Real-Time PPP with Galileo, paving the way to European High Accuracy Positioning

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BIOGRAPHY

Guillermo Tobías González holds an MSc in Telecommunication Engineering by the University of Zaragoza. He has 7 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 coordinating R&D activities related to PPP services and he is the technical manager for the development of the Galileo Commercial Service Demonstrator, which will include the provision of a HA service.

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Daniel Rodriguez holds an MSc in Telecommunication Engineering by the Polytechnic University of Catalonia. He has more than 10 years of experience in the satellite navigation, precise orbit determination, time synchronisation and precise positioning areas. He is also an expert in the development of distributed/real-time/mission critical systems. In the past, he has been in charge of the development of the *magicGNSS* real time services. He is currently the technical leader of the Galileo Time Validation Facility, which acts as a preliminary Galileo Time Service Provider (GTSP).

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ABSTRACT

Precise Point Positioning (PPP) is a positioning technique providing centimeter-level error. PPP processes dual-frequency pseudorange and carrier-phase measurements from a single user receiver, using detailed physical models and corrections, and precise GNSS orbit and clock products calculated beforehand. PPP is different from other precise-positioning approaches like RTK in that no reference stations are needed in the vicinity of the user receiver. The only observation data that must be processed are measurements from the user receiver. Another advantage of PPP is that since the GNSS orbit and clock products are by nature global, the PPP solutions are also global, i.e., the PPP approach works for a receiver located anywhere on or above the Earth surface, and the resulting position is referred to a well-known terrestrial reference frame (normally ITRF). PPP can be applied at post-processing level and also in real-time applications, provided that real-time input orbits and clocks are available. One disadvantage of standard PPP however is its relatively slow convergence time, which is of the order of half an hour for decimetric accuracy, as compared to nearly instantaneous convergence with centimetric accuracy in short-baseline RTK.

After the last launch of Galileo IOV satellites in October 2012 and the foreseen launches in late 2014 and early 2015, the European GNSS constellation will soon reach a worthy of consideration size. Even before it reaches its Full Operational Capability, Galileo is already providing an increase in satellite availability with respect to the GPS+GLONASS scenario, providing the additional advantage with regard to the GPS+GLONASS scenario of not having to estimate the so-called inter-frequency biases (as for the case of GLONASS), but a single inter-system bias with respect to GPS.

GMV's *magicGNSS* suite (www.magicgnss.gmv.com), already allows a registered user to perform multi-GNSS Precise Orbit Determination (POD) processing based on observation RINEX files. The products for the different satellite constellations are generated in an Orbit Determination and Time Synchronisation (ODTS) process. This process receives as input dual-frequency code and phase measurements from a network of reference stations and produces as output satellite orbits and clocks, together with additional estimated parameters such as station clock biases, tropospheric delays and phase ambiguities.

The disposition of the 4 Galileo IOV satellites provides up to 3 hours of common view over Europe, making it feasible to perform a Galileo only PPP solution. By means of the aforementioned *magicGNSS* suite, GMV has already tested the achievable performances of a Galileo only PPP in batch mode, obtaining centimetric positioning error.

GMV has been developing over the last years an infrastructure for the generation of precise GPS and GLONASS orbits and clocks in real time. This infrastructure acquires via NTRIP data streams from a worldwide IGS station network, and produces orbit updates every fifteen minutes and clock updates every second from a combined GPS and GLONASS solution that can be then used consistently for real-time PPP applications.

In parallel to the real time HA products generation platform, a real-time GPS+GLONASS PPP client has been also developed and integrated in a portable hardware device supporting in-the-field real-time PPP. This device connects to a standard geodetic-class receiver through a serial interface to retrieve the observations, and features mobile communications with the PPP corrections server using GSM or Iridium. The communications have been optimized in order to provide a good balance between the data provider costs (mainly when using Iridium) and the positioning performances. This approach allows the use of a real-time PPP service with many existing geodetic-class receiver (although in the future it is foreseen the availability of dual-frequency receivers at reasonable prices) without the need for upgrading or replacing them, thus extending their operational capabilities.

Both the aforementioned real-time products generation server and the real-time PPP client have been recently redesigned and evolved in order to turn them into a fully multi-GNSS infrastructure. This has enabled GMV to test in the end user improvements obtained when adding Galileo to the already processed GPS and GLONASS constellations.

In this paper we describe the real-time server and PPP client developments undertaken, and we present both the server (i.e. orbit and clock) performances achieved and the resulting positioning performances, together with the performance improvement when adding Galileo to a challenging kinematic PPP scenario.

PRECISE POINT POSITIONING

PPP is a position location process which performs precise position determination using ionosphere-free measurements, obtained from the combination of undifferenced, dual-frequency observations coming from a single GNSS receiver, together with detailed physical models and corrections, and precise GNSS orbit and clock products calculated beforehand (for example products from IGS, the International GNSS Service [1]). The quality of the reference orbits and clocks used in PPP is critical, as they are both two important error sources in GNSS positioning.

Apart from observations and precise reference products, PPP algorithm also needs several additional corrections which mitigate systematic effects which lead to centimeter variations in the undifferenced code and phase observations, for example phase wind-up corrections, satellite antenna offsets, station displacements due to tides (earth and oceanic), etc.

At a given epoch, and for a given satellite, the simplified observation equations are presented next:

$$l_P = \rho + c(b_{Rx} - b_{Sat}) + Tr + \varepsilon_P \quad (1)$$
$$l_\emptyset = \rho + c(b_{Rx} - b_{Sat}) + Tr + N\lambda + \varepsilon_\emptyset \quad (2)$$

Where:

- l_P is the ionosphere-free combination of L1 and L2 pseudoranges
- $l\phi$ is the ionosphere-free combination of L1 and L2 carrier phases
- b_{Rx} is the receiver clock offset from the reference (GPS) time
- b_{Sat} is the satellite clock offset from the reference (GPS) time
- c is the vacuum speed of light
- Tr is the signal path delay due to the troposphere
- λ is the carrier combination wavelength
- N is the ambiguity of the carrier-phase ionosphere-free combination (it is not an integer number)
- ε_P and ε_ϕ are the measurement noise components, including multipath and other effects
- ρ is the geometrical range between the satellite and the receiver, computed as a function of the satellite (x_{Sat}, y_{Sat}, z_{Sat}) and receiver (x_{Rx}, y_{Rx}, z_{Rx}) coordinates as:

$$\rho = \sqrt{(x_{Sat} - x_{Rx})^2 + (y_{Sat} - y_{Rx})^2 + (z_{Sat} - z_{Rx})^2} \quad (3)$$

The observations coming from all the satellites are processed together in a process that solves for the different unknowns; the receiver coordinates, phase ambiguity terms, the receiver clock offset and the zenith tropospheric delay.

Most implementations of PPP algorithms use a sequential filter in which the process noise for the coordinates is adjusted depending on the receiver dynamics, the time evolution of the clock is more or less unconstrained (white noise with a high sigma), and the process noise for the tropospheric delay is adjusted to standard tropospheric activity. In the case of phase ambiguities, they are considered as a constant per pass. This type of filter is required for real-time applications.

Given that PPP is not a differential technique, it cannot resolve integer carrier phase ambiguities (at least, without new enhancements). Hence, it cannot converge to a precise solution in a short time, as other techniques do (RTK, for instance), and requires longer observation times for static positioning.

PPP has been normally conceived as a global service, taking into account that the orbit and clock products are themselves 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.

Under the previous assumption, good visibility of the satellites along all their orbits can be expected, and the accuracy of the orbit and clock estimations does not depend on the receiver location. This approach may lead to some limitations as there are mainly two options in order to fulfill the global coverage:

1. To deploy a global stations tracking network. This may be complex for political and logistic reasons for example, and possibly too expensive to operate for a regional service provider, whose target may not necessarily be to guarantee a global positioning service.

2. To relay on an external precise orbit and clock product provider. This may limit accuracy, real time capabilities and multisystem approaches. For instance, the IGS products (ultra-rapid, rapid, or final) are widely used due to their known high accuracy, however the IGS does not currently provide GLONASS clocks. Furthermore, official IGS products (IGS Real Time Project, www. rt.igs.org, provides precise ephemeris corrections with few seconds' latency) have a latency of several hours, which makes them not valid for real-time PPP.

A third option which does not imply such a large infrastructure deployment or data provision is to use a regional network for providing a regional PPP service [2].

REFERENCE PRODUCTS FOR REAL TIME PPP

PPP positioning performances are directly related to the accuracy of the reference GNSS orbit and clock products. Therefore, prior to the performance comparison between PPP and RTK, the process followed for the generation of the precise satellite orbits and clocks used in regional PPP will be explained. A complex process as it implies facing the challenge of generating products for a real time PPP service.

For the past years, GMV has been developing an infrastructure for the generation of precise multi-GNSS orbits and clocks with very low latency in a first step, and in real time in a second step [3]. A high-level layout of the infrastructure is shown in Figure 1.

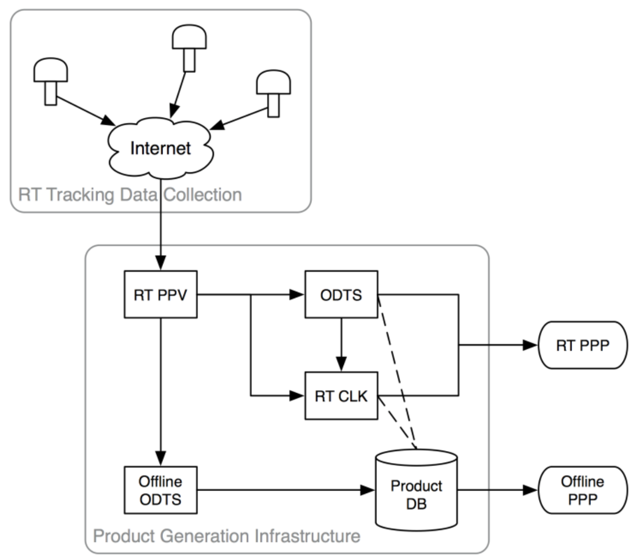


Figure 1 Product Generation Infrastructure High-level Layout

This process retrieves dual-frequency code and phase measurements in real time from a worldwide station network, via Networked Transport of RTCM via Internet Protocol (NTRIP)

Once collected, they are pre-processed also in real time by a Pre-Processing and Validation module (PPV), which then makes iono-free and geometry-free measurements available to the different algorithms.

The reference product generation is based on an Orbit Determination and Time Synchronisation (ODTS) process, which runs every 15 minutes. The ODTS processes 2 days of data in every execution, and provides updated satellite orbits and other estimated parameters (such as phase ambiguities, station tropospheric zenith delays and Earth orientation parameters).

In parallel to the ODTS, another process called RT_CLK estimates the satellite clocks in real time taking as input the pre-processed observations coming from PPV and the outputs from the last ODTS execution. There is a small latency in the delivery of the clock estimate, which is associated to the time that the algorithm waits for the arrival of the measurements from the station through the Internet; typically one or two seconds.

All the configured GNSS constellations are processed together, in order to ensure a consistent solution. It is necessary to estimate an *inter-channel bias* when processing GLONASS data. This must be done in order to compensate for the different internal delays in the pseudorange measurements through the GLONASS receiver, associated to the different frequencies used by the different satellites. Otherwise the station clock estimate would not be coherent with the pseudoranges. It has been observed that in GPS data this effect is much smaller and therefore negligible; normally it is not necessary to estimate such an inter-channel bias for GPS data. For the rest of the GNSS constellations, different *inter-system bias* values are also estimated.

The real time orbit and clock reference products are also contributing since 2012 to the Real Time IGS Project; their performances versus IGS rapid products can be seen in Figure 2. It covers the period from April 2013 till June 2014.

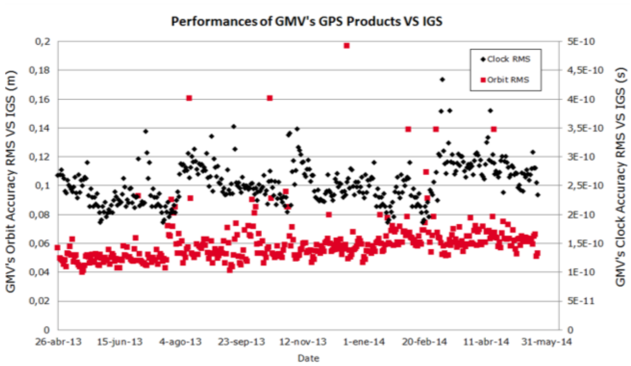


Figure 2 GMV's Real Time products VS IGS

Typical orbit accuracy is about 6 cm, RMS, and clock accuracy is about 0.25 ns, RMS.

Figure 3 shows the analogue comparison for GLONASS. This comparison has been carried out by comparing the real time orbit and clock generated by *magicGNSS* with respect to ESOC (European Space Operations Centre) products. The orbit RMS stays around 10 cm, and the clock RMS stays around 0.4 ns, as shown in

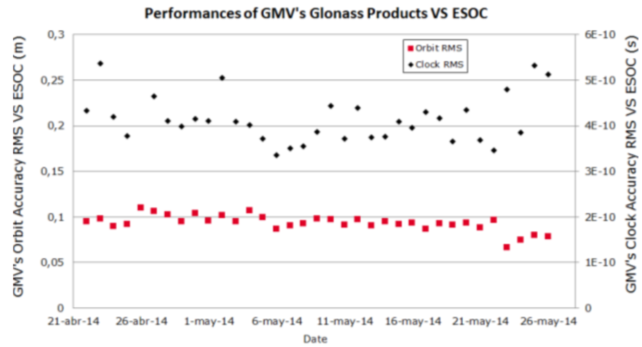


Figure 3 GMV's Real Time GLONASS products VS ESOC

The network used (mostly IGS stations from IGS' NTRIP caster http://rt.igs.org/), which is represented in Figure 4, provides global coverage and some redundancy to cover the relatively frequent (especially from some stations) outages of the real-time data streams. The different colours indicate the number of stations (also called Depth-of-Coverage or DOC) that are tracking a satellite when it is flying over a particular location.

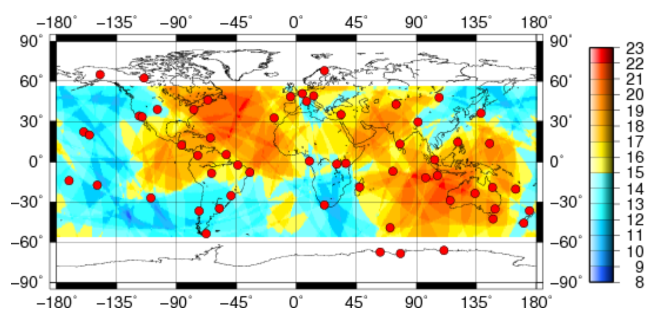


Figure 4 NTRIP Tracking Station Network

Together with the comparison of the off-line reference products with IGS rapid products, their quality is also assured by performing PPP for several IGS stations of known coordinates, over 1 day observation period.

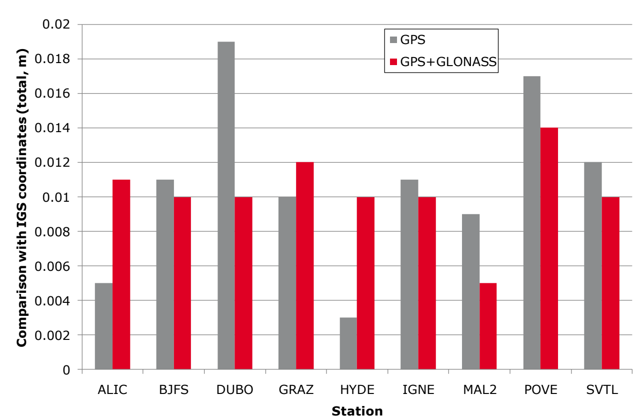


Figure 5 Static PPP Performances VS IGS coordinates (24-hours)

Figure 5 shows the positioning performances for 9 IGS stations with respect to the published IGS coordinates. It can be seen that the accuracy of the PPP solution is around 1 cm, both for GPS and GPS+GLONASS. This result illustrates the good quality of the reference products (both for GPS and for GLONASS) as well as the level of performances of the PPP algorithm. The Galileo product performances will be also presented throughout the paper.

RTCM-BASED INFRASTRUCTURE

It is worth to remark that the mentioned real-time numerical results from the previous section are only for GPS and GLONASS. The reason for this is that even if *magicGNSS'* real-time infrastructure is ready for processing multi-GNSS RTCM MSM (Multiple Signal Messages) messages, the data availability is quite limited as very few commercial receivers provide this kind of messages.

As mentioned before, *magicGNSS'* real-time infrastructure has been designed to be RTCM-based, which means that both the received inputs (observations and ephemeris) and the generated precise products (ephemeris corrections) follow the latest published RTCM 10403.2 standard from November 2013 [4].

This standard makes *magicGNSS'* real-time infrastructure (both HA product server and PPP client) compatible with any commercial receiver which provides GNSS RTCM observations and ephemeris, and is able to process GNSS ephemeris corrections generated by any High Accuracy service provider which had been computed according to the RTCM standard (SSR (State Space Representation) RTCM messages).

Most of the commercial GNSS receivers already provide GPS and GLONASS observations and ephemeris in RTCM format, however, the multi-GNSS MSM message definition is quite recent, and very few GNSS receivers have upgraded their firmware to generate those messages. This makes it very difficult to generate HA products in a real-time basis without having access to the different manufacturer's ICDs where their proprietary multi-GNSS messages' format is defined.

The problem for generating real-time multi-GNSS HA product in an RTCM frame is not just limited to the aforementioned issue, but also to the computation of the GNSS ephemeris corrections. Even if the latest RTCM standard already defines the ephemeris messages for Galileo and QZSS, it does only defines SSR messages for GPS and GLONASS, which at present prevents (it is expected to change in the near future with additional multi-GNSS RTCM message definition) the generation of multi-GNSS ephemeris corrections.

IGS' MGEX PROJECT

The only known real-time network which currently provides RCTM MSM messages is IGS' Multi-GNSS Experiment (MGEX) network (www.igs.org/mgex), shown in Figure 6.

Figure 6 IGS' MGEX station network

The MGEX network is composed by around 110 stations located in 90 sites, providing data for GPS, GLONASS, Galileo, BeiDou, QZSS and SBAS. Most of these stations provide data in real-time, and can be retrieved through the MGEX caster (http://mgex.igs-ip.net/) in RTCM3-MSM format. As mentioned before, very few GNSS receivers provide observations as RTCM MSM messages, but in their own proprietary formats (many of them non-public). In order to tackle this issue, the MGEX project uses a Raw2MSM conversion tool for converting the real-time data streams coming from the MGEX network to RTCM MSM messages so that any user can process them without the need of specific manufacturer's ICD.

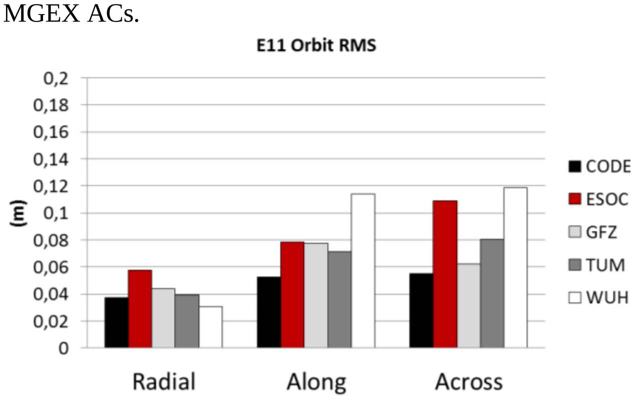
The access to this data is free and open, and it only requires a user to be registered in http://register.rtcm-ntrip.org/cgi-bin/registration.cgi in order to have access to up to 5 simultaneous RTCM streams. These 5 streams, although meaningful for developing and testing purposes, are not enough for generating accurate multi-GNSS products in real-time. However, both the observations and the ephemeris are also stored in RINEX 3 format [5] at CDDIS, IGN and BKG data archives, and are also freely available without data download limitation. As *magicGNSS'* web server is already able to process RINEX 3 observations using as algorithmic core the same libraries as the ones used by *magicGNSS'* real-time server, we have been able to take advantage of this for generating precise GPS, GLONASS and Galileo orbits and clocks with similar performances to the ones that are expected to be obtained by *magicGNSS'* real-time server when processing multi-GNSS MSM messages, except for data latency issues which may affect the real-time processing.

Figure 7 ***magicGNSS'*** **web server with MGEX stations**

As mentioned before, the official IGS products only contain information for GPS (orbits and clocks) and GLONASS (orbits), so it is difficult to assess the quality of the Galileo products generated by *magicGNSS* without a reliable reference as IGS. Fortunately, within the MGEX project, different Analysis Centers provide routinely (through ftp://cddis.gsfc.nasa.gov/pub/gps/products/mgex/) Galileo precise orbits and clocks (among other core products) which can be used as a reference to assess the quality of the aforementioned *magicGNSS'* Galileo products. These Analysis Centers are:

- CODE (Center for Orbit Determination in Europe)
- ESOC (European Space Operations Centre)
- GFZ (Deutschen GeoForschungsZentrums)
- TUM (Technische Universität München)
- WUH (Wuhan University)

A comparison was performed for March 15 2014 between *magicGNSS'* Galileo orbits and the ones provided by the MGEX ACs.



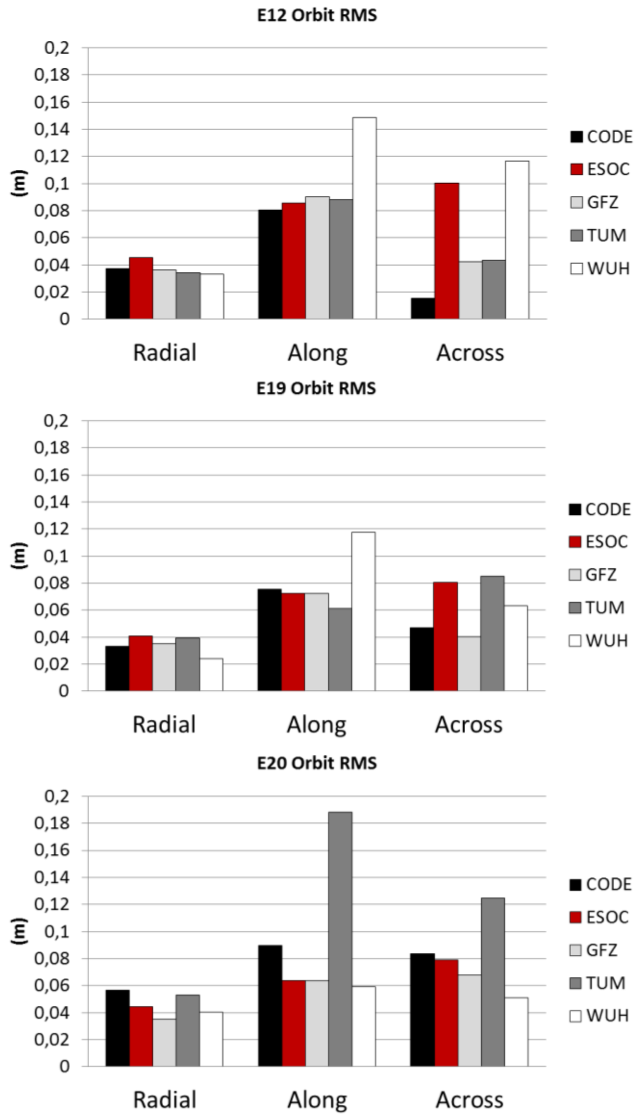


Figure 8 ***magicGNSS'*** **Galileo orbits VS MGEX's ACs**

The obtained results in Figure 8 show that the performances are comparable to the ones provided by the different ACs, with centimetric consistency between all the solutions (except with TUM for E20 and WUH for E12 and E19), and therefore suitable for being used as reference for PPP.

GALILEO-ONLY PPP

Since October 2012, 4 operational Galileo IOV satellites provide up to 3 hours of common view over Europe, making it feasible to compute a Galileo-only PPP solution for the first time since the beginning of the Galileo project.

Back in 2013, GMV already computed a batch Galileo-only PPP by means of its *magicGNSS* web server. Figure 9 show on the left a Trimble R10 which was place at the roof of GMV's premises and recorded data for over 6 hours during May 31st 2013.

Figure 9 R10 Trimble receiver placed at GMV's roof

Based on the MGEX RINEX data, a set of GPS+GLONASS+Galileo reference products were generated by means of *magicGNSS'* ODTS, which were then used to compute a Galileo-only PPP taking advantage of *magicGNSS'* PPP. Figure 10 shows the positioning error between the Galileo-only PPP and a PPP using as reference products IGS rapid products, and how the differences are at the centimeter level.

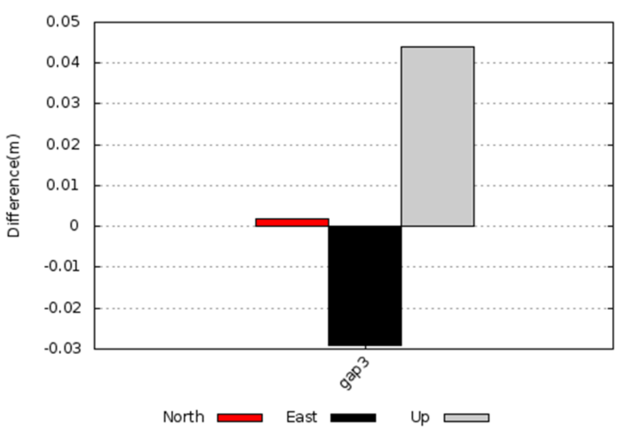


Figure 10 Galileo-only batch PPP performances

The previous result, although promising regarding the future Galileo positioning performances, did not prove the feasibility of a real-time Galileo-only PPP, as a single ambiguity value was estimated per pass and a single position was computed for the whole estimation arc. Therefore, in order to test the expected performances of a Galileo-only PPP, *magicGNSS'* PPP was run in sequential mode.

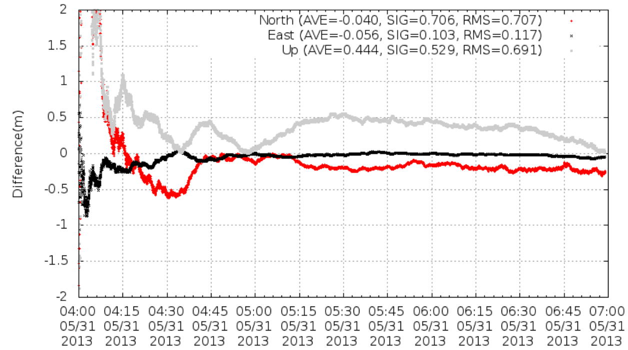


Figure 11 Galileo-only sequential PPP performances

Figure 11 shows the differences between the position estimated by the Galileo-only sequential PPP and the receiver's calibrated position. It can be seen how the position error stays below 50 cm after the PPP has converged.

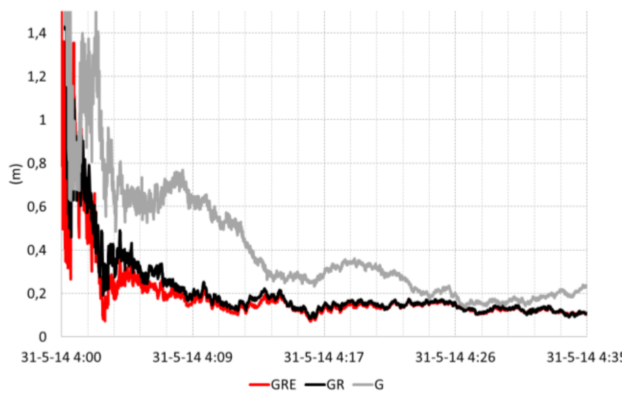


Figure 12 Sequential PPP convergence time

Based on the same multi-GNSS reference products described previously, a sequential multi-GNSS PPP was run for analyzing the improvement of the convergence time when adding the Galileo satellites to the GPS+GLONASS PPP. Figure 12 shows how the convergence time is reduced when adding the Galileo data to the GPS+GLONASS PPP.

SEQUENTIAL KINEMATIC MULTI-GNSS PPP

One of the main experimentation tasks within the *magicGNSS'* R+D activities has been the extensive testing of its real-time PPP client under challenging environments [6]. Carrying on with these experimentation activities, one of the aims of this paper was to analyse how the inclusion of Galileo in the real-time PPP processing could enhance the final positioning performances and its robustness.

Although *magicGNSS'* real-time infrastructure has been already upgraded for the multi-GNSS RTCM-based processing, the previously mentioned limited availability of multi-GNSS RTCM MSM data sources and the lack of multi-GNSS RTCM SSR messages definition (apart from

GPS and GLONASS), limits the real-time performance testing for the time being.

Nevertheless, several offline sequential tests had been carried out which have provided valuable results which are believed to be representative of the ones that will be obtained on a real-time scenario once the aforementioned issues have been solved.

One of the tests consisted on placing our Trimble R10 receiver on the roof of a car by means of a magnetic base, and record multi-GNSS observations around Tres Cantos (close to GMV's premises in Madrid) on August 21st for around 25 minutes. Figure 13 shows the trajectory around Tres Cantos, which included narrow streets and under trees.

Figure 13 Route for field tests through Tres Cantos

Our experience has shown that driving under trees, makes most of the tested GNSS receivers loose the L2 tracking, which greatly degrades the performances of our GPS+GLONASS real-time PPP when testing it under these circumstances.

The main target of this test was to analyse how the addition of Galileo (even with just 3 satellites) could ease the impact of the L2 tracking loses in the end PPP performances. In order to do this, a set of reference GPS+GLONASS+Galileo products were computed offline by means of *magicGNSS* web server based on the RINEX data generated by the MGEX network shown in Figure 7.

Based on the recorded RINEX and the reference GPS+GLONASS+Galileo orbits and clocks, 2 sequential PPPs were run. First a GPS+GLONASS one was executed, obtaining accurate results for most of the trajectory except for those areas which were under trees where the PPP performances were clearly degraded due to the aforementioned L2 tracking loses, as it can be seen in Figure 14.

Figure 14 GPS+GLONASS PPP performance degradation due to L2 tracking loses

A second PPP was then run adding the Galileo satellites to the process. The results were clearly improved in the problematic areas as the E5 tracking was not lost. Figure 15 shows a clear improvement of the PPP performances once the Galileo satellites were added to the processing, providing additional robustness to the process.

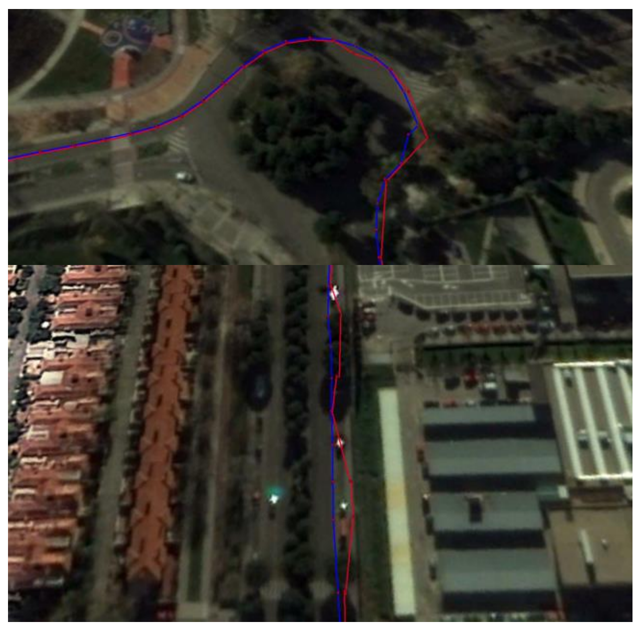


Figure 15 PPP performance improvement due to the addition of Galileo to the GPS+GLONASS solution

The main issue throughout the aforementioned test is the lack of a reliable reference trajectory due to the fact that RTK was affected by the same L2 tracking loses as the PPP was. In future tests, the usage of precise IMUs (Inertial

Measurement Unit) will be analysed for obtaining a precise trajectory in the absence of a reliable RTK solution.

CONCLUSIONS AND FUTURE WORK

Even with only 3 operating satellites, Galileo has proven to provide a remarkable contribution to the PPP performances; reducing the convergence time and increasing the PPP robustness under challenging environments.

Although the presented sequential PPP results can be extrapolated to a real-time environment, our *magicGNSS'* real-time infrastructure still needs to be tested once the mentioned RTCM issues (MSM data availability and multi-GNSS SSR message definition) are solved.

Our future work will focus on testing our *magicGNSS'* real-time infrastructure to try to make the service even more robust and analyse the benefits of using additional GNSS constellations.

Work is going on, as well, for providing the user with an indication of the accuracy of its solution, in the form of "protection levels". More information can be found in [5].

ACKNOWLEDGMENTS

RTK solution is calculated using RTKLIB, developed by Tomoji Takasu (www.rtklib.com).

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