A low-cost multi-GNSS PPP-RTK solution for precision agriculture: a preliminary test

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A low-cost multi-GNSS PPP-RTK solution for precision agriculture: a preliminary test

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***Abstract*—The agriculture and food sector will increasingly play a major role in the well-being of humanity. World-scale events, such as wars, climate changes, desertification, pandemic, etc., revealed how fragile humanity is from the point of view of food supply. Therefore, precision farming can provide a remarkable positive contribution to the primary sector globally at various levels. Nowadays, the employment of platforms for product data capture related to farming production and management is extensively available in several fields through local devices. Those systems comprehend sensors, automatic guidance systems with Global Navigation Satellite Systems (GNSSs), and central processing systems. Specifically, GNSS technology plays a central role in the autonomous guidance of tractors and farming robots. Until some years ago, high accuracy was a prerogative of expensive geodetic receivers whereas today high accuracy can be achieved also with low-cost receivers thanks to several factors, among all: the increased availability of GNSS interoperable constellations as well as the accessibility to several augmentation techniques both satellite- and ground-based. These factors are triggering the diffusion of autonomous machinery for farming purposes. This research aims to investigate the performance of a commercial Precise Point Positioning-Real Time Kinematic (PPP-RTK) correction service, employing a low-cost receiver. Two tests have been carried out with two different-grade antennas (a geodetic and a low-cost one). The tests showed that the employment of cost-effective equipment along with the exploitation of correction services allows reaching subdecimetre-level precision in less than one minute when employing a geodetic antenna; accuracy slightly degrades to decimetre-level with the low-cost antenna but the integer ambiguity is resolved in less time. Mean time-to-fix attests to 57 s for test 1 (geodetic antenna) and 30 s for test 2 (low-cost antenna). The times to obtain the first float ambiguity solution are equal to about 15 s for both tests. Integer ambiguity fixed solutions reveal a DRMS of 0.09 m and 0.012 m for test 1 and test 2, respectively. Float solutions reach a DRMS of 0.45 m and 0.63 m for test 1 and test 2, respectively. Lastly, when corrections are not available at all, single point positioning solutions reveal a DRMS of 1.36 m for test 1 and 3.15 m for test 2.**

***Index Terms*—precision farming, PPP-RTK, GNSS, low-cost, ambiguity resolution, precision agriculture**

I. Introduction

In the next years, the agriculture and food sectors will increasingly play a major role in the well-being of humanity. World-scale events, such as wars, climate changes, and desertification, revealed how fragile humanity is from the point of view of food supply. Therefore, precision farming can provide a remarkable positive contribution to the primary sector globally at various levels. The state-of-the-art approach to precision farming is based on highly-customizable technology solutions with high interoperability. The spreading of innovative techniques, supported by their capability to adapt to different farming conditions, can significantly contribute to the modernisation of the Italian primary sector. Nowadays, the employment of platforms for product data capture related to farming production and management is extensively available in several fields by means of local devices. Those systems comprehend sensors, automatic guidance systems with Global Navigation Satellite Systems (GNSSs), and central processing systems. Specifically, GNSS technology plays a central role in the autonomous guidance of tractors and farming robots; given that most driving-related decisions will be based primarily on the location of the vehicle provided by the satellite positioning system, the importance of a robust, ubiquitous, and reliable PNT can't be overlooked. Until some years ago, GNSS receiver accuracy was a prerogative of expensive high-grade geodetic receivers. Today, high accuracy can be achieved also with low-cost receivers (See for example [3], [8], [9] thanks to several factors. Among all, the increased availability of GNSS interoperable constellations as well as the accessibility to several augmentation techniques both satellite- and ground-based. These factors are triggering the diffusion of autonomous machinery for farming purposes. To increase this spreading, the next challenge will be to further reduce the costs of these technologies, developing low-cost navigation equipment for farming robots capable of providing a navigation solution that meets the accuracy, integrity, continuity, and availability requirements. Given the potential advantage of bringing high accuracy and precision positioning to consumer-grade devices, a new impetus has been given to the study and implementation of augmentation techniques and correction services. GNSS has been the most widely used system for navigation. However, despite its capability to provide absolute navigation information with a long-time accuracy, this system suffers from problems related to signal propagation, especially in urban environments, where buildings, trees, and other structures hinder the reception of GNSS signals [15]. In addition, low-cost receivers can't assure the required performance if compared to high-grade ones [5] [14]. For these reasons, to employ

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low-cost receivers for navigation purposes, their performance must be augmented [4]. Then, the increasing demand for high-accuracy and high-integrity navigation solutions can be fulfilled by low-cost GNSS receivers with implemented augmentation techniques. This research aimed to investigate the phase-ambiguity fixing performance of a commercial Precise Point Positioning-Real Time Kinematic (PPP-RTK) correction service, employing a low-cost receiver. Tests comprehending consecutive shutdowns of the receiver have been carried out.
The remainder of this paper is organized as follows: Section 2 briefly recalls the principles of the PPP-RTK technique. Section 3 presents the experiment, and Section 4 provides and discusses the preliminary results.

II. Methodology

The methodology's development contemplates the experimentation of a low-cost receiver with implemented PPP-RTK correction service. Aiming to provide robust decimetre-level accuracy with a stand-alone low-cost receiver, different GNSS positioning techniques are available, among all: Real-Time Kinematic (RTK), Precise Point Positioning (PPP), and the hybridisation of these (PPP-RTK). The most advanced adaptation of RTK is network RTK (NRTK) [12]. It has been the most popular GNSS signal augmentation technology for many industries such as surveying and agriculture and it is particularly prevalent in regions with well-developed Continuously Operating Reference Station (CORS) networks like Europe. NRTK provides near-instant, high-accuracy positioning up to 1 cm +1 ppm [1]. In this technique, each CORS transfers its observations to a control center; the latter calculates systematic effects modeling corrections over the entire serviced area. In this manner, rovers inside the network area connect to a server receiving corrections via a direct bi-directional communication channel. This allows the rover to resolve the ambiguities of the differenced carrier phase data and to estimate the coordinates of its position. The drawback of this technique resides in the non-trivial communication requirements since a bi-directional communication channel is required.

PPP is a global precise positioning service, requiring the availability of precise reference satellite orbit and clock products. It exploits a network of CORS. Combining the precise satellite positions and clocks with a dual-frequency GNSS receiver, PPP minimizes GNSS errors to achieve better accuracy positioning. The corrections are delivered to the user via satellite L-band or through internet protocol (IP), resulting in decimetre-level accuracy with light ground infrastructure requirements. To resolve any local biases, such as the ionosphere and troposphere effects, multipath, and satellite geometry, PPP solutions typically take a period of 5-30 min, mostly for atmospheric error modeling, thus resulting in long AR times [2].

To overcome limitations related to these positioning techniques, the research community is hybridising PPP and RTK obtaining benefits from both technologies [17] [23]. The principles of this hybridization have been described by Teunissen et al. in [18] where the analytical expressions for the variance matrices of the ambiguity-fixed and ambiguity-float PPP-RTK corrections have been described. Subsequently, Khodabandeh et al. in [11] provided an analytical study of the quality of the PPP-RTK corrections as well as their impact on the user ambiguity resolution performance. Khodabandeh [10] conducted an analytical study showing that the number of satellites and the number of frequencies work in tandem to increase the correction latency, while ensuring successful single-receiver ambiguity resolution. Indeed, PPP-RTK appears to be a promising technique for present and future precision farming. The concept behind PPP-RTK is to improve PPP estimations with precise undifferenced atmospheric and satellite clock corrections from a network of CORS; in this manner, the near-instantaneous AR is attainable for rovers inside the network, reducing considerably fixing times. As reported by Wübbena et al. in [22] and [21], PPP-RTK exploits a 2D distribution of atmospheric errors created based on the raw measurements of the network of CORS; the quality of this "map" defines the AR capability of the service. The performance of a PPP-RTK system is highly dependent on how much data can be provided to the receiver and how fast it can be made available [1]. The quantity and frequency of data that can be delivered to users are limited by the available bandwidth and the data size. These two factors must be well balanced since less quantity of data means a reduction of accuracy and longer convergence times, whilst the reduction of the corrections update rate may introduce latencies.

III. Experimental setup

This paper shows a preliminary test of the PPP-RTK technique, employing a low-cost receiver. This research is the continuation of the work done in [6]. Two different tests have been carried out. The first employs a geodetic antenna while the second a low-cost one . The hardware employed in the first test consisted of a low-cost multi-constellation multi-frequency GNSS receiver, namely the u-blox zed-f9p, connected via SubMiniature (SMA) cable to the Topcon PG-A1 geodetic antenna [19]. The survey consisted of a static PPP-RTK positioning on a point of known coordinates. The test refers to a 2 hours GNSS acquisition in the L1/E1, L2, and L5/E5b frequencies. The test site is located in Naples, Italy; this scenario is expected to be a quasi-open-sky and low-multipath environment. For the second test, the same conditions have been provided except for the employment of the u-blox GNSS ANN-MB low-cost antenna [20]. Regarding the correction service, it exploits the IP network and delivers two types of messages in SPARTN 2.0 format [7]: satellite clock corrections every 5 seconds and satellite orbits, bias, and atmosphere every 30 seconds. A geodetic receiver, connected to the same antenna, namely the Topcon Hiper Hr, has been employed for comparison. The results were analysed by exploiting MATLAB® software, developed specifically for this work. The latter extracts some information from the binary u-blox proprietary file, e.g. high-precision positions and solution status, among others. The paper consists of a preliminary study, aiming to investigate the time it takes for AR and

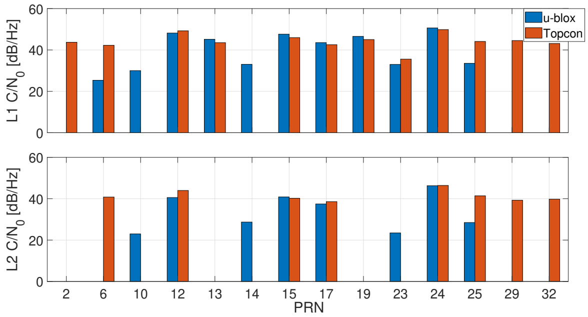

Fig. 1. Mean of C/N_0 values for GPS constellation comparison between low-cost and geodetic receivers. Blue bars represent the low-cost receiver, red bars represent the geodetic receiver: the top row depict mean of C/N_0 for GPS L1 band; the bottom row depicts the mean of C/N_0 for GPS L2 band.

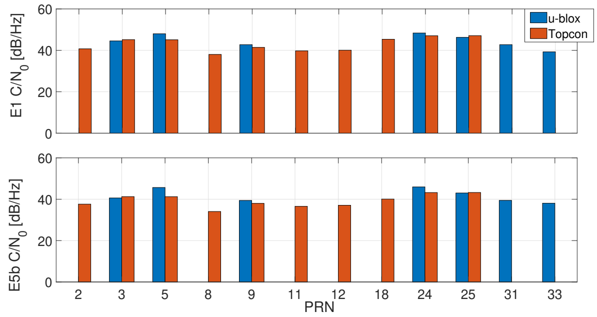

Fig. 2. Mean of C/N_0 values for GALILEO constellation comparison between low-cost and geodetic receivers. Blue bars represent the low-cost receiver, red bars represent the geodetic receiver: the top row depict mean of C/N_0 for GALILEO E1 band; the bottom row depicts the mean of C/N_0 for GALILEO E5 band.

the influence of the antenna; therefore, 8 consecutive hot starts were imposed, interspersed with a few minutes of fixing maintenance. According to the u-blox integration manual, in hot start mode, the receiver simulates a short-time shutdown (4 hours or less), so that its ephemerides are still valid.

IV. Preliminary results and discussion

Figure 1 and Figure 2 refer to test 1 and depict the mean carrier-to-noise density ratio (C/N_0) comparison between the low-cost and geodetic receivers for the different GNSS constellations. C/N_0 output by a receiver indicates the accuracy of the tracked satellite observations and the noise density as seen by the receiver's front-end. It also indicates the level of noise present in the measurements. The lower the signal-to-noise ratio the worse the quality of the measurements. Since the antenna is shared by both receivers, these Figures are useful to assess the signal gain over the noise as seen by the receiver's front-end. Figure 1 refers to the GPS constellation; the top row of this figure shows that on L1 frequency only the geodetic receiver tracks PRN 2, 29, and 32, while only the low-cost receiver tracks PRN 10 and 14; the bottom row, referred to L2 frequency, demonstrates that PRN 6, 29, and 32 were tracked only by the geodetic receiver while PRN 10, 14, and 23 only by the low-cost one. Similarly, Figure 2 refers to the Galileo constellation; the top row of this Figure shows that, on E1 frequency, only the geodetic receiver tracks PRN 2, 8, 11, 12, and 18 while only the low-cost receiver tracks PRN 31 and 33; bottom row, referred to E5b frequency, depicts the same behaviour, in terms of satellites tracked by receivers. The figure shows that also satellite E18 from the Galileo constellation has been tracked; according to [16] and [13], this satellite presents a highly eccentric orbit. It can be noted that second frequencies (bottom panels of previous figures) are characterized by lower C/N_0. The employed PPP-RTK correction service supports GPS (L1 C/A, L2P, L2C, L5), GLONASS (L1 C/A, L2 C/A), and Galileo (E1, E5A/B). Therefore, the Beidou constellation, even if it is tracked by u-blox receivers, is not supported for PPP-RTK corrections, so far.

Table I reports the times needed for resolving the integer-ambiguity for test 1 (geodetic antenna) and test 2 (low-cost antenna). Limiting the analysis to the time taken for solving the integer ambiguity, it can be noted that, during test 2, the system takes less time to resolve the integer ambiguity; in particular, the mean times needed are 57 s and 30 s for test 1 and test 2, respectively. Nevertheless, as shown by the next figures, this speeding up will turn out in a degradation of the accuracy in the positioning domain. Figures 3 and 4 show the performance of the low-cost receiver depending on the solution quality status for test 1 (geodetic antenna) and test 2 (low-cost antenna), respectively. The top, middle, and bottom panels refer to the north, the east, and the vertical error components, respectively. The errors are computed as differences between the low-cost receiver solutions and the ground truth obtained with a geodetic receiver in differential positioning mode. Different colors represent different solution statuses: orange markers represent the single point positioning, yellow markers refer to the DGNSS solution (i.e. solutions augmented with corrections provided by EGNOS) while green and violet markers belong to RTK. In particular, green represents float solutions while violet refers to phase ambiguity-fixed solutions. Tables II and III depict the statistics of the different solution quality statuses for test 1 (geodetic antenna) and test 2 (low-cost antenna), respectively. The tables report the mean errors, the standard deviations, and the RMS both for horizontal and vertical components. Regarding test 1, Integer ambiguity-fixed solutions reveal better statistics with respect to other types of solutions, as expected; fixed solutions reveal a DRMS of 0.09 m; degrading to float solutions the DRMS is equal to 0.45 m. Moreover, when corrections are not applied at all and only SPP/DGNSS solutions are achievable, the DRMS degrades to 1.36 m. Regarding vertical accuracy, Table II reports the mean, the standard deviation, and the RMS statistics, depending on the solution quality statuses; according to horizontal error behaviour, when AR is achieved, vertical error statistics are one order of magnitude less than the others; indeed, vertical RMS for ambiguity-fixed solutions attests to 0.14 m, while float solutions reach an RMS of 1.00 m. When

PPP-RTK corrections are not applied at all, SPP/DGNSS solutions show a vertical RMS equal to 2.11 m. Results from test 2 confirm that integer ambiguity-fixed solutions reach better statistics with respect to other types of solutions; indeed, fixed solutions show a DRMS of 0.12 m; when the ambiguity is of float type, the DRMS is equal to 0.63 m. Moreover, when PPP-RTK corrections are not applied at all, SPP/DGNSS solutions are characterized by a DRMS equal to 3.15 m. Regarding vertical accuracy, Table III reports the mean, the standard deviation, and the RMS statistics, depending on the solution quality statuses; as before, when integer ambiguity resolution is achieved, vertical error statistics are one order of magnitude less than the others; indeed, vertical RMS for ambiguity-fixed solutions attests to 0.20 m, whereas float solutions show an RMS of 1.83 m. Lastly, SPP/DGNSS solutions show a vertical RMS equal to 9.05 m. Table IV shows the comparison between the results from test 1 and test 2, summarizing the mean errors, the standard deviations, and the DRMS for each horizontal component. As shown in Table IV, the employment of the geodetic antenna results in slightly better performance; in particular, the the mean horizontal error and the DRMS are about 61 % and 32 % smaller, respectively.

TABLE I
FIXING TIMES FOR EACH HOT START. IN PARENTHESIS ARE SHOWN THE RELATIVE TIMES TO OBTAIN THE FIRST AMBIGUITY-FLOAT SOLUTION. THE FIRST ROW REFERS TO TEST 1 (GEODETIC ANTENNA) WHILE THE SECOND TO TEST 2 (LOW-COST ANTENNA).

# hs	1 (s)	2 (s)	3 (s)	4 (s)	5 (s)	6 (s)	7 (s)	8 (s)	Mean (s)
T 1	51 (13)	62 (10)	68 (17)	72 (28)	68 (0)	44 (14)	46 (16)	46 (16)	57 (14)
T 2	26 (17)	40 (16)	36 (6)	30 (22)	29 (18)	20 (13)			30 (15)

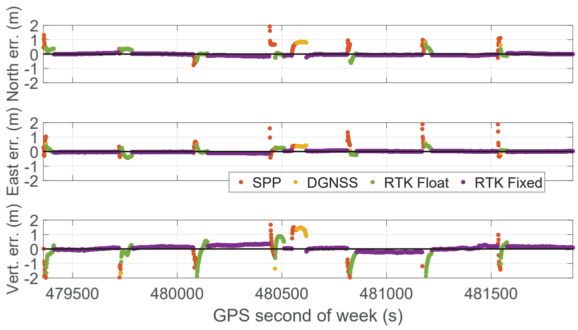

Fig. 3. Positioning errors for data collected during test 1 (geodetic antenna) versus processed time expressed in GPS second of the week: the top row refers to the North error component; the middle row refers to the East error component, and the bottom row refers to the vertical error component.

Figure 5 shows the comparison of the scatter error plots for the ambiguity-fixed solutions of test 1 and test 2. These figures highlight what was declared before: the speeding up of the integer ambiguity resolution results in a degradation in the positioning domain. Indeed, the DRMS is higher for test 2. Considering the previous analysis of the times needed for resolving the integer ambiguity and the error analysis in the

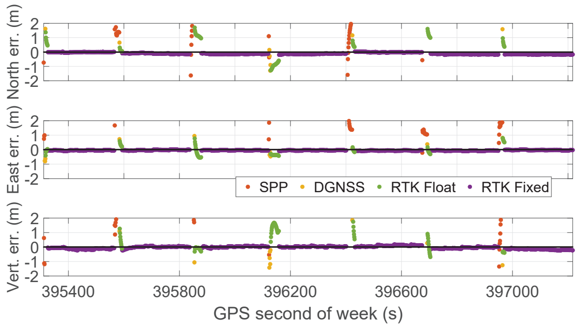

Fig. 4. Positioning errors for data collected during test 2 (low-cost antenna) versus processed time expressed in epochs GPS second of the week: the top row refers to the North error component; the middle row refers to the East error component, and the bottom row refers to the vertical error component.

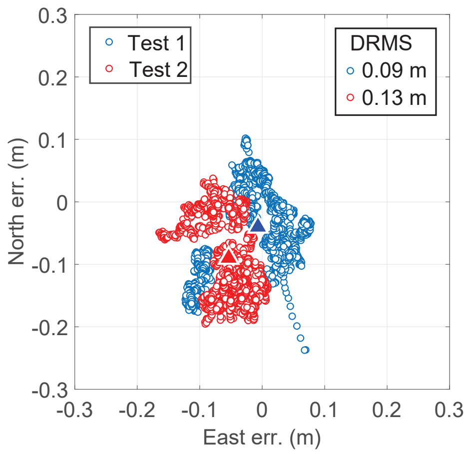

Fig. 5. Scatter plot error comparison of PPP-RTK ambiguity-fixed positions between test 1 (geodetic antenna) and test 2 (low-cost antenna). Blue markers represent errors for data collected during test 1 while red circles represent errors for data collected during test 2. Blue and red triangles represent the mean errors for test 1 and test 2, respectively.

positioning domain, it can be noted that the employment of a geodetic antenna allows obtaining better accuracies than those obtainable with the default low-cost antenna provided with u-blox zed-f9p receiver; however, this improvement in accuracy requires longer times for integer ambiguity resolution.

TABLE II
POSITIONING PERFORMANCE FOR DIFFERENT TYPES OF SOLUTION STATUS FOR TEST 1 (GEODETIC ANTENNA).

Solution type	# of solutions	Horizontal error mean (m)	Horizontal error std (m)	Horizontal error DRMS (m)	Vertical error mean (m)	Vertical error std (m)	Vertical error RMS (m)
SPP/DGNSS	336	1.11	0.79	1.36	-0.53	2.04	2.11
RTK Float	2913	0.39	0.24	0.45	0.82	0.57	1.00
RTK Fixed	1949	0.08	0.04	0.09	0.05	0.13	0.14

V. PRELIMINARY CONCLUSIONS

In this paper, PPP-RTK has proved to be a promising technique for subdecimetre-level accuracy with low-cost receivers.

TABLE III
POSITIONING PERFORMANCE FOR DIFFERENT TYPES OF SOLUTION STATUS FOR TEST 2 (LOW-COST ANTENNA).

Solution type	# of solutions	Horizontal error			Vertical error		
		mean (m)	std (m)	DRMS (m)	mean (m)	std (m)	RMS (m)
SPP/DGNSS	346	1.84	1.50	3.15	6.99	5.75	9.05
RTK Float	598	0.14	0.48	0.63	0.93	1.57	1.83
RTK Fixed	1949	0.07	0.05	0.12	0.18	0.09	0.20

TABLE IV
POSITIONING PERFORMANCE COMPARISON FOR PPP-RTK FIXED SOLUTIONS OF TEST 1 (GEODETIC ANTENNA) AND TEST 2 (LOW-COST ANTENNA)

	Solution availability	mean err. E	mean err. N	mean horiz. error	std E	std N	DRMS
Test 1	2077	-0.007	-0.040	0.041	0.048	0.059	0.086
Test 2	1949	-0.054	-0.090	0.105	0.031	0.064	0.127

Two tests have been carried out. The same conditions have been provided for both tests except for the antenna: data have been collected with a geodetic antenna during test 1 while a low-cost antenna has been employed for test 2. The results showed that the employment of cost-effective equipment along with the exploitation of correction services allows reaching decimetre-level accuracy within a few seconds and subdecimeter-level accuracy in less than one minute when employing a geodetic antenna. Conversely, when a low-cost antenna is used, results indicate that a decimetre-level accuracy is still attainable in a few seconds and an almost decimetre-level accuracy is obtainable in 30 s. Results achieved have revealed promising for precision farming applications. In detail, as reported in the previous section, integer ambiguity-fixed solutions reveal a DRMS of 0.09 m and 0.12 m for test 1 (geodetic antenna) and test 2 (low-cost antenna), respectively. Float solution's DRMS are equal to 0.45 m and 0.63 m, for test 1 and test 2, respectively. Lastly, when PPP-RTK corrections are not available at all and only SPP/DGNSS solutions can be obtained, DRMS are equal to 1.36 m and 3.15 m. Also, the analysis on the times needed to resolve the integer-ambiguity has been presented. The mean times to obtaining the fixed status attest to 57 s and 30 s for test 1 and test 2, respectively. Experimentation has shown that the employment of a low-cost antenna has strongly reduced the AR time-to-fix at the cost of reducing the quality of the positioning performances. Nonetheless, in the past, this level of near-instantaneous accuracy was a prerogative of high-grade receivers; nowadays, thanks to the deployment of ground- and satellite-based correction services, both code and phase measurements can be exploited for accurate positioning with low-cost equipment.

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