magicGNSS’ RTCM-based service, a leap forward towards multi-GNSS High Accuracy Real-Time processing

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BIOGRAPHIES

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.

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ABSTRACT

Over the recent years, the GNSS community has witnessed how the upcoming GNSS constellations; Galileo, BeiDou and QZSS are becoming a tangible reality together with the already consolidated GPS and GLONASS constellations. The early stages of the aforementioned constellations are falling behind, and new algorithmic improvements, capabilities and services are being developed thanks to the new signals, modulations and frequencies available.

These advantages do not come “for free”. New challenges need to be faced too; such as the implementation of new attitude models and new Solar Radiation Pressure models in order to be able to provide the GNSS community with precise satellite orbits and clocks to enable their usage for High Accuracy (HA) applications, such as PPP (Precise Point Positioning).

Regarding the precise multi-GNSS product generation, the International GNSS Service (IGS) has been consistently providing precise GPS products for the last 25 years to the GNSS community, which are considered to define the “state-of-the-art” on GPS processing; however, the leap for generating precise multi-GNSS products has not been officially taken yet. For the time being, IGS’s Multi-GNSS Experiment project (MGEX) provides precise multi-GNSS orbits and clocks from different Analysis Centers (ACs). This initiative is definitely contributing to boost the development of multi-GNSS services and applications, but these products are not to be considered as official IGS products yet. In this regard, GMV’s *magicGNSS* suite, already allows a registered user to perform multi-GNSS precise satellite orbit and clock determination processing based on observation RINEX files.

With respect to multi-GNSS PPP processing, several online PPP services are currently available for the GNSS user; CSRS-PPP (by the Natural Resources Canada), GAPS (by the University of New Brunswick), APPS (by the Jet Propulsion Laboratory) and *magicPPP* (GMV). Many performance comparisons between these services have been performed and published, showing remarkable consistencies among them. The main difference lies on the fact that whereas the first three services are GPS-based, *magicGNSS’* PPP service provides a user with the capability of computing a multi-GNSS PPP solution using

GMVs rapid products, which are generated on a daily basis using the IGS' MGEX station network as reference.

Beyond the post-processing capabilities, GMV has been developing over the last years an infrastructure for the generation of precise multi-GNSS orbits and clocks in real time. This infrastructure acquires via Networked Transport of RTCM via Internet Protocol (NTRIP) data streams from IGS' MGEX station network, which provide multi-GNSS observations in RTCM format via Multi-Signal Messages (MSM). Based on these observations, it produces orbit updates every fifteen minutes and clock updates every second from a combined multi-GNSS 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 multi-GNSS PPP client has been also developed and integrated in an Android-based device supporting in-the-field real-time PPP processing. This terminal connects to a standard geodetic-class receiver through a serial interface in order to retrieve GNSS observations in RTCM format, and allows mobile communications with the PPP corrections server.

There are already several real time high accuracy multi-GNSS solutions; omniSTAR, RTX, StarFire, VERIPOS Appex, etc. However, these are closed solutions, which rely on their own station networks for the generation of precise multi-GNSS products, and use proprietary messages for feeding their own PPP solutions. In this regard, GMV has embraced RTCM as the standard to be used within their multi-GNSS infrastructure in order to allow interoperability with third party solutions which are aligned with the RTCM standard.

This RTCM-based real time multi-GNSS infrastructure has been evaluated under several field scenarios representing many situations that potential users could address in real operations. These include; static, kinematic and combined use cases. In the tests, different visibility conditions have been assessed (open sky or different types of obstacles such as trees or walls), as well as the robustness of the solution against communication losses of different durations. The real-time PPP solutions have been validated against Real-Time Kinematic (RTK) and/or post-processed PPP.

Throughout this paper, *magicGNSS*` multi-GNSS real-time orbits and clocks generation server and the real-time PPP client developments undertaken are described, together with both the server (i.e. orbit and clock) performances achieved when compared to IGS and the resulting positioning performances, emphasizing how any RTCM-based software can be easily tested and integrated within the presented infrastructure, providing a powerful tool for the GNSS community. The emphasis will be put on describing how the complete service architecture deals with the processing of an increasing number of GNSS signals, the support of multiple combinations of different constellations and implementation of an adaptable and flexible RTCM-based service.

INTRODUCTION

Different technologies based on GNSS (alone or augmented and/or hybridized) are currently being used for many different applications. GPS and GLONASS are fully operational systems, and Galileo and BeiDou are now being deployed. Augmentation systems such as WAAS, EGNOS, MSAS and GAGAN are providing improved accuracy and integrity over the basic GNSS navigation solutions, and SDCM is in progress. RTK, PPP and the integration with sensors, mapping data, local ionospheric information and other non-GNSS signals are allowing the achievement of excellent accuracy and reliability levels, and spreading the application of GNSS based technologies to many different fields. The receivers market is continuously evolving, incorporating innovative features as the systems are being developed and improved, for being able to provide a wider range of positioning navigation solutions to a growing community of users.

GMV has acquired a strong background in the GNSS area over the last decade. The algorithms that enable the generation of high accuracy products and corrections used in order to obtain a precise Position, Navigation and Timing (PNT) solution have been continuously improving in order to obtain a "state-of-the-art" multi-GNSS suite; *magicGNSS*.

The architecture of the *magicGNSS* suite comprises three different modules:

- Post-processing SW
- Real-Time product server
- Real-Time PPP client

Figure 1 shows the high level architecture of *magicGNSS*, which will be described in the following sections of the document.

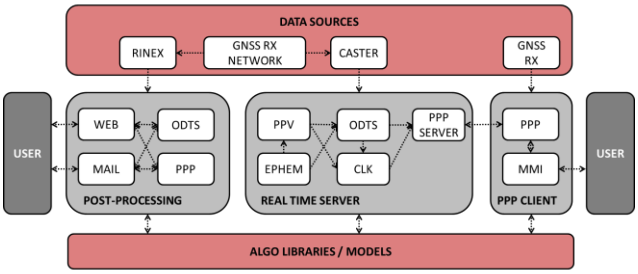
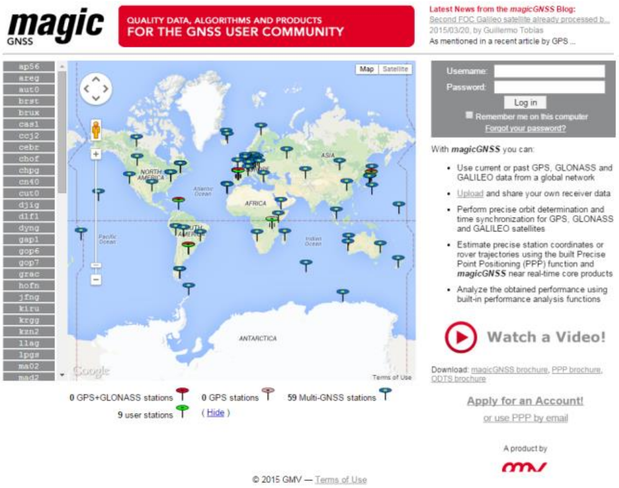


Figure 1: *magicGNSS'* architecture overview

The three main modules share the same low level algorithmic libraries which guarantees the consistency of the results and SW maintainability.

magicGNSS' post processing service is accessible through http://magicgnss.gmv.com, its web interface is presented in the Figure 2.



Latest News from the *magicGNSS* Blog:
Second FOC Galileo satellite already processed b...
2015/03/20, by Guillermo Tobias
As mentioned in a recent article by GPS ...

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With ***magicGNSS*** you can:

- Use current or past GPS, GLONASS and GALILEO data from a global network
- Upload and share your own receiver data
- Perform precise orbit determination and time synchronization for GPS, GLONASS and GALILEO satellites
- Estimate precise station coordinates or rover trajectories using the built Precise Point Positioning (PPP) function and ***magicGNSS*** near real-time core products
- Analyze the obtained performance using built-in performance analysis functions

Download: magicGNSS brochure, PPP brochure, ODTS brochure

Figure 2: *magicGNSS'* webpage

Different GNSS tools are available to registered users by means of the aforementioned interface. The detailed description of *magicGNSS'* web service capabilities have been deeply described in [1], whereas the scope of the current paper is to describe *magicGNSS'*:

- Multi-GNSS post-processing reference products generation
- Real-Time RTCM multi-GNSS product generation
- Multi-GNSS post-processing PPP scheme
- Real-Time multi-GNSS PPP Client
- Single Frequency PPP and magicPPP mobile application

MULTI-GNSS POST-PROCESSING REFERENCE PRODUCTS GENERATION

The generation of orbit and clock reference products (available to registered users for multi-GNSS PPP processing) in post-processing mode is based on an ODTS (Orbit Determination & Time Synchronization) process which takes advantage of a batch least-squares algorithm that processes GNSS measurements from stations data files in RINEX format, solving for orbits, satellite and station clock offsets, phase ambiguities, station tropospheric zenith delays, and station coordinates.

Although GMV is not an IGS AC, *magicGNSS'* ODTS is aligned with IGS' recommendations published as part of IGS' 2nd Data Reprocessing Campaign (http://acc.igs.org/reprocess2.html) regarding:

- IERS Conventions (2010)
- Reference Frame aligned with ITRF2008
- Usage of igs08.atx "absolute" antenna calibrations
- EGM2008 geopotential
- Etc.

Satellite and station clock offsets are estimated with respect to a reference clock, normally provided by one of the stations, or a reference timescale. Clocks are calculated as snapshot values, i.e., as instantaneous values at the measurement time stamp. Thus, clocks are estimated at the same rate as the internal measurements used by the ODTS (typically every 5 minutes). These estimated snapshot values are adjusted to a linear model that can be extrapolated into the future for clock prediction.

The implemented ODTS algorithm is able to process measurements from all the GNSS constellations, i.e. GPS, GLONASS, Galileo, BeiDou and QZSS. One of the main challenges of processing a multi-GNSS scenario comes from the fact that a GNSS receiver presents different internal delays in the pseudorange measurements of the different constellations. In order to overcome this problem an inter-system bias is estimated for each constellation. In the same way 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 FDMA (Frequency Division Multiple Access) scheme, different frequencies used by the different satellites.

magicGNSS' multi-GNSS post-processing reference products are generated on a daily basis using a network of 60 stations that provide worldwide coverage as it is represented in Figure 3. The observation files are retrieved from IGS' Multi-GNSS Experiment (MGEX) ftp server (ftp://cddis.gsfc.nasa.gov/pub/gps/data/campaign/mgex/).

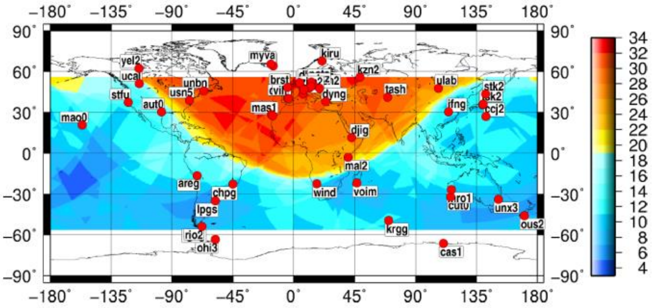

Figure 3: *magicGNSS* post-processing GNSS network

The most common approach for multi-GNSS ODTS is to process all the constellations together. However, in order to reduce the computational load that implies the fact of dealing with a worldwide station network and all the GNSS constellations, *magicGNSS* proposes an innovative step-based processing scheme which allows reducing the computational effort and, at the same time, permits to obtain the same level of performances as when all the constellations are processed at the same time. The step-based capability estimates the following stations' parameters only once making use of the constellations configured for the first processing-step:

- ERPs
- Station clocks
- Station positions
- Zenith tropospheric delay

These parameters are fixed in the following steps and therefore, only the parameters related to the new constellations to be processed are to be estimated. A sketch describing the process has been included in the Figure 4. Note that, as it will be further explained in the following section, the computational load is a key factor in the Real-time performances.

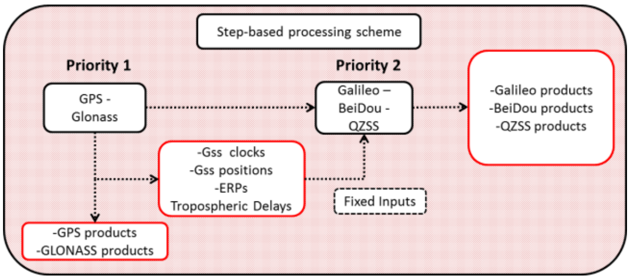

Figure 4: Step-based processing scheme overview

Ideally, the reference clock products should be available at a sampling rate of at least 30 seconds in order to provide precise GNSS products for PPP solutions working with observations at a sampling rate of up to 1 second. This need comes from the fact that extrapolating reference clocks with a sampling rate over 30 seconds (in order to compute a PPP solution with a 1 second rate) introduces a significant noise in the estimated position due to the clock extrapolation error. Figure 5 shows the PPP performance degradation when computing a 1-second solution extrapolating reference clock products which have been generated with 30, 60 and 300 seconds respectively for the same time period.

The results show how the PPP performances are significantly degraded when using reference clock products at rates over 30 seconds.

On the other hand, an ODTS with a 30-second sampling rate would lead to an excessive computational burden. In order to alleviate this constrain, *magicGNSS* densification feature is available. This capability, which is based on an estimation filter, allows the processing of the ODTS with a sampling rate of 300 seconds and a later clock densification at the desired rate.

The quality of the multi-GNSS *magicGNSS'* reference orbits and clocks has been assessed over the last year. The results have been compared with IGS products, for GPS and GLONASS constellations, with those obtained by the different Analysis Centers (TUM, CODE, CNES and GFZ) in the frame of IGS' MGEX (http://igs.org/mgex/) for Galileo and BeiDou and the products provided by the Japan Aerospace Exploration Agency (JAXA) for the QZSS products.

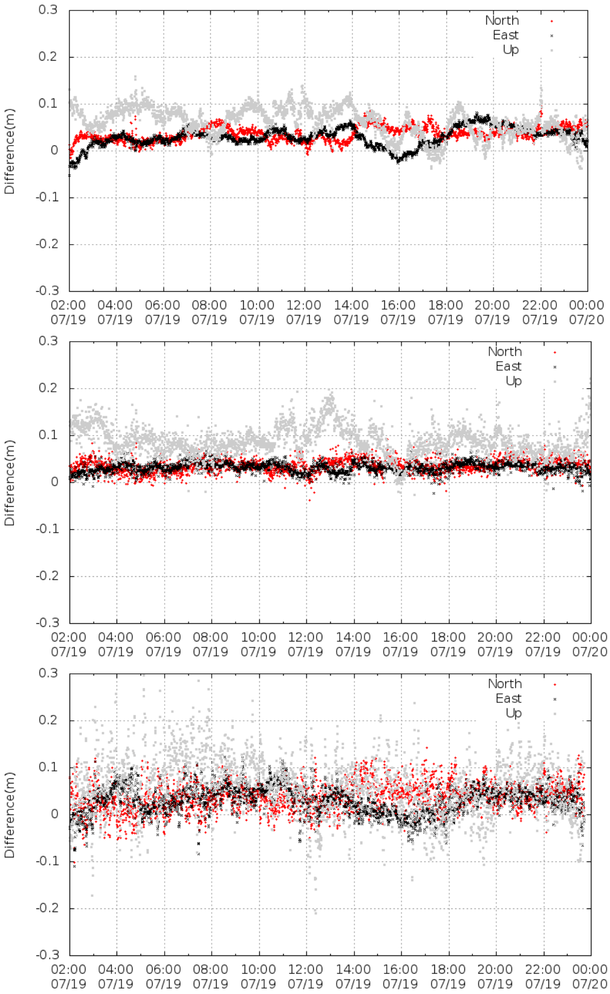

Figure 5: 1-second PPP performances with 30, 60 and 300 second reference clocks

Figure 6 and Figure 7 show that nominal performance is around 2.5 cm (RMS) for GPS orbits and 3 cm (RMS) for GLONASS orbits. In addition, the comparisons of the products obtained by different ACs against the reference IGS final products shows that GMV's products are comparable to the obtained by the ACs.

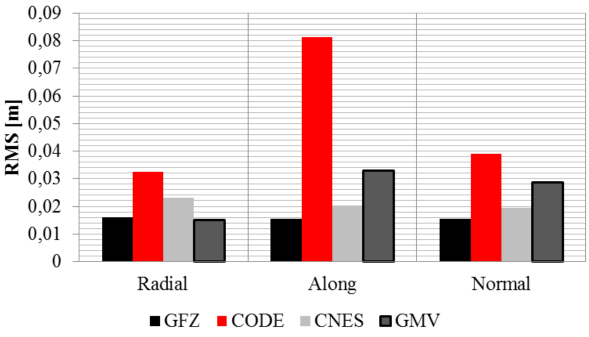

Figure 6: Comparison between IGS' GPS products and those obtained by different ACs and GMV.

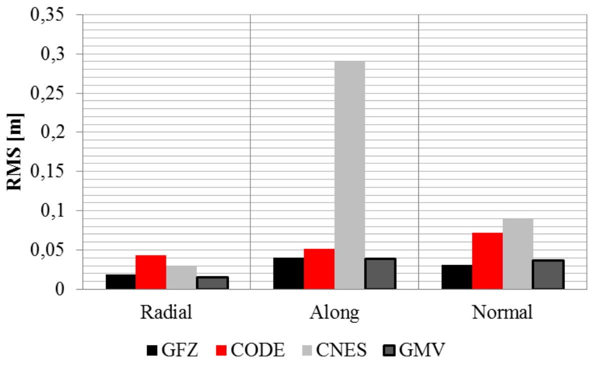

Figure 7: Comparison between IGS' GLONASS products and those obtained by different ACs and GMV.

In order to assess the consistency of the products that will be used as reference in the quality assessment of the Galileo and BeiDou products, a comparison of the products obtained by GFZ and CODE has been performed. Figure 8 shows consistency of 15 cm (RMS) when considering Galileo products and around 22 cm (RMS) when analyzing BeiDou products. Note that these results must be taken into account when GMV's products are analyzed.

Figure 9 and Figure 10 show the typical performances of the *magicGNSS'* products for Galileo and BeiDou constellations. Taking into account the consistency between the different Analysis Centers, it can be concluded that GMV's BeiDou and Galileo products are comparable to those obtained by the centers used as reference.

Finally, the quality assessment of the QZSS products, namely the satellite J01, has been carried out comparing the GMV's solution against JAXA' solution. Note that, according to the Japan Aerospace Exploration Agency, the accuracy of their reference products is approximately 20 cm [2].

The nominal performances for the different GNSS constellations along with the products used for the assessment have been summarized in Table 1.

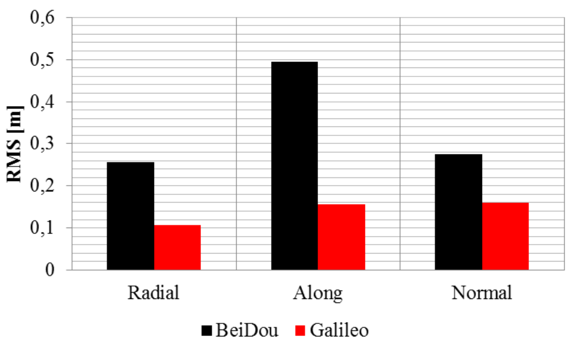

Figure 8: Comparison between Galileo and BeiDou products (GFZ & CODE).

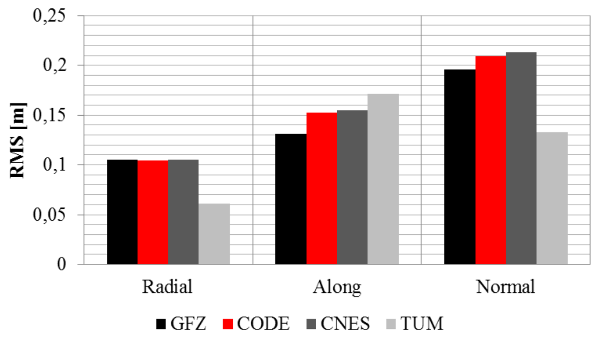

Figure 9: Comparison between *magicGNSS'* Galileo orbits and MGEX's

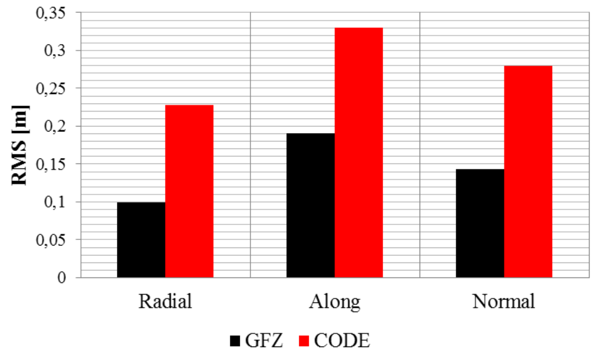

Figure 10: Comparison between *magicGNSS'* BeiDou orbits and MGEX's

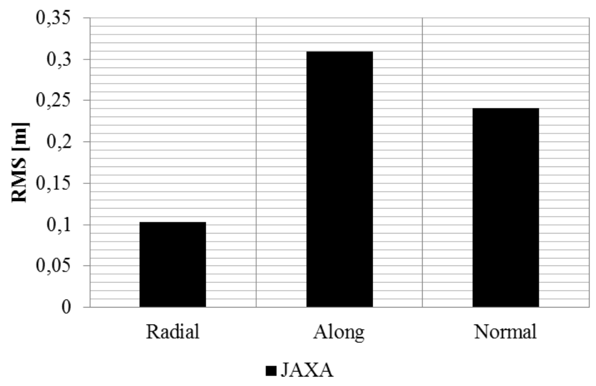

Figure 11: Comparison between *magicGNSS'* QZSS orbits and JAXA's

Table 1: Summary of *magicGNSS'* orbits quality

Constellation	Nominal performance	Reference products
GPS	2,5 cm	IGS
GLONASS	3 cm	IGL
GALILEO	15 cm	MGEX's ACs
BEIDOU	20 cm	MGEX's ACs
QZSS	22 cm	JAXA

All the results presented up till now have been obtained by processing all the constellations at the same time, which implies a great computational effort. The quality of the innovative step-based scheme has also been assessed within the same scenario. On the first step, GPS and GLONASS constellations have been processed, whereas Galileo and BeiDou have been processed on a second step. In this way, GPS and GLONASS observations are used for the estimation of the station parameters, which will be fed into the ODTS algorithms in the second step as fixed inputs. From Figure 12 to Figure 15 the quality of the performances in terms of the median of the RMS with respect to the different reference products has been represented. In addition, the results have been summarized in Table 2. The most important conclusion that can be drawn from the analysis of these figures is that the performances are comparable to those obtained when processing all the constellations at the same time. It is of special interest the results depicted in Figure 14, which shows an improvement in the quality of the products when using the step-based scheme. This is due to the effect of including BeiDou in the nominal processing and therefore it can be concluded that the step-based approach is more robust to the addition of new constellation even if their characteristics are not as accurately defined as for GPS or GLONASS constellation or if the number of operational satellites in the constellations is lower.

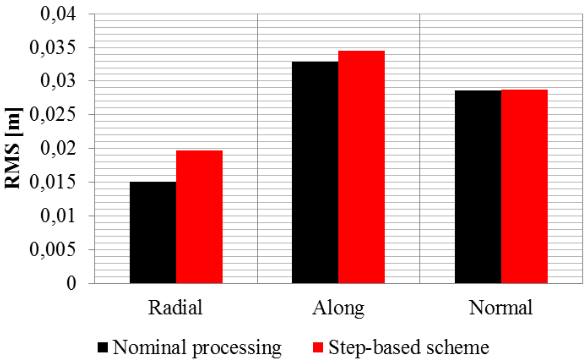

Figure 12: Quality of the GPS products obtained using the step-based scheme.

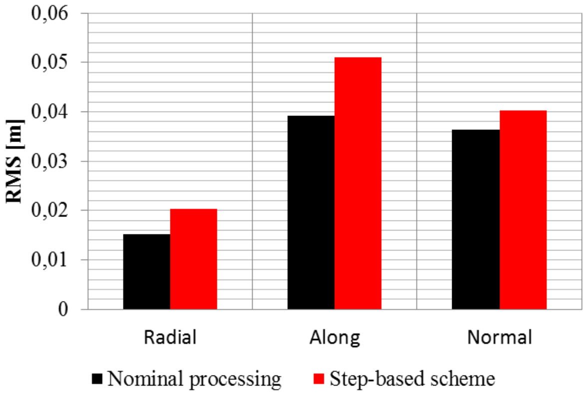

Figure 13: Quality of the GLONASS products obtained using the step-based scheme.

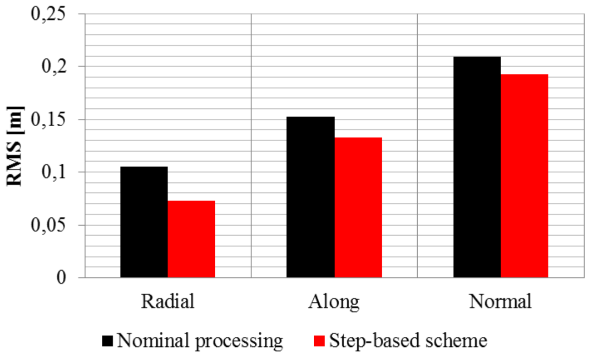

Figure 14: Quality of the Galileo products obtained using the step-based scheme.

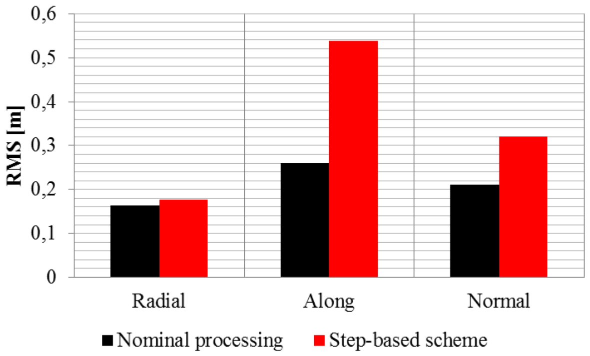

Figure 15: Quality of the BeiDou products obtained using the step-based scheme.

Table 2: Summary of *magicGNSS'* step-based scheme orbits quality

Constellation	Nominal processing	Step-based scheme
GPS	2,5 cm	2,8 cm
GLONASS	3 cm	4 cm
GALILEO	15 cm	14 cm
BEIDOU	20 cm	37 cm

REAL-TIME MULTI-GNSS PRODUCT GENERATION

The multi-GNSS products generation in real-time mode is based on the algorithms already described in the previous section. However, an additional effort has to be undertaken in order to overcome the inherent difficulties introduced by the real time environment given that High Accuracy products must be provided on a Real Time basis. Measurements are received and processed in real time and the ODTS processing time is now an important limitation.

Dual-frequency code-phase and carrier-phase measurements are retrieved in real time from the worldwide station network as the one shown in Figure 16, via Networked Transport of RTCM via Internet Protocol (NTRIP).

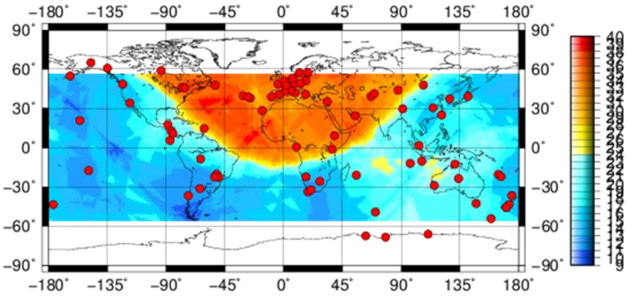

Figure 16: *magicGNSS'* Real-time GNSS network

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

This standard makes *magicGNSS'* real-time infrastructure (both High Accuracy (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 products 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, BeiDou and QZSS, it does only define SSR messages for GPS and GLONASS. In order to temporarily solve this problem and allow the generation of multi GNSS corrections, a proprietary message format has been defined prior to the establishment of the RTCM standard definition. The PPP performances obtained with the multi-GNSS corrections will be analyzed in the following sections.

MULTI-GNSS POST-PROCESSING PPP SCHEME

The PPP algorithm implemented in *magicGNSS* is a position location process which performs precise position determination using iono-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. The quality of the reference orbits and clocks used in PPP is critical, as it is one of the main error sources of the positioning solution. Apart from observations and precise reference products, PPP algorithm also needs several additional corrections which mitigate systematic effects which lead to centimetre 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.

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.

magicGNSS' PPP algorithm implementation has been modified in the same way as in *magicGNSS'* ODTS in order to process all the available GNSS constellations (GPS, GLONASS, Galileo, BeiDou and QZSS). Measurements from all GNSS constellation are now preprocessed by a pre-processing and validation module and then used together with the precise multi-GNSS Orbits and Clocks products to estimate the position of the GNSS receiver.

magicGNSS generates the precise products to be used as input for computing a multi-GNSS PPP solution. As mentioned before, *magicGNSS'* ODTS module is in charge of generating daily rapid multi-GNSS precise products with a 30s clock sampling using data from the MGEX network (60 stations). Having available precise products with a high sampling rate gives the advantage of being able to process 1s or 30s RINEX files for the computation of a PPP solution without adding noise to the process due to the clock interpolation.

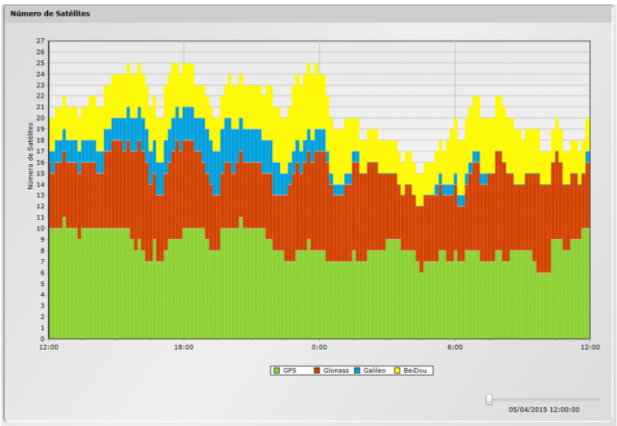

Figure 17: Different constellations availability for JFNG station on 2015/04/05 at 12:00 [3]

The multi-GNSS PPP implementation in *magicGNSS* allows the user to have more satellites available for its positioning computations. This is useful when trying to estimate a position under low visibility scenarios, or when having a lot of satellites in eclipse that could be degrading the solution.

magicGNSS implements two PPP algorithms :

- 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.
- Other implementations feature a **batch algorithm** instead, and, therefore, no process noise has to be modelled. In this case, the receiver clock offset is estimated at every measurement epoch, the coordinates are adjusted for the entire observation interval (**static mode**) or per epoch (**kinematic mode**), the tropospheric delay is estimated at regular fixed intervals and the phase ambiguities are also estimated per pass.

magicGNSS' post-processing PPP SW is able to run in both modes: sequential and batch (static and kinematic), although only batch processing is available through the webpage. Meanwhile, *magicGNSS'* Real-Time PPP SW does only implement the sequential filter, inherent to real time processing. For the different PPP solutions presented within this paper, the batch PPP has been used to assess the post-processing performances and the sequential PPP has been used to simulate the Real-Time conditions.

In order to show the capabilities of the post-processing multi-GNSS PPP provided by *magicGNSS*, the following scenario has been defined:

- JFNG station has been selected as user receiver, given that it gathers observations for all the considered constellations.
- The precise multi-GNSS products used as input are those generated by *magicGNSS* on an operational routine bases.
- The selected period covers from 2015/04/06 22:00 to 2015/04/07 01:00.
- The reference position comes from a *magicGNSS* PPP batch execution using IGS products.

Different PPP executions have been performed changing the selected constellations and then the solutions have been compared against the reference position. The results are shown in Figure 18. The analysis of these results shows that the more constellations included in the process, the better the post-processing positioning performances can be achieved.

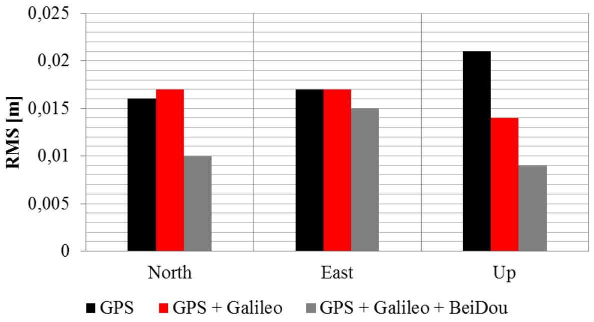

Figure 18: Performances of the *magicGNSS* post-processing PPP

REAL-TIME MULTI-GNSS PPP CLIENT

A PPP client has been developed as part of the *magicGNSS* suite, which is able to compute an accurate user position in a real-time basis. Figure 19 shows the high-level architecture of the real-time PPP client. GMV has been deeply tested this client throughout the past years, both in static and kinematic environments.

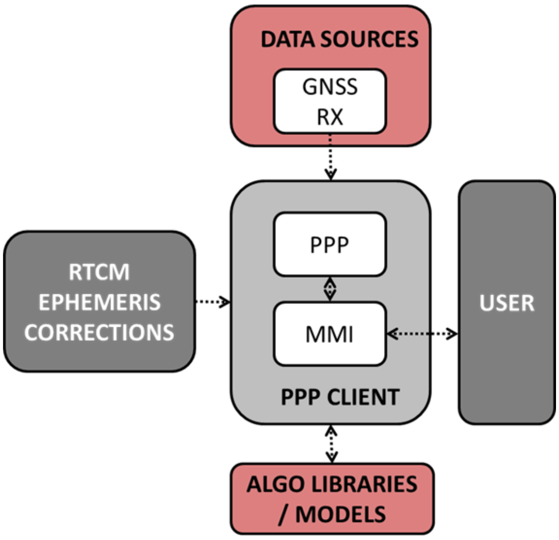

Figure 19: Overview of the *magicGNSS'* PPP client.

Several reference stations are being permanently monitored by means of several instances of the real-time PPP client. Figure 20 shows the typical PPP positioning error (with respect to the previously calibrated position) over a 24-hour period for one of the monitored stations, in order to assess the quality of *magicGNSS'* real time (RT) reference products. The statistical horizontal position error is below 10 cm and the vertical position error is below 15 cm during 95% of the time over the first quarter of 2015.

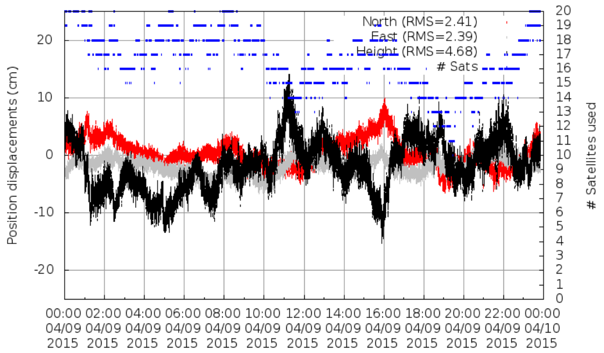

Figure 20: Quality of the *magicGNSS* RT PPP

Dozens of dynamic tests have also been performed for testing the real-time PPP performances under very different situations: open sky; trees, nearby buildings or other obstacles; and several connection dropouts [4]. For these tests, a GNSS rover receiver has been placed on the roof of a car and different driving routes going not further than 15 km from a base station have been considered. It is important to stay closer to a RTK base station so that reference trajectories can be generated with RTK (although RTK sometimes has performance issues at this distance).

Convergence time is one of the major issues affecting real-time PPP users. The PPP solution takes typically not less than 20 minutes to reach 10-cm horizontal accuracy (RMS), due to the time needed to properly estimate parameters such as the tropospheric delay and the phase ambiguities. While this might not be considered a showstopper for many applications, at least for the start of operations, a 20-min or more re-convergence time after a total loss of satellites is a major issue for its use in the field.

The results obtained for the post-processing *magicGNSS* PPP, although promising regarding the future multi-GNSS positioning performances did not prove the feasibility of a real-time multi-GNSS 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 multi-GNSS PPP, *magicGNSS'* PPP was run in sequential mode.

Table 3: Configuration of the RT instances

RT instance	Constellations (Number of satellites in view)
1	GPS (10)
2	GPS (10) and Galileo (4)
3	GPS (10) and BeiDou (4)
4	GPS (10), Galileo (4) and BeiDou (4)

In order to assess the RT PPP performance on a multi-GNSS environment, 4 instances of the RT PPP Client for the same reference station, JFNG, have been run in parallel for a period of time of 1 hour. The instances have been started at a time when the visibility conditions of the different constellations were advantageous. The characteristics of the different configurations are described in Table 3. Note that GLONASS constellation has not been included in the processing. This has been done in order to emphasize the effect of including Galileo and BeiDou constellations.

The results of the positioning solutions of the different RT instances have been included in the Figure 21. The numeric RMS values at different timestamps have been included in Table 4, where G stands for GPS, E stands for Galileo and C stands for BeiDou for an easier analysis of the results.

Table 4: RMS of the different RT PP solutions (different timestamps).

Timestamp [mins]	RMS [cm]			
	G	G+E	G+C	G+E+C
5	0.69	0.32	0.46	0.26
10	0.40	0.22	0.23	0.14
15	0.28	0.17	0.18	0.10
30	0.12	0.09	0.07	0.09
45	0.09	0.06	0.06	0.08
60	0.03	0.05	0.02	0.04

First, from the inspection of the convergence time of the different solutions, it can be observed that adding Galileo or BeiDou satellites improves the performances. An even more significant improvement is achieved when the three constellations are processed together. On the other hand, it can also be seen that, once the convergence has been achieved, the performances of the different RT PPP solutions are very similar.

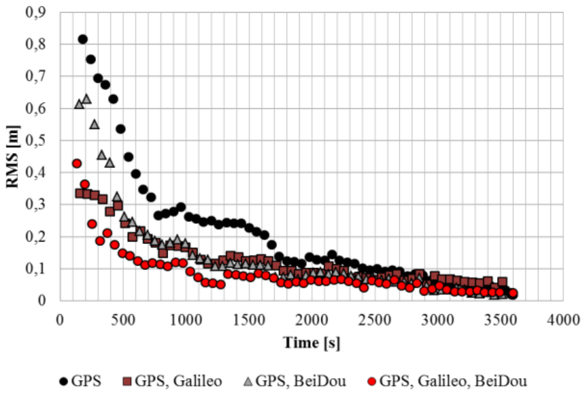

Figure 21: Performances of the multi-GNSS RT PPP Client

SINGLE FREQUENCY PPP AND MAGICPPP MOBILE APPLICATION

As part of the evolutions of *magicGNSS*, an ambitious plan to migrate the real-time *magicPPP* algorithms to a common mobile platform has been carried out.

The feasibility of executing the PPP algorithms in a mobile device was carefully evaluated previous to launching the migration process. Several metrics such as the necessary processing and memory resources, the battery consumption and the available interfaces to communicate with potential receivers were analyzed, the outcomes of these analyses confirmed that the resources available in the current mid-range smartphones supports the necessary workload of our PPP algorithm.

The migration activities started with the development of an application for Android OS. The main reason for choosing Android was the high flexibility and low restrictions offered by this OS to application developers.

magicPPP App is now a reality and it aims to become a reference point for a new generation of GNSS applications and services. In order to achieve this goal, *magicPPP* completes its portfolio of capabilities by adding two novel characteristics, single-frequency PPP processing and an integrity isotropy protection level (IBPL) solution. This new *magicPPP* version, together with an external receiver and a stream of accurate satellite products, provides an integrated PPP solution able to join in one single mobile application the algorithms needed by advance GNSS users, and also make available the GNSS high-accuracy and integrity technology to a new market segment that cannot afford the cost of acquiring multiple high-end multi-frequency receivers. Snapshots of the Android PPP Application are shown in Figure 22.

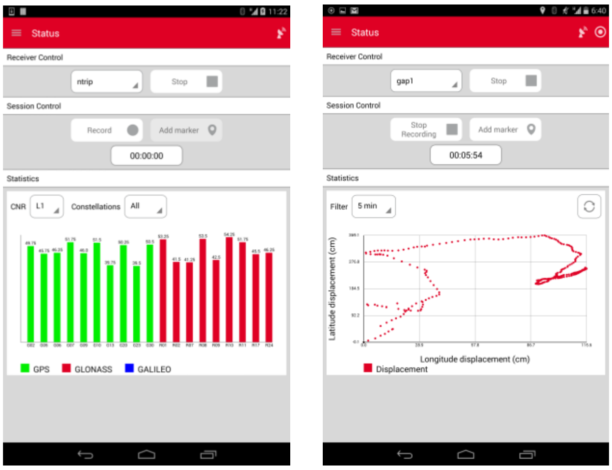
ntrip
00:00:00
CNR L1
Constellations All
gap1
00:05:54
Filter 5 min

Figure 22: magicPPP Android application screenshots.

Single-frequency PPP data processing with integrity assurance capabilities implemented in *magicPPP* represent the cornerstone where a new GNSS concept will be sustained, Low Cost Precise Point Positioning.

Supporting single-frequency receivers means extending *magicPPP* solution to a huge range of low cost devices, which can now navigate with decimeter-level accuracy. Figure 23 and Figure 24 show the performance obtained by the PPP algorithm both in single-frequency and dual-frequency modes for the same period. The results obtained by the single-frequency PPP show the suitability of the algorithm for its use in multiple end-user applications with decametric accurate requirements.

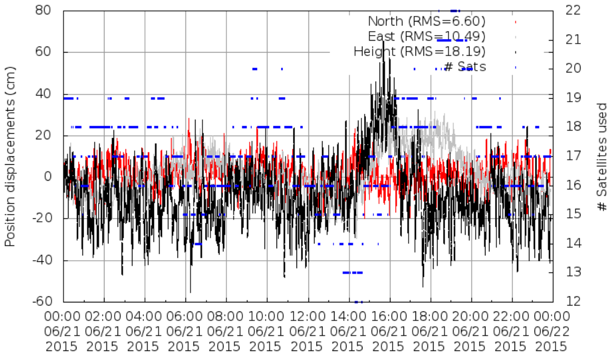

Figure 23: Single frequency RT PPP performance

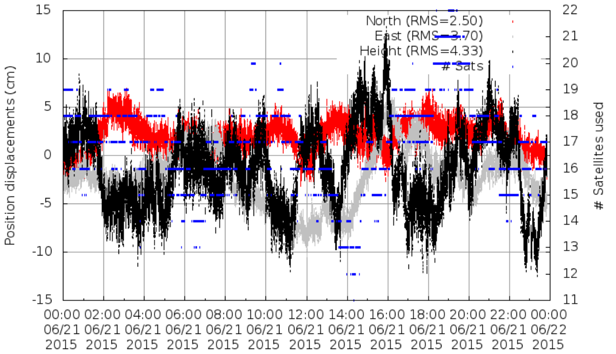

Figure 24: Dual frequency RT PPP performance

CONCLUSIONS AND FUTURE WORK

The upcoming GNSS constellations, along with the signals, modulations and frequency have opened the possibility of providing more accurate positioning solutions and at the same time rise new challenges that had had to be faced.

Algorithmic improvements, both at software and operational level, have been carried out in order to allow the processing of a multi-GNSS scenario. An innovative approach, the step-based scheme, has been proposed. It allows the processing of a multi-GNSS scenario with a reduced computational time and being robust to the addition of new constellations.

The performances of the GMV's *magicGNSS* suit under a multi-GNSS scenario have been assessed. It has been shown that the obtained products are comparable to those obtained by the different Analysis Centers. In addition, the advantages of using a multi-GNSS scenario in the PPP performance have also been set.

GMV has embraced RTCM as the standard to be used within their multi-GNSS infrastructure in order to allow interoperability with third party solutions that are aligned with the RTCM standard. The relevance of taking this approach has also been described.

The undergoing activities for *magicPPP* migration to Android OS, together with the single-frequency PPP improvements are meant to be one of the key challenges in the upcoming months, while further improving the quality of *magicGNSS'* multi-GNSS products.

ACKNOWLEDGMENTS

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