 1/6\, B (-3 + 4 \sin^2\sigma_{i+1}) (-3 + 4\cos^2 2\sigma_m) \cos 2\sigma_m]\} \sin\sigma_{i+1}$

$\sigma_{i+1} = s/bA + \Delta\sigma$

f) Compute arrival point and arrival azimuth

$\sigma \quad = \quad \sigma_{i+1}$

$Y \quad = \quad \sin\beta_1 \cos\sigma + \cos\beta_1 \sin\sigma \cos \alpha_1$

$X \quad = \quad (1- f) [\sin^2 \alpha_e + (\sin\beta_1 \sin\sigma - \cos\beta_1 \cos\sigma \cos\alpha_1)^2]^{1/2}$

$\Phi_2 \quad = \quad$ atan (Y/X)... 2 quadrant arctan

$Y \quad = \quad \sin \sigma \sin \alpha_1$

$X \quad = \quad \cos\beta_1 \cos\sigma - \sin\beta_1 \sin\sigma \cos\alpha_1$

$Z \quad = \quad$ atan2 (Y, X).... 4 quadrant arctan

Z is positive east

$C \quad = \quad f/16\, [4 + f(4 - 3\cos^2\alpha_e)]\cos^2\alpha_e$

$\lambda_2 \quad = \quad \lambda_1 + Z - (1 - C) f\{ \sigma + C [\cos 2\sigma_m + C (-1 + 2\cos^2 2\sigma_m) \cos\sigma] \sin\sigma\} \sin\alpha_e$

$Y \quad = \quad \sin \alpha_e$

$X \quad = \quad - \sin\beta_1 \sin\sigma + \cos\beta_1 \cos\sigma \cos \alpha_1$

$\alpha_2 \quad = \quad$ atan2 (Y, X) ... 4 quadrant arctan

Note that $\alpha 2$ is the bearing at the arrival point, of the arriving geodesic which originated at the departure point. The so called back azimuth, or initial bearing of the geodesic which departs from the arrival point and returns to the departure point, is

$\alpha_2 \pm \pi$

L.7 Validation

The Indirect Problem algorithm described above was tested by computing the range and bearing of the geodesics between all ordered pairs of distinct locations listed in RTCA DO-208 MOPS. The value of the termination criterion ε used was 10^{-12}. The maximum number of iterations required in any of these 552 cases was 8, with a mean of 4.92 and a median of 5.

Geodesic curves on an ellipsoid may be computed by solving the following system of nonlinear ordinary differential equations, where the unknown quantities are the geodetic latitude B, longitude L, and bearing α, at each point on the geodesic, and where the independent variable t is arclength along the geodesic divided by a:

$$dB/dt = [(1 - e^2 \sin^2 B)^{3/2} \cos\alpha] (1-e^2)$$

$$dL/dt = [(1 - e^2 \sin^2 B)^{1/2} \sin\alpha] \cos B$$

$$d\alpha/dt = (1 - e^2 \sin^2 B)^{1/2} \sin\alpha \tan B$$

(For a derivation of these equations, see pp. 80-83 of [2]).

For each departure point, range, and bearing (at the departure point), the actual terminal point of the corresponding geodesic curve was computed by numerically integrating these equations, using the Runge-Kutta-Fehlberg algorithm of order (4, 5), and a local truncation error tolerance of 10^{-14}. The distance between the actual terminal point and the desired arrival point was then computed. In every case, this distance was less than two-tenths of one millimeter.

For the convenience of anyone wishing to implement the above algorithm in software, seven test cases are supplied here. (These test cases are suggested in [4]). Table L-1 below lists the geodetic latitude of the departure points, and the geodetic latitude and longitude of the arrival points. (The departure points are all on the Greenwich meridian).

TABLE L-1 TEST CASE INPUT

Case	Departure Latitude	Arrival Latitude	Arrival Longitude
1	37.331931575000	26.128566516667	41.476529802778
2	35.269791283333	67.370771216667	137.791198430556
3	1.000000000000	-0.998286322222	179.296674991667
4	1.000000000000	1.020885977778	179.771622900000
5	41.696077777778	41.696166666667	0.000155555556
6	30.000000000000	37.892351622222	116.321302341667
7	37.000000000000	28.260193152778	-2.627646994444

The results for each of these cases are shown in Table L-2 below. (The value of the termination criterion ε used was again 10^{-12}).

TABLE L-2 TEST CASE OUTPUT

Case	Departure Bearing α_1	Arrival Bearing α_2	Ranges
1	95.4669065012712	118.100037749533	4,085,797.71045745
2	15.7398635998781	144.927624307827	8,084,459.01281178
3	89.0255041313847	90.9762395789926	19,959,214.6261821
4	5.0047450389878	174.995222917504	19,779,362.8384626
5	52.6771685463032	52.6772720198999	16.2833273117916
6	45.0000844826718	129.136526168938	10,002,067.6833720
7	-165.000275690672	-166.421458799296	999,975.508415485

Table L-3 below shows the required number of iterations, and the error (distance between the desired arrival and the actual terminal point), for each test case.

TABLE L-3 NUMBER OF ITERATIONS

Case	Number of Iterations	Error	Significant Decimals		
			α_1	α_2	s
1	5	$1.38189930304136 \times 10^{-5}$	10	10	5
2	4	$5.62351088062680 \times 10^{-5}$	7	9	4
3	5	$1.42575492953545 \times 10^{-4}$	6	5	4
4	18	$1.41770874909204 \times 10^{-4}$	8	7	4
5	3	$6.87589522482552 \times 10^{-8}$	7	6	7
6	4	$4.84762978049413 \times 10^{-5}$	9	9	4
7	5	$7.19785012259682 \times 10^{-6}$	9	9	5

Note that the data shown in Table L-2 are the literal output obtained by running the algorithm on a particular platform, and that not all of the digits shown are significant. The last three columns of Table L-3 give the number of digits to the right of the decimal point which are considered to be significant, for each of the data shown in Table L-2. These were obtained by rounding, in turn, the departure bearing, arrival bearing, and range for each case, to different levels of precision, and computing the actual terminal point of the corresponding geodesic. For the arrival bearing, the departure point and arrival point were exchanged, and the departure bearing was replaced by the arrival bearing minus 180°). The number of decimals considered to be significant was determined by the minimum level of precision which resulted in the error between the actual terminal point and the desired arrival point being within fifty percent of the value shown in Table L-3.

The Direct Problem algorithm was validated with above data as well, with nearly identical results.

As a final validation, it is recommended that random pairs of (B_1, L_1) and (B_2, L_2) be generated. These pairs may then be fed into the Indirect Problem algorithm to produce α_1, α_2 and s. Then, (B_1, L_1), α_1 and s may be fed into the Direct Problem algorithm to obtain (B_2, L_2) and α_2. The differences (B_2 - B_1), (L_2 - L_1), (α_2- α_1) should small, < 10^{-10}. This is the closed form validity check.

L.8 References

1. Frederick Pearson II, Map projections: theory and applications. CRC Press, Boca Raton-Ann Arbor - London - Tokyo, 1990.
2. T. Vicenty, "Direct and inverse solution of geodesics on the ellipsoid with application of nested equations", Survey Review, No. 176 (1975), pp. 88-93.

3. E.M. Sodano, "General non-iterative solution of the inverse and direct geodetic problems", Bulletin Géodésique, No. 75 (1965), pp. 69-89.

4. R.H. Rapp, Geometric Geodesy: Part II. Department of Geodetic Science and Surveying, The Ohio State University, Columbus, Ohio, March 1993.

5. Department of Defense World Geodetic System 1984: Its definition and relationships with local geodetic systems, second edition. Defense Mapping Agency Technical Report TR-8350.2, Defense Mapping Agency, Fairfax, Virginia, September 1991.

APPENDIX M

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M.1 Introduction

This appendix presents the statistical justification for the testing and pass/fail criteria presented in sections 2.3.3, 2.3.4, and 2.3.6. In addition, simulator scenario guidelines for these sections are presented.

M.2 (Initial) Acquisition and Reacquisition Testing Statistical Justification

Tests for (initial) acquisition and reacquisition time can be considered to follow a binomial distribution based on the following assumptions:

a) Each acquisition attempt is an independent trial, i.e. the results of any single trial do not depend on the results of any previous trial, and

b) Only two test states are possible - (re)acquire (within the specified time and accuracy) or not (re)acquire.

The binomial distribution is represented by the following:

$$\sum_{y=0}^{n} P(y) = \sum_{y=0}^{n} \binom{n}{y} p^y q^{n-y}$$

where:

$$\binom{n}{y} = \frac{n!}{y!(n-y)!}$$

and

P(y)	=	Probability of failing a test
a	=	Graduated sampling variable (0, 1, or 2)
y	=	Number of failures
n	=	Number of trials
p	=	Probability of failing a single trial
q	=	Probability of passing a single trial

A graduated sampling approach will be employed to keep test times within reason. The graduated sampling variable (a) will be allowed to vary between zero and two, according to the approach shown in Table M-1. The acquisition test is broken out into a series of three segments each composed of ten trials. The "quit-while-ahead" concept will be used. For example, if no failure occurs in the first 10 trials, success would be declared and the test terminated. If one failure occurred in the first 10 trials, at least 10 more trials (after the first 10) would be required prior to declaring the test successful. Therefore let:

α	=	Probability of rejecting a good receiver
β	=	Probability of accepting a bad receiver

Rationale for this method of testing is based on achieving an acceptably low β risk with a small number of samples and deferring rejection of a good receiver (low α) until a larger sample is obtained. Such a test concept will, on the average, shorten the duration of the testing. The overall probability of passing the three-segment, 30 trial test is related to the probability of success per individual trial. Receivers that are nominally designed to have a 0.95 probability of passing a single test will have 0.86 probability of passing the overall test. Conversely, the probability of a "bad" receiver, one that has a 0.80 chance of passing a single trial, will only pass the overall test with a probability of 0.16. Thus, this graduated test procedure has a high probability of rejecting a bad receiver. Figure M-1 shows the probability of passing the overall test after each 10-segment trial for receivers of varying quality.

TABLE M-1 GRADUATED SAMPLING PASS/FAIL CRITERIA

Trials	Cumulative Failures within Specified Time	Test Disposition
First Ten (10)Trials	Zero (0) One (1) Two (2) or More	Pass Run Ten (10) More Fail
Second Ten (10) Trials	Zero (0) One (1) or Two (2) Three (3) or More	Pass Run Ten (10) More Fail
Third Ten (10) Trials	Zero (0) One (1) or More	Pass Fail

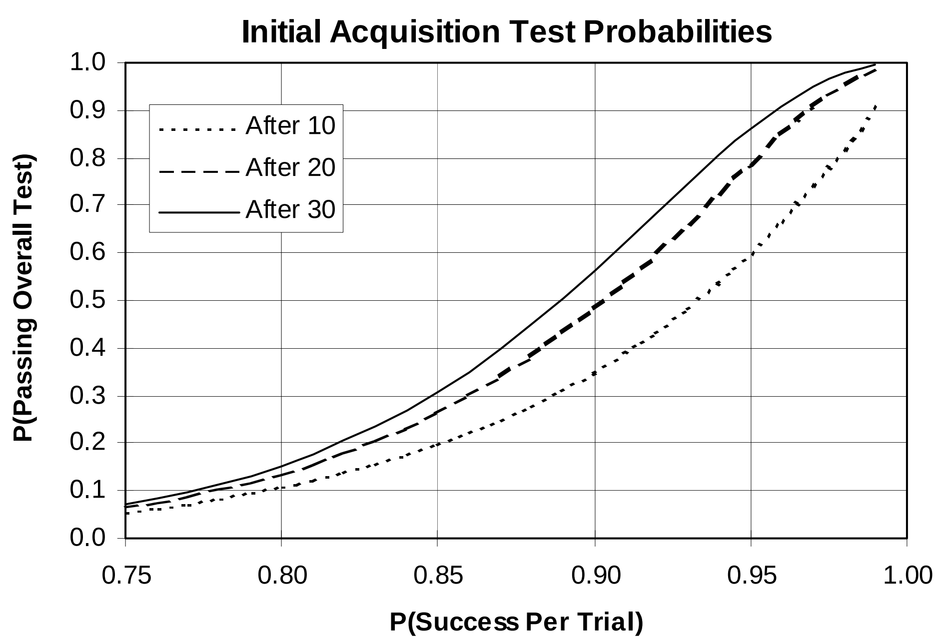

FIGURE M-1 (RE)ACQUISITION TEST PROBABILITY STATISTICS

M.3 Accuracy Statistical Justification

The accuracy test is designed to ensure an acceptably low risk of passing the test for equipment that fails to meet its claimed accuracy as represented by its σ_{noise} output. This β risk is formally specified as:

$$\beta = \Pr\{\text{test is passed} \mid \sigma > 1.1\sigma_{noise}\} \leq 0.1$$

where σ represents the actual RMS accuracy of the equipment. This risk specification can be used to develop a pass criterion for the normalized accuracy statistic

RMS_PR(M). Under the steady-state tracking conditions specified in Section 2.3.6, assuming that the residual pseudo-range errors are zero mean and Gaussian random variables with variance σ^2, it can be shown that the probability distribution of RMS_PR(M) is equal to the Chi distribution with NIS degrees of freedom and with parameter σ/σ_{noise}:

$$\Pr\{\text{RMS\_PR(M)} \le X\} = \chi(X, \sigma/\sigma_{noise}, \text{NIS})$$

The pass threshold T can be found as a function of NIS by solving the implicit equation:

$$\chi(T, 1.1, \text{NIS}) = 0.1$$

The solution is graphed as a function of NIS in Figure M-2.

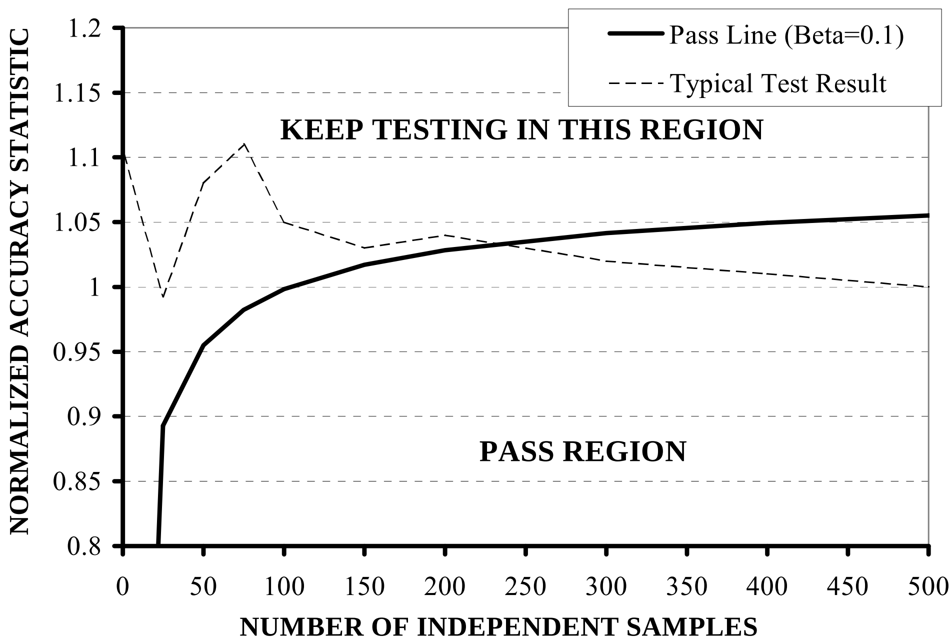

FIGURE M-2 PSEUDORANGE ACCURACY TEST PASS CRITERIA

The probability of passing the test for equipment that meets the requirement, PP(NIS), can be determined by evaluating the following Chi distribution:

$$PP(\text{NIS}) = \chi(T, 1, \text{NIS})$$

The pass probability as a function of NIS is shown in Figure M-3.

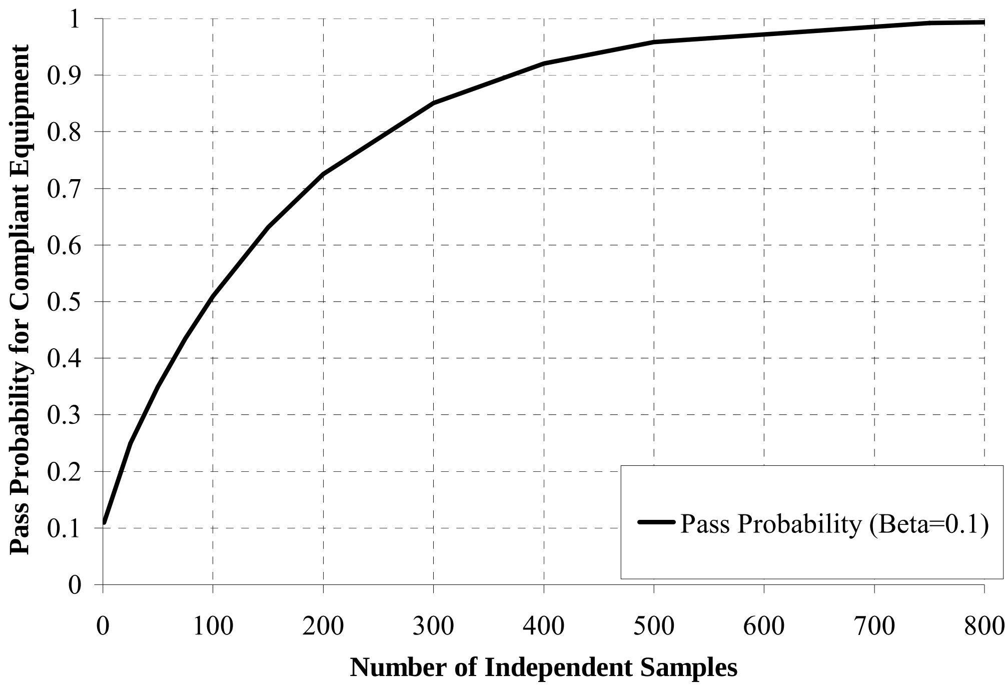

FIGURE M-3 PSEUDORANGE ACCURACY TEST PASS PROBABILITY

M.4 General Simulator Scenario Conditions

Nominal GPS Constellation: GPS 24 Satellite Constellation (Appendix B)

Starting Coordinates: Chosen By Manufacturer

Assumed Mask Angle: 5°

Guidelines

Removal of unwanted GPS satellites to meet the required number of satellites for a test can be accomplished by selecting appropriate starting coordinates or by turning the RF off for unwanted satellites. If the RF is turned off, the almanac must reflect the actual satellites simulated (for which RF is on). Time dependent satellite removal (and reapplication) will be accomplished by turning the satellite of interest on and off (RF control), in a manner approximating satellite blockage or shielding. During the initial acquisition portion of all tests, the same satellites will be applied throughout, with no satellites rising or setting.

M.5 Example Test Set-up and Compensation of Signals, Noise and Interference

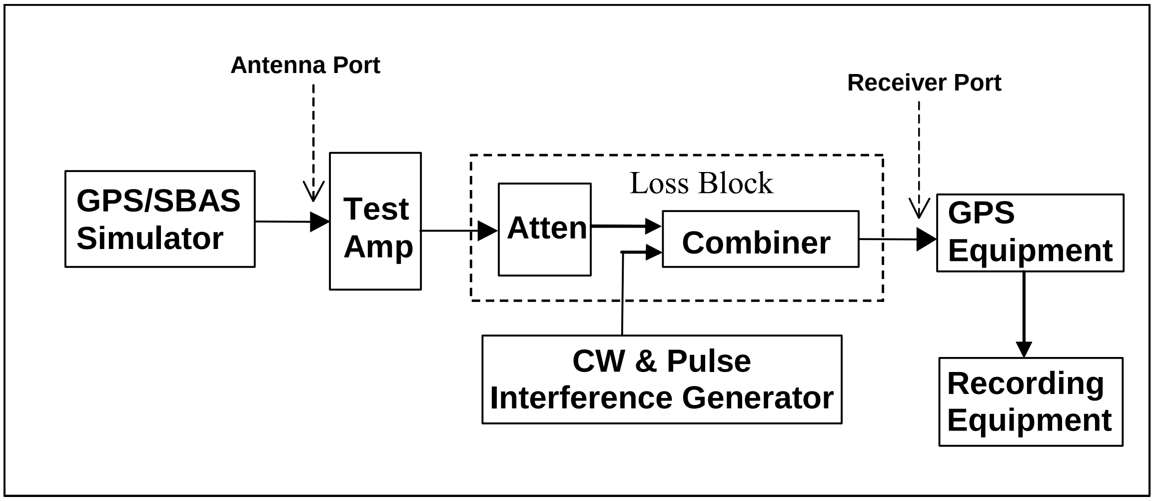

FIGURE M-4 EXAMPLE TEST SET-UP

M.5.1 Description of the Test Set-up

The test set-up in Figure M-4 approximates a real installation, where satellites and the radiation pattern of the antenna are replaced by the GPS/SBAS simulator, the active portion of the antenna is replaced by a test amplifier with the same gain as the active antenna preamplifier, and the loss block has the same total loss as an installation. The loss block is composed of a variable attenuator, a combiner, and associated cabling from the test amplifier output to the receiver port for a total loss of L_{Block}. The loss from the combiner input to the receiver port is $L_{combiner}$.

This set-up uses a test amplifier with an adjustable noise figure in order to insert the appropriate broadband noise at the input of the amplifier. An alternate set-up would include a noise generator and a combiner prior to the test amplifier, and both the simulator output and noise generator would have to be adjusted to achieve the desired signal and broadband noise (specified as noise density in the test procedures) at the input to the test amplifier. The amplifier also has adjustable gain, G_{Amp}. An alternate test set-up could use the active subassembly of the antenna, provided the subassembly was calibrated to have known gain and noise figure and all signal and interference levels adjusted to compensate for any difference with the specified characteristics of the integrated antenna including production variations.

The CW and pulse interference is inserted after the test amplifier. It is calibrated to output a signal with power $C_{interference}$ as referenced to the input of the combiner. It could also be inserted prior to the test amplifier, and the simulated power level would have to account for any filtering in the amplifier (assuming the inserted power were within the operating range of the amplifier).

In this example, the equipment under test is designed for use with a minimum standard antenna. The installation criteria is as follows:

a) L_{max} = 15 dB and L_{min} = 5 dB.
b) $N_{sky,antenna}$ = -172.5 dBm/Hz.
c) Gain of the active portion of the antenna $G_{Ant} = 30 \pm 3$ dB.
d) Active antenna Selectivity per DO-301, for example -50 dB at 1626 MHz.

The equipment is calibrated to determine noise levels and loss. In this example, the following values are used:

a) GPS/SBAS Simulator: $I_{Simulator}$ = -174 dBm/Hz with an adjustable signal level of $C_{Simulator}$ both referred to the input of the test amplifier.
b) Combiner with loss $L_{Combiner}$ = 5 dB from its input to the Receiver Port.

M.5.2 Use of the Test Set-up for the Accuracy Test (See 2.3.6)

As the broadband noise is generated by the simulator and the adjustable noise figure of the amplifier, the appropriate noise figure must be determined for the accuracy tests. Two levels must be computed for the minimum signal level tests since some tests include external broadband interference and some do not. An additional level must be determined for the test with all satellites at maximum power.

For the minimum signal level tests, the test amplifier gain (G_{Amp}) is set to 27 dB (minimum G_{Ant}) and the total loss to 15 dB ($L_{Block} = L_{max}$). A ten-channel simulator is used, with one GPS satellite at maximum power (-121 dBm), seven minimum-power GPS satellites (-134 dBm) and two minimum-power SBAS satellites (-134 dBm). In order to determine the required GNSS test noise, the effective noise of the satellites simulated in the test is subtracted from the total GNSS noise of -171.9 dBm/Hz. Using the equation in 2.3.6.2:

$$\begin{aligned} I_{Test} &= 10\log10[(N_{GL})10^{I_{GL}/10} + (N_{GH})10^{I_{GH}/10} + (N_{SL})10^{I_{SL}/10} + (N_{SH})10^{I_{SH}/10}] \\ &= 10\log10[(7)10^{-196.5/10} + (1)10^{-183.5/10} + (2)10^{-198.3/10} + (0)10^{-179.8/10}] \\ &= -182.0 \text{ dBm/Hz} \end{aligned}$$

and

$$\begin{aligned} I_{GNSS,Test} &= 10\log10[10^{I_{GNSS}/10} - 10^{I_{Test}/10}] \\ &= 10\log10[10^{-171.9/10} - 10^{-182.0/10}] \\ &= -172.4 \text{ dBm/Hz} \end{aligned}$$

The noise that must be generated by the test amplifier is determined by subtracting the simulator noise from the total broadband noise for the test (the sum of $N_{sky,antenna}$, $I_{GNSS,Test}$ and $I_{Ext,Test}$). The external noise is -170.5 dBm/Hz for those cases that include external noise, so that the equivalent test noise that must be generated is:

$$\begin{aligned} I_{Total,Test} &= 10\log10[10^{N_{sky,antenna}/10} + 10^{I_{GNSS,Test}/10} + 10^{I_{Ext,Test}/10} - 10^{I_{Simulator}/10}] \\ &= 10\log10[10^{-172.5/10} + 10^{-172.4/10} + 10^{-170.5/10} - 10^{-174/10}] \\ &= -167.9 \text{ dBm/Hz} \end{aligned}$$

The equivalent noise factor is determined as:

$$NF_{Amp(ext)} = 10\text{Log}10(1 + 10^{I_{Total,Test}/10}/k/290) = 7.06 \text{ dB}$$

For those tests without external broadband noise (e.g., CW and pulse interference cases and to expedite initial acquisition in other tests):

$$I_{Total,Test} = 10\log10[10^{Nsky,antenna/10} + 10^{I_{GNSS,Test}/10} - 10^{I_{Simulator}/10}]$$
$$= 10\log10[10^{-172.5/10} + 10^{-172.4/10} - 10^{-174/10}]$$
$$= -171.3 \text{ dBm/Hz}$$

And the equivalent noise factor is determined as:

$$NF_{Amp(no\ ext)} = 10Log10(1 + 10^{I_{Total,Test/10}}/k/290) = 4.55 \text{ dB}$$

The CW and pulse interference levels must be adjusted based on the specified antenna gain, antenna frequency selectivity and installation loss. To determine the power level at the signal generator the loss of the combiner must be offset. For example, for the +8 dBm CW signal at 1626 MHz:

$$C_{Interference,CW} = I_{Int} + G_{Amp} - \text{Selectivity} - L_{Block} + L_{Combiner}$$
$$= +8 + 27 - 50 - 15 + 5$$
$$= -25 \text{ dBm}$$

The pulse power is limited by the maximum output of the active antenna (P_{out}):

$$C_{Interference,pulse} = P_{out} - L_{Block} + L_{Combiner}$$
$$= +20 - 15 + 5$$
$$= +10 \text{ dBm}$$

Repeating the analysis for the maximum signal case yields the following:

$L_{Block} = L_{min} = 5$ dB.
G_{Amp} = maximum G_{Ant} = 33 dB.
Eight maximum level GPS satellites: $C_{Simulator} = -121$ dBm.
Two maximum SBAS satellites: $C_{Simulator} = -115.5$ dBm

$$I_{Test} = 10\log10[(N_{GL})10^{I_{GL}/10} + (N_{GH})10^{I_{GH}/10} + (N_{SL})10^{I_{SL}/10} + (N_{SH})10^{I_{SH}/10}]$$
$$= 10\log10[(0)10^{-196.5/10} + (8)10^{-183.5/10} + (0)10^{-198.3/10} + (2)10^{-179.8/10}]$$
$$= -172.5 \text{ dBm/Hz}$$

$$I_{GNSS,Test} = 10\log10[10^{I_{GNSS}/10} - 10^{I_{Test}/10}]$$
$$= 10\log10[10^{-171.9/10} - 10^{-172.5/10}]$$
$$= -181.4 \text{ dBm/Hz}$$

For Broadband External Interference Noise of $I_{Ext,Test} = -170.5$ dBm/Hz:

$$I_{Total,Test} = 10\log10[10^{Nsky,antenna/10} + 10^{I_{GNSS,Test}/10} + 10^{I_{Ext,Test}/10} - 10^{I_{Simulator}/10}]$$
$$= 10\log10[10^{-172.5/10} + 10^{-181.4/10} + 10^{-170.5/10} - 10^{-174/10}]$$
$$= -169.5 \text{ dBm/Hz}$$

So:

$$NF_{Amp,ext} = 10Log10(1 + 10^{I_{Total,Test}/10}/k/290) = 5.82 \text{ dB}$$

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APPENDIX N

REFERENCE MATERIAL FOR DETERMINING THE MEAN SEA LEVEL HEIGHT FROM WGS-84 COORDINATES

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N.1 Introduction

The material in this appendix is provided as guidance material only. There are no requirements associated with this appendix.

The GPS coordinate system is known as the WGS-84 coordinate system. The WGS-84 reference ellipsoid is the surface on which GPS longitude, latitude, and altitude are computed. The GPS computed WGS-84 altitude is not the Mean Sea Level (MSL) altitude.

All map reference charts used in aviation make reference to altitude expressed as a MSL altitude.

A model has been developed to relate WGS-84 altitude to the MSL Altitude. The MSL altitude is itself based on a model of the Mean Sea Level. The model referenced in this appendix is the Earth Gravitational Model of the year 1996 (EGM-96). More information on EGM-96 can be found at the website: http://cddisa.gsfc.nasa.gov/926/egm96/egm96.html. The National Imagery and Mapping Agency, NASA Goddard Space Flight Center, and Ohio State University developed this model. It provides the mathematical conversion between WGS-84 and the Mean Sea Level.

Note: EGM-96 has been updated to EGM2008. The EGM-96 model is still available at the NASA website listed above and either is acceptable for use as a geoid model.

The true MSL altitude and the EGM-96 model are equivalent in theory. The practitioner is cautioned against drawing the conclusion that the EGM-96 model is equivalent to a QNH pressure altitude. The reason is that the EGM-96 model integrity has not been established in these MOPS. Establishing the integrity of the EGM-96 model and establishing the equivalence between EGM-96 and the QNH pressure altitude is beyond the scope of these MOPS. Despite this, the EGM-96 model is a reasonable approximation to the MSL altitude.

The NGA has released an update to the Earth Gravitational Model. The 1996 Model will still be maintained on the website listed above. The new model (EGM2008) can be found at http://earth-info.nga.mil/GandG/wgs84/gravitymod/egm2008/index.html. Either EGM-96 or EGM2008 can be used as a reasonable approximation to the MSL altitude.

N.1.1 General Altimetry

Aircraft altitude may be obtained from a pressure altimeter, a radar altimeter, or a GPS sensor. Although these instruments produce an altitude measurement, they are not measurements of the same fundamental quantity and therefore, these measurements cannot be used inter-changeably. As mentioned above, the primary altitude instrument in the aircraft is the pressure altimeter, the GPS sensor altitude is not recognized at this time as the primary altitude sensor.

N.1.2 Mean Sea Level (MSL) Altitude

The MSL is an average sea level surface and is understood to be the zero MSL altitude surface. The MSL surface cannot be directly observed due to tidal actions, weather, melting of glaciers, tectonic plate movement, and other effects. Measuring the MSL surface is done by measuring the earth’s gravity with satellites and developing a mathematical model of an average and constant gravity surface. This constant gravity surface defines the MSL zero-altitude surface and is referred to as the geoid. The geoid is a complicated surface and is described by formidable set of functions and is provided by the above referenced website.

N.1.3 Barometric Altitude

The primary aircraft altitude instrument is the pressure altimeter. Pressure altimeters are employed in three different operating modes:

a) QNH mode: the standard pressure altitude is corrected using local correction data, typically from a nearby weather station, usually located at the destination airport

b) QNE mode: the standard setting of 29.92 in.Hg (1013.2 millibars) is used as the MSL zero altitude (the standard atmospheric model)

c) QFE mode: the altimeter is set to read zero when on the airport surface thereby showing height above the airfield.

At and above a transition altitude, all aircraft use the standard QNE altimeter setting, and altitudes are termed flight levels (FL). For example, 29,000 ft becomes FL290. The transition altitude in United States airspace is 18,000 ft (FL180) or 5500 m. Regardless of how the actual air pressure changes in the atmosphere, the QNE barometric altitude has the same definition (and conversion from air pressure to altitude) for all aircraft. Note that QNE altitude is not true MSL altitude. However, all aircraft flying above FL180 use QNE to set their altitude. QNE and MSL altitude are not the same fundamental quantity.

N.1.4 Radar Altitude

All radar altimeters measure the smallest range between the terrain immediately below the aircraft and the aircraft radar altimeter antenna. The radar altimeter is intended for instrument approaches that require accurate height above the landing runway threshold. Most radar altimeters do not operate at heights greater than 2500 ft (750 m) above ground.

N.1.5 GPS Altitude

GPS sensors provide WGS-84 altitude information. The WGS-84 altitude is not a MSL altitude. GPS altitude is derived as an altitude above the WGS-84 reference ellipsoid. MSL models exist that allow conversion between GPS altitude and MSL altitude. One such model is the EGM96 model. A MSL model allows conversion between GPS and MSL altitude.

APPENDIX O

GLOSSARY AND ACRONYMS

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AC - Advisory Circular

ACARS - Aircraft Communications, Addressing and Reporting System

Accuracy - GNSS position error is the difference between the estimated position and the actual position. For an estimated position at a specific location, the probability should be at least 95% that the position error is within the accuracy requirement.

Active Antenna - A generic term for a passive antenna element integrated with a preamplifier; it refers to both the minimum standard antenna and a specific antenna.

Active Waypoint - A waypoint to or from which navigational guidance is being provided. For a parallel offset, the active waypoint may or may not be at the same geographical position as the parent waypoint. When not in the parallel offset mode (operating on the parent route), the active and parent waypoints are at the same geographical position.

ADS - Automatic Dependent Surveillance

ADS - B - Automatic Dependant Surveillance-Broadcast

Advisory - An annunciation that is generated when crew awareness is required and subsequent crew action may be required; the associated color is unique but not red or amber/yellow. (Source: Advisory Circular AC 25 - 11).

AGL - Above Ground Level

Applications - Specific use of systems that address particular user requirements. For the case of GNSS, applications are defined in terms of specific operational scenarios.

Area Navigation (RNAV) - Application of the navigation process providing the capability to establish and maintain a flight path on any arbitrary chosen course that remains within the coverage area of navigation sources being used. RNAV utilizing capabilities in the horizontal plane only is called 2D RNAV, while RNAV that also incorporates vertical guidance is called 3D RNAV. Time navigation (TNAV) may be added to either 2D or 3D systems. TNAV added to a 3D system is called 4D.

ASIC - Application Specific Integrated Circuit

ATC - Air Traffic Control

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.

Barometric Altitude - Geopotential altitude in the earth's atmosphere above mean standard sea level pressure datum surface, measured by a pressure (barometric) altimeter.

BCD - Binary Coded Decimal

BNR - Binary Numbers

BPSK - Binary Phase Shift Keying

BW - Bandwidth

C/A - Coarse Acquisition

Center of Navigation - The mathematical point, referenced to the aircraft coordinate frame, associated with the GNSS navigation solution. This point would typically be the phase center of the GNSS antenna, but could also be an offset or translated point (e.g., might be translated vertically to the level of the wheels of a large aircraft).

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 predicted to exist throughout the operation.

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

CW - Continuous Wave

CWI - Continuous Wave Interference

DOD - U.S. Department of Defense

DOP - Dilution Of Precision

ECEF - Earth Centered Earth Fixed

En Route - A phase of navigation covering operations between departure and termination phases. En route phase of navigation has two subcategories: en route domestic/continental and en route oceanic.

FAA - Federal Aviation Administration

FD - Fault Detection

FDE - Fault Detection and Exclusion

Flight Technical Error (FTE) - The accuracy with which the aircraft is controlled as measured by the indicated aircraft position with respect to the indicated command or desired position. It does not include blunder errors.

FMS - Flight Management System

FTE - Flight Technical Error

GDOP - Geometric Dilution of Precision

Geodesy - The science related to the determination of the size and shape of the earth (geoid) by such direct measurements as triangulation, leveling and gravimetric observations; which determines the external gravitational field of the earth and, to a limited degree, the internal structure.

Geometric Dilution of Position (GDOP) - The ratio of position error of a multilateration system. More precisely, it is the ratio of the standard deviation of the position error to the standard deviation of the measurement errors, assuming all measurement errors are statistically independent and have a zero mean and the same standard distribution. GDOP is the measure of the "goodness" of the geometry of the multilateration sources as seen by the observer; a low GDOP is desirable, a high GDOP undesirable. (See also PDOP, HDOP and VDOP.)

GL - Ground Level

Global Navigation Satellite System (GNSS) - GNSS is a world-wide position, velocity, and time determination system, that includes one or more satellite constellations, receivers, and system integrity monitoring, augmented as necessary to support the required navigation performance for the actual phase of operation.

Global Positioning System (GPS) - A space-based positioning, velocity and time system composed of space, control and user segments. The space segment, when fully operational, will be composed of 24 satellites in six orbital planes. The control segment consists of five monitor stations, three ground antennas and a master control station. The user segment consists of antennas and receiver-processors that provide positioning, velocity, and precise timing to the user.

GLONASS - Global Orbiting Navigation Satellite System

GNSS - Global Navigation Satellite System

GPS - Global Positioning System

HAL - Horizontal Alert Limit

HORIZONTAL ALERT LIMIT (HAL) - 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.

HEL - Horizontal Exclusion Level

HORIZONTAL EXCLUSION LEVEL (HEL_{FD}) - 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.

HIRF - High Intensity Radiation Fields

Horizontal Dilution of Precision (HDOP) - The ratio of user-referenced horizontal position error to measurement error of a multilateration system. (See GDOP for a more detailed description.)

Horizontal Figure of Merit ($HFOM_P$) - 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.

HOW - Hand Over Word

HPL - Horizontal Protection Level

HORIZONTAL PROTECTION LIMIT (HPL_{FD}) - Horizontal Protection $Level_{Fault\ Detection}$ (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.

HUL - Horizontal Uncertainty Level

HORIZONTAL UNCERTAINITY LEVEL (HUL) - 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).

Hz - Hertz (cycles per second)

ICAO - International Civil Aviation Organization

IFR - Instrument Flight Rules

INS - Inertial Navigation System

Integrity - A measure of trust that can be placed in the correctness of the information supplied by the total system. Integrity includes the ability of a system to provide timely and valid warnings to the user (alerts)

IOD - Issue of Data

IODC - Issue of Data Clock

IODE - Issue of Data Ephemeris

I/S - interference-to-signal ratio

L1 - 1575.42 MHz

LNAV - Lateral Navigation

LORAN - Long Range Navigation

LSB - Least Significant Bit

LSR - Least Squares Residual

m - Meters

Mask Angle - A fixed elevation angle referenced to the user's horizon below which satellites are ignored by the receiver software. Mask angles are used primarily in the analysis of GNSS performance, and are employed in some receiver designs. The mask angle is driven by the receiver antenna characteristics, the strength of the transmitted signal at low elevations, receiver sensitivity and acceptable low elevation errors.

MASPS - Minimum Aviation System Performance Standards

Mcps - Mega-chips/second

Minimum Standard Antenna - Active antenna compliant with the minimum requirements of RTCA/DO-301.

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.

MOPS - Minimum Operational Performance Standards

MSL - Mean Sea Level

MTBF - Mean Time Between Failure

NACv – Navigation Accuracy Category for Velocity

NAS - U.S. National Airspace System

NAV - Navigation

NAVAID - Navigation Aid

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. The oceanic/remote mode is optional; if it is not provided, the en route mode can be substituted for the oceanic mode.

NIS - Number of Independent Samples

NM - Nautical Mile

Nonprecision Approach - Operationally, a standard instrument approach procedure in which no glideslope/glidepath is provided. (Source: FAA Order 7110.65, Air Traffic Control)

NPA - Nonprecision Approach

NSE - Navigation System Error

PDOP - Position Dilution of precision

Planned Primary Means of Navigation - Planned primary means of navigation refers to the capability of planning an operation around scheduled outages so that the system is available for a particular flight and the operational continuity, integrity and accuracy requirements are met.

Position Dilution of Precision (PDOP) - The ratio of user-referenced three-dimensional position error to measurement error of a multilateral system. PDOP is the root-sum-square of HDOP and VDOP.

Position Fix - A derived location of an entity in a common coordinate system.

Position Fixing Error - The accuracy with which a navigation sensor in combination with a navigation computer can calculate and provide an output of actual location in relation to desired location in an operational environment.

PR - Pseudo Range

PRN - Pseudo Random Noise

Pseudorange - The distance from the user to a satellite plus an unknown user clock offset distance. With four satellite signals it is possible to compute position and offset distance. If the user clock offset is known, three satellite signals would suffice to compute a position.

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.

RAIM - Receiver Autonomous Integrity Monitoring

Receiver Autonomous Integrity Monitoring (RAIM) - A technique whereby a civil GNSS receiver/processor determines the integrity of the GNSS navigation signals without reference to sensors or non-DoD integrity systems other than the receiver itself. This determination is achieved by a consistency check among redundant pseudorange measurements.

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

Required Navigation Performance (RNP) - A measure of the navigation system performance within a defined airspace, route, or procedure, including the operating parameters of the navigations systems used within that airspace. (Source: Adapted from the ICAO Separation Panel).

RF - Radio Frequency

RNAV - Area Navigation

RNP - Required Navigation Performance

rss - Root-Sum-Square

RTCA - RTCA, Inc. (publishes documents with the RTCA designator)

s - Second

SA - Selective Availability (also written as S/A)

SATCOM - Satellite Communications

Selective Availability (S/A) - A set of techniques for denying the full accuracy and selecting the level of positioning, velocity, and time accuracy of GPS available to users of the Standard Positioning Service (L1 frequency) signal.

SC - Special Committee (RTCA Special Committees)

SNR - Signal to Noise Ratio

Specific Antenna - An active antenna that complies with all the minimum performance requirements of RTCA/DO-301 but is specified to exceed some requirements. The testing methods of RTCA/DO-301 are used to demonstrate performance.

SPS - Standard Positioning Service

sps - symbols per second

Standard Positioning Service (SPS) - The standard specified level of positioning, velocity and timing accuracy that is available, without qualifications or restrictions, to any user on a continuous worldwide basis.

SV - Satellite Vehicle

TC - Tropospheric Correction

TCAS - Traffic Alert and Collision Avoidance System

Terminal Area - A general term used to describe airspace in which approach control service or airport traffic control service is provided.

TOD - Time of Day; Top of Descent

Total System Error (TSE) - Generic: The root-sum-square of the navigation source error, airborne component error, display error and flight technical error. Specific: The root-sum-square of the position fixing error, display error, course selection error and flight technical error.

TOW - Time of Week

TSE - Total System Error

TSO - Technical Standards Order

TTA - Time to Alert

TTFF - Time To First valid position Fix

UERE - User Equivalent Range Error

URA - User Range Accuracy

User Range Accuracy (URA) - The one-sigma estimate of user range errors in the navigation data for each individual satellite. It includes all errors for which the space or control segment is responsible. It does not include any errors introduced at the user set.

UTC - Universal Time Coordinated

VDOP - Vertical Dilution of Precision

Vertical Dilution of Precision (VDOP) - The ratio of user-referenced vertical position error to measurement error of a multilateration system (see GDOP for a more detailed description).

Vertical Navigation (VNAV) - A function of RNAV equipment that calculates, displays and provides guidance to a vertical profile or path.

Vertical Profile - A line or curve, or series of connected lines and/or curves in the vertical plane, defining an ascending or descending flight path either emanating from or terminating at a specified waypoint and altitude, or connecting two or more specified waypoints and altitudes. In this sense, a curve may be defined by performance of the airplane relative to the airmass.

VFR - Visual Flight Rules

VHF - Very High Frequency

VNAV - Vertical Navigation

VOR - VHF Omni-directional Range

Warning - An annunciation that is generated when immediate recognition and corrective or compensatory action is required; the associated color is red. (Source: Advisory Circular AC25 - 11)

WGS-84 - World Geodetic System 1984

World Geodetic System (WGS) - A consistent set of parameters describing the size and shape of the earth, the positions of a network of points with respect to the center of mass of the earth, transformations from major geodetic datums, and the potential of the earth (usually in terms of harmonic coefficients).

APPENDIX P

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APPENDIX Q

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APPENDIX R

REQUIREMENTS AND TEST PROCEDURES FOR TIGHTLY INTEGRATED GPS/INERTIAL SYSTEMS

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R.1 Introduction

This appendix includes assumptions, requirements and verification procedures for equipment that utilizes a tight integration of GPS and inertial information to enhance navigation performance for en route through approach (LNAV). Tightly integrated systems process and monitor pseudo ranges individually based on inertial information in order to prevent pseudo-range errors from causing system integrity violations. Systems that perform blending of GPS and Inertial Reference System (IRS) position information with no access to individual pseudorange measurements are not tightly integrated. Examples are included to clarify the meaning of assumptions, requirements and validation procedures. The requirements in this appendix apply to tightly integrated GPS/inertial systems using an aircraft-based integrity augmentation (fault detection and exclusion).

Note 1: "Equipment" is defined as a GPS receiver, inertial sensor, and integration function.

Note 2: The FAA's TSO process allows for certification of incomplete systems, and as part of this process, the equipment manufacturer is responsible for identifying the TSO requirements that are not applicable to their device.

R.2 Requirements

Section 2.1.2.2.2 provides the basic requirements for any FDE implementation. Section R.2.1 clarifies the application of these requirements to GPS/inertial applications. Additional requirements that are unique for this type of integration are included in Section R.2.2.

R.2.1 General FDE Requirements

Tightly integrated GPS/Inertial systems shall [GPS 280] meet the FDE requirements summarized in Table R-1. The table also includes the requirement applicable to rare normal (fault free, HPL_{FF}) errors (such as inertial sensor errors) affecting a single user.

TABLE R-1 SUMMARY OF FDE REQUIREMENTS

Parameter	Requirement
Missed alert probability (satellite failure)	0.001
False alert rate	10^{-5}/hour
Probability (p_{MI}) of exceeding HPL_{FD}	10^{-7}/hour
Probability (p_{MI}) of exceeding HPL_{FF}	10^{-5}/hour
Failed exclusion probability (satellite failure)	0.001

The equipment shall [GPS 281] be capable of computing the horizontal protection level HPL_{FD}. HPL_{FD} shall [GPS 282] be a function of measurement accuracy and geometry only and shall [GPS 283] not depend on individual measurements.

Note 1: This appendix focuses on the detection and exclusion of satellite failures. Failures may also occur in the equipment providing baro altitude, the GPS receiver e.g. receiver clock, the inertial sensors and inertial data processing. Traditionally these types of equipment failures has been detected and excluded based on dual or triple redundancy of equipment. Some of these errors can however alternatively be detected by the tightly integrated system. Guidelines for single string (no redundancy) detection and exclusion of such failures have not *yet been developed by the RTCA. It must be demonstrated that the tightly integrated GPS/Inertial system as installed provides adequate detection and exclusion capability to meet the system integrity requirements also when considering equipment failures.*

Note 2: The integrity risk of 10^{-7} per hour covers all types of satellite signal failure conditions including ionospheric anomalies such as ionospheric storm fronts.

Note 3: There is no system level requirement to annunciate or exclude a satellite from the tightly integrated solution if HPL continues to bound horizontal position error. Systems may compensate for satellite failures by incorporating models of satellite failures in their estimation algorithms instead of simply excluding satellites from the solution. The conditions under which this compensation is done and when an exclusion is done will be system design dependent and should be substantiated through the certification process. Additionally, the compensation and exclusion function monitor intervals must be taken into account to address the possibility of multiple satellite failures.

R.2.1.1 Fault Free Performance

GPS stand-alone fault free performance has two performance components, the 95% accuracy and the rare normal performance. The 95% accuracy requirements are found in Section 2.1.2.1. The rare normal performance is tied to the fault free horizontal protection level (HPL_{FF}), which is a 10^{-5}/ hour limit. The rare normal performance factors in local rare normal atmospheric conditions and inertial sensor induced rare normal drifts.

There is no allocation for rare normal events in section 2.1.2.1. The reason for this is that the protection level for the faulted condition, HPL_{FD}, in most cases bounds the rare normal level, HPL_{FF}, in a <u>snapshot algorithm</u> so that HPL = max (HPL_{FF}, HPL_{FD}) = HPL_{FD}.

In a tightly integrated system, inertial coasting may cause the rare normal limit to be dominant over the limit for the faulted condition in times of poor satellite coverage.

The probability per hour of a rare normal event assuming a time between independent events of τ in hours and a probability of exceeding HPL_{FF} based on the horizontal error (inertial sensor errors, ionospheric delay, multipath, thermal noise) distribution of p_{ffd} is p_{ffd}/τ_ρ . The time between independent events is a function of the dynamic properties of the error.

For example, if the time between independent events is 0.2 hours and the error is bounded by a normal distribution, the rare normal limit (HPL_{FF}) for a snapshot algorithm based on a 10^{-5} per hour integrity risk allocation, corresponding to a probability p_{ffd} = 10^{-5}/hour × 0.2 hour = 0.2×10^{-5} which corresponds to a 4.75-sigma (two sided Gaussian), is

$$HPL_{FF} = K_{ffd}\,HDOP\,\sigma = 4.75\,HDOP\,\sigma \qquad \text{(R-1)}$$

Where σ is the 1-sigma of the error in the pseudo range. For comparison, the protection limit HPL_1 calculated by a snapshot FDE algorithm using Gaussian statistics under the hypothesis of one faulty satellite is

$$HPL_{FD} = \max\ \{ HPL_{FD,n} \} \qquad \text{(R-2)}$$

where

$$HPL_{FD,n} = a_n K_{fd} \sigma_d + K_{md} b_n \sigma \qquad \text{(R-3)}$$

In these equations a_n (n=1,..,N) and b_n (n=1,..,N) are geometry dependent parameters of the same order of magnitude as the HDOP. The sigma numbers for false detection and missed detection are approximately $K_{fd} = 5$ and $K_{md}=3$. This demonstrates that the HPL_{FD} generally exceeds HPL_{FF} in snapshot Receiver Autonomous Integrity Monitoring (RAIM) and the HPL_{FF} is therefore usually not emphasized. In integrated systems where inertial signals are used to propagate GPS information between GPS filter updates, the HPL_{FF} contribution to the integrity risk is essential.

In addition, mis-modeling of the inertial sensor errors may result in an incorrect 1-sigma position accuracy, which in turn results in an incorrect HPL_{FF}. To ensure integrity, it is important to verify that the accuracy requirement is met with all significant error sources included. For integrated GPS/inertial systems it is further important to include gyro/accelerometer noise and bias instability as well as the errors induced by normal airplane dynamics (acceleration and angular rates).

R.2.2 Unique Additional Requirements

R.2.2.1 Assumed Failure Mechanisms

Tightly integrated GPS/inertial systems can readily detect and exclude range rate error steps greater than 2 meters/second. Averaging of the RAIM discriminator (see Section R.2.2.6) can improve the RAIM based HPL for drifts smaller than 0.1 meters/second. The dependence on the failure characteristics makes it necessary to use a set of representative failure mechanisms for testing. An Integrity FMEA (reference 6) has been conducted on Block I, II and IIA satellites and provided predictions of the misleading information (MI) failure probability for all known failure mechanisms. Observed failure rates have confirmed that these probabilities are conservative. In order to provide some additional margin and to factor in the uncertainty associated with future satellite failure modes, the assigned failure probabilities are enlarged (3.448 ×) relative to the predicted probabilities, and the minimum assumed failure probability has been inflated to 10^{-6} /hour/satellite. The step of 700-3000 meters is already required to be detected by the step monitor in Section 2.1.1.3.1 and this failure mode is therefore not included. Table R-2 lists the predicted failure types, the predicted probability, assigned test range and assigned probability. The assigned MI failure probabilities will be updated if appropriate FMEA data becomes available.

TABLE R-2 SUMMARY OF FAILURE TYPE PROBABILITIES

Predicted MI Failure Type, meters/second (m/s)	Block I, II, IIA Predicted MI Failure Probability in units of 10^{-7}/ hour/satellite	Assigned Test Range	Assigned MI Failure Probability in units of 10^{-6}/ hour/satellite
Ramp 0.01 m/s	2	Ramp 0.01-0.05 m/s	1
Ramp 0.1 m/s	1	Ramp 0.05-0.25 m/s	1
Ramp 0.5 m/s	3	Ramp 0.25-0.75 m/s	1
Ramp 1.0 m/s	10	Ramp 0.75-2.5 m/s	3.5
Ramp 5.0 m/s	12	Ramp 2.5-5.0 m/s	4.1
Step 300 meters	1	Step 300-700 meters	1
Step 3000 meters	34	Step 700-3000 meters	N/A

Note 1: The IFMEA and observed failure rates for Block I, II, and IIA satellites indicate that larger acceleration errors occur with a probability that is negligible versus 10^{-7}/h, and that failure induced accelerations with a probability of 10^{-7}/h or higher, can not exceed 0.1 μg. Performance degradation due to small accelerations (<0.1μg) are covered by the 0.01 m/s ramp and an acceleration failure mechanism is therefore not included.

Note 2: The model for the data in Table R-2 has been established based on experimental data and Integrity Failure Modes and Effects Analysis (IFMEA) by ARINC in El Segundo, California. The data used to establish this model is summarized in the Aberration Characterization Sheets (ACS) documented in reference 6.

R.2.2.2 Detection limit

The probability, p_{MI}, of exceeding HPL_{FD} with no integrity alert (integrity risk) specified in Table R–1 shall [GPS 284] be defined as

$$p_{MI} = \sum_{k=1}^{K} p_{f,k}\, p_{md,k} \quad \text{(R-5)}$$

where $p_{md,k}$ is the conditional probability of exceeding HPL_{FD} for failure mode k, $p_{f,k}$ is the assigned MI failure probability in Table R-2 and K is the number of failure modes. The continuity risk p_{cont} associated with a satellite failure that cannot be excluded before a loss of function occurs, shall [GPS 285] be defined as

$$p_{cont} = \sum_{k=1}^{K} p_{f,k}\, p_{fexl,k} \quad \text{(R-6)}$$

where $p_{fexl,k}$ is the conditional probability of failed exclusion for failure mode k.

Note 1: The HPL provided by the tightly integrated system as defined in this appendix only needs to consider the limited set of failure scenarios defined above.

Note 2: The required continuity risk depends on operational considerations and is expected to be in the range 10^{-7}/h – 10^{-5}/h.

R.2.2.3 SatZap

Due to the monitoring performed by the GPS control segment (SatZap) and the changes planned to occur as part of the GPS modernization it is expected that slowly drifting satellites will be detected and removed before the error has any significant impact. As soon as this monitoring is in place and its performance documented it will be possible to make use of the synergy between tightly integrated systems and the control segment monitoring by modifying the equipment to comply with a different set of MI failure probabilities.

R.2.2.4 Receiver Clock Aiding

The receiver clock frequency random walk 1-sigma shall [GPS 286] not exceed 1 feet/s $/\sqrt{s}$ under steady state thermal conditions. The frequency drift shall [GPS 287] not exceed 3 ppm/°C under transient thermal conditions.

Note 1: When using a Kalman filter based integration or other equivalent integration the receiver clock error is usually incorporated in the state model. To assure interoperability when using different GPS receivers a minimum clock standard is required.

Note 2: The maximum temperature rate of change specified in DO-160D for all equipment categories is 5°C /minute.

Note 3: A significantly lower temperature sensitivity than 3 ppm/°C would require the use of an oven-controlled crystal oscillator (OCXO) and exclude the use of a temperature compensated crystal oscillator (TCXO) in the GPS receiver.

Note 4: This requirement applies to the GPS receiver oscillator, and does not directly place requirements on the tightly integrated GPS/inertial function.

If receiver clock aiding is used to enhance integrity, the algorithms that perform calibration shall [GPS 288] be designed to prevent the satellite failure itself from affecting the integrity of the calibration. Conventional Kalman filter integrations using clock states for offset and drift rate with no further enhancements to protect these states in a failure situation will not meet this requirement.

Note: Oscillators are temperature sensitive devices. The drift stability in a transient thermal environment, such as a receiver just turned on, is significantly degraded relative to a steady state thermal environment. An airplane descending from en route to non precision approach experiences significant temperature gradients which affect the stability of the clock.

R.2.2.5 Altitude Aiding

If pressure altitude aiding is used to enhance integrity, the algorithms that perform calibration shall [GPS 289] be designed to prevent the satellite failure itself from affecting the integrity of the calibration. Conventional Kalman filter integrations using a bias error state with no further enhancements to protect this state in a failure situation will not meet this requirement. RAIM algorithms meeting this requirement (without the use of inertial measurements) are included in Appendix G.

Note: When using a Kalman filter based integration or other equivalent integration, the pressure altitude bias error is usually incorporated in the state model.

R.2.2.6 Discriminator Averaging

A system using discriminator averaging when determining the horizontal protection limit (HPL_n) shall [GPS 290] consider: (1) the impact of the temporal correlation, ρ, of the discriminator noise, (2) the impact of slowly changing errors that are not reduced by averaging (e.g. ionospheric error), and (3) the reduction in detection performance for failures with dynamics that are fast relative to the averaging period.

R.2.2.7 Inertial Coasting Performance Evaluation

The inertial sensors in tightly integrated GPS/inertial systems are continuously calibrated using GPS measurements. This means that the system can propagate the established position accurately if the GPS signals are lost due to any unexpected event such as interference, scintillation, masking, unexpected satellite failure, etc. There are two types of coasting considered here – accuracy coasting and integrity coasting. Accuracy coasting is the propagation of the established position and corresponding accuracy bound after the loss of GPS assuming no failures were in progress prior to the loss. The accuracy bound is typically the $HFOM_P$ which represents a conservative 95% limit. Integrity coasting is the propagation of the position and corresponding integrity bound assuming the worst case satellite undetected failure was in progress just prior to the loss of GPS. The bound is the horizontal protection limit (HPL) and must take into account the miscalibration of the hybrid solution due to the undetected failure. To promote the use of this capability a method to establish the coasting performance is defined below.

Note: The performance requirements applicable to inertial coasting are provided in RTCA/DO-236A. The inertial coasting error represents a navigation system error that, combined with the flight technical error, constitutes the total system error defined by the RNP type. The allowed coasting time (coasting capability) is ultimately determined by the NSE tolerance provided by the RNP type. The coasting capability can be established from the horizontal radial error distribution, typically the 95% limit, in meters or nmi as a function of time in minutes from the point the GPS function was lost.

R.2.2.7.1 Accuracy Coasting

The horizontal coasting error distribution as a function of time should be evaluated under the following conditions: Inertial errors should be initialized by either beginning the simulation error-free and flying 60 minutes on pure inertial, or by initializing the simulation with correct or conservative accumulated inertial errors. Then GPS measurements should be incorporated for a calibration time of 60 minutes. The HDOP should stay above 1.5 throughout the calibration. Frozen satellite positions may be used. The evaluation should be performed with correct or conservative gyro/accelerometer noise, correct or conservative gyro/accelerometer bias instability and a representative receiver clock model. Altitude information as mechanized in the system under evaluation, may be used during the coasting phase to prevent vertical channel instability. In this evaluation the calibration and coasting should be performed during straight and level flight. The coasting error distribution is a statistical measure and covariance propagation techniques may be used to determine the performance. At least 500 Monte Carlo simulations, including calibration and subsequent coasting, using the algorithms implemented in the system should be run to verify the covariance propagation model used to predict the claimed coasting performance.

Note 1: The 500 Monte Carlo simulations, including initial errors, may be replaced by 500 tests performed on the equipment

Note 2: This requirement is not applicable if a coasting capability is not claimed as part of the equipment performance parameters.

An example of accuracy coasting performance illustrating the order of magnitude of the coasting error during straight and level flight, is shown in Table R-3. Values in the table were generated by simulation using the following assumptions:

a) Steady state achieved prior to coasting.

b) Coasting in straight and level flight in NPA phase.

c) HDOP = 1.5.

d) Pseudorange noise error sigma = 2 m.

e) Pseudorange bias error sigma = 10 m.

f) Filter update rate = 2 min.

g) Gyro bias error sigma = 0.01 deg/hr (τ = 1 hr).

h) Gravity deflection sigma = 5 arcsec.

i) Gravity correlation distance = 20 nmi.

j) Aircraft velocity = 180 knots.

k) Accelerometer bias calibration error sigma = 10 μg.

l) Gyro noise sigma = 0.001 deg/$\sqrt{}$h.

m) Gyro misalignment: 10 ppm.

TABLE R-3 ACCURACY COASTING PERFORMANCE EXAMPLE

Coasting time	95% accuracy
0 min	30 m
10 min	100 m
20 min	340 m
30 min	800 m
60 min	2700 m

For additional information on coasting performance see reference 4 in Section R.6.

Note: It is emphasized that Table R-3 is provided as an example only, and is based on a particular set of assumptions. The results can vary significantly depending on the assumptions.

R.2.2.7.2 Integrity Coasting

If valid HPL outputs continue during GPS outages, the required probabilities must be maintained. The probability of missed alert due to a latent satellite failure shall [GPS 291] remain less than 10^{-3} during outages (a latent satellite failure remains undetected prior to loss of GPS). In other words, an undetected satellite failure prior to the loss of GPS may mis-calibrate the hybrid filter(s), and this impact must be reflected in the HPL.

The false alert rate shall [GPS 292] remain less than 10^{-5}/hour during outages.

If exclusion capability during integrity coasting is claimed, then the probability of failed exclusion (the inability to remove, or properly bound using HEL, all impact of a failed satellite from the position solution) shall [GPS 293] remain less than 10^{-3} during outages.

An example of integrity coasting performance illustrating the order of magnitude of the coasting time that HPL remains below a HAL typical of approach (LNAV) and Terminal operations is shown in Table R-4. Values in the table were generated by simulation using the same set of assumptions in the Accuracy Coasting (R.2.2.7.1) except for the flight profile shown in Figure R-1.

The initial flight direction is as shown in the figure: “T” to “E” for terminal area navigation and “N” to “D” for approach (LNAV). It is assumed that the aircraft always has an hour of calibration on a straight and level flight before it loses the GPS signals. The location of the complete loss of GPS signals is selected such that the no-fault HMI and GPS/IRS HPL requirements are met until the end point (that is, A and B for approach (LNAV) and terminal navigation, respectively).

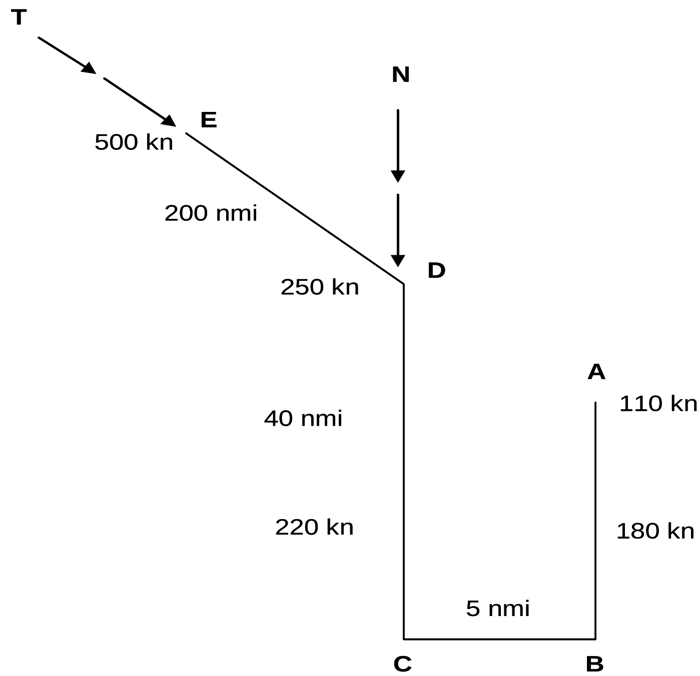

FIGURE R-1 FLIGHT PROFILE ASSUMED FOR THE COASTING TIMES

TABLE R-4 INTEGRITY COASTING PERFORMANCE EXAMPLE

Flight Phase / Operation	Horizontal Alert Limit	Coasting time
Approach (LNAV)	0.6 nmi	13-14 minutes
Terminal	2.0 nmi	23-24 minutes

It is emphasized that Table R-4 is provided as an example only, and is based on a particular set of assumptions. The results can vary significantly depending on the assumptions.

R.2.2.8 Gravity Compensation

Gravity compensation error is a significant source of position drift for two nautical miles per hour inertial navigation systems. Errors in the gravity models can cause errors in the integrated inertial GPS systems that become problematic particularly during coasting conditions. To reduce these errors, some form of gravity compensation algorithms must be applied. The gravity compensation error is typically expressed in terms of gravity deflection and gravity anomaly. Gravity deflection is defined as the deviation of the gravity vector from the vertical. Gravity anomaly is defined as a magnitude error in the size of the gravity vector. Investigations of the distribution of gravity deflection and anomaly data demonstrate that the data does not form a normal distribution. While most of the world can be modeled assuming one-sigma deflection of 5 arc-sec, there are specific isolated regions where the deflections are much larger -- up to 50 arc-sec. These gravity errors do not produce "random" errors, as the same errors will occur on every flight over a local area.

The National Geospatial-Intelligence Agency (NGA, formerly NIMA) maintains an unclassified database of the Earth's gravitational field referenced as the Earth Gravitational Model 1996 (EGM96), and is maintained as part of the WGS-84 world model. NGA has released another model, EGM2008 (WGS-84 version) with additional resolution. This database can be used to create a worldwide gravity model that reduces the total gravity compensation error.

The tightly integrated system shall [GPS 294] properly account for the local gravity anomalies and deflections such that the HPL continues to bound the system errors while operating in areas of increased gravity anomaly/deflections, even when coasting. Suitable mechanisms include an appropriate subset of the following:

a) Over-bounding using a standard model with an elevated sigma level.

b) Compensation using a gravity map.

c) Adjustment of the filter parameters (e.g. increase the process noise).

R.3 Tightly Integrated GPS/Inertial Design Concepts

This section, that is descriptive in nature and contains no requirements, describes basic techniques that can be used to enhance the integrity of tightly integrated solutions.

R.3.1 Integration Methods

Conventional Kalman filters are used to integrate inertial information with external measurements from various ranging sources such as GPS or Loran. The Kalman filter relies on an accurate inertial error model and known statistical inertial sensor error distributions as well as a linearized measurement model for GPS pseudoranges and the associated pseudorange error statistics.

The transient that is produced by a position step or a sudden drift in a satellite, is detectable in the measurement residuals or innovations. This transient behavior can be used to enhance the detection and exclusion capability for a limited set of failure modes.

Note: The conventional Kalman filter in itself does not improve the integrity of the GPS solution since it will easily adapt to and incorporate any GPS position offset or drift as a natural dynamic state (position error state or velocity error state).

In a situation when redundant satellite information is available, errors will develop in all satellite post residuals (after application of measurements) or pre residuals (before application) as a satellite failure progresses and the initial transient has settled. Any method that provides a detection scheme solely based on these remaining residuals (transient assumed gone) is approximately equivalent to traditional RAIM and will therefore not further augment the RAIM function. If the residuals are averaged over time the method is equivalent to RAIM using discriminator averaging. One exception to this simple rule is the Gravity/Schuler coupling, which provides additional detection capability over unaided RAIM (see Section R.3.2.4).

R.3.1.1 Pre-residual (Innovation) Screening

This method is routinely used in Kalman filter based estimators. The statistics of the innovations can be calculated from the covariance matrix P. If one or several innovations associated with a measurement far exceed the expected 1-sigma value, the measurement is excluded. This method provides exclusion capability for large steps, ramps and ramp rates. Multiple measurement failures can be handled. Slow drifts or drift rates are, however, not excluded and detection and exclusion of such failure types can only be provided by other methods, e.g., RAIM. Innovation screening will typically eliminate the faulty measurement and the HPL can be calculated by determining the worst-case navigation error impact over all possible satellite failure modes.

R.3.1.2 Post-Residual Monitoring

The post residual (residual error after processing of measurements) is calculated right after the estimator has processed all the measurements. The statistics of the post residual can be calculated from the covariance matrix P. If one or several residuals far exceed the expected 1-sigma value, it can be concluded that one or more of the measurements must have been in error. Normally this method mixes elements of RAIM and innovation screening and it is not straightforward to sort out which effect that is dominating. Therefore, an exclusion capability is not provided in the general case.

R.3.1.3 Additional Measurement Bias States

The addition of ramp failure states in a Kalman filter based estimator produces a mechanism for detection that is equivalent to RAIM, but no calculation of HPL has been proposed for this method.

R.3.1.4 Multiple Kalman Filters

If multiple Kalman filters are used, where a different satellite has been excluded in each filter, the residual monitoring and additional bias states methods, described above, will provide an exclusion mechanism equivalent to RAIM. However no method for calculating the exclusion limit HEL has been proposed for this method.

R.3.1.5 Extrapolation Method

The extrapolation method utilizes a simultaneous combination of both transient and redundancy effects to detect failures. The measurements are stored in buffers over 30 minute periods. This provides a detection capability, which is enhanced over RAIM for slow failures because of the information that is retained from previously processed measurements (compare discriminator averaging). A bank of parallel Kalman filters is used to: (1) test newly acquired satellites before they are used in the main Kalman filter, and (2) to isolate failed satellites once the failure is detected by the main Kalman filter. The HPL is calculated by computing parallel solutions corresponding to different failure modes. The magnitude of the worst-case failure is determined partially based on simulations to provide probability of detection and correct isolation exceeding 99.9%.

R.3.1.6 Solution Separation Method

A bank of Kalman filters using the solution separation method provides a non transient detection capability that has been enhanced over RAIM based on the redundancy information that is retained from previously processed measurements via the inertial function. A procedure for calculating HPL is an integral part of this method. No assumption is made about the dynamics of the failure when HPL is calculated. The enhancements provided by external aiding information (e.g. filter states representing corrections to external aiding information), such as receiver clock and pressure altitude, will be incorporated in the calculated HPL. No miss-calibration is possible since one of the reference sub-filters using the aiding will not contain the failing satellite.

R.3.2 Detection and Exclusion Mechanisms

R.3.2.1 Transient Detection/Exclusion for 2 nmi/hour Grade Systems

The transient effect can be used to exclude a faulty satellite. This type of monitor provides increased detection and exclusion capability in a situation when RAIM is not effective. If for example a pre residual (innovation) monitor is used to detect ramps, it can be shown by simulation that ramps above 2 meters/second can be detected with a 0.999 detection probability in all situations when RAIM is not effective (assuming at least one hour of good geometry prior to the failure). This leads to 100% (detection and exclusion) availability for ramps above 2 meters/second when RAIM is unavailable. This highly available but restricted exclusion capability demonstrates the basic advantage and also limitation of this type of enhancement.

Note: The detection/exclusion ramp limit of 2 meters/second is achievable by equipment using commercial grade navigation sensors i.e. inertial systems meeting a 2 nmi/hour performance (95%).

R.3.2.2 Satellite Redundancy

Measurement redundancy is the mechanism that is used in RAIM. It is because of the satellite measurement redundancy that Kalman filter post residuals continue to grow with the satellite error after the initial transient has settled. Without any redundancy no such growth will occur.

R.3.2.3 Integrity Coasting

In this case dynamic states that contain redundancy information (defined based on the assumption that only one satellite will fail) are time propagated based on inertial information. An example of this mechanism is the solution separation method where sub-filters and dual covariance propagators are used to retain this redundancy information.

R.3.2.4 Gravity/Schuler Coupling

The Gravity/Schuler coupling effect can be demonstrated by letting the vertical channel, incorporating a z-accelerometer, combine with the Schuler dynamics of one of the horizontal channels in a Kalman filter. As measurements that are the sum of the vertical position and the clock phase error, combine with measurements that are the sum of the lateral position and the same clock phase error, the vertical position error will be pulled in. This effect is not sensitive to the clock performance but is strongly related to the z-accelerometer accuracy. The reason for this effect is that the Kalman filter is able to eliminate the clock phase error due to the radically different dynamics of the vertical and horizontal channels. Most GPS/Inertial Kalman filters will automatically incorporate this type of information. This means that integrity below 1 nmi can be established with only 4 satellites (in good geometry) in view and no altitude aiding if an accurate z-accelerometer is used. It can be demonstrated that an accurate z-accelerometer is approximately equivalent to an altitude measurement. The z-accelerometer versus altitude accuracy relation is summarized in Table R-5 (see Reference 1 in Section R.6).

TABLE R-5 EQUIVALENT ALTITUDE ACCURACY

Acceleration, micro Gs (μg)	Altitude, Meters (m)
300 μg	920 m
100 μg	420 m

40 μg	300 m
20 μg	280 m

R.3.2.5 Other Schuler Coupling Related Effects

When exposed to MI failures (such as ramps) and after the transient has rung out, innovations or residuals often gradually deviate from zero in an oscillatory manner. This phenomenon is due to the horizontal Schuler coupling and other long term coupling effects. The reason for the deviation is that the satellite drift causes a linear position growth while the inertial position error growth has an 84 minute oscillatory component. Due to the long oscillation period (84 minutes) these effects are generally not timely enough to improve the detection and exclusion capability.

R.4 Assumptions

R.4.1 Signal Error Model

Validation activities shall [GPS 295] model pseudorange error using statistical test data that represent all significant sources of measurement error. This data will be generated by the combination of five independent models: ionospheric, tropospheric, satellite clock & ephemeris, receiver noise, and multipath.

Ionospheric error shall [GPS 296] be modeled using the International Reference Ionosphere 2001 (IRI-2001) model. The IRI-2001 model was developed and validated by IRI, an international project sponsored by the Committee on Space Research (COSPAR) and the International Union of Radio Science (URSI). It models the ionospheric daily variation, but does not model storms. Since statistical data is needed from a deterministic model, the model inputs will be randomized in the test procedures. IRI-2001 accounts for temporal and spatial correlation between satellite measurements. Other iono models may be used, but they must be validated.

Tropospheric error shall [GPS 297] be modeled using a first-order Gauss-Markov process with a 30 minute correlation time. The sigma shall [GPS 298] be scaled per the tropo residual error sigma equation defined in Appendix J, Section J.5. Simultaneous measurements from different satellites are assumed to be uncorrelated. Other tropo models may be used, but they must be validated.

Note: The 30 minute correlation time is representative of a typical storm system passing through. The assumption of uncorrelated measurements is the conservative assumption. Correlated components would be mostly removed by the user clock bias states.

Satellite clock & ephemeris error shall [GPS 299] be modeled using a first-order Gauss-Markov process with a 2 hour correlation time and a 2m sigma. No correlation is assumed between satellites. Other clock & ephemeris models may be used, but they must be validated.

Note: References 7 and 8 provide justification for the sigma magnitude. The correlation time can be justified as follows: Ephemeris prediction would be related to the orbit of the satellites (i.e. periodic with a 12 hour period). There may also be occasional (every few hours) small steps due to ephemeris data uploads. Satellite clock errors are most likely a slow integrated random walk process (with occasional resets via uploads). The error model is an approximation of all of these error sources (very slow orbital errors, fast but small resets, and slow noisy clock drift).

Receiver and multipath error shall [GPS 300] be modeled using the airborne receiver error model in Appendix J, Section J.3. If the tightly integrated inertial/GNSS function does not use carrier phase smoothing of the code, the error model shall [GPS 301] use a 25 second correlation time. If smoothing is used, the smoothing constant shall [GPS 302] be used.

Note: *This model is applicable to an aircraft in flight, and not to an aircraft on the ground.*

These models are valid for satellite elevation angles above 5 degrees. If satellites below 5 degrees are used, then adequate steps must be taken to ensure system safety.

R.4.2 Satellite Clock Drift Characteristics

For errors, such as a systematic drift in the atomic clock onboard the satellite, a slow acceleration in the pseudo range error will result. A sudden frequency shift in the satellite clock will lead to a ramp in the pseudo range. Errors in the satellite clock correction parameters in the navigation message will have a similar impact: for instance an error in a_{f1} causes a ramp type failure and an error in a_{f2} causes an (pseudo range) acceleration error.

Note: *For block II/IIA cesium clocks the af_2 term in the navigation message is hard-coded to zero. The block IIR satellites use a rubidium clock that exhibit small accelerations and the af_2 term is used. The maximum acceleration error that could occur if af_2 was incorrect is 0.1 μg. The effect of such a small acceleration on the tightly integrated system is approximately the same as the effects of a small ramp.*

R.5 Validation

R.5.1 Categorization of Detection and Exclusion Mechanisms

Due to the special character of a tightly integrated approach the tests in Section R.5 shall [GPS 303] be performed with correct or conservative gyro/accelerometer noise, correct or conservative gyro/accelerometer bias instability, correct or conservative scale-factor and misalignment errors, normal airplane dynamics and correct or conservative receiver clock model.

Normal airplane dynamics shall [GPS 304] include turns in the terminal area as follows: For terminal and non precision approach use straight and level flight during calibration (when failure is not present) and one single 180 degree turn using a 1.5 degree/second turn rate started right after the failure is initiated. The ground speed is approximately 200 knots.

If altitude and/or clock aiding are used these measurements shall [GPS 305] also be included in the verification.

If the position solution is updated at a low rate (such as a 2.5-min time step) the growth in the solution error between updates must be considered. The performance shall [GPS 306] be measured and verified both before and after the measurement update.

The manufacturer shall [GPS 307] categorize the failure detection and exclusion mechanisms employed by the monitor algorithms that are to be validated. The mechanisms identified in this appendix are:

a) Transient detection and exclusion (e.g. innovation screening)

b) Satellite geometric redundancy (e.g. RAIM)

c) Inertially propagated geometric redundancy (e.g. solution separation)

d) Discriminator or residual time averaging (e.g. RAIM or extrapolation method)

e) Gravity/Schuler coupling

The limitations and performance of each implemented detection/exclusion mechanism shall [GPS 308] be demonstrated in test cases chosen by the manufacturer. This material will be used by the certification authority to assess the authenticity of the claimed improvements over normal RAIM.

R.5.1.1 Examples

The transient detection can be demonstrated by testing different ramp scenarios in geometries with no redundancy (4 satellites).

The performance of the redundancy based monitor (RAIM equivalent) which may include discriminator (residual) averaging, altitude and/or clock aiding can be demonstrated using ramps below the transient exclusion threshold or with the transient exclusion mechanism disabled.

R.5.2 Covariance Simulation

The Kalman filter technique provides a powerful verification tool referred to as covariance simulation. This type of prediction can be used for availability determination for different satellite constellations but shall [GPS 309] not replace off line verification of the implemented detection and exclusion algorithms.

R.5.2.1 Covariance Simulation Methods for Availability Evaluation

When system availability is determined, Monte Carlo techniques for verification of detection probability and false detection probability at each space-time point would be impractical since several million space-time points need to be evaluated. The covariance simulation technique which is based on the statistical 1-sigma and correlation information that can be extracted from the Kalman filter covariance matrix P makes it possible to determine these probabilities based on a single run at the desired space-time point.

The Covariance simulation involves six steps for each failure type:

a) Determine the fault free distributions of the discriminator value.

b) Determine the fault free distribution of the horizontal error.

c) Determine the statistical correlation between the discriminator value and the horizontal error.

d) Determine the fault induced deterministic discriminator value as a function of time with the simulated noise turned off and with the same Kalman filter settings as in step a).

e) Determine the horizontal error as a function of time with the simulated noise turned off and with the same Kalman filter settings as in step b.

f) Establish the radial horizontal protection limit by determining the smallest radial limit (HPL) for which the probability that the test variable are below the thresholds while the horizontal error exceeds HPL is less than or equal to 0.001 for all possible satellite errors (For a detailed discussion on covariance simulation, see Reference 5, Section R.6).

Note 1: Since the Kalman filter is a linear filter the noise distributions in steps a) and b) can be superimposed on the deterministic functions.

Note 2: Steps a), b), and c) define a multidimensional probability density f(t1,…,tm,x1,x2) of horizontal error x1,x2 and test variables t1 ,…, tm combined. The condition |tk| < Dk k=1,…,m and r=$\sqrt{x_1^2 + x_2^2}$ *> HPL is an event that can be defined in this multidimensional space. Usually a manufacturer would use approximate conservative methods to simplify the HPL calculation.*

Note 3: The HPL determined this way relies on a series of assumptions and derivations. The procedure for determining the correct HPL by a multidimensional probability density function is complex and further assumptions would be used to simplify this calculation. It is therefore required that the resulting HPL calculation be validated by Monte Carlo simulation.

R.5.3 False Alert Probability

The false alert rate shall [GPS 310] be verified per 2.3.7.4.2. The time required to achieve enough independent samples to test the required statistical limits may be impractical, so the detection and exclusion thresholds may be adjusted so that the test time is reduced to a reasonable level, such as days rather than weeks or months.

Note 1: If due to the observed event rate in a particular test, the required confidence as defined in 2.3.7.4.1 can be established with less than the nominal number of independent samples, the test can be terminated earlier.

Note 2: To the uninitiated, it seems preferable to increase the measurement noise level (ionosphere) instead of adjusting the threshold so that the tested algorithm remains intact during testing but in tightly integrated systems it is important to preserve the relation between inertial sensor errors and measurement noise during the testing.

All the detection/exclusion mechanisms shall [GPS 311] be active and tested at the same time. The total amount of false detections and exclusions shall [GPS 312] be verified. If more monitors are used the total false detection allocation shall [GPS 313] reflect contributions from each additional mechanism.

R.5.4 Fault Free Accuracy Performance

The snapshot 95% horizontal accuracy test is defined in Section 2.3.3.3. If the inertial integration is performed by a recursive filter with memory, the scaling (1.5/HDOP) used in the test is not appropriate. The testing shall [GPS 314] be performed versus the 2drms accuracy limit that is provided by the integration filter. For a Kalman filter with position error in states 1, 2, 3 (North, East, Down) this limit is expressed as:

$$2\mathrm{drms} = 2\sqrt{p_{11} + p_{22}} \qquad \text{(R-7)}$$

The accuracy test shall [GPS 315] be performed using the signal error models in Section R.4.1 and maximum thermal noise (minimum S/N_0). The accuracy test shall [GPS 316] demonstrate that the instantaneous horizontal position error stays below 2drms, as defined above, 95% of the time.

The test shall [GPS 317] evaluate at least 360 independent samples using the satellite constellation in Appendix B.

Of great importance is the verification that K_{ffd} drms < HPL under all circumstances (see rare normal verification).

R.5.5 Off-Line Rare Normal Verification

A test shall [GPS 318] be performed to verify that the fault-free rare normal HPL (H0) properly bounds the horizontal position error. This test may be performed at the same time as the false alert tests of R.5.3. For the purposes of this test, the sigma multiplier K_{ffd} can be adjusted to increase the allowed integrity failure rate, resulting in a reduced fault-free HPL (H0) such that a 99% confidence that twice the increased integrity failure rate can be demonstrated over the duration of the tests. In this case, up to 47 independent instances of the position error exceeding the HPL (H0) would be allowed.

R.5.6 Off-Line Detection/Exclusion Verification

All position errors shall [GPS 319] be evaluated relative to the HPL that is calculated by the equipment under test or if exclusion is tested the predicted HEL. The test first verifies normal RAIM performance and then moves on to test cases where the claimed HPL(HEL) performance is better than the performance provided by RAIM. The corresponding RAIM baseline performance shall [GPS 320] be provided for all test cases as a reference. A failure to clearly identify and demonstrate the function of the mechanism responsible for the improved HPL (HEL) (relative to RAIM) in a test case, shall [GPS 321] render the test invalid (see Section R.5.1).

Note: The reason for this requirement is that the entire test otherwise could be performed only in regions where RAIM is available and not in regions where the additional performance is claimed.

R.5.6.1 Detection and Exclusion Mechanism Equivalent to RAIM

The off-line detection/exclusion test procedure in Section 2.3.7.3.3 shall [GPS 322] be performed to verify the RAIM equivalent performance, i.e. 1650 trials must be run for each of the 40 geometries (20 for detection and 20 for exclusion) with the (software) algorithm that is implemented in the equipment. The following exceptions apply:

a) The RAIM equivalent performance shall [GPS 323] be verified based on Section 2.3.7.3.3 using ramps that will not trigger any of the other detection/exclusion mechanisms augmenting the RAIM function.

b) If the RAIM algorithm and the augmentation algorithms are implemented separately, the augmentation algorithms may be disabled and RAIM tested according to Section 2.3.7.3.3 using 5 meters/second ramps.

Alternatively the RAIM equivalent performance may be tested according to step 2) to 5) in Section R.5.6.2 using the geometries defined in Section 2.3.7.3.3.

R.5.6.2 Claimed Additional Detection and Exclusion Mechanisms

The equipment manufacturer shall [GPS 324] perform the following:

a) Select 20/20 different typical scenarios i.e. geometries and previous history providing HPL< HPL_{RAIM} / HEL < HEL_{RAIM}.
b) Perform 1650 trials using a mixture of failure modes according to Table R-6 for each scenario (geometry and previous history).
c) For each failure mode, the magnitude of the ramps (step) shall [GPS 325] be distributed uniformly in the interval designated in Table R-6. The failure shall [GPS 326] be introduced in the most difficult to detect/exclude satellite.

d) For each failure mode, the failure ramp and the change in geometry shall [GPS 327] be coordinated so that the desired HPL/HEL would have been exceeded if detection/ exclusion had not occurred.
e) Alternatively, if the geometry history is immaterial for obtaining the claimed HPL/HEL, the desired geometry may be frozen.

Evaluated over all 20 scenarios the number of missed detections/exclusions shall [GPS 328] be less than the 47. The number of trials for detection and exclusion verification is $40 \times 1650 = 66{,}000$.

TABLE R-6 REQUIRED NUMBER OF TRIALS FOR EACH FAILURE MODE

Failure Type	Number of trials for each failure mode	Assumed MI Failure Probability in units of 10^{-5}/h/satellite
Ramp 0.01-0.05 m/s	114	2/29
Ramp 0.05-0.25 m/s	57	1/29
Ramp 0.25-0.75 m/s	170	3/29
Ramp 0.75-2.5 m/s	569	10/29
Ramp 2.5-5.0 m/s	683	12/29
Step 300-700 m	57	1/29

R.5.6.2.1 Examples

R.5.6.2.1.1 RAIM with Transient Detection/Exclusion

The off-line missed detection/exclusion rate verification is to be performed in time-space points where HPL (HEL) < HPL_{RAIM} (HEL_{RAIM}). HPL (HEL) is solely determined by the inertially aided transient exclusion mechanism. Twenty different geometries must be identified and 1650 trials must be performed for each geometry. The failure ramp and the change in geometry must be coordinated so that the desired HPL (HEL) would have been exceeded if detection/exclusion had not occurred. The number of missed detection (exclusion) must be less than or equal to 47.

Note: The transient detection is not effective for slow ramps. This test example would illustrate the outcome of the test in which the integrity enhancement is not meeting the requirements.

R.5.6.2.1.2 Solution Separation Detection and Exclusion

In the regions where this method is claiming no more than snapshot RAIM performance and provided that any transient detection mechanism is disabled, the same method that is used for RAIM verification is also applicable to this method. As the 40 geometry cases are chosen observe that:

a) The geometry may remain fixed through out the test (see Section 2.3.7.3.1)

b) The geometries that reflect a range of HPL/HEL values shall [GPS 329] be chosen based on the solution separation HPL/HEL (HPL_{solsep}/HEL_{solsep}) and not the RAIM related HPL_{raim} (HEL_{raim}).

In the regions where additional performance over RAIM is claimed, the algorithm must be tested separately by choosing 20 geometries each for detection and exclusion that tests detection/exclusion in situations where HPL_{solsep} (HEL_{solsep}) < HPL_{raim} (HEL_{raim}). For solution separation these regions are referred to as RAIM holes. This means that HPL_{raim} (HEL_{raim}) changes from a HPL_{raim} (HEL_{raim}) that meets the horizontal alert limit (HAL) initially, but due to a loss of a critical satellite, subsequently moves to a higher level (above HAL). Each failure ramp and the change in geometry must be coordinated so that the desired HPL_{solsep} (HEL_{solsep}) would have been exceeded if detection/exclusion had not occurred. The 20 integrity limits HPL_{solsep} (HEL_{solsep}) are chosen in the interval specified in Section 2.3.7.3.2.

R.5.6.2.2 Reference RAIM Models

All example integration methods that provide a HPL output presented in this appendix are associated with a specific snapshot RAIM method. For example, the solution separation technique can also be used as a snapshot RAIM method. The associated RAIM algorithm is the solution separation based RAIM. This method has been proved to be equivalent to the parity space based RAIM using a Gaussian discriminator in Reference 1. The extrapolation method is using $\chi 2$ residual statistics as described in Reference 2 and the corresponding RAIM algorithm using $\chi 2$ statistics and the slope concept, has been shown to be equivalent to parity space and range comparison techniques in reference 3.

For pressure altitude calibration aiding, the reference is provided in Appendix G. The RAIM algorithm used as a reference shall [GPS 330] be tested according to Section 2.3.7.

R.5.6.3 Integrity Coasting

If claims of integrity coasting are made, validation shall [GPS 331] be performed for the false alert rate, missed alert probability and failed exclusion probability during GPS outages.

For validation of the false alert rate, a minimum of two coasting geometries shall [GPS 332] be evaluated. Each coasting geometry shall [GPS 333] include the same number of samples as each geometry within Sets 1 and 2 (Sets 1 and 2 are defined in Section 2.3.7.3.2) for the offline false alert test. A coasting geometry requires that enough satellites have been removed such that the system is in an integrity coasting mode. The total number of false alerts within each coasting run shall [GPS 334] be less than or equal to 3. The additional coasting geometries shall [GPS 335] be combined with the false alert results corresponding to R.5.3 by substituting for the geometries within Sets 1 and 2 that had the lowest number of false alerts. After substituting the coasting geometries into the results for Sets 1 and 2, the total number of false alerts shall [GPS 336] be less than or equal to 47.

For validation of the missed alert and failed exclusion probabilities, a minimum of two coasting geometries shall [GPS 337] be evaluated. Each coasting geometry shall [GPS 338] include 1650 trials. A coasting geometry requires that enough satellites have been removed such that the system is in an integrity coasting mode. In general, integrity coasting implies dropping to fewer than five measurements available, but all measurements except altitude must be dropped in this test. For each coasting geometry, the satellite error injection shall [GPS 339] be timed such that detection of the error occurs while the system is in the coasting condition. This verifies that the system can detect/exclude latent failures. The additional coasting geometries shall [GPS 340] be combined with the RAIM Equivalent results corresponding to R.5.6.1 via the following:

a) Substitute the coasting geometries for the geometries within Set 1 that had the lowest number of missed alerts.

b) Substitute the coasting geometries for the geometries within Set 2 that had the lowest number of failed exclusions.

After substituting the coasting geometries into the results for Set 1, the total number of missed alerts shall [GPS 341] be less than or equal to 47. After substituting the coasting geometries into the results for Set 2, the total number of missed alerts and failed exclusions shall [GPS 342] be less than or equal to 47.

R.5.7 On-Line Validation

The on-line validation for tightly integrated GPS/inertial systems follows the guidelines in Section 2.3.7.5. If the off-line simulation is not performed on the target processor using the same software used in the equipment, 40 satellite failure scenarios shall [GPS 343] be run using the off-line simulation and the on-target software and the result evaluated according to Section 2.3.7.5.1. The 40 scenarios shall [GPS 344] be chosen so that all types of detection/exclusion mechanisms subject to off-line testing are represented. The Behavioral test in Section 2.3.7.5.2 shall [GPS 345] be performed as stated but the number of failure scenarios shall [GPS 346] be 5 per detection/exclusion mechanisms.

R.5.8 Gravity Compensation Validation

Gravity disturbances occur because the earth's actual gravity vector does not match that generated from the WGS-84 geoid. Models such as Earth Gravity Model EGM 96 and EGM2008 developed and released by the NGA provide the data necessary to compensate for gravity disturbances and are considered valid for the purpose of GPS/inertial integration. The accuracy of the compensation depends upon the fidelity of the gravity model (i.e. the degree and order of the spherical harmonics implementation of EGM). Even after full compensation there will be residual gravity disturbance errors.

The validation strategy for performance claims related to the effect of gravity disturbances is to exercise the system mechanization in a Monte Carlo evaluation against random gravity disturbances representing the residual errors. The random gravity disturbance model will be generated from valid models of the earth gravity field.

Typically gravity disturbance errors are non Gaussian in nature. The statistical model shall [GPS 347] over-bound the tails of the residual error distribution.

A variety of models are acceptable including those based on Attenuated White Noise (AWN) and Gauss-Markov processes. The key element of the test is that the model used should represent the statistics of the residual gravity disturbances after the integrated system has performed its compensation. The Gauss-Markov process model is used here to illustrate the principle.

The effect of gravity disturbances can be simulated by a statistical model, one example is the Gauss-Markov Gravity Model (GMGM), which is generated from a series of medium order (2^{nd} to 4^{th}) Gauss-Markov processes.

The statistical model includes processes of varying correlation distance. In this appendix the designation M(x) denotes the reduction of the statistical model to processes with correlation distances of x or less. After compensation with the state of the art EGM there will be residual errors which can be represented by M(x) for some x.

Tightly coupled GPS/Inertial systems can be divided into two classes depending on their a priori knowledge of gravity disturbance:

Class 1 systems implement no a priori knowledge – i.e., the gravity vector is generated from the WGS 84 geoid

Class 2 systems implement some a priori knowledge – i.e., the gravity vector is generated from a truncated (reduced degree and order) version of the state-of-the-art EGM.

a) Class 2 includes those systems implementing full a priori knowledge (i.e. truncation is zero).

Tightly-coupled GPS/Inertial systems are mechanized to accommodate gravity disturbances using some combination of the following two techniques:

Deterministic Compensation (DC):

The DC technique is implemented by estimating the actual earth gravity by applying corrections derived from the EGM. The EGM compensations may be derived from the full model or from some reduced degree and order approximation. After DC the residual gravity disturbances may be validly represented by M(x) where x is determined by the level of truncation of the EGM model.

Statistical Compensation (SC):

The SC technique is implemented by adjusting the parameters of the tightly-coupled filter to overbound the degree of variation of the residual (uncompensated by DC) gravity disturbances. The SC technique may incorporate real time adjustment of the filter parameters based on a priori knowledge.

One acceptable method to test a system is to validate:

a) M(x) by subtracting the DC implementation from the full EGM (with no truncation). deriving the statistics of the residuals and comparing them with the statistics of M(x) The use of M(x) for the test is based on the assumption that the implemented DC would have removed all the lower frequency components.
b) the DC implementation values for random geographic locations versus the full EGM model
c) the performance provided by the compensation scheme by running an appropriate sequence of Monte Carlo tests against M(x).

SC mechanisms use a priori knowledge to adjust the tightly-coupled filter parameters. The testing strategy discussed above is randomized and does not permit a priori knowledge. In place of a priori knowledge, the actual output of the M(x) may be used to initiate parameter modification. Because the parameter modification is not based on the full EGM model, a suitable random process should be added to the output of the M(x) to represent the imperfections in a priori knowledge.

R.5.9 Ionospheric Error Models

R.5.9.1 Ionospheric Daily Variation

The IRI-2001 model is deterministic. The location, date, and time model inputs shall [GPS 348] be randomized to generate statistical test data that can be applied to Monte Carlo trials for missed alert, failed exclusion/compensation, and false alert/rare normal tests. The time and date should be randomized over one (eleven year) solar cycle.

R.5.9.2 Ionospheric Storms

In addition to the ionospheric daily variation modeled by IRI, recorded storm data shall [GPS 349] be used as the basis for the ionospheric component of pseudorange error in some trials. HPL shall [GPS 350] always bound position error during these trials.

Storms occurring on the following dates shall [GPS 351] be processed: 06 November 2001, 24 November 2001, 30 October 2003, and 7-8 November 2004.

Note: These dates represent worst-case storms in recent history where ionospheric data is available. Manufacturers should analyze their equipment for sensitivity to these effects, and include proper design margin to cover future, larger storms.

R.6 References

1. Brenner, M., 1995, "Integrated GPS/Inertial Fault Detection Availability," *Proceedings of ION GPS-95*, Palm Springs, CA, September 1995, Institute of Navigation, Alexandria, VA.
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APPENDIX S

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APPENDIX T

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APPENDIX U

GUIDANCE MATERIAL FOR INTERFACING WITH ADS-B

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U.1 Purpose and Scope

This appendix contains guidance information for interfacing equipment conforming to this standard with ADS-B equipment. However, equipment compliant with this MOPS may not satisfy the requirements for initial U.S. applications for ADS-B. Manufacturers will need to consult ADS-B position sensor performance requirements documentation to determine if their equipment provides acceptable positioning source performance.

U.2 Position Output and Validity

As required by Section 2.1.2.6, the equipment will output a position at 1 Hz with a time of applicability within 200 ms of the time of the output. A higher update rate may be provided if desired. Compensation of position from this position to the ADS-B-reported position must be accomplished by the ADS-B equipment in order to calibrate it to the time of transmission. Particular attention should be paid to any alert conditions that may be indicated through other parameters or flags on the interface. When RAIM detects a failure that cannot be excluded, ADS-B equipment should set the position output to invalid rather than adjusting another parameter since there is a position error that is unbounded.

U.3 Horizontal Figure of Merit ($HFOM_P$)

As required by 2.1.2.6, the equipment will output the $HFOM_P$ (defined in 1.7.2) along with the position, at an update rate of at least 1 Hz. The $HFOM_P$ only describes the fault-free accuracy and does not consider non-normal events such as anomalous ionospheric conditions.

U.4 Horizontal Protection Limit (HPL)

As required by 2.1.2.6 and 2.1.1.13.1, the equipment will output HPL. The HPL_{FD} applicable to en route through LNAV approach operations)define the radius of a circle centered on the true position which contains the estimated position with a probability of $1\text{-}10^{-7}$ per hour with respect to signal-in-space failures. Failure of the avionics is not considered in defining the HPL. The equipment may always output an HPL applicable to en route through LNAV.

While the HPL is output at a minimum rate of 1 Hz, the effects of latency and time-to-alert need to be considered in the ADS-B context. The equipment has up to 8 seconds before a fault condition (error exceeding the HPL) must be detected and flagged.

When using the HPL_{FD} applicable to en route through LNAV operations it is important to recognize that the parameter has only been validated down to ~0.1 NM. While HPL values significantly smaller than this are typically output, they may not actually achieve the desired level of integrity as there are some error contributions that are no longer negligible but have not been taken into consideration (e.g., correlation of ionospheric errors across satellites).

Particular attention should be paid to any alert conditions that may be indicated through other parameters or flags on the interface. When a failure is detected, the equipment may output the HUL but this parameter should not be used for ADS-B. Some equipment may continue to output the HPL, but the HPL has no applicability once a failure is detected. ADS-B equipment should set the position output to invalid rather than adjusting another parameter.

U.5 Velocity

As required by Section 2.1.2.6, the equipment will output an estimate of velocity. This estimate may be derived a number of different ways, from measurement of change in carrier phase to a difference of successive position solutions. Appendix F defines a recommended method of determining the velocity estimate and a velocity figure of merit. Section 2.1.2.6.5 contains optional requirements on the velocity accuracy for equipment intended to support ADS-B.

U.6 Vertical Figure of Merit and Vertical Protection Limit (VPL)

The equipment is not required to output vertical Figure of Merit, or VPL. When integrating with ADS-B, the integrator should make no assumptions of the validity of output vertical parameters without additional data from the manufacturer. It is significant to note that there are no industry conventions for defining a VPL that has the same interpretation as the HPL for en route through LNAV.