GALILEO EVOLUTION: ENHANCED ERROR CORRECTION STRATEGIES AND INTEGRITY ASSESSMENTS

B. Belabbas (*), P. Rémi (**), M. Meurer (*)
* DLR (German Aerospace Center), Institute of Communications and Navigation
** TUM (Technical University of Munich), Institute of Communications and Navigation
Germany

OVERVIEW

Galileo corrections will be generated and broadcasted to the users in the navigation message using the same principle as GPS. For that reason the Galileo ground segment determines the ephemeris and satellite clock parameters for all satellites using observations from monitoring stations and estimates the extrapolation parameters to be uplinked to the satellites.

This paper investigates two types of correction strategies one related to the standard single frequency absolute positioning and the other one related to the dual frequency ionosphere free combination.

By using GPS measurements from IGS (International GNSS Service) stations and IGS post processed data, it is possible to compute the instantaneous pseudo range errors for a given period of time. Thanks to the foreseen UERE (User Equivalent Range Error) budget for Galileo, a corresponding error model for Galileo is generated.

The above defined work is made at pseudo range level and constitutes the first part of our study.

A second part of the work deals with the impact of these pseudo range errors at position level for both single and dual frequency (L1-E5a) Galileo receivers. The impact on the accuracy and the integrity of the overall system is analysed.

These performances are assessed and conclusions and recommendations for Galileo evolutions are given.

1. INTRODUCTION

Global Navigation Satellite Systems can be used worldwide to determine the position of a user with an accuracy of up to a few meters. However for applications which are critical with respect to the Safety of Life, not only the accuracy of the position determined by the navigation system is important, but also the integrity of the navigation solution. The protection level, which is a measure of the system's integrity, is affected by the standard deviation of the pseudorange error, where the standard deviation is just another expression for the accuracy.

In this paper the accuracy at pseudo range level will be assessed for single and dual frequency, ionosphere free combination. This part deals with GPS measurements. A detailed analysis of the pseudo range error for single and dual frequency ionosphere free combination will be done for Galileo. Results of the impact of the pseudo range error at position level will be detailed and the integrity will be assessed by providing instantaneous vertical protection levels for both cased. A conclusion and recommendations for Galileo will close this paper.

2. METHOD OF PSEUDO RANGE ERROR DECOMPOSITION

The calculation of instantaneous errors has been detailed in previous papers [1], [2] based on a first order Taylor expansion of the observation equation as described in [3]. In our paper we just recall the fundamental error equation:

$$\mathbf{G} \cdot \Delta\overline{\mathbf{x}} = c \cdot \left(-\Delta\overline{\mathbf{B}} + \Delta\overline{\mathbf{I}} + \Delta\overline{\mathbf{T}} - \overline{\mathbf{v}}\right) + \boldsymbol{\varepsilon} \cdot \left(\overline{\mathbf{R}} - \overline{\mathbf{P}}\right) + \mathbf{A} \cdot \Delta\overline{\mathbf{R}} \equiv \Delta\overline{\boldsymbol{\rho}} \quad (1)$$

Where:

$\mathbf{G}$ is the geometry matrix composed of the unit vectors in a local coordinate system from the user to the satellites and a column of ones (related to the receiver clock bias considered as an unknown of the positioning problem)

$\Delta\overline{\mathbf{x}}$ is the unknown position in 3 dimensions along with the receiver clock bias

c is the speed of light in the vacuum

$\Delta\overline{\mathbf{B}}$ is the vector of errors in the satellite transmission time in seconds also called satellite clock error

$\Delta\overline{\mathbf{I}}$ is the vector of the residual ionospheric error after the correction with either a model (for single frequency GPS with Klobuchar in absolute mode or with broadcast vertical ionospheric corrections in SBAS mode) or thanks to dual frequency ionosphere free correction

$\Delta\overline{\mathbf{T}}$ is the vector of the residual tropospheric error after the correction with a troposphere delay model (in our case the MOPS model using Neill's mapping function)

$\overline{\mathbf{v}}$ is a vector of the receiver noise error and the multipath residual error.

$\Delta\overline{\boldsymbol{\rho}} = \overline{\mathbf{IPRE}}$ is the vector containing the instantaneous pseudo range errors after all possible corrections

By considering the following convention and by replacing each error source by a more intuitive notation, the equation (1) becomes:

$$\mathbf{G}.\Delta\overline{\mathbf{x}} = -\overline{\mathbf{Clk}} + \overline{\mathbf{Eph}} + \overline{\mathbf{Iono}} + \overline{\mathbf{Trop}} - \overline{\mathbf{MN}} = \overline{\mathbf{IPRE}} \quad (2)$$

Where:

$\overline{\mathbf{Clk}}$ is the satellite clock error

$\overline{\mathbf{Eph}}$ is the ephemeris error

$\overline{\mathbf{Iono}}$ is the residual ionospheric error

$\overline{\mathbf{Trop}}$ is the residual tropospheric error

$\overline{\mathbf{MN}}$ is the receiver noise an multipath error

And using the following convention for each individual error:

Error(t)= Estimate(t) – Reference(t)

To generate samples we used the following data processing method:

Error type	Estimate	Reference	Sampling period of reference
Clk	Navigation message	SP3 files	15 min
Eph	Navigation message	SP3 files	15 min
Iono	Navigation message+ Klobuchard model	IONEX files	2 hrs
Trop	MOPS model + Niell's mapping function	SINEX files	2 hrs
MN	No estimation	TEQC from UNAVCO community	15 minutes

TAB 1: Data processing method

3. PSEUDO RANGE PERFORMANCE CONCEPT

3.1. Time series of pseudo range errors

A one year measurement campaign has been used and the following results have been obtained for an IGS (International GNSS service) station ("OBE2") located at Oberpfaffenhofen near Munich (Germany). The period of measurements considered was from 1.1.2003 to 1.1.2004.

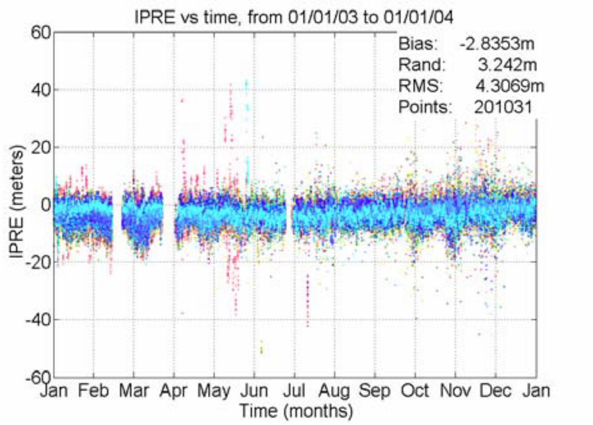

FIG 1: IPRE(t) at Obe2

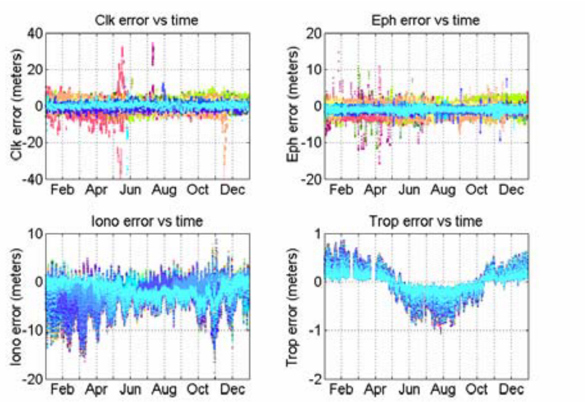

FIG 2: Clk(t), Eph(t), Iono(t), Trop(t) at Obe2

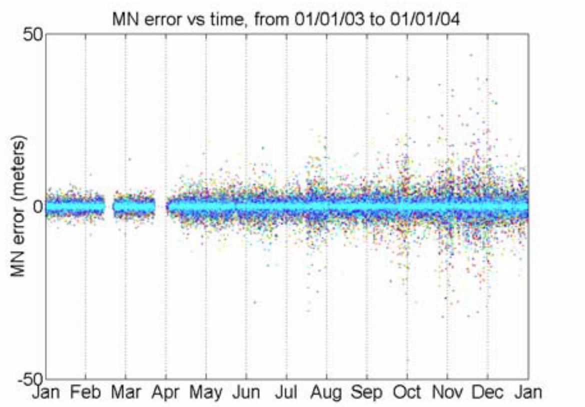

FIG 3: MN(t) at Obe2

3.2. Dual frequency ionosphere free combination

The dominance of the ionosphere error necessitates a correction by either providing a more accurate ionosphere model or by using an additional frequency. The NeQuick model has been a promising candidate but a closer analysis [4] showed that it does not provide much better results than the Klobuchar model. An additional frequency provides the user with a possibility to build the so called ionosphere free combination detailed hereafter:

Given the code range on L1 and the code range on L2, it is possible to build a combined L3 observation using the following formula:

$$L_3 = \frac{1}{f_1^2 - f_2^2}\left(f_1^2 L_1 - f_2^2 L_2\right) \quad (3)$$

Where f_i represents the frequency of the signal i.

L3 is called the ionosphere free combination because it removes the first order ionospheric error which is proportional to the inverse of the frequency squared.

By using the notations of paragraph 2, the equation is equivalent to:

$$IPRE_3 = \frac{1}{f_1^2 - f_2^2}\left(f_1^2 IPRE_{L1} - f_2^2 IPRE_{L2}\right) \quad (4)$$

By decomposing $IPRE_{Li}$ into the elementary error components, we have:

$$IPRE_{L1} = -Clk_1 + Eph_1 + \frac{A}{f_1^2} + Trop_1 - MN_1$$

And

$$IPRE_{L2} = -Clk_2 + Eph_2 + \frac{A}{f_2^2} + Trop_2 - MN_2$$

Satellite clock, ephemeris and troposphere do not depend on the frequency used so we can write:

$$Clk_1 = Clk_2 = Clk$$

$$Eph_1 = Eph_2 = Eph$$

$$Trop_1 = Trop_2 = Trop$$

However multipath and receiver noise have no reason to be equivalent in magnitude. We can see that they are totally decorrelated. After decomposition, the equation … can be written as follows:

$$IPRE_3 = -Clk + Eph + Trop - \frac{1}{f_1^2 - f_2^2}\left(f_1^2 MN_1 - f_2^2 MN_2\right) \quad (5)$$

In this equation we can see the same type of errors as in a single frequency measurement except that the ionosphere error is cancelled out but in turn a contribution from errors due to multipath and receiver noise on L2 appears in the equation. In the following, measurements over a period of one year at Potsdam (Germany) provide us the level of the instantaneous pseudo range error in L1 versus time (top plot) and the IPRE for the ionosphere free combination (bottom plot).

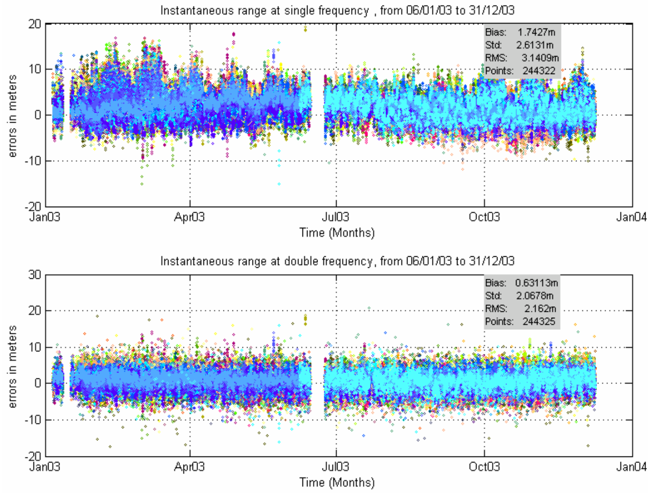

FIG 4: Instantaneous pseudo range error for single and dual frequency measurements shown for a period of one year.

An important property of the ionosphere free combination is to provide more "stationary" data. The ionospheric error is replaced by a higher amount of multipath and noise error. This technique is advantageous when the level of multipath is relatively low with respect to the level of the ionospheric error. In the case of severe multipath environment, dual frequency techniques could be even worse than single frequency ones.

The difference between the single frequency measurement and the dual frequency ionosphere free combination is even more obvious when zooming in on only one week of measurements as for example at Singapore:

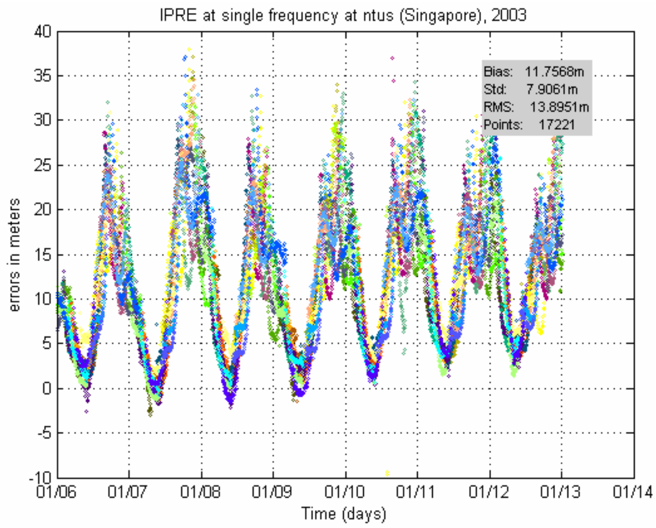

FIG 5: Instantaneous pseudo range error for single frequency measurements shown for a period of one week.

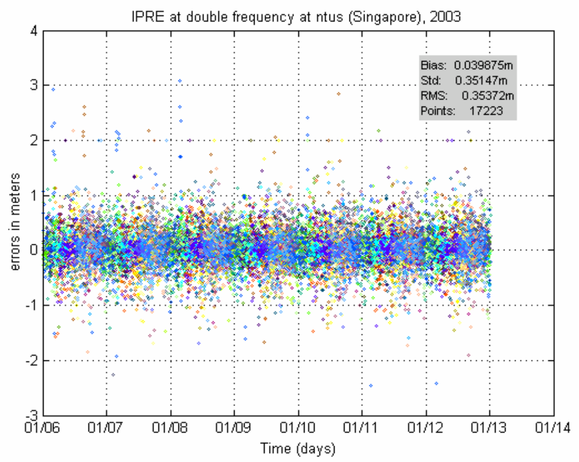

FIG 6: Instantaneous pseudo range error for dual frequency measurements shown for a period of one week.

The ionospheric error in this area (equatorial region) is very high and therefore even in a high multipath environment it is still advantageous to use a dual frequency ionosphere free combination to improve the accuracy of the navigation solution.

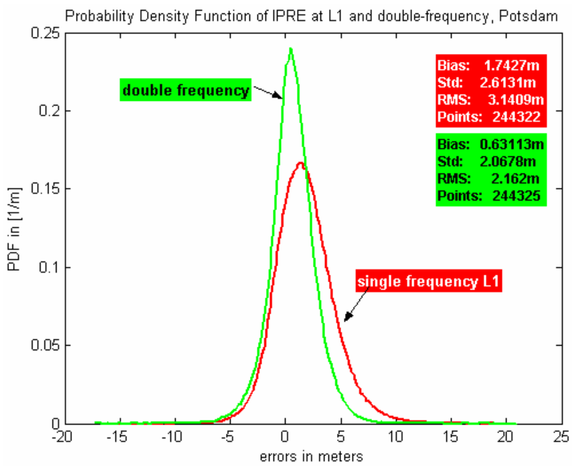

FIG 7: Probability density function of the IPRE of single and dual frequency measurements with a *low* level of multipath error.

However, when the level of multipath error is too high, the benefit of using the dual frequency observations disappears as we can see below at Oberpfaffenhofen.

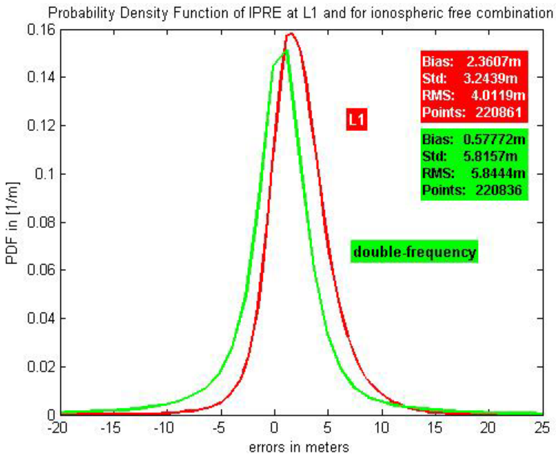

FIG 8: Probability density function of the IPRE of single and dual frequency measurements with a *high* level of multipath error.

Here the standard deviation of the ionosphere free combination is higher than for the single frequency pseudo range error.

4. POSITION PERFORMANCE AND INTEGRITY ASSESSMENTS

4.1. Impact on position level

At position level, the impact of the ionosphere error will remain dominant especially in the vertical direction due to the satellites' distribution in the sky and the spatial correlation of the ionosphere error. When using a dual frequency ionosphere free combination, the error will have a more spherical distribution in the position domain.

4.2. Integrity assessment

In a fault free mode, the integrity parameters will be influenced by the model taken for the pseudo range error. Therefore the use of single or dual frequency measurements will impact a lot the protection level (measure of integrity of the system).

But the threats are not of the same nature. In a dual frequency ionosphere free combination, the ionosphere can't be considered as a threat any more or only in a degraded mode with the loss of one frequency. The multipath and receiver noise threat can't be ignored especially when the second frequency is subject to radio frequency interferences as it is the case for GPS L5 and for Galileo E5a-E5b. As long as a high multipath error only affects one or two satellites, it can be corrected easily by using robust RAIM (Receiver Autonomous Integrity Monitoring) algorithms [3]. When using single frequency receivers, the ionosphere threat is the most important one i.e. that it can cause the highest impact on the position accuracy. Self consistency checks are less efficient because of the high degree of spatial correlation of this effect. Almost all satellites will be affected by a high ionosphere activity for example.

5. APPLICABILITY TO GALILEO

For Galileo, ionospheric and tropospheric errors will not change with respect to GPS considering the same frequencies. The main differences will be in the satellite clock and ephemeris errors and multipath and receiver noise error for which the results are expected to be much better [5].

In a previous paper [2], it has been shown that Galileo E1 BOC (1,1) provides a higher multipath rejection for a given multipath scenario. In the following subsection, we illustrate through an example of multipath scenario, one ground reflexion, the difference between GPS L1 and Galileo E1 BOC(1,1) signal.

5.1. Multipath scenario

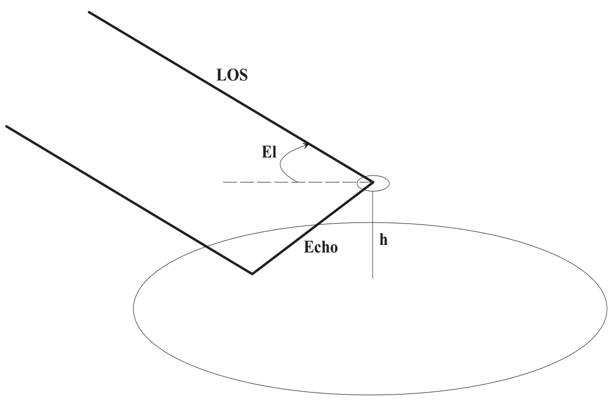

FIG 9: Multipath reception.

The first step was to determine the delay of the multipath with respect to the elevation angle of the satellite:

$$\tau = 2h\sin\left(El\right) \quad (6)$$

With τ the delay of the echo, h the height of the antenna with respect to the reflector and El is the elevation angle of the satellite.

Another characteristic parameter is the relative power of the echo with respect to the line of sight. For that we considered that the echo is a left hand circular polarized signal (100%) when the incident signal is right hand circular polarized.

We considered the following antenna gain pattern:

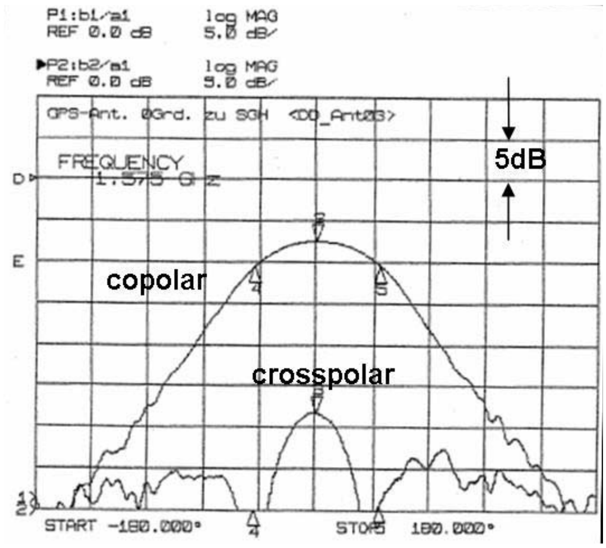

FIG 10: Antenna gain pattern.

With these considerations, the following results have been obtained for different elevation angles:

Elevation angle (°)	Relative power of echo (dB)	Delay of echo (ns)	C/N0 in dBHz for GPS BPSK(1)	C/N0 in dBHz for Galileo BOC(1,1)
90	-32,57	13,34	48,20	53,20
80	-32,28	13,14	47,91	52,91
60	-28,27	11,55	46,48	51,48
30	-22,99	6,67	40,46	45,46
10	-16,28	2,32	35,07	40,07
5	-13,59	1,16	33,52	38,52

TAB 2: Dependency of multipath parameters on the elevation angle.

We assumed the following receiver characteristics: use of a narrow correlator with a bandwidth of 20MHz and a chip spacing of 0.1.

The results obtained by using the DLR's NAVSIM simulator are as follow:

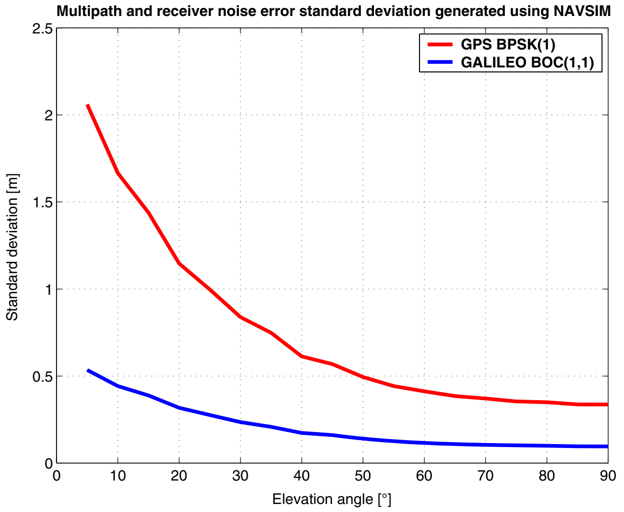

FIG 11: Standard deviation of the error due to multipath and receiver noise in dependency of the elevation angle.

The standard deviation of multipath and receiver noise errors is about four times lower for Galileo than for GPS. This property will lead to a higher quality of Galileo measurements.

By generating random errors for one year of measurements we obtain the following time series of multipath and receiver noise error using both a GPS (FIG12) and a Galileo (FIG13) constellation:

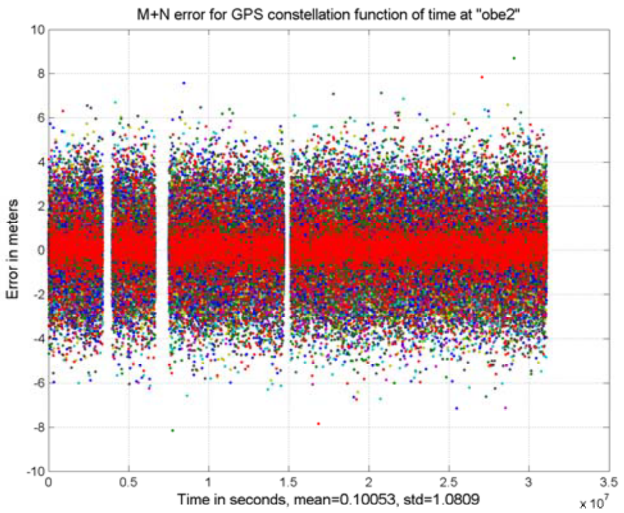

FIG 12: Multipath and receiver noise error for the GPS constellation.

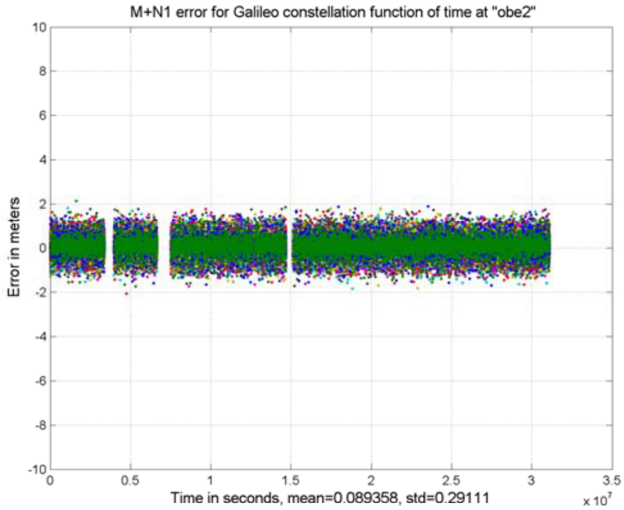

FIG 13: Multipath and receiver noise error for the Galileo constellation.

The gaps have been intentionally introduced in order to take into account the lack of measurements for other errors for this period of time.

5.2. Dual frequency performance expectations

It is obvious that the dual frequency ionosphere free combination will be much more efficient for Galileo than for GPS thanks to the lower level of multipath and receiver noise error.

5.2.1. Simulation assumptions

In this section simulations using the latest known information of Galileo were used. For the ionosphere free combination, L1 and E5a were considered.

5.2.1.1. Orbit determination and time Synchronisation error

The standard deviation of the orbit determination and time synchronisation error (ODTS) has been considered to be equal to 0,65 m and is independent on the elevation angle as assumed in [5].

5.2.1.2. Ionospheric and tropospheric error

The procedure to calculate the ionospheric and tropospheric error is detailed hereafter.

In order to consider a realistic ionospheric and tropospheric error, we have used the measurements from a previous GPS study which was adapted to the Galileo constellation. This was done sample by sample by interpolating the ionosphere error function of the elevation angle of the satellite in view using a 3rd degree polynom. The ionospheric and tropospheric error for Galileo were generated using the elevation angle of simulated visible satellites. The location chosen is Oberpfaffenhofen and the residual ionospheric and tropospheric errors used where those corresponding to the year 2003. The ionospheric error is generated for frequency L1 which is taken as the reference observation for the ionosphere free combination.

5.2.1.3. Multipath and receiver noise error

Multipath and receiver noise error are extracted from GIOVE-A measurements [6] taken on May 28th 2006 for both L1 and E5a. It is of course not the topic of this paper to discuss the applicability of these values to general applications. As far as we know, these values have been generated for a specific area and for a restricted period of measurements.

Elevation angle	Multipath and receiver noise error for L1 BOC (1,1) in meter	Multipath and receiver noise error for E5a in meter
5	0,91	0,51
15	0,72	0,46
25	0,42	0,24
35	0,34	0,21
45	0,30	0,2
55	0,25	0,21
65	0,23	0,14
75	0,25	0,19
85	0,26	0,17

TAB 3: Dependency of errors due to multipath and receiver noise on the elevation angle.

5.2.2. Time series of pseudo range errors

We have used the foreseen almanac parameters for the Galileo constellation and the user location considered is Oberpfaffenhofen (near Munich).

5.2.2.1. Orbit determination and time Synchronisation error

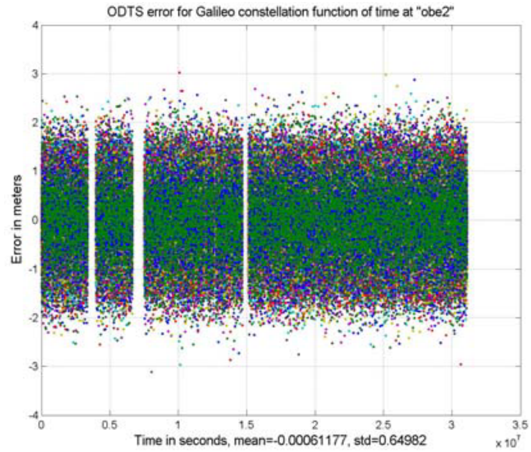

FIG 14: Orbit determination and time Synchronisation error (ODTS) for the Galileo constellation.

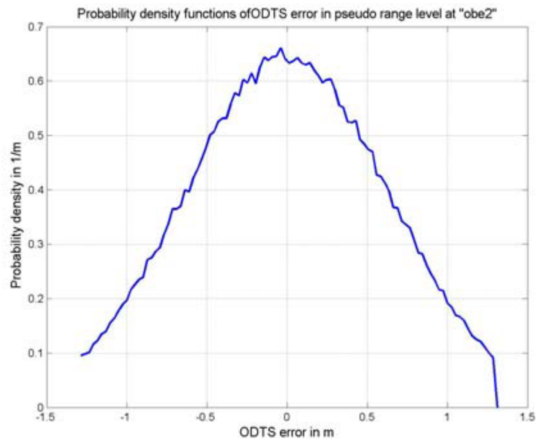

FIG 15: Probability density function of the ODTS.

5.2.2.2. Ionosphere error

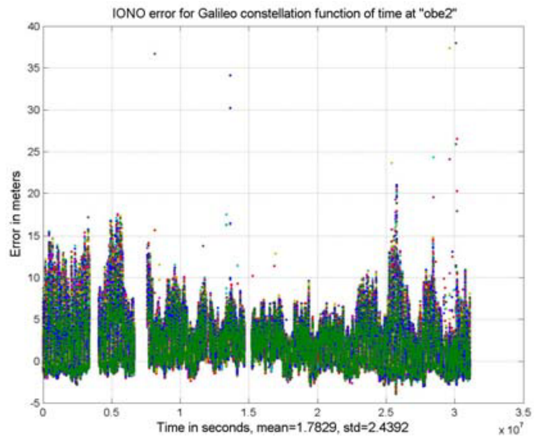

FIG 16: Ionospheric error for the Galileo constellation.

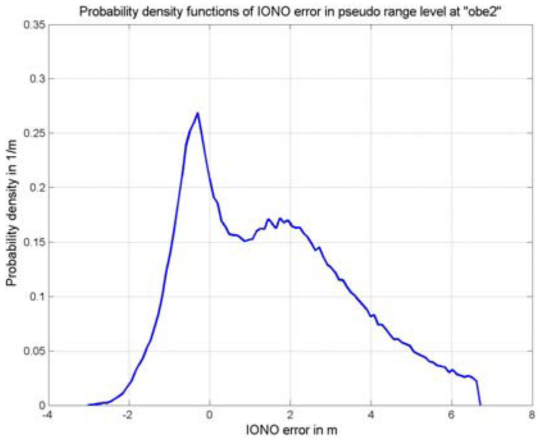

FIG 17: Probability density function of the ionospheric error.

5.2.2.3. Troposphere error

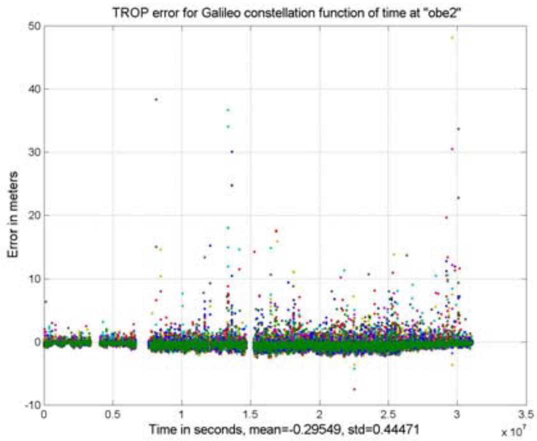

FIG 18: Tropospheric error for the Galileo constellation.

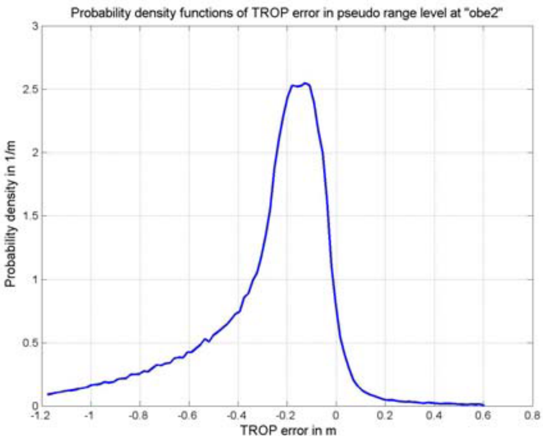

FIG 19: Probability density function of the troposperic error.

5.2.2.4. Multipath and receiver noise in L1

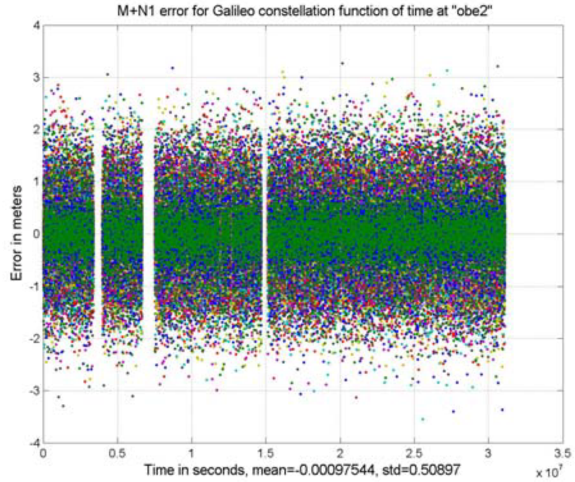

FIG 20: Multipath and receiver noise error for the Galileo constellation.

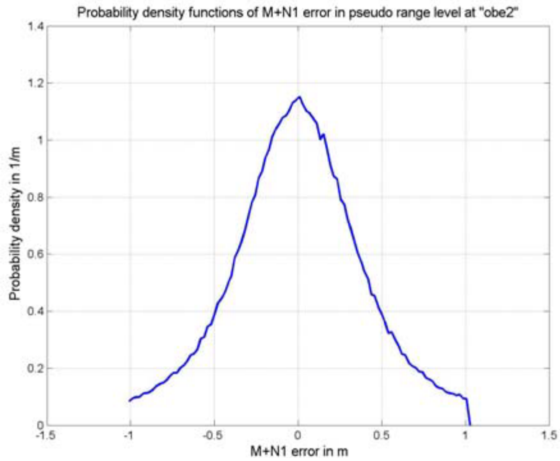

FIG 21: Probability density function of the multipath and receiver noise error.

5.2.2.5. Multipath and receiver noise in E5a

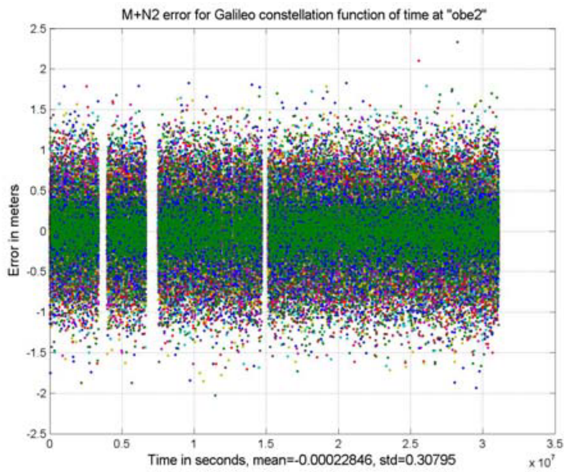

FIG 22: Multipath and receiver noise error for the Galileo constellation using frequency band E5a.

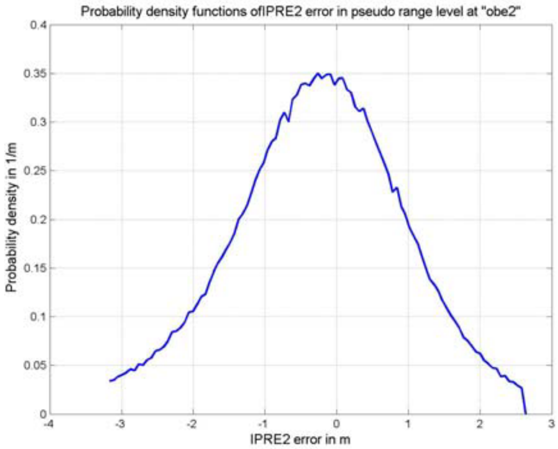

FIG 23: Probability density function of the IPRE2.

5.2.2.6. IPRE for single frequency

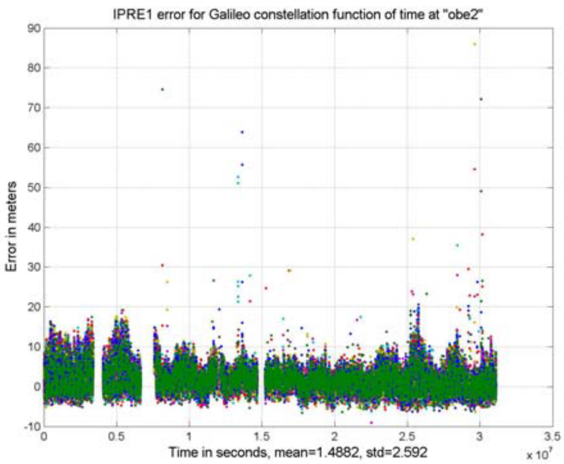

FIG 24 IPRE1 for the Galileo constellation.

5.2.2.7. IPRE of ionosphere free combination

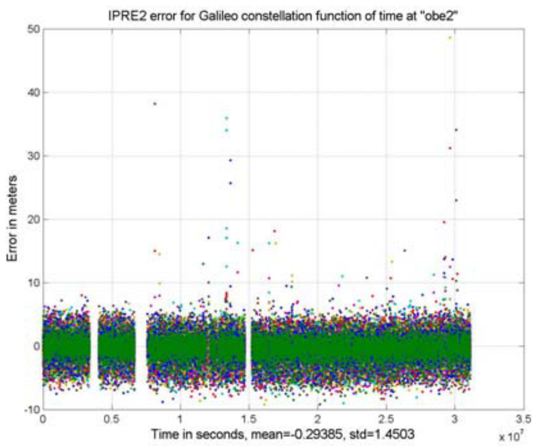

FIG 25 IPRE2 for the Galileo constellation.

5.2.2.8. Single frequency vs. dual frequency

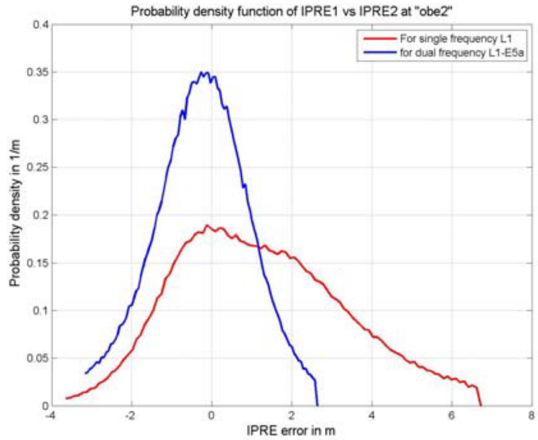

FIG 26: Probability density function of the IPRE1 and the IPRE2 for Galileo.

Thanks to the low level of multipath error, the ionosphere free combination is providing very good results. This result has to be compared with GPS for which the high level of multipath and receiver noise error provides relatively poor benefit of using dual frequency ionosphere free technique.

5.2.3. Position Error and Protection levels

5.2.3.1. Position error for single and dual frequency (L1-E5a)

The position error is calculated using the linearized equation:

$$\mathbf{G}.\Delta\overline{\mathbf{x}} = \overline{\mathbf{IPRE}} \quad (7)$$

A weighted least square solution is applied and we obtain the following result:

$$\Delta\overline{\mathbf{x}} = \left(\mathbf{G}^{T}\mathbf{W}\mathbf{G}\right)^{-1}\mathbf{G}^{T}\mathbf{W}\cdot\overline{\mathbf{IPRE}} = \mathbf{S}\cdot\overline{\mathbf{IPRE}} \quad (8)$$

Where W is the inverse of the covariance matrix of pseudo range error estimated (use of the complete number of samples collected during one year). An interpolation model using a 4^{th} degree polynomial has been generated to provide a standard deviation of the errors function of the elevation angle of the satellite.

For each case (single dual frequency) the corresponding IPRE function has been taken in the determination of the position error from equation (8).

5.2.3.1.1. Position error for single L1 frequency

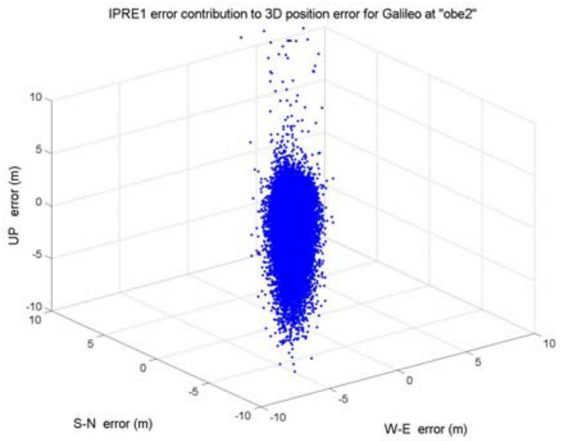

FIG 27: 3D position error using single frequency L1.

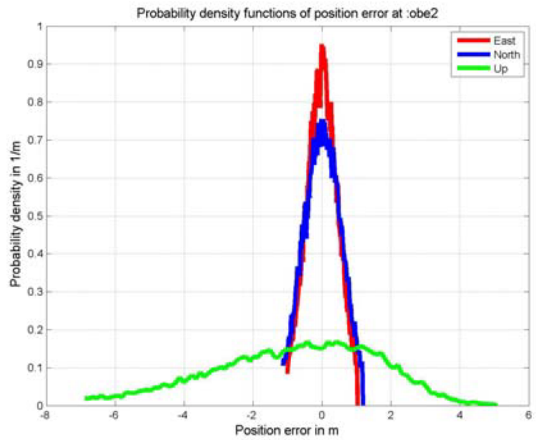

FIG 28 PDF of position error for single frequency

5.2.3.1.2. Position error for dual (L1-E5a) frequency ionosphere free combination

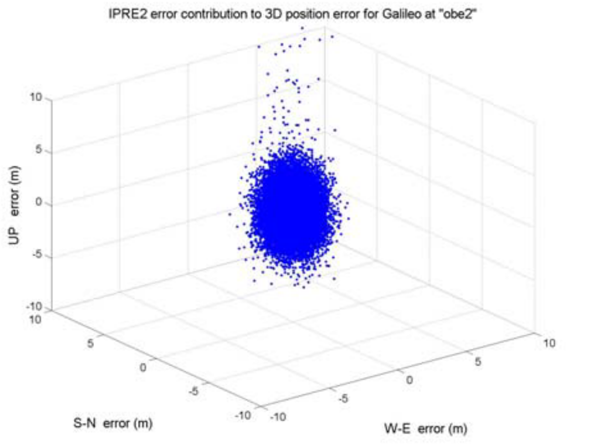

FIG 29 3D position error using dual frequency L1-E5a.

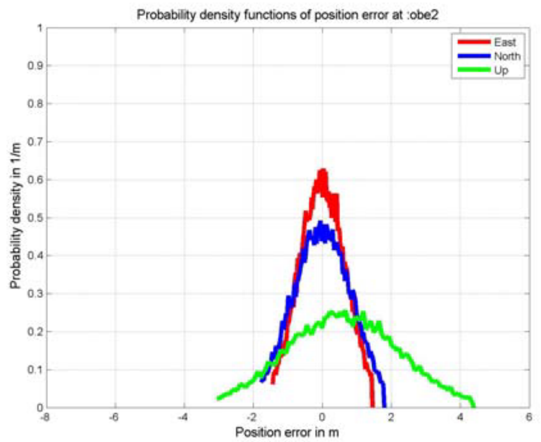

FIG 30 PDF of position error for dual frequency.

5.2.3.2. vertical protection levels

in this approach we decided to use an overbounding of the instantaneous pseudo range error as follow:

For ODTS error a margin of 30% is applied as suggested in [5]

For the global error a margin of 10% is applied to all data.

The resulting overbounded IPRE will be used in the determination of a WAAS look alike protection levels.

The Vertical protection level can be written as follow [DO229C]:

$$VPL = K_V \sqrt{\sum_{i=1}^{N} s_{3,i}^2 \sigma_i^2} \qquad (9)$$

Where $s_{3,i}$ is the 3rd line (corresponding to the vertical component) of the matrix S (see equation 8) corresponding to the i[th] visible satellite. σ_i is an overbounding of the standard deviation of the user equivalent range error considering the assumptions defined above in this section.

Finally we obtained the following results for the same period of simulation as before and for both single and dual frequency solutions.

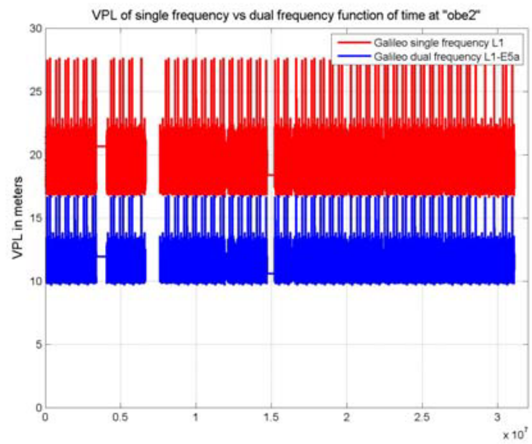

FIG 31 VPL for single vs. dual frequency Galileo

6. CONCLUSION

It is clear that a user with a single-frequency receiver will basically face the same problems for both the Galileo and the GPS constellation. Although the multipath error in the same environment is clearly lower for Galileo L1 than for GPS L1 using the same type of correlation method (advantage of the BOC signal with respect to the BPSK signal), the influence of the ionosphere will still remain the dominant source of error. That is why the user will also lose the advantage of having a good multipath error rejection and a lower receiver noise error when using only one frequency. From an integrity point of view, the ionosphere is still a threat and causes the need to sustain a high level of magnitude of protection levels. The way to take a full advantage of the multipath rejection capability of Galileo is to use the Galileo constellation with dual frequency measurements. After building a ionosphere free combination, the remaining dominant error component is then caused by the multipath and receiver noise. In that case the benefit of using the BOC signal at L1 will dramatically decrease the level of pseudo range noise and therefore will reduce the protection levels in the same way. Another advantage of the Galileo constellation is to have an improved geometry characterised by lower values of the dilution of precision. This is the second effect that permits a high confidence in the position solution by again reducing the protection levels.

7. ACKNOWLEDGEMENT

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