X. GNSS Performance Characteristics Relevant to ADS-B

This section contains information regarding ADS-B performance provided by GNSS. Because performance strongly depends on user equipment characteristics, information regarding GNSS UE ADS-B performance is included. Information is provided in the following areas:

- Which performance characteristics needed for ADS-B Out service are required to be met by existing types of GNSS user equipment
- Information regarding the information output by GNSS user equipment (e.g., rate of output, meaning of data, time of applicability, and delay of information output) relevant to ADS-B service.
- Availability and continuity of ADS-B Out service and other ADS-B services
- Other topics

X.1 Comparison of Performance Characteristics Needed for ADS-B and Minimum Requirements of Existing Types of GNSS User Equipment

ADS-B service may be provided by several types of GNSS-based user equipment (UE) that exist now or will exist in the future. Types of GNSS UE that currently exist or will exist in the near future and may be used for ADS-B Out service are as follows:

- GPS UE that meets the standards of RTCA/DO-208 [1] as modified by FAA TSO-C129 [2] or C129a [3]
- GPS UE that meets the standards of RTCA/DO-316 [4] and FAA TSO-C196 [5]
- SBAS/GPS UE that meets the standards of RTCA/DO-229C [6] and TSO-C145a [7] or C146a [8]; or of RTCA/DO-229D [9] and TSO-C145b [10], C146b [11], C145c [12], or C146c [13]

GBAS/LAAS UE [14] might also be used for potential future ADS-B applications on the airport surface and in the terminal area, but its coverage does not extend throughout en route airspace.

Existing GPS UE installed on air carrier aircraft was approved using the Type Certification (TC) or Supplemental TC (STC) process and was not approved using the TSO process in many cases. However, the equipment meets most or all of the requirements of one or more of the above TSOs.

FAA Advisory Circular (AC) 20-165 [15] provides guidance for the installation and airworthiness approval of ADS-B Out systems in aircraft. Existing GNSS equipment that meets one or more of the above standards [1-13] does not necessarily support all performance characteristics specified in AC 20-165. RTCA Special Committee 159 conducted a gap analysis that compared the requirements of GPS and SBAS UE equipment to the performance characteristics of AC 20-165. The results are in the form of tables that describe, for each performance characteristic in AC 20-165, whether the characteristic is required to be supported by each type of GPS or SBAS UE. In addition, if the characteristic is not required to be supported, a verification method is described to indicate how a manufacturer may demonstrate that a given model of equipment supports the performance characteristic in AC 20-165. These tables are expected to be approved at the SC-159 plenary meeting on 18 November 2011.

Note: AC 20-165A is in preparation and will supersede AC 20-165.

X.2 Information Regarding Information Output by GNSS User Equipment Relevant to ADS-B Service

Guidance information for interfacing SBAS UE with ADS-B equipment is contained in Appendix U of DO-229D[1]. Similar guidance information for interfacing TSO-C196 UE with ADS-B equipment is contained in Appendix U of DO-316. This ADS-B MASPS does not contain all information in Appendix U of DO-229D or DO-316. However, a few examples of information from those documents are given below in order to illustrate the types of information contained in them:

- Integrity information output by SBAS UE is in the form of a Horizontal Protection Level (HPL) and a separate alert indication. When SBAS UE is operating in en route, terminal, or LNAV mode, the integrity assurance function can be provided either by SBAS-provided integrity information or by the Receiver Autonomous Integrity Monitoring (RAIM) fault detection (FD) or fault detection and exclusion (FDE) function. In the former case the HPL is called HPL_{SBAS}, and in the latter, HPL_{FD}. The presence of a RAIM-detected alert condition that cannot be excluded (i.e., HPL_{FD} is not assured to bound horizontal position error with the required probability) is not reflected in the size of HPL_{FD}. Instead, the alert condition is reflected in a separate alert flag or parameter output by the UE, which must be used by ADS-B equipment to set the position output to "invalid".

[1] Note that although Section U.1 of DO-229D states that all classes of equipment compliant with DO-229D are expected to satisfy the requirements for initial U.S. applications of ADS-B, a few requirements in AC 20-165 (e.g., Integrity Validity Limit, Velocity Accuracy, output of Height Above Ellipsoid, and others) are not minimum requirements of DO-229D or DO-316 UE. The matrices referred to in Section X.1 of this MASPS describe the requirements gaps.

- SBAS UE may not indicate whether the HPL that is output is HPL_{SBAS} or HPL_{FD}. But when in en route through LNAV modes, both HPLs bound horizontal radial position error with a probability of $1 - 10^{-7}$ per hour.

- When SBAS UE is in LNAV/VNAV, LPV, or LP mode, the HPL that is output bounds horizontal position error (HPE) with a probability of $1 - 2 \times 10^{-7}$ per approach, where an approach duration is assumed to be 150 seconds. SBAS UE may not provide an indication of the mode. If no mode indication is provided, then ADS-B equipment may multiply HPL by 1.03 in order to account for the possibility that SBAS UE is in LNAV/VNAV, LPV, or LP mode, and ensure that the HPL bounds HPE with a probability of $1 - 10^{-7}$ per hour.

- The "time of applicability" associated with the position output will be within 200 ms of the time of the output. An aircraft flying, for example, 250 kts groundspeed travels about 26 meters in 200 ms, which might be significant for some applications. Compensation of position from this position to the ADS-B position must be accomplished by the ADS-B equipment.

- The latency (delay) in HPL reflecting a fault condition for en route through LNAV flight can be as much as 8 seconds.

- When RAIM FD is used to assure integrity, DO-229D and DO-316 UE might output an HPL that is less than 0.1 nautical miles (NM), but if SBAS ionospheric corrections and associated error bounds are not applied (always true for DO-316 UE), the HPL is not assured to bound HPE with a probability of $1 - 10^{-7}$. This is because the ionospheric error model associated with the use of GPS single-frequency ionospheric corrections has not been validated to levels below about 0.1 NM.

Information similar to that provided in Appendix U for DO-229D and DO-316 UE has not been compiled for TSO-C129/129a UE. Principal differences between DO-316 UE and equipment complying with only the minimum requirements of TSO-C129 or C129a are listed in the gap matrices referred to in Section X.1 and in the next section, Section X.3.

X.3 ADS-B Availability and Continuity Provided by GNSS User Equipment

The level of availability and continuity of ADS-B Out service experienced by GPS user equipment depends strongly on certain GPS and SBAS performance characteristics [16, 17, 18]. The U.S. government commitment on GPS constellation performance is described in the GPS Standard Positioning Service (SPS) Performance Standard (PS) [19]. Key performance commitments are in the following areas:

- Availability: the number and orbital locations of useable (operational-healthy) GPS satellites. The GPS SPS PS assures that at least 21 of 24 defined orbital plane/slot position will be filled with operational-healthy (useable) satellites (or, when the constellation is in an expanded slot configuration, satellite pairs) with a probability of at least 98%. The PS also assures that at least 20 of 24 defined plane/slot positions will be filled with operational-healthy satellites (or, in an expanded slot configuration, satellite pairs) with a probability of at least 99.999%. (The PS further states that the probability that the constellation will have at least 24 operational satellites is at least 95%, but those satellites may not be useable, and may not be in defined plane/slot positions.)

- Continuity: the probability of an unpredicted satellite signal outage. The SPS PS assures that the average probability of not losing a useable satellite signal due to an unscheduled failure is at least 0.9998 over any hour, given that the satellite signal is available at the beginning of the hour. This is equivalent to a 5000 hour mean time between unscheduled outages of a given satellite. An earlier 2001 version of the SPS PS states that the historical frequency of unscheduled "downing events" was 0.9 per satellite per year, equivalent to a 9700 hour mean time between unscheduled outages. The most recent PS contains no commitment on the probability of not losing a satellite signal due to an unscheduled maintenance action, but no such events are known to have occurred. An outage is unscheduled if it is not announced in a Notice Advisory to Navstar Users (NANU) at least 48 hours in advance. Any loss of a useable signal exceeding 10 seconds is considered an outage.

  GPS Block IIA satellites are known to experience a loss of useable signal of one satellite in the entire constellation for a period of 6 seconds about once every month or two, during uploads. Such events have not been observed on Block IIR, IIR-M, or IIF satellites and are not expected to occur on future satellites.

- Signal-in-space (SIS) user range error (URE) accuracy. The SPS PS assures that the root-mean-square (RMS) satellite pseudorange data set error will be less than or equal to 4 meters. Ionospheric error, the largest source of error for SPS users, is not counted in this commitment. In recent years, the actual GPS SIS RMS error (excluding ionospheric error) is less than 1 m.

  Ionospheric error at the GPS L1 frequency is generally small (a few meters or less), but during ionospheric storms near the maximum of the 11-year solar cycle, ionospheric range delay experienced by users within about 30 degrees of earth's magnetic equator to satellites at low elevation angles can be approximately 150 meters. The GPS single-frequency ionospheric correction model is likely to correct 50% or more of the error.

- SIS user range rate error (URRE) accuracy. The SPS PS assures that the 95% global average user range rate error over any 3-second interval during normal operations will be less than or equal to 0.006 meters/second for operational-healthy satellites. Ionospheric error is excluded.

Note that these commitments are stated in the range domain, whereas what is of interest to ADS-B users is performance in the position domain, e.g., availability of a NIC of 7 or of a NACp of 8.

The US government commitment on WAAS performance is described in the WAAS Performance Standard [20]. Performance is described in the position domain for phases of flight including en route, terminal, LNAV, and LPV service in each of five Zones. Examples of WAAS performance commitments include an availability of 99.999% and continuity of $1 - 10^{-5}$ per hour for a HAL of 0.3 NM in CONUS. No defined level of WAAS service corresponds exactly to a NIC of 7 or a NACp of 8.

The providers of other GNSS core constellations (e.g., GLONASS, Galileo) or other SBASs (e.g., MSAS, EGNOS) have not yet published Performance Standards.

Besides depending strongly on GPS and SBAS performance, the level of availability and continuity of ADS-B Out service also depends strongly on the characteristics of GNSS UE. For the purpose of this subsection, GNSS UE may be grouped into three main categories, with availability and continuity characteristics being similar with each category:

- The first category is "SA-unaware" GPS UE. Selective Availability (SA), an intentional degradation of GPS range and position error, was set to zero by the US Department of Defense on May 1, 2000. However, some GPS UE on existing aircraft still use RAIM algorithms that are based on the assumption that SA is "on". TSO-C129/129a UE RAIM algorithms are commonly based on the assumption that SA is "on" and that the standard deviation of GPS pseudorange error is large (33.3 meters). The consequence is that RAIM availability is significantly lower for such equipment compared to the other categories of GNSS UE. Figure X-1 shows the availability of a NIC of 7 (HAL = 0.2 NM) for a particular set of assumptions on GPS constellation satellite performance; estimated average availability of a NIC of 7 is less than 90% in many US locations. The assumptions on GPS constellation performance are consistent with the US government commitment on GPS constellation performance in the GPS SPS PS [19] described above. Historical GPS constellation performance has far exceeded the minimum commitment in the GPS SPS PS, but there is no assurance that future constellation performance will continue to be as good as historical performance. The results shown are based on a 2° user equipment mask angle.

TSO-C129 and C129a UE is not required to have the receiver autonomous fault exclusion function. If a GPS integrity anomaly occurs during flight, TSO-C129/129a UE may declare a RAIM alert and be unable to exclude the malfunctioning satellite's range measurement from the user position solution. Aircraft with TSO-C129/129a user equipment are required to have another means of navigation. However, the other means of navigation may not support ADS-B Out requirements. Thus, the aircraft may need to revert to backup procedures when in ADS-B airspace. According to the 2008 GPS SPS PS, approximately 3 GPS integrity anomalies may occur in the entire constellation per year on average. Because approximately one-third of the satellites are in view of a given user location at any given time, such an event might occur about once per year. All aircraft that have TSO-C129/129a UE and that are using the faulty satellite may experience an unexcludable fault at the same time. A frequency of once per year is equivalent to a probability of about 1.1×10^{-4} per hour.

- The second category of GNSS UE is "SA-aware" GPS UE. A majority of GPS UE on existing air carrier aircraft and DO-316 UE takes advantage of the fact that SA has been set to zero, and consequently experiences higher availability than "SA-unaware" GPS UE. DO-316 is also required to have the fault exclusion function, and other "SA-aware" GPS UE also has it. Figure X-1 shows that under a GPS constellation assumption consistent with the US government commitment in the GPS SPS PS, averaged estimated availability be between 99% and 99.9% in the U.S. Estimated availability is significantly higher if the GPS constellation performance is consistent with historical levels. But as stated previously, future GPS constellation performance may not be consistent with historical levels. The results shown are based on a 2° user equipment mask angle.

- The third category of GNSS UE is SBAS UE. SBAS UE provides significantly increased availability compared to GPS UE in areas of SBAS coverage, if other factors are equal. This is because the SBAS integrity assurance function requires only 4 SBAS-monitored ranging sources. In contrast, GPS UE requires the use of the RAIM function detection function to assure integrity, which requires a minimum of 5 ranging sources. In addition, SBASs provides clock, ephemeris and ionospheric corrections, which reduce error and provide service in conditions of poorer user-to-satellite geometry (dilution of precision). Furthermore, some SBAS (WAAS and MSAS) geostationary satellites provide a GPS-like ranging function, reducing dependence on GPS. Estimated average WAAS availability is shown in Figure X-1 and exceeds 99.99% in the U.S. Results are based on the following assumptions:

  – GPS constellation performance assumptions are the same as for the other availability analyses.

- It is assumed that two WAAS geostationary satellite is operating; currently WAAS has three geostationary satellites.

- Results are shown for SBAS Class 1 UE that does not apply WAAS ionospheric corrections, but instead uses the GPS single-frequency ionospheric correction model. Estimated availability would be significantly higher for WAAS UE that applies WAAS ionospheric corrections.

- UE has a 2° mask angle.

Results are not shown for the range of GNSS UE characteristics that have a significant effect on availability. Availability is significantly smaller for UE with a higher mask angle such as 5° or 7.5°.

Other equipment characteristics that vary across UE are the presence of barometric altimeter aiding and whether UE uses carrier smoothing to reduce pseudorange noise and multipath. Barometric altimeter aiding significantly improves availability for HALs larger than the value of 0.2 NM associated with a NIC of 7, but the effect is not as significant for a HAL of 0.2 NM. The use of smaller airborne multipath and noise error models associated with carrier smoothing has little effect on availability of a HAL of 0.2 NM. However, carrier smoothing may have a large effect on the availability of a NAC of 9 or 10 required for certain potential future ADS-B applications [21, 22].

Comments on Availability of Accuracy (NACp)

The size of HPE provided by all types of GNSS UE is significantly smaller than 92.6 m, the 95% HPE associated with the ADS-B Out NACp 8 constraint. However, due to conservatism of the error assumed for SA in SA-unaware UE and conservatism of the ionospheric error model associated with the use of GPS single-frequency ionospheric corrections in SA-aware and minimum Class 1 SBAS UE, the horizontal figure of merit (HFOM) and equivalently, the NACp, are sometimes larger than the 95th percentile of HPE (under conditions of poor user-to-satellite geometry). Of the various MOPS, only DO-253A specifies a method of computing HFOM. It is possible that future versions of DO-229 or DO-316 ma specify an optional less conservative method of computing HFOM than using the conservative ionospheric error model developed for the high-integrity navigation application.

X.4 Other Topics

Vulnerability to Radio Frequency Interference (RFI)

GNSS signals are vulnerable to radio frequency interference (RFI). RFI could affect a significant number of aircraft simultaneously, depending on the height and power of the interferer.

Future GNSS User Equipment

The types of UE described in Refs. 1-13 are sometimes referred to as "single-frequency" because they use only the L1 signal broadcast by GPS and SBAS satellites. The center frequency of the L1 signal is 1575.42 MHz. Some future GNSS user equipment is expected to use not only the L1 signal broadcast by current satellites, but also the L5 signal broadcast by two recently launched and all future GPS satellites and by many future SBAS satellites. The center frequency of the L5 signal is 1176.42 MHz. The use of signals at two frequencies will enable GNSS UE to solve for and virtually eliminate ionospheric delay from GNSS satellite measurements, increasing availability. The second frequency will also provide service in case of radio frequency interference (RFI) affecting only a single frequency.

Future types of GNSS UE that may support ADS-B including the following:

- Dual-frequency GPS UE
- Dual-frequency GPS/Galileo UE
- Dual-frequency SBAS/GPS/Galileo UE
- UE using the Chinese COMPASS, Russian GLONASS, Indian INRSS, or Japanese QZSS systems

Lack of a Validated Error Model for the Airport Surface

DO-323 states that the NACp for the SURF IA application shall be derived from the HFOM output by user equipment. The HFOM output by GNSS user equipment is derived using a multipath error model that was validated for airborne flight. Multipath for ground applications is generally larger than in flight. During flight, small changes in aircraft attitude tends to cause multipath error to change quickly and average out when carrier smoothing is done. In addition, the path length of the reflected signal tends to be smaller in flight than on the ground. A ground multipath error model should be developed and validated.

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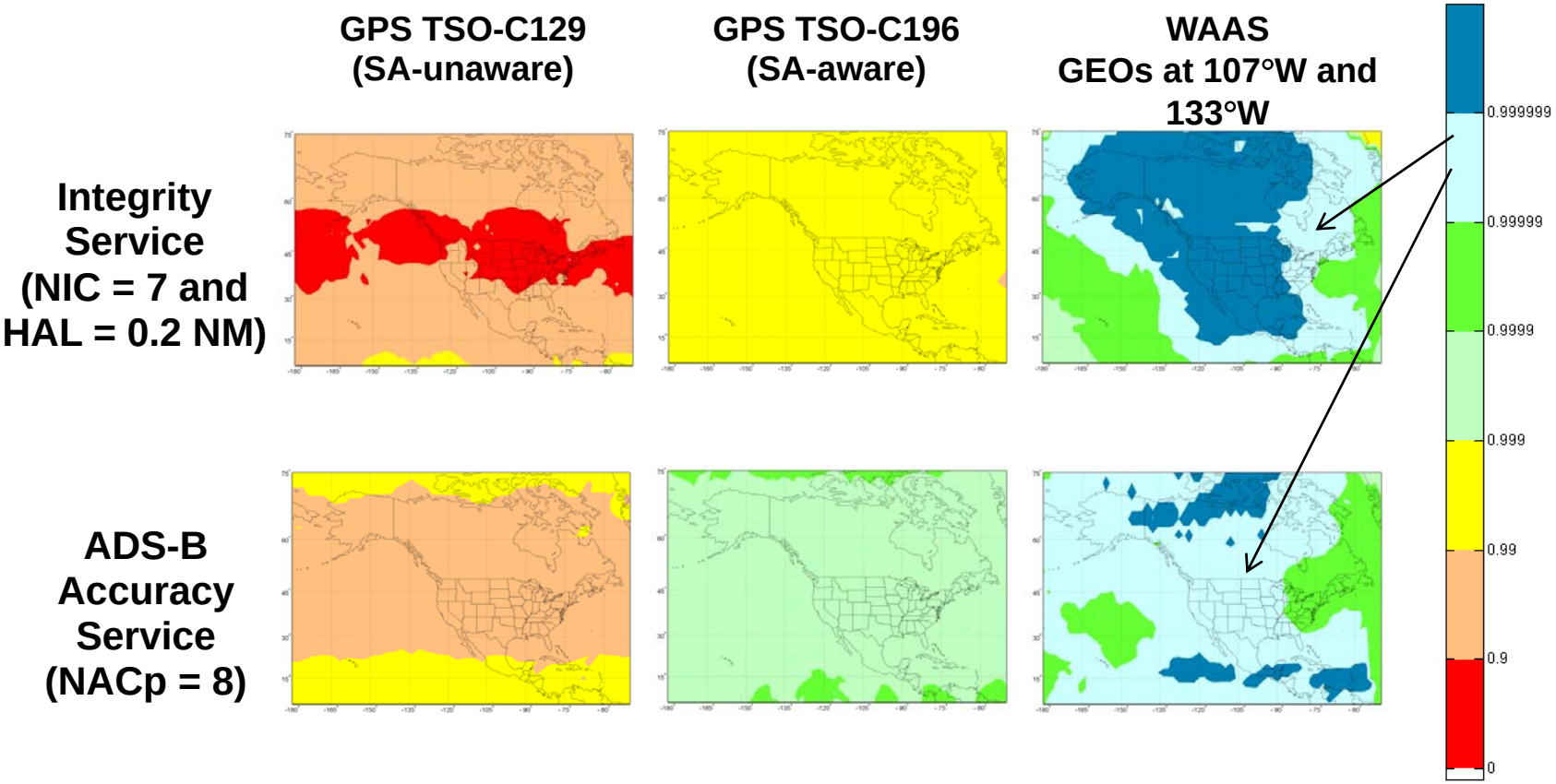

Figure X-1. Average Estimated Availability of NIC 7 and NACp 8 for Three Types of GNSS User Equipment Given a 2° User Equipment Mask Angle and GPS Constellation Performance Consistent with the GPS Standard Positioning Service (SPS) Performance Standard (PS)