Combining Galileo PRS and GPS M-Code

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Giove-B image: ESA/GPS Block IIF image: Boeing

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Although Galileo operates wholly under civil control, it does include encrypted signals, including those of the Public Regulated Service or PRS, which are broadcast near the new GPS military M-code signals at the L1 frequency. Galileo's design calls for PRS use by public safety organizations such as police and fire departments and customs agencies. Because of its design, PRS could also be used for military applications; however, the European Union (EU) has not approved such use and several EU members have gone on record opposing it. Nonetheless, in light of a continuing interest in combined use of M-code and PRS, this article examines some of the technical issues surrounding the subject.

An agreement signed in June 2004 between the European Union and the United States regarding the promotion, provision, and common use of GPS and Galileo has opened a new world of possibilities in satellite navigation.

Simulation studies of the combined use of Galileo and GPS civil signals have demonstrated that users may expect a clear enhancement of performance in terms of positioning accuracy and navigation solution (See the Additional Resources section at the end of this article for further details about these studies). The compatibility and interoperability that the Galileo signal structure will offer with respect to GPS is especially relevant in the E2-L1-E1 band.

After lengthy negotiations, the United States and the EU agreed on the design of the Open Service (OS) signals to be transmitted by Galileo and the future GPS on L1. If we take a more detailed look into the different waveforms, however, we see that not only the Galileo Open Service and the GPS C/A code have a common center frequency on L1 but also the Galileo Public Regulated Service (PRS) and the GPS military M-code.

Because common center frequencies are certainly the main prerequisite for interoperability, the combined processing of PRS and military signals from Galileo and GPS raises the possibility of offering a better positioning and navigation solution. Thus, in this article we want to go one step further to the analysis made in our previous work — cited as [1] and [2] in the Additional Resources section at the end of this article — and assess the performance of a combined Galileo PRS and GPS M-code receiver.

From a political and military point of view, the question of a combined Galileo PRS and GPS M-code service has clearly not been addressed yet and probably it will require time-consuming and lengthy discussions in the future, if the negotiations ever take place. Nonetheless, from a purely technical point of view it makes sense to evaluate the pros and cons as well as the performance that such a service could offer some day, and the time is certainly right for doing that now.

Therefore, this article first evaluates the performance of the two single services separately using identical assumptions. In order to do so, a refined methodology is proposed to estimate the different sources of error that contribute to the User Equivalent Range Error (UERE), particularly the ranging error caused by reflected signals or multipath. Afterwards the same analysis is carried out for a combined processing of Galileo PRS and GPS M-Code signals for a joint position, velocity, and time solution.

Introduction

Interoperability between civil GPS and Galileo was from the very beginning one of the most important drivers in the design of the Galileo signal structure. For that reason common center frequencies of Galileo and GPS signals in E5A (L5) and L1 were chosen. Figure 1 shows the Galileo frequency and signal structure after the Agreement on the promotion, provision and use of GALILEO and GPS satellite-based navigation systems and related applications signed between the European Union (EU) and the United States.

Although the signal structure for the Galileo OS was specified in this agreement, it still allows some flexibility in the modulation scheme used. Therefore, the EU is still working to optimize the L1 OS signal, which may result in even better performance.

One major point during the negotiations was the necessary coexistence of the Galileo Public Regulated Service (PRS) and Open Service (OS) with the GPS C/A and M-code, in particular on L1 where the necessary separation between the different services played an outstanding role. Thus, the final frequency and signal structure resulted also in the same L1 center frequency for the Galileo PRS and GPS M-code. Figure 2 shows both services in the various frequency bands.

Our previous work evaluated the accuracy of a combined Galileo OS and GPS C/A code service. This article will present the positioning accuracy of a combined Galileo PRS and GPS M-code service from a purely technical point-of-view. No doubt that military and political considerations and decisions would be necessary to realize such a combined service in reality. However, this paper aims to show not only a benefit to use of the interoperability between the two satellite navigation systems for a combined civil service, but also in combining the Galileo PRS and the GPS M-code.

As will be shown, the main source of error is due to the ionosphere. Once this is eliminated by means of differential corrections from satellite-based augmentation systems (SBAS) signals or aiding information provided by assisted-GNSS (A-GNSS) capabilities, for example, multipath remains as the main problem. But one of our main drivers in this article is also to show the potential accuracy that a combined PRS/M-code (military) receiver could offer some day in the future.

In order to accomplish this, we consider realistic and worst-case scenarios. We will first present the main sources of error that contribute to the error budget, and estimate their values using methodology established in previous work (see items [1], [2] and [4] in the Additional Resources section). For a more realistic computation of these values, we introduce a refined methodology.

In the first part of the article we are studying the atmospheric and clock errors, as well as the necessary corrections. The ionosphere-free linear combination for Galileo L1A/E6A and GPS M-code L1/L2 signals will be an important focus of analysis.

Another important source of error is the thermal noise. We analyze the code and phase tracking errors due to thermal noise by means of the Cramer-Rao lower bound of the tracking error variance. A typical value will be obtained by assuming a received C/N_0 under normal conditions (46.5 dB-Hz), while for the worst case we will consider a degradation of 15 dB (31.5 dB-Hz). This represents a considerable attenuation and corresponds to a typical worst case scenario we can find in the real world.

Last but not least, the main unavoidable source of error, namely the multipath error, is analysed exhaustive-

FIGURE 1. Galileo Frequency and Signal Baseline after the Agreement between the European Union and United States in June 2004

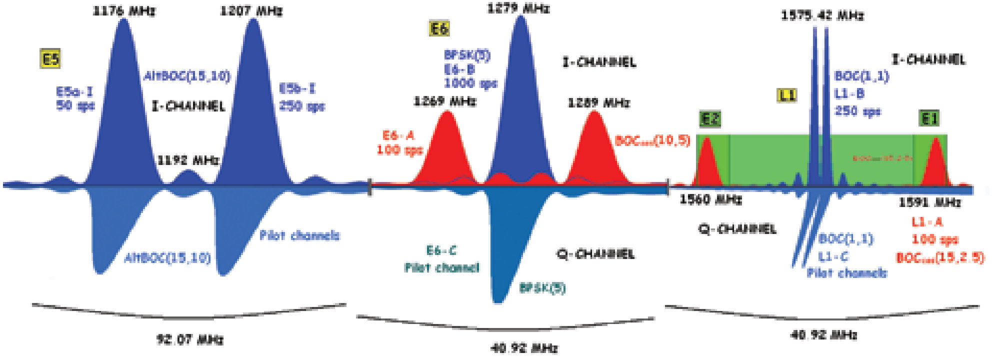
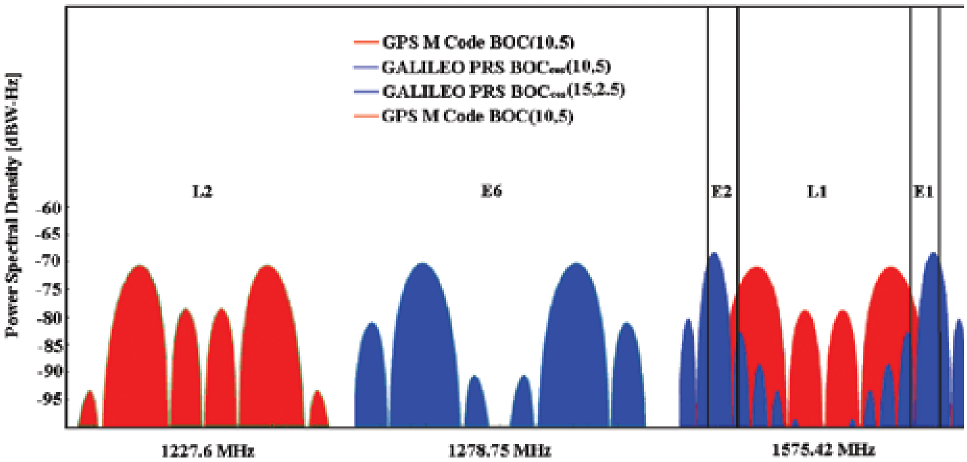


FIGURE 2. Galileo PRS and GPS M-Code Signals



ly under realistic and worst case conditions. Given the substantial effect and characteristics of multipath, special care will be put on estimating its contribution on the total user equivalent range error (UERE). In our analysis we will assume a narrow correlator with a spacing of d = 0.1 chip. In line with the results presented in our previous work cited earlier, a more realistic view of the multipath will be given by employing a model that accounts for the statistical distributions of the amplitudes and geometric path delays of the multipath signals in urban and suburban areas.

Then, the total UERE of Galileo PRS and of GPS M-code will be calculated. In a final step, we will take into account the geometry of the constellation of both satellite navigation systems to obtain the desired positioning accuracy for different scenarios and configurations.

As a conclusion, this article will present the theoretically expected positioning and navigation performance of Galileo PRS and GPS M-code, each alone, as well as the one of a combined service.

GNSS Error Budgets

Systematic errors and random noise affect the code and carrier observations needed for positioning. We can classify these error sources into three groups:

1. Satellite errors:
   a. Clock bias
   b. Orbital errors
2. Signal propagation:
   a. Ionospheric refraction
   b. Tropospheric refraction
   c. Multipath
3. Receiver errors:
   a. Clock bias
   b. Ranging error (thermal noise)

According to this classification, the so-called UERE will be estimated for both Galileo and GPS in a typical and worst case scenario. Next, the different contributors to the UERE are explained more in detail.

Clock and Orbit Errors.

The calculation of the clock and orbit errors depends mainly on the number of monitoring stations around the world. For Galileo PRS as well as for the GPS M-code we will consider two scenarios in line with the approach followed in [1]: a worst case scenario and a typical scenario. For the worst case, we will take a conservative value of 1.2 m ([5], [6]) while for the normal scenario we will assume an error of 50 percent of it. That represents a total satellite error of around 0.6 meter in normal conditions.

Atmospheric Errors. When we analyze the atmospheric errors, we have to distinguish two different sources. The main source of error is the ionospheric path delay while a secondary source arises from the tropospheric path delay. Let us examine both sources in more depth.

Ionospheric Path Delay. As we know, the ionospheric error can be expressed as:

$$e_{ion}\,[m] = \frac{40.3}{f^2}\int N dl \qquad (1)$$

where $\int N dl$ refers to the TEC (Total Electron Content) in el/m² and is the result of integrating N (electron density) along the path between the observer and the satellite. Also, according to the investigation of H. Blomenhofer cited in the Additional Resources, the TEC value of free electrons along the path is shown to range between:

$$20.10^{16}\,\frac{el}{m^2} < TEC < 60.10^{16}\,\frac{el}{m^2} \qquad (2)$$

As can be seen in the work by W.A. Feess et al cited in Resources, the remaining ionospheric error after applying the ionospheric correction with the Klobuchar model for GPS and the NeQuick model for Galileo is approximately 50 percent of the total ionospheric error. Thus, using the TEC range given by Equation (2) and considering only the remaining ionospheric error that contributes to the UERE, we obtain the residual ionospheric errors for the different Galileo and GPS frequencies. For a typical scenario, we will assume a value of TEC = 40.10^{16} el/m². On the other hand, we will assume a value for the TEC of 60.10^{16} el/m² for the worst case scenario. These assumptions lead to the numbers shown in Table 1.

Scenario	Freq. [MHz]	1227.6 (L2)	1278.75 (E6)	1575.42 (L1)
Typical Case	Ion.Error [m]	5.35	4.93	3.25
Worst Case	Ion.Error [m]	8.02	7.40	4.87

TABLE 1. Assumed Residual Ionospheric Errors

We must note that this represents the worst case scenario that we can find in reality with a reasonable probability and not the worst case that could occur when the solar wind activity is very intense. In the latter case the TEC value could reach numbers as high as 220.10^{16} el/m² in some regions of the Earth.

In a second step, when we study the dual frequency combinations of GPS and Galileo, alone and together, we will eliminate the ionospheric effect on the budget by using the ionospheric-free linear combination described shortly more in detail. For the case we assume access to ionospheric corrections a value of 0.4 meter. (This scenario again assumes a single frequency receiver, provided with a means to access corrections such as processing with SBAS signals or A-GNSS capabilities. In this case, we consider that more than 90 percent of the bias is well estimated and that the resulting standard deviation is about 0.4 meter.)

Tropospheric Path Delay. The error caused by GNSS signals propagating through the troposphere is usually removed by incorporating a tropospheric model into the signal processing. In this article, in consonance with our similar work done for the rest of Galileo and GPS signals, we will employ the Ifadis model that leads to residual errors of up to no more than around four centimeters at zenith, based on the work by A. Pósfay et al cited in the Resources section. (See Table 2 for more details). As we know, about 90 percent of the tropospheric error derived from the hydrostatic component (ZHD: Zenith Hydrostatic Delay) can be easily modelled, while the other 10 percent is caused by the wet component, which is more unpredictable with errors commonly ranging from 10 to 20 percent.

MODEL		Mean [m]	Min [m]	Max [m]
Hopfield	Conventional	0.0275	0.0041	0.0713
	Improved	0.0239	0.0039	0.0492
Ifadis	Conventional	0.0287	0.0060	0.0713
	Improved	0.0217	0.0037	0.0409

TABLE 2. Minimum, Maximum, and Mean Values of Zenith Wet Delay and Hopfield and Ifadis Model Precision.

According to this, we will assume for both Galileo PRS and GPS M-code an error contribution of 0.2 meter for the typical scenario, based on observations reported by K. McDonald and C. Hegarty cited in Additional Resources. For the worst case we will make use of the improved Ifadis model values shown in Table 2 (maximum residual error). Because the tropospheric error strongly depends on the signal elevation, we will assume that the worst case corresponds to 10 degrees.

This results in a tropospheric residual error of approximately 1.35 meters. Given that the error increases very rapidly when we approach the horizon, we will not consider this extreme case in order to give a reasonably probable worst case.

Receiver Error: Code Noise. As mentioned in the introduction, we use the Cramer-Rao lower bound to estimate the receiver code noise performance. This corresponds to the theoretical lower bound for the code tracking variance and is achieved with an early-minus-late coherent correlator with the appropriate spacing.

As mentioned above, we can completely eliminate the ionospheric error by making use of the linear combination of two frequencies. The ionosphere-free pseudorange (PR), therefore, can be obtained from the two pseudoranges PR_1 and PR_2 at f_1 and f_2 as follows:

$$PR = \frac{f_1^2}{f_1^2 - f_2^2} PR_1 - \frac{f_2^2}{f_1^2 - f_2^2} PR_2 \qquad (3)$$

where $f_1 > f_2$. Based on (3), the code noise error of the linear iono-free combination propagates according to:

$$\sigma_{PR} = \sqrt{\frac{\gamma^2}{(\gamma-1)^2}\sigma_{f_1}^2 + \frac{1}{(\gamma-1)^2}\sigma_{f_2}^2} = \sqrt{\left(\frac{\partial PR}{\partial PR_1}\right)^2 \sigma_{f_1}^2 + \left(\frac{\partial PR}{\partial PR_2}\right)^2 \sigma_{f_2}^2} \qquad (4)$$

where $\gamma = \left(\frac{f_1}{f_2}\right)^2$ and σ_{f1} and σ_{f2} are the code noise for the pseudoranges on f_1 and f_2, respectively.

Tables 3 and 4 summarize the results of the code noise analysis. We should note that a value of -201.5 dBW/Hz was used for the noise floor and that ideal filters were employed for both GPS and Galileo. Regarding the gain of the receiver, no amplification was taken into account.

For a typical case, we assume the C/N_0 values shown in Table 3, while for a worst

Code Noise Errors For Single Frequency

Signal	Modulation	Power (dBW)	BW (MHz)	Typical C/N_0 (dB-Hz)	Typical Code noise (m)	Worst Case C/N_0 (dB-Hz)	Worst Case Codenoise(m)
Galileo $L1_A$	$BOC_{sin}(15,2.5)$	-155	40	46.5	0.0151	31.5	0.0851
Galileo $L1_A$	$BOC_{sin}(15,2.5)$	-155	32	46.5	0.0154	31.5	0.0868
Galileo $L1_A$	$BOC_{cos}(15,2.5)$	-155	40	46.5	0.0146	31.5	0.0818
Galileo $L1_A$	$BOC_{cos}(15,2.5)$	-155	32	46.5	0.0149	31.5	0.0841
GPS M Code	BOC(10,5)	-155	40	46.5	0.0240	31.5	0.1348
GPS M Code	BOC(10,5)	-155	30	46.5	0.0240	31.5	0.1352
GPS M Code	BOC(10,5)	-155	24	46.5	0.0248	31.5	0.1392
Galileo $E6_A$	$BOC_{sin}(10,5)$	-155	40	46.5	0.0240	31.5	0.1348
	$BOC_{cos}(10,5)$	-155	40	46.5	0.0204	31.5	0.1145

TABLE 3. Assumed Code Noise Errors for Galileo and GPS for a Noise Floor of N_0=-201.5 dBW-Hz. For comparison, the sine phased BOC(15,2.5) modulation is also shown.

Code Noise Errors For Dual Frequency Iono-Free Combination

Iono-free linear combination	Modulation	Power (dBW)	Frequency Band	Bandwidth (MHz)	$\gamma/(\gamma-1)$	$1/(\gamma-1)$	Typical C/N_0 (dBHz)	Typical Code Noise (m)	Worst Case C/N_0 (dBHz)	Worst Case Codenoise(m)
GPS M Code	BOC(10,5)	-155	L1	30	2.55	1.55	46.5	0.072	41.5	0.127
	BOC(10,5)	-155	L2	30			46.5		41.5	
Galileo PRS	BOCcos(15,2.5)	-155	L1	40	2.93	1.93	46.5	0.058	41.5	0.103
	BOCcos(10,5)	-155	E6	40			46.5		41.5	

TABLE 4. Assumed Code Noise Errors for Galileo and GPS for the Studied Iono-Free Linear Combinations

case scenario an attenuation of up to 15 decibels considerably deteriorates the received C/N_0, consequently increasing the expected code noise error of the receiver. The same assumptions apply to Table 4 where the iono-free linear combinations L1-L2 are built for GPS while for Galileo we have L1-E6.

Multipath Error

Multipath error is the most important unavoidable source of error contributing to the UERE, because it is very difficult to model. As we saw, the ionospheric error indeed presents worse values in a general case, but an appropriate receiver would be able to eliminate it or at least reduce its contribution with corrections coming from SBAS or A-GPS. In this article, we focus on the rural/suburban channel described in [4]. Typical parameters for the various environments are given in Table 5. As shown in the table, the typical multipath delay for the rural/suburban scenario is about 90 meters.

Multipath Environment	Typ. Path Delay τ_0
Maritime	15 m
Aeronautical (Wing Reflection)	6 m
Aeronautical (Ground Reflection)	0-9000 m
Rural, Suburban	90 m

TABLE 5. Typical Path Delays for Different Multipath Environments (in meters)

As shown in [1] and [4], the probability of occurrence of the multipath can be expressed as the product of

$$\rho(\tau)=\frac{1}{\tau_0}e^{-\frac{\tau}{\tau_0}} \qquad (5)$$

and

$$A(\tau)=\alpha_0 e^{-\frac{\tau}{2\tau_0}} \qquad (6)$$

where $\rho(\tau)$ models the probability distribution of multipath path delays and $A(\tau)$ represents the distribution of the relative multipath amplitudes. Thus, using these equations we can easily calculate the probability that the multipath signal is coming from a given distance, with a given amplitude, if we have the coefficient of reflection α_0 and the typical path delay τ_0, which characterizes the multipath environment. Therefore, using the multipath envelopes together with the probability density function (pdf) that corresponds to the environment, we can obtain weighted multipath envelopes that also account for the known fact that short distance multipath is more probable than long distance multipath.

Combining now Equations (5) and (6) the new distribution $D(\tau)$ of multipath delays and amplitudes can be written as follows:

$$D(\tau)=\rho(\tau)\cdot A(\tau)=\frac{\alpha_0}{\tau_0}e^{-\frac{3\tau}{2\tau_0}} \qquad (7)$$

If we now normalize to 1 in order to have the pdf of the multipath error, thus:

$$\int_0^\infty D(\tau)d\tau=\int_0^\infty \rho(\tau)\cdot A(\tau)d\tau=\frac{\alpha_0}{\tau_0}\int_0^\infty e^{-\frac{3\tau}{2\tau_0}}d\tau=\frac{2\alpha_0}{3} \qquad (8)$$

we obtain the desired multipath pdf:

$$D'(\tau)=\frac{3D(\tau)}{2\alpha_0}=\frac{3e^{-\frac{3\tau}{2\tau_0}}}{2\tau_0}\ [1/\mathrm{m}] \qquad (9)$$

For the worst case scenario we will estimate the multipath error by taking the maximum in absolute value of the multipath envelopes when the amplitude of the reflected signal is only attenuated 3 decibels with respect to the direct path. For the typical scenario, on the contrary, we will estimate the mean value using the multipath error envelopes with an attenuation of α=-10 dB. Going beyond our previous work, we estimate the mean value in a more refined way, from a mathematical point of view.

If we let e be the variable that represents the multipath error in absolute value, then the mean value of the multipath envelopes can be expressed as:

$$E\{e_{multipath}\}=\int_0^\infty e\,p(e)\,de \qquad (10)$$

Additionally, it can be shown that

$$p(e=e_0)de=\sum_i p(\tau_i/E'(\tau_i)=e_0)d\tau=\sum_i D'(\tau_i)d\tau \qquad (11)$$

where $E'(\tau_i)$ refers to the amplitude of the mean absolute multipath envelope at a distance, assuming a coherent correlator spacing of 0.1 and an attenuation of -10 dB for the reflected signal.

Moreover, in order for the multipath envelope to correspond to a typical scenario, its amplitude will be multiplied by one-half. In fact, if we assume that the phase of the multipath reflected signal is uniformly distributed, the mean amplitude of the multipath envelopes in absolute value will be half that of the sum of the absolute values of the positive and negative multipath envelopes, which are, as the name suggests, the envelopes of all the intermediate possible amplitudes.

Now we can easily estimate the typical multipath value by integrating the product of the pdf given by Equation (9) with the semi-sum of the absolute positive and negative multipath envelopes, divided by 2. In other words, the estimation of the multipath error for the typical scenario can be calculated as:

$$E\{e_{multipath}\}=\frac{1}{2}\int_0^\infty E'(\tau)D'(\tau)d\tau=\frac{1}{2}\int_0^\infty\frac{\left[\|E_{\max}(\tau)\|+\|E_{\min}(\tau)\|\right]}{2}D'(\tau)d\tau \qquad (12)$$

Multipath Errors For GPS M-Code And Galileo PRS

Freq.Band	Signal	BW	Code Multipath Error [m] α=-10dB			Code Multipath Error [m] α=-3 dB		
			Narrow Correlator (d=0.1)			Narrow Correlator (d=0.1)		
			Worst case [m]	Typical value [m]	Area[m^2]	Worst case [m]	Typical value [m]	Area [m^2]
E2-L1–E1	BOC_{cos}(15,2.5)	40MHz	0.3072	0.0583	12.2414	1.6033	0.2966	62.0764
	BOC(10,5)	24MHz	0.4855	0.0716	12.7620	2.5390	0.3653	64.9077
E6	BOC_{cos}(10,5)	40MHz	0.4022	0.0523	8.6929	2.1067	0.2667	44.2136

TABLE 6. Assumed Multipath Errors for Galileo and GPS in a Rural/Suburban Environment

Multipath Errors For Dual Frequency Iono-Free Combination

Iono-free linear combination	Signals	Frequency Band	BW	Dual Frequency Code Multipath Error [m]		
				Narrow Correlator (d=0.1)		
				Worst case [m]	Typical Value [m]	Area [m^2]
GPS M Code	BOC(10,5)	L1	30MHz	1.7329	0.2117	35.3639
	BOC(10,5)	L2	30MHz			
Galileo PRS	BOC_{cos}(15,2.5)	L1	40MHz	1.7077	0.3120	66.0304
	BOC_{cos}(10,5)	E6	40MHz			

TABLE 7. Assumed Multipath Errors for Dual Frequency Iono-Free Combination

	NARROW CORRELATOR™ (d=0.1)							
	TYPICAL CASE				WORST CASE			
Service / Error source	PRS BOC_{cos}(10,5)	PRS BOC_{cos}(15,2.5)	M Code BOC(10,5)	M Code BOC(10,5)	PRS BOC_{cos}(10,5)	PRS BOC_{cos}(15,2.5)	M Code BOC(10,5)	M Code BOC(10,5)
Band	$E6_A$	$L1_A$	L1	L2	$E6_A$	$L1_A$	L1	L2
Bandwidth(MHz)	40	40	24	24	40	40	24	24
Clock and Orbit	0.6	0.6	0.6	0.6	1.2	1.2	1.2	1.2
Ionospheric	4.93	3.25	3.25	5.35	7.40	4.87	4.87	8.02
Tropospheric	0.20	0.20	0.20	0.20	1.35	1.35	1.35	1.35
Multipath	0.052	0.058	0.072	0.072	2.107	1.603	2.539	2.539
Code Noise	0.020	0.015	0.025	0.025	0.114	0.082	0.139	0.139
Total error	4.97	3.31	3.31	5.39	7.90	5.44	5.78	8.61

TABLE 8. Galileo and GPS Error Budget for Typical and Worst Case in [m]

	DUAL FREQUENCY, NARROW CORRELATOR™ (d=0.1)			
	TYPICAL CASE		WORST CASE	
Service / Error source	PRS	M Code	PRS	M Code
First Signal	BOC_{cos}(15,2.5)	BOC(10,5)	BOC_{cos}(15,2.5)	BOC(10,5)
Band	$L1_A$	L1	$L1_A$	L1
Second Signal	BOC_{cos}(10,5)	BOC(10,5)	BOC_{cos}(10,5)	BOC(10,5)
Band	$E6_A$	L2	$E6_A$	L2
Bandwidth[MHz]	40	30	40	30
Clock and Orbit	0.6 m	0.6 m	1.2 m	1.2 m
Ionospheric	–	–	–	–
Tropospheric	0.2 m	0.2 m	1.35 m	1.35m
Multipath	0.312 m	0.212 m	1.708 m	1.733 m
Code Noise	0.058 m	0.072 m	0.103 m	0.127 m
Total error	0.71 m	0.67 m	2.49 m	2.51 m

TABLE 9. Galileo and GPS Error Budget When the Iono-Free Linear Combination is Considered

The estimates of the multipath errors are summarized in Tables 6 and 7. (In the tables, the area value is obtained by integrating the error, weighted by the probability, between zero and infinity. Thus, since the error is expressed in metres and the variable of integration is the multipath delay expressed in metres as well, the results are in square meters.) The Figures 3 and 4 show in more detail the multipath envelopes for the Galileo PRS and GPS M-code signals (on the top), as well as the product function in the integrand (on the bottom).

We find that the new proposed methodology to estimate the typical multipath errors offers a qualitative improvement in the estimations by using in a more correct way the information contained in the probability density functions given by Equations (5) and (6). Additionally, because we no longer work with the amplitude of the multipath envelopes but rather the divided semi-sum of the absolute amplitudes, we also have a more realistic estimation of the phase of the reflected signal and, therefore, of the real effect of the multipath on the total UERE, which is our main objective in this study.

Galileo and GPS Accuracy

Using the values obtained and analyzed graphically in the preceding sections, we will next calculate the error budget as defined in the introduction for Galileo PRS and GPS M-code alone and for a combined service, in the presence of ionospheric error and with corrected values.

Based on the previous multipath figures, Tables 8 and 9 show some of the graphical results and assumptions made for the different contributors of error to the UERE, for single- and dual-frequency receivers, respectively.

Once we have calculated the error budget, the next step is to estimate the absolute positioning accuracy the signals are expected to have. To do so, we need to know the satellite geometry of the system, which is reflected by the dilution of precision (DOP) value.

Table 10 shows the DOP values assumed in our analysis, based on [5], using GPS and Galileo satellites separately and together:

Now, using the values shown in Table 10 and the UERE with the errors as estimated in the Tables 8 and 9, we can make the final estimation of the positioning error for the two considered scenarios.

Accuracy of the Position (95%)	PDOP	HDOP	VDOP
Only GPS	2.7	1.2	2.40
Only Galileo	2.7	1.2	2.40
GPS+Galileo	1.12	0.5	1

TABLE 10. Assumed DOP for Galileo and GPS

Finally, we arrive at the main objective of this article: namely to analyze the performance of a combined Galileo PRS and GPS M-code receiver. As was shown in Table 10, the geometry of both systems improves considerably in this case.

To calculate the total error resulting from processing signals coming from Galileo and GPS, the following approximation for the weighting of the respective contributions is employed:

$$e_{GPS+Galileo} = \sqrt{\frac{2}{\frac{1}{e_{Gal}^{2}} + \frac{1}{e_{GPS}^{2}}}}\, DOP_{GPS+Galileo} \qquad (13)$$

where the variable e refers to the error budget of Galileo and GPS respectively.

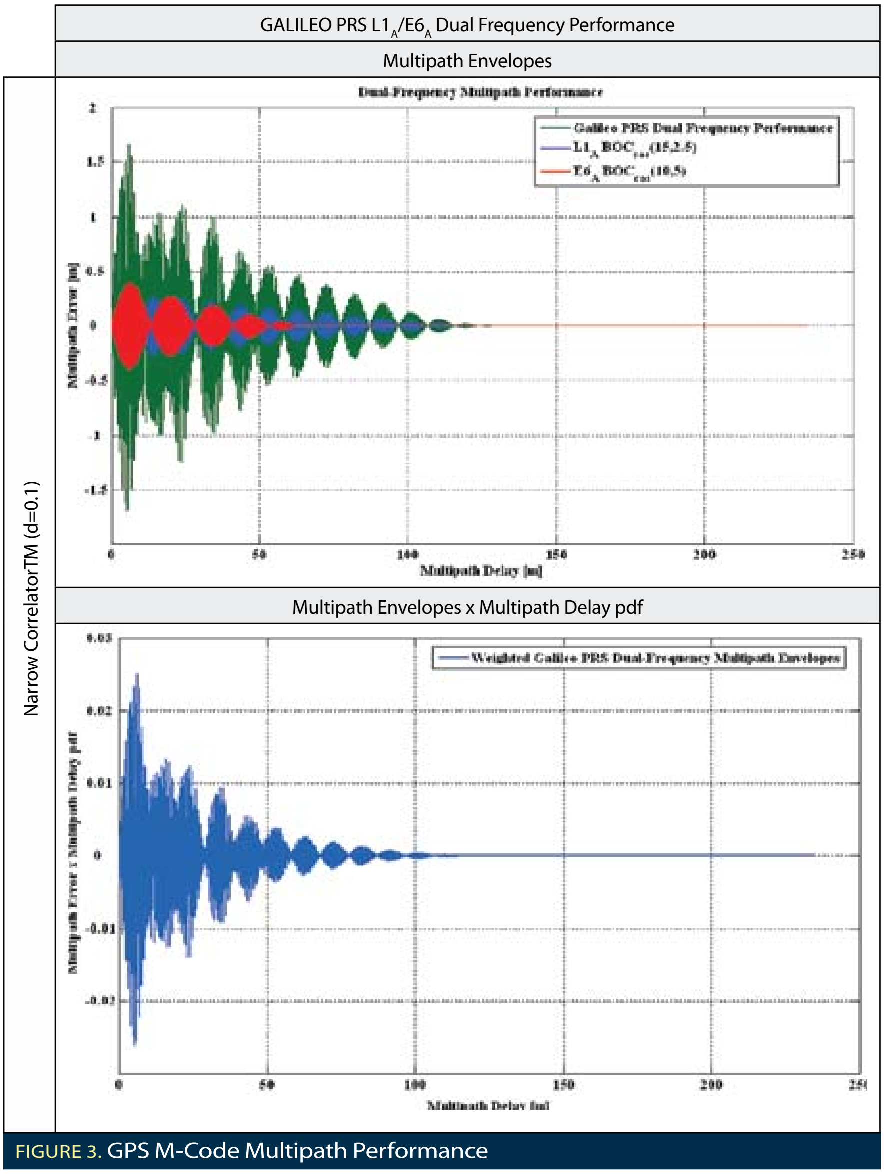


FIGURE 3. GPS M-Code Multipath Performance

Conclusions

We have analysed in depth the different contributions to the error budget that the Galileo PRS and the military GPS M-code are expected to show in worst case and typical environments. Additionally we have calculated the positioning accuracy for both services, alone and operated together. Tables 11 and 12 summarize the most relevant results of our analyses.

In summary, the following conclusions can be drawn:

- Galileo PRS and GPS M-code alone perform more or less the same in a typical rural/suburban scenario.
- As it has been shown, the combined processing of Galileo PRS and GPS M-code signals will bring an excellent performance for the potential user. Horizontal accuracies of even 0.26 meter could be achieved, which would represent a reduction of the positioning error of about 64 percent compared to use of GPS M-code or Galileo PRS alone.
- This article has also shown that the main source of error comes from the ionosphere for a single frequency receiver. Then, when the iono-free linear combination is applied and the ionospheric error is eliminated, the main source of error that still remains is the multipath.

Because the form and amplitude of the multipath envelopes is characteristic of every modulation, the modulation has a clear and direct impact on the error budget and, therefore, on the whole performance of the system. Many efforts have been undertaken in the past to optimize the Galileo signal modulations in order to achieve the potential of being better than the current GPS signals. Our results here prove that this work was more than justified.

- The multipath error estimations were made only for the rural/suburban environment. Future work must be carried out using other types of potential scenarios.

Additional Resources

[1] Avila-Rodriguez, J.A. et al. (2004), "Combined Galileo/GPS Frequency and Signal Performance Analysis", Proceedings of ION 2004–21-24 September 2004, Long Beach, California, USA

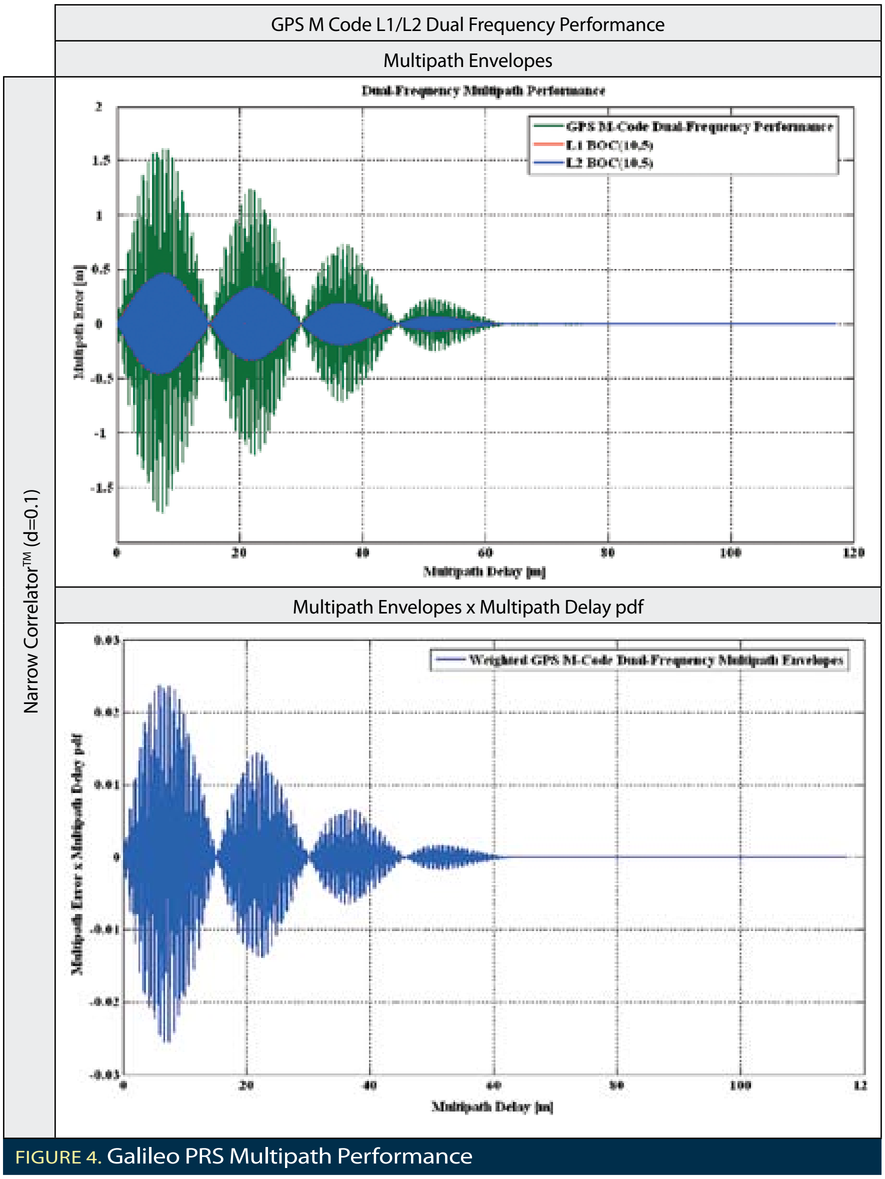


FIGURE 4. Galileo PRS Multipath Performance

	L1A GALILEO PRS	L1 GPS M-CODE	COMBINED GALILEO/ GPS L1 RECEIVER	COMBINED GALILEO/ GPS RECEIVER
Horizontal	3.97 m	3.97 m	1.65 m	0.34 m
Vertical	7.94 m	7.94 m	3.31 m	0.69 m
3D-P	8.94 m	8.94 m	3.71 m	0.77 m

TABLE 11. Typical Accuracies for the Galileo PRS, GPS M Code and Combined Positioning

	L1A GALILEO PRS	L1 GPS M-CODE	COMBINED GALILEO/ GPS L1 RECEIVER	COMBINED GALILEO/ GPS RECEIVER
Horizontal	0.72 m	0.72 m	0.30 m	0.26 m
Vertical	1.45 m	1.45 m	0.60 m	0.52 m
3D-P	1.63 m	1.63 m	0.68 m	0.59 m

TABLE 12. Typical Accuracies for the Galileo PRS, GPS M Code and Combined Positioning with ionospheric correction

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[10] Guenter W. Hein, Jose-Angel Avila-Rodriguez, Lionel Ries, Laurent Lestarquit, Jean-Luc Issler, Jeremie Godet, Tony Pratt, Members of the Galileo Signal Task Force of the European Commission (2005), "A Candidate for the Galileo L1 OS Optimized Signal," Proceedings of ION 2005 – 13-16 September 2005, Long Beach, California, USA

Glossary

A-GNSS	Assisted GNSS
AltBOC	Alternative BOC
BCS	Binary Coded Symbols
BOC	Binary Offset Carrer
BOCcos	Cosine phased BOC modulation
BOCsin	Sine phased BOC modulation
BPSK	Binary Phase Shift Keying
C/A	Coarse/Acquisition
CBCS	Composite Binary Coded Symbols
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
OS	Open Service
PR	Pseudorange
PRS	Public Regulated Service
SBAS	Satellite Base Augmentation System
TEC	Total Electron Content
UERE	User Equivalent Range Error
DOP	Dilution of Precision
HDOP	Horizontal Dilution of Precision
VDOP	Vertical Dilution of Precision
PDOP	Positioning Dilution of Precision

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