5G positioning and hybridization with GNSS observations

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BIOGRAPHIES

Roc Maymo-Camps has had engineering masters by Escola Tècnica Superior d'Enginyeria Industrial de Barcelona (UPC) and ENAC (2007). He has been working at Telespazio for over 10 years in the navigation department.

Benoit Vautherin received his engineering degree from Ecole supérieure d'électricité, Metz, France, in 2015, and his MSc degree in space science and engineering from University College London, United Kingdom, in 2015. He joined Thales Alenia Space, Toulouse, France, in April 2015. Since then, he has been working as a navigation and data collect system engineer for many European and national R&D projects.

M.Sc Jani Saloranta is a PhD student at University of Oulu, Finland. He received his Master's degree in Mathematics (Group Theory) with minors from Statistics and Computer Sciences from University of Oulu in 2008. Since 2009 he has been a research scientist at Centre for Wireless Communications, University of Oulu, Finland. Currently 2012 he is working towards his PhD degree from the title of Semantic Positioning in Department of Communications Engineering, University of Oulu, Finland. His research on a positioning algorithm based on algebraic confidence was awarded with the best student paper award at the IEEE 9th Workshop on Positioning, Navigation and Communication (WPNC'12). His other research interests are in Algorithms and Protocol design, as well as in Graph theory for applications under low-power wireless networks.

Romain Crapartis graduated from the engineering school Institut Supérieur de l'Aéronautique et de l'Espace ISAE (2016) and works as a GNSS engineer on Space-embedded and smartphone receivers.

ABSTRACT

The present paper depicts the tests and experimentations that have been carried out to show how GNSS and 5G can be used to provide better positioning solutions. In this frame, the design made during the 5GChampion project has led to a solution combining both positioning systems in different environments to show in which cases one solution is better than the other and in which cases they can be complementary. The experimentations show the interest of GNSS in open-sky and rural areas where 5G base stations will not be close to the user and will not be able to provide accurate positioning data. On the other extreme, in canyons and urban environments where many satellites can be masked by buildings and multipath abundant, the inclusion of 5G positioning data from stations that tend to be close to the user can improve the performances. At the end of this paper, a table summarized the performances improved, namely the accuracy and availability. On top of these analysis, PPP solutions have been computed in order to see the benefits of PPP and 5G solutions combined.

1 INTRODUCTION

The paradigm of ubiquitous location information has risen a requirement for hybrid positioning methods, as a continuous data location cannot be provided by any single wireless system alone. Thus such hybrid methods have been interest of research community and different joint techniques accounting different data sources and/or types have been proposed, *e.g.* coupling GNSS with vision sensors (Takasu & Yasuda, 2008) or inertial sensors (Angrisano, 2010). Nevertheless, the upcoming fifth generation (5G) networks jointly with Global Navigation Satellite System (GNSS) are still to be investigated.

It is expected that 5G positioning will be able to provide more precise location and enhanced availability in all kinds of environments, especially urban canyons, where most GNSS signals are blocked and suffer from severe multipath conditions. The 5G observations can be added to both single and precise point positioning (PPP) GNSS solutions.

The work was carried out during the EU-Korean "5GCHAMPION" project (Mueck & et.al., 2016). The rest of the paper is organized as follows. In Section 2, we present the objectives of the work. In Section 3, we discuss about the research methods and the presented objectives. In Section 4, we explain the technologies and methods from a positioning point of view for the proposed hybrid 5G–GNSS method and infrastructure. Then in Section 5 results based on simulations and real life measurements are presented, and finally, in Section 6 concluding remarks are given.

2 OBJECTIVES

This study has three main objectives:

- Assess the positioning performance of the mm-Wave technology.
- Assess the gains of 5G positioning over known GNSS positioning methods.
- Assess the positioning performance of the hybridized mm-Wave/GNSS solution

3 METHOD

The fulfillment of the objectives is done in two phases.

Firstly, each solution is described to provide a technical understanding and to assess preliminary performance of each technology.

Secondly, a testing phase is provided with definition of Key Performance Indicators (KPI) and test cases. Then the test cases are executed and post-processed to assess the performance of each solution in real life.

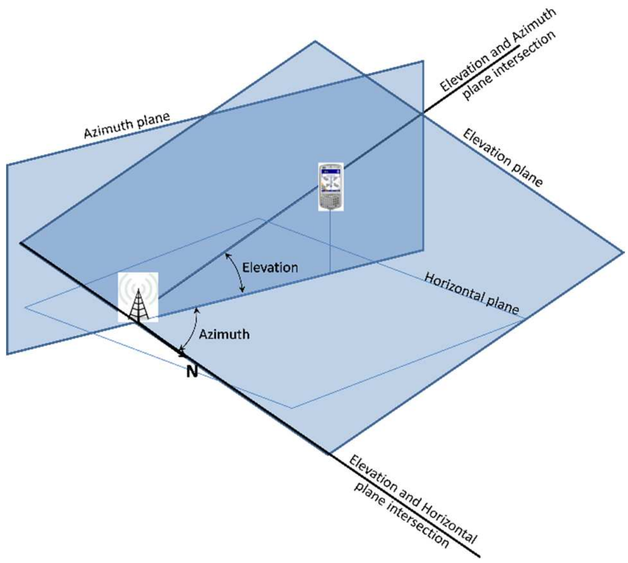
4 TECHNOLOGY DEFINITION

4.1 mm-Wave Positioning

The millimeter wave (mmWave) technology[1] is considered as one of the key properties of the 5G communication networks (Saloranta & Destino, 2017). This technology mainly brings the use of high data rate and the use of beamforming feature via large antenna arrays (Kutty & Sen, 2016). Such feature is used for the angle of arrival (AOA) positioning method. Furthermore the characteristic of the mmWave channel is sparsity, *i.e.* only few dominant paths exists in the channel estimation process, and from where the spatial-temporal domain information can be exploited in the estimation process. (Saloranta & Destino, 2016). To provide an effective solution utilizing a real hardware, we will exploit the angular domain information only.

4.2 Single Positioning and Hybridization

5G observations are azimuth and elevation angle defined in the figure hereafter.



Explanation of single GNSS positioning is not the objective of this study but the main mathematical implementation resides in the following equations. 5G observations are in angular domain (azimuth and elevation) and are added to the iterative least square method. This system is given as

$$\begin{pmatrix} \frac{(x_i-\hat{x}_u)}{\hat{r}_i} & \frac{(y_i-\hat{y}_u)}{\hat{r}_i} & \frac{(z_i-\hat{z}_u)}{\hat{r}_i} & c \\ \frac{(x_j-\hat{x}_u)}{\hat{r}_j} & \frac{(y_j-\hat{y}_u)}{\hat{r}_j} & \frac{(z_j-\hat{z}_u)}{\hat{r}_j} & c \\ azp_x & azp_y & azp_z & 0 \\ elp_x & elp_y & elp_z & 0 \end{pmatrix} \cdot \begin{pmatrix} \Delta x_u \\ \Delta y_u \\ \Delta z_u \\ \Delta t_u \end{pmatrix} = \begin{pmatrix} \widehat{\rho_i} - \rho_i \\ \widehat{\rho_j} - \rho_j \\ azp^T \cdot R \\ elp^T \cdot R \end{pmatrix}$$

where

- $(\Delta x_u \quad \Delta y_u \quad \Delta z_u \quad \Delta t_u)$: State vector residuals
- $(\hat{x}_u \quad \hat{y}_u \quad \hat{z}_u)$: Estimated user position
- $(x_i \quad y_i \quad z_i)$: Estimated position of satellite *i*
- $\hat{r}_i$: Estimated range between receiver and satellite *i*
- $\widehat{\rho_i}$: Estimated pseudo-range between receiver and satellite *i*
- ρ_i : GNSS observation of pseudo-range *i*
- *c*: The constant of the speed of light
- *R*: Range between estimated user position and base station (BS) expressed in ECEF.
- $azp = (azp_x \quad azp_y \quad azp_z)$: Azimuth plane vector expressed in ECEF coordinates. The vector is orthogonal to the azimuth plane.
- $elp = (elp_x \quad elp_y \quad elp_z)$: Elevation plane vector expressed in ECEF coordinates. The vector is orthogonal to the elevation plane.

The associated covariance matrix Σ of observations is as

$$\Sigma = \begin{pmatrix} var(\rho_i) & 0 & 0 & 0 \\ 0 & var(\rho_j) & 0 & 0 \\ 0 & 0 & var(azp^T \cdot R) & cov(azp^T \cdot R, elp^T \cdot R) \\ 0 & 0 & cov(elp^T \cdot R, azp^T \cdot R) & var(elp^T \cdot R) \end{pmatrix}$$

The variance of GNSS observation is the User Range Equivalent Error (UERE) which is well documented, but the variance of 5G observation is quadratic with the

[1] A radio frequency band of 30 – 300 GHz via exact definition. Although relaxed definition are e.g. from 23 – 32 GHz bands [P1].

distance of the estimated position from the station which comes from the angular nature of the observation.

4.3 Precise Point Positioning and Hybridization

Based on undifferenced and uncombined code and phase measurements, Precise Point Positioning (PPP) techniques achieve decimeter level accuracy in kinematic mode and centimeter level or better in static mode thanks to the precise orbit, clock and error models. PPP-WIZARD (With Integer and Zero-Difference Ambiguity Resolution) software developed by CNES (French Space Agency) has been used in this paper for hybridization with 5G observations. This software uses recent techniques such as ambiguity resolution, fast convergence, gap bridging, etc. and presents the possibility of single frequency PPP (Laurichesse & Privat, 2015). These techniques improve the accuracy and the convergence time of the solution.

The GNSS/5G hybridization has consisted mainly in adding 5G observations in the measurement vector of the PPP Extended Kalman Filter, and completing the covariance matrices according to the equations (1) and (2), thanks to the following 5G equations that express the fact that 5G BS and the user are both on the azimuth plane:

$$azp_x x_u + azp_y y_u + azp_z z_u = azp_x X_S + azp_y Y_S + azp_z Z_S$$
$$elp_x x_u + elp_y y_u + elp_z z_u = elp_x X_S + elp_y Y_S + elp_z Z_S \qquad (3)$$

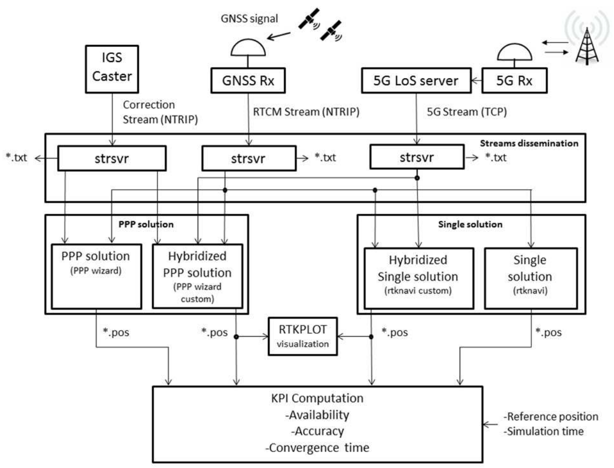
with (*Xs, Ys, Zs*) and (x_u, y_u, z_u) respectively the BS and the user coordinates in ECEF .
The state vector (estimated parameters) is as:

$$\Delta X = \left[P, Clk_{1,..n}, B_{fi_{1,..n}}, \Delta Tr, sI, N\right] \qquad (4)$$

- P : position vector (x_u, y_u, z_u)
- $Clk_{1,..n}$: receiver clock for each constellation
- $B_{fi_{1,..n}}$: estimated biases for each constellation and frequency
- ΔTr : zenithal tropospheric delay
- sI : slant ionospheric delay
- N : phases ambiguities
- n : number of constellations

5 RESULTS

5.1 Test Architecture



The PPP corrections are retrieved from an IGS caster, and the GNSS observations are recorded from a mass market receiver (Samsung Galaxy S8 or ublox M8T). They are provided as RTCM streams through an NTRIP connection. 5G observations are provided through a TCP stream.

The hybridization with Precise Point Positioning is computed with the customized software PPPwizard, while the hybridization with classical GNSS solution is computed with the customized rtknavi software from the open source suite RTKLIB.

Each solution is provided under the same format and post-processed with a Matlab code.

5.2 KPI

The defined KPI are the availability, the accuracy and the convergence time (below 1 meter) of the solution.

5.3 Test Cases

The GNSS test conditions are visibility conditions and are chosen to be clear-sky, urban and canyon environments. GPS, GLONASS and GALILEO constellations are used in the L1 band in order to be as close as possible to current mass market receivers.

The 5G conditions are the relative position of the 5G base stations (BS) with respect to the User Equipment (UE). The following BS locations are used:

- N20: North 20 meters (azimuth angle equals 180 deg from the 5G BS)
- N20 E20: North 20 meters and East 20 meters (2 5G BS: 180deg and 270deg)
- N20 SE20: North 20 meters and South-East 20 meters (2 5G BS: 180deg and 315deg)

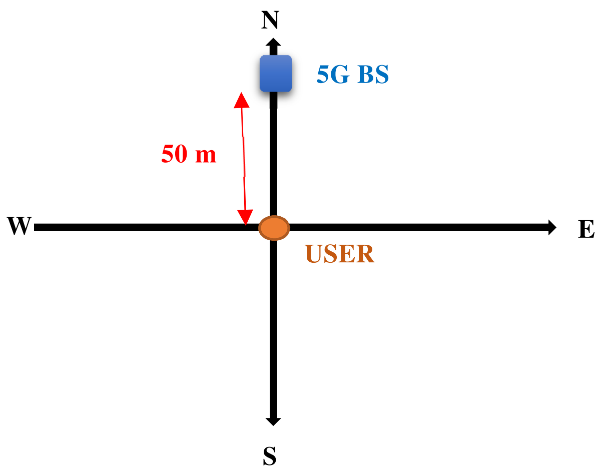
5.4 Compared Performance

An extract of the results is presented hereafter.

5.4.1 Clear Sky

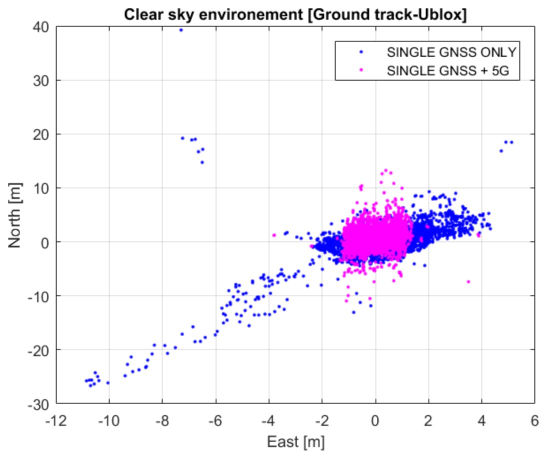
5.4.1.1 N50

The user is placed at 50 m from 5G BS.

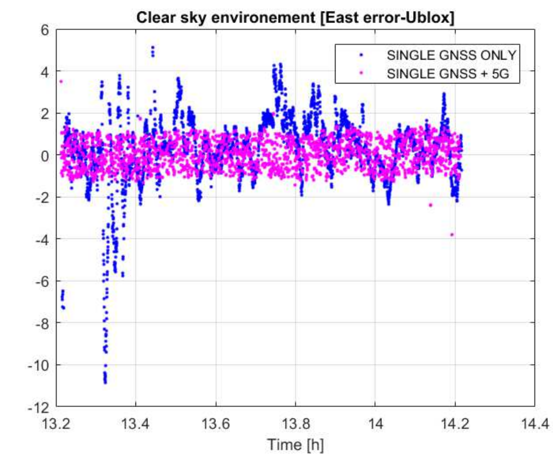


N50 case

5.4.1.1.1 Single positioning

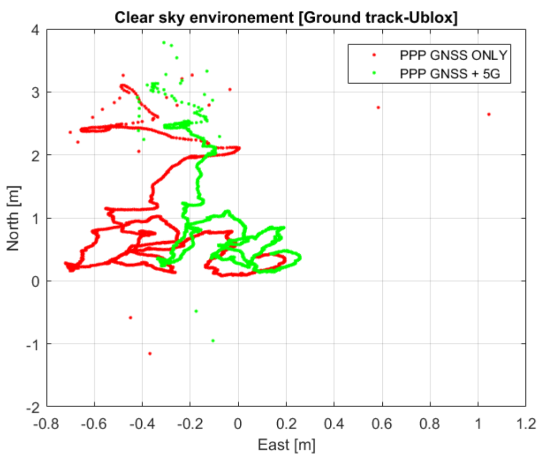


Ground track (Single positioning)

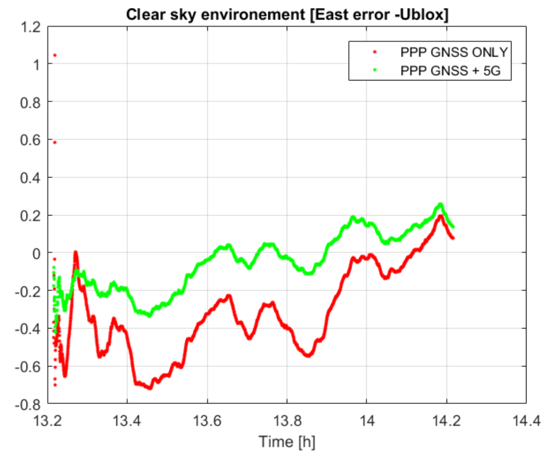


East errors (Single positioning)

5.4.1.1.2 Precise Point positioning



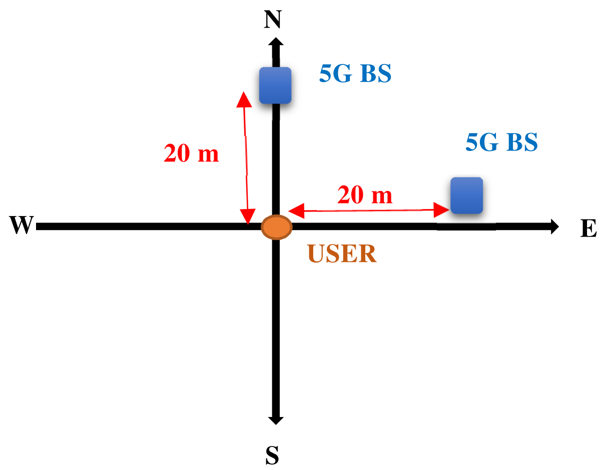
Ground track (PPP)



East errors (PPP)

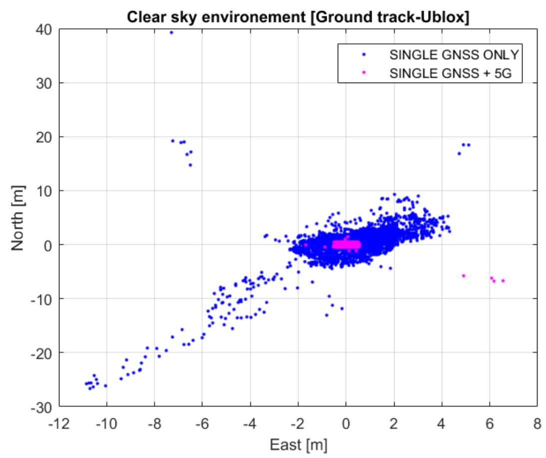
5.4.1.2 N20 E20

The user is placed at 20 m from two 5G BS placed at East and North.

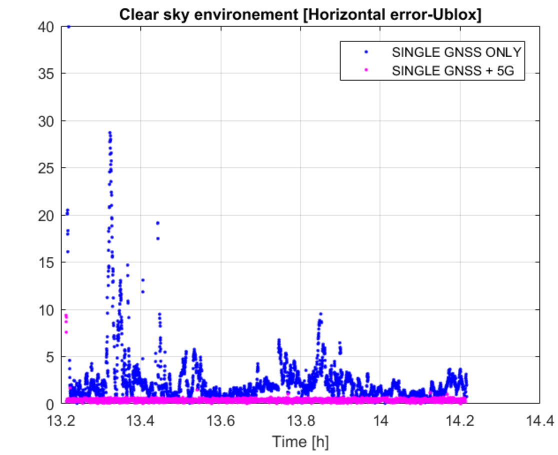


N20 E20 case

5.4.1.2.1 Single positioning

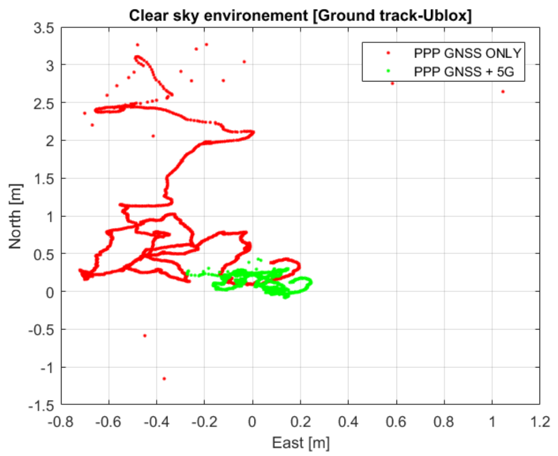


Ground track (Single positioning)

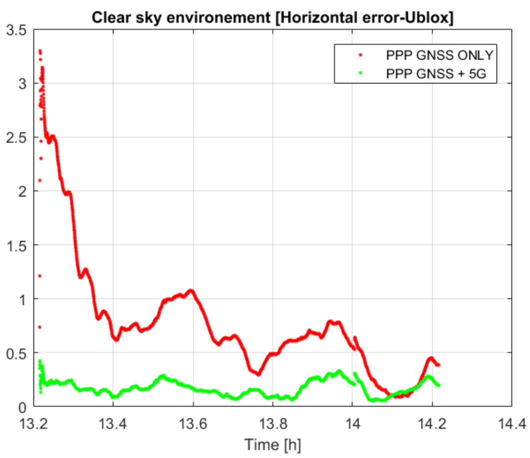


Horizontal errors (Single positioning)

5.4.1.2.2 Precise point positioning



Ground track (PPP)

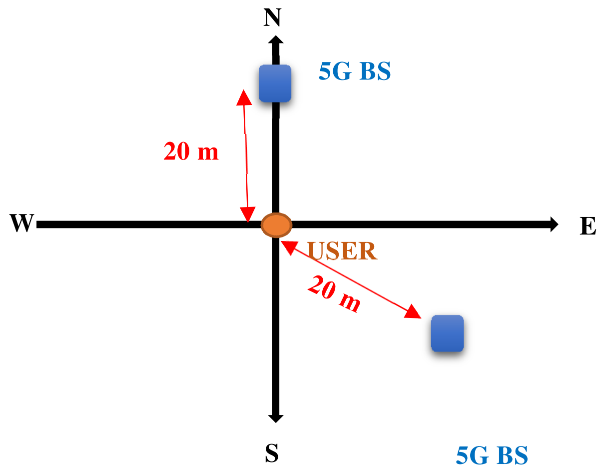


Horizontal errors (Single positioning)

5.4.2 Urban

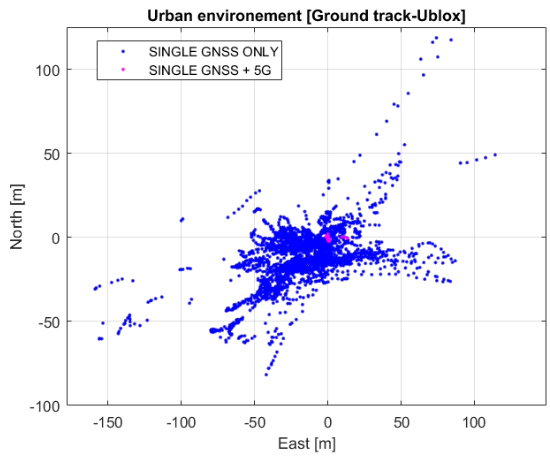
5.4.2.1 N20 SE20

The user is placed at 20 m from two 5G BS placed at South-East and North.

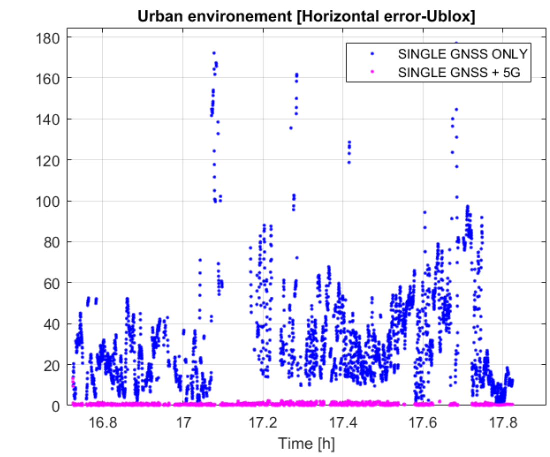


N20 SE20 case

5.4.2.1.1 Single positioning

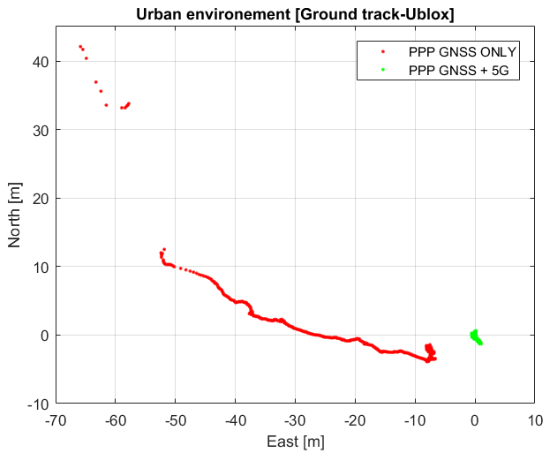


Ground track (Single positioning)

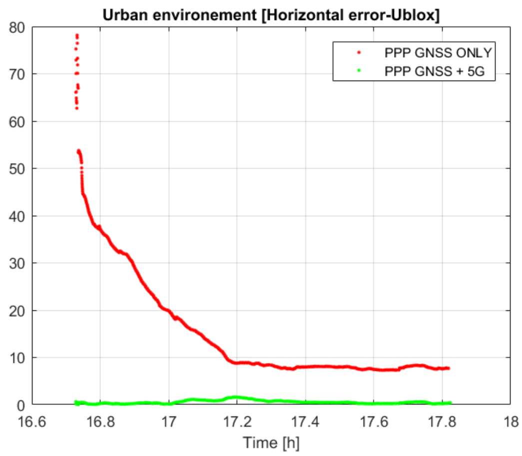


Horizontal errors (Single positioning)

5.4.2.1.2 Precise Point Positioning



Ground track (PPP)



Horizontal errors (PPP)

5.5 Sum-Up

Previous results provided graphically are summed up on table form hereafter. More use cases have been conducted and the corresponding results are shown into the sum-up table. The canyon scenario has been run to observe the limits of the solution proposed by reusing the input data from the urban scenario adding a satellite mask of 45° and using GPS only which leads to solutions with 3 satellites only.

Test Case	Conf.	Method	Availability [%]	Accuracy [m]					Convergence time [mn]
				Mean	Std	70th prctl	95th prctl	99th prctl	
Clear sky	No 5G	PPP	99.917	0.492	0.224	0.634	0.790	0.964	23.53
		Single	98.89	1.845	1.279	2.147	4.244	6.448	NA
	N50	PPP 5G	99.917	0.483	0.213	0.602	0.860	0.962	23.86
		Single. 5G	99.972	1.635	1.165	1.873	4.063	5.754	NA
	N20 E20	PPP 5G	99.917	0.172	0.068	0.216	0.287	0.320	0
		Single. 5G	99.74	0.381	0.150	0.467	0.595	0.663	NA
	N20 SE20	PPP 5G	99.917	0.265	0.131	0.331	0.466	0.623	0
		Single. 5G	99.722	0.518	0.273	0.622	1.008	1.160	NA
Urban	No 5G	PPP	91.722	15.174	11.509	16.068	37.975	53.170	No Conv.
		Single	72.645	41.789	101.768	40.389	84.826	175.059	NA
	N20	PPP 5G	91.722	2.012	2.070	2.269	3.002	4.023	No Conv.
		Single. 5G	77.645	14.504	30.005	14.872	31.662	114.191	NA
	N20 E20	PPP 5G	91.722	0.492	0.202	0.597	0.836	0.923	28.217
		Single. 5G	72.396	0.430	0.198	0.516	0.745	0.918	NA
	N20 SE20	PPP 5G	91.764	0.479	0.208	0.572	0.858	0.949	31.8
		Single. 5G	72.757	0.725	0.448	0.904	1.608	1.901	NA
Canyon	NO 5G	PPP	0	No fix	No fix	No fix	No fix	No fix	NA
		Single	0	No fix	No fix	No fix	No fix	No fix	NA
	N20	PPP 5G	49.669	405.91	428.39	397.17	1402.5	1421.5	NA
		Single. 5G	39.458	2256.062	14277.033	1310.511	4880.827	28832.353	NA
	N20 E20	PPP 5G	61.556	341.22	277.27	384.71	835.27	1277.5	NA
		Single. 5G	66.105	0.4006	0.1848	0.4787	0.6449	0.7272	NA
	N20 SE20	PPP 5G	61.556	328.55	220.86	386.21	715.44	1020.60	NA
		Single. 5G	66.157	0.517	0.280	0.605	1.029	1.197	NA

For the canyon tests, only the solutions with 5G are possible. The test with a single 5G station show extremely bad results. When checking the geometry of the solution, one sees that at one point the 3 satellites used are aligned east-west. These leads to a geometric solution like a line north-south which is parallel to the plain equation provided by the 5G station.

6 CONCLUSIONS

The addition of a 5G antenna clearly improves the positioning accuracy in the direction perpendicular to the antenna.

Sub-metric accuracy is achievable even in an urban environment with the use of two perpendicular 5G antennas 20m apart.

The outcome of these experimentations have shown the added value of the 5G when it comes to positioning performances. As observed in the last table, the 5G is especially important in the urban environments where GNSS signals are less available and the base stations are close enough. On the other hand, the interest of using 5G diminishes with the distance to the base station. The results when using a station at 50m are hardly improved by 5G. One can imagine that in a rural environment, 5G positioning will not improve GNSS.

The results including PPP improve the GNSS + 5G results as could be expected.

ACKNOWLEDGMENTS

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