EU-US Cooperation on Satellite Navigation

Working Group C

COMBINED PERFORMANCES FOR SBAS RECEIVERS USING WAAS and EGNOS

Final version

July 19, 2010

The technical information contained in this note does not represent any official US Government, FAA, EU or EU Member States position or policy. Neither organization from the US or the EU makes any warranty or guarantee, or promise, expressed or implied concerning the content or accuracy of the views expressed herein.

Executive Summary

The US-EU Agreement on GPS-Galileo Cooperation signed in 2004 laid down the principles for the cooperation activities between the United States of America and the European Union in the field of satellite navigation. In particular, the work undertaken by Working Group A has lead to an interoperable and compatible signal design for the GPS and Galileo systems.

The Agreement also foresaw "a working group to promote cooperation on the design and development of the next generation of civil satellite-based navigation and timing systems", which is the focus of Working Group C.

This note has been prepared as part of the Working Group C activities, with the purpose of ensuring interoperability of Space-Based Augmentation Systems (SBAS), as provided by the EU through the European Geostationary Navigation Overlay System (EGNOS) and the US through the Wide Area Augmentation System (WAAS). This work is also intended to complement analysis of the interoperability of open service capabilities of GPS and Galileo.

SBAS was developed to meet the rigorous requirements of safety-of-life applications. Key among those user requirements has been the aviation community, whose high integrity requirements are among the most demanding. This paper assesses the performance achieved by an SBAS receiver for several SBAS-supported aviation applications as provided by current versions of the SBAS systems. The analysis assumes a receiver qualified to the minimum performance standards for an aviation-quality SBAS receiver.

This study has confirmed that the combined performance of EGNOS and WAAS provide excellent availability and coverage throughout Europe and the US, while also improving performance in other portions of the globe as the SBAS signals cover the majority of the earth. The results confirm that the combined performance of WAAS and EGNOS provides coverage over a significant portion of the globe, with a fully interoperable capability. The improvements of SBAS, as compared to GPS alone, are greatest for tighter performance requirements and when the GPS constellation is degraded in any capacity (an orbital slot without a healthy and transmitting signal). The results also show the effects of a geostationary satellite ranging signal in improving performance throughout the satellite footprint.

Working Group C also promotes the interoperability of WAAS and EGNOS. In addition to the safety-of-life applications, these services are already in use by millions of open-service receivers as a means to augment the performance and availability of GPS. The performance for these users has not been evaluated in this paper, as there are no user receiver standards upon which to base assumptions for the analysis.

This technical note has been prepared by the Working Group C with the Federal Aviation Administration, European Space Agency and Mitre Corporation as main contributors.

TABLE OF CONTENTS

List of Figures

1 INTRODUCTION AND PURPOSE

The US-EU Agreement on GPS-Galileo Cooperation signed in 2004 laid down the principles for the cooperation activities between the United States of America and the European Union in the field of satellite navigation. In particular, the work undertaken by Working Group A has lead to an interoperable and compatible signal design for the GPS and Galileo systems.

The Agreement also foresaw "a working group to promote cooperation on the design and development of the next generation of civil satellite-based navigation and timing systems", which is the focus of Working Group C.

This note has been prepared as part of the Working Group C activities, with the purpose of ensuring interoperability of Space-Based Augmentation Systems (SBAS), as provided by the EU through the European Geostationary Overlay System (EGNOS) and the US through the Wide Area Augmentation System (WAAS). This work characterizes the performance offered by the current versions of SBAS (i.e. single frequency GPS augmentation, GEO ranging capability offered by WAAS but not by EGNOS, etc.) A trade-off analysis of the performance provided to GPS/SBAS receivers as compared to GPS/RAIM only receivers is provided as well. Finally, this work is also intended to complement analysis of the interoperability of open service capabilities of GPS and Galileo.

SBAS was developed to meet the rigorous requirements of safety-of-life applications. Key among those user requirements has been the aviation community, whose high integrity requirements are among the most demanding. This paper assesses the performance achieved by an SBAS receiver for several SBAS-supported aviation applications. The analysis assumes a receiver qualified to the minimum performance standards for an aviation-quality SBAS receiver.

The main focus of the discussion is set on navigation service availability, which can be briefly defined as follows in non-technical terms: service is available when (and only when) the integrity of the navigation solution meets the requirements of the flight operation for which navigation guidance is desired.

Section 2 presents an overview of SBAS and the receiver considered in the study, the environmental assumptions (ionosphere, troposphere, and multipath) and the GPS, WAAS and EGNOS constellation assumptions. Section 3 defines the performance metrics, describes the process followed to obtain them, and presents the simulation results. Section 4 presents the conclusions. The document is completed by some appendixes which provide the required background to understand the assumptions and the process followed.

This technical note has been prepared by the Federal Aviation Administration, the European Space Agency, and the MITRE Corporation.

1.1 SBAS Overview

The SBAS concept was initially developed to provide service to aviation over wide areas (e.g., continental areas) because navigation solutions derived from GPS alone did not provide the level of integrity required for flight operations. In addition to providing integrity information on GPS satellites, current SBAS implementations also provide corrections to improve the accuracy of ranging measurements from GPS satellites, and thereby improve the accuracy of the navigation solution. SBAS correction and integrity information is broadcast to the users from geostationary earth orbiting (GEO) satellites using a signal structure similar to that of the GPS civil (Coarse Acquisition, C/A) signal on the GPS L1 frequency. This design choice makes it possible for SBAS GEOs to operate as additional ranging sources, and current SBAS implementations either already provide this additional functionality, or plan to provide this additional functionality in a future system upgrade. A further consequence of this design choice is that SBAS User Equipment (UE) uses the same antenna as GPS UE, which minimizes the amount of retrofit work needed in order to upgrade an existing installation from GPS UE to SBAS UE.

Three SBAS implementations are currently operational: the Wide Area Augmentation System (WAAS) from the US, the European Geostationary Navigation Overlay System (EGNOS) from the EU, and the MTSAT Satellite Augmentation System (MSAS) from Japan[1]. A fourth SBAS implementation, the GPS-Aided and GEO-Augmented Navigation System (GAGAN) from India, is in a later stage of development. A fifth SBAS implementation, the Russian Wide Area Augmentation System (SDCM) is currently in an early stage of development.

1.2 SBAS Interoperability

The ICAO Standard and Recommended Practices (SARPs) in Annex 10 [1] provide high-level requirements ensuring the safety and interoperability of SBAS implementations from different Air-Navigation Service Providers (ANSPs). However, SBAS implementations are complex systems with multiple layers of requirements. Therefore, several international forums have been created for ANSPs to address issues raised by potentially different interpretations, or implementations, of requirements, and resolve these issues so as to ensure the highest possible level of assurance in the safety and interoperability of the different implementations. One of these forums is the well-established SBAS Inter-operability Working Group (IWG). In this context, the close coordination between the US and EU implementation programmes has enabled to establish clear guidelines for the interpretation of standards.

1.3 Basic SBAS Architecture

The basic SBAS architecture comprises a set of ground reference stations distributed across the main service area, one or more master stations, one or more satellite uplink stations, one or more geostationary earth orbiting satellites (GEOs), and a communication network linking the various ground components. The reference stations continuously collect ranging and information data from all GPS satellites in view and transmit that information to the master stations. Using that information as well as the surveyed positions of reference station receiving antennas, the master stations compute corrections and integrity information, format the information in a set of pre-defined messages, and transmit that information to the uplink stations. The uplink stations modulate the messages on uplink signals and transmit these signals to navigation payloads on the GEOs. The navigation payloads then broadcast the augmentation signals (at the GPS L1 frequency) to the users. The uplink stations also drives the timing of the

[1] Currently, two of these SBAS implementations (WAAS and MSAS) have been commissioned for Safety-of-Life (SoL) applications; the third SBAS implementation (EGNOS) is currently operational for non-SoL applications, but it is undergoing certification and is expected to be commissioned for SoL applications by the middle of 2010.

GEO augmentation signals to allow those signals to be used as additional ranging sources. Redundancy is typically built throughout the entire system (reference receivers, master stations, communication network, uplink stations and GEOs) in order to achieve a high continuity performance as well as high system reliability.

1.4 SBAS Services

SBAS has the ability to support navigation in all phases of flight from en route navigation to vertically guided approach procedures with a Decision Height as low as 200 ft above runway threshold, in other words procedures that are essentially equivalent to Precision Approach Category I. This type of vertically guided approach procedure is known as Localizer Performance approach with Vertical guidance (LPV). SBAS is able to achieve the level of performance required for vertically guided approach procedures because: (1) it performs a real-time monitoring of all GPS satellites in view (and its own GEOs) as well as a real-time monitoring of the signal propagation delays caused by the ionosphere in the region of the main service area, and (2) it broadcasts satellite and ionospheric corrections and associated integrity information, which the SBAS UE uses to improve the navigation solution and compute sufficiently small integrity bounds for the navigation solution.

Airborne-Based Augmentation System (ABAS) relying on GPS and Remote Autonomous Integrity Monitoring (RAIM) (hereafter simply GPS/RAIM) is another GNSS-based navigation technology that is widely used in aviation. GPS/RAIM relies on the integrity information broadcast by GPS satellites, which has a much lower degree of assurance than SBAS integrity information, and the RAIM algorithm, which raises the integrity level of the navigation solution to meet the aviation requirement. The RAIM algorithm performs a consistency check of the position solution: it requires a sufficient number of GPS satellites in view and a favourable geometric arrangement of these satellites. Due to the performance limitations of this technical approach, GPS/RAIM is authorized for en route navigation to non-precision approach (also called Lateral Navigation or LNAV), but not for LPV[2]. Other benefits of SBAS as compared to GPS/RAIM include improved and more consistent positioning accuracy, improved continuity of service, and improved availability of service (in particular during time periods when the GPS constellation is temporarily degraded due to one or more satellite failures or to ground control segment maintenance action requiring one or more satellites to be taken temporarily out of service).

As mentioned above, each SBAS has a main service area defined as the area where it provides the highest level of service and minimum performance levels are guaranteed by the service provider. However, an SBAS also provides services well beyond its main service area; in fact it does so wherever the signals from its GEOs can be received. Such services include corrections on GPS satellites that are in common view of the user and the network of SBAS reference stations as well as additional ranging sources (from SBAS GEOs). SBAS UE can take advantage of this information in order to improve the navigation solution as compared to GPS/RAIM.

---

[2] GPS/RAIM here refers to the current single-frequency, single-constellation implementation. Whether future multi-frequency, multi-constellation GPS/RAIM designs might be able to provide LPV service is currently a subject of active research.

As a result of the improved accuracy and availability of PNT services provided by SBAS, reliance on SBAS signals-in-space has expanded well beyond the world of aviation and has penetrated into the worlds of road, rail and maritime navigation, as well as agriculture, geophysics, and many others.

1.5 SBAS Evolution

Current SBAS implementations provide services to users relying exclusively on the GPS L1-frequency signal (so-called single-frequency users), and for this reason also rely on the L1-frequency to broadcast their augmentation signals. However, improved dual-frequency services are expected to become available within the next 10 years. In fact, SBAS service providers are now drawing plans for future enhancements to SBAS in response to the modernization of the existing core constellations, GPS and GLONASS, and the planned deployment of new GNSS core constellations such as GALILEO and COMPASS. These enhancements aim at providing improved services based on dual-frequency, multi-constellation navigation solutions. This includes in particular potential future SBAS services based on augmentation of the GPS L1 and L5 signals, and possibly augmentation of the GALILEO E1 and E5 signals as well. The enhanced PNT services will provide further improvements in accuracy, availability and continuity performance. They will also be extremely robust to potential degradations of core satellite constellations, as well as environmental effects resulting from severe ionospheric storms and other disrupting ionospheric phenomena (e.g., ionospheric depletions in equatorial regions). For such new services to become reality, standards will need to be developed both for the SBAS infrastructure and for user equipment. System enhancements will need to be developed, implemented and certified. Avionics will need to be developed, certified, commercialized and installed on aircraft, and the new core constellation signals will need to be available on a sufficient number of satellites to ensure operational benefits. In addition, dual frequency SBAS will be a significant element in increasing LPV coverage beyond today’s SBAS core areas.

2 SBAS OVERVIEW

2.1 Receiver Assumptions

Two types of user equipment (UE) were considered in the analysis:

- GPS/RAIM UE compliant with the new GPS UE Minimum Operational Performance Standard (MOPS) [2].
- SBAS UE compliant with the SBAS UE MOPS [3].

Common design features were assumed for the two UE types, e.g., "all-in-view" receivers using the typical elevation mask angle of 5 degrees and identical RAIM algorithms. SBAS UE includes a RAIM algorithm to ensure that the UE will provide a navigation service at least as good as GPS/RAIM in regions of the globe where either no SBAS signal is received (e.g., over the poles), or the geometry of SBAS-corrected GPS satellites is not sufficiently good to support service using an SBAS-based navigation solution only (e.g., in the higher latitudes of the southern hemisphere). Additional inputs, which are sometimes used in some airborne implementations to further improve performance (e.g., barometric altimeter aiding and inertial reference unit aiding), were not considered in the analysis.

2.2 System Assumptions

Service availability is highly dependent on the state of the constellation. While the GPS constellation has operated with 30 or more satellites for the last few years, the commitment of the US Government regarding the maintenance of the GPS constellation is expressed as follows [4]:

- ≥ 0.957 probability that a slot in the baseline 24-slot configuration will be occupied by a satellite broadcasting a healthy signal-in-space.
- ≥ 0.98 probability that at least 21 slots out of the 24-slots will be occupied by a satellite broadcasting a healthy signal-in-space.

For this analysis, the following assumptions were agreed regarding the GPS constellation:

- 24-satellite nominal constellation.
- 28-satellite extended constellation representing a conservative approximation to the state of the GPS constellation over recent years[3].

In both cases, the state of the constellation remains constant throughout the analysis; in other words satellite outages are not assumed to occur at any time.

[3] In a few rare instances, the total number of satellites broadcasting a useable signal dropped to 28 for a few hours due to maintenance action by the GPS ground control segment.

3 PERFORMANCE

SBAS performance is typically defined from a user perspective and expressed in terms of the accuracy, availability, continuity, and integrity of the different user services supported. Minimum requirements for these different performance metrics are provided in the ICAO SARPs, not only for SBAS but for other GNSS technologies as well. As mentioned earlier, one of these other technologies is ABAS relying on GPS/RAIM. In this case, the level of integrity required for flight operations is achieved via the RAIM algorithm. Since GPS/RAIM is a very common means of navigation in aviation, including air-transport aircraft, much can be learned from comparing the service availability performance from GPS/RAIM and SBAS.

Integrity is an absolute requirement for aviation applications. Integrity is assured by the design of the RAIM algorithm in the case of a GPS/RAIM application, and by the design of the SBAS implementation (and SBAS avionics) in the case of an SBAS application. However, the final integrity check is performed by the avionics, which computes a high confidence bound on the residual error in the navigation solution and compares this bound to a pre-established tolerance to determine whether the service can be used operationally (is available). The high confidence bound in the horizontal dimension is known as Horizontal Protection Level (HPL). The pre-established tolerance to which HPL is compared is known as a Horizontal Alert Limit (HAL) to determine if a given operation can be supported.

GPS/RAIM UE computes HPL from the integrity information broadcast by GPS using the RAIM algorithm. SBAS UE computes HPL from the integrity information broadcast by SBAS using prescribed formulas. (SBAS UE can also compute HPL using the integrity information broadcast by GPS and the RAIM algorithm in regions where SBAS service is not available.) The avionics compares HPL to the HAL value established for the desired flight operation (and known to the avionics). Service is available (i.e., the flight operation can be conducted using the selected mode of navigation) if and only if HPL does not exceed HAL (i.e., HPL ≤ HAL). For flight operations that include vertical guidance such as LPV in addition to horizontal guidance, a second condition must also be satisfied: the Vertical Protection Level (VPL) computed by the UE must not exceed the Vertical Alert Limit (HAL) associated with the flight operation (i.e., VPL ≤ VAL).

Integrity being assured by design, the next performance metric of interest from an operational point of view is availability. Availability performance depends on the technology used to verify that the navigation solution has integrity (RAIM or SBAS), the state of the GPS constellation, the design of the avionics receiver, and the specific values of the HAL established for the desired flight operation. The integrity technologies, GPS constellation states, and flight operations assumed in the analysis provided in this section are briefly described in the following sub-sections.

3.1 Performance Definition

The analysis considered four different service levels defined in terms of HAL values:

- HAL = 1.0 nm
- HAL = 0.5 nm
- HAL = 0.3 nm
- HAL = 0.15 nm

These values were selected as representative of the following Required Navigation Performance (RNP) operations: RNP 1.0, RNP 0.5, RNP 0.3 and RNP 0.15. The following caveat however should be noted. RNP performance is an airframe characteristic that depends on the Total System Error (TSE), which accounts for both the Navigation System Error (NSE) and Flight Technical Error (FTE). HAL is a bound on NSE. Therefore, the RNP level and HAL value differ for some aircraft types. However, they are the same for many aircraft types, which explains the selected HAL values.

3.2 Process Description

The analysis results included in this section were obtained via simulation, modelling the behaviour of both WAAS and EGNOS under the identified assumptions. The results were aggregated to yield a comprehensive depiction of the coverage afforded by both systems.

3.3 Performance Results

A first set of results was originally produced in a joint effort by the delegations of United States (US) and the European Commission (EC) to the ICAO Navigation System Panel (NSP) [5]. This set contains worldwide availability maps showing the availability performance at each point of the maps between 70°N and 70°S for two GPS constellations with 24 (nominal constellation) and 28 satellites. A second set of results was obtained using the same original data for a degraded GPS constellation with 23 out of 24 satellites. Finally a map showing Localizer Precision with Vertical guidance (LPV) availability was generated for the 24 satellite case.

For all RNP results, the availability (probability of service) of any user location is indicated via the colour of the pixel corresponding to the location of that user. The colour scale is as shown below (1.0 indicates that service was available on all simulated epochs, i.e., no service outage obtained during the simulation).

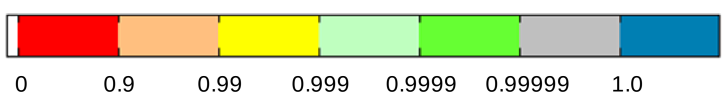

Figure 1: Service Availability Scale

LPV results use a different colour scale, which is provided with the figure showing LPV availability results.

3.3.1 Service Availability Performance with a 24-Satellite Nominal GPS Constellation

Figure 2 shows the service availability results obtained with a 24-satellite nominal GPS constellation. The results apply to single-frequency GPS/RAIM and SBAS users. The improvement is the most pronounced for the tighter performance requirements, as they are more sensitive to the geometry of GPS satellites. Over South America, the performance is enhanced by SBAS message type 28 and the ranging signals provided by the WAAS satellites (the EGNOS ranging function is currently not operational). Message type 28 provides a more precise characterization of the potential spatial decorrelation of error as observed by the ground network to positions outside the contour of the ground network.

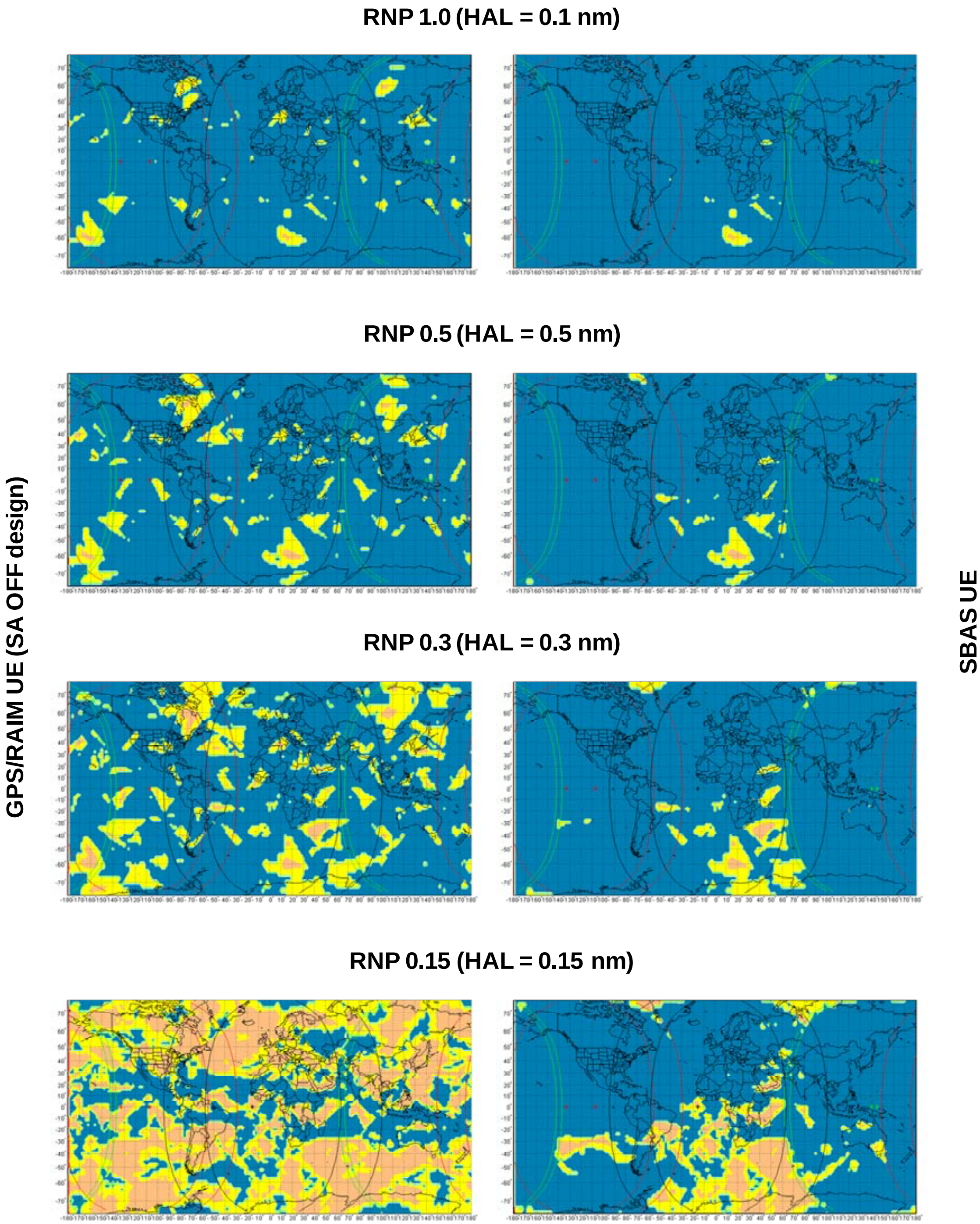

Figure 2: Service Availability Performance with a 24-Satellite Nominal GPS Constellation

3.3.2 Service Availability Performance with a 28-Satellite Extended GPS Constellation

Figure 3 shows the service availability results obtained with a 28-satellite extended GPS constellation. As with the standard 24-satellite constellation, the SBAS improvement is most significant for the tighter performance requirements. Due to the additional GPS satellites, the improvement is smaller than shown in Figure 2.

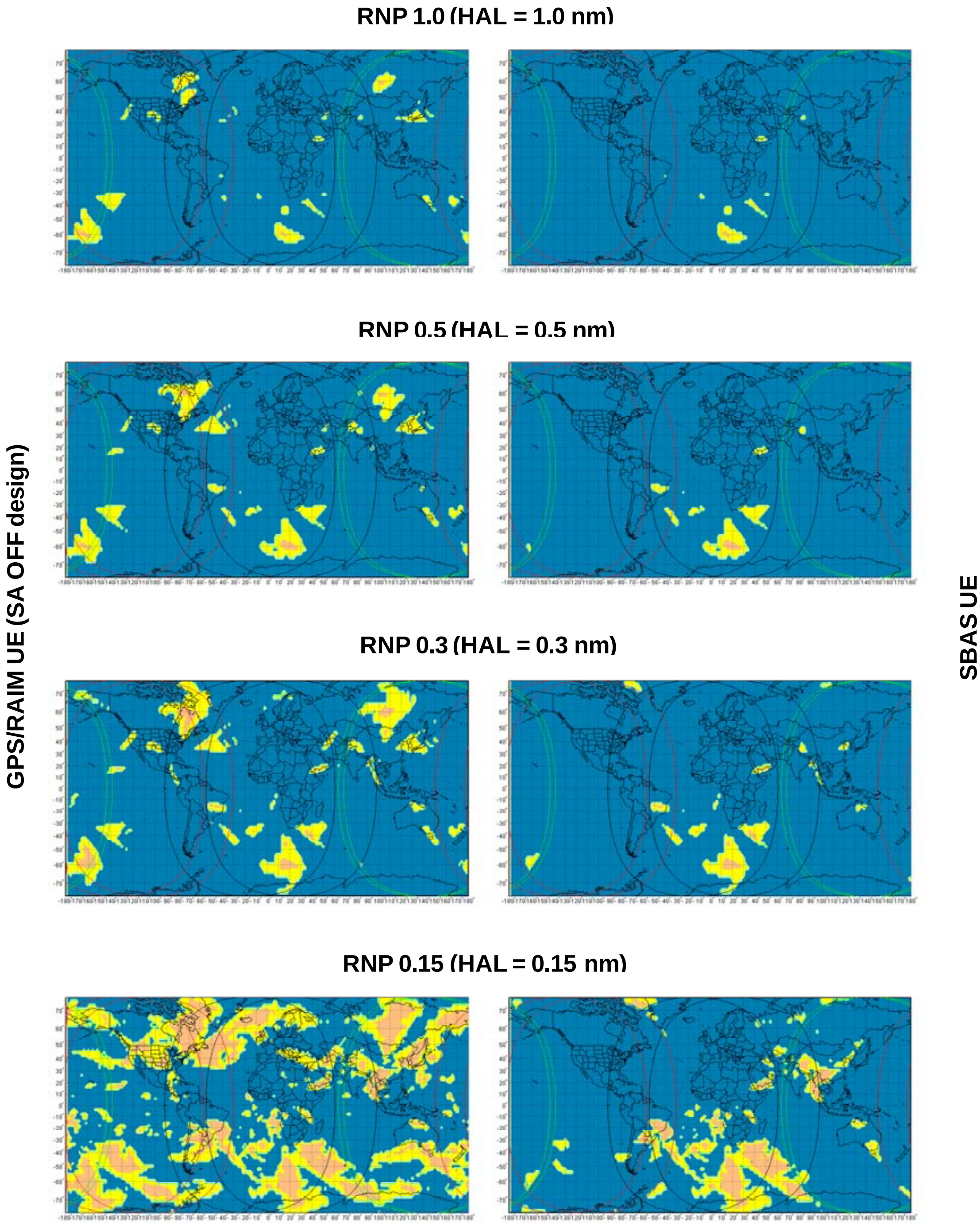

Figure 3: Service Availability Performance with a 28-Satellite Extended GPS Constellation

3.3.3 Service Availability Performance with a Degraded 24-Satellite GPS Constellation

Figure 4 shows the service availability results obtained with a degraded 24-satellite GPS constellation with only 23 satellites operating. The results below show the average availability computed over all 24 cases of one satellite out of 24 being unusable. Similar results would be achieved when there are more than 24 operational GPS satellites, and a single satellite is out of service without a spare satellite in the same slot. As shown in the figure, a single satellite out of service can significantly reduce the availability for GPS equipment but has little effect on SBAS equipment. The WAAS ranging signal can be clearly seen, as it provides another ranging source within the entire footprint. The SBAS message type 28 also contributes to the improved performance in South America.

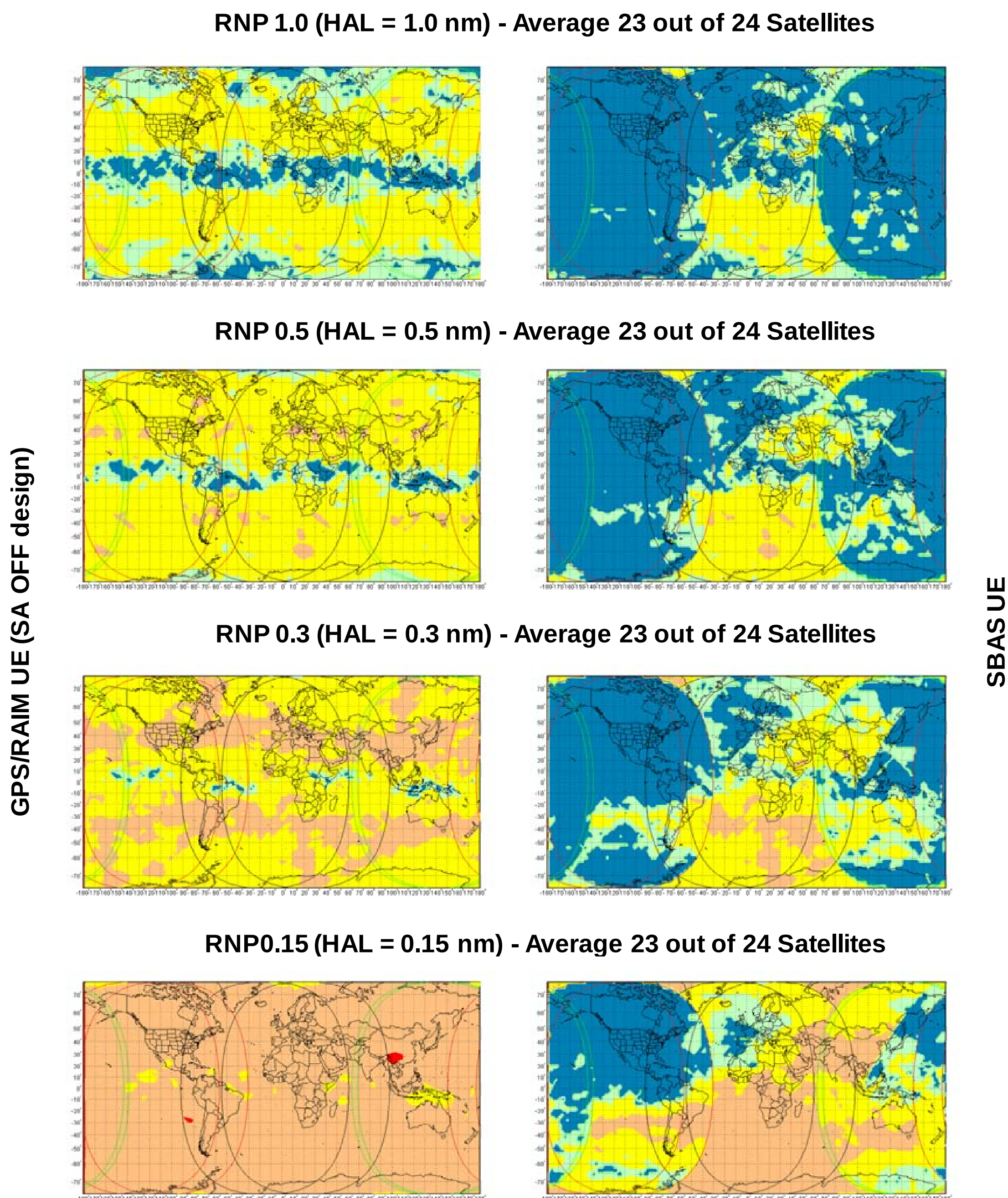

Figure 4: Service Availability with a Degraded GPS Constellation (23 out of 24 Satellites)

3.3.4 LPV Service Availability Performance with a 24-Satellite GPS Constellation

Figure 5 shows the LPV service availability results obtained with a nominal 24-satellite GPS constellation. The results apply to single-frequency SBAS users only, as GPS/RAIM UE cannot achieve this performance. The availability of LPV service is constrained by HAL of 40 m and, in addition, a Vertical Alert Limit (VAL) of 50 m. This performance enables an aircraft to fly a precise path to a runway, while remaining in clouds down to 250 feet above the runway. Before this capability was provided by SBAS, dedicated systems had to be installed at each individual runway end in order to support this type of approach. SBAS also provides vertically guided approach procedures with a Decision Height as low as 200 ft above runway threshold using a VAL of 35 m. The EGNOS service area is currently constrained by message type 27 definition of service area. EGNOS removal of this constraint is currently under assessment.

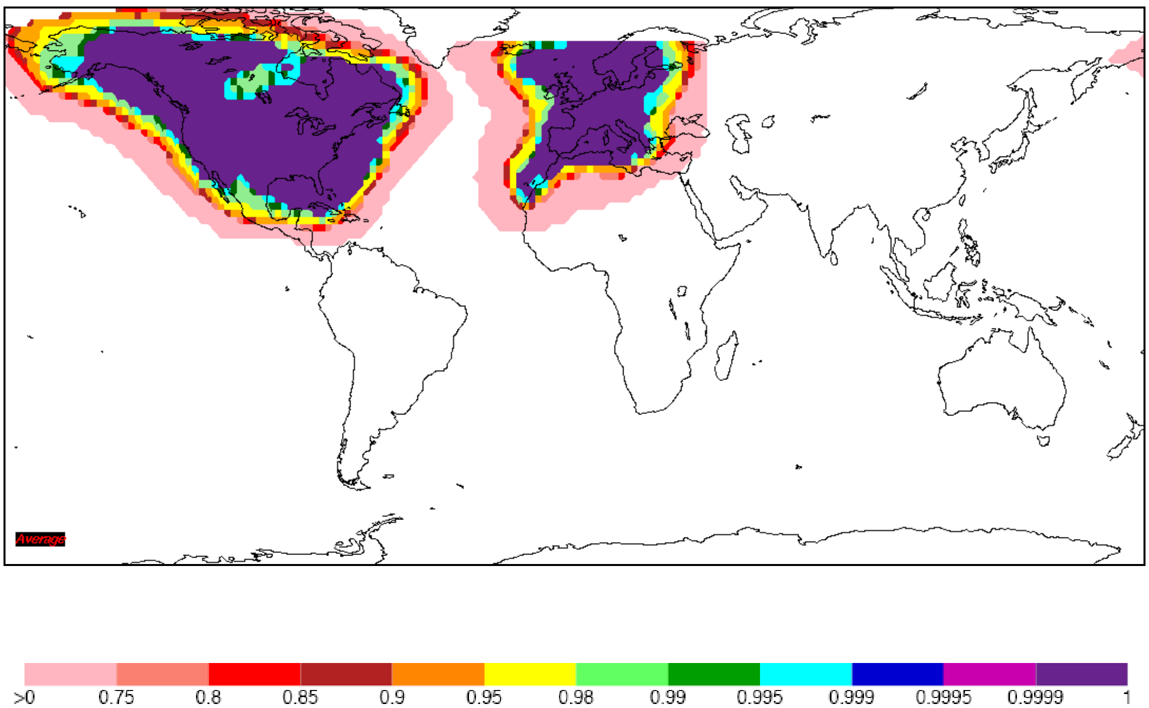

Figure 5: LPV Service Availability (SBAS UE – 24 Satellite Nominal GPS Constellation)

4 CONCLUSIONS

As the above results show, the availability obtained with SBAS UE is always better than that obtained with GPS/RAIM. The difference between the availability obtained with GPS/RAIM UE and SBAS UE is greatest for services associated with a smaller HAL, and when the GPS constellation is degraded.

Comparing the results in Sections 4.1 and 4.2 demonstrates that the addition of 4 satellites to a 24-satellite constellation does not necessarily results in a significant improvement in service availability. This result, which may seem counter-intuitive at first, follows from the fact that the locations of the satellites in the nominal 24-satellite constellation are optimized, while the locations of the additional satellites in the extended 28-satellite constellation are not. Adding a few satellites in non-primary orbital slots provides an effective mitigation technique for some satellite failures, but this does not necessarily result in a greatly improved PNT service. In fact, it is quite possible to obtain poorer service from a constellation with several additional satellites in non-primary orbital slots if some of the primary orbital slots do not have a satellite transmitting a usable signal. This situation has been observed many times when satellites in primary orbital slots are declared temporarily unusable for maintenance action or to adjust their orbits, for example. In those circumstances, the resulting performance is similar to that shown in Figure 4.

Comparing the results in Sections 4.1 and 4.3 demonstrates the fairly significant impact that satellite outages can have on service availability. The service availability reduction would be even greater if the number of unusable (or failed) satellites in the constellation was greater than one. The degradation in SBAS services resulting from satellite outages is noticeably less than the corresponding degradation in GPS/RAIM service. The results would be even further accentuated in case multiple satellite failures are taken into account. It should also be noted that the provision of a GEO ranging function efficiently improves the service available throughout the GEO broadcast area.

Finally, the results also illustrate the improvement throughout the geostationary coverage of providing another ranging signal and more precise characterization of spatial degradation (through message type 28). These improvements are currently available from WAAS, and cause the differences shown in coverage between South America and Africa.

This paper concludes the first stage of the EU-US WG-C on next generation of civil satellite-based navigation and timing systems. It highlights the benefits that can be expected from the combined deployment of interoperable regional SBAS systems in conformance with international standards. WAAS and EGNOS deliver LPV services for the civil aviation community in two areas of the world with the highest density of air traffic. The US and Europe have cooperated in the development of SBAS for over ten years, and have been instrumental to the successful introduction of SBAS solutions at international level. This coordination will continue through the EU-US agreement, addressing improvements to SBAS capabilities that could improve and expand services. A more detailed work programme is currently under preparation to conduct some tasks.

Appendix A

References

[1] "International Standard and Recommended Practices, Aeronautical Telecommunications, Annex 10 to the Convention on International Civil Aviation", Amendment 84, ICAO, 19 November 2009.

[2] "Minimum Operational Performance Standards for Global Positioning System/Aircraft Based Augmentation Airborne Equipment", RTCA, DO-316, 14 April 2009.

[3] "Minimum Operational Performance Standards for Global Positioning System/Wide Area Augmentation System Airborne Equipment", RTCA, DO-229D, 13 December 2006.

[4] "GPS Standard Positioning Service -- Performance Standard", 4th Edition, September 2008.

[5] NSP Nov09 WGW/IP17, *Worldwide Service Availability Results*, November 2009.