Galileo, an Ace Up in the Sleeve for PPP Techniques

I. Rodríguez-Pérez, L. Martínez-Fernández, G. Tobías-González, J. D. Calle-Calle, M. Romay, M. D. Laínez, P. F. Navarro, *GMV*

BIOGRAPHY (IES)

Irma Rodríguez has a MSc in Telecommunication Engineering, from the Universidad Politécnica de Madrid, Spain. She is Head of the GNSS Algorithms and Products Division within the GNSS Business Unit of GMV, being responsible for a division in charge of, among other activities, the GMV's *magicODTS* and *magicPPP* services, the Galileo CS Demonstrator and the Galileo Time and Geodetic Validation Facility.

Laura Martínez Fernández holds a Degree in Aerospace Engineering from Polytechnic University of Valencia, specialty in Aero-navigation, and an MSc in Aeronautical Engineering from Polytechnic University of Catalonia, specialty in Space. When Laura Martínez finished her internship in GMV, she joined the company as a GNSS engineer working in activities related with *magicGNSS*, more concretely in precise orbit determination, precise positioning and integrity algorithms.

Guillermo Tobías González holds an MSc in Telecommunication Engineering by the University of Zaragoza. He has 8 years of experience in GNSS, notably in the area of Precise Orbit Determination and Clock Synchronisation, including contributions to the Galileo Program and the IGS. He has been the GMV's responsible for the *magicGNSS* suite for the last years. He is currently Head of PPP and Authentication Products and Services Section.

J. David Calle has a Master of Science in Computer Engineering from the University of Salamanca. He joined GMV in 2008 and he is currently working in the GNSS business unit designing and developing GNSS algorithms, applications and systems. He has been involved in the development of the *magicGNSS* suite and the Galileo Time and Geodetic Validation Facility. He is currently the technical responsible for the development of the Galileo Commercial Service Demonstrator.

Miguel M. Romay Merino is the GNSS Business Unit Director at GMV Aerospace and Defence. Miguel leads the GMV Unit that has become one of the strongest groups of GNSS experts thanks to its key involvement in GPS, EGNOS and Galileo. Miguel has been a pioneer in the Galileo Program, collaborating on aspects such as constellation design, precise orbit determination, integrity, performance evaluation, system definition, etc. Miguel is today involved in GMV research activities in the definition of novel GNSS applications and on the design of new generation GNSS.

María D. Laínez Samper is currently coordinating the GMV research activities in the field of Satellite Navigation, and in particular those related to precise positioning applications. She has also worked in experimentation and verification activities, in the Operational Systems Division, during the preliminary phases of the Galileo Program, and has been the responsible for the clock prediction and navigation message computation modules in the Galileo E-OSPF (Experimental Orbitography and Synchronization Processing Facility).

Pedro F. Navarro Madrid has a Master of Science in Mathematics from the University of Murcia (Spain) and Postgraduate studies in Theoretical Physics at the University of Valencia (Spain). He has worked at GMV since 2002 as an engineer in the development of Galileo and later in R&D activities covering both the ground and user segments.

ABSTRACT

Back in 2012, Mozo et al. [Ref. 1.] presented the results of an experimentation campaign aimed at demonstrating the benefits of using the Galileo signals for real-time Precise Point Positioning (PPP) solutions. Furthermore, *magicGNSS*, GMV's suite of GNSS tools and services, was already used to compute one of the first Galileo-only PPP solution in post-processing mode using the four IOV satellites [Ref. 2.]. Now in mid-2016, with 11 Galileo satellites set in orbit and “running”, it is possible not only to analyze more deeply the benefits of processing these satellites to compute a PPP solution, but also to perform real-time Galileo-only PPP with substantially good performances.

With the aim of demonstrating the previous statement, GMV has been performing during the last months an extensive experimentation campaign with two main objectives: on the first hand, to evaluate the benefits of introducing the processing of Galileo satellites into a PPP solution and, secondly, to assess the achievable performances for Galileo-only PPP. The purpose of this paper is to present the results of these testing activities and the main conclusions drawn from these results.

INTRODUCTION

By mid-2016, the Galileo constellation has already reached 14 satellites in orbit, and taking into account the foreseen 4 additional satellites to be launched throughout the current year, the potential impact of Galileo for precise positioning applications appears to be self-evident. The current status of the Galileo constellation provides the means for testing and improving multi-constellation PPP performances.

In this context, GMV's real-time *magicPPP* service (http://magicgnss.gmv.com/magicGNSS_Correction_Service_Technical_Specifications.pdf) was upgraded in 2015 in order to provide ephemeris corrections not only for GPS and GLONASS, but also for Galileo, BeiDou and QZSS and the official version, available for any applicant user, was launched by the beginning of 2016. This newest *magicPPP* version does also implement a series of enhancements at algorithmic and processing level. Some of these new functionalities are related to the multi-constellation capabilities, for example a step-wise processing technique implemented in order to reduce the processing time in a scenario with more than eighty operational satellites. Other new implementation added to the PPP positioning solution is the integrity layer, necessary for the provision of certain critical applications. One of the main features of this integrity approach is that it combines in a well-balanced way, information from the system and information from the user, in order to build optimum horizontal and vertical protection levels. Besides this, and tightly related to the final application, additional sources of information for complementing the integrity information can be considered, such as consistency checks with non-GNSS measurements, for example. For more information, see [Ref. 6.].

As aforementioned, during the last months, GMV has been executing an intense experimentation campaign with a twofold objective: evaluating the benefits of introducing the processing of Galileo satellites into a PPP solution and assessing the achievable performances for Galileo-only PPP. This paper presents some of the results of these testing activities, for static and kinematic PPP users, in open-sky and urban scenarios, in order to show the performances of the real-time *magicPPP* service with Galileo, both in stand-alone mode (i.e. Galileo-only) and in multi-GNSS mode.

The main Key Performance Indicators (service availability, orbit accuracy, clock accuracy, position accuracy and position protection levels, among others) and the associated statistics are computed in an automatic way thanks to a centralized monitoring platform.

The experience gained with the aforementioned experimentation campaign as well as from other previous activities ([Ref. 6.], [Ref. 7.], [Ref. 8.] and [Ref. 9.]) has proven that *magicPPP*'s PPP solution with Galileo is consistent with the solutions provided by the different IGS (International GNSS Service) Analysis Centers. Furthermore, the positioning accuracy results obtained in the multi-GNSS real-time tests show a significant improvement with respect to those achieved using just GPS for example.

The experimentation campaign has comprised two different types of tests. On the first hand, the real-time PPP solution for several static GNSS receivers worldwide distributed, and with different constellation combinations, has been continuously evaluated thanks to a centralized monitoring platform. This platform shows the temporal evolution of the horizontal and vertical positioning error for each station with respect to a calibrated reference together with the number of satellites per constellation in view at each epoch. This procedure allows assessing in real-time the quality of the precise orbit and clock corrections as well as the achievable performances at user level, depending on the location of the receiver and the environmental conditions. In addition, the PPP analysis tool has been used to compute different Key Performance Indicators such as service availability, positioning accuracy, convergence time and protection levels, among others. Their statistics are also computed in an automatic way so that any anomaly can be detected immediately and the performances can be checked in real-time or further evaluated in post-processing mode.

The second type of tests consists of a set of field trials aimed at evaluating the real-time PPP performances for kinematic users. Again for these tests, the same Key Performance Indicators as for the static receivers have been computed and the results have allowed assessing the real-time PPP performances with Galileo for a series of trajectories along different environmental conditions (open sky, semi-urban and urban canyons).

In both static and kinematic modes, the performances are analyzed for different constellation combinations depending on which constellations are included in the PPP processing. The different configurations that have been configured are:

- GPS-Only
- Galileo-Only
- GPS + Galileo
- GPS + GLONASS
- GPS + GLONASS + Galileo

PRECISE POINT POSITIONING (PPP)

Nowadays the creation of new applications based on navigation concepts keeps continuously growing, and as a consequence high precision solutions such as Precise Point Positioning are becoming a must in daily life. Since PPP is an absolute service (versus another systems like Real Time Kinematic technique, a differential GNSS technique which provides high positioning performance in the vicinity of a base station whose position is well known), it is likely to become popular for ordinary positioning algorithms.

On the other hand, as shown in Figure 1, more constellations have been deployed in the past few years, allowing multi-constellation PPP techniques, obtaining better performances than the ones that can be achieved with only one constellation and, for this reason, it is important to implement the algorithms needed to process multiple constellations within the PPP processing.

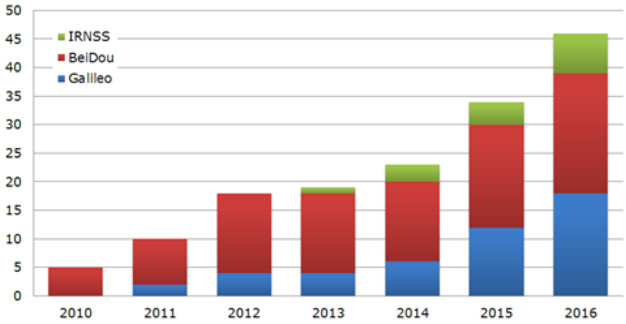

Figure 1: ***Upcoming constellations availability over the past 6 years***

PPP is typically conceived as a position location process which performs precise position determination using iono-free or single frequency measurements. Iono-free ones are obtained from the combination of dual-frequency observations coming from a single GNSS receiver, together with physical models and corrections, and precise GNSS orbit and clock products calculated beforehand, using an orbit determination and time synchronization (ODTS) process. The quality of the reference orbits and clocks used in PPP is critical, as they are two important sources of error in GNSS positioning. Typical orbit accuracy in real-time is about 4 cm (RMS), and typical real-time clock sigma is on the order of 3-4 cm (accuracies for products obtained using *magicGNSS* tool). Analogous accuracies for the off-line products are around 2.5 cm (RMS) for the orbits, and around 2 cm (1-sigma) for the clocks. [Ref. 6.].

Apart from observations and precise reference products, PPP algorithms also need several additional corrections which mitigate systematic effects which lead to centimeter-level variations. Examples of these corrections are the phase wind-up corrections, the satellite antenna offsets, the stations' displacements due to tides (earth and oceanic), etc.

Most implementations of PPP algorithms use a sequential filter in which the way to estimate the measurement noise depends on the receiver's dynamics, the evolution of the receiver's clock is obtained at each epoch, the tropospheric delay is adjusted using a physical model and the ambiguities in phase measurements are considered as a constant per pass. Other implementations use a Batch algorithm instead. In this case, the receiver's clock offset is estimated at each epoch, the coordinates adjusted for the entire observation interval (static mode) or per epoch (kinematic mode), the troposphere is estimated at regular fixed intervals and the ambiguities are estimated per pass [Ref. 6.].

The main difference between the sequential filter and the Batch one is the later has all the necessary information from the beginning. This allows to use the sequential filter in real-time, while the Batch algorithm can only be used in post-processed mode. Obviously, better performances are obtained using the Batch algorithm, but since the main goal of this paper is to analyse the performances obtained by the PPP algorithm in real-time when different constellations are used, the sequential filter has always been used for obtaining the result presented hereinafter.

PPP is considered as a global service, since the orbit and clock products that PPP uses as inputs are also global. This assumption can only be considered valid as long as the tracking network used for the computation of the precise products has worldwide coverage [Ref. 6.].

In this regard, the real time global orbits and clocks products are obtained based on global tracking network composed of IGS stations (see http://www.igs.org/network) using *magicGNSS*, which provides products for all GNSS constellations: GPS, GLONASS, BeiDou, QZSS and Galileo.

¡Error! No se encuentra el origen de la referencia. summarizes the PPP process described here above. As it can be seen, the precise GNSS orbits and clocks are obtained by means an ODTS process using *magicGNSS* suite and the code and phase observations are retrieved from the stations or receivers whose position we want to calculate. All these data is process in the PPP algorithm (using either sequential or Batch filter) and finally the High Accuracy solution is obtained.

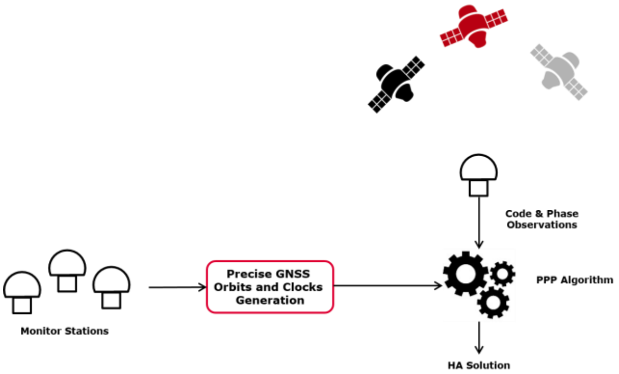

Figure 2: ***magicPPP*** **process overview**

GNSS TODAY AND FUTURE EVOLUTIONS

Nowadays, with 94 operative satellites (32 GPS satellites, 27 GLONASS, 20 BeiDou, 14 Galileo and 1 QZSS), and planned to have more than 100 satellites in orbit by the year 2020, it is evident that GNSS is a reality, and that the future for GNSS and its applications is quite promising.

With regards to the future of Galileo, Figure 3 depicts the planned deployment strategy [Ref. 5.]. It can be observed how since 2013, when the first phase of validation of critical algorithms started, the Galileo constellation has grown significantly. Once the Galileo In-Orbit Validation (IOV) phase had finished, with 4 fully operational satellites and ground segment deployed, the Full Operation Capability (FOC) phase started in 2015. Nowadays, 14 fully operational satellites have been deployed, 2 of them launched in 2016 and being four more planned to be launched before the year ends.

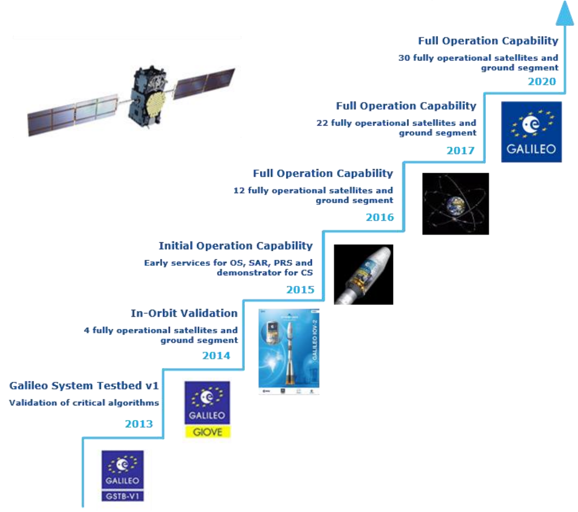

Figure 3: Galileo evolution. Adapted from GSA

With 10 satellites launched in the past two years, and 12 satellites (at least) more planned to be launched in the next two years (four more in 2016, four in 2017 and four in 2018), Galileo fully deployment is becoming now a reality.

Together with the evolution of the rest of constellations (such as the new IIF GPS satellites or future CDMA GLONASS), the use of multi-GNSS data, including Galileo, in the PPP process can be a significant improvement in contrast to processing only one constellation data (such as GPS-only or GLONASS-only) or GPS plus GLONASS.

MULTI-CONSTELLATION PPP

It is real that IGS and the different Analysis Centers are moving in the multi-constellation direction. They are now not only able to generate precise orbit and clock products for all constellations satellites, but also to provide ephemeris corrections in real-time.

The possibility for a GNSS receiver to obtain more GNSS measurements under a multi-constellation configuration (because more satellites are available) implies that most of the PPP performances can be improved, mainly the convergence time. In order to cope with the multi-constellation scenario, a new *magicPPP* suite version was developed during 2015 and launched at the beginning of 2016. This *magicPPP* version implements a series of enhancements at algorithmic and processing level. Some of these new functionalities are related to the multi-constellation capabilities, for example, a step-wise processing technique has been implemented in order to reduce the processing time in a scenario with more than eighty operational satellites. Other evolutions have been aimed at improving the robustness of the solution; such is the case of the new reference time scale based on the combination of multiple clocks or the automatic and dynamic selection of the reference station and core network. Apart from all that, new orbit models such as the ECOM2 or a Box-Wing model for the Solar Radiation Pressure have been implemented and tested with the objective of optimizing the accuracy performance.

As already mentioned, the main objective of this paper is to demonstrate the benefits of using multi-GNSS, especially Galileo, for Precise Point Positioning Techniques. In order to do this, two types of analysis have been performed:

- Multi-constellation PPP in order to show the benefits and improvements of introducing Galileo.
- Galileo-only PPP in order to show the achievable performances.

These two types of PPP tests have been run and the results have been analyzed in both static and kinematic scenarios. The results obtained from these analyses are presented in the following sections.

MULTI-GNSS PPP ANALYSES

The first set of test cases to be analysed in this paper consists on assessing the real-time PPP solution for several static GNSS receivers worldwide distributed, and with different constellations combination each. For this purpose, the GNSS stations shown in Figure 4**¡Error! No se encuentra el origen de la referencia.** have been selected:

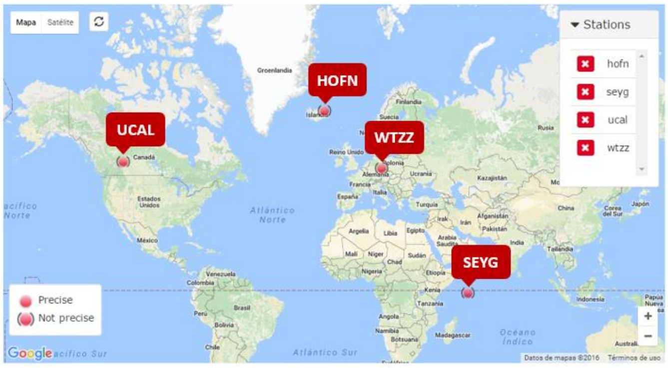

Figure 4: Selected stations

The constellations combinations analysed for each of these stations are:

- GPS-Only (G)
- GPS + GLONASS (GR)
- GPS + Galileo (GE)
- GPS + GLONASS + Galileo (GRE)

Examples of the obtained results, in terms of horizontal and vertical accuracy, are shown in the following figures.

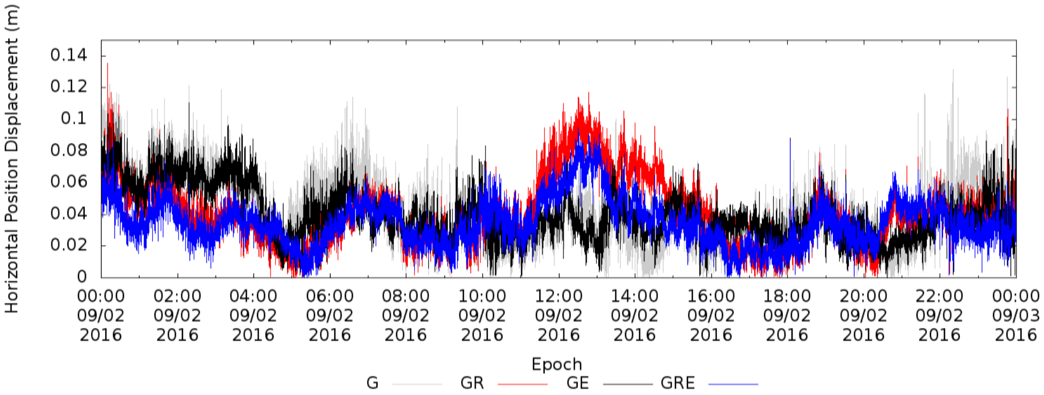

Figure 5: Horizontal Displacement Analysis – WTZZ station

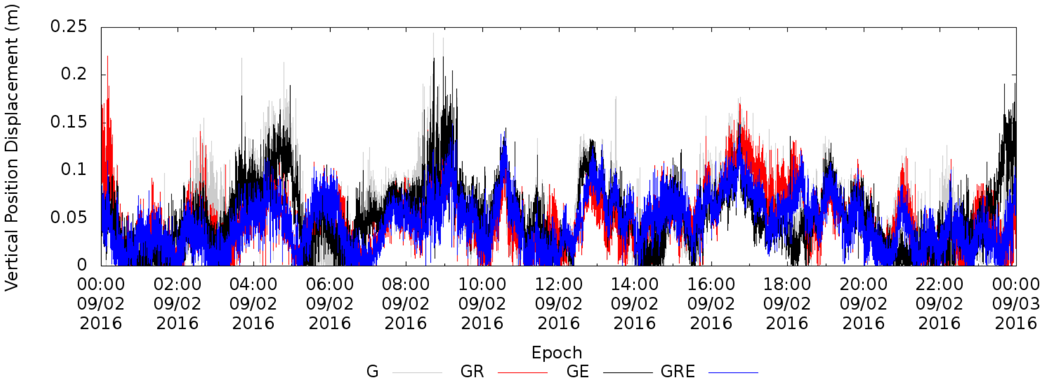

Figure 6: Vertical Displacement Analysis – WTZZ station

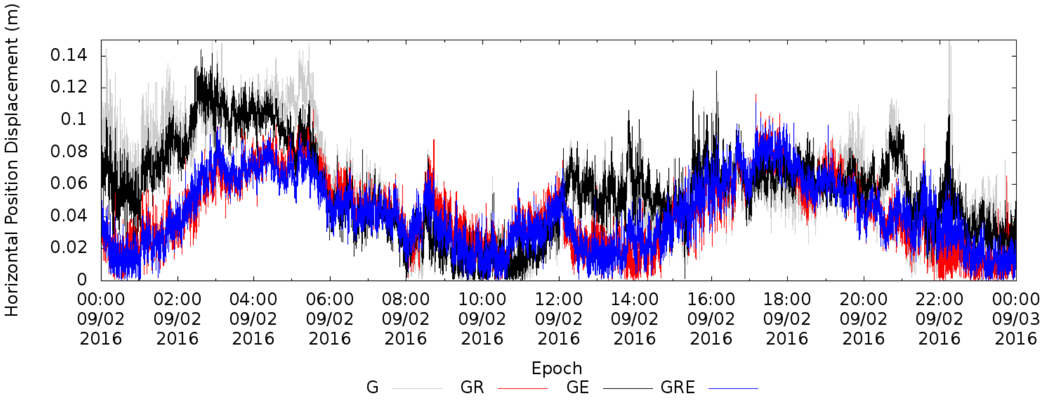

Figure 7: Horizontal Displacement Analysis – UCAL station

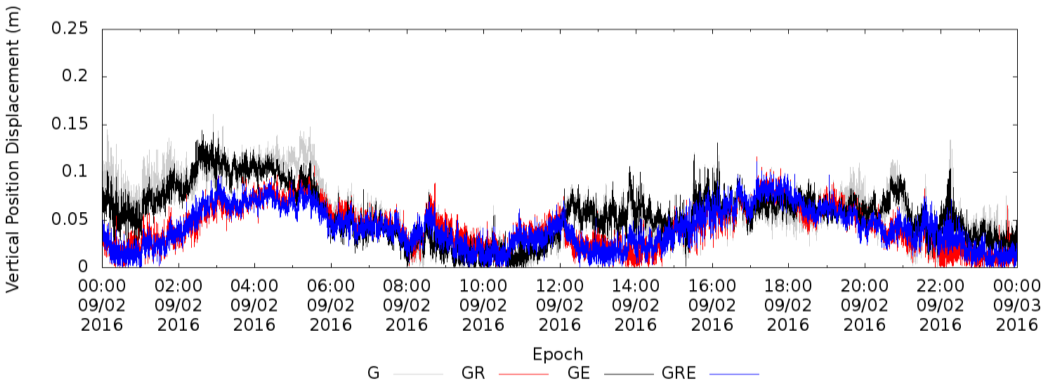

Figure 8: Vertical Displacement Analysis – UCAL station

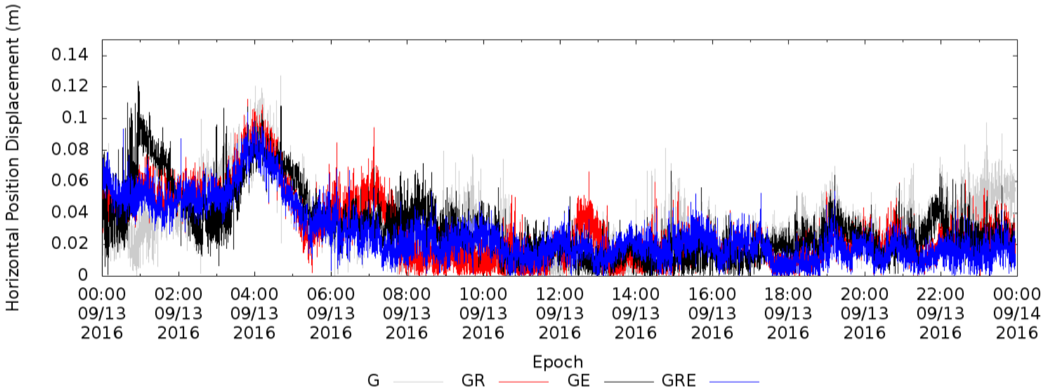

Figure 9: Horizontal Displacement Analysis – HOFN station

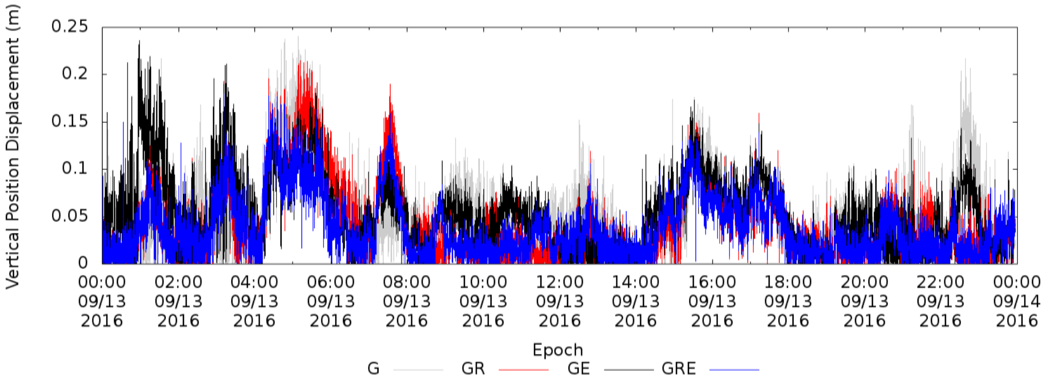

Figure 10: Vertical Displacement Analysis – HOFN station

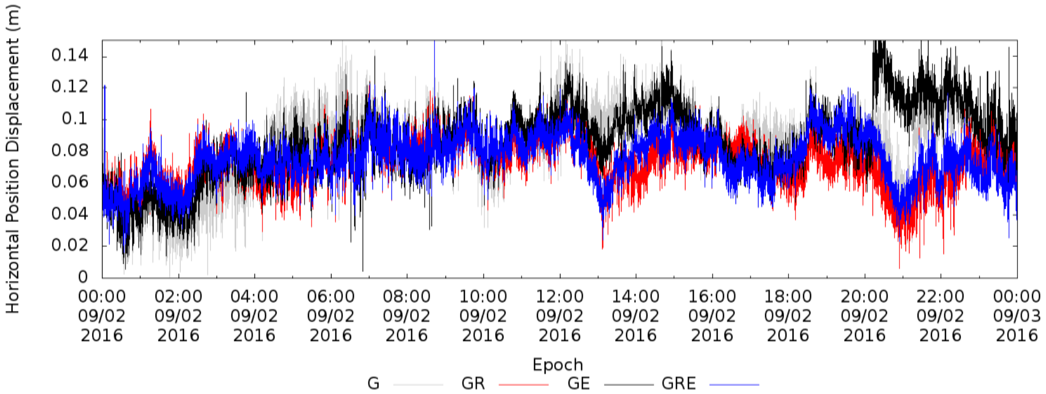

Figure 11: Horizontal Displacement Analysis – SEYG station

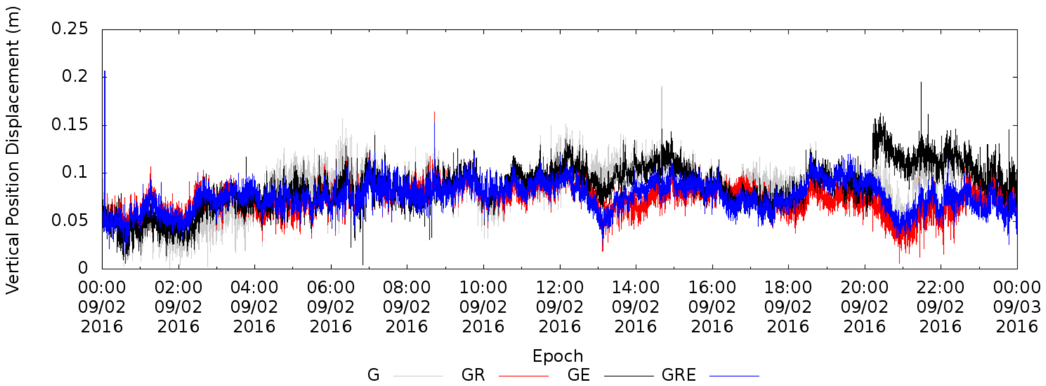

Figure 12: Vertical Displacement Analysis – SEYG station

In Table 1, the receiver type of each station can be found.

Station	***Receiver***
WTZZ	JAVAD TRE_G3TH DELTA
UCAL & SEYG	TRIMBLE NETR9
HOFN	LEICA GR25

Table 1: GNSS receivers type for open-sky analyses

Table 2 summarizes the results for the station located in Central Europe (WTZZ). This station is located in Germany, with latitude 49.14º, longitude 12.88º and height 665.9 meters. The idea with this station is to show the results obtained for a GNSS receiver in mid-latitude.

	G	***GR***	***GE***	***GRE***
H (RMS, m)	0.05	0.05	0.04	0.04
V (RMS, m)	0.07	0.06	0.06	0.05

Table 2: Results for WTZZ station

As it can be seen in Table 2, an improvement between the 20% and the 30% is achieved when Galileo satellites are introduced into the solution. As expected, the best results are obtained when all constellations are used in the PPP process, while the worst ones are obtained in the GPS-only scenario. Note that Figure 5 and Figure 6 do not include the convergence period (the performances are always below the convergence criteria). The convergence time will be analysed in the following section and the convergence criteria are defined in the following table.

Position Accuracy	***Horizontal (m)***	***Vertical (m)***
Single-Frequency	0.15 (95% availability)	0.30 (95% availability)
Dual-Frequency	0.05 (95% availability)	0.10 (95% availability)

Table 3: Convergence criteria

In the case of the UCAL station, the results are summarized in Table 4. This station is located at latitude 51.08º, longitude -114.13º and height of 1118.80 meters. The latitude is similar to the WTZZ one, while the longitude is quite different. Also altitude is higher in the case of the UCAL. In this case, the improvement is between 0 and 15%.

	G	***GR***	***GE***	***GRE***
H (RMS, m)	0.07	0.05	0.06	0.06
V (RMS, m)	0.05	0.05	0.05	0.05

Table 4: Results for UCAL station

The third station is HOFN, located in Iceland. Its latitude, longitude and height are 64.27º, -15.19º and 82.50 meters, respectively. Table 5 summarizes the results for this case.

	G	***GR***	***GE***	***GRE***
H (RMS, m)	0.04	0.03	0.04	0.04
V (RMS, m)	0.07	0.06	0.06	0.05

Table 5: Results for HOFN station

It is worth mentioning that, due to the configuration of the Galileo constellation, the results obtained for high latitudes improve significantly when Galileo satellites are included in the solution. This phenomenon can be seen in Table 5, which shows an improvement of 25-30% when using Galileo, which is higher than for the other stations

The last station is SEYG. It is located in the Seychelles Islands, with coordinates: -4.68ª (lat), 55.53º (long) and -37.08 meters of height. As expected, the worst results have been obtained for this station, which is located close to the equatorial region, where the impact of the ionosphere is more severe.

	G	***GR***	***GE***	***GRE***

H (RMS, m)	0.09	0.07	0.09	0.08
V (RMS, m)	0.06	0.05	0.04	0.04

Table 6: Results for SEYG station

In terms of availability of the PPP solution, the availability was between 91.22% and 100% during the analysis interval. It is considered that the service is available at a given epoch when two conditions are met: 1) there is a PPP solution and 2) the Protection Levels (statistical bound errors computed so as to guarantee that the probability of the absolute position error exceeding said number is smaller than or equal to the target integrity risk) computed by the integrity algorithm are valid. Some parameters are taken into account in order to determine if the Protection Levels given for each epoch are valid: correct integrity algorithm computation and minimum number of satellites in view for this epoch, among others. For more details see [Ref. 6.].

With the same stations and configurations, we can also analyse the convergence time. Since more satellites are available when the Galileo constellation is taken into account, better results are expected. Figure 13 and Figure 14 show the convergence time performance for WTZZ and UCAL. In each figure, the evolution of the horizontal error is shown for all configurations: GPS-only, GPS+GLONAS, GPS+Galileo and GPS+GLONASS+Galileo.

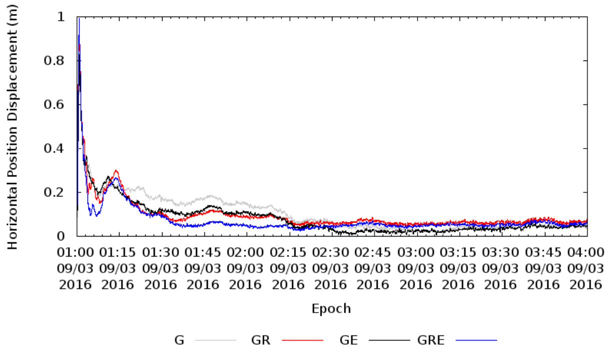

Figure 13: Convergence time analysis – WTZZ

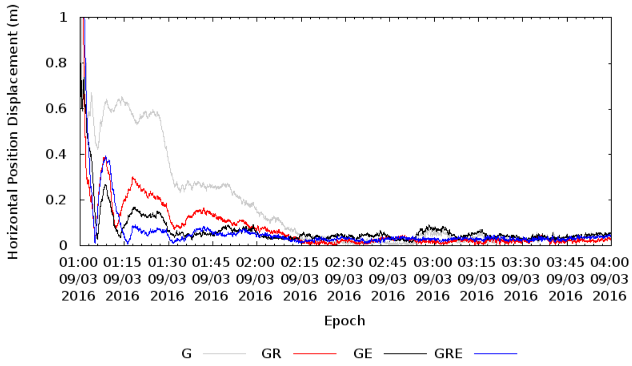

Figure 14: Convergence time analysis – UCAL

As expected, the worst results in terms of convergence time are obtained when only GPS constellation is processed (grey line), while the best results are obtained for the scenario using all constellations (blue line).

Table 7 summarizes the obtained results. Comparing the results in the GPS-only scenario and in the GPS and Galileo one (for UCAL station for instance), it can be easily seen the gained improvement. While the convergence time in GPS-only is around two hours, this time is reduced down to one hour in the multi-constellation scenario (being the convergence criterion the ones shown in Table 3). This means a reduction in the convergence time of almost 50%.

Station	***Convergence time (h)***			
	G	**GR**	**GE**	**GRE**
WTZZ	1.85	-	1.58	1.34
UCAL	1.42	1.30	1.12	1.18

Table 7: Convergence time results

In conclusion, it has been shown that the introduction of Galileo in PPP algorithms can improved the accuracy performances up to 30% (being the most considerable improvement when receiver is at high latitudes). The performances do also improve in terms of availability and the PPP solution is available almost all the time. Moreover, a major improvement is observed in the convergence time, thanks to the availability of more satellites in view of the receiver.

GALILEO-ONLY PPP ANALYSES

The second type of the tests consists of an analysis of the performance obtained with the Galileo-only configuration against the GPS-only one when using a static receiver. Additionally, a set of field trials aimed at evaluating the real-time PPP performances for kinematic users have also been analysed. For these tests, the same Key Performance Indicators as for the static receivers have been computed and the results have allowed assessing the real-time PPP performances with Galileo for a series of trajectories along different environmental conditions (open-sky and urban scenario).

Firstly, the results for the static scenario have been analyzed. Figure 15 and Figure 16 show the position displacement (North, East and Up components) for both the GPS-only and the Galileo-only scenarios. The station selected for this test has been the WTZZ. Table 8 shows the results of the error (RMS) obtained for both the horizontal and the vertical components.

	GPS-Only	***Galileo-Only***
H (m)	0.04	0.06
V (m)	0.05	0.08

Table 8: Positioning error (RMS). static receiver, GPS-only vs Gal-only

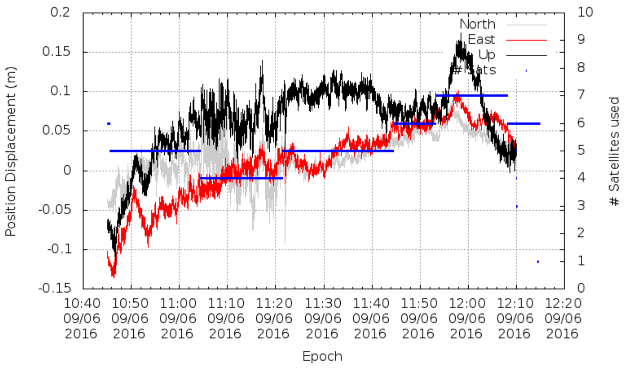

Figure 15: Position Displacement – Galileo-only

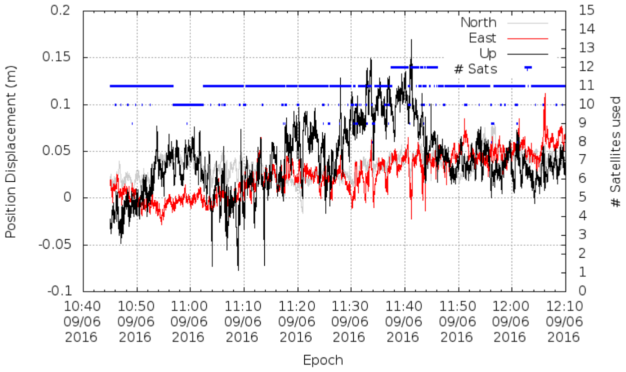

Figure 16: Position Displacement – GPS-only

As it can be seen in the Table 8, the performances obtained with both constellations are quite similar. If the horizontal error is analysed, a difference of two centimeters is found, while in the vertical component the difference is 3 centimeters. Taking into account that there were between 10 and 12 satellites in line of sight for GPS (see right hand side vertical axis in Figure 16), and between 4 and 7 satellites for Galileo (see right hand side vertical axis in Figure 15Figure 16), the results for a PPP solution using only the Galileo constellation are very promising.

The kinematic scenario under study can be split into the open-sky part and the urban one. As it is obvious, better results are expected for open-sky scenario since there are not multipath effects or loss of carrier-phase tracking (e.g. when passing under trees), among others. The whole kinematic scenario is presented below.

- Test Initial Time: 31/08/2016 – 11:50:00 (UTC)
- Test End Time: 31/08/2016 – 13:07:39 (UTC)
- Place: Tres Cantos (Madrid)
- Trajectory description:
    - From 11:50:00 h (UTC) to 12:16:37 h (UTC) → Receiver is static in a reference position.
    - From 12:16:37 h (UTC) to 12:29:19 h (UTC) → Receiver moves under open-sky conditions.
    - From 12:29:19 h (UTC) to 12:38:46 h (UTC) → Receiver is static in a reference position.
    - From 12:38:46 h (UTC) to 12:50:06 h (UTC) → Receiver moves under open-sky conditions.
    - From 12:50:06 h (UTC) to 12:56:00 h (UTC) → Receiver is static in a reference position. End of the open-sky part of the scenario.
    - From 12:56:00 h (UTC) to 13:07:39 h (UTC) → Receiver moves under urban conditions. Urban part of the scenario.

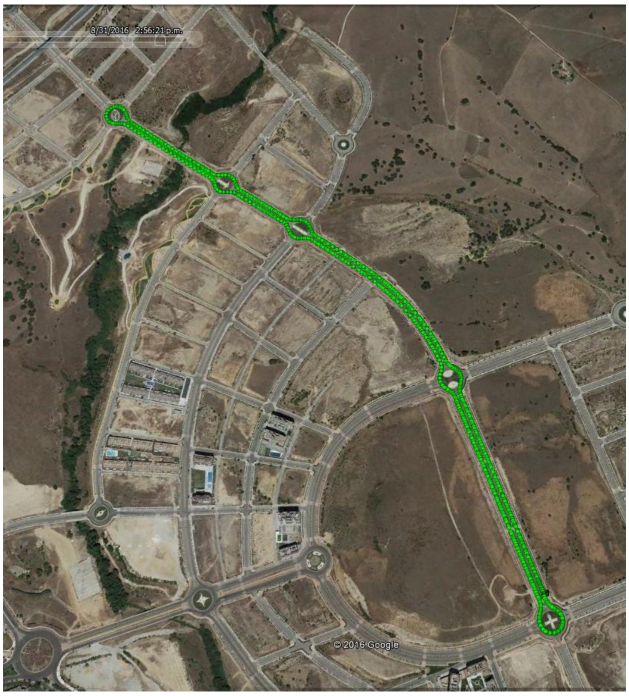

Figure 17: Kinematic scenario - Open-sky part

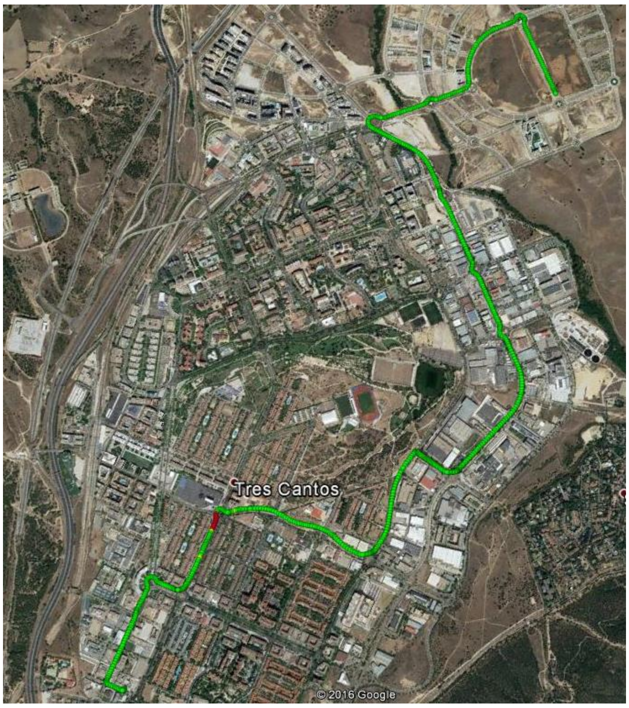

Figure 18: Kinematic scenario – Urban part

Figure 17 and Figure 18 show the trajectory followed by the receiver during the test.

The receiver used for this test was the Trimble R10, a multi-GNSS receiver which is not able to track Galileo Eccentric satellites (E14 and E18).

Three different configurations are compared for this test:

- GPS only
- Galileo only
- GPS + Galileo

The number of Galileo satellites in line of sight for the test date was 5 satellites (see Figure 19). One of them was the satellite E14, which could not be tracked by the receiver since it is one of the Galileo eccentric satellites.

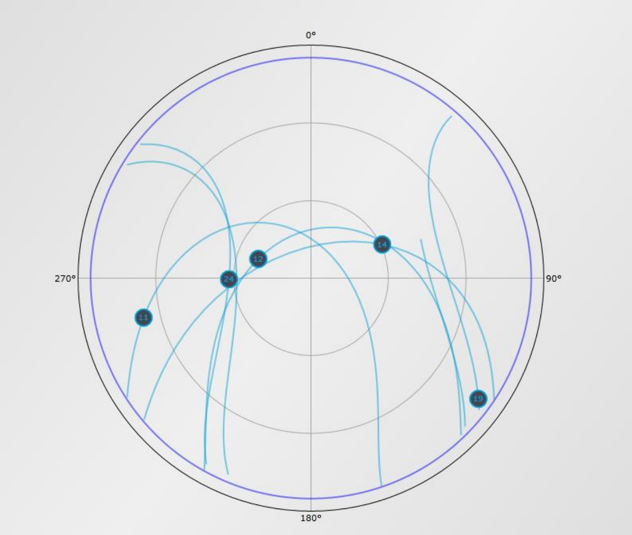

Figure 19: Sky-plot for kinematic test date. Galileo satellites

Table 9 and Table 10 show the error (RMS), taking the RTK trajectory as a reference, for each constellation combination and for both open-sky and urban parts.

	GPS-Only	*Galileo-Only*	*GPS + Galileo*	*GPS + GLONASS*
H (m)	0.05	0.67	0.04	0.04
V (m)	0.10	0.99	0.05	0.07

Table 9: Results for kinematic test – Open sky part

	GPS-Only	*Galileo-Only*	*GPS + Galileo*	*GPS + GLONASS*
H (m)	0.64	1.89	0.06	0.08
V (m)	1.45	4.01	0.12	0.17

Table 10: Results for kinematic test – Urban part

In the following figures, the evolution of the horizontal error is represented for each configuration.

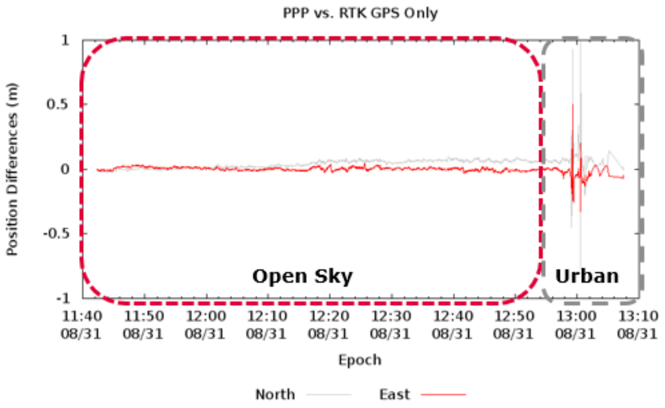

Figure 20: Horizontal error evolution – GPS Only

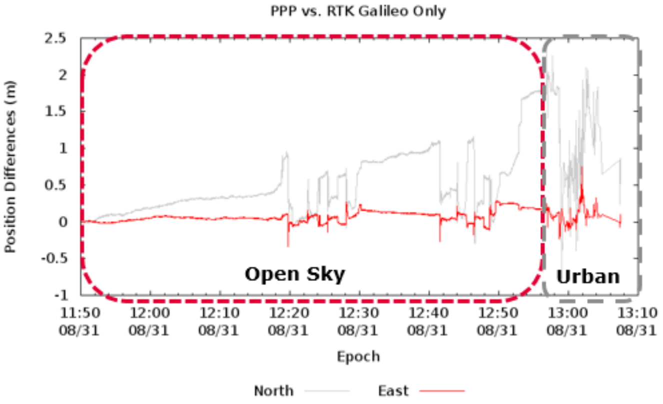

Figure 21: Horizontal error evolution – Galileo Only

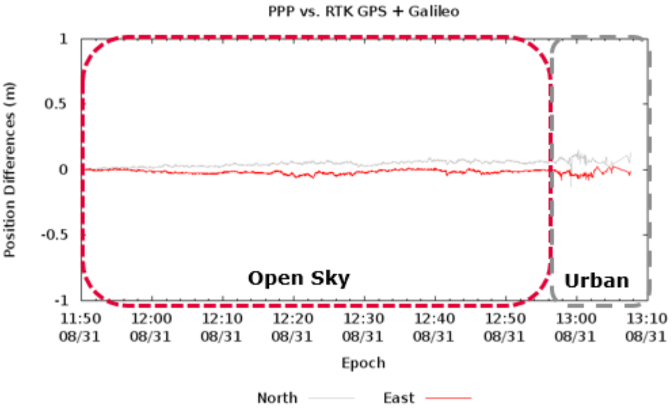

Figure 22: Horizontal error evolution – GPS+Galileo

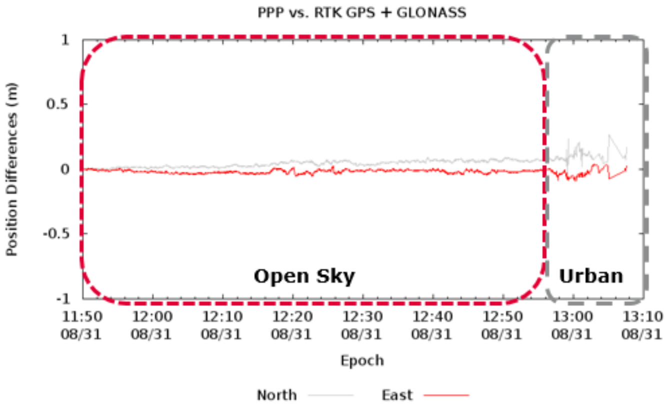

Figure 23: Horizontal error evolution – GPS+GLONASS

It is important to note that in the Galileo-only scenario there were between 1 and 4 satellites available, while in the GPS-only scenario there were between 5 and 10. This fact will gain importance, especially in the urban part of the scenario.

On the one hand, in the open-sky part both the horizontal and vertical accuracy for the Galileo-only are below the meter (which is a quite good result taking into account that there are only 4 satellites in line of sight). If Figure 20 (GPS-only) and Figure 21 (Galileo-only) are compared, it can be seen that when the rover starts moving, the Galileo-only scenario performances get worse, while in the GPS-only case the error does not change. This is due to the fact that the fewer satellites the receiver can track, the worse performance level is met. Besides, the fact of having one of the Galileo satellites at a very low elevation does not help either. This circumstance, together with having the other three satellites very close to each other in the sky plot, make the Dilution of Precision (DOP) really poor in this particular scenario. Finally, when GPS and Galileo are used, an improvement of 70% (comparing with the GPS-only scenario) in the vertical error is obtained and the PPP accuracy (see Table 3) is achieved in a kinematic scenario.

On the other hand, in the urban part of the trajectory the performance improves only if Galileo satellites are processed together with GPS. An improvement of 42% is obtained for the horizontal error and of 68% for the vertical error. As it can be seen in the Table 10, the error is below a half a meter for both the horizontal and the vertical components in the urban part when using GPS and Galileo. Apart from that, when more satellites are used, the re-convergence of the PPP algorithm after the carrier-phase tracking is reset for several satellites (e.g. when passing under a bridge) is faster and better. The algorithms implemented at user level in *magicPPP* do also improve this convergence by using the fact that the jump in the ambiguity after the gap must equal an integer number times the wavelength of the signal (“gap bridging”).

Finally, if GPS+GLONASS and GPS+Galileo scenarios are compared (Figure 22 and Figure 23), an improvement when using Galileo can be seen. It is important to note that only four GLONASS satellites have been used in order to compare two similar scenarios (taking into account that only four Galileo satellites are in view for this scenario). The GLONASS satellites that have been used are: R06, R12, R21 and R22. They have been chosen in order to obtain the most similar configuration between Galileo and GLONASS satellites (see Figure 24), taking into account the GLONASS satellites in view for the test interval.

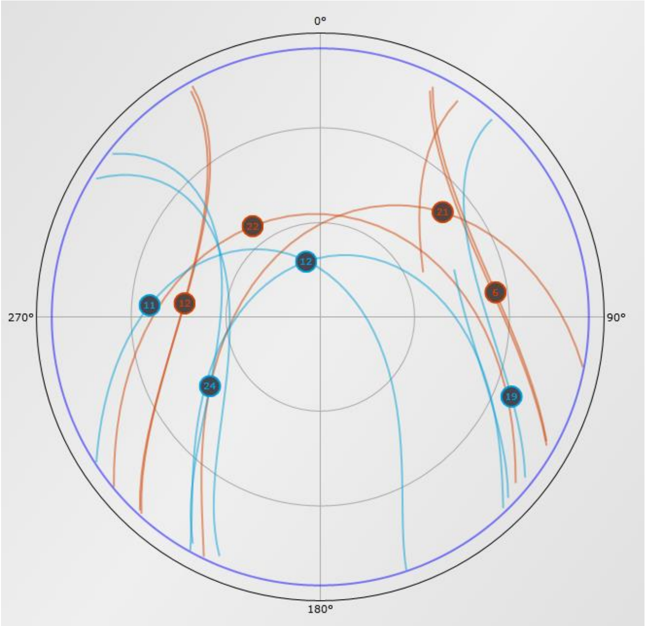

Figure 24: Sky-plot for kinematic test. GLONASS and Galileo satellites

As shown in Table 9 and Table 10, better results are obtained in terms of error (RMS). Differences in horizontal error (RMS) in the open-sky part between GPS+GLONASS and GPS+Galileo scenarios are not notable, while an improvement of 2 cm is obtained in the vertical component when using Galileo instead of GLONASS.

When urban part is analyzed, bigger differences can be found. An improvement of 25% is obtained in horizontal component and of 30% in vertical component. Since the signal provided by Galileo satellites is considered to be more robust than the one provided by GLONASS satellites, better results can be obtained in urban scenarios. Besides, it is not necessary to compute the inter-frequency biases in the GPS+Galileo scenarios, being needed when GLONASS satellites are used.

With all, it has been shown that similar performances are obtained in open-sky scenarios when using GPS+Galileo than when using GPS+GLONASS, while better results are obtained in urban scenarios when using Galileo instead of GLONASS. In addition, the computation difficulty is reduced since inter-frequency biases are not necessary to be computed when using Galileo.

CONCLUSIONS

The main conclusions that can be obtained from the test campaign are:

- Galileo is becoming a reality. Full Operation Capability phase is planned to be finished in the next two years.
- The introduction of Galileo satellites in the PPP solution significantly improves the performances:
  - In open-sky scenarios at high latitudes
  - In urban environments
- Convergence period is reduced using Galileo satellites.
- The performances of Galileo-only PPP solutions are comparable to GPS-only solutions in open-sky scenarios. It is expected to be the same for kinematic scenarios once more Galileo satellites are available.
- The performances of GPG+Galileo PPP solution are comparable to GPS+GLONASS solutions in open-sky scenarios, while solution obtained when using Galileo instead of GLONASS is better when urban scenarios are analysed.
- In late 2007, it is foreseen to have 22 Galileo satellites orbiting which will represent a major step-forward for PPP.

FUTURE WORK

As mentioned during the paper, more Galileo satellites are planned to be in orbit by the next few years. As a consequence, better PPP performances will be obtained since more and better data (more satellites will be deployed and improvements in the satellites' signals will be carried out) will be available. Since both the algorithms to support multi constellations PPPs and the analysis platform are already developed, when more Galileo satellites will be available, a test campaign will be carried out easily in order to assess the improvement in the PPP performance.

On the other hand, the improvement of the products quality in real time is also an important point to be developed in order to take a step forward to achieve a similar PPP performances when real time mode is used than when using off-line one.

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Also the sky-plots presented in the kinematic test results have been obtained using a GNSS Planning Online tool, developed by Trimble (www.trimble.com/GNSSPlanningOnline).

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