PUSHING THE LIMITS OF LOW-COST PPP WITH REAL-TIME IONOSPHERIC CORRECTIONS

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ABSTRACT

One of the major drawbacks of Precise Point Positioning (PPP), and one of the main reasons that prevents it from jumping into the mass-market user segments is the high cost of the hardware typically used for this type of positioning solution, i.e. the need to use a high-grade geodetic receiver. The intention of GMV is to foster cost-saving by opening the possibility of providing users with a high-end PPP algorithm able to work with a low cost receiver. For this purpose, GMV has recently developed cutting-edge algorithms in a twofold frame. On the one hand *magicPPP* –GMV's real-time PPP algorithm at user level– has been enhanced and refined in order to cope with the difficulties of low-cost measurements processing. On the other hand, an innovative algorithm at server level has been developed fully in-house, which is capable of performing a high-quality prediction of the ionospheric delays making use of regional estimation techniques applied under a global correction provision philosophy.

Throughout this paper *magicFAST*, GMV's concept of Low-Cost PPP based on the Single Frequency PPP techniques using ionospheric corrections is introduced. In addition, in this paper the results of the experimentation campaign will be presented, including a detailed description of the achievable performances in different user scenarios.

INTRODUCTION

Precise Point Positioning (PPP) has traditionally played an important role in applications related to surveying. These applications rely on high-performance geodetic receivers capable of delivering stable, precise and smooth code and phase measurements. In addition, high-grade receivers provide multi-frequency measurements, which can be combined to produce ionosphere-free observables to be processed by the PPP algorithm.

Nevertheless, in the recent years low-cost receivers have undergone a massive improvement in terms of measurements quality. Even if these receivers do not currently provide multi-frequency measurements, the improved performance has opened up new opportunities and encouraged GMV to develop a single-frequency PPP algorithm adapted to low-cost receivers.

According to the last GNSS Market Report [1] by the European GNSS Agency (GSA), Location-Based Services (LBS) will suffer an extraordinary growth in the upcoming years. As Fig. 1 yields, in 2020 more than 2 billion units will be shipped every year, and up to more than 2.5 billion units by 2023. The market will be dominated by GNSS smartphone chipsets, but Personal Navigation Devices (PNBs) will be outnumbered by In-Vehicle Systems (IVS) applications.

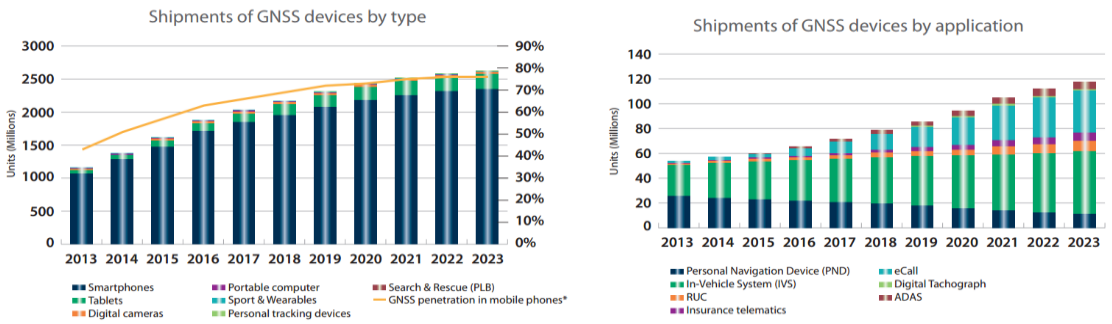

Fig. 1: Forecast of GNSS devices shipments by type (left) and application (right). Extracted from [1]

The market trend clearly shows a niche opportunity for low-cost PPP, especially in the automobile sector for In-Vehicle Systems. In this line, GMV has devoted a substantial effort to develop the algorithms and infrastructure to be able to provide a real-time PPP service with single-frequency low-cost receivers, focusing on the optimization of two performance indicators: Fast Convergence and High Accuracy. High Accuracy is the ability to provide a positioning solution with an error of few centimeters in steady state, while Fast Convergence is the capability to reach High Accuracy in a short period of time after the PPP algorithm is started.

For this purpose, the real-time infrastructure of *magicGNSS* has been upgraded with the new *magicFAST* product. This additional service is able to compute ionospheric delays in real-time and provide them to the user in addition to the satellite orbit and clock corrections furnished by the pre-existing *magicGNSS* real-time infrastructure. In addition, *magicPPP* has also been upgraded in order to add the capability to estimate the ionospheric delays present in single-frequency measurements, and to process the information provided by *magicFAST*. The positioning performances obtained make the new low-cost PPP algorithm suitable for the automobile sector in applications such as lane change detection for Autonomous Driving (AD) and Advanced Driver Assistance Systems (ADAS), as well as many other applications such as Pay-As-You-Drive, thanks to the reduced cost of the hardware required at the user end.

The following paragraphs give a description of the algorithms and infrastructure developed for *magicFAST* at server level, and *magicPPP* at user level. In addition, the experimentation results both in static and kinematic representative scenarios are shown and relevant conclusions drawn.

MAGICFAST AND MAGICGNSS REAL-TIME INFRASTRUCTURE

In the real-time infrastructure of *magicGNSS*, a real-time server generates corrections based on the observations from a worldwide network of stations. The user receives these corrections and applies them to improve the positioning solution provided by *magicPPP* [2]. With the traditional approach, these corrections are only focused on GNSS satellite orbits and clocks. However, the provision of regional corrections has been identified as a major factor for the improvement of PPP performance. Among these regional corrections, the ionospheric corrections are especially important, as they allow higher accuracy in single-frequency and a reduction of noise in dual-frequency solutions. Apart from these improvements, the usage of ionospheric corrections allows a faster estimation of ambiguities and consequently a faster convergence of the PPP algorithm.

The generation of ionospheric corrections in *magicGNSS* infrastructure is done in a separate server, which processes observations from a set of stations to estimate the ionospheric information in the target region. Fig. 2 contains a schema of the *magicGNSS* real-time infrastructure, both for the server and the user side. On the server side, observations from a network of stations are processed to generate corrections, both for satellite orbits and clocks and for ionospheric delays. On the user side, observations from the user receiver and corrections from the server are used to estimate the position of the user.

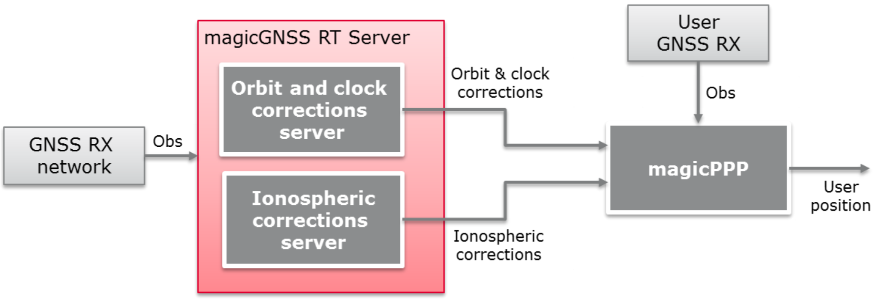

Fig. 2: *magicGNSS* real-time infrastructure

There are therefore two main modules in the *magicGNSS* real-time server, one for the estimation of satellite orbits and clocks and the generation of corrections to the parameters in the navigation message, and the other one for the estimation of ionospheric information and the generation of regional ionospheric corrections. Even if both modules use observations from a network of stations to perform their estimations, they are totally independent. It is possible to use a different number of stations for both modules. Typically, estimation of satellite orbits and clocks requires a smaller set of stations distributed over the whole planet, while the estimation of ionospheric information and regional corrections require more stations mainly placed on the areas where users are located.

Even if the ionospheric corrections depend on the region where the user is located, it is possible to compute corrections with a limited number of stations around this region. As an example, the station network in Fig. 3 would be enough to generate accurate ionospheric corrections for any user located in Southwestern Europe. This capability of working with only a short set of stations dramatically reduces the cost of deployment and eases system monitoring tasks.

Fig. 3: Station network for the generation of ionospheric corrections in Southwestern Europe

This new concept for the generation and provision of ionospheric corrections in *magicGNSS* is the basis of the new product *magicFAST*. It is an important update to the previous configuration of *magicGNSS* real-time environment, which only included corrections for satellite orbits and clocks. This new approach is dramatically improving the performance of PPP solution, both in terms of convergence time and positioning accuracy.

MAGICPPP

During the last years, GMV has been working in the development of a real-time PPP client able to compute an accurate user position on a real-time basis, known as *magicPPP*. This PPP client interacts with the *magicGNSS* real-time infrastructure, according to the schema in Fig. 2. This interaction allows the PPP client to obtain information about satellite orbits and clocks and in the *magicFAST* approach also information about ionospheric delays.

The traditional PPP solution is based on processing iono-free measurements to estimate the precise position of the user, according to (1) and (2), as follows:

$$l_p = \rho + c\left(b_{Rx} - b_{sat}\right) + Tr + HW_p + \varepsilon_p \quad (1)$$

$$l_\phi = \rho + c\left(b_{Rx} - b_{sat}\right) + Tr + HW_\phi + N\lambda + \varepsilon_\phi \quad (2)$$

Where:

- l_P is the ionosphere-free combination of L1 and L2 pseudoranges
- l_ϕ is the ionosphere-free combination of L1 and L2 carrier phases
- b_{Rx} is the receiver clock offset from the reference time
- b_{Sat} is the satellite clock offset from the reference time
- c is the vacuum speed of light
- Tr is the signal path delay due to the troposphere
- HW_p and HW_ϕ are the hardware biases of satellites and stations
- 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.

The observations are processed in a sequential filter, together with the information provided by the servers, to obtain the precise coordinates of the user.

The usage of iono-free combination is a good approach in case of geodetic receivers, which provide low-noise observations for all the available frequencies. However, PPP algorithms are also intended to be used in the case of mass-market receivers. In the latest years, many applications requiring precise positioning in portable devices have appeared, and for these applications the improvement of PPP algorithms with mass-market receivers has become essential. In these cases, the management of ionospheric delays is needed, as most mass-market receivers work with only one frequency. Even those receivers able to work with more than one frequency are noisier than geodetic receivers, and could take advantage of the ionospheric information to reduce this noise.

For a single frequency user, the observations of iono-free combination should be replaced by the observations for the available frequency, according to (3) and (4), as follows:

$$l_{1p} = \rho + c\left(b_{Rx} - b_{sat}\right) + Tr + I + HW_p + \varepsilon_{1p} \quad (3)$$

$$l_{1\phi} = \rho + c\left(b_{Rx} - b_{sat}\right) + Tr - I + HW_\phi + N_1\lambda + \varepsilon_{1\phi} \quad (4)$$

Where:

- l_{1P} is the L1 pseudorange
- $l_{1\phi}$ is the L1 carrier phase
- I is the signal path delay due to the ionosphere
- N_1 is the ambiguity of the carrier-phase L1 observation
- ε_{1P} and $\varepsilon_{1\phi}$ are the measurement noise components for L1

In the case of dual-frequency solution, it is possible to use either iono-free or single-frequency observations. In the second case, the smaller noise of single-frequency observations contributes to reduce the uncertainty in the estimation of position.

The ionospheric delay in (3) and (4) can be obtained from ionospheric models, such as broadcast Klobuchar or NeQuick, or SBAS ionospheric data. However, the accuracy of these models strongly depends on the state of the ionosphere in the area where the user is located. In *magicPPP* it is also possible to estimate the ionospheric delay in the sequential filter, together with the position of the user. In general, the accuracy of this estimation would depend on the quality of the observations, but it can be highly improved if ionospheric corrections from *magicFAST* are applied.

EXPERIMENTATION ACTIVITIES

After the implementation of *magicFAST* both at Server and PPP client levels, a 5-month open-sky experimentation campaign was launched. *magicFAST* was configured to use the station network shown in Fig. 3, which can be considered as a sparse network, with an average density of stations is of 115000 km^2/station. The real-time data for this network of stations has been obtained from the EUREF Permanent Network (EPN) via the EUREF caster hosted by the Royal Observatory of Belgium (ROB) [3].

In addition, the user-side experimentation activities (PPP) have been carried out in the surroundings of GMV's headquarters in Tres Cantos (Madrid). The closest station in the network to the user position is located in Leon, at a distance of 290 km. The experimentation results obtained with this combined set-up are representative of a European service based on a low-density network of stations. Both *magicGNSS* and *magicPPP* were configured to provide corrections and process only GPS+Glonass data, since the availability of observables from the EPN is limited to these constellations.

Static Open-Sky Testing

The static open-sky campaign was mainly focused on the evaluation of the achievable performances in a benign static open-sky scenario using a low multipath choke-ring antenna connected to a low-cost receiver. For the purpose of this campaign, a U-Blox NEO-M8T receiver evaluation kit was connected to an active splitter sharing the Topcon CR-G5 antenna used for GMV's reference station GAP1, located in Tres Cantos (Madrid). The U-Blox receiver was configured to output raw code and carrier-phase measurements, and the RTKlib [4] was used to convert from U-Blox proprietary format to RTCM MSM messages [5], which is the standard interface supported by *magicPPP*. In addition, *magicPPP* was receiving satellite clock and orbit corrections to the navigation message, as well as ionospheric regional corrections computed by the *magicGNSS* real-time server, see Fig. 4.

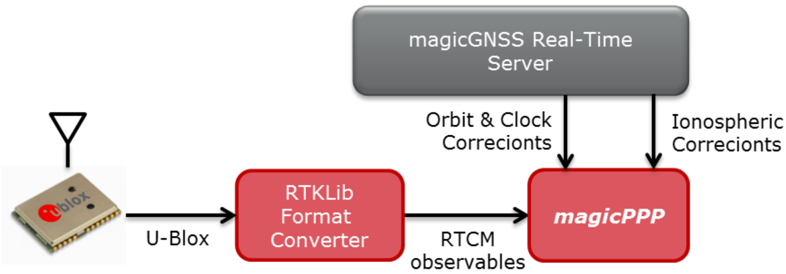

Fig. 4: Static open-sky experimentation set-up

In order to be able to compare *magicFAST* performances to a benchmark solution based on a low-cost receiver, a parallel instance of *magicPPP* was configured to run the PPP solution using ionospheric information from the Klobuchar model broadcast in GPS navigation messages. The algorithmic processing mode and configuration for the benchmark and *magicFAST* solutions were identical; the only difference is the source of ionospheric data. Both solutions were configured to restart the estimation every 15 minutes, what allowed for continuous analysis of convergence time as well as the stability of the solution in the first period of the steady state.

The open-sky experimentation campaign was used as a continuous improvement platform for *magicFAST*. Results of both the benchmark and *magicFAST* PPP solutions were analysed on a daily basis to investigate the behavior of the ionosphere estimation and its effect on the PPP solutions. These investigations were the main inputs for the continuous refinement and fine-tuning of the algorithms both at Server and PPP client level.

Static Open Sky (Choke Ring Antenna) – October 5, 2016

Fig. 5 shows the horizontal positioning convergence of *magicPPP* using *magicFAST* corrections (in red) together with the benchmark scenario using only the Klobuchar model (in black). The horizontal positioning error has been computed using as reference the calibrated position of the antenna used for GMV's reference station.

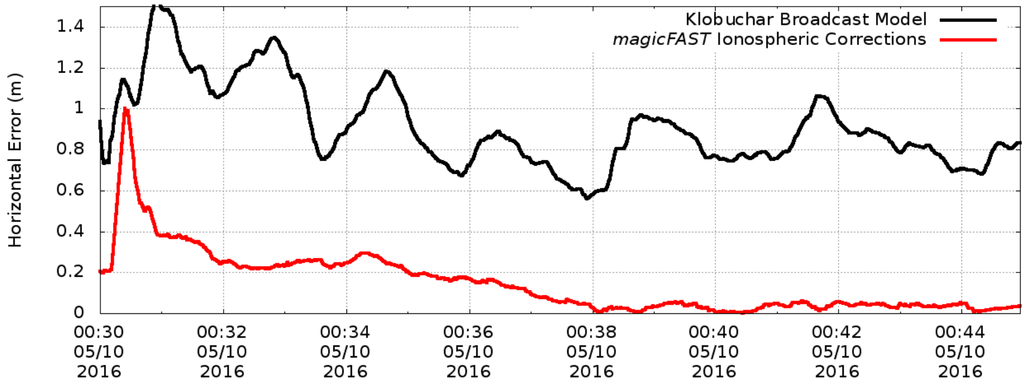

Fig. 5: Static open-sky horizontal positioning error

Results shown in Fig. 5 are a representative example of the performances achievable with *magicFAST*. As this figure yields, the positioning error is below 50cm one minute after the cold start of the PPP algorithm. After 10 minutes, the positioning solution has converged to an error bound by 10cm. Note that this test does not include a cold start of the receiver (i.e. wake-up and acquisition times are excluded), as the purpose is to analyse the performance of the PPP algorithm.

Typical GNSS performances for ITS applications require a positioning error of 30cm in the cross-track direction as a minimum for lane change detection. Current *magicFAST* positioning outperforms this requirement after 2 minutes when the low-cost receiver uses a high-grade geodetic antenna. Results with a low-cost patch antenna are presented in the following sections.

Kinematic Testing

The kinematic testing campaign was carried out in parallel to its Static counterpart. The objective of the campaign was to test the performance of *magicFAST* in realistic road applications. For this purpose, *magicAPK* (GMV's *magicPPP* client for Android devices) was installed on a Samsung Nexus 7 tablet and connected via USB to the U-Blox NEO-M8T low-cost receiver development kit.

The receiver was connected to a low-cost patch antenna located on the testing car. In addition, a Trimble R10 professional rover receiver was located next to the patch antenna, separated by a distance of 40cm in the longitudinal direction of the car. This distance has been chosen from a trade-off between the positioning error introduced by the antenna separation and the multipath and satellite occultation brought in by the R10 receiver onto the patch antenna. Fig. 6 shows the relative disposition of the patch antenna and the R10 receiver on the testing car.

Fig. 6: Kinematic hardware set-up

The reference trajectory has been calculated from the data gathered with the R10 receiver, using the RTK technique provided by RTKlib [4]. For its computation, L1+L2+L5 observables were used in order to reduce the effect of foliage and non-line-of-sight effects. GMV's multi-constellation base station GAP4 was used as reference station, furnished with a Topcon NET-G5 base receiver and a CR-G5 choke ring antenna. Finally, the longitudinal distance between the reference R10 trajectory and the patch antenna is corrected using the estimated velocity. It is important to note that although this technique is accurate for a straight trajectory, the accuracy of the positioning error estimation is affected in turns and bent trajectories.

Kinematic Open Sky (Patch Antenna) – October 4, 2016

The objective of this test was to assess the kinematic positioning capabilities of *magicFAST* in an open-sky scenario, as well as the convergence behavior, using a low-cost antenna. The scenario was recorded in the outskirts of Tres Cantos through a residential area with isolated buildings. The obstruction conditions in this scenario can be considered benign, whereas the multipath effect on the patch antenna cannot be neglected with respect to the open sky scenario with choke-ring antenna. Fig. 7 shows the complete trajectory, together with a close-up of a roundabout where the excellent positioning performance of the low-cost PPP can be observed.

Fig. 7: Kinematic open-sky. Left: Estimated trajectory
Right: Estimated (red dots) vs. Reference trajectory (yellow line), roundabout close-up

The testing car was parked for approximately 5 minutes at the beginning of the test in order to evaluate the static convergence performance. Fig. 8 shows the positioning error throughout the test. During the first minute a sharp convergence occurs as the first ionospheric corrections are received. After 5 minutes, the solution converges to a positioning error below 20cm. Past 10:11 the solution slightly oscillates, and although the solution cannot be considered converged to its best achievable performance –which typically occurs after 10 minutes–, the positioning error outperforms the requirements for road applications in open sky.

After 5 minutes, the kinematic part of the test is conducted at ground speeds in the range of 10-50 km/h. As the vehicle starts moving, multipath correlation decreases leading to an initial improvement in the positioning accuracy. See Fig. 8 from 10:12 to 10:14.

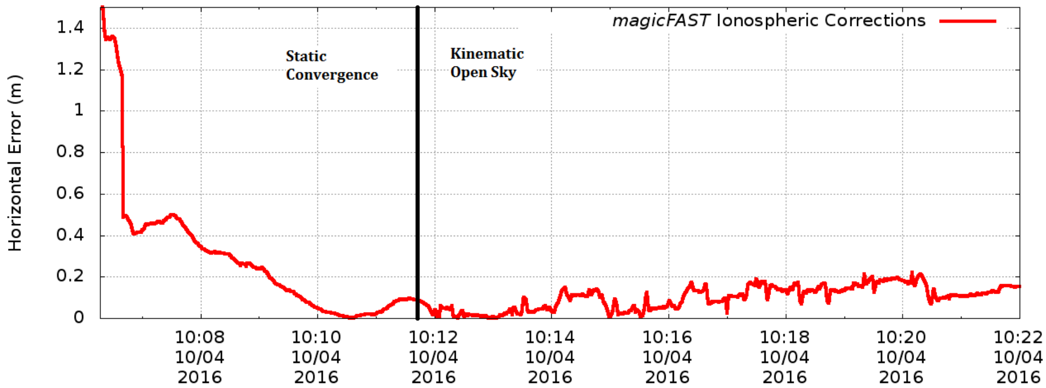

Fig. 8: Kinematic open-sky horizontal positioning error

Since the test was conducted in an expanding area of Tres Cantos, there was a high activity related to the building sector. Although tall buildings were not present, trucks were frequently encountered introducing non-negligible non-line-of-sight effects on the patch antenna, as well as signal obstruction. Positioning error peaks observed in the kinematic part of Fig. 8 are related to these effects, together with the trajectory misalignment between the reference receiver and the patch antenna that is introduced in bent and circular trajectories such as depicted in Fig. 7 (right).

Kinematic Suburban (Patch Antenna) – October 5, 2016

The purpose of this test was to evaluate *magicFAST*'s performances in suburban environments ranging from weak suburban to strong suburban. The estimated trajectory of the test is shown in Fig. 9.

Fig. 9: Kinematic suburban estimated trajectory

The test starts in an open sky area in a residential neighbour near Tres Cantos. However, this time the selected area is in a more advanced stage of urbanization. The environments throughout the test can be split in the following:

1. Weak Suburban: The first part of the test is conducted in an expansion area in a middle stage of urbanization. Tall building blocks up to 8 stories are present in an intermittent manner. The typical building density is of one 8-story building every 4-5 unconstructed land properties at each side of the road.

2. Suburban: The second part of the test is carried out in an industrial area with different factories at both sides of the street. The height of these does not usually go above a 3-story building, introducing signal occultation up to approximately 20 degrees of satellite elevation. Trees are present but foliage density is low.

3. Strong Suburban: The final part of the test is conducted through a strong suburban environment including buildings with an average height of 3 stories to one side of the street and presence of dense foliage. The signal occultation introduced by the buildings oscillates between 20 and 35 degrees of satellite elevation, whereas the open sky canyon is reduced to up to 60 degrees of elevation by the trees. See Fig. 10 for pictures of the strong suburban environment taken during the execution of the test (right) and extracted from Google Maps (left).

Fig. 10: Strong suburban environment

Fig. 11 shows the horizontal positioning error throughout the different parts of the test. In this plot the convergence period has been omitted for the sake of clarity. The weak suburban environment is dealt with by the PPP algorithm with no major issues when compared to the open sky environment. When driving past a tall but isolated building approximately half of the lines-of-sight are lost for at most two epochs. However, the positioning accuracy is maintained thanks to the remaining lines-of-sight, while new incoming ionospheric corrections contribute to the ambiguity re-estimation process by reducing the noise of measurements. The U-Blox receiver used for testing is designed to operate in hash environments; hence the tracking sensitivity is reduced at the expense of higher measurement noise, but resulting in fast signal reacquisition.

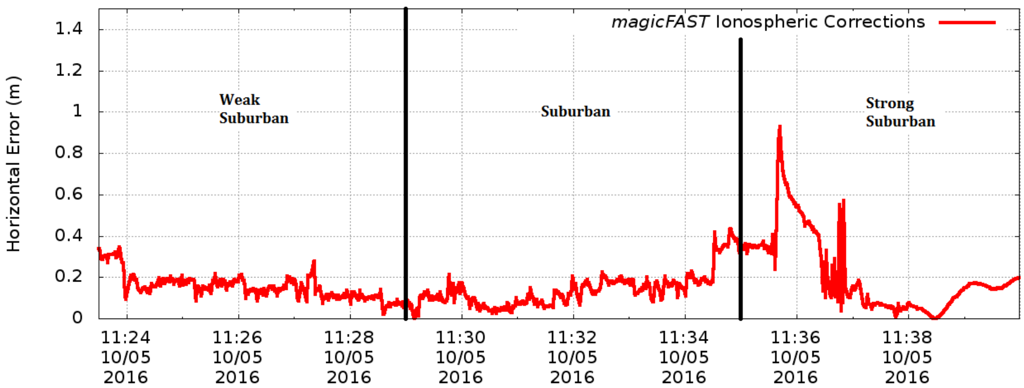

Fig. 11: Kinematic suburban horizontal positioning error

Throughout the suburban part of the test, the positioning error slightly increases from 11:32:30 to 11:34:30 due to the progressive increase of measurement noise and multipath introduced by surrounding factories and light foliage. At 11:34:30 the positioning error sharply increases as the foliage density increases gradually. From 11:34:30 to 11:35:30 there is an increased positioning bias –from 20cm to 40cm error– caused by a poor re-estimation of phase ambiguities due to continuous interference caused by increased foliage density and multipath induced by closer buildings.

During the strong suburban route, the positioning error presents peaks caused by isolated areas of lower satellite visibility. The highest peak observed at approximately 11:35:40 occurs when going through an area where trees cover part of the signals being tracked at the zenith. This area is shown in Fig. 10 (left). Nevertheless, the positioning error plot shows how fast re-convergence is achieved when the signal quality increases, going down to the 20-30cm range before the next peak appears. The last peak observed at approximately 11:36:50 appears when circulating through a roundabout populated with dense foliage, photographed in Fig. 10 (right). The peak is noisier as in this case the quality of the reference trajectory is also affected, and the antenna distance correction is degraded as the car is driven on the circular trajectory.

Finally, on the way back to GMV's premises, a short lane-change detection test was performed. A close-up of the positioning results is presented in Fig. 12. This test was carried out in an urban environment, with buildings of 4-story height at both sides of the street and medium-density foliage. As this figure yields, *magicFAST* is capable of performing lane-change detection in environments ranging from open-sky to urban of standard complexity.

Fig. 12: Lane change detection in urban environment
Estimated (red dots) vs. Reference (yellow line) trajectory

CONCLUSIONS

Throughout this paper, *magicFAST* has been introduced as new GMV's real-time product able to achieve Fast Convergence and High Accuracy with low-cost user hardware using ionospheric corrections. The total cost of the end-user hardware (GNSS receiver and antenna) employed is below 100€.

The positioning performance capabilities of *magicFAST* have been demonstrated both in static open sky and urban environments. In the current state, *magicFAST* is capable of providing 20cm of positioning accuracy after only 5 minutes of PPP convergence and maintain these performances both in open sky and suburban environments with a low-cost receiver and a patch antenna. The PPP solution is affected by multipath and foliage, but the robustness of the solution is increased by rapid re-convergence using *magicFAST* ionospheric corrections. This performance is being continuously improved by reassessing the number and geographical disposition of stations used in the generation of ionospheric corrections and implementing improved algorithms both on server and client sides.

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