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Agriculture Machine Guidance Systems: Performance Analysis of Professional GNSS Receivers

Abstract.

GNSS (Global Navigation Satellite Systems) plays nowadays a major role in different civilian activities and is a key technology enabling innovation in different market sectors. For instance, GNSS-enabled solutions are widespread within the Precision Agriculture and, among them, applications in the field of machinery guidance are commonly employed to optimize typical agriculture practices. The scope of this paper is to present the outcomes of the agriculture testing campaign performed, employing a real tractor under different scenarios, by Thales Alenia Space Italia in the implementation of a contract signed with the European Agency for the Space Programme (EUSPA) and financed by the European Union under the Galileo Programme budget. The main objective of the test campaign was to evaluate the performance of a set of professional GNSS receivers from a user point of view, employing different combinations of GNSS constellations, signals, and positioning techniques. In particular, the added value introduced by Galileo in combination with other GNSS constellations is analyzed in this paper. The paper presents anonymized performance of six professional GNSS receivers, tested in parallel under the same live conditions. The receivers have been tested on real fields in both open sky and close to forest scenario, with the latter representing a more challenging environment. In particular, GNSS Single Point Positioning (with both Single Frequency and Multi-Frequency approach), Satellite Based Augmentation System (SBAS), Precise Point Positioning (PPP), Real Time Kinematic (RTK) and PPP-RTK modes have been tested for single and multi-GNSS processing (GPS, Galileo, GLONASS and BeiDou). The paper summarizes the results obtained comparing 6 different GNSS receivers fixed on the rooftop of a tractor moving at around 6 km/h. The comparison between the different receivers has been based on typical Key Performance Indicators for agriculture-based applications as cross-track and pass-to-pass accuracy, solution availability, continuity, convergence time and number of losses of lock. The preliminary results highlight, on average, comparable performances between the different receivers when analogous positioning strategies are employed. Furthermore, Galileo signals, used in combination with the other GNSS systems, are proven to enhance the performance of the different GNSS receivers evaluated in most of the test cases.

Keywords.
GNSS, Galileo, Agriculture Market Segment, EGNOS.

Introduction

Nowadays, GNSS (Global Navigation Satellite System) represents a key technology for location-based applications, providing cost-effective solutions to users.

The European navigation system, Galileo, was declared operationally ready in December 2016, starting to offer its services worldwide. The performance and limitations of the Galileo Initial Services, together with the system configuration, are described in [1]. Galileo offers a highly accurate service despite, for the time being, the system is not yet in Full Operational Capability (FOC). More specifically, starting from December 2016, with the Early Operational Capability, the constellation evolved and reached the number of 22 usable satellites in July 2021. Further information on the Galileo satellites available for Position, Velocity and Time (PVT) computation can be found in [2].

Manufacturers are gradually enabling Galileo services into their products, and in order to check the status of the implementation in professional receivers, EUSPA (European Union Agency for the Space Programme) commissioned two testing campaigns, between 2020 and 2021. The focus of the testing campaigns was on the precision agriculture market segment, in particular in the field of machine guidance. The first testing campaign, executed in July 2020 and detailed in [3], exploited a rail-carriage configuration in an open sky scenario, to observe the behavior of the receivers in a controlled environment. During the second one, performed in July 2021, the receivers were fixed on a real tractor in two different scenarios, open sky and close to forest, to appreciate the achievable performance in an operational environment.

In this paper the main outcomes of the 2021 agriculture machine guidance testing campaign are shown and analyzed, to highlight differences and commonalities in the results obtained by the tested receivers from a user point of view.

The main aim of the testing campaign was to evaluate the performance of a set of GNSS professional receivers, analyzing the added value of the Galileo system in the GNSS market segment of agriculture machine guidance. Moreover, the testing campaign was also oriented towards the support of the manufacturers, pointing out the benefits on the use of Galileo and providing feedbacks on their products.

The tested positioning modes are reported in Table 1, together with the selected frequency mode (single or multiple). SPP (Single Point Positioning), SBAS (Satellite Based Augmentation System), PPP (Precise Point Positioning), PPP-RTK and RTK (Real Time Kinematic) positioning modes were tested. Additionally, the table also specifies whether the specific test cases were performed in open sky, close to forest, or both of the scenarios. As it can be noted, except for the SBAS test case (REF-01), only multi frequency modes were tested in close to forest, as they generally represent a more robust solution. It is interesting to note that PPP-RTK extends the concept of PPP, also including the corrections for atmospheric errors (caused by the GNSS signal travelling through the ionosphere and troposphere) which are calculated using a CORS (Constantly Operating Reference Station) network [4].

The different positioning strategies, characterized by their own achievable performance, can target different applications. As described in [5], type A applications are related to activities like livestock tracking and geofencing, that do not require extremely accurate positioning modes. On the other hand, type B/C applications like soil sampling and precision viticulture target more accurate systems, able to provide sub-m level horizontal errors. Moreover, type D applications require very accurate positioning modes, like PPP and RTK, to accomplish tasks like farm machineries guidance and automatic steering.

The six RUTs (Receivers Under Test) were tested in single and multi-GNSS configurations, with single and multi-frequency modes. In particular, the SPP mode was tested with GPS-only and Galileo-only in single (L1 and E1) and multi-frequency modes.

Table 1 Positioning modes and selected frequency in Open Sky (OS) and Close to Forest (CF) scenarios

Test ID	Constellations	Freq	Pos. mode	OS	CF
REF-01	GPS	SF	SBAS	✓	✓
REF-02	GPS + GLO	MF	RTK	✓	×
RTK-01	GPS+GAL+GLO	MF	RTK	✓	✓
RTK-02	GPS+GAL	MF	RTK	✓	×
PPP-01	GPS+GAL+GLO	MF	PPP	✓	✓
PPP-02	GPS + GAL	MF	PPP	✓	×
PPP-03	GPS+GLONASS	MF	PPP	✓	×
PPP-04	GPS+GLO + GAL + BDS	MF	PPP	✓	×
YYY-01	GPS+GAL+GLO	MF	PPP-RTK	✓	✓
YYY-02	GPS + GLO	MF	PPP-RTK	✓	×
YYY-03	GPS+GAL	MF	PPP-RTK	✓	×
NOC-01	GPS+GAL+GLO	MF	SPP	✓	✓
NOC-02	GAL	MF	SPP	✓	✓
NOC-03	GPS	MF	SPP	✓	✓
NOC-04	GAL	SF	SPP	✓	×
NOC-05	GPS	SF	SPP	✓	×

On the other side, the triple constellation in SPP and the augmentation modes were all tested in multi-frequency configuration. For the multi-frequency test-cases all the available frequencies supported by the receivers were enabled for the PVT estimation, as shown in Table 2.
It should be underlined that the BeiDou constellation was exploited only in PPP mode, to investigate the possible benefits of a quadruple constellation configuration, mainly in challenging scenarios, in order to ensure high availability of the PVT.

Table 2 Selected frequencies for different positioning modes

Constellation	Standalone	SBAS	PPP/PPP-RTK	RTK
GPS	L1/L2/L5	L1	L1/L2/L5	L1/L2/L5
Galileo	E1/E5a/E5b/E5AltBOC	-	E1/E5a/E5b/E5Alt BOC	E1/E5a/E5b/E5Alt BOC
GLONASS	L1/L2/L3	-	L1/L2/L3	L1/L2/L3
BeiDou	-	-	B1/B2	-

The paper is organized as follows. The next section describes the set-up of the testing campaign focusing also on the main KPIs relevant for the agriculture market segment. The main results of the testing campaign are then presented, through the comparison of the performance of the tested receivers and the indicative benchmarking with user's requirements. Finally, the conclusions of this work are shown in the last section.

Tests setup and KPIs

In this section the setup of the tests and the selected KPIs (Key Performance Indicators) are detailed.

Test Setup

As already anticipated, the main objective of the test campaign was to evaluate professional receivers' performance, highlighting the added value of Galileo and EGNOS in the GNSS market segment of Agriculture Machine Guidance. The RUTs were tested in an operational scenario, mounted on a real tractor performing typical working lines in different configurations, in order to evaluate under real conditions the resulting performance.

As shown in Figure 1, two different scenarios were selected: open sky and close to forest. The first one envisaged visible satellites with an elevation greater than 5° and with a very low multipath fading. The receivers were mounted on a tractor moving at a constant speed of around 6 km/h, performing both straight lines and U-turns. This is the scenario in which the best performance is expected. In synergy with the majority of the manufacturers, also the close to forest scenario was considered. In such a scenario the RUTs experienced obstructions in the signal reception, increased multipath fading with respect to the open sky scenario and, in general, a more challenging environment. In fact, the tractor proceeded at constant speed (4 km/h) around a forest, with one side always covered by the woods.

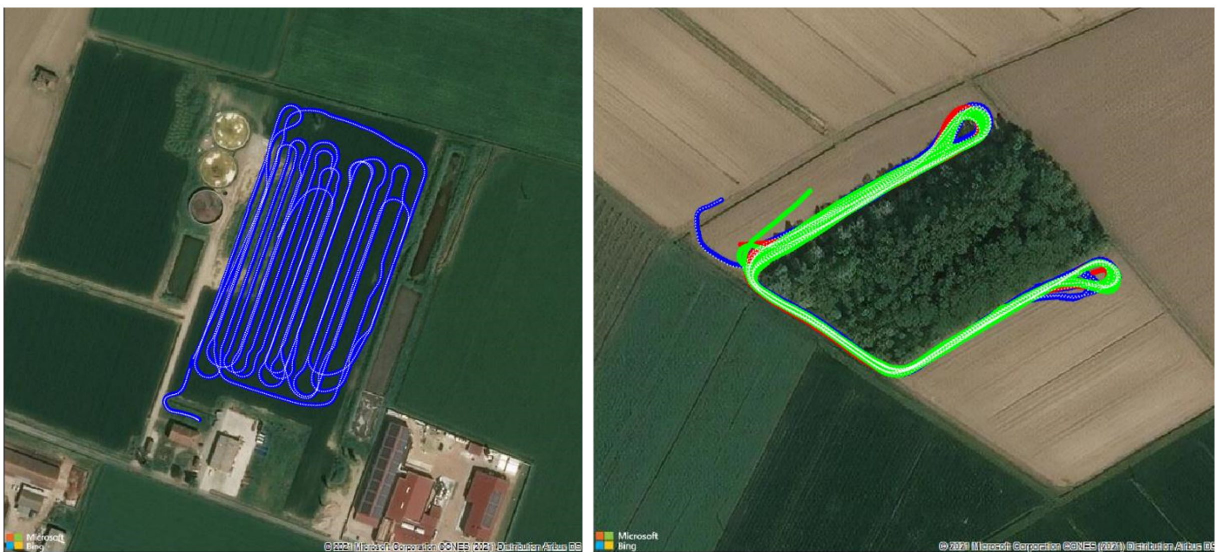

Figure 1 Testing campaign working lines in Open Sky (left) and Close to Forest (right) scenarios.

The data collection duration of each test was of 1 hour. Since the aim of the test campaign was not the validation of the service but the characterization of the real-user experience, a test duration of one hour represented a fair trade-off between the high number of test cases to be executed and the quality of the results obtained.

For what concerns the PPP test cases, the proprietary PPP services were exploited. Data collection started half an hour after the power on of the receivers, to ensure the convergence of the PVT solution. On the other hand, for the RTK, differential corrections were transmitted by a georeferenced base station located a few kilometers from the testing fields.
For this testing campaign, all the additional features (i.e., RAIM, Hatch filters - based smoothing, integration with additional sensors) implemented by the receivers were enabled, in order to evaluate the performance that a real user would achieve during agriculture operations. Moreover, the RUTs were tested in parallel to compare their performance under the same conditions. As an

additional information, five of the six tested receivers were smart antennas, while one of the RUTs was tested using an external antenna provided by the manufacturer.

Key Performance Indicators

For each test case, the agriculture related KPIs showed in Table 3 have been assessed. In Figure 2, cross-track and pass-to-pass accuracy are showed in detail. In particular, for the computation of the accuracy performance, the 95 percentiles of the CDFs (Cumulative Distribution Functions) of the parameters of interest were considered.

Table 3: KPIs definition and computation

KPI	Definition	Computation
Trajectory Error (95%ile)	Variation between the actual tilling trajectory with respect to the reference one	Cross-track accuracy is calculated from a subset of the measurements, excluding the U-turns performed by the tractor. On the other hand, the horizontal accuracy also considers the U-turns, with all the measurements obtained during the test interval
Pass to Pass (P2P) Accuracy (95%ile)	Amount of skip or overlap field area that occurs during agriculture operations	Difference between cross-track errors over a 15 minutes interval
PVT availability	Percentage of time over which the PVT has been computed by using the chosen configuration	Number of epochs with PVT available in the desired mode divided by the number of epochs for the specific test case
Losses of lock vs time	Indicates the change from one solution type to another during the data collection (i.e. RTK fixed to RTK float).	-
Number of tracked/used satellites vs. time	Number of used or tracked satellites by the receiver for PVT estimation during the data collection.	-
HDOP (Horizontal Dilution Of Precision)	Dilution of precision due to the not ideal satellites geometry	$\sqrt{\sigma_N{}^2 + \sigma_E{}^2}$ Square root of the trace of the reduced (2 by 2) covariance matrix, in East and North coordinates
Continuity (over 15 s time window)	Probability that the operational performance (PVT estimation with defined positioning mode) is kept over a fifteen seconds period	This parameter has been calculated by using a 15s moving window
Convergence time	Time that the position estimates need to reach steadily a specific accuracy level, without leaving this level of accuracy	The convergence time was calculated either from NMEA GPGGA message (Quality Indicator) or from raw data files

For the assessment of the positioning errors, the measured positions, extracted from the NMEA (National Marine Electronics Association) files generated by the receivers, were compared with a reference true trajectory generated using a post-processing double differences carrier-phase algorithm included in a commercial third-party software. However, for some of the RUTs, due to the lack of GNSS observations, the reference trajectory was estimated using the Least Squares approach with a minimum of 3 other receivers' reference trajectories.
It should be noted that in the computation of the HDOP, the first two elements of the diagonal of the covariance matrix were used (in East and North coordinates).

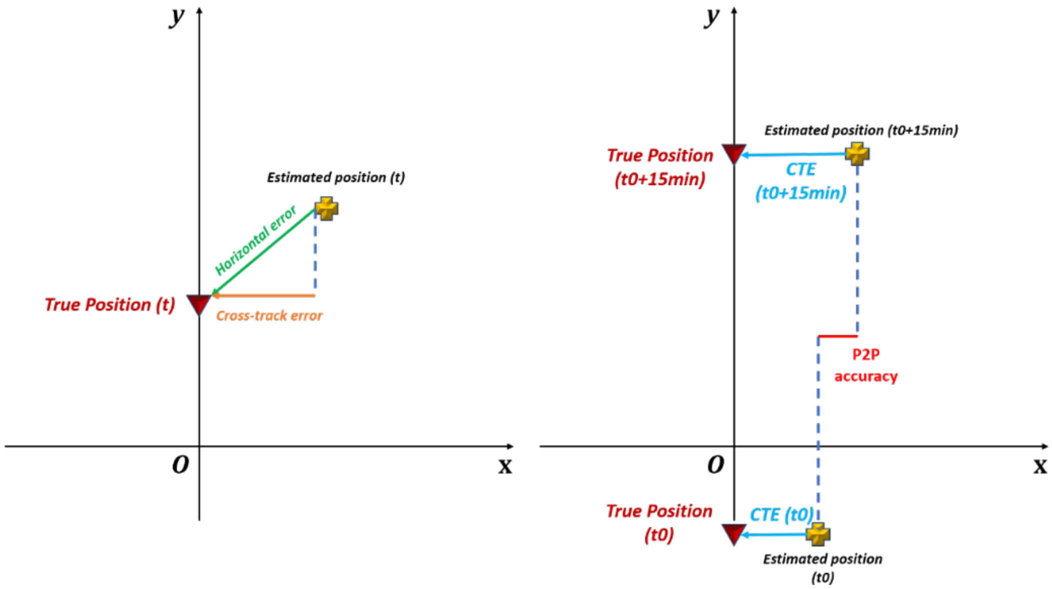

Figure 2: Agriculture-related KPIs: cross-track error (CTE, on the left) and pass-to-pass accuracy (on the right).

Results

The two parameters selected to compare the results obtained during the testing campaign are the 95%ile of the CDFs (Cumulative Distribution Functions) of cross-track and pass-to-pass accuracy. In fact, these two parameters represent the most important accuracy indicators concerning precision agriculture requirements and can thus be used to make a qualitative comparison between the tested configurations and receivers. However, it is important to highlight, from a statistical point of view, that the tests were performed in parallel, thus the test execution for different configurations was not simultaneous. In this sense, the different tests were executed under different satellite's geometry.

The reported histograms are often adjusted on the vertical axis to improve the readability of the data. This may bring some (unexpected) results to be partially hidden on the graph, as specified in the following sections.

Open Sky

In the figures below cross-track and pass-to-pass accuracy results are represented in histograms, divided into positioning modes and configurations. The number of receivers exploited for each test case is not the same between the two testing campaigns, as not all the RUTs had the same configurations available for both the testing campaigns, but it is still possible to make several considerations on the outcomes. Availability and continuity, as expected in open sky scenario, were always very close to 100% for all the test cases. However, some exceptions are reported in the following.

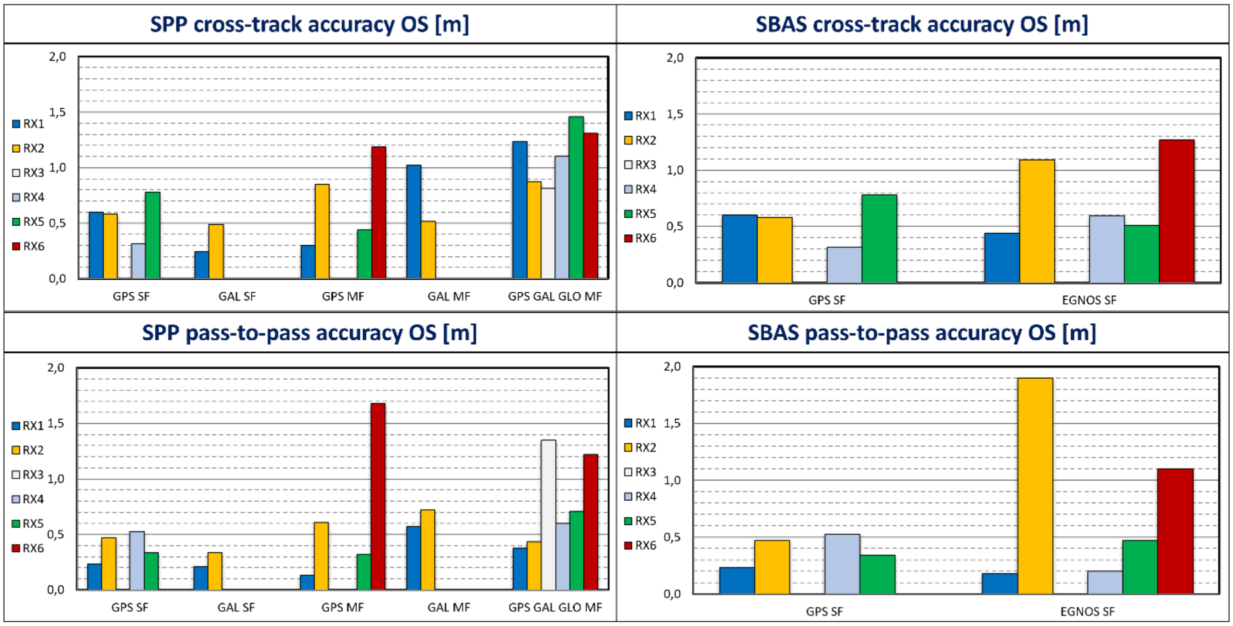

Figure 3: Single Point Positioning (SPP) and SBAS (EGNOS) cross-track and pass-to-pass accuracy histograms [m]

From Figure 3, it is clear that the single constellation configurations, on average, obtained better results with respect to the triple constellation configuration, for both cross track and pass to pass accuracy. As a matter of fact, GPS single frequency had an average reduction of around the 46% for cross track accuracy with respect to the GPS + Galileo + GLONASS mode. The same behavior can be highlighted also for Galileo single and multi-frequency and for GPS multi-frequency, with the first one obtaining an average cross track accuracy of around 26 centimeters (an improvement of the 68% when compared to the triple constellation results). This outcome could have been caused mainly by two factors. The proprietary algorithms, maybe optimized for the single constellation, could have enhanced the accuracy performance in single frequency mode. At the same time, especially in open sky scenario, it should be considered that the adoption of the triple constellation configuration may increase the complexity within the estimation algorithm including additional unknowns related to the synchronization errors of different GNSS constellations. Furthermore, the different satellites geometry cannot be neglected considering that the different configurations were tested non-simultaneously. However, it should be noted that all the results are in line with the meter level expectations, and sometimes the RUTs offered results even above the expectations. As a general trend, the multi frequency configurations did not provide any significant improvement over the respective single frequency modes. Moreover, it should be noted that, in single frequency mode and with a similar number of satellites, Galileo provided comparable or better results than GPS, for both cross track and pass to pass accuracy.

For what concerns SBAS, in Figure 3 (right) cross track and pass to pass accuracies for EGNOS + GPS L1 are compared with GPS single frequency mode. In general, it is expected to see enhanced results when exploiting EGNOS corrections over the respective standalone positioning mode. However, some of the RUTs had accuracy improvements, while others performed in a slightly worse way, probably due to the significant enhancements in the GPS L1 results. In fact, it can be noted that, with an average 77 centimeters of cross track (despite the unexpected behavior of RX2 and RX6), the results are perfectly in line with the expectation and with the meter/sub-meter user requirements (shown in Figure 7, type B/C). Moreover, RX1, RX4 and RX5 obtained a pass to pass between 10 and 50 centimeters, that confirm the suitability of such an augmentation method for agriculture activities like soil sampling and precision viticulture.

For RX2, that obtained meter level accuracy in SBAS mode, an 82% availability was registered, together with a 96% continuity, that partially justify the outcomes.

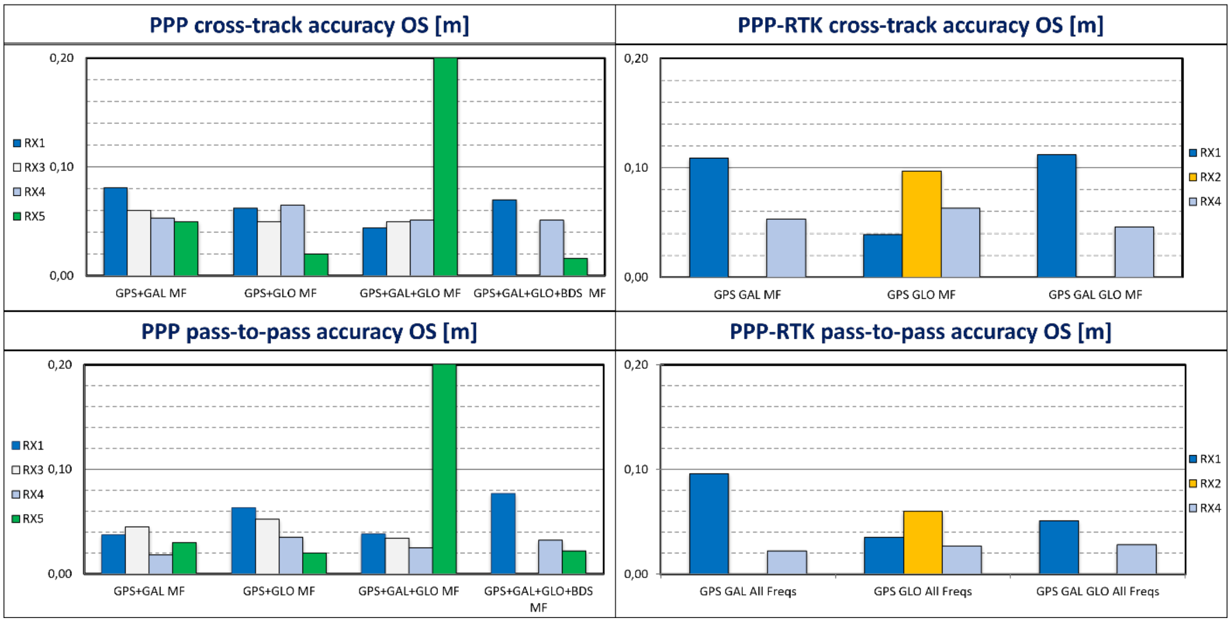

Figure 4: PPP and PPP-RTK cross-track and pass-to-pass accuracy histograms [m]

In Figure 4, the results obtained in PPP and PPP-RTK modes are shown. It can be noted that the Precise Point Positioning and the PPP-RTK configurations were always analyzed in multi-constellation multi-frequency mode, as it represents the most interesting setup for a real user. The obtained cross-track and pass-to-pass accuracies do not show any major discrepancy between the receivers for both PPP and PPP-RTK, aside from the unexpected results observed for RX5 with the triple constellation configuration in PPP mode. Once again it can be noticed that the triple constellation, as well as the quadruple constellation (also exploiting BeiDou), does not provide significant improvements in open sky scenario, as the number of satellites used for PVT is already sufficient with the GPS + Galileo configuration to obtain a certain accuracy level. Overall, the accuracy performance is perfectly in line with the expectations, as for both PPP and PPP-RTK cross track and pass to pass accuracies are generally below 10 centimeters. It should be considered that, especially for RX4, PPP-RTK obtained comparable accuracy performance with significantly lower convergence times. As a matter of fact, PPP-RTK convergence times, on average, resulted to be inside the 1 to 5 minutes range, while in PPP, a real user would have to wait 20 to 40 minutes to obtain a converged solution.

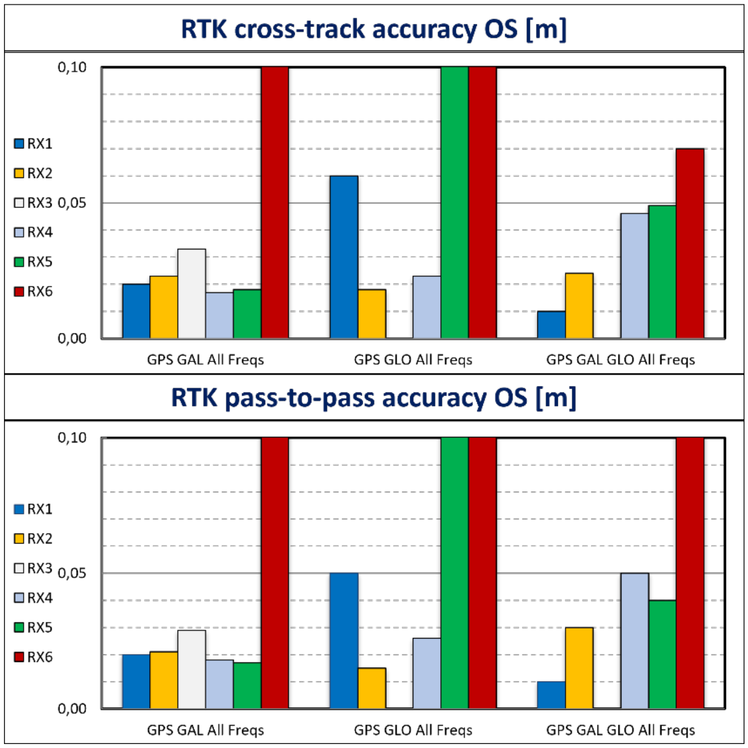

Figure 5: RTK cross-track and pass-to-pass accuracy histograms [m]

For what concerns the RTK configurations, cross track and pass to pass accuracies are reported in Figure 5. In particular, in the agriculture testing campaign with real machineries, the receivers showed accuracy performance around 2 centimeters, with a slight worsening with the triple-constellation configuration. As it can be seen in the histograms, RX6 performed under the expectations in all the RTK test cases and RX5 also had issues with the GPS + GLONASS configuration in 2021. Overall, RTK remains the most reliable and accurate positioning mode, even in the harsh conditions in which the receivers operated. More specifically, RTK is the only tested positioning mode that appears to be suitable for the most stringent user requirements listed in [5], like farm machineries guidance and automatic steering, that require accuracies up to 2.5 centimeters.

Close to Forest

In this section cross track and pass to pass errors for the close to forest scenario are described, to highlight differences and commonalities between the tested configurations, receivers, and scenarios. Close to Forest results shall be interpreted with more attention, as the harsh environmental conditions lead to more variance of the results and due to the low statistics. As expected, availability and continuity are generally lower than the ones obtained in open sky.

The accuracy results obtained in close to forest scenario for standalone positioning mode, PPP, PPP-RTK, RTK, and SBAS are reported in Figure 6. It is evident that the single constellation configurations obtained degraded results with respect to the open sky scenario. In particular, GPS and Galileo, in multi frequency mode, registered a rise in the average cross track error of, respectively the 56% and (excluding RX3, that exploited a very low number of satellites for PVT in Galileo only-mode) 34%, with average cross tracks of around 1.95 and 1.10 meters. For RX1, unfortunately, due to the low availability, it was not possible to compute the pass-to-pass accuracy in Galileo standalone positioning mode, thus it is not represented in Figure 6. Moreover, RX3, probably due to the low number of satellites exploited for PVT, obtained unexpected results.

For the triple constellation configuration, on the other hand, results' degradation was less evident, with only an 18% worsening in the cross-track accuracy, that reached an average of around 1,37 meters. This outcome highlights the added value of the triple constellation mode in close to forest scenario, as it performed in a similar way with respect to the open sky scenario.

For what concerns the other positioning modes (on the right in Figure 6), the receivers performed slightly below the expectations in close to forest scenario. It should be noted that the scale of the histograms is different between the left and the right side of the figure. In particular, it can be seen that in RTK mode, the RUTs obtained cross-track and pass-to-pass accuracies between 4 and 12 centimeters. RX6, on the other hand, performed in an unexpected way, with a cross track of around 85 centimeters. Looking at the GPS Quality indicator in the NMEA file, it was discovered that the RUT did not operate in RTK fixed mode, probably due to connection problems with the base station. However, RTK registered the best results among the positioning modes employed in close to forest scenario, being suitable for the majority of the agriculture applications, even in such a harsh environment.

PPP and PPP-RTK obtained degraded results with respect to the open sky scenario. As a matter of fact, only RX5 in PPP, and RX2 and RX4 in PPP-RTK managed to keep the cross-track error below 15 centimeters. For the other test cases, the presence of the woods constantly covering one side of the tractor led to problems in the signal reception, and thus degraded the performance of PPP and PPP-RTK services, based on satellite corrections.

The GPS L1 + EGNOS configuration performed below the expectations, probably for the same reason explained for the PPP mode. However, for cross-track accuracy, RX1 and RX5 performed in line with the expectations, with sub-meter level results. The other RUTs, as it can be noted, obtained meter level results for both cross-track and pass-to-pass accuracy.

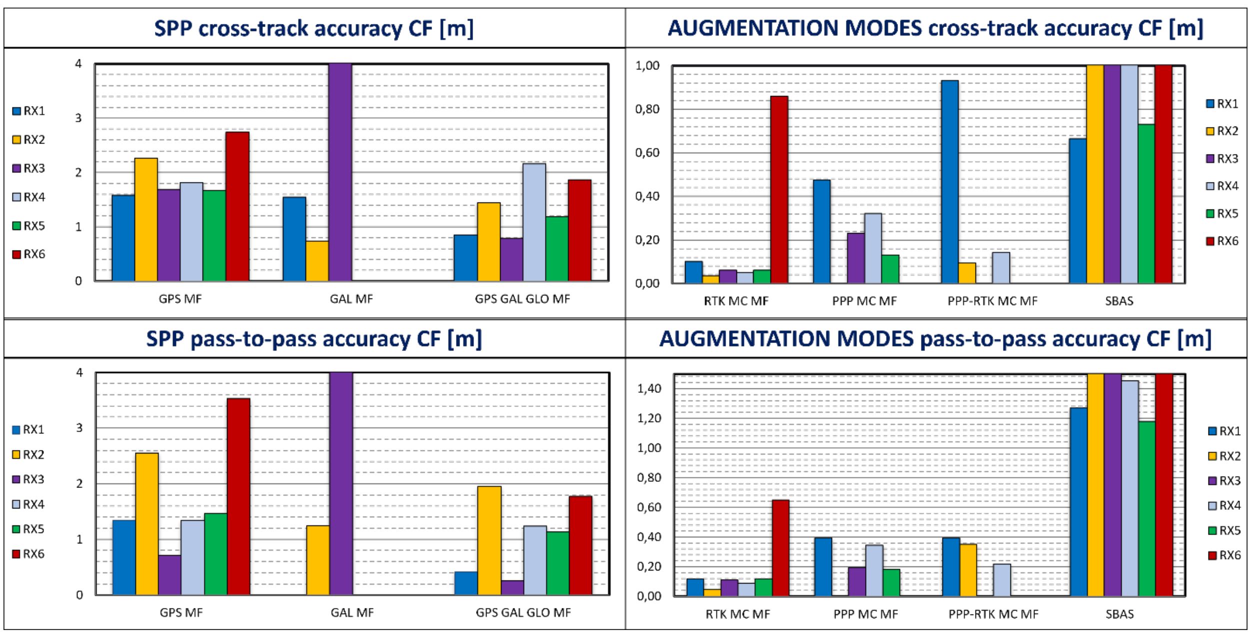

Figure 6: Close to forest cross-track and pass-to-pass accuracy histograms [m]

Average performance benchmarked with agriculture requirements

In this section the average results are listed and compared with the agriculture specific requirements for all the tested configurations. The application type is defined with a specific accuracy requirement and associated to a certain configuration, that is expected to be suitable for that operation.

As it can be seen in Figure 7, GPS-only configurations are required to obtain m-level results, suitable for applications like livestock tracking, virtual fencing and geotraceability. These accuracies were provided both in open sky and in close to forest, with, as expected, better performance in open sky scenario.

For what concerns the triple constellation and the Galileo-only configurations, the target is set at m/sub m-level. In the agriculture machine guidance campaign all the mentioned configurations obtained the required results, being suitable for the type B/C applications, like soil sampling and precision viticulture, both in open sky and close to forest scenario. A similar target is defined for SBAS, that managed to obtain results in line with its user requirements in open sky, while experienced degraded performance in close to forest.

PPP and PPP-RTK modes are selected as suitable for applications requiring accuracies between 2.5 cm and 10 cm, perfectly in line with the obtained results for both the positioning modes in open sky. On the other hand, the obstructions caused by the woods in close to forest scenario degraded the performance and demonstrated that these positioning modes are not always able to provide the required cross-track accuracy for type D applications in such a harsh environment.

It is clear that, for RTK configurations, the operational environment brought to performance not always in line with the most stringent user requirements in both open sky and close to forest, but still in line with the expectations. In particular, the GPS + GLONASS configuration highlighted some unexpected performance, not suitable for the specified type D applications, like automatic steering and VRA-high (Variable Rate Applications).

Scenario	Positioning Mode	Constellation	Application Type (required cross-track accuracy)	Average performance
Open Sky	SBAS	GPS + EGNOS	Type B/C – sub-metre	✓
Open Sky	RTK	GPS + GLONASS	Type D – down to 2.5 cm	⚠
Open Sky	RTK	GPS + GLONASS + GALILEO	Type D – down to 2.5 cm	✓
Open Sky	RTK	GPS + GALILEO	Type D – down to 2.5 cm	✓
Open Sky	PPP	GPS + GLONASS	Type D – 2.5 – 10 cm	✓
Open Sky	PPP	GPS + GLONASS + GALILEO	Type D – 2.5 – 10 cm	✓
Open Sky	PPP	GPS + GALILEO	Type D – 2.5 – 10 cm	✓
Open Sky	PPP	GPS + GLONASS + GALILEO + BDS	Type D – 2.5 – 10 cm	✓
Open Sky	PPP-RTK	GPS + GLONASS + GALILEO	Type D – 2.5 – 10 cm	✓
Open Sky	PPP-RTK	GPS + GLONASS	Type D – 2.5 – 10 cm	✓
Open Sky	PPP-RTK	GPS + GALILEO	Type D – 2.5 – 10 cm	✓
Open Sky	Standalone	GPS + GLONASS + GALILEO	Type B/C – meter-sub-metre	✓
Open Sky	Standalone	GALILEO	Type B/C – meter-sub-metre	✓
Open Sky	Standalone	GPS	Type A – meter-level	✓
Open Sky	Standalone	GALILEO (SF)	Type B/C – meter-sub-metre	✓
Open Sky	Standalone	GPS (SF)	Type A – meter-level	✓
Close to Forest	Standalone	GPS + GLONASS + GALILEO	Type B/C – meter-sub-metre	✓
Close to Forest	Standalone	GALILEO	Type B/C – meter-sub-metre	✓
Close to Forest	Standalone	GPS	Type A – meter-level	✓
Close to Forest	RTK	GPS + GALILEO + GLONASS	Type D – down to 2.5 cm	⚠
Close to Forest	PPP	GPS + GALILEO + GLONASS	Type D – 2.5 – 10 cm	⚠
Close to Forest	PPP-RTK	GPS + GLONASS + GALILEO	Type D – 2.5 – 10 cm	✓
Close to Forest	SBAS	GPS + EGNOS	Type B/C – sub-metre	⚠

Legend
Type A - meter-level of accuracy (*Livestock tracking and virtual fencing, Geotraceability*)
Type B - meter-level/sub-metre (*Soil Sampling, Farm machinery monitoring and asset management*)
Type C - sub-metre (*Harvest/Yield Monitoring, Biomass Monitoring, Precision viticulture, Precision Forestry, Field delineation*)
Type D - cm-level (*Farm Machinery Guidance, Automatic Steering, VRA-Low, VRA-High*)
✓ In line with expectations ⚠ Improvements needed

Figure 7: Average performance highlighted by the testing campaign. Required cross-track accuracy is defined in [5].

Galileo added value

The results obtained in this testing campaign highlighted the added value of Galileo for positioning accuracy performance. In most of the tested configurations, Galileo brought an added value in terms of cross-track and pass-to-pass accuracies. Indeed, although the Galileo constellation was not yet fully deployed (tests were performed throughout the month of July 2021), it is recorded that Galileo, in some test cases (with a comparable number of satellites), provided better positioning accuracy performance than GPS, in terms of cross-track and pass-to-pass accuracy, reaching sub-meter level in open sky scenario and contributing to reach high PVT availability in close to forest scenario.

An example of results showing the added value of Galileo is reported in Figure 8, displaying that Galileo all frequencies outperformed GPS all frequencies in standalone positioning with RX2, for both open sky and close to forest scenario.

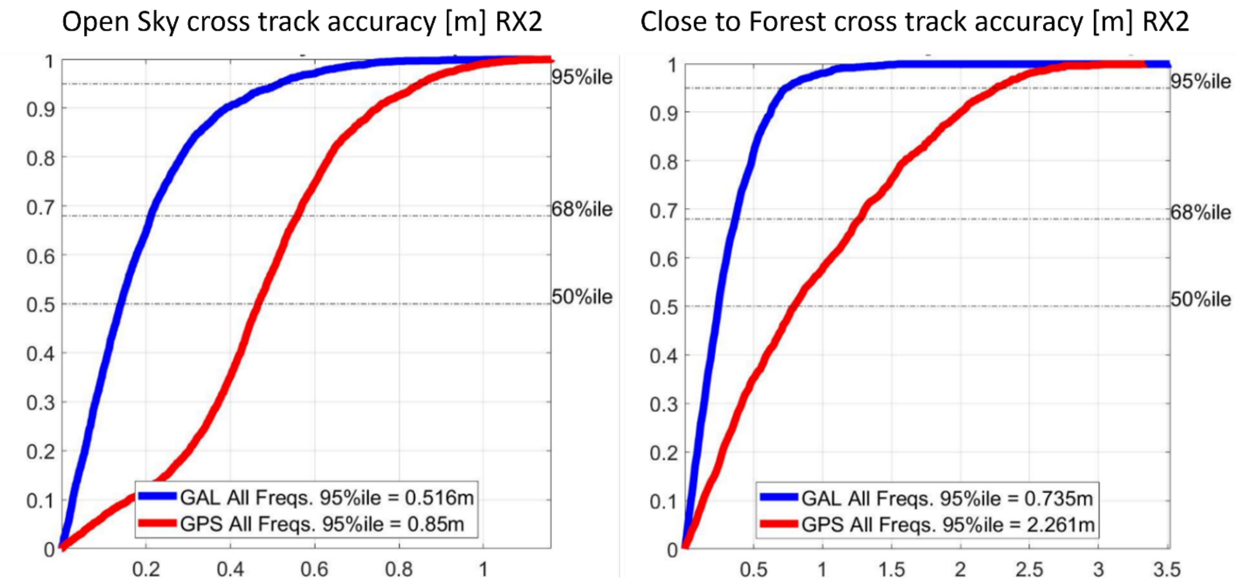

Figure 8 – Galileo vs GPS Agriculture performance (CDF) – RX2 in Open Sky and Close to Forest scenario

Conclusions

This paper analyzed the performance of six GNSS receivers and the added value of the Galileo constellation in the agriculture machine guidance domain. The analysis was carried out considering different positioning modes: SPP, SBAS, PPP, RTK and PPP-RTK, all tested in an operational environment. The results demonstrated that the RUTs provided comparable or better results (under the same testing conditions and with a comparable number of satellites) than GPS-only modes with Galileo-only configurations. Moreover, the Galileo constellation showed to be able to contribute to multi-constellation configurations' availability and accuracy performance.

Considering the cross-track KPI, in standalone positioning mode and in open sky scenario, the RUTs obtained sub-m accuracies with the single constellation configurations and m-level accuracies with the triple constellation. SBAS and PPP also kept the cross-track error inside the required bounds, with results respectively of under 50 and 10 centimeters in open sky. RTK showed cm-level results, mostly in line with the very stringent accuracies required for activities like automatic steering and VRA-high (Variable Rate Application).

For what concerns the close to forest scenario, on the other hand, the obtained results were not in line with the user requirements only for PPP, SBAS and RTK modes, while all the other tested configurations, even if with degraded results when compared to the open sky ones, registered performance in line with user's requirements.

References

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