Gate-to-Gate with Modernized GPS, GALILEO and GBAS

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Abstract

This paper discusses current challenges, as a result of the rapid increase in air travel, and future navigation needs of Civil Aviation. The objectives pursued by ANASTASIA, a sixth framework European Commission project, are presented. The methods used in the derivation of the navigation performance requirements are introduced and discussed in the context of precision approaches. High-level impacts on the avionics receiver of integrating additional multi-frequency ranging signals from a modernized GPS and Galileo into the current navigation architecture are investigated. Expected performance achievements are presented.

Keywords: ANASTASIA; Avionics; GBAS; Navigation; PBN.

1. Introduction

The current, mainly ground-based, infrastructure for Civil Aviation faces various challenges as a result of the rapid increase in air traffic [1]. Space-based Technologies such as Satellite Communications (Satcom) and Satellite Navigation (modernized GPS, Galileo) offer not only the potential to overcome these limitations, but also to increase operational capacity and safety.

Current limitations in the use of Global Navigation Satellite Systems (GNSS) as primary navigation means are at the institutional and technical levels. The service availability is not guaranteed and current stand-alone GPS is unable to satisfy the performance requirements for the most stringent phases of flight, such as Category-III approaches and surface movement.

In order to be able to use space-based navigation systems for gate-to-gate operations, the European Union has been developing the civil-controlled Galileo system. In parallel, the USA have been developing a modernized GPS to address current performance issues. However, neither modernized GPS nor GALILEO[1], a combination of both or augmented by Aircraft-Based Augmentation Systems (ABAS) are expected to satisfy the performance requirements for all phases of flight [2].

Technical issues may be addressed by various augmentation systems currently under development: Space-Based Augmentation Systems (SBAS) such as the Wide Area Augmentation System (WAAS) developed by the USA or the European Geostationary Navigation Overlay Service (EGNOS) developed by the European Union and the Multi-Functional Transport Satellite (MTSAT) developed by Japan, provide regional differential corrections, ranging signals and integrity information. These are broadcast via geostationary satellites, resulting in an improved navigation performance. The service coverage is however limited and SBAS data does not protect against localized error sources. As a result, SBAS does not appear to be able to satisfy the performance requirements for a gate-to-gate service, being unable to meet the stringent performance requirements of Category-II and III precision approaches [3].

Ground-Based Augmentation Systems (GBAS) provide local area differential corrections and integrity information, broadcast by a ground station at or in the vicinity of the airport. When augmenting GPS, GBAS can support precision approaches up to Category-I. Whether GBAS will be able to satisfy the performance requirements of Category-II and III approaches will largely depend upon the performance requirements ultimately established. If the European Organization for Civil Aviation Equipment (EUROCAE) performance requirements were adopted as the standard, current indications are that Galileo augmented with GBAS will be able to support Cat-II/III approaches, with better performance expected from a combined GPS/Galileo augmented by GBAS [3]. If, on the other hand, Radio Technical Commission for Aeronautics (RTCA) performance requirements were adopted, suggestions are that even current GPS augmented with GBAS could potentially satisfy the requirements for Cat-III landing, at least in terms of accuracy and integrity [4]. Table 1 gives an overview of the navigation architectures expected to be required for the various phases of flight.

Table 1: GNSS minimum infrastructure required for the various flight phases [3, 5]

Phase of Flight	Required Minimum Infrastructure
En Route	GPS + ABAS (RAIM/AAIM) [2] or Galileo (SBAS desirable)
Terminal, NPA, Cat-I	GPS + SBAS or Galileo
CAT-II/III	Galileo + GBAS or GPS + Galileo + GBAS
Surface	GPS + GBAS (or SBAS?) or Galileo + GBAS (or SBAS?)

This paper reviews the future needs of civil aviation and the key issues to be addressed by the ANASTASIA Consortium. The performance requirements for Category-I, II and III precision approach operations derived from the current Instrument Landing System (ILS) and from current Airworthiness

[1] Galileo in this context should be understood as referring to the core satellite system, excluding the local elements.

[2] RAIM – Receiver Autonomous Integrity Monitoring. AAIM – Aircraft Autonomous Integrity Monitoring.

Certification Requirements for landing are discussed. The impacts of modernized GPS and Galileo on the avionics architecture are then analyzed and expected performances of select GNSS configurations presented.

2. Future Needs – ANASTASIA Objectives

Due to the rapid increase in air travel, most major airports and airspaces currently operate near or at their capacity limit [1]. In order to accommodate the foreseen increase in traffic density and maintain (or improve) current safety standards, advanced concepts in the current Communication, Navigation and Surveillance (CNS) architecture must be introduced.

In the context of precision approaches and surface movement, the main needs to be addressed are enhanced approach and sustainable capacity and safety for all weather operations, including in difficult environments such as Alaska.

ANASTASIA (Airborne New and Advanced Satellite techniques and Technologies in A System Integrated Approach) is an integrated project which receives funding from the European Community's Sixth Framework Programme (DG research); see www.anastasia-fp6.org. In the context of increased autonomous aircraft operation, ANASTASIA aims to carry out research, evaluation and cost benefit analyses to define new Communication and Navigation technologies and avionics architectures based on satellite technology in the European Air Traffic Management environment that will meet the needs of civil aviation in the period 2010 to 2020. The project aims to define an optimised avionics architecture and to provide recommendations for the necessary supporting ground and space infrastructure. A preliminary system development of advanced airborne systems for flight trial evaluation will be followed by the dissemination of the results for standardisation activities. The objectives of ANASTASIA can be classified into three categories: communications, navigation and surveillance. The emphasis of this paper is on navigation.

Multi-constellation and multi-frequency configurations of modernized GPS and Galileo offer the possibility to improve the performance capabilities compared to current single-frequency mono-constellation avionics receivers. This will allow an increase in aircraft autonomy and a more cost effective solution to air navigation. In addition to improvements in the space-and ground-segments of GNSS, user level GNSS receiver techniques and technologies will need to be adapted.

ANASTASIA aims to define the optimal satellite-based architecture for future aircraft navigation systems satisfying the performance requirements for all phases of flight and all weather conditions. In order to be in line with the gate-to-gate concept, this includes surface movement. With detailed technical scientific research, ANASTASIA aims to provide evidence that Galileo and/or modernized GPS is able to overcome the limitations of current satellite-based technology within costs and technical constraints.

3. Required Navigation Performance (RNP)

The navigation performance requirements attributed to each phase of operation of the aircraft are a key element of the operational safety. Defining these requirements for precision approach phases is therefore of utmost importance and is the foundation of research in ANASTASIA.

Originally, navigation capability was associated with the mandatory carriage and use of specific navigation equipment, which constrained the optimum application of modern equipment and the use of new navigation aids. Currently, navigation performance is based on the Performance Based Navigation (PBN) concept, specified independently of navigation equipment in terms of accuracy, integrity, continuity, availability[3] and functionality required for the proposed operations in the context of a particular airspace. The specifications of PBN refer to the total system performance requirements for a given airspace, which can be divided into navigation system performance and flight technical performance.

Table 2 (Appendix) summarizes the latest values of the required navigation system performance for the various phases of flight. The presence of two different values for the accuracy and alert limits for Category-II and III approaches reflects the ongoing debate between the regulatory agencies for certifying aviation procedures, the RTCA and EUROCAE.

Early attempts to develop requirements for GNSS to support Category-II and III operations were based on the so-called *ILS Look-Alike* method, trying to match system performance at the Navigation System Error (NSE) level through linearization of the ILS performance specifications at a given height (see Figure 1). This method was used to define the performance requirements for Category-I approaches. A careful assessment of the various error sources of both the localizer and glide-slope in this paper show overall good agreement with the values obtained by EUROCAE in [6], yielding errors that are ~5-10% less stringent. This difference can be attributed to the inclusion of various other minor error sources in addition to the error sources considered in [6]. Issues currently under consideration are the choice of linearization height and how these errors should be transformed into GBAS performance specifications. Given the very different nature of these two systems, this is not straight-forward, and is the subject of ongoing research [16].

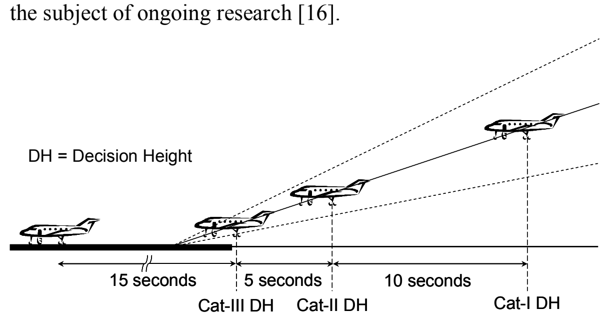

Figure 1: ILS Linearization Methodology [6]

Another method used to model GBAS performance is based on autoland system performance evaluations. The "*Autoland Method"*[4] (see Figure 2) is based on the idea of providing a performance equivalent to ILS in terms of safety of operation. This method is based on the interpretation of Airworthiness Certification requirements [7, 8] of landing operations.

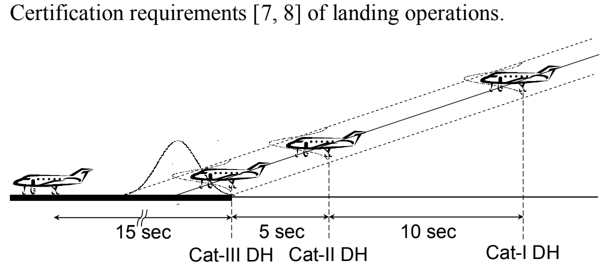

Figure 2: Autoland Performance Methodology [4]

[3] The parameters used depend on whether RNP or RNAV is specified.

[4] For more details, see [4].

In principle, protecting the safety of the landing operation with a GBAS augmented GNSS should be the ultimate goal. However, the derivation of the *Autoland* method is based upon a specific ground architecture, making various assumptions about the monitors and their thresholds to be used in the detection of errors. Moreover, it is sensitive to the flight technical error (FTE) assumptions of the aircraft and the point chosen as the nominal touch-down point (NTDP). In order to successfully use the *Autoland* method for the derivation of the performance requirements, the assumptions in the derivation of GBAS system errors need careful investigation. Currently the demonstration of *Autoland* performance uses a GBAS error model that has not been validated. New validation methods involving extensive field trials should be developed to demonstrate performance.

Depending upon whether the *ILS Look-Alike* or the *Autoland* method is used, different performance requirements are arrived at. Results in Table 2 (Appendix) suggest that the former leads to more stringent performance requirements than the latter, although it has been argued that the *ILS Look-Alike* method is overly stringent [17].

A detailed study, currently ongoing within the ANASTASIA Consortium to investigate in detail the discrepancies between these two methods suggests that the most significant difference between these two method is the assumption made on the FTE of the aircraft during the landing phase. The Autoland method assumes a FTE of current Boeing aircraft, which is significantly better than the FTE implicitly assumed in the ILS Look-Alike method. Additionally, the *Autoland* method in [4] derives the performance requirements based upon ground monitors, making the performance requirements architecture- and aircraft-dependent. The detailed results of this study are reported in [16].

In summary, initial results indicate that to harmonize the performance requirements obtained from the Autoland and ILS Look-Alike methods, a choice will have to be made on whether to keep the current FTE requirements from ILS approaches or whether new FTE requirements can be validated, hence relaxing the GBAS NSE requirements. Simultaneously, a choice will have to be made whether the GBAS NSE performance requirements should be generic and independent of any ground-based architecture or whether ground monitors may be used in their derivation. If so, monitors on the ground will take over part of the integrity checking of the user and, as a result, lead to more relaxed performance requirements at user level. Ultimately the choice of performance requirements will have a significant impact upon the GNSS configurations (together with their augmentations) that will be able to satisfy the requirements for a Category-III landing.

Irrespective of whether the values between the *Autoland* and the *ILS-Look-Alike* methods can be reconciled, from a certification perspective it may still be preferable to use the *ILS Look-Alike Method* to define the performance requirements for Category-II and III approaches since this method has been validated by many years of operational experience with ILS.

4. Impact on Avionics Architecture for the Airborne Phases of Operation

The introduction of new signals and frequencies for GPS and the introduction of the new Galileo system require a number of modifications to the airborne receiver. In this paper, the discussion emphasizes navigation software developments required, paying particular attention to bandwidth requirements between the GBAS ground segment and the airborne receiver, as well as variations in required central processing unit (CPU) usage. Only high-level results are presented since a detailed technical study requires the performance requirements to be established first.

4.1 Ranging Signals

Current airborne receivers are required to be capable of simultaneously tracking and continuously decoding the associated navigation data for at least 8 ranging sources. With a combined constellation of GPS and Galileo, about 20 satellites are expected to be visible in open space at any time [10]. This increased number of ranging sources, including new geo-stationary satellites of SBAS, will significantly increase the Digital Signal Processing (DSP) throughput required in order to use the full potential of this new configuration. It is estimated that a DSP throughput of 9600 MIPS is required to simultaneously track 20 channels for dual-frequency configurations. If triple-frequency use is required (e.g. for Real-Time Kinematics – RTK), the DSP throughput may increase to approximately 14400 MIPS.

4.2 Information from GBAS

The increase in the number of satellites to be tracked also leads to an increase in the amount of information to be received by the airborne receiver from the GBAS ground segment over the VHF data link. Current GBAS messages, designed to support mono-frequency GPS, will have to be extended to cater for dual-frequency GPS as well as Galileo ranging sources.

The *message length* (and possibly structure) will have to be adapted. Additional differential corrections for the new ranging sources and signals need to be provided. Current application data capability for each transmission slot is limited to 1776 bits. With dual-frequency and dual-constellation configurations, differential corrections alone would use 25% of the VHF data link capacity of the GBAS to operate at 2 Hz. An increase in transmission rate may however be required to comply with the stringent time-to-alert requirements of 1 – 2 seconds for Category-II/III approaches. Consideration should also be given to condense information contained within these messages in order to reduce the required bandwidth.

The *ionosphere* currently creates one of the largest uncertainties in the bundled differential corrections transmitted to the user. As a result of localized behaviour of the ionosphere (e.g. during periods of high solar activity), significant spatial decorrelation of the delays between the ground station and the airborne receiver may exist. Given the specific frequency dependence of these delays, they can be computed with high accuracy by dual-frequency receivers. It would therefore be of interest for both the ground reference receivers and the airborne receiver to be dual-frequency, with the airborne receiver computing its own accurate correction for the ionospheric errors. This would imply that the ground-station would have to transmit differential corrections excluding the ionospheric errors, together with an estimate of the residual error of removing the ionospheric corrections from the bundled differential corrections. At the same time, however, for the sake of interoperability with mono-frequency airborne receivers, the ionospheric differential corrections would have to be transmitted as well. To assure integrity, the GBAS ground subsystem transmits B-values to the airborne receiver. However, additional integrity parameters may be needed in the presence of abnormal signal propagation errors, especially for the legacy mono-frequency user, not capable of mitigating the risks associated with the ionosphere.

Error models for NSE, including tropospheric delays and multipath, specifically developed for the GPS-L1 C/A signal, will have to be adapted for the new signals. The impacts of the difference in emitted power, the code chipping rates and modulations and the signal propagation effects in the ionosphere as well as specific multipath environment due to the proximity to the ground of the aircraft during Category-II/III approaches, will have to be carefully evaluated.

The *availability* of ranging sources during the approach is of significant concern and will have a direct impact upon the continuity of the system. The very stringent continuity requirements of precision approaches require a careful choice of the ranging sources that can be used during the approach. The data content of the availability prediction that needs to be transmitted to the user will be dependent upon the environment of the approach path, and may significantly increase the bandwidth required for a given approach.

The gate-to-gate concept includes taxiing from the runway to the gate under virtually zero-visibility conditions. Given the proximity of other aircraft, vehicles and buildings, the requirements for surface movement (SM) are expected to be very stringent, potentially at the decimetre level with very high integrity, continuity and availability requirements. Current code-based ranging methods are limited in their accuracy and it is anticipated that these methods would not be able to satisfy such performance requirements. Modernized GPS and Galileo together with GBAS have increased the potential of using RTK. Preliminary results indicate that an accuracy at the decimetre level, with high integrity, can potentially be achieved within a few seconds.

Carrier-Phase differential corrections are required for RTK. The current message type (MT) 6 is limited to 18 ranging source measurements (corresponding to 6 ranging sources in triple-frequency mode) and needs to be extended for a larger number of ranging sources. Alternatively, the transmission of several MT6 may be considered, with implications, once again, on data link requirements. These requirements are estimated to be at least 9.6kbps capacity with update rates of at least 2Hz [2]. The exact impact upon CPU requirements of the airborne receiver are dependent upon the ambiguity search algorithms and observation equations used.

4.3 Navigation Algorithms

In designing new navigation software to incorporate signals from both Galileo and GPS, interoperability issues between these two systems, as well as interfrequency-bias in dual-frequency mode need to be carefully considered. Measurement models and integrity schemes will have to be adapted.

Reference Time: the difference between the GPS-Galileo Time Frames must be taken into consideration when using a combined configuration. Possible solutions are to determine the time-offset at user level, using a fifth parameter in the navigation solution. Alternatively, the GPS-Galileo Time Offset (GGTO) could be transmitted by both satellite systems, with impacts upon the navigation message content requirements. Both solutions could also be combined, with the GGTO being used from the navigation message (in order to reduce the user CPU load) and being computed at user level when the GGTO is not available. From a CPU usage, the usage of GGTO transmitted by the satellites would be optimal. However, the accuracy is expected to be limited to about 1 m, potentially not sufficient for the more demanding phases of operation, such as surface movement.

Reference Frame: WGS84 and GTRF, used by GPS and Galileo respectively, are identical at the 2 cm - level [11]. Only if any adjustments are made, resulting in this difference to become larger, a transformation between the two frames would be required. The correction information could potentially be provided at system level, with the transmission of this information to the user. In differential mode however, it is likely that such corrections would automatically be absorbed since the ground subsystem is expected to operate in one particular reference frame only.

Inter-frequency Bias: The inter-frequency bias may have to be processed by the user receiver, placing an additional load on the user receiver. At satellite level, this bias is a very stable term that can be computed by the ground segment. For select frequency combinations, this bias may have to be transmitted via the navigation message [12].

Dual-frequency Mode: as mentioned previously, potentially large variations in the ionospheric error contribution over relatively short baselines[5] are of concern. As a result, in order to meet the integrity requirements of precision approaches, it is necessary to compute ionospheric corrections both at the ground station and the aircraft. In addition to current requirements for single-frequency use, the airborne receiver algorithms will therefore have to compute the ionosphere-free observable from the measured pseudorange pair, apply ionosphere-free differential corrections from the ground station and compute the residual error, combining the residual errors from the ground station and the user receiver. Carrier-phase corrections will also have to be adapted.

Measurement Model: the Position And Navigation (PAN) equipment for current GPS receivers computes three-dimensional positions and a time output using a linearized, weighted least-squares solution based on a set of differentially corrected pseudoranges meeting the requirements described in Section 2.3.8.1 of [13]. If the GGTO is not provided at system level, or if a higher accuracy solution is required, this model will require adaptation: a possible measurement model is, as for current GBAS-enabled GPS receivers,

$$\Delta y = G\Delta x + \varepsilon \,, \qquad \textbf{(1)}$$

where Δx is the true position/time vector relative to the position/time vector x for which the linearization was made. Δy is a vector containing the differentially corrected pseudorange measurements minus the expected ranging values based on the location of the satellites and of the user (x).

The difference with GPS-only receivers would be in the observation matrix *G*, containing the line of sight vectors from each satellite to the user, augmented by the clock parameters, and potentially other parameters such as the GGTO, etc. The i^{th} row can be written in terms of the azimuth angle Az_i and the elevation angle El_i:

$$G_i = \begin{bmatrix} -\cos El_i \cos Az_i, -\cos El_i \sin Az_i, -\sin El_i, \\ 1, \alpha_1, \cdots \end{bmatrix} \qquad \textbf{(2)}$$

where the α_I are any additional parameters to be determined at user level as a result of using a combined dual-frequency Galileo - GPS configuration. ε is a vector containing the errors in *y*.

It should be noted that in dual-frequency mode, the residual ionospheric error can be incorporated into the σ_{air} term, replacing the classical expression

$$\sigma_i^2 = \sigma_{pr\_gnd}^2[i] + \sigma_{tropo}^2[i] + \sigma_{pr\_air}^2[i] + \sigma_{iono}^2[i] \qquad \textbf{(3)}$$

with

$$\sigma_i^2 = \sigma_{pr\_gnd}^2[i] + \sigma_{tro}^2[i] + \sigma_{air-DF}^2[i] \qquad \textbf{(4)}$$

where for a L1-L5 dual-frequency receiver, the σ_{pr_gnd} could incorporate the residual error due to the removal of the

[5] Based upon empirical data collected in the USA, the worst case ionospheric delay gradient was established to be 0.3 m/km [15].

ionospheric corrections by the ground subsystem and the $\sigma_{air\text{-}DF}$ would be given by [14]

$$\sigma^2_{air,L1L5} = \left(\frac{f_1^2}{f_1^2 - f_5^2}\right)^2 \sigma^2_{air,L1} + \left(\frac{f_5^2}{f_1^2 - f_5^2}\right)^2 \sigma^2_{air,L5} + \sigma^2_{SV,L1L5}$$
$$= 5.1\sigma^2_{air,L1} + 1.6\sigma^2_{air,L5} + 0.03098 \qquad \textbf{(5)}$$

with $\sigma_{SV,L1L5}$ corresponding to the satellite hardware group delay computed at system level.

Integrity Schemes: while Galileo integrity is well-defined and guaranteed at system level, this integrity information is not sufficient to meet the Cat-II/III integrity requirements [12]. An important issue to be addressed is how the integrity for GPS and Galileo should be treated. A separate treatment of the integrity of the two systems would provide better continuity if one of the systems is lost. However, overall performance may be improved if GPS and Galileo are treated as a single system for integrity computations. In the mid-term (assuming that Galileo dual-frequency becomes available before GPS dual-frequency), dual-frequency Galileo could provide improved integrity for GPS single-frequency measurements. Additionally, if RAIM is to be used during Category-III approaches, this may have significant implications on the load placed onto the receiver CPU.

4.4 Summary – Impacts on Avionics Architecture

The performance requirements of the most stringent phases of operation (Category-II and III approaches as well as surface movement) are the main drivers for the design of a single-system airborne receiver architecture. A detailed study of the performance requirements is currently being carried out. An overview of the high-level impact of modernized GPS and Galileo on the design of the airborne receiver architecture was presented. A more detailed quantitative study of the above-mentioned effects will be carried out after the performance requirements for Category-II and III as well as surface movement have been firmly established.

5. Performance Achievements

Table 3 (Appendix) gives an overview of the expected performance achievements of GNSS augmented by GBAS for various satellite configurations. Being limited through the potential of spatial decorrelation of ionospheric delays, the table includes indications as to the distance over which these performances can be achieved. Where no values are given, performance requirements are expected to be met within the service volume of the GBAS ground station. The ANASTASIA project is expected to provide evidence to validate this preliminary analysis.

Conclusions

Advanced guidance concepts and procedures are required to respond to the rapid increase in air traffic. To this end and that of achieving gate-to-gate with a single integrated navigation system, a new navigation architecture needs to be defined. One of the aims pursued by ANASTASIA is to define the optimal satellite-based architecture for future aircraft navigation systems satisfying the performance requirements for all phases of flight, including surface movement, and all weather conditions within cost and technical constraints.

Whilst performance requirements have been established for Cat-I approaches, not all requirements can be met with the current GPS. Modernized GPS and Galileo will however change this situation. The configurations of GPS and/or Galileo that can be used for Cat-II and III approaches will much depend on the performance requirements determined to provide equivalent (or better) performance than current ILS. A detailed study is currently being performed to determine these requirements for Category-II and III approaches.

An overview was given of the high-level impacts of modernized GPS and Galileo on the airborne receiver architecture. A detailed study will follow after the establishment of the performance requirements for Category-II/III approaches and surface movement.

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Appendix

Table 2: Performance Requirements for GNSS SIS [9]

Phase of Operation	Accuracy	Integrity			Continuity	Availability
	SIS Accuracy (2σ)	Alert Limits	Integrity Risk	TTA	Continuity Risk	
En-route	2 nm (L) N/A (V)	**Oceanic/low density** 4 nm (L) N/A (V) **Continental** 2 nm (L) N/A (V)	1E-7/h	5 min	1E-4 /h – 1E-8/h	0.99 – 0.99999
En-route, Terminal	0.4 nm (L) N/A (V)	1 nm (L) N/A (V)	1E-7/h	15 s	1E-4 /h – 1E-8/h	0.99 – 0.99999
Initial approach, Intermediate approach, NPA, Departure	220 m (L) N/A (V)	556 m (L) N/A (V)	1E-7/h	10 s	1E-4 /h – 1E-8/h	0.99 – 0.99999
APV-I	16 m (L) 20 m (V)	40 m (L) 50 m (V)	2E-7/150 s	6 s	8E-6/15 s	0.99 – 0.99999
APV-II	16 m (L) 8 m (V)	40 m (L) 20 m (V)	2E-7/150 s	6 s	8E-6/15 s	0.99 – 0.99999
Cat-I	16 m (L) 4 m (V)	40 m (L) 10 m (V)	2E-7/150 s	6 s	8E-6/15 s	0.99 – 0.99999
Cat-II	**6.9/6.1 m (L)** **2.0/1.4 m (V)**	**17.3/17.9 m (L)** **5.3/4.4 m (V)**	1E-9/15 s	2 s	4E-6/15 s	0.99 – 0.99999
Cat-IIIa	**6.2/3.6 m (L)** **2.0/1.0 m (V)**	**15.5/10.4 m (L)** **10.0/2.6 m (V)**	1E-9/15 s	2 s	4E-6/15 s	0.99 – 0.99999
Cat-IIIb	**6.2/3.6 m (L)** **2.0/1.0 m (V)**	**15.5/10.4 m (L)** **10.0/2.6 m (V)**	1E-9/30 s (L) 1E-9/15 s (V)	2 s	2E-6/30 s (L) 2E-6/15 s (V)	0.99 – 0.99999
Surface Movement (SM) – Surveillance	7.5 m	TBD	TLS[6] Risk = 3E-9	Update rate: 1 s	TBD	
SM – Routing	TBD		TLS Risk = 1E-9	TBD		
SM – Guidance			TLS Risk = 3E-9			
SM – Control			TLS Risk = 3E-9 $P_{MD}<0.001$			

Table 3: Expected Performance Achievements

GBAS Augmenting…	Frequency	Cat-I	Cat-II/IIIa	Cat-IIIb
GPS/Single-Frequency	L1	Marginally	(*)	(*)
	L5	10 km	10 km	10 km
Galileo/Single-Frequency	L1	10 km	(*)	(*)
	E5a	10 km	10 km	10 km
GPS/Dual-Frequency	L1/L5	Yes	Yes	Yes
Galileo/Dual-Frequency	E1/E5a	Yes	Yes	Yes
GPS/SF + Galileo/SF	L1/E1	Yes	Yes	Yes
	L5/E5a	Yes	Yes	Yes
GPS/SF + Galileo/DF	Any comb.	Yes	Yes	Yes
GPS/DF + Galileo/DF	Any comb.	Yes	Yes	Yes

(*)Potentially supported if a VAL = 10 m is adopted.

6 TLS = Target Level of Safety.