System Volume Simulation for Carrier Phase Positioning

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Abstract— **The GNSS System Volume Simulation is a tool designed to predict the Carrier Phase Ambiguity Resolution User Techniques (PPP) Performances in different environments and with single and multiple GNSS systems. The obtained performance can drive the design (and improvements) of a GNSS system and its integration with others in a multi-constellation scenario. In this paper, a system volume simulator for PPP users implementation is presented. Different environments are considered: urban and rural. Signal impairments for mobile users are introduced in order to add realism to the simulations. Those signal impairments are obtained from real mobile measurements campaigns. The System Volume Simulation will be referred herein as CPP-SVS.**

I. Introduction

Nowadays the creation of new applications based on navigation concepts keeps continuously growing, and it will continue to grow in the future with the final deployment of Galileo and BeiDou-3. As a consequence high precision solutions such as PPP are becoming a must in daily life. PPP has been receiving more attention as it provides a cheaper and simpler way (no need of reference stations) than the differential techniques like Real Time Kinematic to achieve sub-meter level.

The immediate role of CPP-SVS primarily lies in the characterization in position accuracy and availability in a multiple and single GNSS constellation scenarios. This paper introduces the implementation of the Raw Data Generation (RDG) and Service Volume Simulation (SVS) capabilities of the CPP-SVS and provides first results with prime focus on the position accuracy and availability of the Galileo system.

II. Precise point positioning

PPP techniques can be defined as a process where a single GNSS receiver can precisely compute its position (down to centimeter level) by autonomously using its raw pseudorange and carrier phase measurements with precise satellite orbits and clocks. They are provided to the receiver by different types of communication channels (e.g. GEO satellite, Internet or other data links).

PPP based positioning techniques have been extensively investigated and developed in the last years. These methods are now rather mature and provide a very good mean to achieve in real time a few centimeters of accuracy in worldwide areas, where other solutions like RTK are impracticable (no reference stations nearby, e.g. marine environment) or too expensive. The main advantages of PPP techniques are that they provide a global high accuracy with no need of a network of stations in the vicinity of the user.

The achievable PPP performance and availability (specially in challenging environments) is expected to further improve with the upcoming Galileo and BeiDou-3 which are currently under deployment.

As already mentioned, the main objective is to develop a simulation environment to study the performance behavior of using multi-GNSS for PPP. In order to do this, two types of analyses have performed:

- Multi-constellation PPP in order to show the benefits and improvements of introducing Galileo. The constellations combinations analyzed are:
  - GPS + Galileo.
  - GPS + Galileo + Glonass.
- Single constellation PPP in order to show the achievable performances and be the reference for the improvement in multi-constellation scenario.

These two types of PPP tests have been analyzed in kinematic scenarios and processed with kinematic algorithms (similar to the ones designed to work in real time). They can be divided into the open-sky and the urban tests. As it is obvious, better results are expected for open-sky since the satellites tracking availability is higher and better quality of the observables (less multipath and carrier slips).

III. CPP-SVS simulation capabilities

It provides a single simulator that uses alternative models depending upon the type of analysis the end-user wishes to perform:

1. The *Service Volume simulation* (SVS) capability allows the analysis of the navigation performance over long time periods and geographical areas. In particular, it allows the user to assess several relevant Figures of Merit on global or regional grids

of user locations (mobile or static users). Main Figures of Merit are:

a. **Positioning Accuracy**, refers to the position difference between the PPP solutions and the reference trajectories. Analysis implemented here returns the mean, maximum, minimum, 68 and 95 percentile for horizontal, vertical and 3D .
b. **The number of satellites**, it returns the total number of satellites available to perform the carrier-based positioning accuracy over time.
c. **Positioning availability**, refers to the percentage of time with carrier-based solution with respect to the total simulated time.
d. **Availability of Accuracy**, refers to the percentage of time with carrier-based solution below a defined accuracy threshold.
e. **Convergence time**, the convergence criteria is the simultaneous achievement of a horizontal and vertical accuracy at 95% below a defined accuracy threshold.

2. The *Raw Data Generation* (RDG) capability uses high fidelity models to generated GNSS observables. It generates GPS, GLONASS and Galileo observables. These observables are generated synthetically at code and carrier phase level. Several time delays associated with the signal propagation and the clocks have been taken into account (Relativistic Path Range Correction, Receiver clock offset, Satellite clock offset, Troposphere delay, Carrier Phase wind-up effect, Antenna Phase Center correction, solid tides effect, inter-system biases).
3. The *Environment-User Effects Contributions* (EEC) capability allows to take into account GNSS environment effects in harsh propagation situations, where the tracking of weak GNSS signals is challenging due to the presence of shadowing (fading, blockages) and multipath effects. A large test campaign have been conducted with the ESA van in the Netherlands in several environments. TABLE I. summarizes the description of the analyzed mobile tests. The real collected measurements have been analyzed to detect cycle-slips and extract multipath series in order to generate representative statistics with regard to the satellite elevation in those environments. The tracking periods have also been user to simulate realistic environments.

CPP-SVS provides interfaces to generate and read external data from RINEX, IONEX, SP3, CLK, ATX and BIA files. The RDG Export feature allows user to export RINEX 3.0. The data produced by RDG can be injected into other tools for further analysis (RINEX/SP3). An important part of this SVS development has been an integrated module to process the raw data in a representative state-of-the-art PPP SW, for instance RTKLib.

TABLE I. DESCRIPTION OF THE MOBILE TESTS

Test	Date	Environment
#1	10/03/2016	Urban Environment
#2	23/03/2016	
#3	30/03/2016	
#4	25/04/2016	
#5	28/04/2016	
#6	02/05/2016	
#7	15/04/2016	Rural Environment
#8	19/04/2016	
#9	21/04/2016	
#10	22/04/2016	

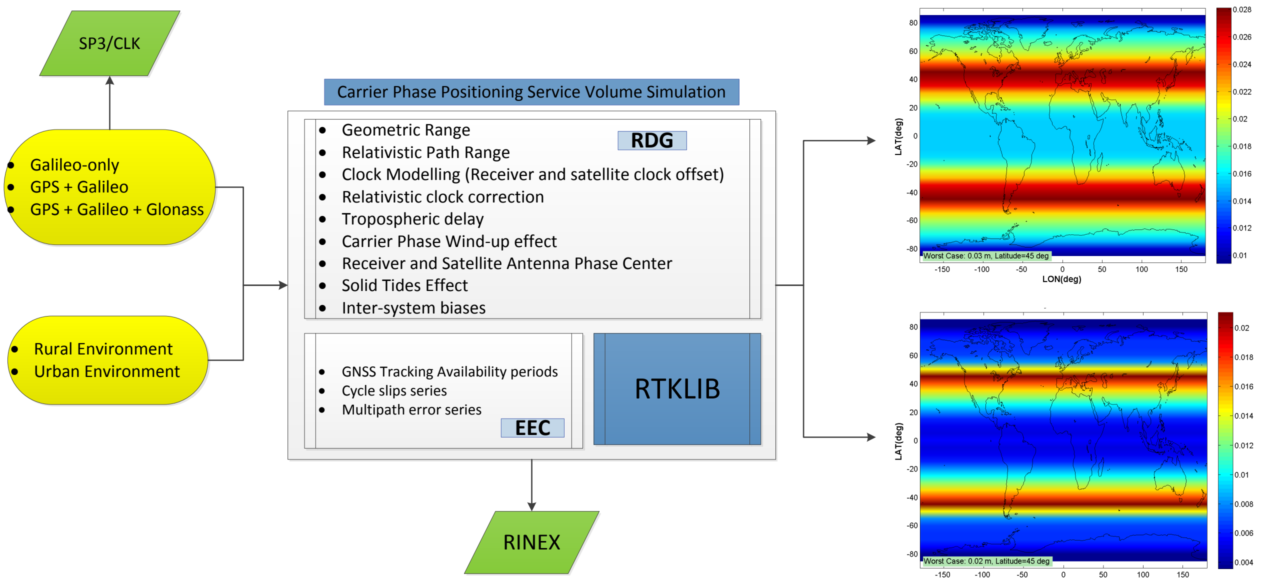

Fig. 1. CPP-SVS Overall Architecture

IV. RAW DATA GENERATION (RDG)

The RDG module addresses the generation of GNSS observables as defined by the user. This data contains in the code and carrier phass, several time delays associated with the signal propagation and with the clocks. The aim of this section is to provide information about the data generation use as the input to the Precise Point Positioning algorithms [2]:

1. *Geometric Range Modelling*: it is the Euclidean distance between the satellite and receiver antenna phase center coordinates at transmission and reception time, respectively.
2. *Relativistic Path Range Correction*: The effect is called the Shapiro signal propagation delay and it introduces a general relativistic correction into the geometric range. Due to the space-time curvature produced by the gravitational field, it can be only required for high accuracy positioning.
3. *Clock Modelling*: The clock offsets are due to clock synchronization errors referring to the GNSS time scale. The modelling of such offsets, as well as its effect on the navigation solution, are described as follows:
   a. *Receiver clock offset (dt_r):* This is estimated together with the receiver coordinates and the zenith tropospheric delay.
   b. *Satellite clock offset (dt^s):* This can be split into two terms:
   $$dt^s = \widetilde{dt}^s + \Delta_{rel}$$
   The first term ($\widetilde{dt}^s$) can be calculated from the precise products available from IGS centers or other providers. The second term (Δ_{rel}) is a small relativistic correction caused by the orbital eccentricity:
   $$\Delta_{rel} = -2\frac{r^{sat} \cdot v^{sat}}{c^2}$$
4. *Tropospheric delay*: an accurate method developed at the University of New Brunswick was used for modeling the a priori troposphere's dry and wet components at zenith without meteorological sensors. This model uses the Niell mapping function, which considers different obliquity factors for the wet and dry components. [4][5].
5. *Ionospheric Delay*: it refers to the delay that the GNSS electromagnetic signals suffer through this part of the terrestrial atmosphere that extends from about 60km up to more than 2000km. This environmental contribution has not been used since the PPP approach form the "ionosphere-free" linear combination to remove the first-order (up to 99.9%) ionospheric effect, which depends on the inverse square of the frequency.
6. *Carrier Phase Wind-up Effect:* it only affects the carrier phase measurements, not the code pseudoranges. It is due to the electromagnetic nature of circularly polarized waves. The wind-up effect on phase measurements depends on the relative orientation of the satellite and receiver antennas, and the direction of the line of sight.
7. *Antenna Phase Center Correction:* The GNSS measurements are referred to the Antenna Phase Center (APC) position. As this location is frequency dependent, a point tied to the base of the antenna is used as more suitable reference, this point is called Antenna Reference Point (ARP). Manufacturers provide technical information on the APC position relative to the ARP. IGS is providing relative and absolute corrections in the ANTEX files respectively for several antenna models.
8. *Satellite Antenna Phase Center:* the precise orbits and clocks are referred to the Satellite Mass Center (MC), thus it is necessary to account for the phase center offset vector. This offset is given in a satellite-fixed coordinate frame in the ANTEX file.
9. *Solid Tides Effect Modelling:* These concern the movement of Earth's crust (and thus the variation in the receiver's location coordinates) due to gravitational attractive forces produced by external bodies, mainly the Sun and the Moon. A simplified model for the tidal displacement, to a few millimeters of accuracy, is given by **[3]**.

V. ENVIRONMENT-USER EFFECTS CONTRIBUTIONS (EEC)

The *EEC* capability allows the user to take into account GNSS environment effects in harsh propagation situations, where the tracking of weak GNSS signals is challenging due to the presence of blockage, fading and multipath effects. These errors are based on real collected measurements from a test campaign in the Netherlands. These real measurements have been processed and analyzed in detail in order to extract firstly the tracking availability versus satellite elevation. Secondly the cycle-slips (detected with the use of multi and single frequency techniques). And finally, the multipath has been extracted to generate representative synthetic data. The used techniques and methods are further explained in this section.

A. Tracking Availability w.r.t. satellite elevation

In order to generate realistic scenarios in the CPP-SVS, tracking periods have been widely analyzed at both code and phase level. This data characterization can be divided into the rural (open-sky) and urban environments. TABLE II , TABLE III ,TABLE IV and TABLE V highlight some tracking statistics from the rural and urban environment, respectively. Where C and L are referred to code and phase observables, and the indexes 1 and 2 referring to the first and second frequency.

TABLE II. PROBABILITY OF CODE AND CARRIER PHASE TRACKING (PERCENTAGE) W.R.T. SATELLITE ELEVATION. RURAL ENVIRONMENT

E_i	E_f	C1	L1	C2	L2
5	10	96.3%	84.3%	84.8%	82.5%
10	20	99.7%	94.5%	95.8%	94.1%
20	30	99.8%	98.0%	99.0%	97.9%
30	40	100.0%	99.2%	99.9%	99.2%
40	50	100.0%	98.9%	99.8%	98.8%
50	60	100.0%	99.1%	99.9%	99.1%
60	90	100.0%	99.7%	100.0%	99.7%

TABLE III. AVERAGE TRACKING TIME BEFORE LOSING THE TRACKING (SEC) W.R.T. SATELLITE ELEVATION. RURAL ENVIRONMENT

E_i	E_f	C1	L1	C2	L2
5	10	113	56	57	60
10	20	597	122	126	128
20	30	2838	267	419	283
30	40	5329	463	588	343
40	50	6503	369	735	366
50	60	7758	397	1115	392
60	90	8855	1167	3747	1167

TABLE IV. PROBABILITY OF CODE AND PHASE TRACKING (PERCENTAGE) W.R.T. SATELLITE ELEVATION. URBAN ENVIRONMENT

E_i	E_f	C1	L1	C2	L2
5	10	24.1%	10.3%	8.5%	8.1%
10	20	52.4%	22.6%	19.7%	18.6%
20	30	77.2%	43.8%	43.1%	39.5%
30	40	87.5%	54.9%	58.1%	52.1%
40	50	92.6%	66.8%	71.4%	64.9%
50	60	94.1%	77.8%	82.1%	76.8%
60	90	95.9%	90.9%	93.4%	90.7%

TABLE V. AVERAGE TRACKING TIME BEFORE LOSING THE TRACKING (SEC) W.R.T. SATELLITE ELEVATION. URBAN ENVIRONMENT

E_i	E_f	C1	L1	C2	L2
5	10	13	21	28	32
10	20	18	18	22	26
20	30	25	21	23	27
30	40	39	22	22	25
40	50	66	27	28	31
50	60	155	43	50	45
60	90	270	104	141	107

As it is expected, better results have been obtained for the rural scenario since the measurements are collected in an area without tall buildings that would increase the loss of tracking. Only few trees were around the measurement route. In contrast, the urban scenarios the majority of the measurements were collected in an area with tall buildings or in a residential zone with wide streets and trees (with foliage on both sides). The signal tracking was showing a lot of discontinuities, and carrier phase cycle slips occurred mainly because trees shadowing.

Fig. 2. Rural (left) and Urban (right) routes

Fig. 3. Rural (left) and Urban (right) representative instance in the route

B. Cycle-slips Detection Techniques

Receiver losses of lock cause discontinuities in the phase measurements (*cycle slips*) that are seen as jumps of integer numbers of wavelengths λ (i.e. the integer ambiguity N changes by an arbitrary integer value). Different methods are used for cycle-slip detection, the methods presented in this section are oriented towards single receiver positioning, and thus do not require any differencing of data between receivers, being suitable for implementation in real time. Moreover, they are based on using only combinations of measurements at different frequencies, or just one frequency measurement.

1) Multi Frequency Cycle-Slips Detectors: Cycle slip detector based on the Melbourne-Wübbena (MW) combination of code and carrier phase measurements. [8] [3]

2) Single Frequency Cycle-slips Detectors: The used single-frequency detector presented next is based only on data measurements of a receiver (e.g. mass market) and do not use any geometric delay model. [3]

C. Multipath Observable Technique

GNSS measurements suffer from signals including multipath. Multipath degrades the positioning accuracy and becomes really important at low satellite elevations. The **observables combination** of code and carrier phase from a dual-frequency receiver will be assessed to extract the multipath error from the real measurements. This time series are used to generate synthetic multipath that will be added to the synthetic generated pseudoranges. For this combination, it is crucial to detect the cycle slips correctly beforehand and remove the ambiguity.

$$M_{L_1} = C_1 - L_1 + 2\alpha_1(L_2 - L_1) - mean(C_1 - L_1 + 2\alpha_1(L_2 - L_1))$$
$$M_{L_2} = C_2 - L_2 + 2\alpha_2(L_2 - L_1) - mean(C_2 - L_2 + 2\alpha_2(L_2 - L_1))$$

where $\alpha_1 = \frac{1}{\gamma_{12}-1}$, $\gamma_{12} = \left(\frac{f_1^2}{f_2^2}\right)$, $\alpha_2 = 1 + \alpha_1$

This calculation has been done for all the tracked satellites (shown in Fig. 4) and the resultant multipath error time series have been aggregated per group of elevations (shown in Fig. 5). As it can be seen in the following figure, the multipath error becomes a major contribution at low elevations and play a crucial role in GNSS positioning in urban environments.

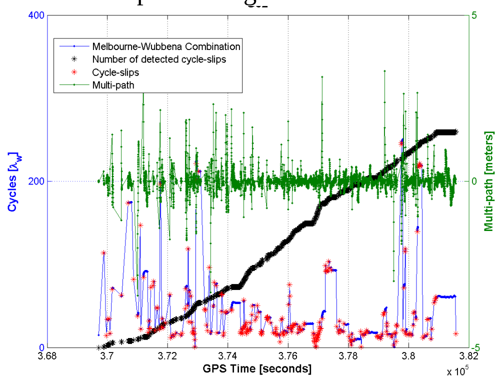

Fig. 4. Multipath error time series

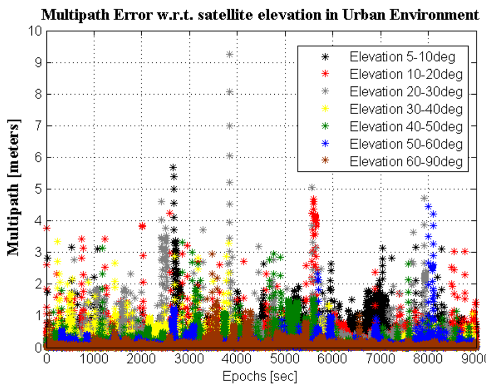

Fig. 5. Aggregated Multipath time series w.r.t. satellite elevation

VI. Simulation Scenarios

The following sections provide the scenarios for CPP-SVS performance evaluation. The common reference scenario information used for these examples is provided in TABLE VI.

TABLE VI. Common reference scenario information

CPP-SVS	Urban	Rural
Duration	1 day	10 days
Sampling rate	1 second	2 seconds
Grid of users	4x4deg	4x4deg
Processing Mode	Kinematic	Kinematic
Multipath error	Yes	Yes
Cycle slips	Yes	Yes
Tracking availability	Yes	Yes
Ranging Accuracy (RMS)	Negligible	[0, 23cm]
GNSS cases	SC, EG and EGR	SC and EGR

Where SC, E, G and R stand for Single Constellation, Galileo, GPS and GLONASS respectively. It is important to remark that this grid of ´static´ users have been processed with PPP in kinematic mode (that algorithm has demonstrated to provide the same performance as a mobile user in ideal open sky scenario without multipath and other signal impairments). The impact of Ranging Accuracy has only been assessed in rural environment because as it was shown in [1], in urban environment and with the state-of-the-art algorithms only negligible position accuracy differences were found between Ranging Accuracy products (main position accuracy drivers were the satellite accessibility, multipath and carrier cycle slips). However, in rural environment where the position availability is expected to be 100% in a multi-GNSS scenario, the PPP feasibility is mainly related to how much the Ranging Accuracy can be improved. In order to achieve this, a range of synthetic satellites orbit and clock product,s between perfect orbits and clocks to 23cm RMS WUL (Worst User Location), have been generated and used.

A. *Rural Environment*

1) Single Constellation PPP

It represents the first approach considered to have a limited representativeness for a real user. It has also been utilized to validate the CPP-SVS: the process started from a scenario which aimed to minimize the differences between the measured and simulated data by replacing the individually validated RDG models with data sources with the signal impairments calculated from the test campaign.

This mild environment is also useful for characterizing the performance of services offered by single constellation distinctive services (e.g. GPS M-code). In those services the user rely only in one constellation, not being the multi-constellation an option. Fig. 5 and Fig. 6 shows the horizontal and vertical error in rural environment, respectively. The positioning availability is depicted in Fig. 1.

The horizontal and vertical errors at 95% worldwide have been plotted with regard to Ranging Accuracy as shown in Fig. 8, sub-meter accuracy can be achieved below 20cm 1-sima Ranging Accuracy. The results is an open-sky scenario can also be seen in the plot, this scenario without signal impairments (no cycle slips and no tracking visibility periods) has been used for validation and calibration of the CPP-SVS.

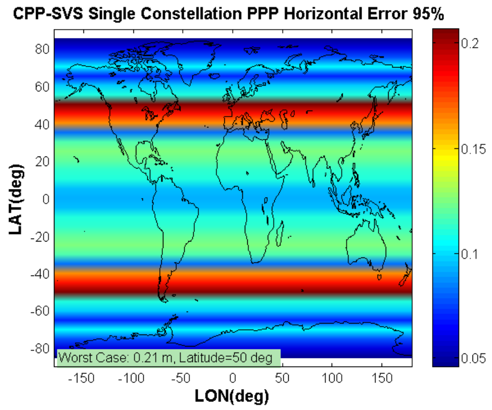

Fig. 6. CPP-SVS Single constellation PPP Horizontal Error 95%

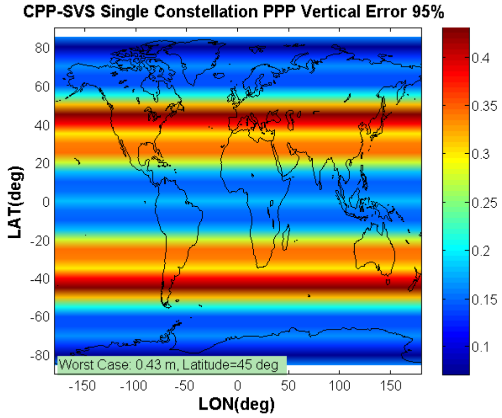

Fig. 7. CPP-SVS Single constellation PPP Vertical Error 95%

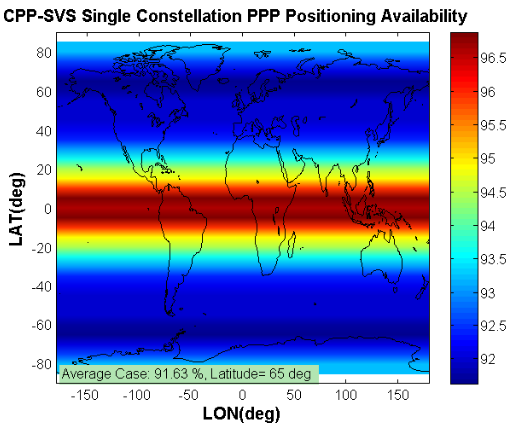

Fig. 8. CPP-SVS Single Constellation PPP Positioning Availability

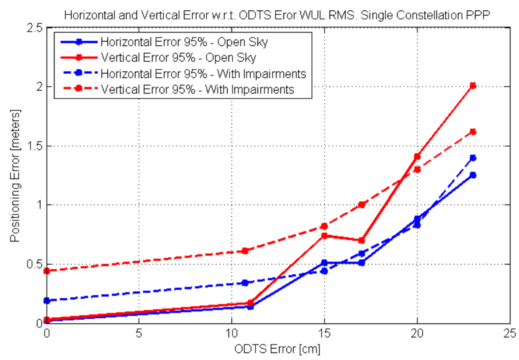

Fig. 9. Horizontand and Vertical Error Galileo-only PPP w.r.t Ranging Accuracy in rural environment

2) Galileo + GPS + Glonass PPP

Simulated in rural environment with position availabilities between 91.6% and 100% for Galileo-only PPP solution. As expected the multi-GNSS PPP option will improve the number of satellites and the satellite geometry. These will improve the positioning accuracy and availability (see Fig. 9 and Fig. 10), especially those cases where the single GNSS system solution does not provide sufficient good results. Besides, the fact of having a high number of available (tracked) satellites allows the algorithms to discard satellites that are not expected to degrade the position accuracy (e.g. NLOS tracked satellites normally having a low C/No). This will allow to provide a better performance, as shown in TABLE VII. In summary, the average number of satellites is really high so the algorithm can reject satellites with low CNR or in NLOS conditions.

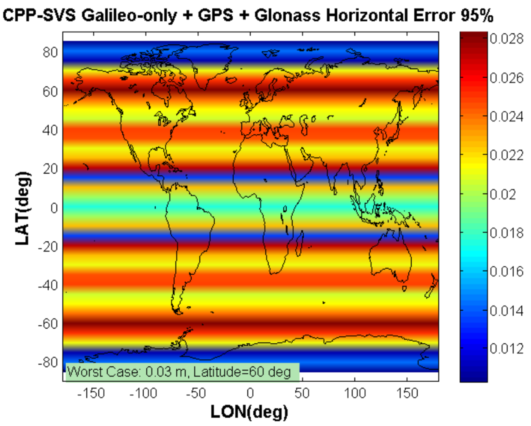

Fig. 10. CPP-SVS Galileo+GPS+Glonass PPP Horizontal Error 95% in rural environment

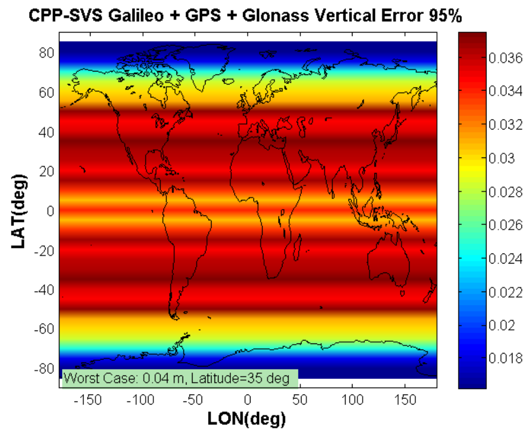

Fig. 11. CPP-SVS Galileo+GPS+Glonass PPP Vertical Error 95% in rural environment

TABLE VII. SUMMARY IN RURAL CONDITIONS

Figure of Merits – Worst Case	SC	EGR
H68% / V68% (m)	0.06/0.12	0.02/0.02
H95% / V95% (m)	0.21/0.43	0.03/0.04
Average number of satellites	7	22
Minimum number of satellites	1	6
Positioning Availability	91.6%	100.0%

B. *Urban Environment*

1) Single Constellation PPP

This section has been included in the study to show the big limitations when using single-constellation carrier-based positioning in harsh propagation situations. It is not expected to be representative of a real user in the future, which should track all the different possible constellations in the future to improve the performance. As in rural environment, both the horizontal and vertical error have been assessed but only the horizontal error will be shown in urban conditions. The CPP-SVS is focused on terrestrial users where the horizontal error is considered more important. Fig. 11 and Fig. 12 show the horizontal error and positioning availability respectively in urban environment, it can be seen how the accuracy is far from sub-meter level and low positioning availability (worst case 73.96%). As the user is moving along the city, it will lose, track and reacquire new satellites continuously, degrading the solution. The satellite visibility plays a crucial role as shown in TABLE VIII , the average number of satellites is below 5 (minimum required for PPP single-constellation).

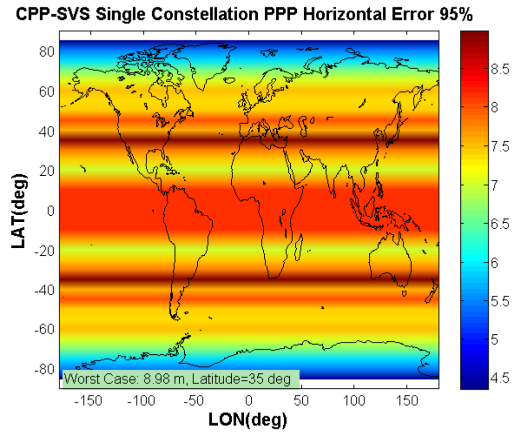

Fig. 12. CPP-SVS Single Constellation PPP Horizontal Error 95%

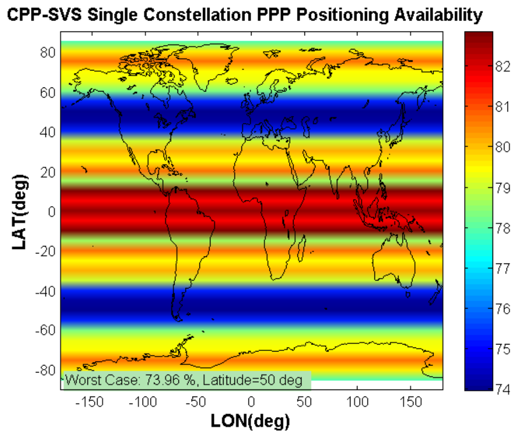

Fig. 13. CPP-SVS Single Constellation PPP Positioning Availability

2) Galileo + GPS PPP (EG)

This section shows the benefits of adding a 2nd constellation in urban conditions. Fig. 13 shows the percentile 95% horizontal error with Galileo + GPS, the improvement is at least a factor of 2 for this case. The number of satellites available to perform carrier-based positioning has also increased considerably as shown in Fig. 14 w.r.t. the previous section but it is still not enough for all the scenario duration. However, high positioning availability (with no accuracy requirements) can be obtained with two GNSS constellations, worst case worldwide is 93.74%.

Additionally, results show poor performance in urban environment conditions with two constellations because the limited number of visible satellites on top of the difficulty of an accurate/available carrier phase tracking. Indeed, the observed PPP solutions are not converging (ambiguity not solved) and errors are in the order of several meters. Therefore, the use of at least 3 constellations for the derivation of acceptable PPP solutions in urban conditions seems to be the minimum.

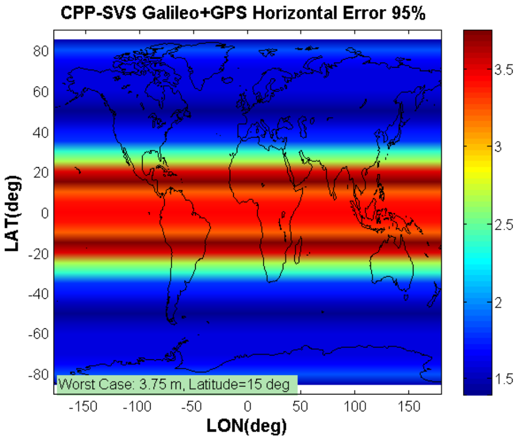

Fig. 14. CPP-SVS Galileo+GPS PPP Horizontal Error 95%

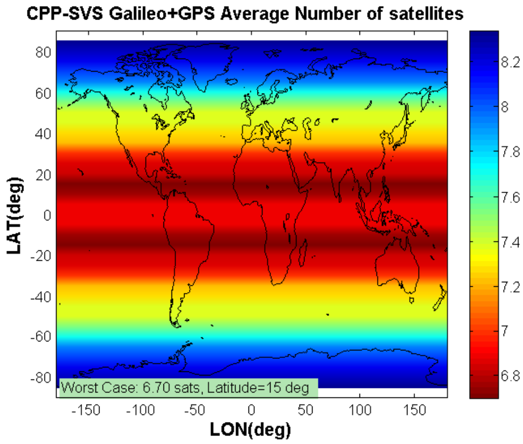

Fig. 15. CPP-SVS Galileo+GPS PPP Average Number of Satellites

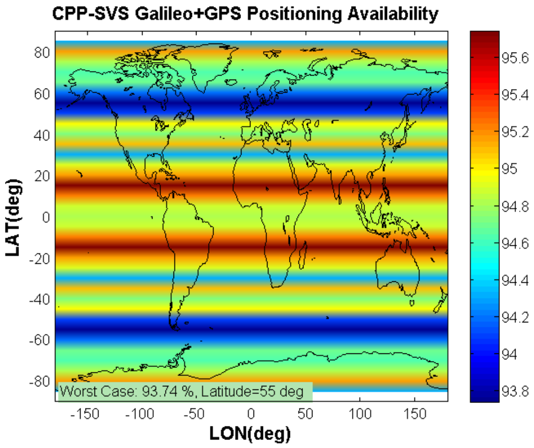

Fig. 16. CPP-SVS Galileo-only PPP Positioning Availability in urban environment

3) *Galileo + GPS + Glonass PPP (EGR)*

In urban environment conditions the use of multi-GNSS is known to be a must in order to have a good positioning availability and accuracy. The satellite geometric diversity provided by Galileo, GPS and Glonass helps to have a greater positioning availability (Fig. 17) and improve the positioning error (Fig. 16). TABLE VIII. summarizes the obtained results in urban conditions:

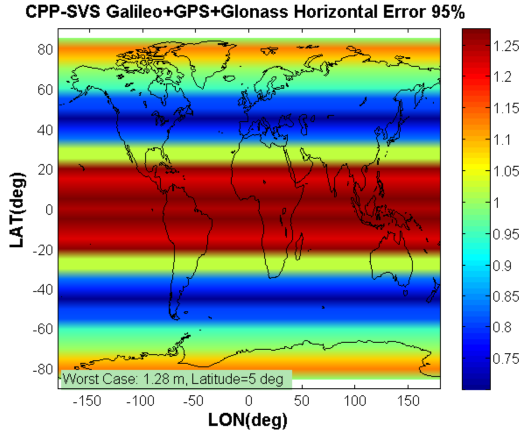

Fig. 17. CPP-SVS Galileo+GPS PPP Horizontal Error 95% in urban environment

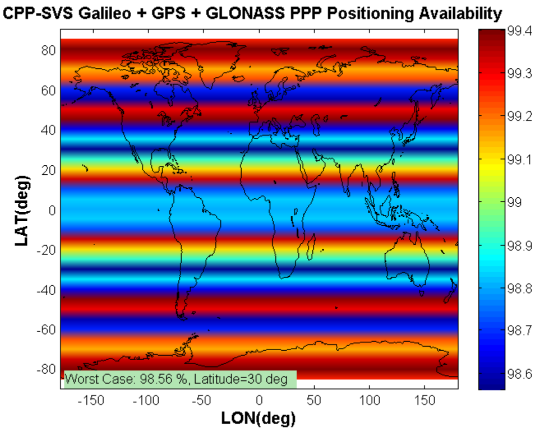

Fig. 18. CPP-SVS Galileo-only PPP Average Number of Satellites in urban environment

TABLE VIII. SUMMARY IN URBAN CONDITIONS

Figure of Merits – Worst Case	E	EG	EGR
H68% (m)	2.18	0.34	0.25
H95% (m)	8.98	3.75	1.28
V68% (m)	4.62	0.86	0.82
V95% (m)	18.8	9.41	6.00
Average number of satellites	3.75	6.70	10.23
Minimum number of satellites	1	1	4
Positioning Availability	74.0%	93.7%	98.6%

The feasibility of dual-frequency carrier-based positioning in urban environment is expected to become a reality with at least 3 GNSS constellations as shown in TABLE VIII , the use of an extra constellation will help to improve the minimum number of satellites, the worldwide positioning availability and reduce the data gaps that are affecting the positioning accuracy (see Fig. 19 and Fig. 20). Fig. 19 shows that about 95% of the data gaps have a duration smaller than 10 seconds, so these discontinuities could be mitigated with the integration of low-grade IMU observations.

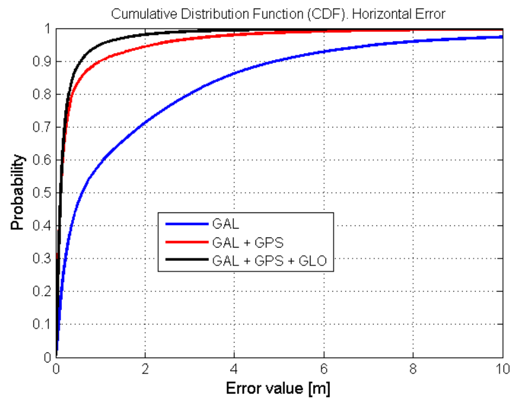

Fig. 19. CDF Horizontal Error. Urban Environment

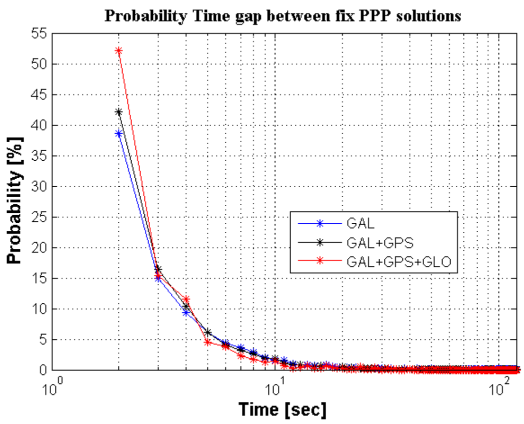

Fig. 20. Probability of a Time gap with a duration of X (where X are the values in the x-axis) between fix PPP solutions when there is a data gap. The addition of all points is 100%

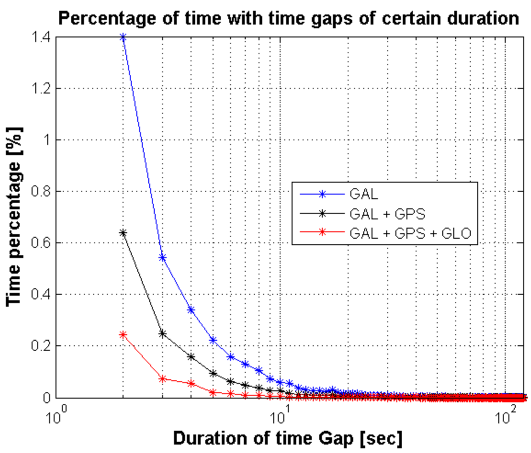

Fig. 21. Time percentage, wrt total simulated time, occupied by data gaps of Xseconds (where X is the values of the x-axis of the plot)

VII. Conclusions

The CPP-SVS simulator is presented in this paper and their used algorithms described. It allows to perform dual-frequency PPP performance characterization with high accuracy orbit and clock products. It allows data to be generated from user-defined scenarios, using high-fidelity models, so that many aspects of the complete system can be tested prior to the availability of the system itself. It is possible to generate measurement data for not only single GNSS constellation, but also for multiple constellation (GPS, GLONASS and Galileo). In further versions of the tool, the BeiDou-3 constellation will also be available.

CPP-SVS provides a single simulator that uses alternative models depending upon the type of analysis the end-user wishes to perform. It provides interfaces to generate and read external data from RINEX, IONEX, SP3, CLK, ATX and BIA files. The RDG Export feature allows user to export RINEX 3.0. The data produced by RDG can be injected into other tools for further analysis (RINEX/SP3). An important part of this SVS development has been an integrated module to process the raw data in a representative state-of-the-art PPP SW, RTKLib. The results presented in this paper demonstrate how CPP-SVS can be applied in particular for the use of carrier-based positioning in both rural and urban environment.

In rural environment, the single-constellation carrier-based positioning can be an option in those services where the user can only rely in one constellation, not being the multi-constellation an option. The multi-GNSS option will enhance the overall positioning availability and accuracy, improving in cases when the single-constellation shows a limited performance.

In urban environment, the satellite visibility is considered the main driver. Results show poor performance with 2 or less constellations because the low satellite visibility on top of the difficulty of an accurate carrier phase tracking. The use of at least triple system (Galileo, GPS and GLONASS) is a must for the feasibility of PPP in harsh propagation conditions, where the tracking of weak GNSS signals is challenging due to the presence of blockage, fading and multipath effects.

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