Galileo Performance Assessment for Aerial Navigation

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Abstract
Galileo is now reaching its Full Operational Capability with 26 active satellites in orbit, 22 of them fully operational, allowing today a level of accuracy that matches, or even outperforms the other GNSS systems. In the scope of the Galileo Reference Centre-Member States (GRC-MS) Project, an evaluation of the performance of the Galileo services is provided to the European GNSS Agency (GSA). The University of Porto team is responsible for assessing Galileo performance for aerial navigation and applications.
This work presents results from some of the aerial test campaigns realized in 2019 and 2020. A Septentrio multi-frequency, multi-GNSS receiver was installed in an aircraft with a AeroAntenna. Galileo-only, GPS-only and Galileo+GPS and Galileo+GPS+GLONASS+ BeiDou solutions, were computed using code and carrier-phase measurements in differential and SPP modes. A PPP solution was also performed by the CSRS-PPP online processing tool and used as reference.
Results show the Galileo-only solutions reached the centimeter level and that the Galileo only solutions are of identical, or better quality, than the GPS only solutions, both for the horizontal and the vertical components. Furthermore, the SPP solutions fulfill the requirements for aeronautics navigation.

Keywords 1
Aerial, Galileo, Kinematic, PNT

1. Introduction

The use of GNSS (Global Navigation Satellite Systems) is nowadays an indispensable tool whether on land, sea or air, allowing efficiency gains in the most diverse applications in these fields, through PNT (Positioning, Navigation and Timing) services. The European navigation system Galileo, the first entirely civilian GNSS system, is now reaching its Full Operational Capability (FOC) with 26 active MEO (Medium Earth Orbit) satellites in orbit of a total of 30 satellites, 22 of them fully operational [1]. Galileo, supported by the most advanced atomic clocks and new signal modulation techniques, is opening new opportunities for Europe and the world in the exploration of GNSS signals, bringing some advantages over other existing GNSS systems, as a greater resistance to spoofing and jamming interferences and allowing tracking of weaker signals, especially relevant in difficult GNSS environments, such as urban or forestry areas.

In the scope of the Galileo Reference Centre-Member States (GRC-MS) Project [2], funded by the European GNSS Agency (GSA) an evaluation of the performance of the Galileo services, and also an analysis of the performance of the other GNSS, is to be provided to GSA. In this context, the University of Porto team is responsible for assessing Galileo performance in aerial navigation. Towards that goal, several aerial campaigns took place since last quarter of 2018 around the Porto region in Northwest Portugal.

In this paper we present and analyze some of the solutions obtained in three of those campaigns, using code and carrier-phase measurements both in differential and SPP modes, for the Galileo-only,

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GPS-only, as well as Galileo+GPS and Galileo+GPS+GLONASS+BeiDou combinations. For the comparisons a PPP reference solution was also computed using independent software. The results show that, in differential mode, the triple frequency Galileo-only solutions can reach the centimeter level while for the single frequency SPP solutions are below 1 meter, in both components. This confirms the good performance of Galileo for aerial applications, being the constellation that provides better results when used alone.

2. Experimental setup

For the realization of all the airborne campaigns, a multi-GNSS, multi-frequency Septentrio PolaRx5 receiver was used with a dedicated aerodynamic antenna, model AT1675-381B from AeroAntenna (equivalent to the AT1675-81 model at ANTEX NGS file), which was mounted on the fuselage of a CESSNA C210 airplane from the Portuguese company InfoPortugal S.A.

Figure 1 shows the airplane with the antenna installation. All the flights were planned to last around one and a half hour, at a time with good satellite visibility. Special attention was given to the Galileo constellation, but due to several constraints (weather, flight clearance, etc.), the plans sometimes had to be changed. The flights took off from the Maia aerodrome, near Porto, Portugal, and followed different trajectories along the coast, or over urban and countryside areas. Trajectories were pre-defined in order to cover a diversity of flight conditions. Some followed a straighter and stable flight, while others included several maneuvers with significant changes in the airplane attitude, in order to test Galileo performance in different flight conditions.

Figure 1: CESSNA C21A airplane (left), AeroAntenna (right top) and PolaRx5 (right down)

The GNSS raw data from the PolaRx5 was collected in the proprietary Septentrio format (SBF files) at a rate of 1 Hz. The SBF Converter tool from Septentrio software RxTools [3] was used to convert observation files to RINEX format. Measurements were recorded in all frequencies available: E1/E5a/E5b/E6 for the Galileo, L1/L2/l5 for the GPS, G1/G2 for the GLONASS and B1/B2/B3 for the BeiDou.

The data analyzed in this work was collected in three different GRC-MS aero campaigns realized in: March 22, 2019, January 6, 2020 and June 10, 2020. The corresponding trajectories are shown in Figure 2 below.

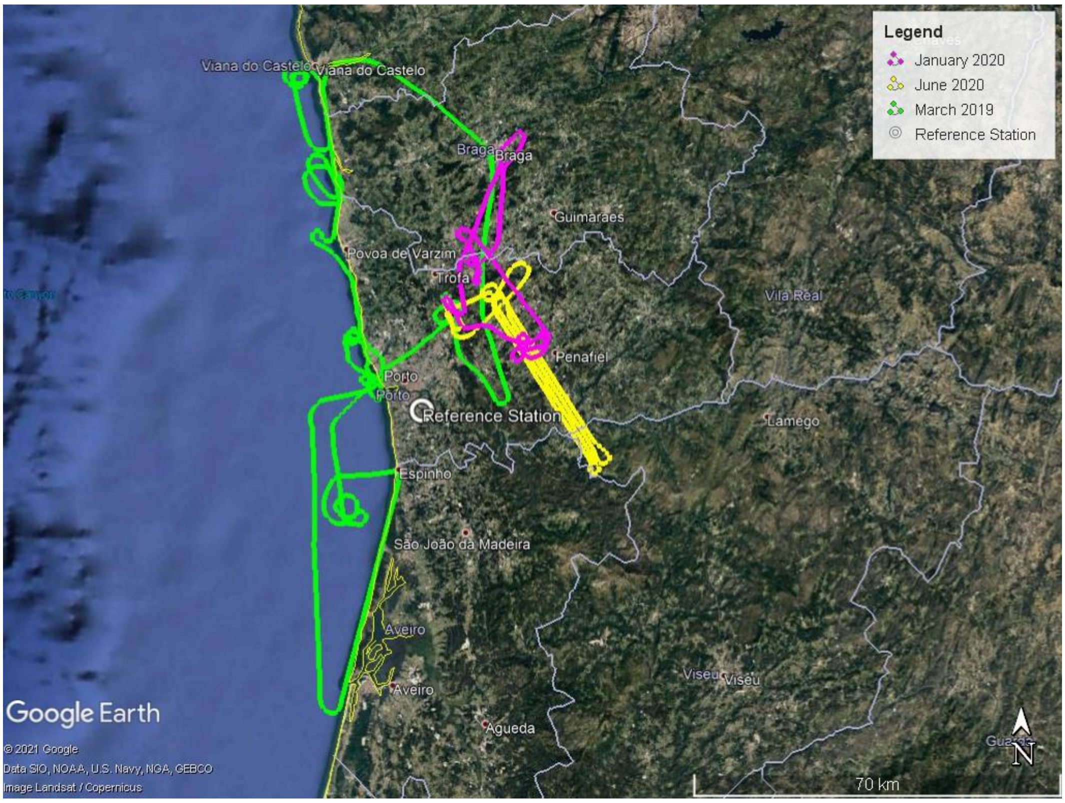


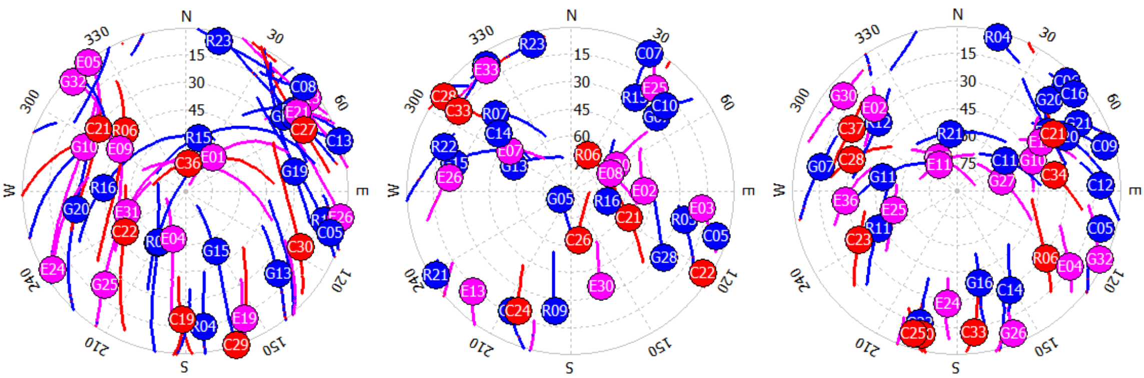
Figure 2: The three GRC aero campaigns used in this work.

For the differential positioning a permanent reference station located at AOUP (Astronomical Observatory of University of Porto) grounds, in the city of Vila Nova the Gaia, was used (see figure 2). This station is equipped with a multi-constellation, multi-frequency Trimble Alloy receiver and a Zephyr GNSS Geodetic II antenna and is at maximum at a distance of 68 km from the airplane, in the March 2019, 56 km in the January 2020 campaigns and 36 km in the June 2020 campaign.

3. Data analysis and data processing results

For the analysis of the satellite visibility, coverage and recorded data, the Septentrio Rx Tools software tool was used.

Figure 3 shows the skyplots of Galileo (identified with letter E), GPS (G), GLONASS (R) and BeiDou (C), for the three campaigns. The color codes are: red for single frequency, blue for dual frequency and fuchsia for triple frequency.



a) b) c)

Figure 3: Skyplots for March 2019 (a), January 2020 (b) and June 2020 (c) campaigns

Figures 4 and 5 show the average DOP (Dilution of Precision) and number of satellites for the aforementioned constellations, in each campaign.

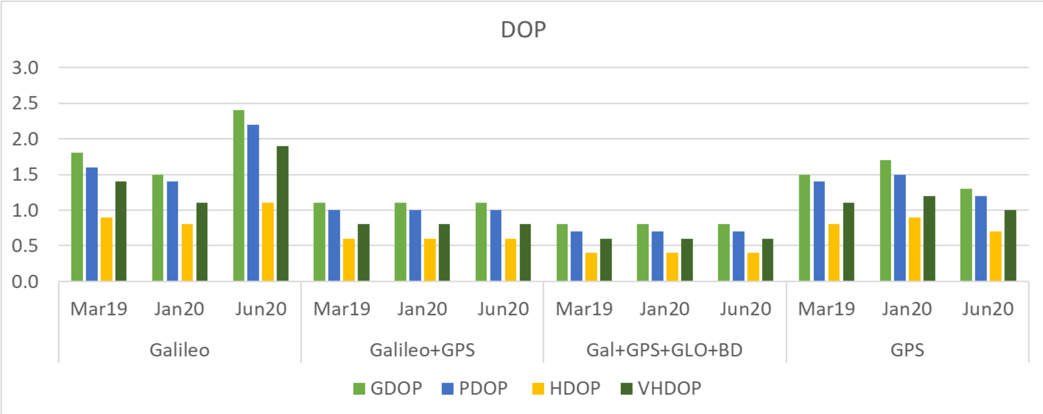


Figure 4: Dilution of Precision for the different constellations in the different campaigns

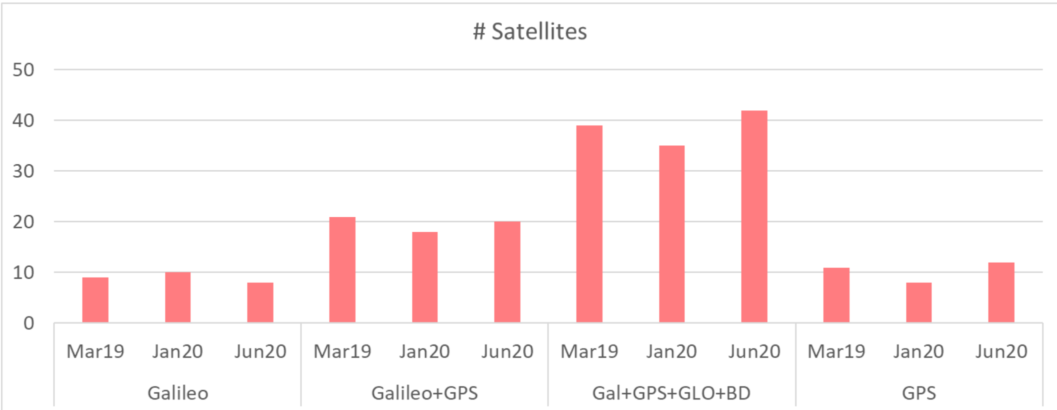
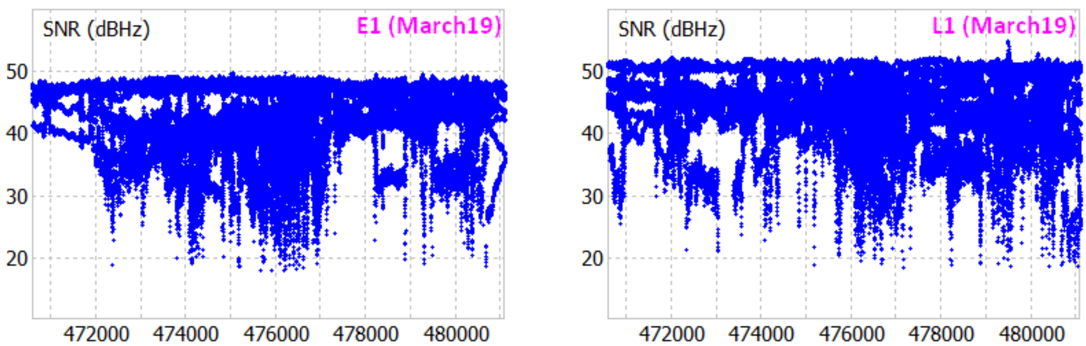


Figure 5: Average number of satellites for the different campaigns and constellations

DOP values show that satellite geometry for Galileo is slightly worse than for GPS due to the lower number of Galileo satellites available. This is because Galileo does not yet have the full constellation available. As expected, the combination of the four GNSS systems presents the best values, related also to the significant higher number of satellites available.

To analyze the quality of the signals, Figure 6 shows the SNR (Signal-Noise-Ratio) for the Galileo E1/E5a/E5b frequencies and GPS L1/L2/L5 frequencies from the March 2019 campaign. The Galileo and GPS SNR are similar, except for the L2, which presents worse maximum (<45 dBHz) and minimums (<10 dBHz) values. The other two campaigns present an identical behavior.



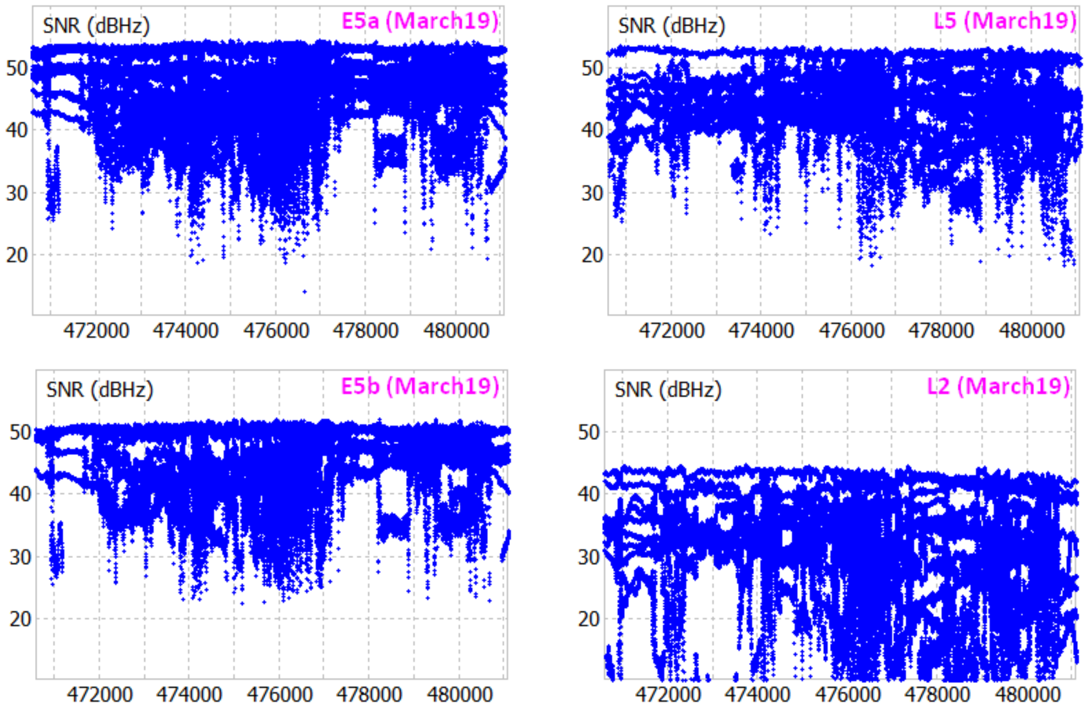


Figure 6: SNR for Galileo frequencies (left) and for GPS frequencies (right) for March 2019 campaign

To compute GNSS solutions, phase and code measurements in different frequencies were processed using the RTKLIB Demo5 [4] software based in the RTKLIB [5]. Galileo-only, GPS-only, and combined Galileo+GPS and Galileo+GPS+GLONASS+BeiDou solutions were produced both in differential, PPP and standalone modes. The CSRS-PPP online processing tool from the Canadian Geodetic Survey of Natural Resources Canada (NRCAN) [6] was used to derive a combined GPS+GLONASS independent solution. Due to the difficulty in having an absolute reference to assess the quality of precise GNSS aerial navigation solutions, the use of the NRCAN solution seemed a reasonable choice. This also gives the possibility for an easy comparison with results from other researchers to assess the quality of Galileo kinematic solutions.

Solutions were all referred to the ITRF2014 reference frame at the observations epoch.

The relative positioning solutions were obtained with triple-frequency (TF) carrier-phase measurements for Galileo, GPS and Galileo+GPS. For the standalone SPP (Single Point Positioning), the absolute positioning, single-frequency code solutions were calculated.

The settings used for processing were: frequencies E1/E5a/E5b and L1L2L5 for the Galileo, GPS and Galileo+GPS solutions. In the four systems combination solutions, the previous frequencies plus the E6 in the Galileo and the double-frequencies G1/G2, B1/B2 for GLONASS and BeiDou were used; elevation mask 10º; broadcast ephemerides; Klobuchar and Saastamoinen models for ionosphere and tropospheric correction; ANTEX file ngs14.atx; earth tides correction IERS Conventions 2010 (Solid), Bos & Scherneck (OTL) [7] and IGS ERP format (EOP).

The reference trajectory PPP solutions were obtained using the CSRS-PPP, with the following settings: frequencies GPS L1/L2 and GLONASS G1/G2 frequencies; elevation mask 7.5º; precise ephemerides from IGS; ionosphere free and VMF1 models for ionosphere and tropospheric correction; ANTEX file ngs14_nrcan.atx; earth tides correction IERS Conventions 2010 (Solid), Bos & Scherneck (OTL) and IGS ERP format (EOP).

The next plots show the statistics of the comparisons of the differential solutions and the SPP solutions with the reference solution. Standard deviation (σ), mean and 95% confidence interval errors, are presented for the Galileo-only, GPS-only and Galileo+GPS solutions.

Figure 7 shows the statistics for the TF solutions.

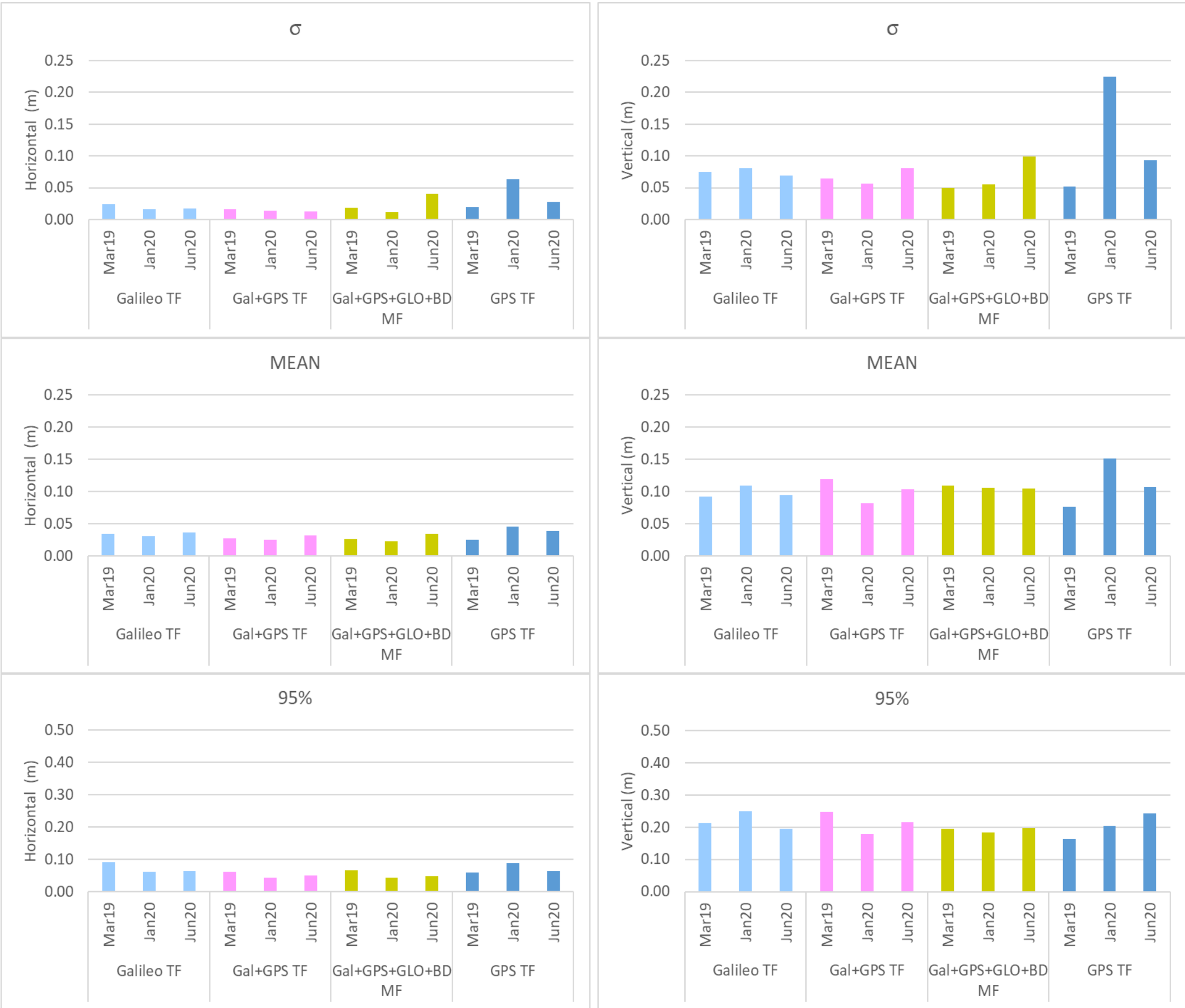


Figure 7: TF solutions errors plots

Figures show that, for the horizontal component, the TF Galileo-only solution has a standard deviation (σ)below 0.02 m, lower than the standard deviation of the GPS-only solution.

Concerning the 95% confidence interval, the two systems alone have identical values, below 0.10 m. The combinations Galileo+GPS+GLONASS+BeiDou, and Galileo+GPS have similar behaviors, and always better than GPS or Galileo alone.

For the vertical component σ values are higher, but the Galileo-only solutions, are better than, or at least identical to, the GPS-only solutions. For the 95% confidence interval, values are below 0.25 m in all cases, showing no significant differences between Galileo and GPS-only or the combinations of systems.

The statistics for the results for the standalone SPP solutions are presented in Figure 8 below.

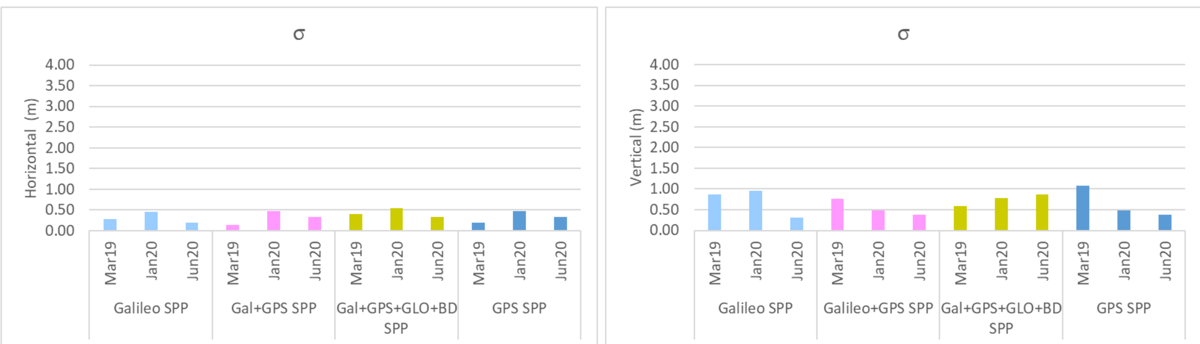


Figure 8: SPP solutions errors plots

We can see that, for the horizontal component, the standard deviation for the Galileo-only solution is smaller than for the GPS-only solution, and also smaller that for the combined solutions.

Concerning the 95% confidence interval, values are generally below 1 meter for Galileo-only, while for the other systems, or combination of systems, values are above 1 meter.

For the vertical component, the Galileo-only solution is equivalent to the GPS-only and also to the combined GPS+Galileo solution.

The combination of the four systems, Galileo+GPS+GLONASS+BeiDou, does not, in general, increase the performance neither in the horizontal nor in the vertical components. In some cases, it even introduces some degradation of the solution.

4. Conclusions

The results obtained in the different campaigns allow us to conclude that, in general, Galileo has a similar, or better, performance than GPS, and slightly worst that the combined Galileo+GPS solutions.

For the triple-frequency (E1/E5a/E5b), the Galileo-only differential solutions have standard deviations with values below 0.10 m both for the horizontal and the vertical components.

For the standalone SPP solutions, Galileo-only solutions present errors below 0.5 m and 1.0 m respectively for the horizontal and the vertical components, revealing a better performance than all the other solutions. This shows that, in terms of accuracy, Galileo has the potential to fulfill the requirements for aerial navigation as specified in the GSA GNSS Market Report [8] (a 95% accuracy below 16 m for the horizontal component and 4 m for the vertical component).

Taking in consideration that the Galileo constellation is not yet totally complete, these are very promising results and, with Galileo entering now its FOC phase, we can expect that it will deliver quality results for all types of applications, from the more demanding geodetic type to the less demanding services for the mass market applications. Combined with other GNSS constellations it will allow a step forward in precise positioning and navigation.

5. Acknowledgements

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