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# Multisystem Real Time Precise-Point-Positioning, today with GPS+GLONASS in the near future also with QZSS, Galileo, Compass, IRNSS

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## Abstract

This paper presents a platform for real-time multi-constellation Precise Point Positioning (PPP), and the PPP performances obtained with a combined GPS+GLONASS solution. The on-going work towards a real-time precise kinematic positioning solution will be also outlined. In addition, the results of some simulations to evaluate the improvements that can be achieved by adding additional measurements coming from QZSS, Compass, Galileo and IRNSS will be shown.

## Key words

Precise Point Positioning, GNSS, Real-Time, Multi-constellation

## 1. Introduction

Nowadays, a growing number of GNSS users demand highly-accurate positioning with minimal latency. PPP is a relatively new positioning technique providing centimeter-level error. PPP processes measurements from a single user receiver, using detailed physical models and corrections, and precise GNSS orbit and clock products. PPP differs from other precise-positioning approaches like Real Time Kinematic (RTK) in that no reference stations are needed in the vicinity of the user. Another advantage is that since the GNSS orbit and clock products are by nature global, the PPP solutions are also global. However, it should be noted that it is possible to set up a regional PPP service using a regional network of tracking stations to generate the GNSS orbit and clock products. In this case, the PPP performances will be only achieved at locations within the area of service. One disadvantage, though, is its slow convergence time, in comparison to nearly instantaneous convergence in dual-frequency short-baseline RTK.

Nevertheless, the use of combined GLONASS and GPS measurements leads to significantly better results when the observation time is short. This represents a very interesting option today, as the GLONASS constellation is currently being enlarged. The Russian government intends to bring the GLONASS System to fully deployed status by 2011. For the GNSS user, this means that up to 18 GPS+GLONASS satellites can be simultaneously visible in open-sky areas, which represents an increase of around 60% in satellite availability compared to the GPS-only scenario. This will lead to higher accuracy and faster convergence in precise positioning applications.

In the near future, even more measurements from additional systems will become available. Signals from the QZSS or from the Galileo In-Orbit Validation (IOV) satellites are expected in the next months, and Compass or IRNSS may be coming soon as well.

## 2. Overview of a PPP algorithm

The PPP algorithm uses as input code and phase observations from a dual-frequency receiver, and precise satellite orbits and clocks, in order to calculate precise receiver coordinates and clock. The dual frequency observables are used undifferenced, and combined into the so-called *ionosphere-free combination*. The highlights of the algorithm are described next.

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

$\lambda$ is the carrier combination wavelength

$N$ is the ambiguity of the carrier-phase ionosphere-free combination (it is not an integer number)

$\varepsilon_P$ and $\varepsilon_\phi$ are the measurement noise components, including multipath and other effects

$\rho$ 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 filter that solves for the different unknowns, namely the receiver coordinates, the receiver clock, the zenith tropospheric delay and the phase ambiguities.

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 modeled. In this case, the receiver clock offset is estimated at every measurement epoch, the coordinates are adjusted for all the observation interval (static mode) or per epoch ( kinematic mode), the troposphere is estimated at regular fixed intervals and the ambiguities are also estimated per pass.

The slant tropospheric delay Tr is expressed as a function of the zenith delay (which is the parameter that is actually estimated in PPP) through the use of a mapping function. The precise modeling of Earth dynamics (causing variations of the static receiver coordinates with respect to the terrestrial reference frame) is normally based on the IERS (International Earth Rotation and Reference Systems Service) recommendations. Such models can include solid Earth tides, ocean loading and Earth Rotation. The modeling of the observables includes for instance the offset between the antenna phase center and the satellite center of mass, and the so-called phase wind-up at the receiver.

The accuracy of the satellite clocks and orbits is one of the most important factors affecting the quality of the PPP. Normally, the IGS (International GNSS Service) [1] products are used due to their high accuracy; however the IGS does not currently provide GLONASS clocks. Furthermore, IGS products have a latency of several hours, which makes them not valid for real-time PPP. Another relevant factor that affects the PPP performances is the amount (number of satellites in view at each epoch) and quality (noise, multipath) of the observations. For instance, more satellites in view improve the observability of the zenith tropospheric delay. Therefore, a possible way to increase the reliability of this technique is to process GPS and GLONASS observations together.

Given that PPP is not a differential technique, it cannot resolve carrier phase ambiguities and they need to be estimated with the aid of the code measurements. This fact makes the convergence period longer than in other techniques (RTK, for instance), thus requiring longer observation times for static positioning.

## 3. Reference Products for GPS+GLONASS Real Time PPP

As mentioned before, the positioning performances of the PPP technique are directly related to the accuracy of the reference GNSS orbit and clock products. Therefore, the generation of precise satellite orbits and clocks in real time becomes a major challenge for enabling a real time positioning service.

GMV has developed an infrastructure for the generation of precise GPS and GLONASS orbits and clocks with very low latency in a first step, and in real time in a second step. The products generated this way are contributed to the IGS Real Time Pilot Project, and are also used to feed GMV's PPP service, part of the web application magicGNSS [2].

The product generation is based on an Orbit Determination and Time Synchronisation (ODTS) process, which runs typically every 15 minutes. This process receives as input dual-frequency code and phase measurements collected in real time from a world-wide network of IGS stations, using the NTRIP protocol. Then, they are pre-processed also in real time by a Pre-Processing and Validation module (PPV) and made available to the different algorithms. The high-level layout of the infrastructure is shown in Fig. 1.

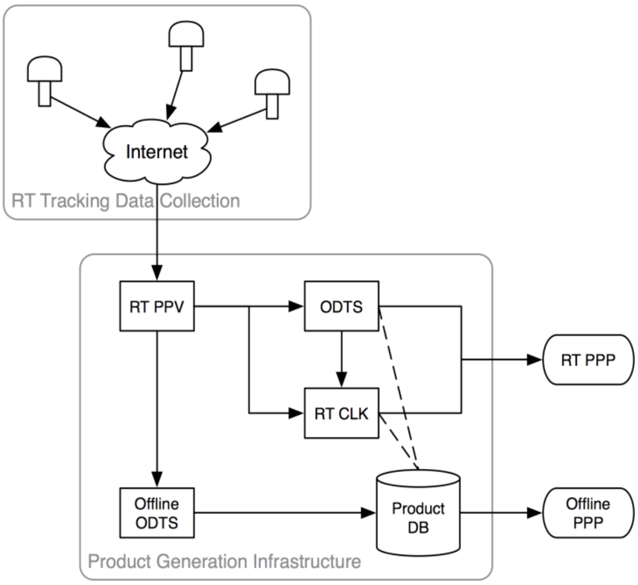

Fig. 1: Product Generation Infrastructure Layout

The network, which is represented in Fig. 2, provides global coverage and some redundancy to cover the relatively frequent (especially from some stations) outages of the real-time data streams. The color in the figure represents the number of stations that are tracking a satellite when it is flying over a certain point. The red circles show the station positions.

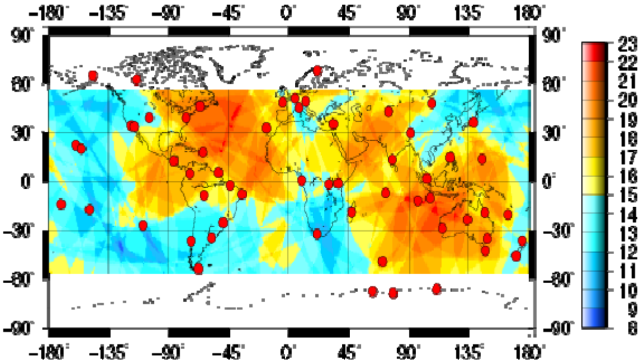

Fig. 2: Tracking Station Network

The ODTS processes 2-days of data in every run, 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 estimates the clocks in real time taking as input the observations and the outputs from the last ODTS execution. There is a small latency in the delivery of the clock estimation, 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.

The GPS and GLONASS satellites 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 estimation 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.

The real-time orbits and clocks are available as a data stream to real-time processing algorithms (such as real-time PPP), and stored in standard formats (SP3, clock RINEX) for offline use.

The quality of the products is monitored by performing comparisons of the overlapping solutions, and by calculating at regular intervals a PPP solution of five control stations of known coordinates. When the quality of the most recent solution is considered insufficient, a prediction from the previous one is used instead, until a new valid solution is available. In addition, the products are also compared to the IGS solutions when they are available.

The comparison of real-time solutions with the IGS Rapid products is shown in Fig. 3. The typical value for orbits (3D RMS for all satellites, read on the left y-scale) is around 6cm, and for clocks (read on the right y-scale) it is around 0.3 ns.

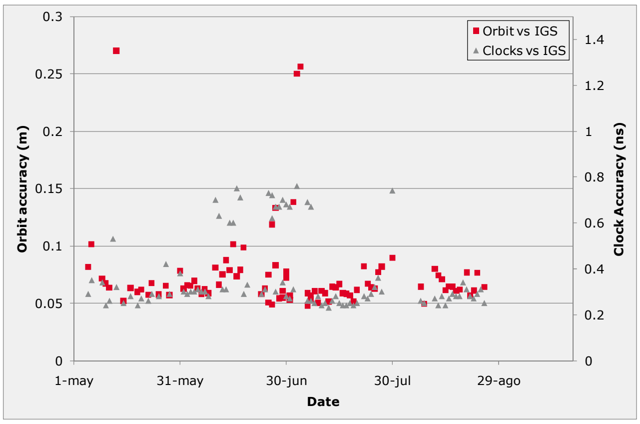

Fig. 3: Performances of Real Time GPS Products

As it is also represented in Fig. 1, there is also another ODTS process running in off-line post-processing mode with a latency of 2 days and specific setup, which allows the generation of more precise products. When available, such products are then used for off-line PPP in replacement of the ones generated previously in real time. The comparison of the off-line products with the IGS for a typical day is show in Fig. 4. In this case the typical orbit performances are better than 3cm, and clock accuracy is around 0.1ns.

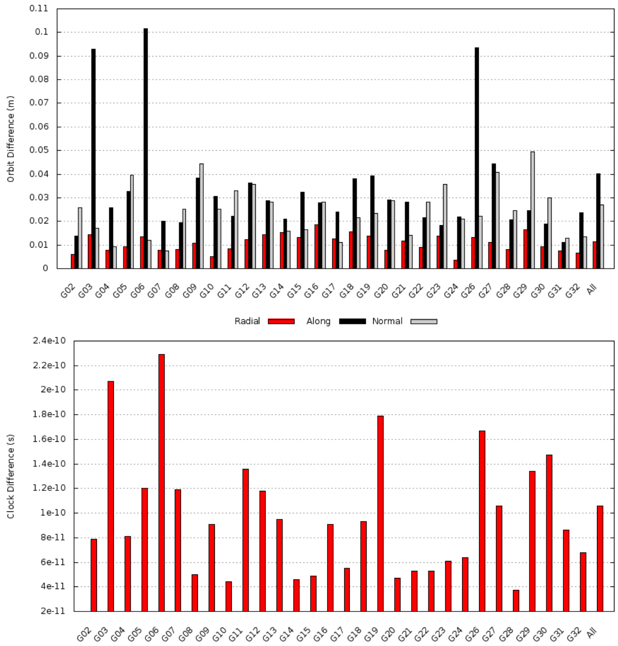

Fig. 4: Example performances of off-line GPS Products

The performances of the GLONASS products are shown in Fig. 5. Orbit performances (again, 3D RMS for all satellites) are given in terms of overlaps (available after each ODTS) and comparisons with IGS orbits (available with 2-week delay for GLONASS), and read in the left y-scale. The typical value is below 5 cm. Clock performances are given in terms of overlaps only, since the IGS does not currently publish GLONASS clocks. The typical value ranges between 0.1 and 1 ns, and varies notably from day to day. The reason is the estimation of the inter-channel biases, which are correlated with the clocks and therefore make the estimations less stable. However, there is no impact on positioning performances as every solution is always consistent.

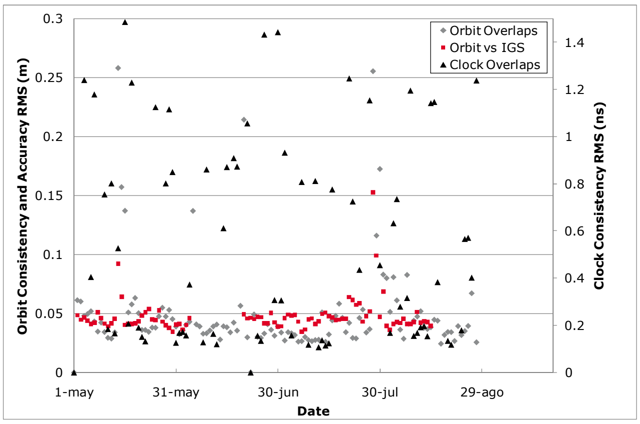

Fig. 5: Performances of GLONASS Products

## 4. Performances of GPS+GLONASS PPP

Fig. 6 presents the positioning performances of PPP at several IGS stations of known coordinates, when the observation time is 1 day. It can be seen that the accuracy of the PPP solution (vs. the coordinates published by the IGS) is around 1 cm, both for GPS and GPS+GLONASS. This test 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.

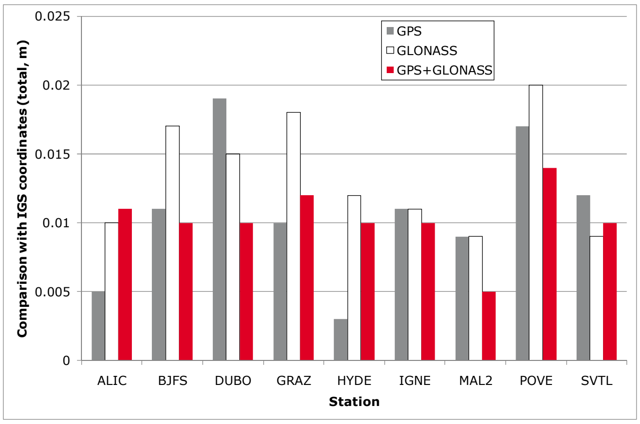

Fig. 6: Static PPP Performances (24-hours)

An observation time of 24 hours is adequate for a high accuracy post-processing solution, but is not very suited to field measurement, where shorter measurement intervals would be more practical. Fig. 7 shows the performances of Static PPP of one IGS station selected as test user (GLSV), for different observation times ranging from 1 to 24 hours. The results for GPS-only and GPS+GLONASS are shown together for comparison. It can be clearly seen that there is a benefit from longer observation time with a significant improvement after 3 hours. For 1-hour observation time, there is also a significant improvement coming from the multisystem configuration.

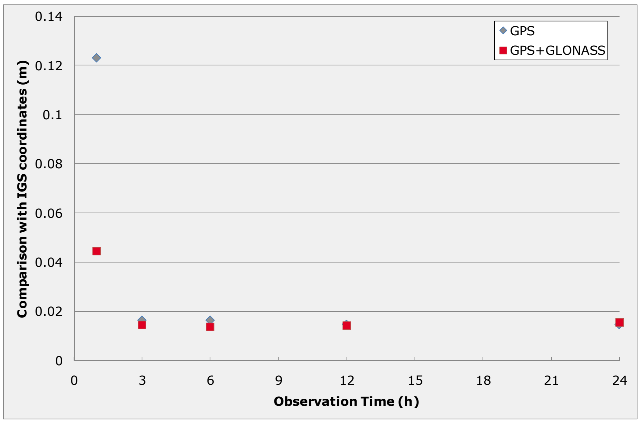

Fig. 7: Static PPP Performances at GLSV

In the following example, PPP with 1-hour observation time performances are presented for the test station GLSV, considering the 1-hour observation intervals starting at different times of the same day. It can be seen that when the observation time is short, GPS+GLONASS improves significantly the repeatability of the results, thus providing more stable results along time.

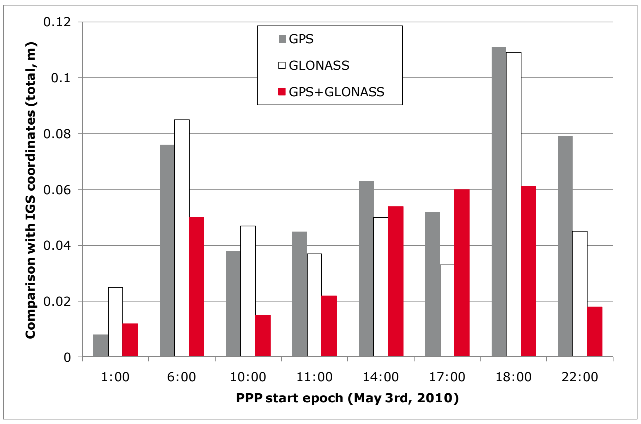

Fig. 8: Repeatability of 1-hour PPP solutions at GLSV

The previous results present multi-system PPP as an interesting option for precise positioning, since sub-dm accuracy (sometimes much better) can be reached with one hour observation time. The latency with which the solution can be obtained depends only on the latency of the reference products. Real-time generation of products implies that the solution is available immediately after the collection of the measurements (the PPP processing time is almost negligible).

The main application of real-time PPP, however, is kinematic positioning. A kinematic version of **magicGNSS'** PPP algorithm is under development. The initial version, already available, supports only off-line processing. A real-time version is planned for the coming months.

In order to evaluate the performances, a receiver was installed on the roof of a van, and data were recorded during a 30-min drive in the countryside near GMV premises, illustrated in Fig. 9.

Fig. 9: Test route for kinematic PPP

The data (GPS only in this case) were then processed off-line with the new kinematic PPP and compared with a reference trajectory. This reference path was calculated with RTK, using a reference station installed at GMV premises (a few km away). The difference between the solutions versus time (over the 30-min drive) is shown in Fig. 10.

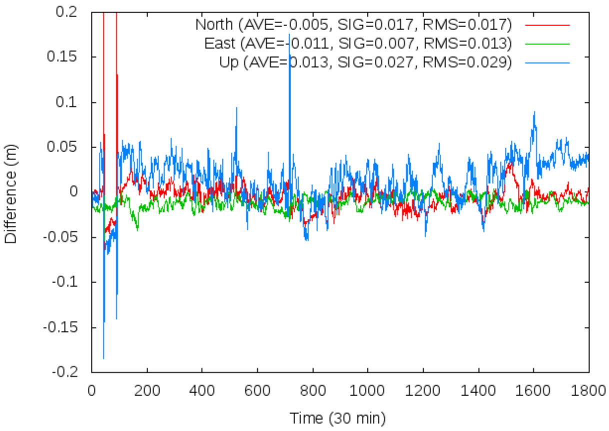

Fig. 10: Kinematic PPP vs RTK solutions

The results match up to a few cm. Additional tests in more challenging visibility conditions and with other type of users (e.g. flight trajectories) are currently on-going, with very promising results as well. It is expected that the addition of GLONASS will improve the performances in more challenging visibility conditions.

## 5. Regional service

In the previous sections the PPP has been defined as a global service, considering that the orbit and clock products are themselves global. This is true as long as the tracking stations used for the computation of the products are distributed worldwide. In this case, there is good visibility of the satellites along all their orbits, and the accuracy of the orbit and clock estimations does not depend on the location.

It is possible, however, to use a regional network of tracking station for the ODTS. In this case, the accuracy of the orbits and clocks is degraded but this degradation occurs mainly outside the area where the stations are deployed. Inside this region, the combination of orbit and clock products is such that the positioning performances are good. Indeed, with a sufficient number of stations inside a region (typically comprising several countries), it is possible to achieve positioning performances at the same level as with a global network. This opens very interesting possibilities to regions already operating networks of GNSS receivers (e.g. for RTK), as they can deploy a PPP service using their own resources. Such service could complement RTK for areas far away from any of the base stations.

In order to demonstrate this concept, a test has been made using data from the EGNOS stations (Fig. 11) for the generation of reference products.

Fig. 11: EGNOS station network

The products generated with regional data have then been used to perform static PPP on several test stations across Europe. The obtained coordinates are then compared with the coordinates calculated using IGS products, which are global. As it can be seen in Fig. 12, the positions agree to the cm level (and one order of magnitude better for the horizontal component).

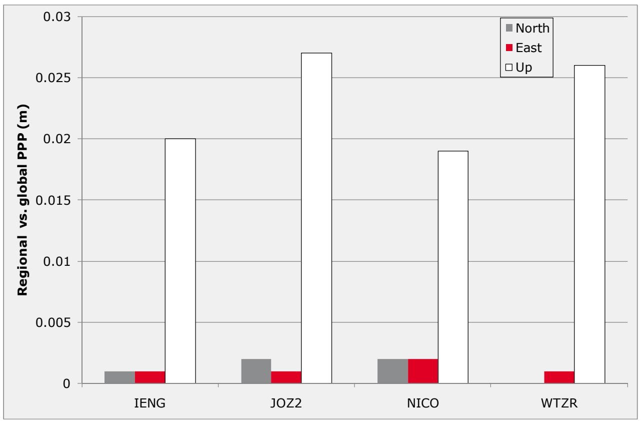

Fig. 12: Comparison between regional and global PPP

## 6. Multisystem PPP. Future Perspectives

Previous sections describe the PPP results obtained with real data using existing constellations, namely GPS and GLONASS. The obtained show the benefits of using more than one constellation; these benefits consist mainly of better accuracy, shorter converge times and more robustness, especially for shorter time intervals. Several regional or global navigation systems are currently under development, QZSS, IRNSS, Compass, Galileo, etc. This section will analyse the improvements that could be expected when those systems enter into operation and more satellites could be used for performing PPP solutions.

To evaluate the performances that can be achieved by considering additional constellations a simulation tool has been developed. This simulation tool reproduces with a high level of detail the PPP algorithms and conditions. To validate this tool simulated PPP solutions using GPS and GLONASS have been compared with PPP solutions obtained using real data. The coherence of the obtained results gives confidence on the simulation tool used. Note that the PPP simulation tool has been calibrated to be consistent with the current static version of the **magicGNSS**' PPP algorithm, and thus the results presented in this section will probably need to be updated when the kinematic version development is completed.

Several simulated scenarios have been created for analyzing the use of multi-constellations applied to PPP: combinations with QZSS at one location in Japan (138.1º E, 35.6º N), IRSS at one location in India (77.5º E, 19.3º N), and the full Galileo constellation in Europe (2.3º W, 41.6º N). The results, presented below, show that using more than one constellation helps improving the PPP convergence time, especially for short observation periods (mainly because the troposphere is less observable in this case). The results obtained with Galileo, are believed to be equivalent to those potentially attainable with Compass over China.

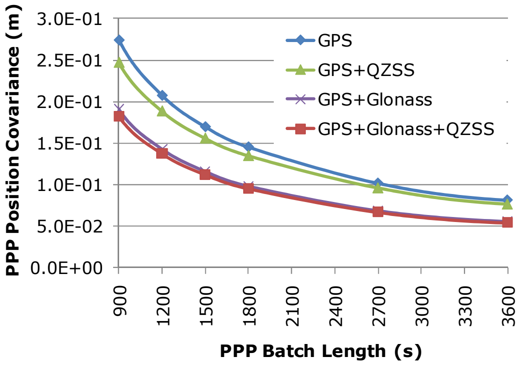

Fig. 13: Multisystem Simulated PPP over Japan

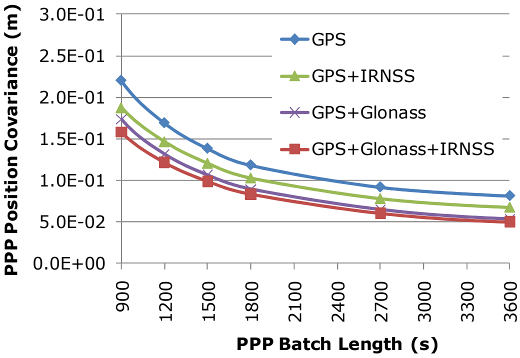

Fig. 14: Multisystem Simulated PPP over India

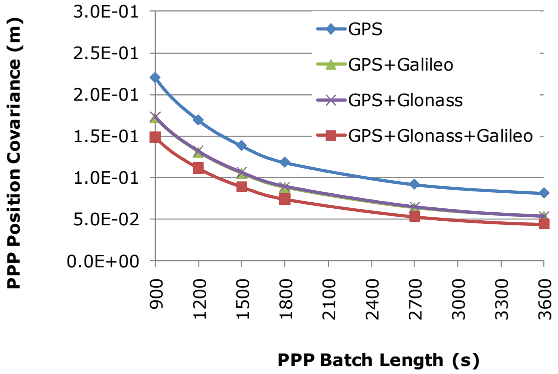

Fig. 15: Multisystem Simulated PPP over Europe

## 7. Conclusions

PPP is becoming an alternative for precise positioning even in real time applications. A significant improvement is expected in the coming years as new navigation systems will become available.

GMV has already developed a PPP infrastructure that can be used and installed in any region of the world. It is compatible with existing RTK networks and it can use the existing RTK stations allowing increasing the service area. It is also compatible with standard dual frequency geodetic receivers.

The developed PPP infrastructure provides about the same accuracy as current RTK systems, both for static and dynamic users, but requires significantly less stations, reducing consequently the deployment and maintenance costs. It can work with a regional network of stations, with no need for a global network of stations as other PPP solutions. In addition to that, it provides a lot of flexibility for selecting the location of the stations facilitating the possibility of doing precise positioning in remote areas, such as mountainous areas, deserts, oceans, etc.

One of the main advantages of PPP with respect to RTK is that PPP allows providing added value services on top of precise positioning, such as integrity, clock synchronization, atmospheric monitoring, etc. The main limitations are associated with the convergence time and with the robustness in difficult environments. Current results are very promising and we are working to improve the current PPP solutions.

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