Testing the Test Satellites: the Galileo IOV Measurement Accuracy

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Abstract — **The European GNSS, Galileo, is currently in its In-Orbit Validation (IOV) phase where four satellites are finally available for computing the user position. In this phase, the analysis of the measurements obtained from the IOV satellites can provide insight on the performance and potentialities of the Galileo system. In this paper, a methodology based on the use of precise orbits and ionospheric corrections is suggested for the analysis of the Galileo IOV pseudorange and pseudorange rate errors. Several hours of data were collected using a Septentrio PolarRxS receiver and used to determine figures of merits such as RMS and maximum errors of the Galileo observables. From the analysis it emerges that Galileo measurements have accuracies comparable with those of GPS. The benefits of combined GPS-Galileo positioning are also highlighted and results relative to the computation of a Galileo-only navigation solution based on broadcast ephemerides are provided.**

Keywords – accuracy, Galileo, In-Orbit Validation, IOV, precise orbits, pseudorange, pseudorange rate

I. INTRODUCTION

Galileo, the European Global Navigation Satellite System (GNSS), is currently in its In-Orbit Validation (IOV) phase and four satellites are finally available for computing the user position. In December 2005, the first Galileo In-Orbit Validation Element (GIOVE) experimental satellite, GIOVE-A, was launched whereas a second satellite, GIOVE-B, was placed into orbit in April 2008. Although the two GIOVE satellites did not allow the computation of the user position, it was possible to test the performance of new acquisition and tracking algorithms designed to fully exploit the benefits of the new Galileo signals. GIOVE satellites also allowed researchers to assess the ranging capabilities of future Galileo signals [1] and provided a significant experience for the design of next generation Galileo satellites.

In October 2011, the first two IOV satellites were launched. Two additional IOV satellites were placed into orbit in October 2012, completing the satellite quartet required for positioning. In the same year, GIOVE-A and GIOVE-B where decommissioned. Although the four IOV satellites transmit signals on E1, E5 and E6 bands, Galileo-only positioning has been possible only in rare occasions when valid ephemerides are broadcast. On March 2013, the European Space Agency (ESA) anticipated the forthcoming IOV test campaign and disseminated valid Galileo ephemerides allowing the first positioning entirely based on the Galileo transmitted Signal-In-Space (SIS). Several research groups reported successful Galileo-only positioning [2, [3] including the authors (http://pang.uniparthenope.it).

Despite, the fact that Galileo ephemerides are still not broadcast in a continuous way, the ranging capabilities of IOV satellites can be assessed employing the precise orbits determined using the approach described in [4] and available from ftp://cddis.gsfc.nasa.gov/pub/gps/products/mgex. These orbits, the availability of ionospheric corrections and a professional receiver placed in a surveyed location allow one to determine figure of merits such as the Root Mean Square (RMS) and the maximum error of the Galileo observables, i.e., pseudoranges (PR) and PR rates.

In this paper, a methodology based on the availability of the products mentioned above is developed and used to assess the quality of Galileo IOV observables. The methodology is an extension of the techniques developed in [1] and employed to characterize the PRs of GIOVE satellites. With respect to [1], the following elements of innovation have been introduced: precise ephemerides are used to obtain a more accurate satellites position and Global Ionospheric Maps (GIM) are adopted to compute the ionospheric delay. Finally, the analysis is extended to PR rates.

Several hours of data were collected using a Septentrio PolarRxS receiver and used to characterize the quality of Galileo observables. From the analysis, it emerges that Galileo measurements have accuracies comparable with those of GPS showing the potential of the European GNSS.

It is noted, that although several groups focused on Galileo-only or combined Galileo-GPS positioning, no result has been published on the accuracy of IOV measurements. These results along with the methodology proposed are the main contributions of this paper. In addition to this, the benefits of combined GPS-Galileo positioning are also highlighted and some considerations on Galileo-only location are provided. More specifically, results obtained using Galileo broadcast ephemerides are also analyzed.

The remainder of this paper is organized as follows. The navigation states are described in Section II along with the methodology adopted for characterizing the errors affecting

Galileo observables. The experimental setup adopted for the analysis is detailed in Section III whereas experimental results are described in Section IV. Section V discusses the benefits of GPS-Galileo combined positioning and the potentiality of Galileo-only location. Some conclusions are finally drawn in Section VI.

II. NAVIGATION STATES AND OBSERVABLE ERRORS

A. *Navigation solution*

GNSS positioning is based on the one-way ranging technique: the time of travel of a signal, transmitted by a satellite, is measured and scaled by the speed of light to obtain PRs which can be modeled as:

$$\rho = d + cdt_u + \varepsilon_\rho \tag{1}$$

where ρ is the PR measurement, d is the geometric satellite-receiver distance, cdt_u is the receiver clock offset scaled by the speed of light, c and ε_ρ contains the residual errors after atmospheric and satellite-related corrections [5[6].

A GNSS receiver is also able to provide Doppler measurements defined as the time derivative of the carrier phase [5[6] and containing information about the relative motion between satellite and receiver; Doppler observables can be directly converted into PR rates which can be modeled as:

$$\dot{\rho} = \dot{d} + c\dot{d}t_u + \varepsilon_{\dot{\rho}} \tag{2}$$

where $\dot{d}$ is the geometric distance rate of change, $c\dot{d}t_u$ is the clock drift scaled by the speed of light and $\varepsilon_{\dot{\rho}}$ accounts for residual errors. PR and PR rate measurements from different satellites are combined by the receiver and used to compute the user position, velocity and the clock parameters:

$$\begin{aligned} \underline{x} &= \begin{bmatrix} \underline{P} & \Delta cdt_u \end{bmatrix} \\ \underline{v} &= \begin{bmatrix} \underline{V} & \Delta c\dot{d}t_u \end{bmatrix} \end{aligned} \tag{3}$$

Navigation solution (3) can be computed using different techniques such as the Weighted Least Squares (WLS) with weighting matrix related to the satellites elevation [6].

Eqs. (1), (2) and (3) are valid when a single GNSS is used and all the measurements refer to common time scale. For example, when both GPS and Galileo are considered, different clock biases and drifts have to be accounted for. GPS time is connected to the Coordinated Universal Time (UTC) from which differs for an integer number of seconds (leap seconds). Additionally, GPS time and UTC (USNO) time scales are maintained by different master clocks; this offset typically is less than 100 ns and is broadcast to the users within the navigation message [7].

Galileo System Time (GST) is a continuous time scale maintained by the Galileo Mission Segment and synchronized to the International Atomic Time (TAI). The time difference between GPS and Galileo will be broadcast within the Galileo navigation message and using parameters such as the Galileo/GPS Time Offset (GGTO) [8], it will be possible to align GPS and Galileo measurements with respect to a common time scale. As mentioned in Section I, Galileo ephemerides are currently transmitted in a discontinuous way and the GGTO is thus not available. A solution to this problem is the inclusion of two additional unknowns [9], representing the bias and drift between GPS time and GST, which need to be estimated. In this way, the position and velocity state vectors become:

$$\begin{aligned} \underline{x} &= \begin{bmatrix} \underline{P} & cdt_u^{GPS} & cdt_{GAL}^{GPS} \end{bmatrix} \\ \underline{v} &= \begin{bmatrix} \underline{V} & c\dot{d}t_u^{GPS} & c\dot{d}t_{GAL}^{GPS} \end{bmatrix} \end{aligned} \tag{4}$$

where cdt_{GAL}^{GPS} and $c\dot{d}t_{GAL}^{GPS}$ are the bias and the drift between GPS time and GST, respectively. Note that also the PR and PR rate models, (1) and (2), need to be modified in order to account for the additional clock terms. In particular, when Galileo measurements are considered, cdt_{GAL}^{GPS} and $c\dot{d}t_{GAL}^{GPS}$ are added to the PR and PR rate models, respectively. Models (3) and (4) will be used in Section V to compute and analyze Galileo-only and combined GPS-Galileo navigation solutions.

If the user position and velocity are known then it is possible to estimate ideal Galileo and GPS measurements which in turn can be used to study residual errors in the GNSS observables. This analysis has been performed using the algorithm depicted in Figure 1 which allows one to determine residual PR and PR rate errors. Additional details on residual measurement errors are provided in the following section.

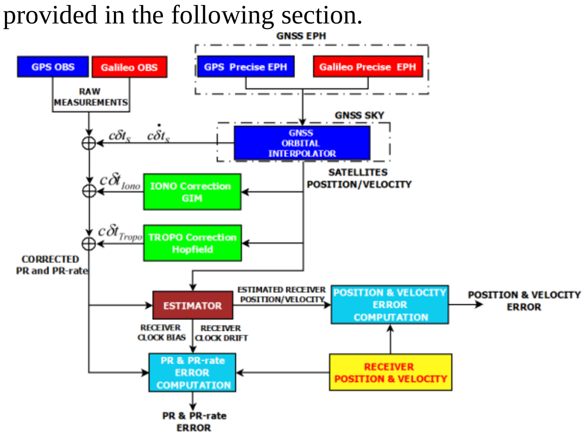

Figure 1: schematic representation of the algorithm developed for determining PR and PR-rate residual errors.

B. *Observable Errors*

In order to compute Galileo PR and PR rate error, GPS and Galileo observations are used.

Raw PR and PR rate measurements are corrected for the satellite clock error, relativistic effects, the Sagnac effect and atmospheric delays according to:

$$\begin{aligned} \rho_c &= \rho + cdt_{sv} - cdt_u + cdt_r + cdt_{sag} - d_I - d_T - cdt_{GAL}^{GPS} \\ \dot{\rho}_c &= \dot{\rho} + c\dot{d}t_{sv} - c\dot{d}t_u + c\dot{d}t_{sag} - c\dot{d}t_{GAL}^{GPS} \end{aligned} \tag{5}$$

where cdt_{sv} and $c\dot{d}t_{sv}$ are the satellite clock bias and drift, cdt_r is the relativistic correction, cdt_{sag} and $c\dot{d}t_{sag}$ are the Sagnac effect corrections, d_I is the ionospheric correction computed using GIM, d_T is the tropospheric correction computed using the Hopfield model; in order to compute the clock biases and drifts, a combined GPS/Galileo navigation algorithm is developed and cdt_u and $c\dot{d}t_u$ are removed from the raw measurements.

The raw PR are not corrected for the time group delay T_{GD} term, because this parameter, included in the navigation message, is not yet available for Galileo; so this choice has been performed for a fair comparison between GPS and Galileo.

After computing the corrected PR (5), the residual PR error is defined as:

$$E_{PR} = \rho_c - d \tag{6}$$

The PR rate error is computed in a similar way using GPS and Galileo Doppler measurements:

$$E_{PRrate} = \dot{\rho} - \dot{d} \tag{7}$$

where $\dot{d}$ is the projection of the satellite velocity along the satellite-receiver direction; d and $\dot{d}$ are obtained computing satellites position and velocity starting from the satellite ephemeris and the known receiver position.

Since most of the error sources related to the signal propagation have been removed, PR and PR rate errors only contain residual biases due to the signal and its transmission. They can thus be used to assess the potentiality of a GNSS.

III. Experimental Setup

In order to collect Galileo and GPS observables, a Javad RingAnt-G3T was mounted on the rooftop of the European Microwave Signature Laboratory (EMSL) in the Joint Research Centre (JRC) premises in Ispra, Italy. The EMSL which is the highest building of the area was selected in order to minimize the amount of multipath received by the antenna.

The antenna was then fed to a Septentrio PolarRxS receiver able to simultaneously collect GPS, GLONASS and Galileo measurements on several GNSS bands. In this paper, only the Galileo E1 band is considered and the analysis of measurements from other frequencies is left for future work.

In order to verify the hypothesis of absence of multipath, data collected using the PolarRxS receiver were processed using the Translating, Editing and Quality Checking (TEQC) software [11]. TEQC allows one to analyze the impact of multipath and ionospheric disturbances at a given site. With respect to multipath, a metric is obtained by combining PR and carrier phase measurements. Large and correlated values of this metric indicate the presence multipath. In this case, the observed multipath metric assumes low values support the hypothesis of reduced multipath.

For the processing a Delay Lock Loop (DLL) bandwidth equal to 0.25 Hz was used. The Phase Lock Loop (PLL) bandwidth was equal to 15 Hz whereas the integration time was set to 10 ms. The same processing parameters were used for GPS and Galileo.

The position of the antenna was carefully surveyed using double difference carrier phase positioning. This information was in turn used compute d and $\dot{d}$.

With this calibrated setup, it was possible to collect several days of data which were used for the characterization of Galileo observables discussed in the following.

IV. Experimental Results: Galileo Observables

One week of data, on L1 frequency, is used for the PR and PR rate analysis and results relative to IOV Satellite Vehicle (SV) 11, 12, 19 are presented below. It is noted that SV 20, the fourth IOV satellites, started broadcasting only recently and the delay in uploading SP3 ephemerides has not allowed the use of SV 20 measurements in the analysis presented below. Measurements from SV 20 are analyzed in Section V where results obtained using broadcast ephemerides are presented.

PR and PR rate errors are analyzed in terms of RMS, mean and maximum values. In Figure 2, the absolute value of the PR errors is shown as a function of the satellite elevation and Carrier-to-Noise power spectral density ratio (C/N_0) and Galileo and GPS performance is compared. This type of plot is commonly used in the literature [12, [13] and is obtained by depicting the instantaneous PR error as a function of the satellite elevation and C/N_0. The area covered by the different error values provides an immediate representation of the magnitude of the average error and allows a simple comparison between GPS and Galileo errors. It clearly emerges that Galileo PR errors are smaller with respect to GPS: this is an indication of the potential of the European navigation system.

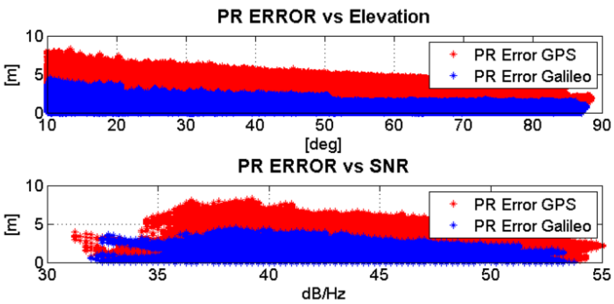

Figure 2: PR error versus Satellite Elevation and C/N_0.

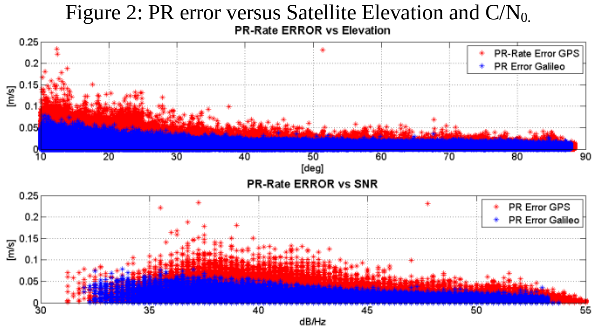

Figure 3: PR rate errors versus Satellite Elevation and C/N_0.

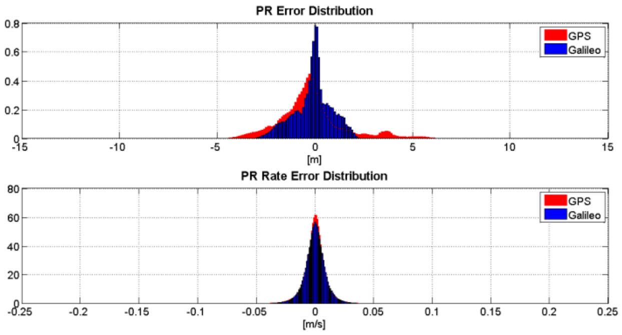

Figure 4: Measurements error distribution.

Analogously, GPS and Galileo PR rate errors are plotted as a function of satellite elevation and C/N_0 in Figure 3. The two systems are characterized by similar PR rate errors with slight lower maximum error in the Galileo case. The PR and PR rate error distributions are shown in Figure 4; PR error distributions are not Gaussian and this due to the presence of un-modeled residual systematic errors. Thus, the results presented here should be considered as upper bounds for the actual performance that can be achieved using Galileo. PR error distributions are characterized by small means (0.57 m for GPS and 0.38 m for Galileo) and the distribution tails show that the maximum PR error of Galileo is reduced with respect to the GPS one. Summary statistics for GPS and Galileo PR errors are summarized in TABLE I.

TABLE I: PR ERROR STATISTICS

	RMS (m)	Mean (m)	Max (m)
GPS	2.52	0.57	12.65
Galileo	2.41	0.38	8.20

PR rate error distributions are analyzed in the bottom part of Figure 4 and show a Gaussian distribution; the means are in the mm/s order and, as for the PR case, the distribution tails shown that the maximum PR rate error of Galileo is reduced with respect to the GPS one. Summary statistics for GPS and Galileo PR errors are summarized in Table II.

TABLE II: PR-RATE ERROR STATISTICS

	RMS (m/s)	Mean (m/s)	Max (m/s)
GPS	0.0132	0.0015	0.2263
Galileo	0.0160	0.0025	0.0132

A. *Measurement variance*

Two main factors contribute to the PR and PR rate errors analyzed in the previous section: systematic errors due to the transmitted signal and random noise variations. The latter component is due to the thermal noise affecting received signals and its final contribution strongly depends on the receiver front-end and processing. For example, [14] showed that the variance of Doppler measurements (and thus of PR rate observables) depends on the signal C/N_0, the bandwidth of the carrier tracking loop and the smoothing strategy adopted for the generation of the final measurements.

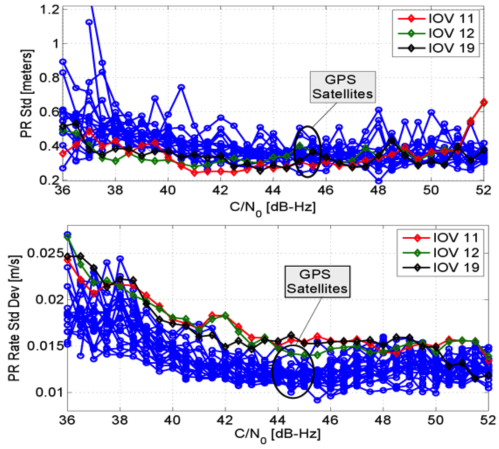

Figure 5: Standard deviation of GPS and Galileo measurements as a function of the input C/N_0

A processing strategy for estimating the measurement variance as a function of the signal C/N_0 was also suggested. This strategy is adopted here to analyze the Galileo PR and PR rate measurements and isolate the contribution of random noise.
The standard deviations estimated for the GPS and Galileo observables are depicted in Figure 5 as a function of the signal C/N_0. Standard deviations were computed by first removing constant terms from the measurement errors using a moving average filter [14]. Although this pre-processing stage allows one to remove most predictable systematic biases, residual errors can be present. This fact can be observed in the upper part of the Figure 5 for the Galileo PR standard deviation. In particular, measurement standard deviations were expected to increase as the C/N_0 decreases. In the Galileo case, standard deviations tend to flatten out at high C/N_0 values indicating the presence of residual uncompensated biases. The values shown in Figure 5 should be thus considered conservative estimates and better performance are likely achievable. From the upper part of Figure 5, it emerges that Galileo PRs are affected by lower standard deviations then GPS. Although, this is likely due to the processing strategy adopted by the receiver, this result suggests that the improved structure of Galileo signals allows a GNSS receiver to extract less noisy PR measurements for the same input C/N_0.
From the bottom part of Figure 5, it emerges that Galileo PR rate measurements are affected by higher standard deviations then GPS. This fact is in agreement with the results in TABLE II which shows higher RMS values for the Galileo PR rate errors. The cause of this phenomenon needs further investigation and could be due the different processing parameters adopted by the receiver for the generation of GPS and Galileo measurements. The difference between GPS and Galileo is however marginal and is in the order of few mm/s.

V. PVT ANALYSIS

Two different PVT (Position Velocity Time) analyses are carried out: for the first one, precise SP3 ephemerides are adopted for both GPS and Galileo. In the second case, broadcast ephemerides are used to analyze the performance of Galileo-only positioning. Position and velocity performance is analyzed in terms of RMS and maximum error for horizontal and vertical components.

A. GPS/Galileo Position and Velocity Analysis

One week of data (GPS week 1725) are used for PVT analysis. Data were collected according to experimental setup described in Section III with a 1 Hz rate.

The horizontal position error of the GPS alone and GPS/Galileo joint positioning are shown in Figure 6; the joint solution is computed considering the three aforesaid Galileo satellites and including the GPS/Galileo time offset as additional unknown. In order to present a fair comparison, the two solutions are analyzed during those epochs when the Galileo satellites are available.

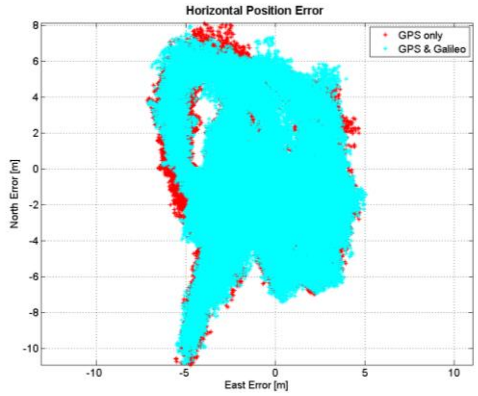

Figure 6: Horizontal Position Error

The number of visible GPS/Galileo satellites varies between 7 and 14 (with a mean of 10) and the PDOP varies between 1.2 and 2.9 (with a mean value of 1.8), as expected in the open-sky condition.

Although the clouds are very similar, slight improvements are observable when Galileo measurements are included; the position error statistics are summarized in TABLE III which shows that the RMS values of GPS/Galileo horizontal and vertical errors are reduced by 20 cm with respect to the GPS alone configuration. The addition of the three Galileo observations also contributes to a reduction of the maximum error.

Table III: POSITION ERROR PARAMETERS

	Horizontal		Vertical	
	RMS [m]	**Max [m]**	**RMS [m]**	**Max [m]**
GPS Only	3.74	12.06	6.23	20.15
GPS/Galileo	3.55	11.97	6.09	19.75

The horizontal and vertical velocity errors for GPS and GPS-Galileo configurations are plotted in Figure 7. In the velocity domain the benefits of Galileo are less evident than in the position domain. This is probably due to the increased variance of the PR rate measurements highlighted in Section IV. An oscillatory pattern is also evident in the bottom part of Figure 7. Investigations are on-going to determine the origin of such phenomenon which seems caused by the use SP3 ephemerides which do not provide corrections for the clock drift.

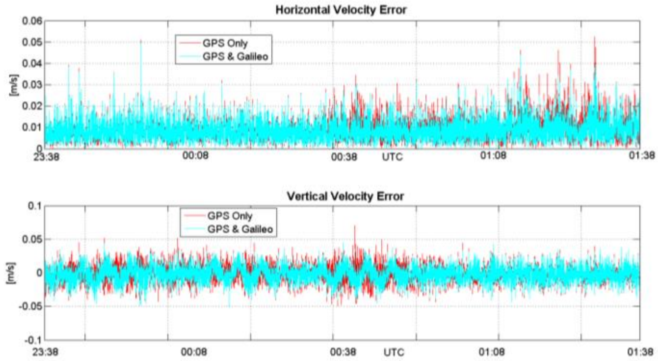

Figure 7: Velocity Error

Figures of merit for the horizontal and vertical velocity errors are provided in Table IV. The statistics of GPS alone and GPS-Galileo combined PVT show similar values.

TABLE IV: VELOCITY ERROR PARAMETERS

	Horizontal		Vertical	
	RMS [m/s]	**Max [m/s]**	**RMS [m/s]**	**Max [m/s]**
GPS Only	0.0099	0.1895	0.0144	0.1352
GPS/Galileo	0.0097	0.1727	0.0141	0.1352

B. Galileo Only Processing

On 12th March 2013, valid Galileo ephemerides were broadcast allowing the analysis of Galileo-only positioning.

For about two hours, all four Galileo satellites were visible from Ispra and a navigation solution was obtained with a 10 meter of accuracy. The horizontal position error of the Galileo standalone positioning is shown in Figure 8 whereas horizontal and vertical velocity errors are depicted in Figure 9.

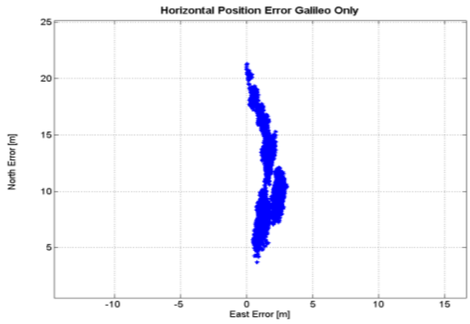

Figure 8: Horizontal Position Error Galileo-only solution.

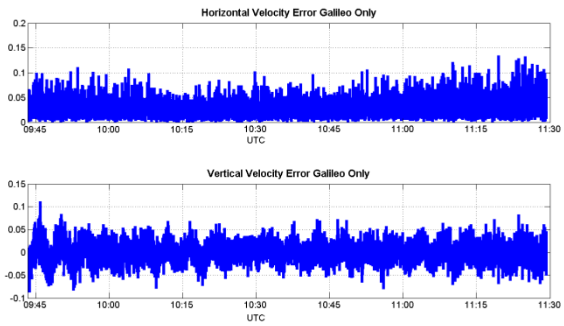

Figure 9: Velocity Error, Galileo-only solution.

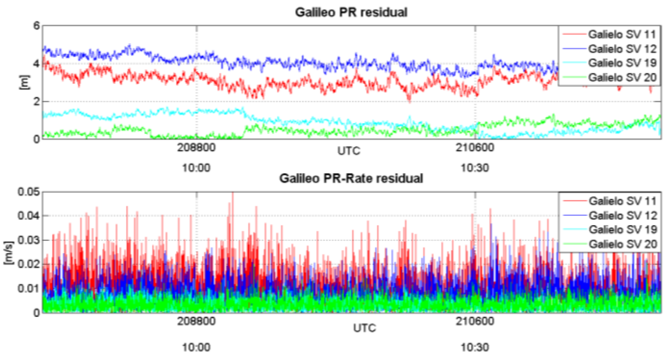

Figure 10: Galileo PR and PR-Rate Residuals.

A combined GPS/Galileo solution has also been computed to analyze the residuals associated to Galileo PRs and PR rates. The residuals are plotted as a function of time in Figure 10. Form the figure, it emerges that the PR residuals are of metric order as expected for a GNSS system. The residuals associated to the PR rates are of cm/s order.

VI. CONCLUSIONS

In this paper, the quality of Galileo measurements and the benefits of their inclusion in single point positioning have been studied. To this end, analyses were performed in measurements and position domain, respectively.

The analysis in the measurements domain demonstrates the competiveness of Galileo with respect to existing GNSS systems. The Galileo PR error is characterized by a small mean (0.38 m) and its maximum value is also smaller than the GPS one; Galileo PR rate measurements have a mean of mm/s order and, as for the PR case, the Galileo maximum error is reduced with respect to the GPS case. The two systems have similar performance in measurement domain with a slight advantage for the European system in terms of maximum errors. A measurement variance analysis was also conducted, from which it emerges that Galileo PR are affected by lower standard deviations then GPS, suggesting that the improved structure of Galileo signals allows a GNSS receiver to extract less noisy PR measurements for the same input C/N_0, whereas Galileo PR rate measurements are affected by higher standard deviations then GPS observables.

To assess the benefits of the inclusion of Galileo measurements, a joint GPS-Galileo navigation solution was performed and compared with the GPS-only case. The comparison was carried out in the position and velocity domain in terms of RMS and maximum errors for the horizontal and vertical components. The combined solution provides slight improvements with respect to the GPS-only solution for all the considered parameters.

On 12th March 2013, valid Galileo ephemerides were broadcast and the first complete navigation solution using only Galileo measurements was carried out. A 10 m position accuracy was obtained whereas velocity errors were in the dm/s range. These results are encouraging given the fact that only four satellites were used for the position computation and the Dilution Of Precision (DOP) was consequently relatively high.

Further tests have to be conducted and more data have to be analyzed (including observations from different frequencies) in order to strengthen the statistical significance of the result presented. For example, the analysis could be enriched assessing the accuracy of the broadcast ephemerides and comparing that with precise orbital products.

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