International Journal of Innovative Research and Scientific Studies, 8(2) 2025, pages: 1439-1451

IJIRSS
International Journal of Innovative Research & Scientific Studies

ISSN: 2617-6548

URL: www.ijirss.com

Analysis of critical satellites for ground-based augmentation system approach service type E

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Abstract

The Ground-Based Augmentation System (GBAS) Approach Service Type C and D, GAST-C/D, has been standardized and recently certified at many airports to support landing operations in aviation since 2012 and 2018, respectively. GBAS landing services use Single-Frequency and Single-Constellation (SFSC), either GPS L1, GLONASS L1, or Galileo E1. However, the advanced GBAS performance, GAST-E, requires the use of Dual-Frequency Dual-Constellation (DFDC) GPS/Galileo L1/E1, which has not been standardized yet. Moreover, the number of critical satellites is a determining factor for GBAS availability in its standardization process. This paper aims to simulate the required allowable number of critical satellites to achieve GAST-E performance using GPS L1 and Galileo E1 frequencies. A validated simulation tool used in a previous study has been reused for this purpose. The results show the feasibility of achieving GAST-E with 6 critical satellites, down from the 10 that were standardized for GAST-C. A further investigation using 2 critical satellites was also proposed. Results show that a change of 4 critical satellites, more or less than 6, would cause a change of nearly 45% in GBAS system availability. Consequently, this research would pave a step ahead in the standardization process for the higher performance of GBAS-based navigational instruments.

Keywords: Galileo, GAST-D, GAST-E, GBAS, GNSS Satellite Navigation, GPS, Instrument Landing Systems.

DOI: 10.53894/ijirss.v8i2.5472
Funding: This study received no specific financial support.
History: Received: 22 January 2025 / **Revised:** 24 February 2025 / **Accepted:** 1 March 2025 / **Published:** 18 March 2025

Competing Interests: The author declares that there are no conflicts of interests regarding the publication of this paper.
Transparency: The author confirms that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.
Publisher: Innovative Research Publishing

1. Introduction

In 2012, at Bremen airport in Germany, the Ground-Based Augmentation System (GBAS) was certified as Category CAT-I (GAST-C) performance for aircraft landing and precision approach down to 200 ft DH: Decision Height at low visibility conditions. That's due to its enhanced accuracy, integrity, and continuity of supported service by the Global Navigation Satellite System (GNSS), GPS, and GLONASS. Since that time, the development of GBAS has grown continuously and led to significant improvements. Therefore, it was intended to gradually replace the conventional Instrument Landing Systems (ILS) due to its reliability, cost-efficiency, and ability to serve multiple aircraft on multiple runways at the same airport instead of the costly multiple ILSs [1-4], and it noticeably increased the air traffic capacity wherever it was implemented [5]. Moreover, in 2018, the GBAS improvements could achieve requirements for GAST-D

(CAT-II) using single frequency single constellation (SFSC) due to improved characteristics of the GNSS signal in space, such as increased power and the use of Binary Offset Carrier (BOC) modulation schemes in both GPS B-III and Galileo GNSS systems [6-8]. More than 100 installations around the world have taken place in either full operation systems or prototype systems; more information can be found in FAA [9].

However, GBAS operates four reference GNSS stations to provide corrections for the aircraft receivers [10]. The GBAS services are classified into six categories of precision approach and combinations of GNSS signals, as extracted from ICAO [11]; DO-245A [12]; EUROCAE [13] and ICAO [14], and summarized in Table 1 and 2. GBAS uses the Differential GNSS (DGNSS) positioning technique, which assumes a correlation of systematic errors in the ephemeris, ionosphere, troposphere, and multipath. Recent studies indicated that the greatest impact comes from ionospheric and multipath error shares [15-18]. Consequently, degrading the level of performance needed for the ICAO CAT-III or GAST-E/F level requires the use of a dual frequency dual constellation (DFDC) configuration.

Table 1.
GBAS Service Levels [11-14].

GBAS Service Level	Typical Operation(s)	Availability Probability
A	Approach operations - Vertical Guidance APV-I	0.9500
B	Approach operations - Vertical Guidance APV-II	0.9500
C	Precision Approach-Category I	0..9500
D	Precision Approach-Category II	0.9975
E	Precision Approach-Category II/IIIa	0.9999
F	Precision Approach Category IIIb	0.9999

Table 2.
Required performance for GBAS Service Levels [prepared by Author][11-14].

Typ. Ops	GSL	Accuracy		Integrity				Continuity
		Lat.	Vert.	Int. Prob.	TAL	LAL	VAL	Cont. prob.
APVI	A	16m	20m	$1-2\times10^{-7}$ in any 150s	10s	40m	50m	$1-8\times10^{-6}$
APVII	B	16m	8.0m	$1-2\times10^{-7}$ in any 150s	6s	40m	20m	$1-8\times10^{-6}$
CAT-I	C	16m	4.0m	$1-2\times10^{-7}$ in any 150s	6s	40m	10m	$1-8\times10^{-6}$
CAT-II	D	5m	2.9m	$1-1\times10^{-9}$ in any 15s vert./30s lat.	2s	17m	10m	$1-8\times10^{-6}$
CAT-IIIa	E	5m	2.9m	$1-1\times10^{-9}$ in any 15s vert./30s lat.	2s	17m	10m	$1-4\times10^{-6}$
CAT-IIIb	F	5m	2.9m	$1-1\times10^{-9}$ in any 15s vert./30s lat.	2s	17m	10m	$1-4\times10^{-6}$

Note: *Typ. Ops: Typical Operation, *GSL: GBAS Service level,
*Lat.: Lateral error in 95% NSE, *Vert.: Vertical error in 95% NSE
*Cont. prob.: Continuity probability in any 15 seconds, *Int. prob.: Integrity Probability
*TAL: Time to alert(s), * LAL: Lat. alert limit (m), * VAL: Vert. alert limit (m)

From one side, the "GBAS continuity of service is the probability that a fault-free aircraft subsystem provides valid outputs during any defined period of an approach, assuming that outputs were valid at the start of the period." For CAT II and CAT IIIA operations, the continuity of service shall be more than or equal to: $1 - 4 \times 10^{-6}$ during any 15s period. Whereas, the "GBAS integrity risk is the probability that the GBAS Ground Subsystem provides information, when processed by a fault-free receiver," which would result in the position error exceeding the alert limit for a period longer than the maximum time-to-Alert without annunciation. For operations in Cat-II/III conditions, the SiS integrity risk value is required to be less than: 1×10^{-9} in any one operation. Moreover, the "GBAS vertical accuracy is defined in terms of vertical Navigation System Error (NSE). The vertical NSE is the difference between the measured and true vertical displacement from the final approach path. The probability that the vertical NSE value is within the limits shown below shall be at least 95% per approach." For CAT-II/III, accuracy limits are between 50-100 feet height above threshold and a constant value of 0.7-1.4 m as per European Standard [13] or a more relaxed figure of 2.9 m as per USA standard in RTCA DO-245A. Finally, the GBAS accumulative availability of the three parameters: accuracy, integrity, and continuity shall be greater than 99.99% of the time.

Furthermore, the standardization of GAST-E/F is also needed; ongoing research within international LAAS/GBAS groups is under development. Among the most important aspects, the number of allowable critical satellites must be identified for continuity availability [19]. However, the critical satellites are those whose loss leads to the loss of continuity for various GBAS service types, such as GAST D1 and E. The number of critical satellites is required to define the continuity allocation in GAST D1 with Galileo E1 and E, which have not been standardized yet. Meanwhile, GAST-C assumes 10 critical satellites [20]. GAST D1 with GPS L1 tends to utilize 6 and 3 as the number of critical satellites for the vertical and lateral directions, respectively. Currently, detailed information regarding the analysis of the number of critical satellites for GAST D1 with GPS L1 is not publicly available from ICAO. Therefore, in [19], the authors in 2023 recommend in their simulation results that GAST-D with GPS L1 would use six and three critical satellites for the vertical and lateral directions, respectively, which is compatible with the same recommendations in a previous study in 2009, as seen in [21].

This research aims to simulate the required allowable number of such critical satellites: 10, 6, and 2, in order to investigate whether they are feasible to achieve GAST-C, GAST-D, and GAST-E performance using GPS L1 and Galileo E1 frequencies, respectively. A validated simulation tool used in a previous study has been reused for this purpose. The results show the feasibility of achieving GAST-E with 6 critical satellites, down from 10 standardized for GAST-C/D. A further investigation using 2 critical satellites was also proposed, with a reduced availability of continuity. Hopefully, this research will step ahead in the standardization process for the higher performance of GBAS-GAST-E/F in the future.

In the following paragraphs, GBAS parameters will be presented first. Then, the simulation planning used will be demonstrated using the ICAO computation models. Finally, the resultant availability values will be subjected to analysis in terms of GAST-C to GAST-E requirements.

1.1. Gabs Parameters Assumptions

The currently error models shown in ICAO [11]; DO-245A [12] and EUROCAE [13] have been identified for airborne/ground subsystems, using GPS/L1 signal with 1st order code-carrier filter (τ= 100s). Furthermore, this error model assumes that the error model for GPS-GBAS system shall be the same as error budget for Galileo-GBAS system. The standard deviation of the error budget for GBAS systems is given by Equation 1 for Measurement Model of satellite i:

$$\sigma_i^2 = \sigma_{pr-ground\ i}^2 + \sigma_{Iono-i}^2 + \sigma_{tropi-i}^2 + \sigma_{air-i}^2 \qquad (1)$$

Where:

$\sigma_{pr-ground\ i}^2$: is the total post correction provided by VHF Data Broadcasting (VDB) link for satellite i.

σ_{Iono-i}^2: is the uncertainty deviation of the residual Ionospheric delay for the i^{th} ranging source.

$\sigma_{tropi-i}^2$: is the standard deviation of Tropospheric error for satellite $\boldsymbol{i}$, computed by the aircraft subsystem.

σ_{air-i}^2: is the standard deviation of the aircraft error contribution for the i^{th} ranging source.

The aircraft error includes the receiver error and the airframe multipath error. And it is given by Equation 2 shown below:

$$\sigma_{air-i}^2 = \sigma_{receiver}^2(\theta_i) + \sigma_{multipath}^2(\theta_i) \qquad (2)$$

Where: $\sigma_{receiver}^2(\theta_i)$ is the standard allowance for the receiver and $\sigma_{multipath}^2(\theta_i)$ is the the standard allowance for multipath.

Therefore, The RMS of the installed multipath error contribution to the error in a corrected pseudorange for either ranging source as a function of the satellite elevation angle, Equation 3:

$$RMS_{multipath}(\theta_i) = a_0 + a_1 . e^{\frac{-\theta_i}{10}} \qquad (3)$$

Where: i: is the ith ranging source, a_0, a_1, and θ_i are parameters determined by the Table 3 shown below, and presented in table 3 below. The advanced reduction can be estimated by dividing the A parameter by factor down to half, fourth and tenth of the standard value A.

Table 3.
Basic Airborne multipath parameters for basic performance.

AMD	θ_i(degrees)	a_0(m)	a_1(m)
A	10	0.130	0.530
B	10	0.065	0.265

Note:*AMD: Airborne Multipath Designation

And the RMS of the total airborne receiver contribution to the GPS/GBAS error in a corrected pseudorange as a function of the elevation angle is given in Equation 5 below:

$$RMS_{pr-air}(\theta_i) = a_0 + a_1 . e^{\frac{-\theta_i}{4}} \qquad (5)$$

Where: i: is the ith ranging source, a_0, a_1, and θ_i are parameters determined by the Table 4 shown below, and presented in Table 5 below. Designator letters A, or B, is associated with performance of the airborne subsystem. These values will be assumed to represent the single frequency configuration of the airborne receiver subsystem, or in other words, low accuracy configuration, if they reduced by 2 or 4(divided by 2 or 4), then they will be assumed to represent the dual frequency configuration.

Table 4.
Basic Airborne Receiver Performance (low accuracy/Single Frequency).

AMD	θ_i(degrees)	a_0(m)	a_1(m)
A	10	0.130	0.530
B	10	0.065	0.265

For the Ground Accuracy Designator Parameters (GAD), the RMS of the total non-aircraft contribution to the GPS/GBAS error as a function of the Elevation angle is given in [12], page 31, Equation 4.

$$RMS_{pr-grnd}(\theta_i) \leq \sqrt[2]{\frac{\left[a_0 + a_1 . e^{\frac{\theta_i}{\theta_0}}\right]^2}{M} + a_2^2} \quad (4)$$

Where M is the number of ground reference receiver subsystems, I is the Ith ranging source, and a_0, a_1, a_2, and θ-i are parameters determined by Table 5 seen below. Each letter of the ground accuracy designator (A, B, or C) is associated with the performance of the ground subsystem reference receiver and a number that indicates the number of reference receivers. These values will be assumed to represent the single frequency configuration of the ground subsystem, or in other words, the low/mid accuracy configuration. If they are reduced by a factor of 0.5, then they will be assumed to represent the dual frequency configuration (or high accuracy configuration).

Table 5.
Basic GS Performance (low accuracy/Single Frequency) [12].

GAD	θ_i(°)	a_0(m)	a_1(m)	θ_0(°)	a_2(m)
A	> 5	0.5	1.65	14.3	0.08
B	> 5	0.16	1.07	15.5	0.08
C	> 35	0.15	0.84	15.5	0.04

The resultant advanced values of GAD, AAD, and AMD is shown in the Figure 1 below, where all values are degraded by factor of 4, from 1 to 0.25 for dual frequency in CAT-III/GAST-E. that's represents the high accuracy configuration.

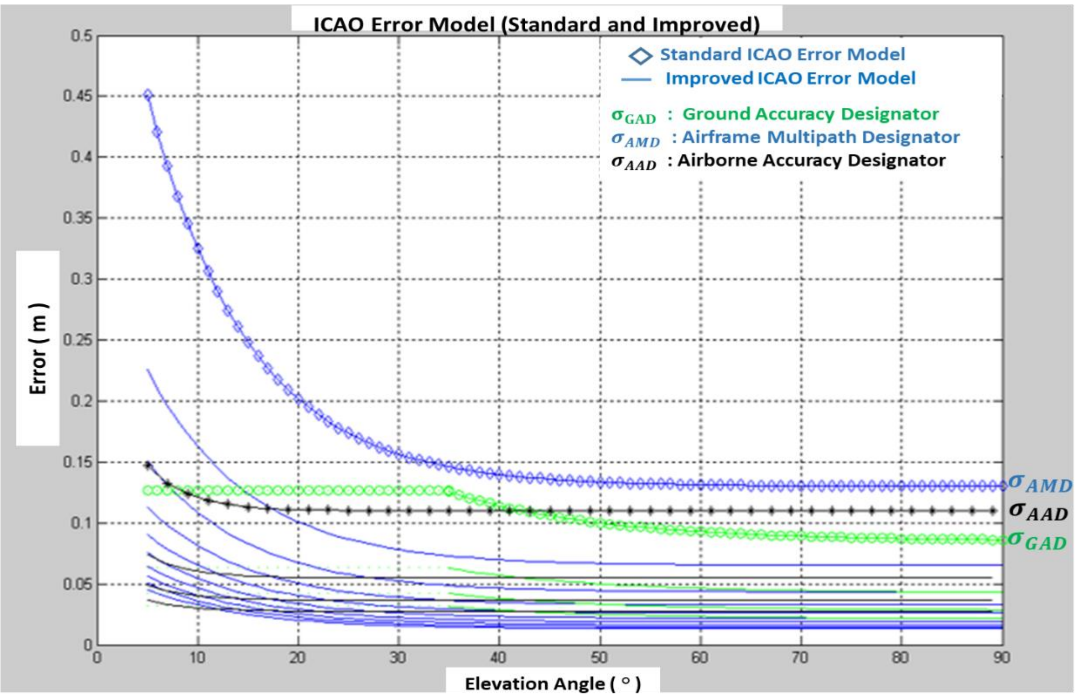

Figure 1.
GAD, AAD and AMD advanced error model assumptions.

Other assumptions that we will use are: (1) The maximum service volume is assumed for all the simulations to be 43 km (23 NM), according to ICAO Annex 10, Amendment 77 [14], page 42F, and according to RTCA-DO245A, page 17 [12]. This parameter has a minor impact on the performance results. (2) The runway heading is assumed to be 100° for all the simulations. This value can be selected arbitrarily and has no impact on the performance results of the simulations. (3) A glide path angle of 2.7° has been selected for all the simulations according to DO-245A [12] RTCA-DO 245A, page 17. Usually, a glide path of 3° is assumed, and the glide path can be up to 7° for specific runways. This parameter has no impact on the performance results of the simulations done here. (4) The time of the approach phase (FAS) is set for all the simulations to 150 s according to DO-245A [12] RTCA-DO245A-Appendix-C. (5) Regarding critical satellites, we use Max=2 for GSL=F, Max=4 for GSL=E, and 10 ("high enough") for GSL=A to D according to RTCA-DO245 A, Table 3-13[12]. This parameter has a significant impact on the performance, as shown in the simulation results. (6) The number of reference receivers is assumed for all simulations to be 4 according to ICAO-Annex 10, Table B-71 [14]. The number of reference receivers has an impact on the performance class that can be achieved by the ground station.

Assumptions for the GNSS constellations Almanacs are as follows: (1) For GPS 24/29 satellites, in which we simulated a constellation of 24 and 29 satellites, used in DO-229C Appendix B, with the following characteristics [22, 23]: Epoch date: June 30, 1993, at 23:34:24. GPS week 703, 344064 seconds. Simulations will be for an 11 hours 58 minutes (≈12 hours) period, and the elevation angle will be 5°. (2) For Galileo 27 satellites, in which we simulated a constellation of 27 satellites, the constellation is a Walker 27/3/1 as defined in Phase B2 of the GALILEO project from ESA [24]. Simulations will be for a 10 days period, and the elevation angle will be 10°.

2. Methodology

The methodology simulation runs in this paper follow a systematic arrangement of the input parameters in three main groups: one group using 6 critical satellites, then lowering them to 2 critical satellites, and the third one using 10 critical satellites. Each simulation run has been performed in two stages: (1) the first stage includes the trajectory almanac data with associated Keplerian parameters to produce the trajectory file; (2) then the GBAS parameters, along with the resultant trajectory file from stage one, are used to produce the availability of integrity. See Figure2.

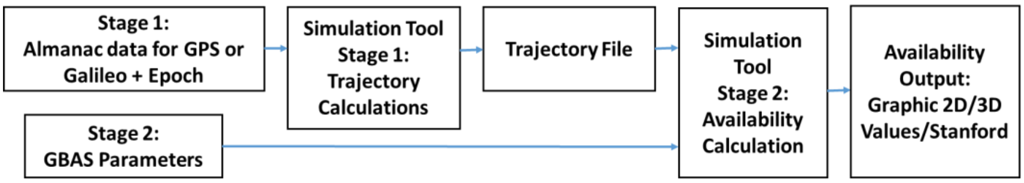

Figure 2.
Simulation Runs: Availability Calculations.

The algorithm used in the simulation tool is commonly used and validated with other similar tools. It utilizes the satellite constellation, including the following parameters: YUMA broadcast ephemerides, fixed WGS84 points for SBAS, PLs, Walker 27/3/1, plus three in-orbit spares for Galileo. The constellations can be used both in combination and separately. Furthermore, SIGi is a standard deviation of measurement post-correction error associated with Satellite i. This sigma is an RSS sum of ground subsystem, airborne receiver, tropo/iono, and uncertainty components. SIGi is used for computing Protection Levels and for weighting the navigation matrix W. The weighting matrix W is formed from SIGi, where i = 1,…,N, and the projection matrix S is formed in a rectangular coordinate frame centered at the GBAS reference point and related to a runway's glide path. This matrix applies for the computation of predicted lateral/vertical protection levels and the simulation of lateral/vertical position errors. The UDRE models generate differential tropospheric and ionospheric residual errors, multipath, and receiver noise errors. These errors can be used as inputs to the XNSE model of Galileo LE. The PXPLs module calculates predicted vertical and lateral protection levels (PXPLs) according to DO-245A, whereas the XNSE model simulates position errors emulating a weighted least squares solution based on matrices W, S, satellite positions, and measurement errors generated by the UDRE model.

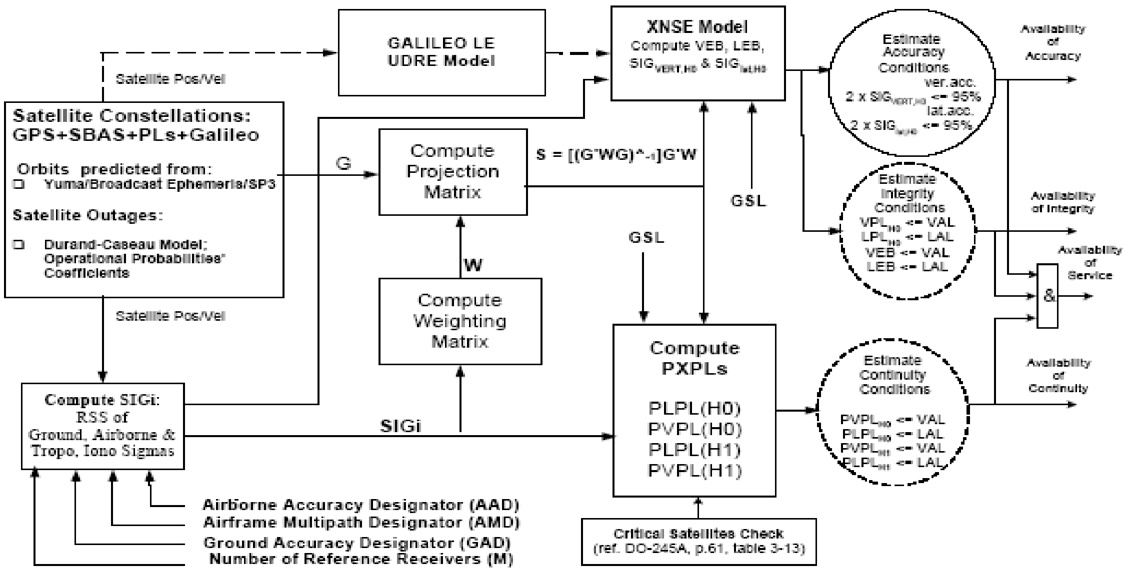

Figure 3.
Models and algorithms of the Simulation Tool.
Note: This image is taken from the manual of the simulation tool, I couldn't have clearer more than this, if necessary, I can re-draw it by power point again. Please let me know your advice concerning.

The simulations were planned in a systematic method by varying all the parameters for a selected number of critical satellites, as seen in Figure 4 below. The analysis procedure shows the following dependency indicators: Dependency on allowable number of critical (10, 6, 2); Dependency on constellation (GPS 24, GALILEO 27, GPS 29); Dependency on Vertical Alert Limits (VAL) of (10m, 5m, and 2.5m); Dependency on Receiver(s) Accuracy Designators (GAD/AAD)

(AA, BB, CB); Dependency on GS/User Receivers Performance (SF, DF); and Dependency on the User Multipath Error (UMPE) / Airborne Multipath Designator (AMD) mitigation level (A, A/2, A/4, A/10).

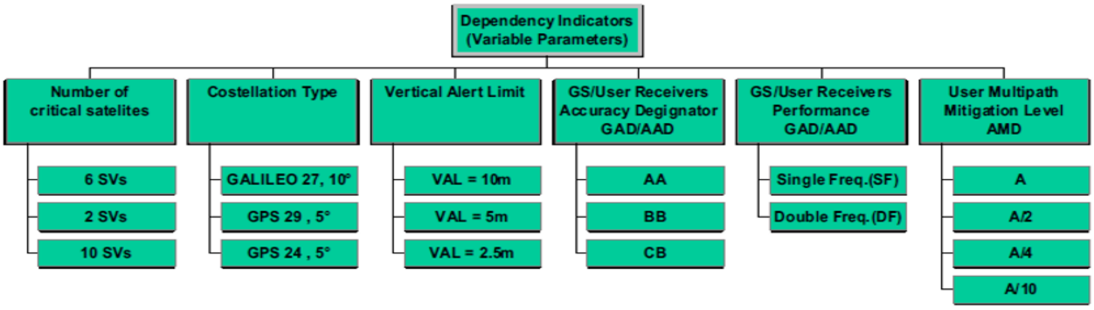

Figure 4.
Dependency Indicators.

The designator parameters are repeated each time for a different number of critical satellites: 6, 10, and 2 each time, as seen in Figure 5 below. Therefore, all the types of the mentioned groups are built together to form the final simulation group tree. The tree was constructed in such a way that some parameters are less varying, like the GNSS constellation type and allowed number of critical satellites, while the more varying parameters include receiver accuracies and AMD mitigation levels. Thus, the analysis will be easier across any combination of parameters to see the effect of changing the number of critical satellites on the selected subgroup of them, for example, CAT-III performance, which is the main purpose of this study. Even more, this will allow for more results extraction in the future as well.

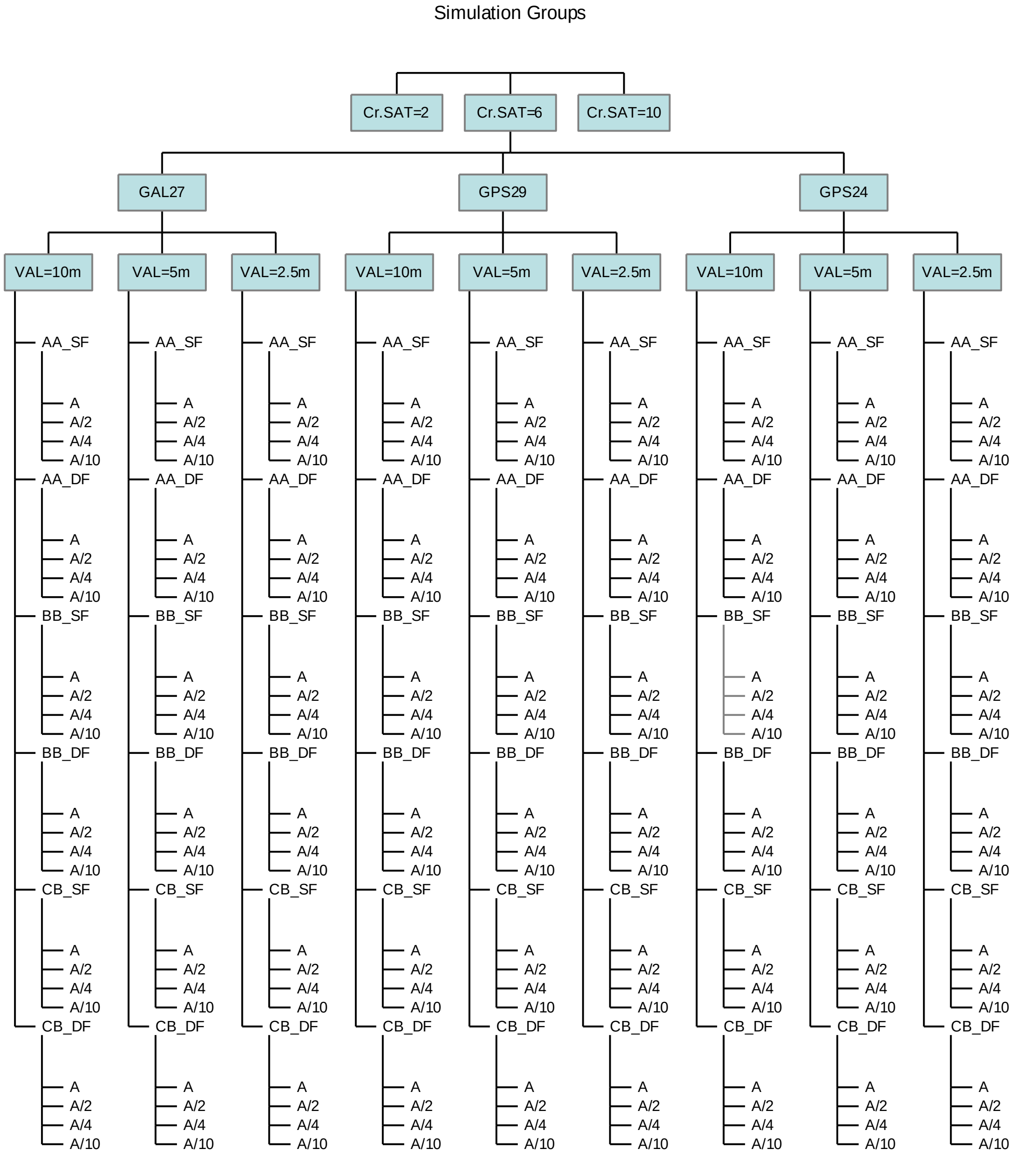

Figure 5.
One part of the three parts of the whole simulation groups' tree.

However, for the standard values in single frequency/single constellation, we used: AA-SF means GAD=A, AAD=A, while BB_SF means GAD=B, AAD=B, and CB_SF means GAD=C, AAD=B. But for the dual frequency performance type (divided by 2 values), we used: AA_DF, BB_DF, and CB_DF accordingly. This is repeatedly used in each major group using different numbers of critical satellites.

3. Results

Actually, a huge number of simulations have been performed according to the methodology explained above: 220 simulations for each selected GNSS constellation, in addition to many other rehearsals and verification simulations, as seen in Table 6 below.

Table 6.
Number and time for simulations' runs

Simulation Run Type	Number of executed runs	Time for each simulation
Testing and Validations	25	1 hours
Galileo 27 Sat, 2.33 days, 5°X5° grid, 6s step	220	3 hours
GPS 29 Sat, 1 day, 5°X5° grid, 6s step	220	1 hour
GPS 24 Sat, 1 days, 5°X5° grid, 6s step	220	30 minutes
Galileo + GPS (combined)	50	3 hours
Total	735	1165 hours (≈145 working days)

3.1. GBAS Availability with 6 Critical Satellites

In this section, I present the results of major group 1 with 6 allowable CVS in the three constellations, as seen below: Figure 6 for Galileo 27 satellites, Figure 7 for GPS 29 satellites, and Figure 8 for GPS 24 satellites. Simulations show that the GBAS system availability performance could meet the aeronautical availability requirements of 99.75% and 99.99% in CAT-I and CAT II respectively, with an integrity risk of 10^{-9} (using the same K-factor according to GBAS Service Level definition) and using an assumed Vertical Alert Limit (VAL) of 10 m and 5 m respectively, providing a certain level of user multipath mitigation was applied (A/4). Allowable critical satellites in the Galileo 27 constellation have relatively better improvement in GBAS performance compared with GPS 29 and 24 constellations. Moreover, all GNSS constellations with all GBAS configurations are not visible to achieve 99.75% nor 99.99% availability on both SF and DF for VAL = 2.5 m that is used in CAT-III (GAST – E/F). DF has a higher increase in availability and higher improvement, in both the maximum and the average, than the SF receiver when UMPE decreases. The cause of that is due to the ionospheric error reduction which is already embedded in the DF technique and not applicable in the SF.

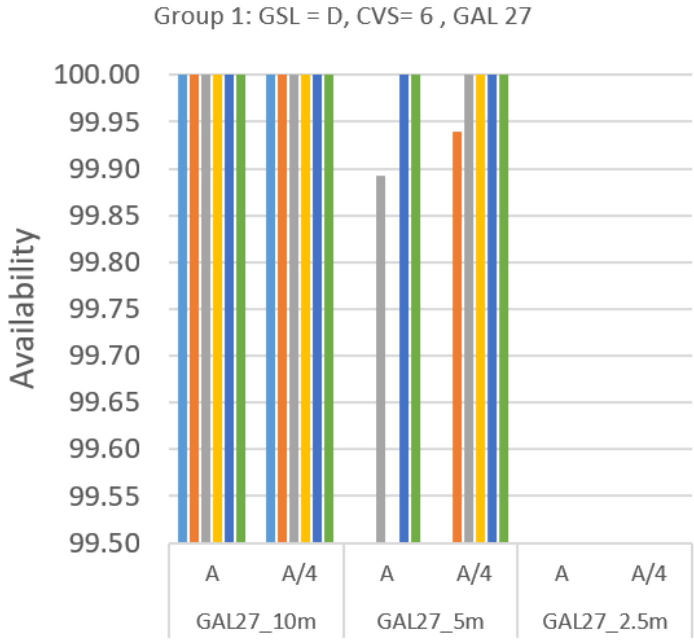

Figure 6.
Availability of GBAS, 6 CVS, Galileo 27 satellites.

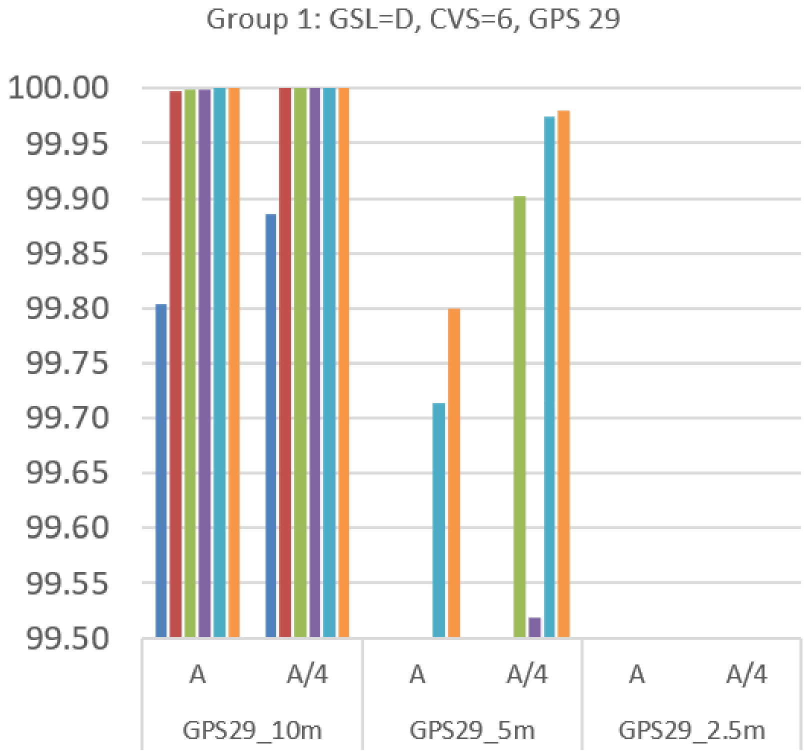

Figure 7.
Availability of GBAS, 6 CVS, GPS 29 satellites.

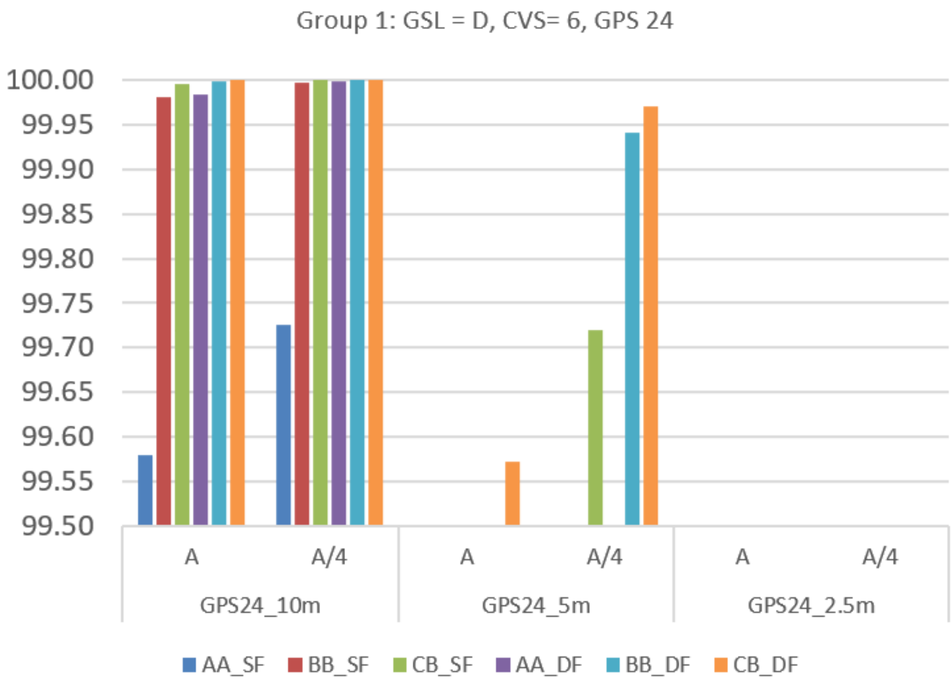

Figure 8.
Availability of GBAS, 6 CVS, GPS 24 satellites.

3.2. GBAS Availability with 2 Critical Satellites

In major group 2, using 2 allowable CVS in the three constellations, as seen in figures 9, 10, and 11, for Galileo 27 satellites, GPS 29 satellites, and GPS 24 satellites respectively. The main observation in group (2) here is a noticeable degradation in GBAS availability. The reason behind that is the critical satellite concept; this means that the number of allowed critical satellites used in the availability calculations for Group (1) was 6, whereas in Group (2) we used only 2, which will reduce the availability. The critical satellites are those satellites which, when removed from the XPL computations, would cause the XPL to rise above the alert limit. This decreases the availability of the system. However, at the same time, allowing more critical satellites in the XPL availability computation will reduce the continuity availability as well as degrade response. Therefore, the number of critical satellites should be optimized to compromise the availability. The maximum decrement in the response of availability was 47%, and the minimum was about 4% with respect to availability measured in Group 1 using 6 CVS.

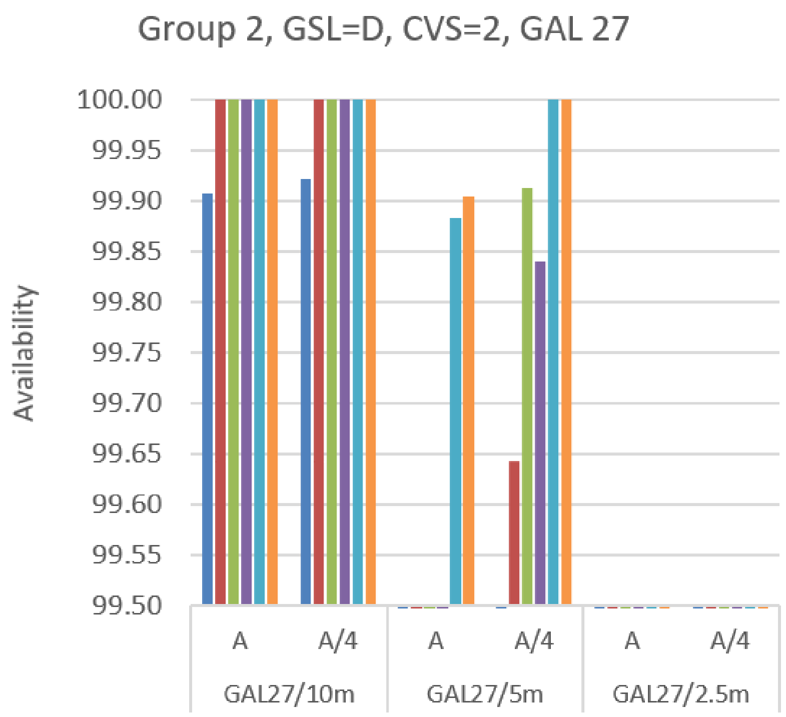

Figure 9.
Availability of GBAS, 2 CVS, GAL 27 satellites.

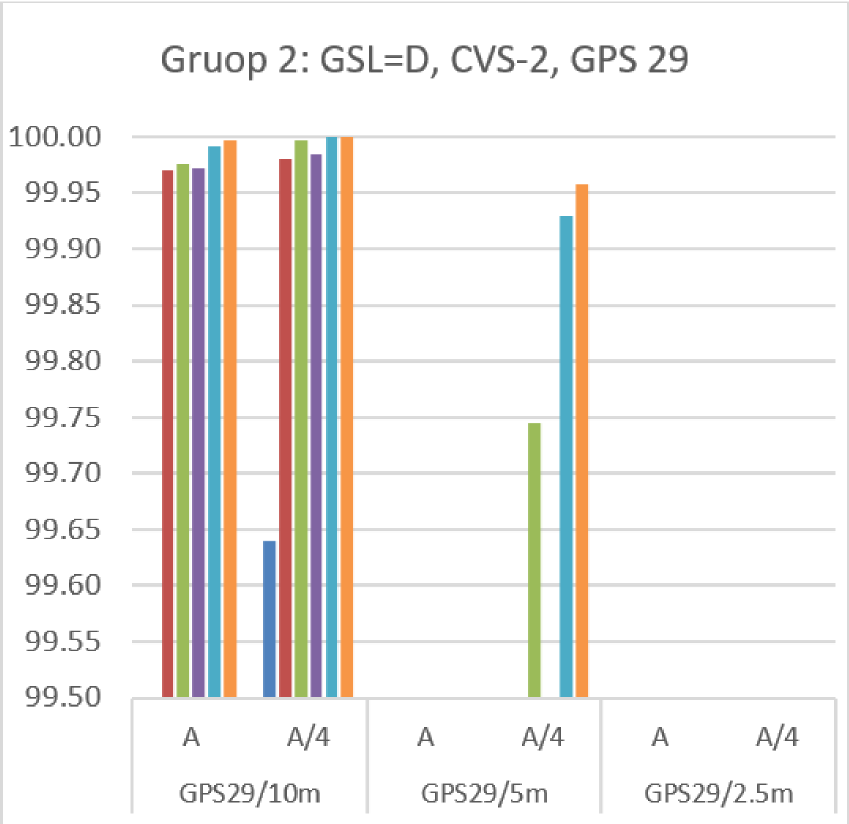

Figure 10.
Availability of GBAS, 2 CVS, GPS 29 satellites.

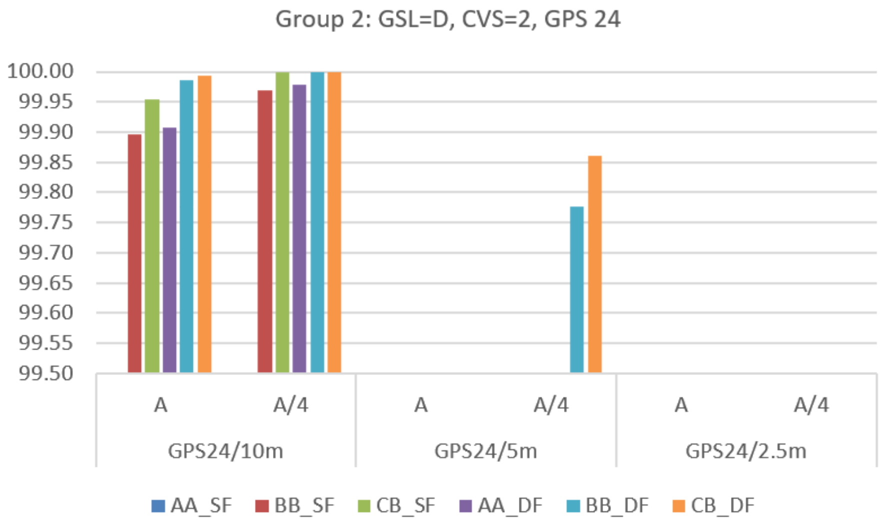

Figure 11.
Availability of GBAS, 2 CVS, GPS 24 satellites.

3.3. GBAS Availability with 10 Critical Satellites

In the parameters' group 3, using 10 allowable CVS in the three constellation types, as seen in figures 12, 13, and 14, for Galileo 27 satellites, GPS 29 satellites, and GPS 24 satellites respectively. The main observation in group (3) is a noticeable increment in availability as well as an increment in response in each parameter set. The reason behind that is the critical satellite concept; this means that the number of allowed critical satellites used in the availability calculations for Group (1) was 6. Here in Group (3), we used 10, which will increase the availability and decrease the availability of the system. However, at the same time, allowing more critical satellites in the XPL availability computation will reduce continuity. The maximum improvement in the response of availability was 46%, and the minimum was about 3% with respect to availability measured in Group 1 using 6 CVS.

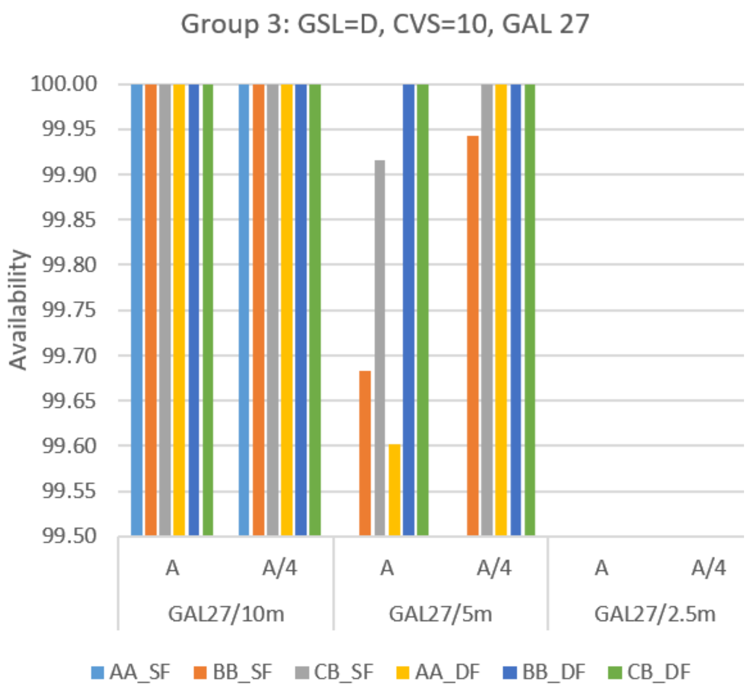

Figure 6.
Availability of GBAS, 10 CVS, GAL 27 satellites.

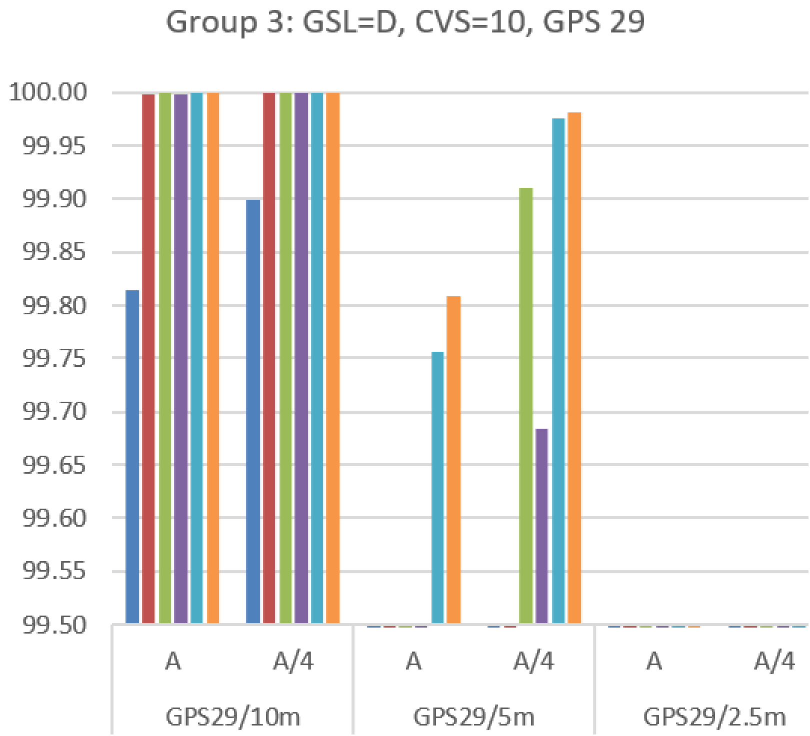

Figure 7.
Availability of GBAS, 10 CVS, GPS 29 satellites.

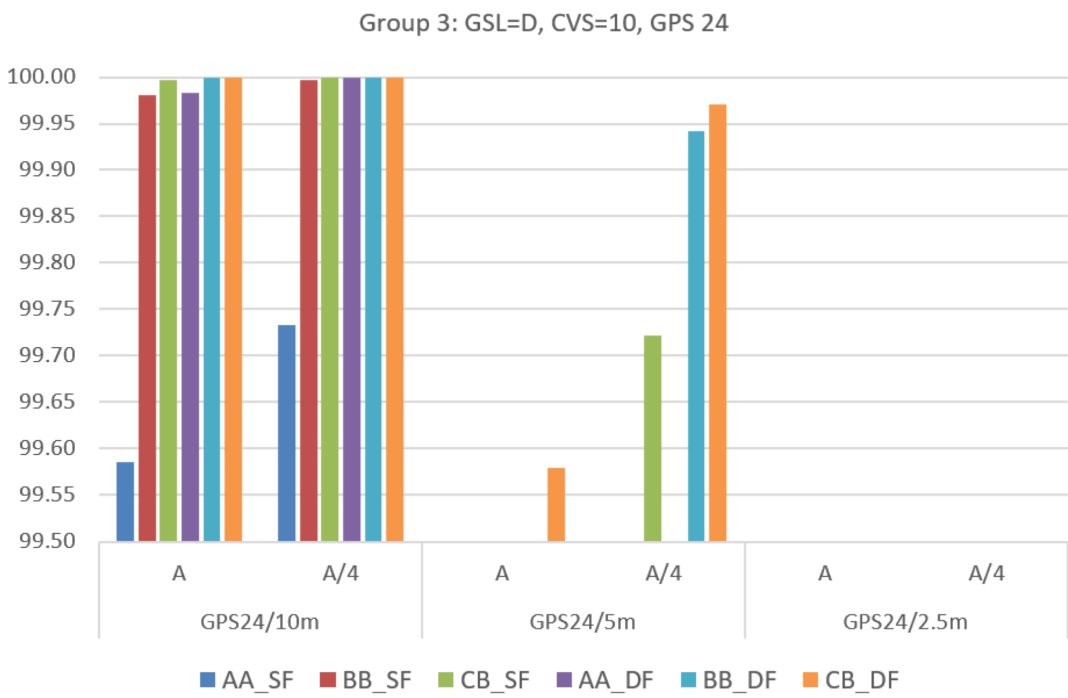

Figure 8.
Availability of GBAS, 10 CVS, GPS 24 satellites.

4. Discussion and Analysis

In order to show the impact of the allowable critical satellites number on the availability of GBAS subsystems in all configurations and with all selected GNSS constellations, a joint analysis is performed across the three groups. We have used three major groups as mentioned before, each with a different number of allowed critical satellites: 6, 2, and 10. It was clear that the increase in the allowed number of critical satellites will cause an increase in availability in general; this was explained in the concept of critical satellites in group (2). This decreases the availability of the system, but at the same time, allowing more critical satellites in the XPL availability computation will reduce continuity. Many cases were noticed to change in availability performance due to the allowable critical satellites number. To simplify the analysis, Group (1), which consists of 6 critical satellites, was considered as the reference group of the analysis, and then we varied the critical satellites number to both 2 in group 2 and 10 in group 3. The changes were recorded in tables in Appendix B. Factors that

played a role in UMPE mitigation levels in these tables are the constellation type and the configuration type of GBAS subsystems. Another point of view to see the changes is listed in the following two comprehensive tables; in these tables, the impact of critical satellites is clearly shown. In general, the change of 4 critical satellites, more or less than 6, will cause an availability swing of around 45% up or down from the referenced 6 CVS. That means reducing the number to 6 for CAT-II/III (GAST-D/E/F) would be a reasonable value to start with. The number of allowed critical satellites impacts proportionally the achieved availability. For sure, more investigations are needed in the future to state such a number.
Furthermore, we have found the following results as well:

- Simulations showed significantly improvement of all the selected GNSS constellation in availability of GBAS if the multipath error mitigation (A/4) is achieved in comparison with A level.
- There was a strong positive impact on the availability of the GBAS system in the lower VAL values compared to the visible impact in the middle VAL values and a minor impact in the higher VAL values.
- Galileo has more sensitive in response over GPS performance does.
- Dual Frequency receivers have higher availability and greater improvement, in both the maximum and the average, than the Single Frequency receivers.
- Major responses in availability due to critical satellites are varying in CB, BB configurations against less improvement responses in AA configuration.

5. Conclusion

In this research, we have simulated the effect of the number of critical satellites, as it is a determinant factor for the availability of service continuity in the GBAS GAST-E/F standardization process. This paper aims to simulate the required allowable number of such critical satellites to achieve GAST-E performance using GPS L1 and Galileo E1 frequencies. The GBAS parameters in the ICAO model were systematically grouped into three groups, using 6, 2, and 10 critical satellites for each group. A validated simulation tool used in a previous study has been reused for this purpose. The results show the feasibility of achieving GAST-E with 6 critical satellites, down from 10 standardized for GAST-C. A further investigation using 2 critical satellites was also proposed, with lesser continuity availability. Results show that a change of 4 critical satellites, more or less from 6, would cause a proportional change of nearly 45% in GBAS system availability. Consequently, this research would pave a step ahead in the standardization process for the higher performance of GBAS-based navigational instruments.

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