Galileo Performance Assessment for CAT III GBAS

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BIOGRAPHY

Boubeker Belabbas is a research fellow at the DLR (German Aerospace Center) at the Institute of Communications and Navigation at Oberpfaffenhofen near Munich. He is a PhD student at ENPC (Ecole Nationale des Ponts et Chaussées) – Paris and an external PhD student at the Technical University of Munich. He received his MSc degree in Mechanics and Energetic from the Ecole Nationale Supérieure d'Electricité et de Mécanique at Nancy (France) in 1995 and a specialised "mastère" in Aerospace Mechanics at the Ecole Nationale Supérieure de l'Aéronautique et de l'Espace "SUPAERO" at Toulouse (France) in 2001. His field of work is the integrity of GNSS with its augmentations and its applicability for Safety of Life receivers.

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Dr. Michael Meurer received the diploma in Electrical Engineering and the Ph.D. degree from the University of Kaiserslautern, Germany. After graduation, he joined the Research Group for Radio Communications at the Technical University of Kaiserslautern, Germany, as a senior key researcher, where he was involved in various international and national projects in the field of communications and navigation both as project coordinator and as technical contributor. From 2003 till 2005, Dr. Meurer was active as a senior lecturer. Since 2005 he has been an Associate Professor (PD) at the same university. Additionally, since 2006 Dr. Meurer is with the German Aerospace Centre (DLR), Institute for Communications and Navigation, where he is the deputy director of the Department of Navigation. Dr. Meurer is the author of four books/book chapters, of more than 90 technical papers and inventor/owner of more than 25 patents. He is a member of VDE/ITG, senior member of the IEEE, of ION and recipient of several awards.

ABSTRACT

Landing aircrafts under low visibility conditions has always been a challenge even with conventional navigation systems like ILS (Instrument Landing System). CAT III, with GBAS (Ground Based Augmentation Systems) and GPS only can't be reached without relaxing the alarm limits and continuity requirements of air navigation. The objective of this work is to analyze the impact of Galileo in the performances of GBAS and to compare the integrity levels obtained with the requirements of CAT III under severe ionospheric gradients. Galileo is providing some promising features like the possibility offered to the aviation community to acquire 3 frequencies: L1, E5a and E5b in the ARNS band (Aeronautical Radio Navigation Service). This will augment the robustness of the complete system and will provide efficient smoothing techniques when considering also the phase observations. Another feature concerns the possibility to have a different constellation with another geometry characteristic; this would improve the Geometry Dilution Of Precision (low GDOP) and the number of visible satellite at any epoch can reach 15 or 16 when coupled with GPS. The BOC (Binary Offset Carrier) signal structure in L1 provides a high multipath rejection capacity that provides promising results at both GBAS ground subsystem and airborne receiver level. The probability of satellite outages coupled with the number of available satellites (27 + 3 spares) will dramatically improve the availability of the combined GPS and Galileo system. Different smoothing algorithms developed at Stanford University (GPS Lab) are applied: The ionosphere free and the divergence free smoothing to mitigate or even to cancel the ionosphere gradient.

The availability of the vertical protection level with respect to CAT III vertical alarm limit is analysed.

As a major result, the ionosphere free combination for a dual constellation dual frequency using an all in view satellites can fulfil CAT III with respect to the protection levels and it provides a robust solution with a very low risk of misleading information.

INTRODUCTION

It is well known that severe ionosphere gradient is the main threat for GBAS while considering precision landing of CAT III. The use of Dual frequency techniques can mitigate this threat and even suppress it. 2

smoothing techniques have been studied see [1]. This paper will investigate the impact of Galileo constellation in the availability of CAT III performances with respect to different ionosphere gradient scenarios and considering the smoothing techniques defined in [1].

A first part of the paper will introduce the general assumptions considered in the simulations and the scenario of the simulations. A second part will recall the smoothing techniques and the satellite selection strategy. The third part will present the results of the simulation and the analysis. At the end we will draw some conclusions with respect to future dual frequency, dual constellation GBAS architectures.

GBAS ARCHITECTURE AND HYPOTHESIS

GBAS Architecture

Future GBAS systems will use multi-frequency multi constellation to enable precision landing of category III. Different configurations are considered but the general architecture standardised in [2] although for single frequency GBAS, will be kept for dual frequency GBAS. It is supposed that the ground subsystem is monitoring both GPS and Galileo constellations and provides the corrections of all satellites in view to the user. A short description of the architecture is presented in the following figure:

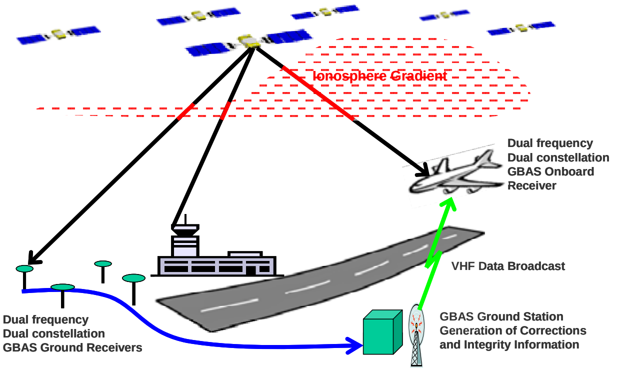


Fig. 1 : GBAS Architecture

The use of 2 constellations and 2 frequencies, will automatically increase the information to be sent to the user through the VDB link. It is assumed that the maximum capacity of broadcast through the VDB link is not reached and that the general structure of the message is not modified.

Constellation hypothesis

For our simulation, GPS will use 28 satellites (corresponding to almanac data in 2005) and Galileo is plan to have 30 satellites (use of the most recent planned almanac data)

Error model

For Galileo, the error models considered are derived from [3]. While comparing with GPS standard values [2] it appears that the error levels are in the same order of magnitude as for Galileo (see figure below).

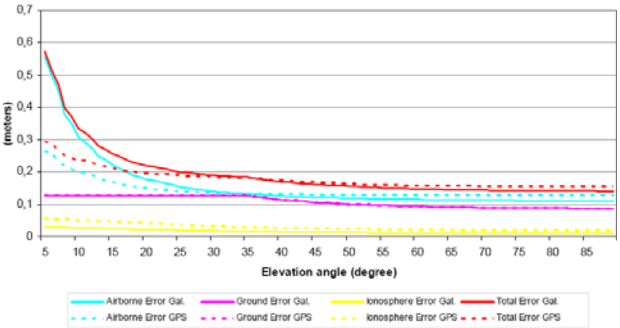


Fig. 2: Residual error for single frequency vs. elevation

To avoid the impact of the error model in the analysis of the results, we decided to use for Galileo and for GPS the same error models i.e the one provided in [3].

Satellite selection strategy

Combined constellations will provide the user with the possibility to receive up to 24 satellites. It is well known that the “all in view” based positioning algorithms will provide an optimized navigation solution with respect to accuracy and integrity. To make this possible, the onboard receiver and the ground station receivers will need to operate 48 channels each. This will drive to more complexity in the hardware and thus less robustness.

An additional algorithm based on selection of 12 satellites among all visible ones using the criteria of minimum GDOP (Geometric Dilution Of Precision) has been developed and implemented in the simulation software.

DUAL FREQUENCY SMOOTHING

In this paper, two smoothing techniques defined in [1] are considered: The ionosphere free smoothing and the divergence free smoothing technique. We recall below these algorithms. The adaptation is made to support GPS with 28 satellites and Galileo with 30 satellites. Concerning the used frequencies, for GPS, it is assumed the use of L1 and L5 for which we have access to code and phase and for Galileo, it is assumed the use of E1 and E5a. The choice of Galileo E5a is motivated for receiver design reasons $f_{L5} = f_{E5a}$ for the combined constellation case.

Single frequency carrier smoothing

Considering single frequency receivers, it is possible to reduce the noise of the code measurement by filtering with the phase measurement because the phase measurement has a very low level of noise.

The classical low pass filter used can be written as follow:

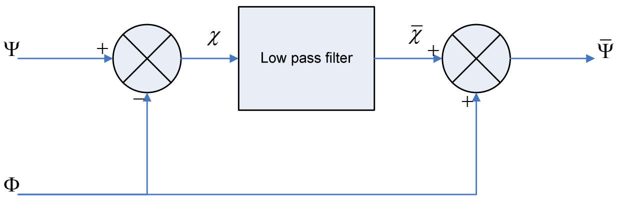


Fig. 2: Low pass filter architecture

Where:

Ψ is the code measurement

Φ is the phase measurement

χ is the input fed in the low pass filter which is for standard single frequency simply the code minus carrier ($\chi = \Psi - \Phi$).

$\bar{\chi}$ is the smoothed χ which can be written in time domain:

$$\bar{\chi}(t+1) = \frac{\tau - 1}{\tau}\bar{\chi}(t) + \frac{1}{\tau}\chi(t+1) \quad (1)$$

Where

τ is the smoothing time constant.

In Laplace domain:

$$\bar{\chi}(s) = F(s)\chi(s) = \frac{1}{\tau s + 1}\chi(s) \quad (2)$$

$\bar{\Psi} = \bar{\chi} + \Phi$ is the smoothed code.

For single frequency carrier smoothing:

$$\begin{aligned} \Psi &= \rho_{L1} = r + I_{L1} + \eta_{L1} \\ \Phi &= \phi_{L1} = r - I_{L1} + N_{L1} \end{aligned} \quad (3a\text{-}b)$$

Where:

$\Psi = \rho_{L1}$ is the code measurement in L1

$\Phi = \phi_{L1}$ is the phase measurement in L1

r is the geometric range from user to satellite including the troposphere delay and the clock off set.

I_{L1} is the ionosphere delay for L1

η_{L1} is the random noise on code measurements in L1

N_{L1} is the integer ambiguity of the carrier measurements in L1.

Thus in this case, the input of the low pass filter can be written as follow:

$$\chi = 2I_{L1} + \eta_{L1} - N_{L1} \quad (4)$$

And the smoothed code measurement can be written as follow in the Laplace domain:

$$\bar{\Psi} = r + (2F - 1)I_{L1} + F\eta_{L1} \quad (5)$$

Divergence free smoothing

For GPS:

$$\begin{aligned} \Psi_{D-Free-GPS} &= \rho_{L1} \\ \Phi_{D-Free-GPS} &= \phi_{L1} = r - \frac{2}{\alpha_{GPS}}(\phi_{L1} - \phi_{L5}) \end{aligned} \quad (6a\text{-}b)$$

With $\alpha_{GPS} = 1 - \frac{f_{L1}^2}{f_{L5}^2}$ (7)

Thus:

$$\bar{\Psi}_{D-Free-GPS} = r + I_{L1} + F\eta_{L1} \quad (8)$$

For Galileo:

$$\begin{aligned} \Psi_{D-Free-Gal} &= \rho_{E1} \\ \Phi_{D-Free-Gal} &= \phi_{E1} = r - \frac{2}{\alpha_{Gal}}(\phi_{E1} - \phi_{E5a}) \end{aligned} \quad (9a\text{-}b)$$

With $\alpha_{Gal} = 1 - \frac{f_{E1}^2}{f_{E5a}^2}$ (10)

Thus

$$\bar{\Psi}_{D-Free-Gal} = r + I_{E1} + F\eta_{E1} \quad (11)$$

Ionosphere free smoothing

For GPS:

$$\begin{aligned} \Psi_{I-Free-GPS} &= \rho_{L1} - \frac{1}{\alpha_{GPS}}(\rho_{L1} - \rho_{L5}) \\ \Phi_{I-Free-GPS} &= \phi_{L1} - \frac{1}{\alpha_{GPS}}(\phi_{L1} - \phi_{L5}) \end{aligned} \quad (12a\text{-}b)$$

$$\bar{\Psi}_{I-Free-GPS} = r + F\left(\eta_{L1} - \frac{1}{\alpha_{GPS}}(\eta_{L1} - \eta_{L5})\right) \quad (13)$$

For Galileo:

$$\begin{aligned} \Psi_{I-Free-Gal} &= \rho_{E1} - \frac{1}{\alpha_{Gal}}(\rho_{E1} - \rho_{E5a}) \\ \Phi_{I-Free-Gal} &= \phi_{E1} - \frac{1}{\alpha_{Gal}}(\phi_{E1} - \phi_{E5a}) \end{aligned} \quad (14a\text{-}b)$$

$$\bar{\Psi}_{I-Free-Gal} = r + F\left(\eta_{E1} - \frac{1}{\alpha_{Gal}}(\eta_{E1} - \eta_{E5b})\right) \quad (15)$$

VPL AND AVAILABILITY CALCULUS

Vertical protection level is calculated with respect to standard documents DO245A (see [2]).

In the case of fault free VPL the formula is as follow:

$$VPL_{H0} = K_{ffmd}\sigma_{VerticalPositionError} \quad (16)$$

$$\sigma_{VerticalPositionError} = \sqrt{\sum_{i=1}^{N} S^2_{vert,i}\sigma_i^2} \quad (17)$$

With

K_{ffmd} is a multiplication parameter derived from the fault free probability of missed detection.

$S_{Vert,i} = S_{3i}$ is the projection of the ith ranging source into the vertical direction.

$$S=\left(G^TWG\right)^{-1}G^TW \quad (18)$$

σ_i is the standard deviation of the fault free residual error at user level for the satellite i. These errors are estimated after smoothing and after differential corrections.

VPL for D-free:

For D-free, the spatial component of the ionosphere gradient is not eliminated and appears as a bias in the residual error. As described in [1], either a perfect monitoring of the ionosphere gradient can be made and the protection levels can be increased in order to take into account the inflation of the ionosphere gradient or there is no perfect monitoring of the ionosphere gradient and in that case the integrity can't be guarantied at all.

An interesting integrity concept was proposed by Hiroyuki Konno in his paper [1]. He suggested adding the bias due to the spatial ionosphere gradient in the VPL in the case of a perfect monitoring of the ionosphere gradient. Thus the VPL can be written in the following form:

$$VPL_{H0}=K_{ffmd}\underbrace{\sqrt{\sum_{i=1}^{N}S_{v,i}^2\left(\sigma^2_{df-gnd,i}+\sigma^2_{df-air,i}\right)}}_{\textbf{A}}+\underbrace{\left|\sum_{j=1}^{M}S_{v,j}\frac{\partial I_j}{\partial x}d\right|}_{\textbf{B}} \quad (19)$$

In this equation, the standard deviations ($\sigma_{df-gnd,i},\sigma_{df-air,i}$) correspond to the residual errors for the divergence free smoothing solution after application of differential corrections.

M is the number of affected satellites.

It is important to notice that "perfect" monitoring means with a very "small" uncertainty because all uncertainties in B will necessary be modelled as random value and has to be moved to A and inflated to be consistent with the acceptable probability of missed detection (K_{ffmd}).

This protection level concept will necessary be updated to take into account the monitoring uncertainty. It is possible, that finally the protections levels resulting from this consideration will even be higher than the protection level of the ionosphere free combination.

VPL for I-free:

For I-free smoothing, the ionosphere free combination in the phase and in the code permits an elimination of the ionosphere delay.

Equation 17 will be transformed as follow:

$$VPL_{H0}=K_{ffmd}\sqrt{\sum_{i=1}^{N}S_{v,i}^2\left(\sigma^2_{if-gnd,i}+\sigma^2_{if-air,i}\right)} \quad (20)$$

In this equation, $\sigma^2_{if-gnd,i},\sigma^2_{if-air,i}$ represent respectively the residual ground receiver error and the residual airborne receiver error after applying the ionosphere free smoothing and the differential corrections.

Availability calculus:

For all presented algorithms, the availability considers only the VPL compared to the VAL for CAT III (5.3 m).

This supposes no failure at any satellite of the constellation. In the reality one has to consider the probability of satellite failure. Nevertheless the impact of a satellite failure for a combined Galileo-GPS constellation will not suffer a lot because of the high number of visible satellites. This is not the case for a single constellation for which a failure in one satellite can drive to availability problem.

SIMULATION SCENARIO AND HYPOTHESIS

The simulations to compute the protection levels and availability of the GBAS system were taken at time steps of 150 seconds for a period of ten days from December 17th, 2005 to December 27th, 2005.

The assumed position of the GBAS station was chosen to be at Blagnac Airport in Toulouse, France. (Lat 43.5786 N, Long 1.3760 W, Height 220m). The simulation considered a fixed user position (Lat 43.6730 N, Long 1.3164 W, Height 449 meters) (constant baseline but constellation varying).

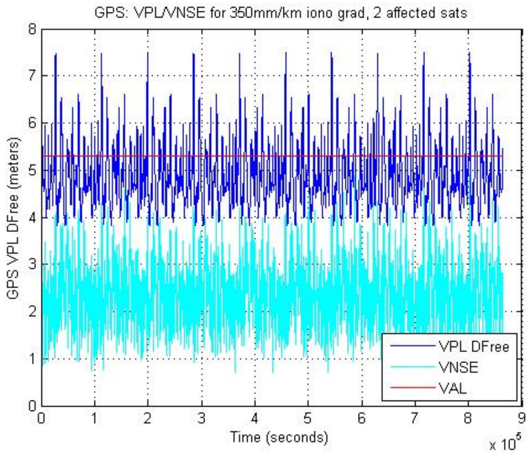
For calculating residual errors, the requirements appropriate for CAT II,III were assumed, i.e. four available GBAS reference stations, the GBAS Service Level F, the airborne accuracy designator B, and the airframe multipath designator B.

The satellite positions used for the simulations were in the case of GPS taken from a YUMA almanac file, and in the case of Galileo from the last available planed almanac data.

RESULTS OF SIMULATIONS AND ANALYSIS

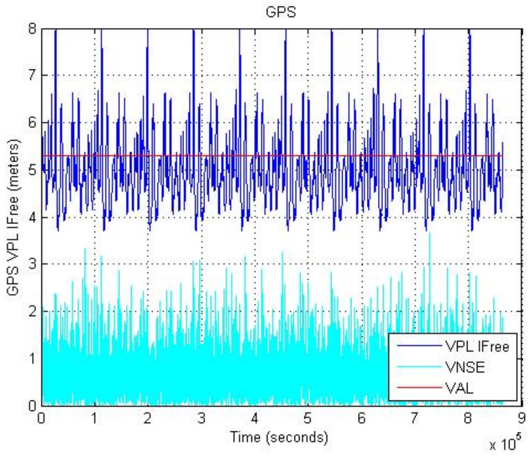
In this paragraph, we present the results of our simulations. Only the case of vertical ionospheric gradient of 350 mm/km has been presented. This case corresponds to an extreme ionosphere storm that is generally very rarely observed. The response of GBAS for different configurations (Dual constellation I-free and D-free using best VDOP technique or all in view) is presented and compared with the use of a single constellation. A table resuming the availabilities of the vertical protection levels for each test case and for D-free using different number of affected satellites (2 to 5) is presented and conclusions are drawn.

VPL for GPS alone using D-free



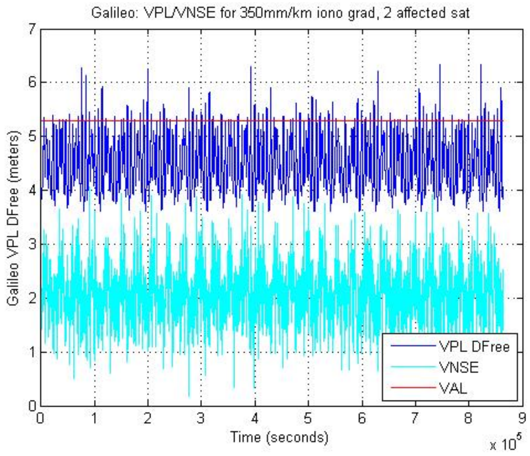
In this figure, we can see clearly that the vertical protection level is very often above the alarm limit. But the most critical aspect is the very low separation between VNSE and VPL which indicates possible misleading information. Divergence free smoothing even in the case of very good ionosphere gradient monitoring can be subject of misleading information. This shows at least that the Vertical Protection level concept as defined above for D-free is not adapted and necessitate to be readjusted using a better overbounding of the vertical position error.

VPL for GPS alone using I-free



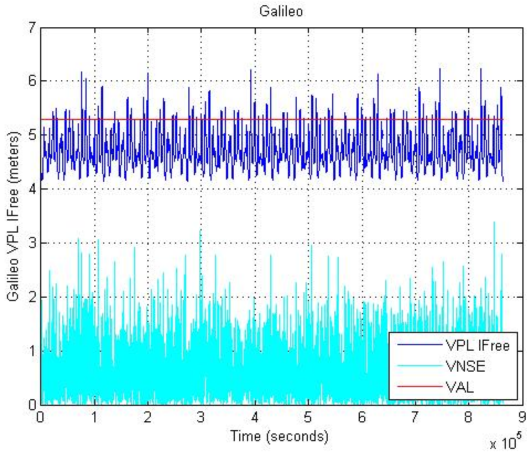
The I-free smoothing provides for GPS alone very high protection levels. Nevertheless while comparing with the previous figure; it appears clearly that the separation between VNSE and VPL is better. This solution even if the availability is low, provides at least a reliable information. The concept of VPL is representative of a good overbounding. The protection levels can be improved either by using higher quality receiver with a higher multipath rejection capacity and lower level of receiver noise or by using a better geometry by adding a second constellation.

VPL for Galileo alone using D-free



We can observe better protection levels than with GPS only due to a better geometry (as an assumption, the same pseudo range error model has been considered for both GPS and Galileo). But as for GPS, the separation between VPL and VNSE is not obvious and can drive to misleading information.

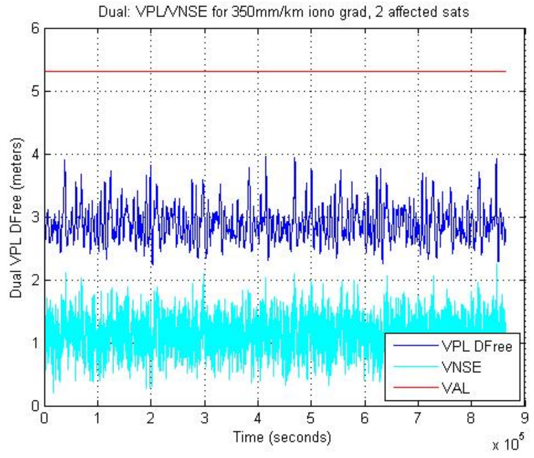
VPL for Galileo alone using I-free



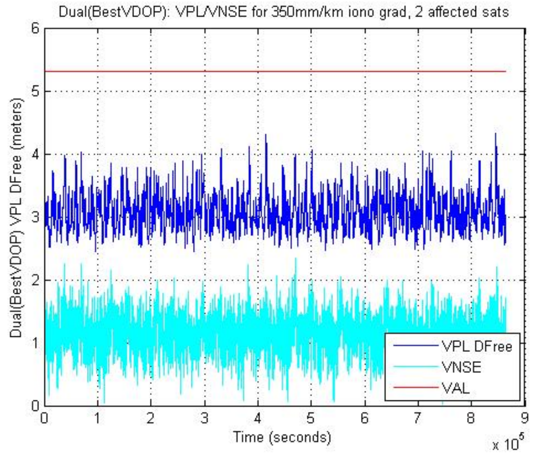
This figure shows clearly promising results and even if the availability is still not sufficient to reach CAT III, improvement especially in the reduction of noise and multipath will certainly conduct to a CAT III solution at least with respect to protection levels.

We can already see that a better geometry can drive to better protection levels. This will be more clearly shown in the following figures.

VPL for combined GPS+ Galileo using D-free

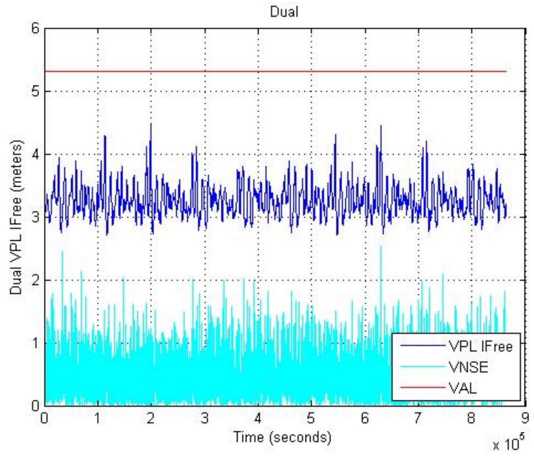


The benefit of using dual constellation can be obviously seen in the figure above: The level of noise is very low and more over the protection levels are less fluctuating. The divergence free provides very good results. The level of noise is maintained at a low level even if the ionosphere gradient is very important. Still there is a room for overbounding the error while always staying under the alarm limit.

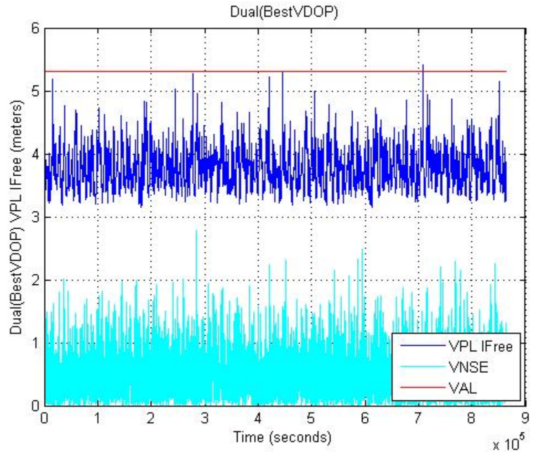


The best VDOP solution still fulfils the requirements. This technique will be very useful while considering limited number of receiver channel. Another aspect that has to be considered is the limited resources of the VHF data broadcast which will also necessitate the choice of a limited number of satellites for which corrections and integrity information are required.

VPL for combined GPS+ Galileo using I-free

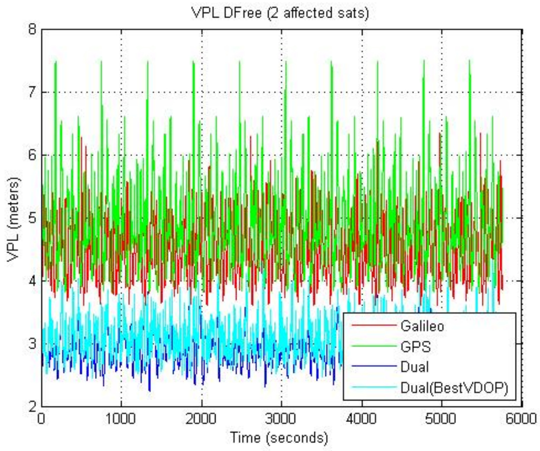


This is probably the most promising result in this paper: the level of ionosphere free smoothing technique using a combined GPS- Galileo constellation. It is well known that this smoothing technique is very robust. Additionally to this robustness (very good separation between VPL and VNSE), the protection levels are much lower than the alarm limit. This architecture needs to be further investigated and robustness against interferences and inter channel biases must be assessed. The continuity aspect will also need to be investigated.



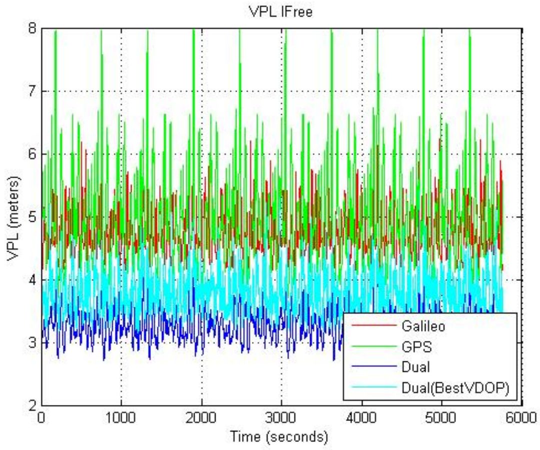
The best VDOP technique provides still promising results but the availability is a little bit lower than for the “all in view” case. By augmenting the capacity to 14 satellites selected rather than 12 it can provide better results. A trade off need to be find between the maximum number of satellite to be monitored at the same time and the protection levels that should be below the alarm limit also for the worst configuration and for the worst place.

Comparison between constellations using D-free:



This figure summarizes the results obtained above. Only the dual constellation can provide acceptable availability with respect to CAT III requirements.

Comparison between constellations using I-free:



The same conclusion can be made with respect to the ionosphere free smoothing algorithm. Even if more conservative than for divergence free smoothing, the protection levels are still below the alarm limit for the combined constellation.

Summary of Availability of Protection level:

Number of affected satellites (for D-free only)	2	3	4	5
GPS D-free	77.895	64.108	68.988	67.477
Galileo D-free	91.596	85.015	83.365	90.137
Dual constellation D-Free	100	100	100	99.947
Dual constellation D-Free using best VDOP	100	100	100	99.947
GPS I-free	74.145			
Galileo I-free	90.797			
Dual constellation I-Free	100			
Dual constellation I-Free using best VDOP	99.982			

This table summarises the results with respect to the availability of the protection levels. Dual constellation provides 100% availability while considering a simulation period of 10 days and simulating a severe ionospheric gradient of 350 mm/km. A single constellation is still providing limited results and suffers from the lack of geometry

CONCLUSION

As a conclusion, a simple study provides promising results while using ionosphere free smoothing algorithms for dual constellation GPS- Galileo dual frequency E1/L1-E5a/L5. There is even freedom to use fewer satellites than visible when suitably selected to provide the best VDOP. Some strong assumptions have been made that need to be tested in the future. Here we supposed to work with nominal constellations without considering the probability of a satellite failure which is for GPS not negligible. The advantage of the ionosphere free smoothing technique is that it doesn’t necessitate a special ionosphere monitoring system as the ionosphere delay is eliminated at receiver level.
D-free provides accurate navigation solution when no spatial ionospheric gradient occurs. This solution can still be envisaged up to a high level of ionosphere storm.

Additional performance parameters need to be investigated as for example the continuity of the service and more related to the implementation: the time to alarm which is for CAT III precision landing set to 1 second.

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