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Assessing Availability of GNSS-GBAS Landing Systems in GAST-D/F Performance

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Abstract

The Ground-Based Augmentation System (GBAS) has been recently approved as CAT II performance (GBAS Approach Type D (GAST-D)) for the precision approach operations, and by using the GPS signals only. But the requirements of CAT III performance (GAST-F) are tended to be approved using dual Constellation by adding the European Galileo system. In this research, the availability of CAT III was assessed using Galileo system. A simulation tool was used to estimate which level of integrity and accuracy is needed for CAT II and CAT III performances, considering the new innovated Binary Offset Carrier (BOC) modulation and the increased power of +6 dB in Galileo signals. The results showed a promising performance of Galileo over Europe space.

Keywords:

GNSS, GPS BIII, Galileo, GBAS, GAST-D/F, CAT II/III, BOC

1 Introduction

The first version of GBAS CAT I performance in so-called GBAS Landing System (GLS) was certified in 2002 by the International Civil Aviation Organization (ICAO) [1], and it was technically detailed in [2]. Afterwards, many systems were deployed in CAT I performance and have been operated successfully in many airports since that time. However, the worldwide research had continued for achieving CAT II performance certification since that time until it was approved in Nov 2020. Its approval was conditioned by using GPS constellation only [3, 4], but it is still not foreseen for CAT III performance, or the newly called GAST-F performance. Furthermore, this latest CAT III/ GAST-F performance is tended to be approved if and only if dual constellation is being used.

A previous study [5] showed that the assumption of having dual constellation is subjected to certain factors, such as: firstly, the delay in time due to phase measurements during phase combination at the receiving antenna, which might cause

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minimizing the accuracy of the (Positioning Navigation & Timing) (PNT) information, or/and minimizing the margin below the stringent Vertical Alert Limits (VAL) in the integrity availability. Secondly, the complexity of using the multichannel receivers can also cause further delay in time. Thirdly, for political reasons, dependence on the own national GNSS constellation would add a significant value of independency in terms of Politics, Economics and Security [6]. On the other hand, the President of the United States of America signed a new Executive Order (EO) on the (PNT) services in Feb. 2020, in which he was encouraging the development of a resilient PNT infrastructure that is not exclusively reliant on the U.S. Global Positioning System GPS. The aim of the EO is to motivate all providers to search for alternatives of such critical infrastructure [7]. However, many of the recently published researches have conducted GBAS coverage individually over certain airports, but neither worldwide, nor over European sky. It is important to note that such regional coverage does not help significantly in the certification process needed by the high organizations bodies, such as the ICAO or the Federal Aviation Agency FAA.

In terms of GBAS implementation, the GBAS is currently being implemented as a non-federal system in USA, there is neither any currently planned FAA acquisition for CAT I or CAT III GBAS, nor the non-federal sponsors (i.e. airports) who would fund the system procedure development. But the deployment is still driven by the user and sponsor interest and investment only, with no FAA deployment schedule in place [8]. Nevertheless, many countries worldwide are still using the system, or tend to use it, one example is the Turkish airlines [9].

Based on the above facts and motivations, the main objective of this paper was to examine the usage of a single constellation in GBAS landing systems, assuming that the potential improvements made in the capability of the newly innovated European Galileo system would meet the GAST-D/F requirements, especially over European space at least. The results showed a better performance of Galileo over the GPS performance, particularly over the same targeted space of Europe.

The structure of this paper started with the availability calculations in GBAS infrastructure, which was followed by the GBAS parameters' assumptions for the errors' contributions in the total error budget. Then an explanation of the simulations runs was interpreted. Afterwards, the results of the availability of the GBAS System were analysed in both ways, firstly, globally over the whole world space, and secondly, over European and USA space separately. Finally, the conclusions were summarized and stated.

2 Availability Calculations in GBAS Infrastructure

In accordance to the recent studies [10, Ch. 7], and [11, pp. 273-295], the Critical Space Infrastructure (CSI) was clearly illustrated, shedding the light on the navigational space. The aircraft subsystem corrects its own pseudo-range measurements for each satellite with the differential correction data received from the ground subsystem. The corrected pseudo-range measurements are then used to more accurately determine the aircraft's position relative to the selected Final Approach Segment (FAS).

Similarly as in the Communication Infrastructure (CI) protection techniques, the GBAS system is broken down to four types of data links as follows: the Space-Ground data downlink, the Space-Aircraft data downlink, the Ground-Aircraft data uplink and the Ground-ATC data link. They are established in order to examine the GBAS system's performance availability as seen in Fig. 1.

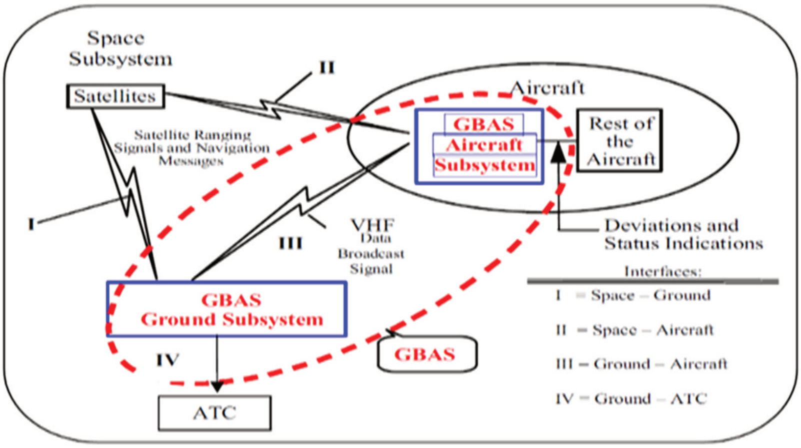

Fig. 1 GBAS System Infrastructure Overview

The required performance of GBAS system is summarized in Tab. 1.

Tab. 1 GSL Required Performance [Edited by author as derived from 1, 2]

Performance Requirements	**GBAS Service Level**	**Accuracy**		**Integrity**				**Continuity**
		Lateral NSE 95 %	**Vertical NSE 95 %**	**Integrity Probability**	**Time to Alert**	**Lateral Alert Limit**	**Vertical Alert Limit**	**Continuity Probability**
CAT I	C	16.0 m (52 ft)	4.0 m (13 ft)	$1\text{-}2\times10^{-7}$ in any 150 s	6 s	40 m (130 ft)	10 m (33 ft)	$1\text{-}8\times10^{-6}$ in any 15 s
CAT II/IIIB	D	5.0 m (16 ft)	2.9 m (10 ft)	$1\text{-}1\times10^{-9}$ in any 15 s vert., 30 s lat.	2 s	17 m (56 ft)	10 m (USA) 5/2.5 m EU	$1\text{-}8\times10^{-6}$ in any 15 s
	E	5.0 m (16 ft)	2.9 m (10 ft)	$1\text{-}1\times10^{-9}$ in any 15 s vert., 30 s lat.	2 s	17 m (56 ft)	10 m (USA) 5/2.5 m EU	$1\text{-}4\times10^{-6}$ in any 15 s
	F	5.0 m (16 ft)	2.9 m (10 ft)	$1\text{-}1\times10^{-9}$ in any 15 s vert., 30 s lat.	2 s	17 m (56 ft)	10 m (USA) 5/2.5 m EU	$1\text{-}2\times10^{-6}$ in any 15 s vert., and $1\text{-}2\times10^{-6}$ in any 30 s lat.

Availability is the portion of time during which the service can be used for CAT I, CAT II, or CAT III operations with reliable navigation information presented to the crew, autopilot, and other systems managing the flight of the aircraft. For GBAS, the availability is given by a combination of the space subsystem availability, the ground availability, and aircraft subsystems availability. In order to provide the same level of performance as an equivalent to conventional Instrument Landing System (ILS), the availability for the different operations supported by the GBAS system shall meet 99.99 % for CAT II/III and 99.75 % for CAT I. Any landing system availability can be defined by Eq. (1):

$$A = A_{\mathrm{P}} \times A_{\mathrm{F}} \times A_{\mathrm{M}} \tag{1}$$

where for Instrument Landing System (ILS) CAT I, the following values have been considered by the experts in GBAS infrastructure evaluations: A = 0.9975 for the following assumed values: A_{P}: is the fault free system availability and set to 1. Then, A_{F}: is the availability of the ground and aircraft subsystems, as determined by the Mean Time Between Outages (MTBO) and the Mean Time To Repair (MTTR) values.

For ILS CAT I, the ICAO Annex 10 requires 500 h for the MTBO of the ground subsystem (1 000 h for the Localizer and 1 000 h for the Glide Path), which results in a 0.998 factor and it was considered a 2 000 h MTBO for the airborne subsystem, with 1h MTTR, which gives 0.9995. The product is 0.9975. Also, A_{M} is the availability of the ground and aircraft subsystems, taking into account scheduled maintenance operations. This factor is set to 1.

In analogy to ILS, for GBAS CAT I case, Eq. (1) can be used for GBAS also, if: A_{P} takes into account the ranging sources constellation and the accuracy performances of the ground and airborne subsystems. This could be considered as the "Geometry-dependent" component of the availability. Again, the scheduled maintenance operations for the space segment are included in A_{P}.

To be consistent with the continuity of service requirement of 1 to 3.3×10^{-6}, the ground subsystem MTBO will be better than 1 263 h, where the continuity of service is given by the ratio of exposition time 15 s over MTBO. Considering a 1 h MTTR, this gives the following ground subsystem availability in Eq. (2):

$$\frac{\mathrm{MTBO} - \mathrm{MTTR}}{\mathrm{MTBO}} = 0.9992 \tag{2}$$

Considering an aircraft subsystem availability of 0.9995, which would be equivalent to ILS receiver, the resulting figure of A_{F} is equal to 0.9987. Considering an aircraft subsystem availability of 0.9995, which will be equivalent to ILS receiver, the resulting figure of A_{F} would be: A_{F} = 0.9987. In order to achieve a global availability figure of 0.9975, the minimum value for A_{P} is equal to 0.9988.

For CAT III Systems availability, ILS CAT III case, A_{P} is the fault-free system availability, set to 1 for an ILS. A_{F} is the availability of the ground and aircraft subsystems, determined by the MTBO and MTTR values. For an ILS CAT III, the requirements for the MTBO are 4 000 h for Localizer LLZ and 2 000 h for Glide path GLI, and MTTR is 1 h. See Eq. (3):

$$A_{\mathrm{gnd}} = 1 - \left[\left(1 - \frac{\mathrm{MTBO}_{\mathrm{LLZ}}\text{-}\mathrm{MTTR}}{\mathrm{MTBO}_{\mathrm{LLZ}}} \right) + \left(1 - \frac{\mathrm{MTBO}_{\mathrm{GLI}}\text{-}\mathrm{MTTR}}{\mathrm{MTBO}_{\mathrm{GLI}}} \right) \right] = 0.99925 \tag{3}$$

For the airborne part, the MTBO is 2 000 h, $A_{\mathrm{air}} = 0.9995$. Therefore, $A_{\mathrm{F}} = 0.99875$ (99.875 %). A_{M} is the availability of the ground and airborne subsystems, taking into account scheduled maintenance operations. This factor is set to 1, considering that the maintenance is performed when the system is not needed. Therefore, for ILS CAT III, the required availability is A = 99.875 %.

In GBAS case; A_P is the fault-free system availability (set to 1 such as for an ILS). It takes into account the ranging sources geometry and the accuracy performance of the ground and airborne subsystems. A_F is the availability of the ground and aircraft subsystems. In order to be consistent with the continuity of service requirement ($1\text{-}2\times10^{-6}$/15 s, i.e. MTBO of 2 083 h), and considering a MTTR of 1 h, the ground subsystem availability will be A_{gnd} = 0.99968. By keeping the same airborne subsystem availability (0.9995, MTBO 2 000 h), AF would be equal to 0.99918. In order to meet a global availability figure equivalent to the CAT III ILS of (99.875 %), A_P would be equal to or greater than 0.99957, which is nearly 99.96 %.

This figure assumes that there is a unique operation at a given time, and the alternate airport is equipped with an available means of landing in case of rerouting. The multiple and simultaneous landing operations are not addressed. However, additional margins should be added to this a priori requirement. For this reason, even if the initial aim is to meet the availability figure of 99.96 %, the more symbolic figure of 99.99 % will be demanded. The recommended A_P would be equal to or greater than 0.9999, and the availability A would be equal to or greater than 99.99 %.

3 GBAS Parameters' Assumptions

The currently used error models described in [1] and [2] have been defined for airborne and ground receivers in the configuration of GPS L1 C/A signal with a first order code-carrier filter (100 s time constant). However, the important differences between the current GPS L1 signal and the new expected signals to establish the model of expectable ranging measurement performance are summarized in the following Tab. 2.

Tab. 2 Ranging measurement performance [1, 2]

	Galileo			**GPS**	
	E1	E5a	E5b	L1 C/A	L5
Chipping rate [MHz]	2	10	10	1	10
Power [dBw]	−155	−155	−155	−160	−154

It takes the advantages of the transmitted power (+6 dB compared to GPS C/A), code chipping rate (2 MHz for Galileo E1 and 10 MHz for Galileo E5), code modulation (BOC for Galileo E1), frequency band E5 and its major interference (DME/TACAN in Galileo E5). Also, it takes the advantages of using a narrow correlator with BOC signal with a 2 MHz chipping rate signal. In GBAS Applications, and as derived from [2], the GPS differentially corrected pseudo-range measurement model for satellite i is given by Eq. (4):

$$\sigma_i^2 = \sigma_{\text{pr-ground}-i}^2 + \sigma_{\text{trobo}-i}^2 + \sigma_{\text{iono}-i}^2 + \sigma_{\text{air}-i}^2 \tag{4}$$

where

$\sigma_{\text{pr-ground}-i}^2$ is the total (post correction) fault free noise term provided by the ground function (via VHF Data Broadcasting (VDB)) for satellite i,

$\sigma_{\text{trobo}-i}^2$ is the term value computed by the airborne equipment to cover the residual tropospheric error for satellite i,

$\sigma^2_{\text{iono}-i}$ is the residual ionosphere delay (due to spatial decorrelation) uncertainty for the i^{th} ranging source.
$\sigma^2_{\text{air}-i}$ is the standard deviation of the aircraft contribution to the corrected pseudo-range error for the i^{th} ranging source. The aircraft contribution includes the receiver contribution and standard allowance for airframe multipath.

The standard deviation of the aircraft contribution error is given by Eq. (5):

$$\sigma^2_{\text{air}-i} = \sqrt{\sigma^2_{\text{receiver}-i}\left(\theta_i\right) + \sigma^2_{\text{multipath}-i}\left(\theta_i\right)} \tag{5}$$

where $\sigma^2_{\text{receiver}-i}\left(\theta_i\right)$ is the standard allowance for the receiver error, and the $\sigma^2_{\text{multipath}-i}\left(\theta_i\right)$ is the standard allowance for the multipath error.

Due to the new expectation of enhanced performance of the GPS/Galileo constellations, the GBAS parameters assumptions will be applied to the following designators: the Ground Accuracy Designator parameters (GAD), the Airborne Accuracy Designator parameters (AAD) and the Airframe Multipath Designator (AMD), for the Ground Accuracy Designator parameters (GAD), and the Root Mean Square RMS of the total non-aircraft contribution to the GPS/GBAS error as a function of the elevation angle which is given in [2], p. 31, Eq. (6):

$$\text{RMS}_{\text{pr-grnd-GPS}}\left(\theta_i\right) \le \sqrt{\frac{\left(a_0 + a_1 \mathrm{e}^{-\theta_i/\theta_0}\right)^2}{M} + a_2^2} \tag{6}$$

where M is the number of ground reference receiver subsystem, i is the i^{th} ranging source, a_0, a_1, a_2 and i are the parameters determined by Tabs 3 and 4 shown below.

Parameters in Tab. 3 are assumed to present the basic GBAS error model [2], p. 31. Each letter of the ground accuracy designator letters A, B, or C is associated with the performance of the ground subsystem reference receiver and the number of the reference receivers. These values are assumed to represent the single frequency configuration of the ground subsystem, or in other words the low/mid accuracy configuration. If they were mitigated, then they are assumed to represent the dual frequency configuration (or high accuracy configuration) as seen in Tab. 4 and plotted in Fig. 2, in which the upper curve resembles the standard model of low accuracy, and the other three lower curves resemble the advanced accuracy for GAD A, B, and C when the errors had been degraded by factors from 1 to 0.25.

Tab. 3 Basic GBAS Performance (low accuracy/Single Frequency) [1, 2]

Ground Accuracy Designator (GAD)	θ_i **[°]**	a_0 **[m]**	a_1 **[m]**	θ **[°]**	a_2 **[m]**
Letter A	> 5	0.5	1.65	14.3	0.08
Letter B	> 5	0.16	1.07	15.5	0.08
Letter C	> 35	0.15	0.84	15.5	0.04
	≤ 35	0.24	0.24	—	0.04

The same technique has been done for Airborne Accuracy Designator Parameters (AAD) and Airframe Multipath Designator (AMD) the upper curve resembles the standard model of low accuracy in AMD, and the other lower curves resemble the advanced accuracy when the errors had been degraded by factors from 1 to 0.10 levels (Fig. 3).

Tab. 4 Basic GBAS Performance (high accuracy/Dual Frequency) [1, 2]

Ground Accuracy Designator (GAD)	θ_i [°]	a_0 [m]	a_1 [m]	θ [°]	a_2 [m]
Letter A	> 5	0.25	0.825	14.3	0.04
Letter B	> 5	0.08	0.504	15.5	0.04
Letter C	> 35	0.075	0.42	15.5	0.02
	≤ 35	0.12	0.12	—	0.02

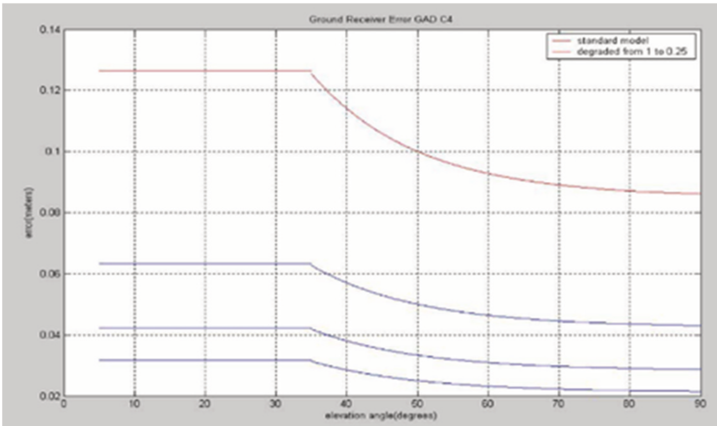

Fig. 2 Mitigated GAD

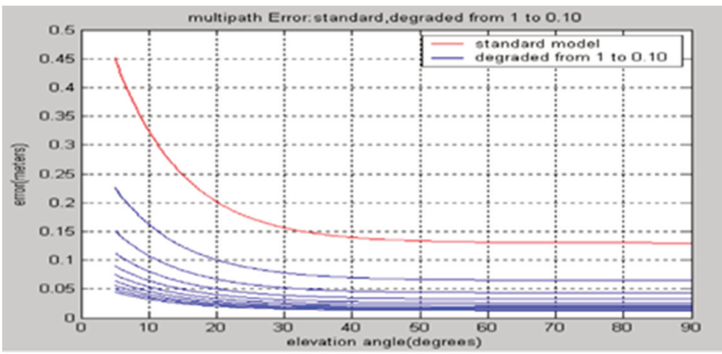

Fig. 3 Mitigated AMD

The multipath mitigation levels were assumed to be extended to four levels, and they vary with other combinations. This has been done to investigate the impact of the multipath error along with other errors. The user multipath error was chosen to be varied because it is the only error with major effect during the landing phase of flights. The chosen levels are as follows: A: the standard level, A/2(B): the currently used level, A/4: the visible level due to the modified mitigation methods, and A/10: the far future level, due to the performance enhancements of the extra +6 dB power and the BOC signals.

Furthermore, the tropospheric and ionosphere parameters are assumed to be taken as seen in Tab. 5 according to [1, 2] for both GPS and Galileo to offset the comparison between them. In Tab. 6 the common parameters are shown.

Tab. 5 Ionospheric and Tropospheric Parameters' assumption [1, 2]

Parameter	Value of the parameter	Reference
Convergence time of the smoothing filter (τ)	100 s	[2] appendix F, p. F-2
$K_{\text{md\_e\_CAT1,GPS}}$	5 (0 to 12.75)	[1] Tab. B-71, p. B-89
$V_{\text{vert\_iono\_gradient}}$	4×10^{-6}	[2] appendix F, p: F-5 (Eqs 3-76, sec. 3.3.2.15, p. 64)
x_{air}	5 400 m, for GSL=D&F (6 000 m, for GSL=C)	
v_{air}	72 m/s, for GSL D&F (77 m/s, for GSL C)	
V_{tropo}	VN =0	[2] appendix F, p:F-5 (Eqs 3-75, sec. 3.3.2.14, p. 64)
Decorrelation factor, P	0.00015m/m	[2] appendix F, p. C-2
Δh	200 m, 500 m, for FAF 15 m, for CAT III	

Tab. 6 Common parameters' assumptions [1, 2]

Parameter	Value of the parameter	Reference
Max. service volume	43 km	[1] amend. 77 Sec. 3.7.3.5.4.4.2.2, p. 42F [2] sec. 2.3.2, p. 17
Runway heading	100°	arbitrary
Glide path angle	2.7°	[2] sec. 2.3.2, p. 17
Time of approach phase (FAS)	150 s	[2] appendix, p. C-2
Critical satellites	Max = 6, GSL = F	[2] Tabs 3-13
Availability threshold	VNSE=2.9 m LNSE=5 m	[2] sec. 2.3.11, pp. 15, 16 Tabs 2-2, and 2-3.
Reference receivers	4	[1] Tab. B-71, p. B-89
Geographic coverage area	90° N to 90° S 180° E to 180° W	Global Coverage assumption.

4 Simulations Runs (Planning Topology and Performing)

Simulations operations have been planned in a systematic method that took into account grouping the selected parameters in a suitable and methodical approach, see Fig. 4. The parameters contain the following: dependency on constellation (Galileo 27, GPS 29), dependency on vertical alert limits (10 m, 5 m, and 2.5 m), dependency on receiver(s) accuracy designators GAD/AAD (AA, BB, CB), dependency on user receivers performance (SF, DF), dependency on airborne multipath designator (AMD) mitigation levels (A, A/2, A/4 and A/10).

Tab. 7 shows the average time needed for each simulation process, and Tab. 8 shows the numbers of the performed simulation in this study.

The used simulation tool is called AVIGA and it is a software program for the analysis of visibility, integrity, geometry, and availability of any GNSS systems. AVIGA is running under WIN98/NT/2000/XP and requires approximately about 30 MB of disk space. It has two calculation steps as seen in Figs 5 and 6 and its algorithm is shown in Fig. 7.

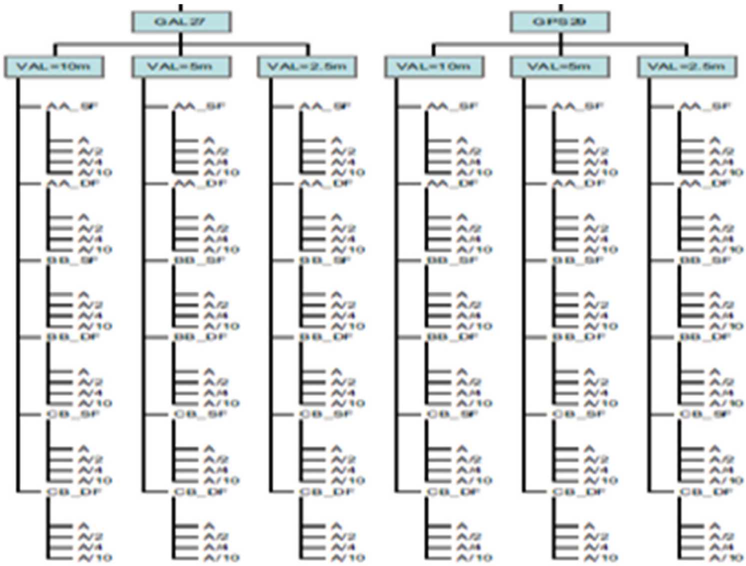

Fig. 4 Simulation group tree combinations

Tab. 7 Average time needed for each simulation process

Simulation operation type	**Operation time**
Simulation with Galileo 27 satellites constellation 10 days' trajectory, 60 s, step: 5×5 grid	9 h
Simulation with Galileo 27 satellites constellation 2.33 days trajectory, 60 s, step: 5×5 grid	3 h
Simulation with GPS 29 satellites constellation 1 day trajectory, 60 s, step: 5×5 grid	1 h
Simulation management (preparing parameters, editing after completing the calculation, saving)	5 min

Tab. 8 Performed number of simulations' runs

Simulation operation type	**Number of single operations**
Test and validation of the AVIGA simulation tool	25
Galileo 27	75
GPS 29	75
WG-28 (Galileo + GPS)	50
Special cases	40
Total	265

Fig. 5 AVIGA step 1: Trajectory calculation

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Fig. 6 AVIGA step 2: Specific operation calculation

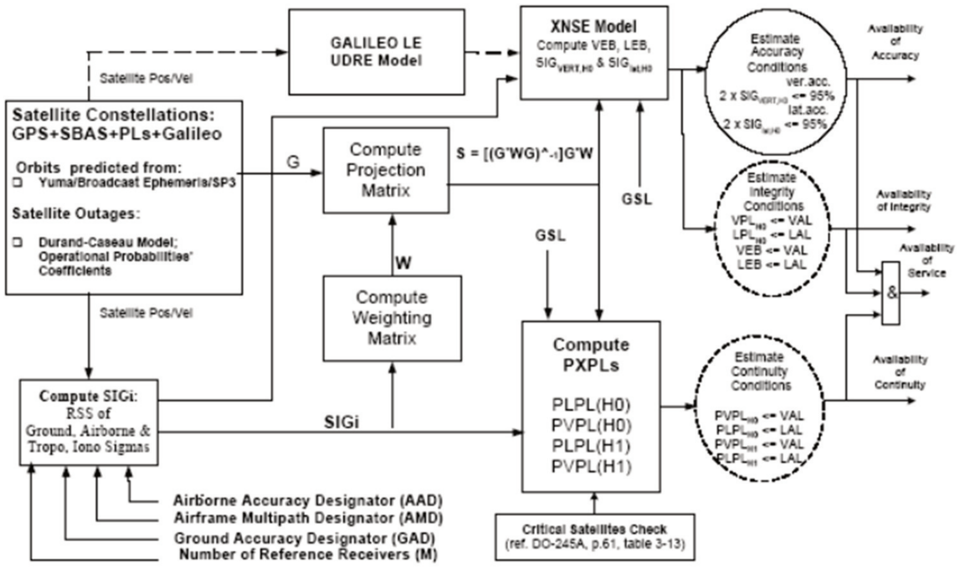

Fig. 7 AVIGA GBAS model scheme/algorithm [as per its designer]

5 Results Analysis

5.1 Global Coverage of GNSS/GBAS Application

First of all, the input parameters used for this research took into consideration the number of critical satellites to be 6 for all the simulations, and the Vertical Alert Limits (VAL) values to be 10 m, 5 m, and 2.5 m for both constellations: GPS and Galileo. The critical satellite number was chosen to be moderate; that is why it was chosen to be 6. The critical satellites are satellites which, when removed from the protection level computations, would cause them to rise above the alert limit. This decreases the availability of the system. But at the same time, allowing more critical satellites in the availability computation will reduce the continuity. The main results are shown in Fig. 8 and interpreted in Tab. 9.

The letters A, A/2, A/4, or A/10 are the chosen multipath mitigation levels with associated parameters to meet the desired availability of 99.75 % or 99.99 % in GBAS applications. The letters VC mean Very Close to the 3rd UMPE mitigation level A/10 (availability > 99.00 %). The letter C means Close to the 3rd UMPE mitigation level A/10 (98.00 % < availability < 99.00 %). The letter V means Visible (< 95.00 % availability < 98.00 %), while the letters NV mean Not Visible (availability

< 95.00 %). The letters NV mean Not Visible at all, they represent the cases in which availability is neither achieved by the chosen UMPE mitigation levels, nor visible to be achieved.

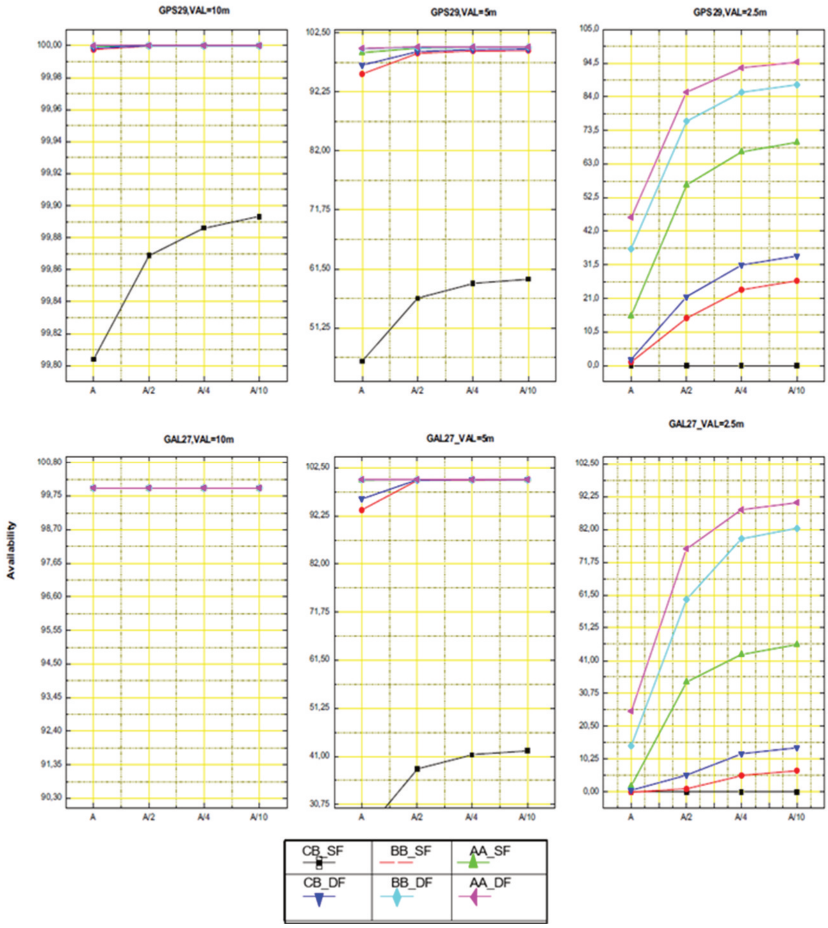

Fig. 8 Main Results of availability of GPS and Galileo systems

Tab. 9 UMPE mitigation levels needed per configuration

VAL [m]	Constel-lation Type	**User Multipath mitigation level needed to meet Aeronautical Availability**											
		99.99 %						99.75 %					
		AA_SF	BB_SF	CB_SF	AA_DF	BB_DF	CB_DF	AA_SF	BB_SF	CB_SF	AA_DF	BB_DF	CB_DF
10	Galileo 27	A	A	A	A	A	A	A	A	A	A	A	A
	GPS 29	VC	A	A	A	A	A	A	A	A	A	A	A
5	Galileo 27	NV	VC	A/2	A/4	A	A	NV	A/2	A	A/2	A	A
	GPS 29	NV	VC	VC	VC	VC	A/10	NV	VC	A/2	VC	A/2	A
2.5	Galileo 27	NV	NV	NV	NV	NV	V	NV	NV	NV	NV	NV	V
	GPS 29	NV	NV	NV	NV	NV	V	NV	NV	NV	NV	NV	V

The main research results are as follows:

- for VAL = 10 m, globally, all the Dual Frequency (DF) GBAS configurations using all single GNSS constellations have achieved both 99.75 % and 99.99 % availability requirements, i.e. GAST D/E/F. On the other hand, all Single Frequency (SF) CB configurations with all single GNSS constellations have achieved 99.75 % availability only, i.e. GAST-D performance only,
- for VAL = 5 m, globally, Galileo constellation achieved 99.75 % availability with all DF GBAS configurations. Since GPS 29 achieved 99.75 % availability with CB-DF configuration only, it needs A/2 UMPE mitigation level with BB-DF configuration. However, Galileo constellation achieved 99.99 % availability in all GBAS configuration except in AA-DF configuration (it needs A/4 UMPE mitigation level). Nevertheless, GPS 29 constellations are very close (VC) to achieve 99.99 % availability and could achieve it with A/10 UMPE mitigation level in CB-DF configuration. On the other hand, and for Single Frequency SF Configuration, all GNSS constellations could achieve neither 99.75 % availability, nor 99.99 % availability with AA-SF configuration. Both GNSS constellations are very close (VC) to achieve 99.99 % and 99.75 % availability with BB-SF configuration, except Galileo could achieve 99.75 % availability only with A/2 UMPE mitigation level. All constellations are very close (VC) to achieve 99.99 % availability using CB-SF configuration, but Galileo constellation could achieve it by A/2 UMPE mitigation level. Galileo constellation achieved 99.75 % availability with CB-SF configuration, whereas GPS 29 constellation could achieve it by A/2 UMPE mitigation level,
- for VAL = 2.5 m, both GNSS constellations with all GBAS configurations are not visible (NV) to achieve 99.75 % nor 99.99 % availability on both SF and DF for VAL = 2.5 m with the exception of CB-DF configurations in GPS 29 and Galileo constellations, they are somehow visible to achieve the 99.75 % or 99.99 % availability requirements.

5.2 Regional Coverage over Europe/USA for GNSS/GBAS Application

During the result analysis in the past section, it was noticed that some of the cases are very close to fulfil the aeronautical requirements of 99.99 % or 99.75 % availability. As we performed the simulation globally, these special cases could meet the requirement if one or more of the following factors has been varied in such a way to increase the availability: (1) some parameters are changed to better configuration of GBAS subsystems, (2) a certain level of User Multipath Error (UMPE) mitigation is applied, and (3) the size of the geographic areas is reduced.

In the case of Galileo 27 satellites constellation, the following GBAS parameters were used: Step Calculation Grid of $5° \times 5°$, Mask angle = 10°, Ground Accuracy Designator (GAD) = C, Airborne Accuracy Designator (AAD) = B, Vertical Alert Limit (VAL) = 2.5 m, Airborne Multipath Designator (AMD) = A, and User Multipath Error (UMPE) mitigation level = A/10.

To start with a logic analysis for this investigation of Galileo Constellation over European sky, we kept the following order sequence in simulation runs:

- case 1: Investigating and comparing the initial global Galileo Coverage in terms of GBAS with its Europe coverage, using the above input parameters,

- case 2: As first reduction in geographic area, the coverage was resized from the global coverage down to the European sky coverage (Latitude = 30° N to 70° N, Longitude = 12° W to 55° E), and with the use of the same parameters, but with step calculation grid of 5°◦×◦5°,

In case 1, when investigating the global coverage for Galileo, as seen in Fig. 9 below, the results showed that the availability was 92.750941 %. In addition, it was noticed that the constellation has guaranteed steady bars of the availability of 100 % over fixed areas of the globe. These areas look like stripes/ bars/sectors bounding the earth over a certain latitude. The nonguaranteed sectors are located in the north part of the earth, as well as in its south part. In the north part, they were from Lat. 06° N up to 30° N, nearly northern the Equator, and from Lat. 74° N up to the North Pole. In the south part of the earth, they were from Lat. 10° S down to 34° S, nearly southern the Equator, and from Lat. 80° S down to the South Pole.

These areas have the following characteristics: they are fixed over the same geographic areas and not varying (moving) with constellation status or with time. They are bounding the earth along the 360 Longitudes. They have the same availability values, therefore, they could be equal-availability areas. They are sloped (inclined) cliff shape, not 90° cliff shape. Their position is GBAS configuration dependent.

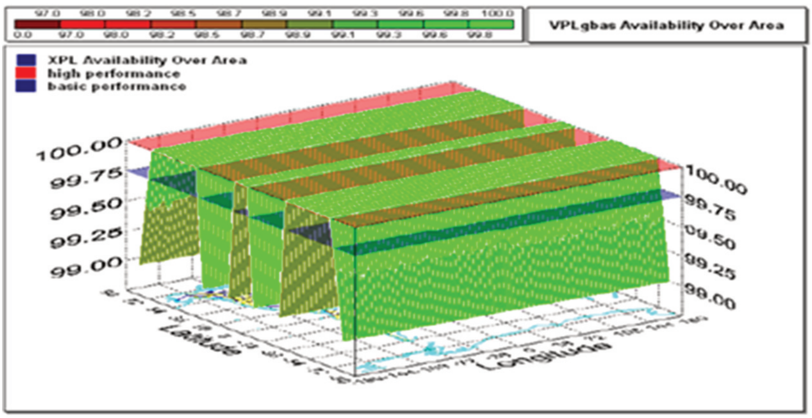

Fig. 9 3D globally availability for Galileo

The shown fixed and equal availability stripes/bars are formulated as a feature of Galileo constellation which consists of three orbits with 120° apart, each orbit having 9 operating satellites and (1 spare satellite in the future), each having periodicity of 10 days. The advantages of the fixed Equal-Availability areas could enable the possibility of operating GBAS systems located in the guaranteed availability areas, and the possibility of avoiding the nonguaranteed availability areas.

In case 2, as the reduction in geographic coverage was reduced from the global coverage down to European sky coverage, the availability improved from 92.750941 % in the global case 1 to 99.501282 % in this case 2, as shown in Fig. 10 below. As we can see, we still have a small part of the nonguaranteed stripes/bars/ areas which will cause a reduction in the availability of GBAS system over European sky.

A second round of the reduction in the geographic coverage over European sky was performed for which we have chosen the following restricted area which covers the European sky exactly: Lat. = 39° N to Lat. = 70° N and Long. = 12° W to

Long. = 55° E. A step grids of 5° × 5°, and 2° × 2° were applied, the resultant availability has increased to 100 % for both step grids. The resultant availability fulfilled the requirements of the aeronautical needs of CAT III, as shown in Fig. 11, the availability has increased due to the best parameters of the used configuration of GBAS subsystems. The A/10 level of User Multipath Error (UMPE) mitigation was applied, as well as the size of the geographic areas was reduced to be within the guaranteed areas.

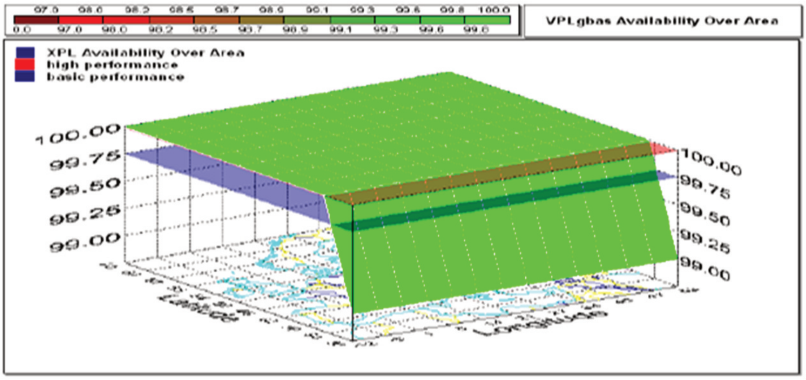

Fig. 10 Availability over Europe 30N to 70N, 5° × 5° grid for Galileo

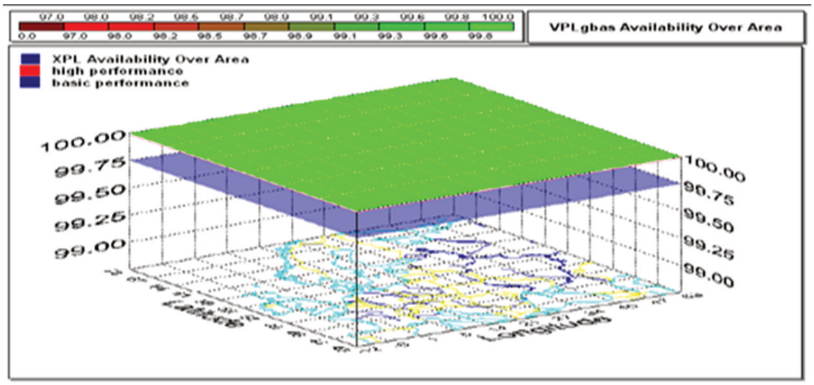

Fig 11 Availability over Exact Europe 30 N *to* 70 N, *Grid 2° × 2° for Galileo*

In order to investigate the Galileo performance over USA region, the same analysis steps were performed for the USA region, with the same input parameters compared with Galileo constellation. Nearly similar results were achieved in this analysis; the achieved availability over USA region was equal to (99.40465 %). In the best case scenario of GBAS input parameters (CB-DF), i.e. the optimized coverage areas and UMPE mitigation level of (A/10) were used in the simulations. But unfortunately, the achieved availability could not meet the aeronautical requirements of 99.99 % for GAST D/E/F. The final result of this section can be summarized as follows: the Galileo 27 constellation was able to meet the aeronautical requirements of both 99.99 % and 99.75 % (GAST-D/E/F) over European sky only with the given input parameters of the best GBAS configuration of CB-DF, and for VAL = 2.5 m (CAT III/GAST – E/F requirements), and it was very close (99.404 %) over USA sky. But the GPS 29 constellation was not capable to meet/achieve these requirements.

6 Conclusions

The requirements of GNSS/GBAS landing system CAT III performance (GAST-F) tend to be approved using the dual constellation by adding the European Galileo signals in the near future. Due to the improved signal in the space availability in Galileo signal structure, the resultant availability was promising in terms of the accuracy and integrity. The results of this research approved that any single GNSS constellation, like Galileo or modernized GPS, will not be able to achieve GAST-E/F GBAS performance globally. However, the results have also proved, by using the same simulation tool, that the European Galileo navigation system can meet the aeronautical requirements of the higher performance of GAST-F over Europe region only. The final result of this research showed that Galileo constellation was able to meet the aeronautical requirements of both 99.99 % and 99.75 % (GAST-D/E/F) over Europe space only with the given input parameters of the best GBAS configuration of CB-DF and for VAL = 2.5 m (CAT III/GAST-E/F requirements), and it was very close (99.404 %) over USA. But the modernized GPS constellation was not able to meet these requirements.

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