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# A BENCHMARK OF THE GPS+GALILEO F9P RECEIVER

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## ABSTRACT

*Still very few publications relate test results of multiconstellation receivers since Galileo satellites massive launch by Ariane 5, leading to more than 20 operational space vehicles in orbit. One can refer to automotive receivers and smartphones test bench made during the European COST action SaPPART (Satellite Positioning Performance Assessment for Road Transport), but this was GPS only or GPS+Glonass. This article gives an overview of a test carried out in the city of Nantes, France, and its suburban area, with a brand new receiver, F9P, of the automotive range of Ublox. The dual constellation configuration GPS+Galileo is tested. This receiver is benchmarked with respect to the previous generation of Ublox LEA6T.*

**Keywords:** *GPS, Galileo, receiver, performance, road transport*

## 1 CONTEXT, METHODOLOGY AND EXPERIMENTAL SET-UP

### 1.1 Context

Still very few publications relate test results of multiconstellation receivers since Galileo satellites massive launch by Ariane 5 in end 2016, end 2017 and mid 2018, leading to more than 20 operational space vehicles in orbit. One can refer to automotive receivers and smartphones test bench made during the European COST action SaPPART [1] (Satellite Positioning Performance Assessment for Road Transport), but this was GPS only or GPS+Glonass [2].

The context is that of two consecutive projects, called INTURB for Urban Integrity, and Urban E-map, both in which 3D city model aiding has been investigated. The former one proved the interest of classifying LOS vs NLOS satellites (Non-Line-Of-Sight) using such model, whilst the second proposed map matching on an enhanced map representing all lanes and all modes (cars, buses, cycles, pedestrians) in order to improve the use of 3D computing.

### 1.2 Methodology

The methodology consisted in reproducing, with the new Ublox F9P series, the trajectories previously done in 2014 with the Ublox LEA former series. These trajectories included rural and urban parts, around and in Nantes, and they lasted approximately 2 hours. Due to long term changes in the GPS constellation at the time of the different tests, both Ublox LEA and F9P series will be embedded in the new campaign. The experiment was planned in 2019.

The objective here is twofold: first, compare the LEA and F9P series in terms of positioning accuracy when tracking the GPS satellites only, and second, assess the improvement thanks to the Galileo satellites on positioning accuracy, those being actually tracked by new F9P multiconstellation multifrequency receivers. Note that the multifrequency capability is not studied in this experimental campaign.

### ***1.3 Experimental set-up***

The test took place on Wednesday August 14, 2019. The acquisition was made with the VERT vehicle (Véhicule d'Essais et de Référence en Trajectographie) shown in Figures 1 and 2. The reference trajectory has been calculated from an hybridization between the GNSS signals received on-board and the vehicle gyroscope and wheel speed sensors, with the same equipment and method as usual in the Geoloc lab, in particular for the 2014 test for Urban Integrity (INTURB) project and also for the 2017 SaPPART campaign. The acquisition and calculation of the reference trajectory have been carried out by the Geoloc team of Ifsttar. VERT is the Vehicle for Experimental Research on Trajectory of IFSTTAR [3]: the reference trajectory considered as the ground truth is provided, in this experimental set-up, by a tactical inertial measurement unit (iXSea LandINS) coupled to GNSS PPK (GPS+Glonass Novatel DL-V3 calculated with a local permanent GNSS station, the one of Nantes Metropole).

The specimens under test were prepared by the CoSys team (where Damien Rivoal was part of, during his internship). Throughout the journey, the acquisition of satellite signals was done using multiband antennas. Two Ublox F9P multiconstellation multifrequency receivers were used, each with its own antenna. These receivers output NMEA frames and raw data. One receiver was dedicated to GPS signals only, and the other to GPS and Galileo signals. This double acquisition will allow – after processing the raw data or directly from NMEA frames – to assess the contribution of the Galileo constellation on positioning accuracy.

Another receiver, Ublox LEA6T, which the lab used formerly for several experiments in particular in 2014, was also installed on-board the vehicle.



Figure 1 – Experimental set-up in the Vehicle for Experimental Research on Trajectory



Figure 2 – Antennas on the roof top of the VERT

Antennas used were multiband Ublox ANN-MB for both F9Ps. The LEA6T was connected to a patch antenna ANN-MS.

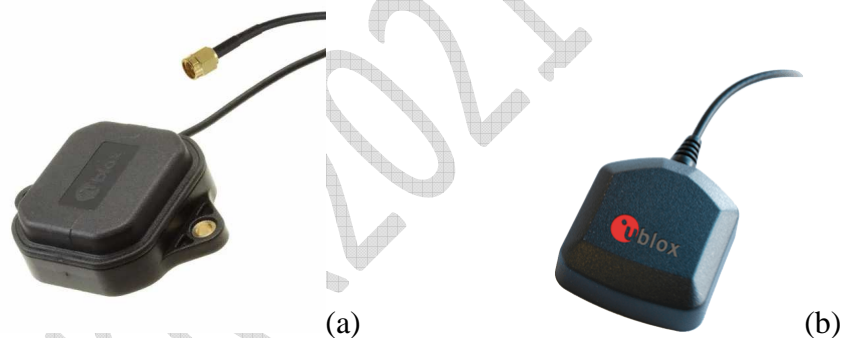


Figure 3 – Model of antenna connected to each F9P receiver (a) and to the LEA6T receiver (b)

Both F9P and LEA6T devices were configured in default mode. Only settings needed for raw data output and NMEA sentences, at 5Hz, were modified (and GPS only for one F9P).

#### ***1.4 GNSS data acquisition***

GNSS data were acquired at a frequency of 5Hz. Two breaks which lasted approximately 600s were made in order to ensure safe log-in of the F9Ps by a laptop running Ucenter data logger (v19.03), which resulted in splitting the data files into three, each of a duration of approximately 1 hour. This was not needed for the LEA6T, which could be logged continuously and without any trouble on another laptop running Ucenter v8.16.

The data files to process are:

- One file of GPS measurements recorded for the LEA6T;
- Three files of GPS measurements recorded for one F9P;
- Three files of GPS and Galileo measurements recorded by the other F9P.

GPS times are converted into UTC times of day, removing also the current 18 leapseconds. Occasionally, data frames may be missing at start or stop of the different acquisitions. The highest start time and lowest stop time between RINEX and GGA are underlined hereafter.

The chronogram of the acquisitions is given in Table 1.

LEA6T_2019_08_14.ubx, converted into RINEX 2.10 with RTKCONV 2.4.2								
2019	8	14	6	26	18.8010000	GPS	TIME OF FIRST OBS	= 23160.80
2019	8	14	9	2	18.8000000	GPS	TIME OF LAST OBS	= <u>32520.80</u>
\$GPGGA,062603.80 ( <u>23163.80</u> ) to \$GPGGA,090200.80 (32520.80)								

F9P_190814_063424.ubx + 190814_073911.ubx + 190814_084055.ubx, GPS only, converted into RINEX 2.10 with RTKCONV 2.4.3								
2019	8	14	6	34	49.8000000	GPS	TIME OF FIRST OBS	= <u>23671.80</u>
2019	8	14	7	28	4.2010000	GPS	TIME OF LAST OBS	
\$GPGGA,063431.80 ( <u>23671.80</u> ) to \$GPGGA,072746.20 (26866.20)								
2019	8	14	7	39	34.5990000	GPS	TIME OF FIRST OBS	
2019	8	14	8	31	1.0000000	GPS	TIME OF LAST OBS	
\$GPGGA,073916.60 (27556.60) to \$GPGGA,083042.80 (30642.80)								
2019	8	14	8	41	19.4020000	GPS	TIME OF FIRST OBS	
2019	8	14	9	0	8.8030000	GPS	TIME OF LAST OBS	= 32390.80
\$GPGGA,084101.20 (31261.20) to \$GPGGA,085950.60 ( <u>32390.60</u> )								

F9P_190814_063120.ubx + 190814_073712.ubx + 190814_083900.ubx, GPS+Galileo, converted into RINEX 3.03 with RTKCONV 2.4.3								
2019	8	14	6	31	54.7890000	GPS	TIME OF FIRST OBS	= <u>23496.80</u>
2019	8	14	7	29	23.3900000	GPS	TIME OF LAST OBS	
\$GPGGA,063136.60 (23496.60) to \$GPGGA,072905.20 (26945.20)								
2019	8	14	7	37	43.8020000	GPS	TIME OF FIRST OBS	
2019	8	14	8	32	9.0030000	GPS	TIME OF LAST OBS	
\$GPGGA,073725.60 (27445.60) to \$GPGGA,083151.00 (30711.00)								
2019	8	14	8	39	30.0020000	GPS	TIME OF FIRST OBS	
2019	8	14	9	0	39.6020000	GPS	TIME OF LAST OBS	= 32421.60
\$GPGGA,083911.80 (31151.80) to \$GPGGA,090021.40 ( <u>32421.40</u> )								

<b>[STATIC]</b>	<b>[MOVE OUT]</b>	<b>[MOVE URB]</b>	<b>[STATIC]</b>	<b>[MOVE URB]</b>	<b>[STATIC]</b>	<b>[MOVE OUT]</b>
[23163.80 23889]	[23889 24828]	[ <u>24828 26824</u> ]	]26824 27667[	[ <u>27667 30627</u> ]	]30627 31381]	]31381 32520.80]
[ <u>23671.80</u> 23889]	[23889 24828]	[ <u>24828 26824</u> ]	]26824 <b>stop</b> 27667[	[ <u>27667 30627</u> ]	]30627 <b>stop</b> 31381]	]31381 <u>32390.60</u> ]
[23496.80 23889]	[23889 24828]	[ <u>24828 26824</u> ]	]26824 <b>stop</b> 27667[	[ <u>27667 30627</u> ]	]30627 <b>stop</b> 31381]	]31381 32421.40]

Table 1 – Chronogram of the data acquisition of the different receivers on 14 August 2019: start and stop times are aligned onto resp. 23671.80 and 32390.60, common to all data files

Only the kinematic sketches (in green in Table 1) will be considered for performance analysis, respectively in rural and urban conditions. The static sketches (initial and on the way during which both stops were made, in red in Table 1) are not processed later on. The corresponding time windows have been defined graphically at starts and stops of the vehicle.

The rural part contains 9742 epochs (~33min) at 5 Hz and the urban part 24782 (~1h23min). Except the two breaks, no frame is missing for F9P GGA logging, whilst a few are missing for LEA6T, both in rural (8 missing) and urban parts (1 missing).

### 1.5 Former LEA6T data acquisition in Nantes

Another file of GPS measurements was recorded formerly on Thursday February 27, 2014, for the LEA6T. Note that it was during winter (whereas during summer in 2019, with different foliage and possibly multipath) and under different constellations.

GPS times are converted into UTC times of day, removing also the 16 leapseconds in 2014. The chronogram of the acquisition is given in Table 2.

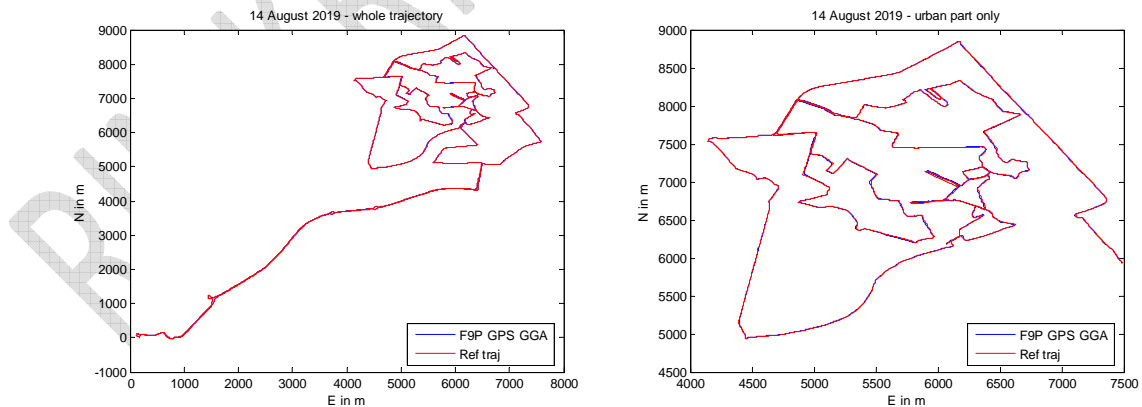
2014_02_27_LEA6T.ubx, converted into RINEX 2.10 with RTKCONV 2.4.2							
2014	2	27	8	34	13.0010000	GPS	TIME OF FIRST OBS = <u>30837.00</u>
2014	2	27	10	22	15.2010000	GPS	TIME OF LAST OBS = <u>37319.20</u>
\$GPGGA,083357.00 ( <u>30837.00</u> ) to \$GPGGA,102159.20 ( <u>37319.20</u> )							

[ <b>STATIC</b> ]	[ <b>MOVE OUT</b> ]	[ <b>MOVE URB</b> ]	[ <b>MOVE OUT</b> ]
[30837.00 31127]	[31127 31977]	[ <b>31977 36432</b> ]	[36432 37319.20]

Table 2 – Chronogram of the data acquisition of the different receivers on 27 February 2014

The rural part contains 8685 epochs (~29min) at 5 Hz and the urban part 22276 (~1h14min). A few GGA frames are missing: 32 and 54 in rural and urban parts resp.

The trajectory carried out during the 2019 test is represented in a local tangent plane (using latitude and longitude of a monument located on lab site) on Figures 4 and 5. Several major detours can be observed compared to the initially planned trajectory similar as the former test in 2014 with LEA6T. (This was due to numerous works along the west part of the travel.)



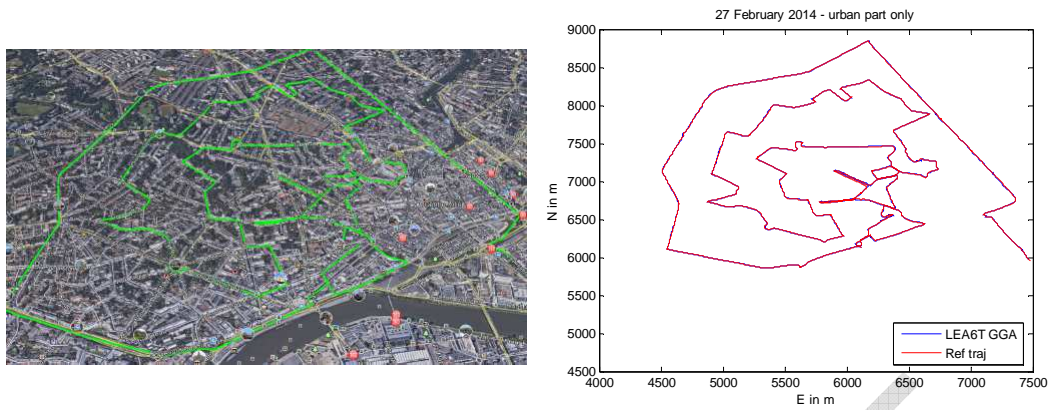


Figure 4 – Whole plane trajectory, August 14, 2019, and in downtown Nantes for F9P GPS: the bottom right subframe shows the urban part collected in 2014, February 27

Figure 5 is a zoom in downtown Nantes, where plane errors are visible. They can reach tens of meters in severe urban canyons.

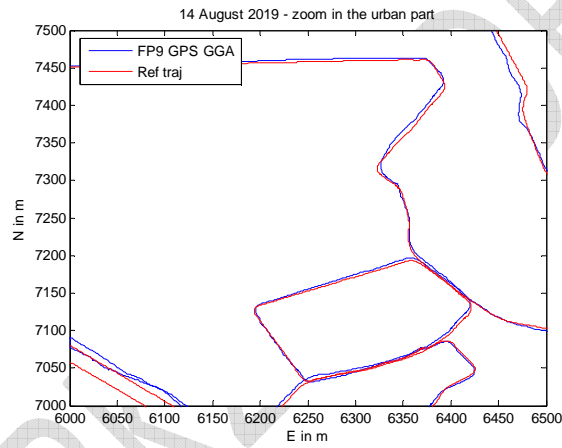


Figure 5 – Zoom in downtown Nantes for F9P GPS, August 14, 2019

## 2 RESULTS BASED ON NMEA FRAMES

First investigations were made on the basis of the GGA frames. They indeed contain the navigation solutions computed by the manufacturer of the equipment (latitude and longitude) along with timing, which enables the computation of the horizontal distance with respect to the VERT reference trajectory, this being interpolated at the same timing.

### 2.1 Accuracy

The analysis compares city centre vs suburban and rural areas, which are part of the total travel (in between the Ifsttar lab and the city centre). The static parts have been removed. Table 3 is based on GGA frames, i.e. on navigation solutions computed by Ublox:

Receiver	urban part	suburban and rural parts
LEA6T (2014)	1.59	0.95
LEA6T	2.04	1.59
F9P GPS	2.67	1.20
F9P GPS+Galileo	1.46	0.89

Table 3 – Median plane errors (in m) in the different parts of the trajectory

### 2.2 Number of satellites

Table 4 is still based on NMEA frames, and it reports the average number of satellites, signal-to-noise ratios (CN0) and HDOP (Horizontal Dilution Of Precision) extracted from the GGA frames during each part. These satellites were actually used in the navigation solutions (among those tracked). CN0 can be extracted from the GSV frames, which were also logged during the tests:

Receiver	urban part	suburban and rural parts
LEA6T (2014)	avg. 8.24 sat. / 43.18dB / 1.28	avg. 8.81 sat. / 45.44dB / 1.02
LEA6T	avg. 7.31 sat. / 41.84dB / 1.33	avg. 8.94 sat. / 42.85dB / 1.08
F9P GPS	avg. 6.69 sat. / 40.48dB / 1.25	avg. 6.90 sat. / 42.33dB / 1.32
F9P GPS+Galileo	avg. 11.44 sat. / 39.80dB / 0.99	avg. 11.66 sat. / 41.09dB / 0.94

Table 4 – Average number of satellites, CN0 and HDOP per epoch in the different parts of the trajectory

### 2.3 Discussion

Based on the NMEA frames, the discussion is threefold:

- First, a question is raised concerning the accuracy of the LEA6T: there is an important difference between the accuracies of the two data sets (2014 and 2019).

In the rural part: the number of satellites is almost the same. The median HDOPs are both close to 1.00. But the average CN0 is 45.44dB in 2014, versus only 42.85dB in 2019. The ranging noise stochastic model from [4] and already used by [5] for Ublox LEA6T gives:

$$\sigma^2 = m (10^{-\text{CN0}/10} - 10^{-55/10})$$



From experience, CN0 has 55dB maximum value. And the parameter  $m$  should be adjusted to match the actual plane accuracy.  $m=45000$  makes sense, giving median plane accuracies of 1.19m, versus 1.53m, for 2014 and 2019 data sets resp.

Thus the difference in CN0 can explain the difference in accuracy.

In the urban part: median HDOPs are close to 1.25. And average CN0 are 43.18dB and 41.84dB resp. Using the same model, this makes 1.68m, versus 1.94m, for 2014 and 2019 data sets resp.

- Second point concerns the F9P tracking GPS only: it seems this receiver experiences multipath with severe impact in the urban environment. Whereas the other receivers have half a meter increase of the median plane error compared to the rural environment, the increase is here much more: 1.5m. The number of satellites tracked, which – if low – mechanically degrades the HDOP, and the perturbation in ranging with buildings around, cannot explain this degradation of the accuracy by itself.

The diminution of the number of satellites used between the rural and urban environments is not more important for F9P than for LEA6T. A hypothesis could be that the LEA6T used to apply a rather severe FDE (fault detection and exclusion) algorithm, compared to F9P. Presumably, Ublox makes use of sequential Extended Kalman Filter (EKF) innovation-based FDE [6], but this is not publicly documented. Degraded measurements remaining in the F9P solution, with one constellation only (GPS), could cause large errors.

- Last, the best accuracy obtained corresponds to using both GPS and Galileo constellations. In rural environment, the median plane error is below one meter (0.89m) and close to 1.5m in the city of Nantes with the F9P receiver.

### 3 RESULTS BASED ON RAW DATA

#### 3.1 Computation of the position of the GNSS satellites

Ephemeris for both GPS and Galileo constellations (among others) were downloaded from [https://igs.bkg.bund.de/root\\_ftp/MGEX/BRDC\\_v3/2019/226/](https://igs.bkg.bund.de/root_ftp/MGEX/BRDC_v3/2019/226/), namely brdm2260.19p.Z file. These broadcasted ephemeris gather GPS+GLO+GAL+BDS+QZSS+IRNSS+SBAS satellites, and they were merged by DLR from streams of about 35 stations, until 2020 (<https://www.igs.org/mgex/data-products>). For 2014, nmcu0580.14n collected in the Nantes permanent station was downloaded from IGN.

Hopfield tropospheric with Essen and Froome parameters and broadcasted ionospheric correction terms have been applied (\*).

#### 3.2 Computation of the ranging errors

Based on the reference trajectory, as well as on the broadcasted ephemeris and atmospheric corrections, receiver-to-satellites ranging errors have been computed, fixing the receiver clock term with the highest satellite in elevation. (Its error becomes consequently null). Note that whereas LEA6T keeps its clock drift within 1ms, it can exceed 10ms for F9P (Figure 6).

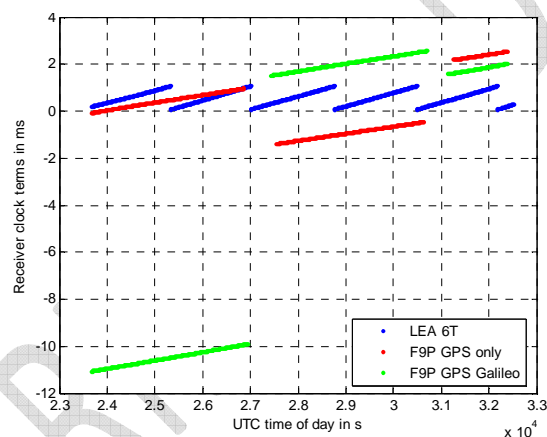


Figure 6 – Clock terms of LEA6T and F9Ps receivers

These errors are represented in histograms in Figures 7 to 10 next.

Each figure displays urban (left) versus rural (right) parts, and histograms for ranging errors (top) and signal-to-noise ratios (bottom).

At first visual inspection, there is obviously a difference between urban and rural ranging errors, in terms of symmetry in the distribution as well as in terms of amplitude of the errors. Positive queues in the distribution are clearly visible in the city of Nantes, irrespective of the receivers and the constellations used.

One can notice that the Gaussian queues have an order of magnitude of several tens of m in urban environment, which is much more than in rural environment. This is the same magnitude as tropospheric corrections, but occasionally these errors may be much larger. (Note that the order of magnitude of ionospheric corrections is only of several m.) Since these corrections are applied, the large errors observed are therefore significant of non-line-of-sight satellite tracking. Histograms of CN0 are also given with CN0 average value (in red). CN0

between 30-35dB are clearly over represented in urban environment, which makes a bump in their distribution, not visible in rural environment.

Table 5 gathers urban parts in 2014 (22276 epochs for LEA6T) and 2019 (24782 epochs in 2 sketches for LEA6T and F9P receivers). Note that the number of satellites which were registered is slightly different from those reported in the NMEA solutions which actually passed Ublox's FDE.

LEA6T 2014	LEA6T 2019
166033 ranges (1 epoch with no range log) - 22275 epochs => 143758 ranging errors 7.45 sat. / epoch	165653 ranges - 24782 epochs => 140871 ranging errors 6.68 sat. / epoch
median(err) = 0.89m (vs 0.61m in rural *) 2.5 percentile = -3.84m (vs -3.61m in rural) 97.5 percentile = 33.30m (vs 8.62m in rural)	median(err) = 0.87m (vs 0.28m in rural) 2.5 percentile = -4.54m (vs -4.47m in rural) 97.5 percentile = 35.69m (vs 19.04m in rural)
errors are 65% positive	errors are 63% positive

F9P GPS 2019	F9P GPS GALILEO 2019
188614 ranges (2 epochs with no range log) - 24780 epochs => 163834 ranging errors 7.61 sat. / epoch	319483 ranges - 24782 epochs => 294701 ranging errors 12.89 sat. / epoch
median(err) = 2.12m (vs 0.93m in rural) 2.5 percentile = -3.00m (vs -1.67m in rural) 97.5 percentile = 49.95m (vs 34.74m in rural)	median(err) = 1.27m (vs -0.01m in rural) 2.5 percentile = -2.99m (vs -3.09m in rural) 97.5 percentile = 42.71m (vs 26.42m in rural)
errors are 80% positive	errors are 73% positive

Table 5 – Median ranging errors showing dissymmetric histograms in urban environment

(\* It appears that the solar activity, impacting ionospheric effect, was high in 2014 and low in 2019, which justified the use of broadcasted vs seasonal alpha - beta parameters in 2014.)

Statistics, and particularly the 97.5 percentiles, confirm the dissymmetry and the distribution of the ranging errors. These percentiles are systematically much larger in Nantes than out of Nantes. In a few words, errors are generally positive, whereas it should be equally distributed around zero. This characterizes multipath impact on ranging in the urban environment.

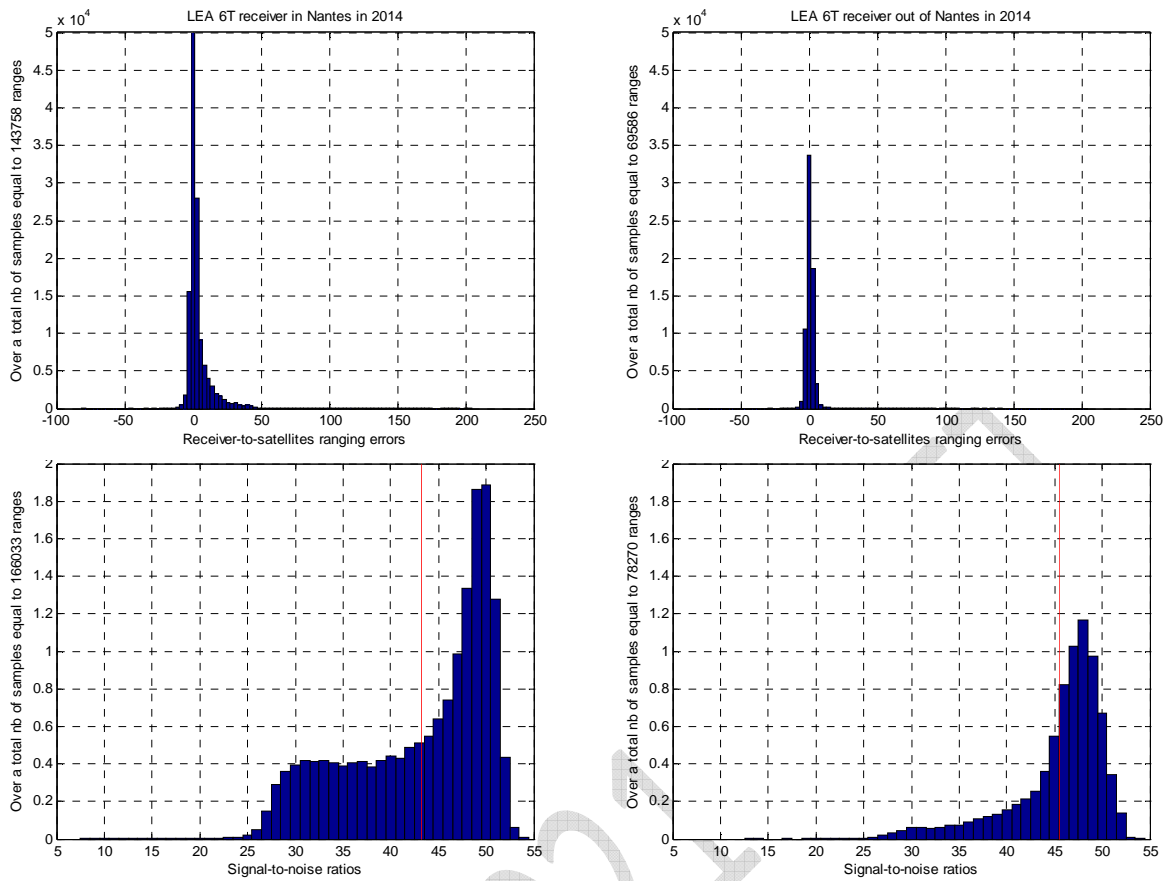


Figure 7 – LEA 6T ranging errors and CN0 (2014) in (left) and out of Nantes (right)

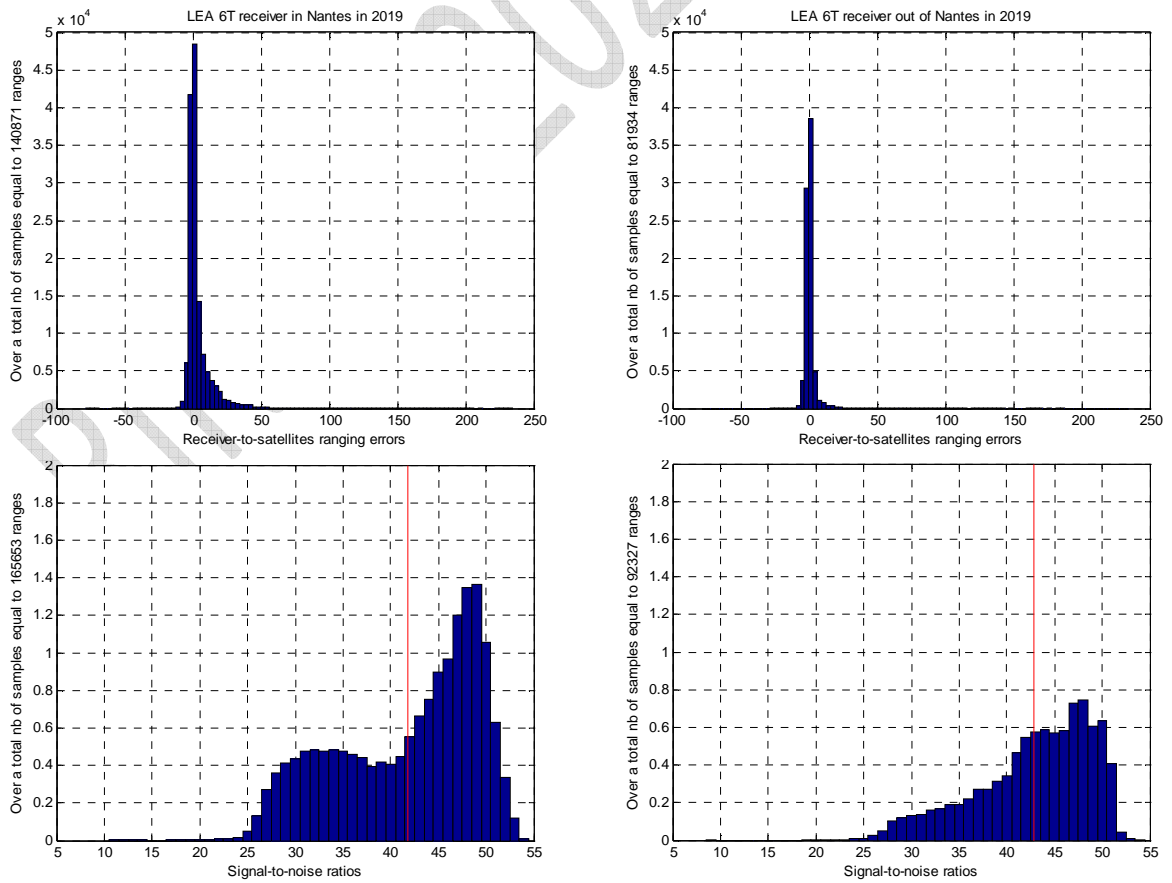


Figure 8 – LEA 6T ranging errors and CN0 (2019) in (left) and out of Nantes (right)

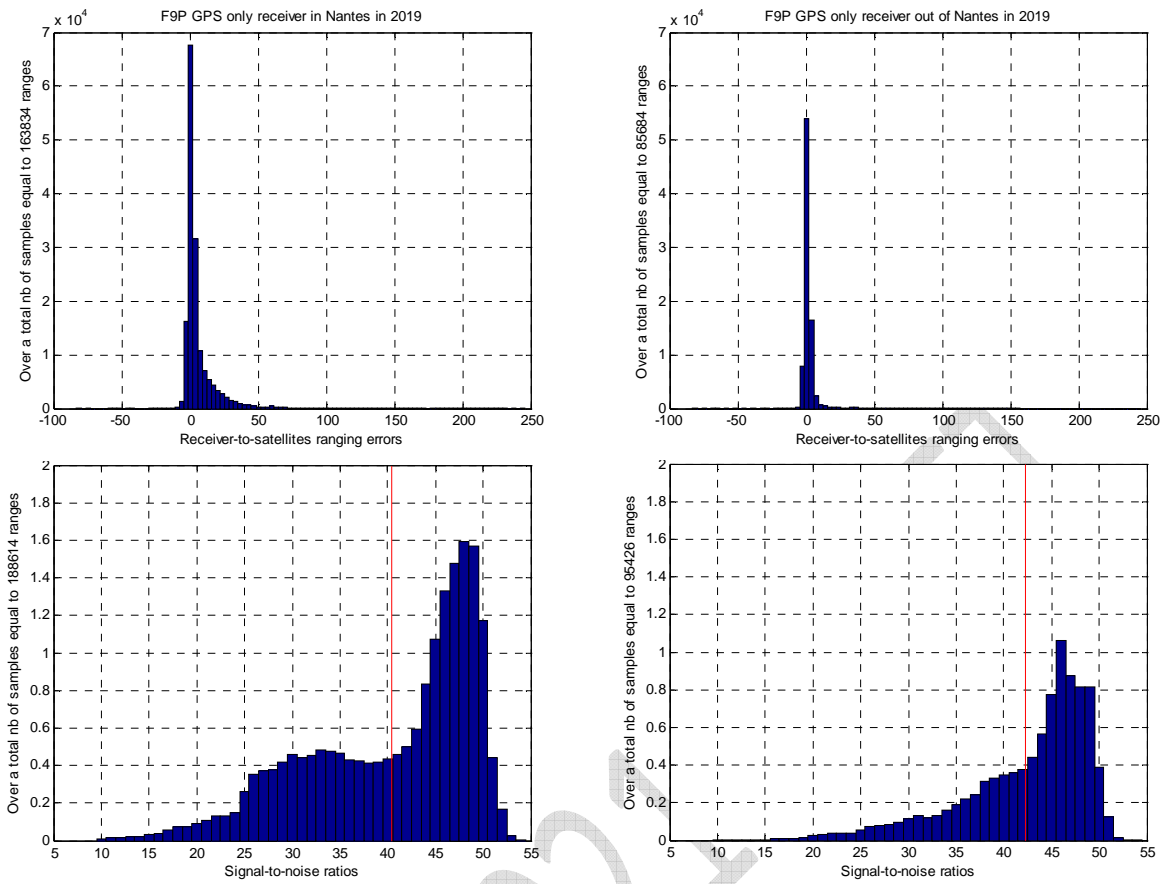


Figure 9 – F9P ranging errors and CN0 (GPS) in (left) and out of Nantes (right)

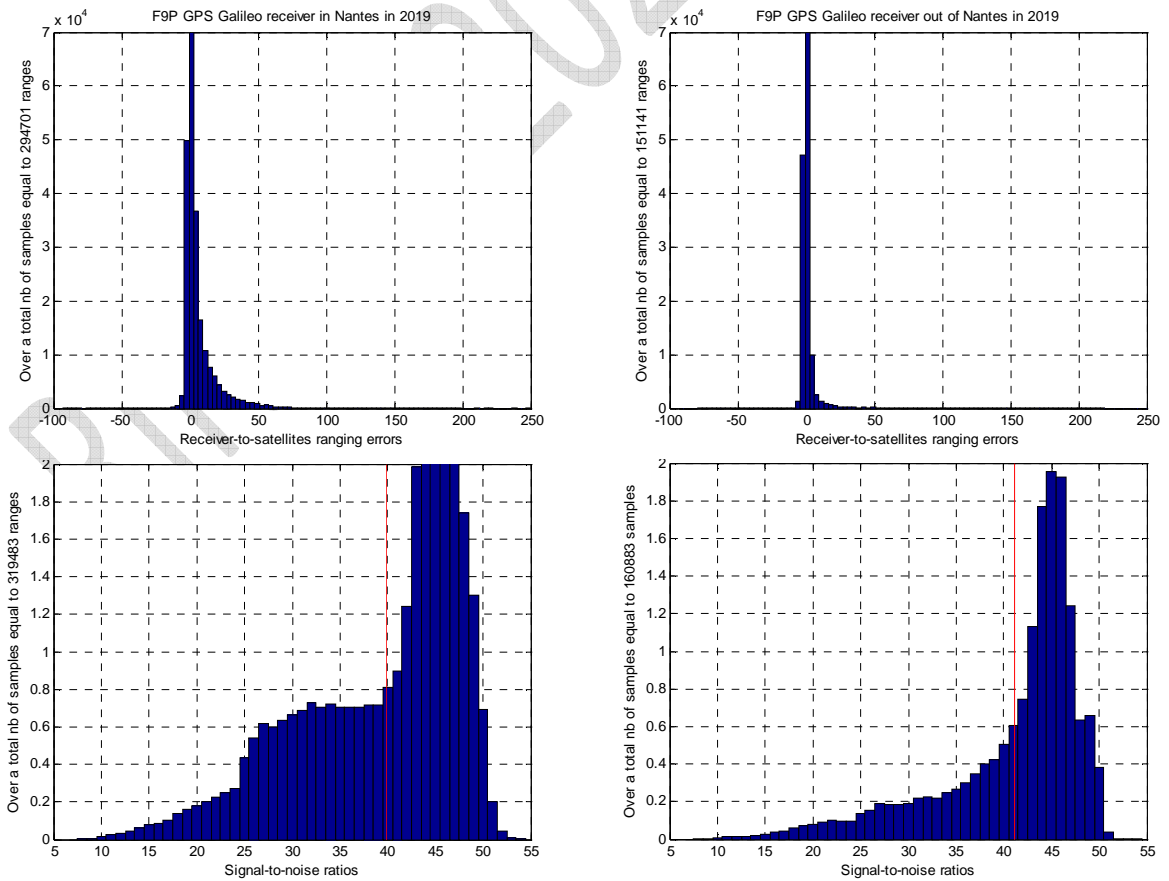


Figure 10 – F9P ranging errors and CN0 (dual GPS Galileo) in (left) and out of Nantes (right)

## Conclusions and perspectives

To conclude, despite urban perturbations, the F9P median plane accuracy assessed in this campaign is around 1.5m, with a clear advantage of sharing GPS and Galileo constellations. Out of the city, the F9P median plane error is below 1m. The potential improvement by 3D city model is challenged for further research, with the aim of approaching the median plane error obtained in rural and suburban environments (less than 1m).

We have clearly identified ranging errors in the urban environment, for GPS observations as well as Galileo. We are currently trying to model and correct them, using 3D city modelling. Next step in this research will be to try to explain the observed ranging errors with local 3D map, and apply the process of downweighting and correction already presented in [5].

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