AN STATISTICAL APPROACH TO STATIC AND DYNAMIC TESTS FOR GNSS RECEIVERS USED IN AGRICULTURAL OPERATIONS

ABSTRACT: In order to better adapt the Global Navigation Satellite Systems (GNSS) technology to the needs of the farmers, it is essential to know the level of accuracy delivered by a receiver in working conditions. There is no methodology indicating the minimum number of replication to perform a statistical comparison. The aim of this study is to advance on the methodological approach for evaluating static and dynamic performance of GNSS receivers commonly used in agricultural operations. For the static test a supporting frame in the ground carried all the receivers receivers with coordinates properly transported and for the dynamic test a circular rail with 9.55 m radius was installed on a level ground with a platform driven by an electric motor to carry the receivers at a constant speed. The transversal error of the receiver to the circular reference line was measured. The E_{95} to receivers without differential correction ranged between 4.22 m and 0.85 m in the static test, and 2.25 m and 0.98 m in the dynamic test. Receivers with differential correction had values of E_{95} below 0.10 m in the static test and 0.16 m in the dynamic test. The minimum number of replications is five to C/A code and 13 to L1/L2 with differential correction signal in the dynamic test. The static test needs nine replicates to C/A and five to L1/L2 with differential correction signal.

KEYWORDS: accuracy, differential correction, RTK, SBAS

INTRODUCTION

The use of Global Navigation Satellite Systems (GNSS) in agriculture has evolved, enabling a revolution in the georeferenced data collection, which is becoming faster, more accurate and less costly. Precise positioning is demanded in several agricultural applications (Kabir et al., 2016). The accuracy of commercial receivers is one of the purchasing requirements for farmers and depends on the operations to be performed in the field. Thus, the accuracy of GNSS signals and how it behaves in agricultural settings should be known. Consequently, one of the biggest challenges in the agricultural operations is to select an adequate source of differential correction signal, depending on the required accuracy and choose the right option, depending on availability, practical aspects, and costs.

Some agricultural operations, as auto-guidance technology for precision inter-row cultivation, require high accuracy, normally below 0.10 m, and it is only possible with the use of some kind of differential correction signals (Machado & Molin, 2011). Real Time Kinematic (RTK) and Satellite-based Augmentation Systems (SBAS) with signal distributed by geostationary satellites stand out as the main options for users of real-time differential correction. RTK uses a base station with radio transmission and provides high-level accuracy (~0.01 m range). Alternatively, the use of Network RTK can be an option to share costs without degrading the positional accuracy (Bae & Kim, 2018). However, for remote agricultural areas in Brazil, there is little or no access to internet networks, making Network RTK unavailable or at a high cost.

SBAS are geostationary satellite systems that provide services for improving the accuracy, integrity, and availability of GNSS signals. It requires no local infrastructure and offers competitive accuracy as a private service, very common in agricultural applications in Brazil (Rovira-Más et al., 2015).

GNSS involves signals from satellites subject to interference, in which it can provide positioning results with a range of common errors over time (Souza & Machado, 2016). There is a relation of the GNSS positioning errors with the satellite signal propagation (ionospheric and tropospheric), satellite orbit, receiver clock, relativity effects, hardware delay, the phase center of receiver antenna, among others (Silva & Marques, 2016; Ye et al., 2018). Satellites available from Russian Federation's Global Navigation Satellite System (GLONASS) combined with United States' Global Positioning System (GPS) provided a higher number of satellites and a lower value of PDOP (Positioning Dilution of Precision) (Banville et al., 2018; Li et al., 2018).

There are some field test procedures developed for evaluating satellite-based auto-guidance systems in agriculture (Kim et al., 2016; Sama & Stombaugh, 2014; Santos et al., 2017). The

American Society of Agricultural and Biological Engineers (ASABE) suggests ASABE X605 (2008) for automated satellite guidance system testing during direct and level travel. ISO 12188-2 (2012) is a standard for testing automatic satellite guidance systems based on ASABE X605 which defines a tracking sensor as an instrument or instrumented system designed to perform repeated horizontal distance measurements required for cross-track error calculations. Machado et al. (2010) and Machado & Molin (2011) evaluated the performance of GNSS receivers installed on an agricultural vehicle, with circular paths in a constant trajectory, using a GNSS receiver with RTK as a reference for accuracy and precision calculations. Kabir et al. (2016) and Carballido et al. (2014) carried out the evaluation of the performance of multi-GNSS receivers in static and dynamic conditions in different agricultural sites.

For the characterization of positioning errors of a GNSS, the Institute of Navigation (ION STD 101, 1997) indicates that for perform dynamic navigation accuracy, the test shall be run over at least three periods of no less duration than 60 minutes each. The number of replicates may lead to an increase in accuracy (Zhang et al., 2018) and to improve the ability of a statistical test to detect smaller differences between estimates of the means of treatments (Danilogorskaya et al., 2017).

Due to limited information regarding the performance of receivers and signals relates to static and dynamic tests, the aim of this study is to advance on the methodological approach for evaluating the static and dynamic performance of GNSS receivers commonly used in agricultural operations, including the statistical issues related to the number of replicates.

MATERIAL AND METHODS

Static and dynamic tests were carried out on the Precision Agriculture Laboratory, Biosystems Engineering Department, at the University of São Paulo, Piracicaba, SP (ESALQ/USP). A supporting frame was allocated at the coordinates 22º42'47.8´´S and 47º37'44.9´´W and ten different receivers, 0.50 m apart, were placed on top and coordinates properly transported (Figure 1).

FIGURE 1. Supporting frame to allocate GNSS receivers for the static test

To perform the dynamic tests a circular metal rail with 9.55 m radius, centered at the same point as in the static test, was placed on a level ground, with a platform driven by an electric motor to realize the circular path of the receivers at a constant speed (Figure 2). The platform stayed 2.0 m behind the electric motor to avoid possible electromagnetic interference in the GNSS antennas.

In this case, only the path error was obtained, based on the perpendicular distance between the position of the receiver and of the line segment of the reference line (Figure 3). To avoid assuming a perfect circumference on the rail, an L1/L2 GPS+GLONASS receiver, TOPCON© model GR-3, was used with an accuracy of 0.003 m+ 0.50 ppm with RTK differential correction in a dynamic condition, with 15.0° elevation mask. It collected positioning data at a frequency of 1 Hz in dynamic condition for 3,600 s, generating the reference line. The receiver's errors were calculated by the difference between the radial value of the radius (R) of the reference line and the radial distance (D) between the point generated by the receiver and the reference coordinate.

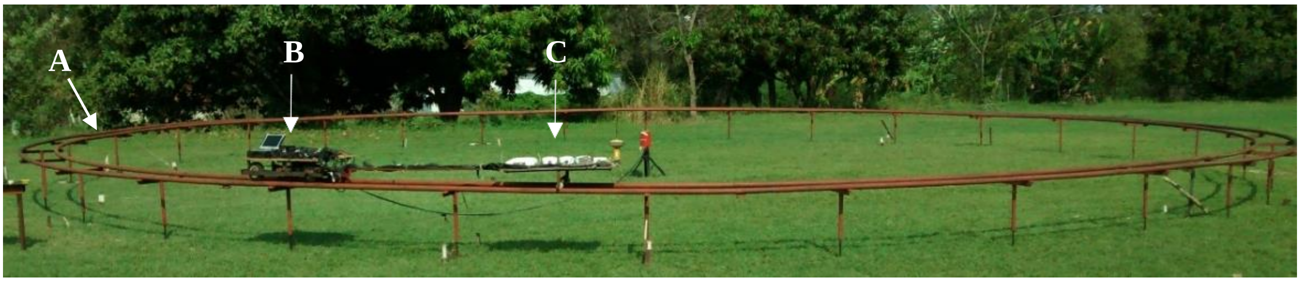

FIGURE 2. Rail for the radial displacement of the receivers (A); platform with an electric motor (B) and platform for the allocation of GNSS receivers (C)

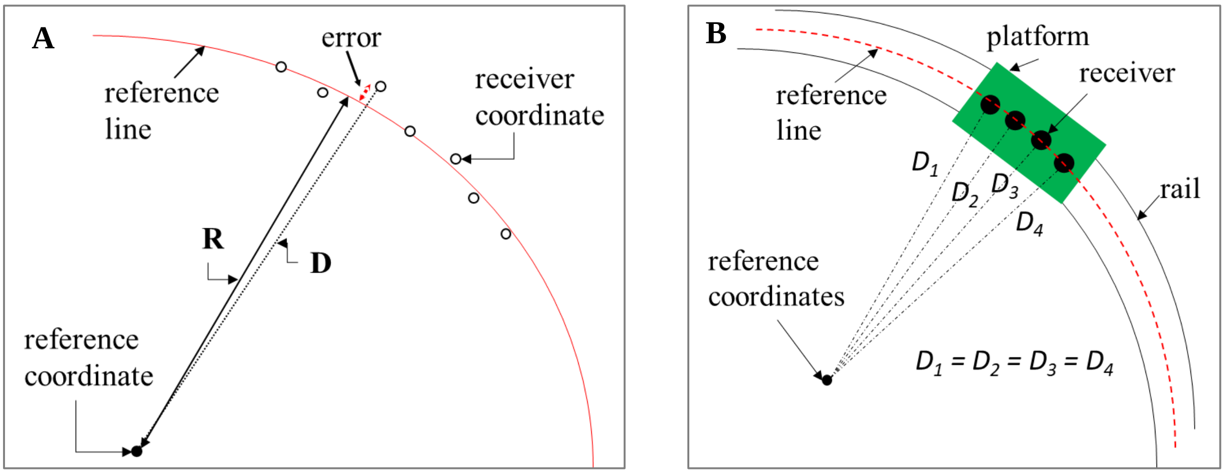

FIGURE 3. Calculation of GNSS receiver signal path error (A); location of receivers all aligned in the same distance from the reference coordinate (B)

Although the site of the tests was not completely free of obstacles, it is considered adequate to perform the tests since it replicates real field conditions, especially the boundary of agricultural fields, with the presence of trees. The shading profile is represented by showing that obstacles did not exceed 30.0° (Figure 4).

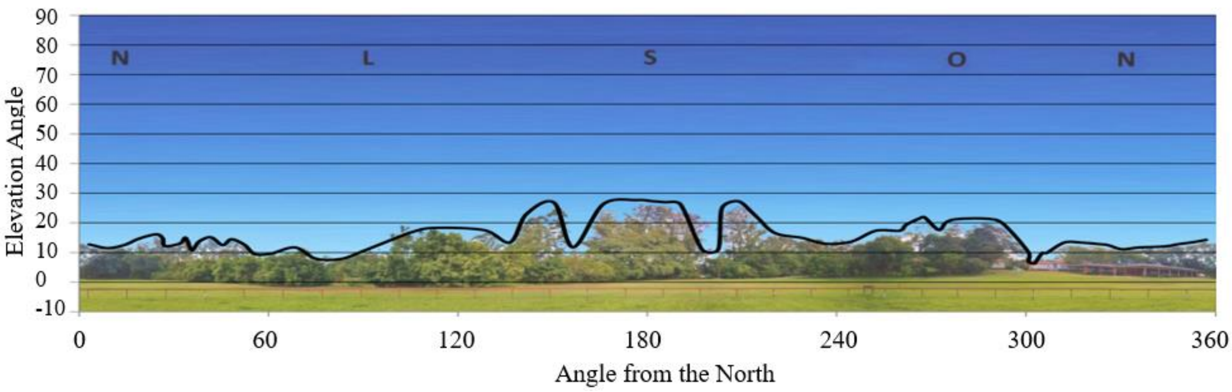

FIGURE 4. Static shadowing profile with a starting point in the true north

Receivers with different specifications and levels of accuracy were used, which is commonly used in agriculture (Table 1). In the group A are the receivers without differential correction and in group B are the receivers with SBAS or RTK correction. The software C7 (CR Campeiro, 2013) was installed on the cell phone to capture and save data. For data collection of the L1 and L1/L2 receivers, portable computers were used with the SST Field Rover II 7.13 software (SST Development Group®). For C/A code receivers, the internal memory of the equipment stored the data.

TABLE 1. Equipment used in the static and dynamic tests

Group	ID	Receivers	Signals	GNSS	Firmware	Differential correction
A	1	Cell phone	C/A	GPS+GLONASS	C7 GPS	-
	2	eTrex® 30	C/A	GPS+GLONASS	4.5	-
	3	eTrex® 30	C/A	GPS+GLONASS	4.5	-
	4	GLO Bluetooth S	C/A	GPS+GLONASS	2.60	-
	5	GeoSpective	L1	GPS+GLONASS	1.04	-
	6	Smart6-L	L1/L2	GPS+GLONASS	6.700	-
B	7	AG-372	L1/L2	GPS+GLONASS	6.15.003.4	SBAS[1]
	8	Smart6-L	L1/L2	GPS+GLONASS	6.700	SBAS[2]
	9	Smart6-L	L1/L2	GPS+GLONASS	6.700	SBAS[2]
	10	GR-3	L1/L2	GPS+GLONASS	-	RTK

[1]Real time extend (RTX) – GNSS with geo-satellite RTXSA connection (Trimble, USA). [2]TerraStar C – GNSS with the geo-satellite AORW connection (Novatel Inc., Canada)

All receivers were set to collect data at 1.0 s interval (1.0 Hz), logging for 4,200 s with five replications in the static test and seven replications for the dynamic test, keeping 3,600 s intervals between replications to allow complete reconfiguration of the satellite constellations. Prior to analyzing the data, we eliminated the initial 300 s and the final 300 s, using a total time of 3,600 s (3,600 points collected). Data were generated in decimal geographical coordinates in the Datum WGS 84 and converted to metric UTM system using the software QGIS 2.16.1 (Geographic Information System).

For the static test, the North-South (E_{NS}) (Equation 1) and East-West (E_{EW}) (Equation 2) errors were calculated, resulting in the radial error (E) (Equation 3), generated by the receiver in relation to the reference point, as described by Machado et al. (2010), using MS Excel.

$$E_{NS} = |Y_{ref} - Y_{real}| \qquad (1)$$

$$E_{EW} = |X_{ref} - X_{real}| \qquad (2)$$

$$E = \sqrt{E_{ns}^2 + E_{ew}^2} \qquad (3)$$

where (X_{real}, Y_{real}) is the coordinate of the reference point (m); (X_{ref}, Y_{ref}) is the coordinate of the GNSS receiver (m).

An algorithm based on Java language was developed for analyzing data from the dynamic test, using the software NetBeans IDE 8.1 to create the reference line and to calculate the path error. Both were expressed as an error with 95% probability (E_{95}) and for each receiver, a root mean squared (RMS) error was calculated (Equation 4) (PÉREZ-RUIZ et al., 2012).

$$RMS_t = \sqrt{\frac{1}{N_t}\sum_{i=1}^{N_t} E^2} \qquad (4)$$

where RMS_t is the RMS error for the t^{th} receiver; N_t is the total number of measurement point for the t^{th} receiver; E is the error of the point i^{th} to the t^{th} receiver.

For the statistical analysis, errors were calculated for each point and the SAS general linear models procedure was used to test for significant differences between receivers using ANOVA. Duncan test was used to compare the performance of the different receivers with respect to their E_{95} mean accuracy, at a 5% error probability level. We applied the probability transformation suggested by Box & Cox (1964) for all distributions, used for transformation of the E to stabilize or reduce the variability among replications. To compare the performance of the different receivers with SBAS and RTK signal correction we did not take in comparison the replications in which there was a loss of the signal correction.

The sensitivity of a statistical test is largely a function of sample size. The power of the test was calculated in order to verify if a supposed difference between the accuracy of receivers was genuine or subject to sample error for the static and dynamic tests. The power of the test corresponds to 1-β, the probability of rejecting the null hypothesis when it is false and indicates the correct decision probability based on the alternative hypothesis. It is usually interpreted as the chance to detect a real difference between averages or proportions. The power of the tests was evaluated, the simulations were made for the various combinations of replication numbers with the nominal level of significance α equal to 5.0%, and admitting a difference between receivers accuracies equal to the standard error of the mean.

RESULTS AND DISCUSSION

In the static test, the error dispersion for the C/A receivers were relatively larger than other receivers were (Figure 5). The L1/L2 receivers without differential correction, ID 6, resulted in a low error dispersion. However, we noticed a shift of the data towards the south in relation to the reference, which generated a higher E_{NS} that decreasing the accuracy of the receiver.

Receiver ID 5 also shows a greater dispersion of errors in second and third quadrants. Receivers with SBAS differential correction have a similar dispersion of E_{NS} and E_{WE}. The high number of observations in the second quadrant of receiver ID 9 can be explained by problems with the SBAS signal correction, observed during the tests. The receiver ID 10 with RTK differential correction obtained less dispersion of the errors when compared to the receivers with SBAS.

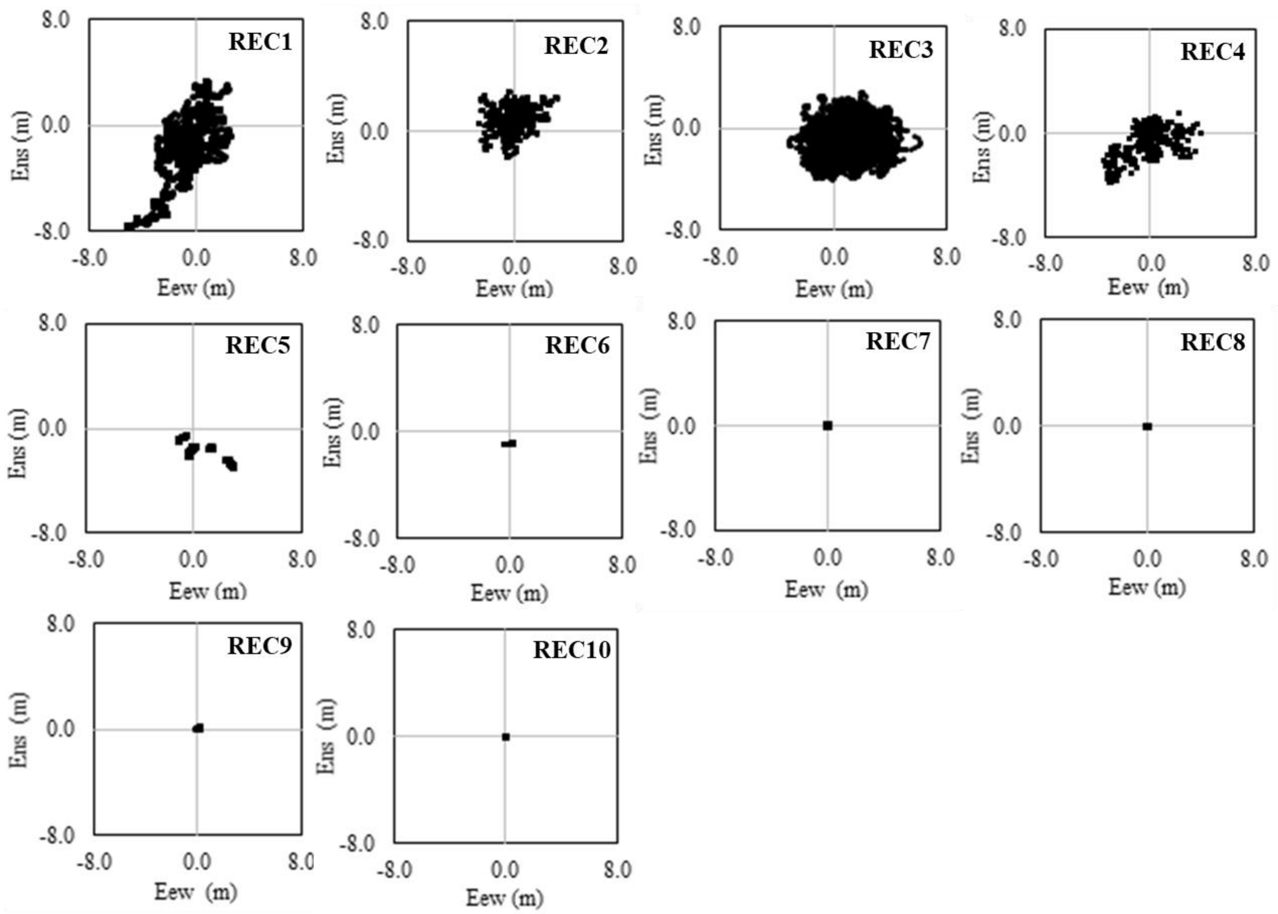

FIGURE 5. Dispersion of North-South (E_{NS}) and East-West (E_{EW}) errors in the static test

The L1/L2 receivers without differential correction showed a low amplitude of variation of E during data collection, within its replications (Figure 6). However, there was a great variation in the temporal stability of the error. In the third replication of receiver ID 7, with SBAS differential correction, there was a visible increase of E. In contrast, in the fourth replication, E started with high value and decreased over time.

No other receiver with differential correction presented such variation in E at the same time, which indicates that receiver ID 7 had the variation of the error due to the quality of the differential correction signal. Receivers IDs 8 and 9 show less E variation than receiver ID 7, and receiver ID 9 lost connection with the signal correction during the third replication. This may explain the greater dispersion of E in the quadrant 2 shown in Figure 6. The comparison between the error dispersion of receiver ID 6 (without differential correction) with receivers IDs 7, 8, and 9 showed an accuracy improvement that SBAS provides. However, depending on the level of accuracy required in agricultural operations, the lack of correction signals may lead to an increase in the positioning error.

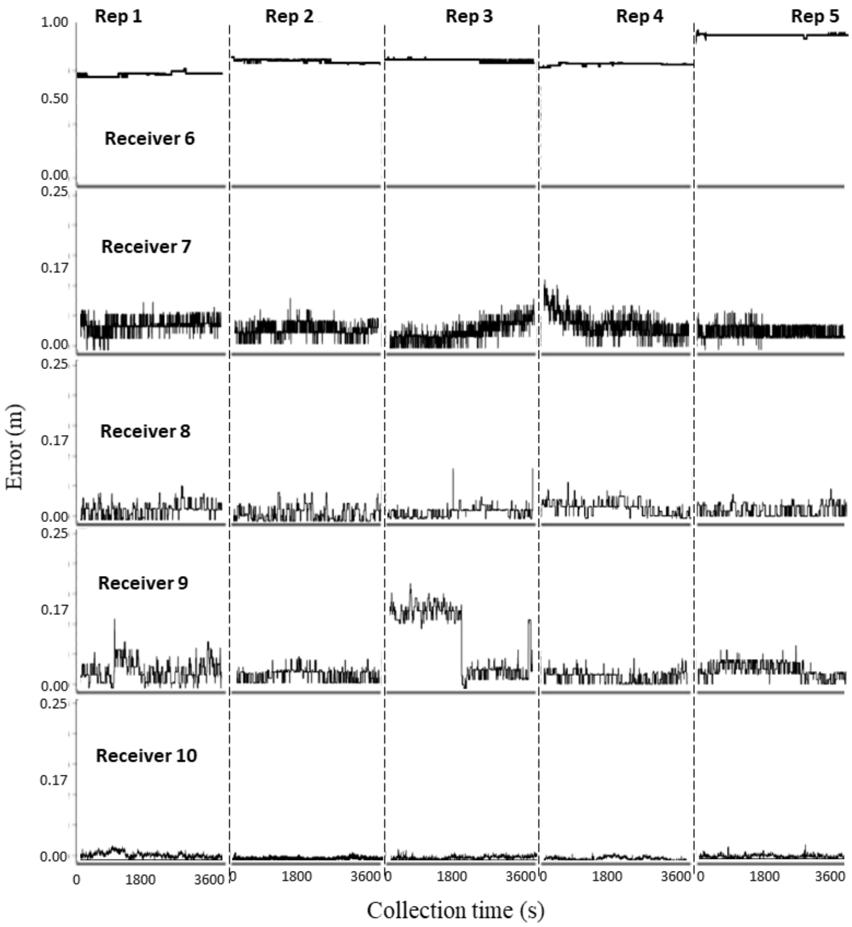

FIGURE 6. Variation of the parallelism error (E) as a function of the time of data collection for all GNSS L1/L2 receivers

Figure 7 shows the dispersion of errors during dynamic tests. There was a small error dispersion for the receiver with RTK differential correction in relation to the other receivers. In general, dynamic test conditions resulted in greater dispersion of errors when compared to the static test. The L1/L2 receiver without differential correction (ID 6) showed a high variation of the error during the time of data collection within replications, which did not occur during the static test, with error values up to 1.45 m.

In addition, a variation of the position errors of the receivers with SBAS, differential correction was greater in the dynamic tests. As in static test, there was a lack of correction signal for receivers with SBAS signal correction, which can be visualized in replication number 4 of the receiver ID 8 and in the replication number 1 of receiver ID 9 when there is more variation of the positioning errors. Although these two replications presented high error amplitude, the other replications presented variation below 0.250 m. However, when compared to the static test, there is a greater variation in the error in the dynamic tests.

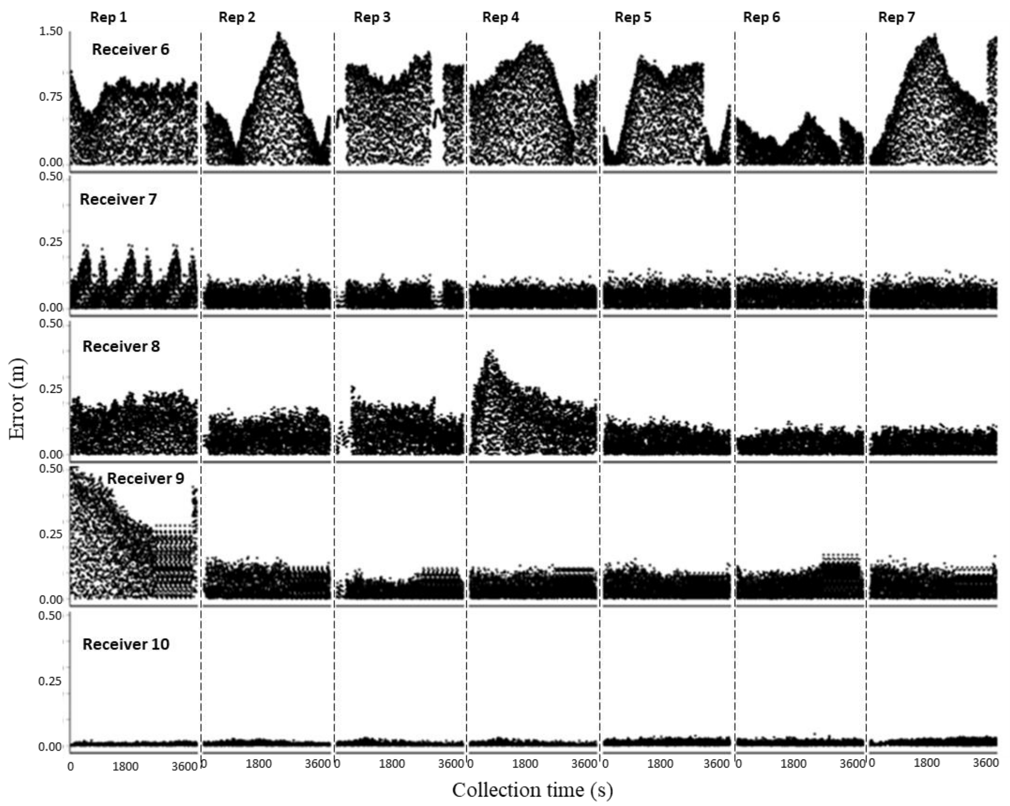

FIGURE 7. Variation of the parallelism error (E) as a function of the time of data collection for all GNSS L1/L2 receivers

The E_{95} of the receivers without differential correction varied from 3.368 m in the static test to 1.280 m in the dynamic test (Table 2). Also, there was no significant difference in the accuracy between receiver ID 2, with only GPS signal, and receiver ID 3 with GPS and GLONASS signals. A smaller positioning error of receiver ID 3 is expected due to the higher number of satellites connection (Banville et al., 2018), but that is only true if the number of visible satellites is the issue, like in conditions of working under tree canopy. In the static test, the accuracy of receiver ID 1 is lower than receivers IDs 5 and 6. Although receiver ID 1 has a low accuracy (E_{95} = 4.218 m), it is not significantly different from the other C/A receivers. In the group A, receiver ID 6 has the highest accuracy, with E_{95} = 0.850 m in the static test and 0.976 m in the dynamic test. Note that in the static test the values of E_{95} is close to the RMS value, indicating low data dispersion, whereas in the dynamic test there is a greater variation between E_{95} and RMS.

For Group A the coefficient of variation (CV) values between the replication did not demonstrate any standard. Some CV values were higher in the static test in relation to the dynamic test and the other receivers showed the lower CV values in the dynamic test. For group B, except for receiver ID 7, there was an increase in error variation between repetitions in the dynamic test. It is considered that the lower the CV estimate, the greater the precision of the experiment and vice versa, and the higher the experimental precision.

TABLE 2. Error values (m) calculated for the static and dynamic tests

Group	ID	Static test				Dynamic test			
		Mean[1]	E_{95}	CV (%)[2]	RMS	Mean	E_{95}	CV (%)	RMS
A	1	2.586	4.218 a	58.14	2.952	1.178	2.256 a	19.85	1.390
	2	1.490	2.480 ab	24.91	1.651	1.147	2.204 a	41.03	1.443
	3	1.712	2.994 ab	53.43	1.911	1.022	2.061 a	33.57	1.303
	4	1.703	2.611 ab	21.02	2.022	1.126	2.226 a	42.96	1.396
	5	1.950	2.170 b	56.54	2.180	1.356	1.945 a	68.70	1.848
	6	0.843	0.850 c	10.70	0.847	0.479	0.976 b	27.42	0.580
B	7	0.040	0.062 a	77.74	0.043	0.048	0.101 a	29.76	0.058
	8	0.019	0.035 ab	25.98	0.021	0.075	0.153 a	32.12	0.114
	9	0.044	0.046 ab	21.82	0.063	0.071	0.099 a	47.68	0.096
	10	0.028	0.031 b	84.72	0.043	0.008	0.017 b	91.95	0.010

[1]Error mean of all points collected by the receiver; [2]The coefficient of variation (CV) of E_{95} between the replications of the same GNSS

It was expected that an L1/L2 receiver without differential correction would be more accurate than C/A code and L1 band receivers. This is due to the better reception capacity of the signal, as it can receive weak signals from the satellites without self-interference, and in addition, they have a better structure for data recovery. Receivers of group A, except receiver ID 6, had higher accuracy in the dynamic test. It was expected a greater variation of the error in the dynamic test in relation to the static test due to the continuous changes in the configuration of the satellite constellation and response time of the receiver, causing a greater variation in the accuracy of GNSS positioning (ASABE, 2008). When performing the static and dynamic tests at different moments, these factors also change, implying a greater variability in the data set.

There was less variation of E_{95} between replications (lower coefficient of variation) in the dynamic test for GNSS without differential signal correction. For GNSS L1/L2 with differential correction, there was a greater variation of E_{95} between the replications in the dynamic test in relation to the static test. In a static test, the GNSS receivers with differential correction had an E_{95} lower than 0.100 m and E_{95} of receiver ID 7 was significantly different from GNSS receiver ID 10, with RTK differential correction. The E_{95} of all receivers used in the static test was closer to the mean errors, indicating low variation in positioning.

GNSS receivers with SBAS resulted in E_{95} greater than receiver ID 10, with RTK differential correction in the dynamic test and SBAS receivers had higher E_{95} in the dynamic test when compared to the static test. Despite having greater variation in the positioning of GNSS receivers in the dynamic test, the E_{95} of receiver ID 10 was higher in the dynamic test.

Comparing the L1/L2 GNSS receivers the E_{95} of the receiver without differential correction is higher than the other receivers with differential correction for both tests. This means that the use of an L1/L2 GNSS receiver without differential correction can generate an E_{95} of 0.802 m higher than a receiver with SBAS signal correction in a static condition, and 0.858 m higher than a receiver with SBAS differential correction in the dynamic condition. Therefore, a lack of differential correction signal can provide a considerable increase in GNSS signal error during agricultural operations.

The effect of the number of replication on the static and dynamic tests indicated that data from receivers with differential correction had a power of 61% in the static and of 44% in the dynamic test (Figure 8), which means that the tests were performed with a small number of replications. The low value of the power of the test for the dynamic test can be explained by the fact that there is a greater variation of the error values in the dynamic than in the static test. The higher the variation, the higher the coefficient of variation, the lower the experimental accuracy and the greater the number of replications required to represent the GNSS positioning error.

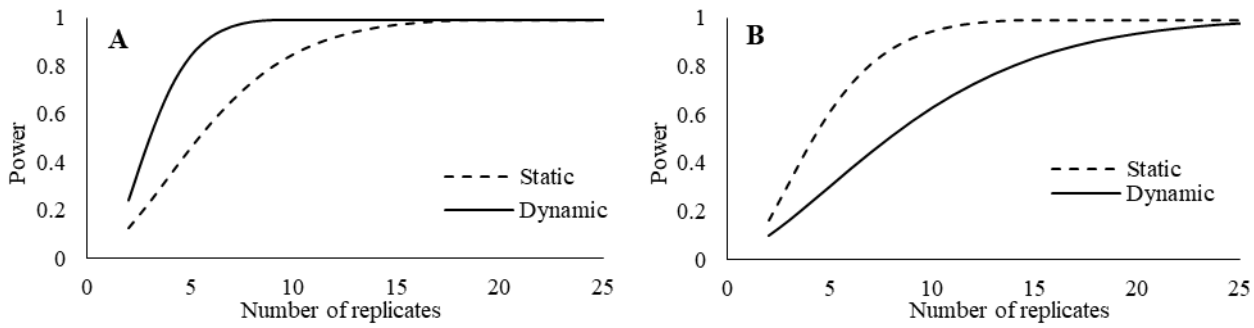

FIGURE 8. Power of the test versus the number of replication on static and dynamic tests for receivers from group A (A); and group B (B)

In order to test receivers with a differential correction to have at least a power of the 80% (β = 20%), seven replications for static test and 13 repetitions for the dynamic condition were done. For receivers with no differential correction (group A), the power of the test was 46% for the static test and 96% for the dynamic test conditions, showing that nine replications are necessary for the static and five replications for the dynamic test conditions to achieve a minimum test power of 80%. Results demonstrate that numbers of replication suggested in the power test to compare different GNSS with differential correction comply with the number of replications indicated by ION STD 101 (1997).

CONCLUSION

This study developed a methodology that allowed analysis of the behavior of GNSS receivers of different levels of accuracy under static and dynamic conditions. The test under dynamic conditions measuring error perpendicular to the path simulates agricultural demands, for example, use of GNSS for auto-guidance on agricultural operations. The signal of the receivers presented a greater variation of positioning error in the dynamic than in static condition, consequently, we verified the need for an increase in the number of replications for which there is a greater power of the statistical test. A minimum of five replications is necessary for dynamic tests to C/A receivers and 13 replications for L1/L2 receivers with differential correction signal. For static tests it is necessary a minimum of nine replications to C/A receivers and five replications for L1/L2 receivers with differential correction signal.

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