DYNAMIC ACCURACY OF GPS RECEIVERS IN CITRUS ORCHARDS

M. Min, R. Ehsani, M. Salyani

ABSTRACT. *The accuracies of six commercially available GPS receivers were studied under static and dynamic conditions in different citrus orchards. The receivers were: Trimble AgGPS®106 Autonomous (T106A), Trimble AgGPS®106 with WAAS (T106W), Trimble AgGPS®132 with Beacon (T132B), Trimble AgGPS®132 with WAAS (T132W), Garmin®18 PC with WAAS at 1 Hz (G18W-1), and Garmin®18 with WAAS at 5Hz (G18W-5). The study evaluated the effects of GPS receiver type, antenna mounting height, and source of differential correction in orchards with three different sizes of trees. Absolute Mean Error (AME) and Relative Error (standard deviation of the cross-track error, SD) were used in describing GPS dynamic accuracy. The AME measures the offsets of the recorded position information from their true position (established by an RTK GPS system). In open field static tests, the accuracies of GPS receivers were similar to the accuracies reported by their manufacturers. However, in dynamic tests, the receivers performed differently under various test and orchard conditions. Overall, receiver type and mounting height had significant effects on GPS accuracies. The two T132 receivers showed the least amount of absolute error in small tree orchards, which agrees with the static test results. Generally, the WAAS differential correction system could provide an accuracy level comparable to the Coast Guard Beacon in most central Florida orchard conditions.*

Keywords. *DGPS, Global Positioning System, GPS accuracy, RTK GPS, WAAS.*

The Global Positioning System (GPS) is one of the key technologies in precision agriculture (PA) for yield mapping (Whitney et al., 2001), parallel tracking (Han et al., 2004), vehicle guidance (Bell, 2000), plant-specific application (Ehsani et al., 2004), and variable-rate application (Anglund and Ayers, 2003). Knowing the accuracy of different GPS receivers is a matter of concern to growers and farmers who own, rent, or are considering purchasing one of these systems. The accuracy of GPS receivers specified by GPS manufacturers is usually based on static test results. However, in most agricultural applications, such as tillage, planting, spraying, and harvesting, GPS receivers are used under dynamic conditions. GPS dynamic accuracy can be very different from static accuracy. Stombaugh et al. (2002) compared the performance of several GPS receivers under static and dynamic conditions. Their test results indicated that some GPS receivers performed worse in dynamic conditions than in static conditions. Recently, GPS dynamic accuracy has been tested in several studies. In the evaluation of GPS dynamic accuracy, GPS receivers were mounted on a vehicle driven through a pre-defined path where all receivers were exposed to the same environmental conditions and GPS satellite configurations. In a dynamic accuracy test, it is also common to use real-time kinetic (RTK) GPS as the reference, which has centimeter-level accuracy (Ehsani et al., 2002; Taylor et al., 2004).

Many factors contribute to the total GPS error. The main factors include satellite position in orbit (ephemeris), receiver clock timing, ionospheric and atmospheric delays, and multipath effects. In addition, several considerations for dynamic GPS receiver testing were addressed by Ehsani et al. (2003). The geometry of the GPS satellites, indicated as dilution of precision (DOP), and number of satellites in use can influence the GPS errors with changes in time and location. The DOP consists of horizontal (HDOP) and vertical (VDOP) components. The former, which affects the accuracy of latitude and longitude, can be calculated by most receivers. When satellites are more evenly distributed throughout the sky, the HDOP value is low, and better GPS accuracy can be obtained. For higher GPS accuracy, HDOP should be less than four, and the number of satellites in use should be more than five. The HDOP can be further divided into north (NDOP) and east (EDOP) components by the relationship of $HDOP = \sqrt{EDOP^2 + NDOP^2}$ (Wu et al., 2005). Due to the 55° inclination of the GPS satellite orbits to the equator and 60° separation of orbital planes, the satellites are distributed within the latitude of 60°. When latitude is beyond 25°, NDOP is larger than EDOP (Wu et al., 2005).

Elevation mask, an angle below which satellites in the horizon are excluded from the position computation, may also affect GPS accuracy because satellite signals would travel a greater distance at lower horizon and become more

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prone to atmospheric delays. Although increasing the elevation mask could ensure a better position fix, it also reduces the number of satellites in view (Trimble, 2000). Multipath error, caused by the reflection of satellite signals on nearby objects (e.g. buildings and trees) could be another source of GPS error.

In prior studies (Han et al., 2004; Taylor et al., 2004; Wu et al., 2005), GPS accuracy tests were conducted in open areas with clear sky. However, when GPS receivers are used in citrus orchards, the GPS accuracy could be affected by tree canopy. When the antennas are mounted on field equipment at a level lower than the tree height, multipath error could affect GPS accuracy. As the antenna mounting height decreases, canopy tends to block the view of the receivers. This effect could be similar to the effect of increasing the elevation mask setting.

Most of the GPS errors can be reduced by using a differential correction signal. In the United States, these signals are available from Coast Guard (C.G.) Beacon, Wide Area Augmentation System (WAAS), OmniSTAR, and John Deere's StarFire system (Perry and Rains, 2005). The commonly used C.G. Beacon and WAAS are free of charge, while OmniSTAR and StarFire are subscription-based differential GPS (DGPS) sources. The C.G. Beacon signal transmits at radio frequencies; therefore, mountainous terrains and vegetative canopy generally do not affect signal reception. However, the signal is very susceptible to natural and man-made noises from alternators, electric fan motors, radio speakers, and high voltage power lines (Trimble, 2000). WAAS uses geostationary satellites to broadcast differential signals which are in the line-of-sight. Canopy cover in the direction of the differential satellite can reduce the signal's strength to unusable levels and wet canopy reduces signals further (Trimble, 2000). In addition, accuracy of the correction signal relies on the presence of ground stations to calculate and correct various errors such as ionospheric delay. The accuracy will be affected with distance from a reference station. Since WAAS has a reasonably large set of base stations across the United States, its accuracy over the United States is uniform except in areas near the coasts and the Canadian and Mexican borders.

OBJECTIVES

The main goal of this project was focused on evaluating the dynamic accuracy of several GPS receivers in citrus orchards in Florida and examining the effect of tree canopy on GPS accuracy. This goal was accomplished through the following specific objectives:

- Comparing the accuracies of six GPS receivers in static and dynamic conditions.
- Evaluating dynamic accuracies with the GPS antenna or receiver at different mounting heights with respect to the top of the tree canopy.
- Investigating the effect of differential correction signal (C.G. Beacon vs. WAAS and WAAS vs. Autonomous) on GPS dynamic accuracies.

MATERIALS AND METHODS

GPS RECEIVERS

Six GPS receivers, Trimble AgGPS® 106 Autonomous (T106A), Trimble AgGPS® 106 with WAAS (T106W), Trimble AgGPS® 132 with Beacon (T132B), Trimble AgGPS® 132 with WAAS (T132W) (Trimble Navigation Ltd., Sunnyvale, Calif.), Garmin® 18 PC with WAAS at 1 Hz (G18W-1), and Garmin® 18 with WAAS at 5Hz (G18W-5) (Garmin® International Inc., Olathe, Kans.), were tested in this study. An RTK GPS (Hiper XT®; Topcon America Corporation, Paramus, N.J.) served as the reference receiver. The Hiper XT® is a completely cable-free base and rover unit and uses both GPS and GLONASS (GLObal NAvigation Satellite System), a dual constellation satellite positioning technology. It has a horizontal accuracy of 10 mm. The specifications and configurations of the tested GPS receivers selected for the study are listed in table 1.

STATIC TESTS

Static tests were conducted to verify the accuracies reported by each receiver manufacturer, and to provide basic information for the dynamic tests. The static tests were conducted on 3 March 2006, at the Citrus Research and Education Center (CREC) in Lake Alfred, Florida (81.73° W and 28.13° N). Data were collected from 8:00 a.m. to 8:00 p.m. in a relatively open area over 15 m from the nearest building or trees. Although it is recommended to conduct a static test for a minimum of 24 hours, this was not necessary in this case, because 12 hours of data was enough to determine that the accuracies fell within the reported range of accuracy data reported by the receivers' manufacturers. A tractor-driven trailer, comprised of a 4.23-m PVC vertical mast and a 3.66-m aluminum cross-bar, was used to support the antennas of all the receivers at a height of 3.80 m (fig. 1).

The order of the antennas from position 1 to 6 was T106W, T132W, G18W-1, G18W-5, T132B, and T106A, respectively. The distance between adjacent GPS antennae was 0.61 m. The elevation masks of T106A, T106W, T132B, and T132W were set to 1° to match the built-in and nonadjustable elevation masks for G18W-1 and G18W-5. For each data point, multiple NMEA (National Marine Electronics Association) data strings, GGA, VTG, and GSV, were used.

Table 1. Specifications[a] and configurations of the six GPS receivers.

GPS Receivers	WAAS	Beacon	Static Accuracy (RMS) (m)	Receiver Channels	Time to First Fix (s)	Output Frequency (Hz)	Number of Ports	Firmware Version	Cost ($)
T106A	-	-	-	8	<90	1	2	3.0	600-1500
T106W	Yes	-	1-3	8	<90	1	2	3.0	600-1500
T132B	-	Yes	<1	12	<30	1	2	3.0	>2500
T132W	Yes	-	<1	12	<30	1	2	3.0	>2500
G18W-1	Yes	-	<3	12	<45	1	1	2.80	80-200
G18W-5	Yes	-	<3	12	<45	5	1	2.80	80-200

[a] As reported by the manufacturers.

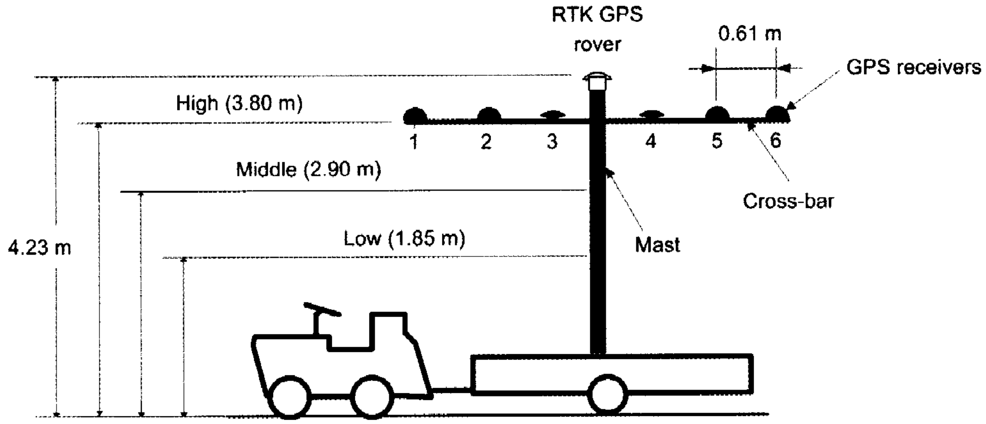

Figure 1. Geometry and height arrangement for GPS antennas used in the static and dynamic tests.

Information of time, position, HDOP, number of satellites in use, and speed were extracted from the NMEA strings. For data acquisition, a rugged computer (ZYNX20; KEE Technology Inc., Mawson Lakes, Australia) was used which provided four RS232 serial ports that could obtain NMEA strings from four GPS receivers simultaneously. Data from another two receivers were collected by a laptop computer (Dell Inc., Round Rock, Tex.) with a USB connection to a Seaport (Sealevel Systems Inc., Liberty, S.C.) which provided four RS232 serial ports.

For each GPS receiver, the terms of static accuracy were calculated according to the averaged coordinates and described by root mean square (RMS) error, mean error, maximum (Max) error, circular error probable at 50% ($CEP_{50\%}$), and circular error probable at 95% ($CEP_{95\%}$). Point-to-point error (PPE), which was the distance of two data points based on a 1-s interval, indicated the noise level of each GPS receiver and provided information for relative error analysis in the GPS dynamic test. Larger PPE indicated a potential for a larger relative error in dynamic tests. Additionally, the data loss (NMEA string without location information, expressed as percentage of total number of the strings) was used to determine the receiver's ability to continuously receive satellite signals. The receiver data ranges in easting and northing were calculated. Ordinarily, larger NDOP than EDOP indicates larger northing error. All the static accuracy data were extracted and averaged on an hourly basis to create 12 sets of data for each tested receiver. Then, an Analyses of Variance (ANOVA) was conducted to test the effects of GPS type on the above mentioned response variables (RMS, $CEP_{50\%}$, etc.). Mean comparisons were made by the Tukey-HSD's test (JMP, Version: 6, SAS Institute Inc., Cary, N.C.).

DYNAMIC TESTS

Dynamic accuracy of the six GPS receivers was tested in two orange orchards near Lake Alfred, Florida (N 28.10° and W 81.70°) (fig. 2). Orchard 1 (test plots 1 and 2) had relatively uniform, mid-size trees in the east-west orientation. The trees were set at 6.1- × 3.0-m spacing and their average height was 4.3 m (SD = 0.6 m). Orchard 2 consisted of two tree sizes in the north-south orientation. The southern part (test plot 3) had relatively small individual trees (3.5 ± 0.2 m) at 6.1- × 4.6-m spacing. The northern part (test plot 4) had larger (5.3 ± 0.4 m) hedge-rowed trees with dense canopies set at 6.1- × 2.3-m spacing. Tree heights were measured using a measuring pole (SK202, Senshin Industry Co., Ltd., Osaka, Japan).

In order to study the effect of tree height on GPS dynamic accuracy, the six receivers (mounted on a cross-bar) were positioned at three heights (fig. 1). The heights were 1.85, 2.90, and 3.80 m above ground level, which were labeled as Low, Medium, and High, respectively. Both ends of the cross-bar were fastened to the vertical mast by rope to reduce antenna vibration during the tests. The RTK rover unit was mounted on top of a central mast at a height of 4.23 m.

During the dynamic tests, the RTK base station was located near the orchards to maintain the best radio link with the rover unit. The coordinates of the base stations were obtained by a 2-h static survey. Collected stationary data from the RTK-base station was post-processed using the U.S. National Geodetic Survey Kinematic and Rapid Static (KARS) software to determine the true position of the RTK base station. The RMS error of the base station was less than 10 mm.

The GPS receivers' data were projected from WGS-1984 Latitude/Longitude to State Plane (NAD 83, Florida West) using ArcView GIS (version 3.3). The test unit was driven through one row middle and returned on the next, with the cross-bar parallel to the rows. The nominal travel speed was 5 km/h. Only four pairs of row middle sections were used in the dynamic analysis (fig. 2, test plots 1-4). The length of each section was about 37.5 m. With data output frequency of 1 Hz, the RTK GPS collected 25-28 data points per section of each test plot.

The regression line of the RTK data was used as a reference line. The reference lines were calculated individually for each plot within each replication. Cross-track error (e_i) was expressed as the distance (northing or easting) between GPS data and the reference line. In Orchard 1, the angles between the reference lines and easting ranged from -2.5° to -0.9° (average deviation of -1.5°). For Orchard 2, the angles between the reference lines and northing ranged from 1.1° to 1.9° (average deviation of 1.6°). The error resulting from these deviations was less than 0.1% of the cross track error, which was considered to be negligible; therefore, the easting and northing errors were included in the cross-track error (e_i) (fig. 3).

For evaluating GPS dynamic accuracy, two error terms were used in each plot:

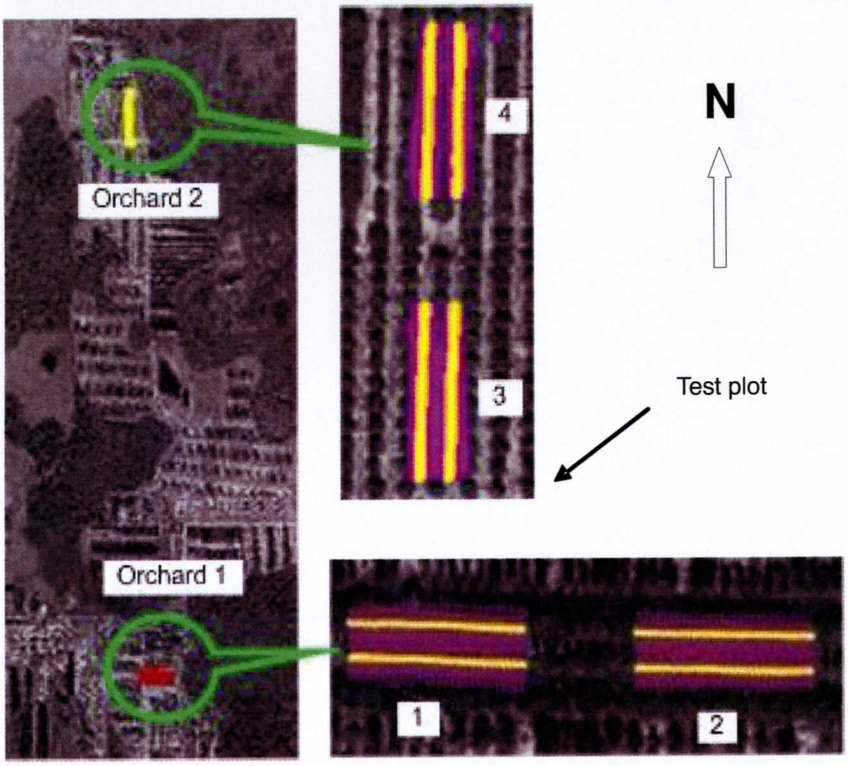

Figure 2. Aerial views of the test plots for the dynamic accuracy testing of GPS receivers.

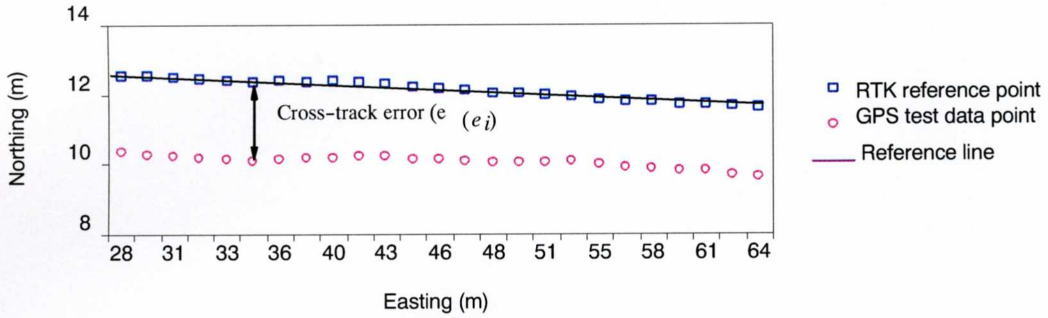

Figure 3. Illustration of the cross-track error in the dynamic tests.

a) Absolute Mean Error (AME) of the cross-track error

$$\bar{e} = \left|\frac{\sum e_i}{n}\right| \tag{1}$$

b) Relative Error (RE) or Standard Deviation (SD) of the cross-track error

$$SD = \sqrt{\frac{\sum_i (e_i - \bar{e})^2}{n-1}} \tag{2}$$

where

e_i = cross-track error of each data point (fig. 3),

$e_i = y_i - \hat{y}_i$ and $\hat{y}_i = a + bx_i$ (for east-west direction),

$e_i = x_i - \hat{x}_i$ and $\hat{x}_i = c + dy_i$ (for north-south direction),

$\hat{y}(x)$ and $\hat{x}(y)$ are the reference lines (regression lines of the RTK in test plots),

a, b, c, d are the coefficients of the regression lines, and n is the number of data obtained from each plot.

The AME describes the closeness of the measurements to the true position (accuracy), while the SD measures the variation of the cross-track errors (precision). Small AME values are considered to be more accurate and small SDs mean good repeatability. Both AME and SD of each receiver were calculated for each test plot. Each of those terms might be appropriate for certain GPS applications. Although high accuracy and high precision are desirable, in practice both qualities may not be achievable from certain receivers. However, averaging of multiple data points may increase the position accuracy to an acceptable level for certain map-based applications. Also, the low accuracy but repeatable data could be improved by compensating the bias value to reduce the offset from a true position.

The tests were conducted on 16, 20, 24 February and 2 March 2006. The satellite constellation was obtained using Planning software (version 2.7; Trimble, 2002). During the 10:00 a.m. - 3:00 p.m. test periods, the HDOP was less than 1.2 and number of satellites in view was more than 9.

EXPERIMENTAL DESIGN

The tests were conducted as a randomized block experiment with three replications. The data were analyzed as a split-block design using antenna height and GPS type as the main and subplot factors, respectively. Table 2 shows the order of the test runs and arrangements of the antennas in different replications. The experiment was repeated in two orchards (fig. 2) on different dates. Since the tree sizes and row orientations were different in different plots of the two orchards, the analysis of variance (SAS GLM procedure) was conducted separately for different test plots with small, mid-size, and large trees. The independent variables were AME and SD. Since AME and SD did not follow the normal distribution, the transformed data set of log(AME) and log(SD) were used in the statistical analyses. The means were compared by Tukey-HSD test. The Student's t-test was used for pair-wise comparison of differential correction sources such as C.G. Beacon versus WAAS and WAAS versus Autonomous. Unless specified, the significance level in all statistical analyses refers to the 5%.

Two other factors, HDOP and number of satellites in use (NOSIU), which indirectly affect GPS accuracy, are affected by the antenna mounting height. At lower heights the trees could block the satellite signals and affect the HDOP and NOSIU; therefore, the relationships between antenna height and HDOP/ NOSIU were also studied.

RESULTS AND DISCUSSION

STATIC TESTS

Analysis of the static test data showed that the type of GPS receiver had a significant effect on all the accuracy parameters such as RMS, CEP$_{50\%}$, PPE, etc. (table 3). Using the main GPS accuracy comparison parameters (average RMS, Average Mean error, and CEP$_{50\%}$) the T132 (T132W and T132B) receivers showed the best static accuracies. However, considering additional comparison parameters listed in table 3, none of the receivers was consistently better than the others. Again, according to the main accuracy comparison parameters, the G18W-1 was the least accurate receiver. Even though the T106 receivers had occasional loss of signal (data string without position information), they showed better accuracies than the G18W-1 receiver. This result might be due to the fact that G18W receivers use only six digits after the decimal points for location information compared to eight digits with others. It should be mentioned that while T106A had total data loss of 22.3%, its loss reached 60% during the time period of 6:00 p.m. to 8:00 p.m. T106W had a total data loss of 10.1%.

The average PPE values of GPS receivers (table 3) were much smaller than their RMS values, which indicate that over a short time period, there were no sudden position jumps. In other words, data points were shifting gradually, which indicate better accuracies over short time periods. T132W had the smallest PPE (0.007 m) as well as the smallest RMS error (0.212 m). The order of average PPE was the same as the order of mean error. In general, northing spread was larger than easting spread due to larger NDOP than EDOP.

Table 2. Arrangements of the six GPS antennas for different runs in the dynamic tests.

			GPS Order from the Front of the Cross-bar					
Replication	Height[a]	Run Order	1	2	3	4	5	6
Replication 1	L	1	G18W-1	T106W	T132W	T132B	T106A	G18W-5
	M	3	-	-	-	-	-	-
	H	2	-	-	-	-	-	-
Replication 2	L	6	T132W	G18W-1	T106W	T106A	G18W-5	T132B
	M	4	-	-	-	-	-	-
	H	5	-	-	-	-	-	-
Replication 3	L	9	T106W	T132W	G18W-1	G18W-5	T132B	T106A
	M	8	-	-	-	-	-	-
	H	7	-	-	-	-	-	-

[a] L = low, M = medium, H = high antenna height levels.

Table 3. Static GPS test results based on hourly data.

GPS Receiver	Avg. RMS (m)	Avg. Mean Error (SD) (m)	Avg. Max. Error (m)	Avg. CEP50% (m)	Avg. CEP95% (m)	Avg. PPE (m)	Avg. Data Loss (%)	Easting Spread (m)	Northing Spread (m)
RTK[a]	0.007	0.006 (0.003)	0.029	0.006	0.012	0.002	-	0.043	0.034
T132W	0.212 a	0.190 a[b] (0.068)	0.469 a	0.182 a	0.368 a	0.007 a	1.459 a	0.626 a	0.734 a
T132B	0.340 a	0.280 a (0.065)	1.036 a	0.252 a	0.593 a	0.016 ab	1.063 a	1.218 a	1.243 a
T106W	1.590 b	1.272 b (0.302)	7.921 ab	1.085 b	3.001 b	0.043 c	10.138 ab	6.718 b	10.670 ab
T106A	2.400 c	1.876 c (0.533)	11.149 b	1.547 c	4.814 c	0.052 c	22.303 b	10.207 bc	13.463 b
G18W-5	2.474 c	2.188 c (0.216)	6.034 ab	2.042 d	4.324 bc	0.027 b	0.405 a	9.795 bc	9.167 ab
G18W-1	3.062 d	2.597 d (0.364)	12.974 b	2.368 e	5.227 c	0.134 d	2.385 a	12.160 c	16.737 b

[a] Average RTK GPS data for 12-h period.

[b] In each column, means followed by unlike letters are significantly different at 5%.

Table 4. Overall results for the dynamic GPS tests.

GPS Receiver	No. of Data Sets	Median AME (m)	Max AME (m)	Median SD (m)	Max SD (m)	Average HDOP	Average No. of Satellites
T106A	21	0.975	6.134	0.162	2.995	2.4 b[a]	3.6 c
T106W	31	0.871	6.732	0.179	2.135	2.7 b	3.8 c
T132B	36	1.203	2.607	0.127	0.383	1.2 a	7.3 b
T132W	36	0.466	1.799	0.176	0.609	1.2 a	7.5 b
G18W-1	36	0.918	2.801	0.178	0.902	1.2 a	8.7 a
G18W-5	36	0.632	3.507	0.134	0.715	1.2 a	8.3 a

[a] In each column, means followed by unlike letters are significantly different at 5%.

DYNAMIC TESTS

Table 4 summarizes all data collected at both orchards. Tukey-HSD's means test was used for average HDOP and number of satellites in use. Since log(AME) and log(SD) had normal distribution and their mean values were equal to their medians, the medians were presented in table 4.

Like static tests, T106 receivers experienced some data loss under dynamic conditions. While T132 and G18W receivers had 36 data sets (3 heights × 3 replications × 2 test plots × 2 orchards), T106A and T106W had only 21 and 31 data sets, respectively. Even in their recorded data sets, there were some missing data points. Since T106A and T106W only had 8-channel capacity, their average HDOP values were larger than other receivers which had 12-channel capacity. The T106 receivers also had the lowest average number of satellites in use (less than four, which could result in less accurate position information). Ordinarily, the 12-channel capability of T132 and G18W receivers could potentially increase the chance of continuous operation. However, Garmin receivers used only 6-decimals to report the location information, which could have some impact on their accuracy levels.

EFFECTS OF ANTENNA HEIGHT AND GPS TYPE ON ERROR TERMS

As mentioned earlier, the log-transformed data of each test plot were analyzed separately. The height of the GPS antennas (HT) did not have a significant effect on the absolute mean error (AME) in any orchard; however, the effect of HT on relative error (SD) was significant in mid-size ($p = 0.006$) and large ($p = 0.006$) trees. The effect of GPS type on AME was significant in small ($p = 0.005$) and mid-size ($p = 0.042$) trees; nonetheless, the effect on SD was not significant in any orchard. For the SD, there were significant interactions between the GPS type and HT in all orchards ($p < 0.003$). These results imply that the difference among GPS receivers could not be sensed in large tree orchards as the signal becomes more variable in that environment.

Table 5 shows the corresponding means of the error terms at each antenna mounting height (high, medium, low). While AME values were not significantly different at three heights in any orchard, SD seemed to generally increase with decreasing antenna height in mid-size and large trees. This is evident by larger SD values at lower levels. Such effect, which is more pronounced at the lowest antenna height, could be attributed to the reduction in the number of satellites in use under those conditions. In orchards with small trees, there was no significant difference between the antenna heights since the antennas were hardly blocked by the canopy at any level.

Table 6 presents the magnitude of the error terms for different GPS receivers. In orchards with small and mid-size trees, there were significant differences between some receivers but that was not the case in large tree orchards. Comparison of the data in small and large trees, which were obtained on the same day and at the same direction, generally shows larger error terms in orchards with large trees. The two T132 receivers showed the least amounts of absolute error in

Table 5. Means of the error terms at different antenna heights within each test plot.

	Small Trees		Mid-size Trees		Large Trees	
Height	AME (m)	SD (m)	AME (m)	SD (m)	AME (m)	SD (m)
High	0.046 a[a]	0.015 a	1.107 a	0.009 a	0.070 a	0.021 ab
Medium	0.096 a	0.017 a	1.361 a	0.012 ab	0.095 a	0.014 a
Low	0.071 a	0.013 a	0.883 a	0.019 b	0.173 a	0.041 b

[a] In each column, means followed by unlike letters are significantly different at 5% using Tukey's test.

Table 6. Means of the error terms for different GPS types within each test plot.

GPS	Small Trees		Mid-size Trees		Large Trees	
Receiver	AME (m)	SD (m)	AME (m)	SD (m)	AME (m)	SD (m)
T106A	0.497 b[a]	0.017 ab	1.714 ab	0.024 ab	0.128 a	0.028 a
T106W	0.084 ab	0.020 ab	1.028 a	0.023 b	0.233 a	0.019 a
T132B	0.007 a	0.009 ab	4.592 b	0.008 a	0.082 a	0.017 a
T132W	0.014 a	0.036 b	0.465 a	0.014 ab	0.049 a	0.019 a
G18W-1	0.164 b	0.016 ab	1.102 a	0.013 ab	0.234 a	0.034 a
G18W-5	0.177 b	0.007 a	0.515 a	0.009 ab	0.080 a	0.024 a

[a] In each column, means followed by unlike letters are significantly different at 5% using Tukey's test.

orchards with small and large trees, which agrees with the static test results. However, the rest of the data did not follow the same trend as in the static tests. This inconclusive result could be attributed to the confounding effects of antenna height, driving direction, and tree height, which might be explained by HDOP and NOSIU.

Since the canopy could block and weaken satellite signals, the effect of decreasing antenna mounting height might be similar to increasing elevation mask. Analysis of variance on the HDOP and NOSIU showed significant effect only for the GPS mounting height (HT) in orchards with the mid-size and large trees. These results imply that the tree size in the small tree orchard was too short to have any effect on GPS signals. As shown in table 7, mean HDOP generally increased at lower antenna heights. This effect was more pronounced in orchards with larger trees. The antenna mounting height also significantly affected the number of satellites in use in mid-size and large trees (table 8). In all orchards, the average NOSIU decreased at lower antenna levels.

EFFECT OF DIFFERENTIAL CORRECTION SOURCE

The source of differential correction (Autonomous vs. WAAS) did not have a significant effect on either AME or SD when comparing T106A and T106W receivers. This finding might be explained by significant numbers of lost data as well as low number of satellites in use with these receivers (table 4). However, there were significant effects on the error terms when comparing the WAAS with Coast Guard Beacon differential correction sources (T132W vs. T132B). While the absolute mean error was significantly lower with the WAAS system in mid-size trees (0.465a vs. 4.592b), the relative error was significantly lower with the Beacon system in small and mid-size tree orchards (0.009a vs. 0.036b and 0.008a vs. 0.014b, respectively). In large trees, the source of differential correction did not have a significant effect on either error term.

The results revealed that the effect of the correction source may not be the same on both error terms (AME and SD). In this study, the WAAS system showed generally lower absolute mean error whereas the Beacon system gave lower relative error. This finding might be important when considering either higher accuracy (smaller AME) or better repeatability (smaller SD) for certain applications.

Table 7. The effect of antenna mounting height on HDOP.

Height	Small Trees	Mid-size Trees	Large Trees
High	1.364 a[a]	1.321 b	1.370 b
Medium	1.197 a	1.643 ab	1.488 b
Low	1.334 a	1.983 a	2.012 a

[a] In each column, means followed by unlike letters are significantly different at 5% using Tukey's test.

Table 8. The effect of antenna mounting height on NOSIU.

Height	Small Trees	Mid-size Trees	Large Trees
High	7.402 a[a]	7.414 a	6.884 a
Medium	7.367 a	7.144 a	6.573 ab
Low	7.276 a	6.085 b	5.630 b

[a] In each column, means followed by unlike letters are significantly different at 5% using Tukey's test.

CONCLUSIONS

In this article, the accuracies of six commercially available GPS receivers were studied under static and dynamic conditions in different citrus orchards. The receivers were: Trimble AgGPS® 106 Autonomous (T106A), Trimble AgGPS® 106 with WAAS (T106W), Trimble AgGPS® 132 with Beacon (T132B), Trimble AgGPS® 132 with WAAS (T132W), Garmin® 18 PC with WAAS at 1 Hz (G18W-1), and Garmin® 18 with WAAS at 5 Hz (G18W-5). The following conclusions drawn from this study are:

- In static (open field) tests, the accuracies of GPS receivers were similar to the accuracies reported by their manufacturers. The T132 receivers with WAAS and Coast Guard Beacon differential correction sources showed the best static accuracy followed by T106 and Garmin receivers.
- In dynamic tests, the receivers performed differently under various test and orchard conditions. Overall, medians of the absolute and relative errors of the receivers were comparable; however, the T106 receivers showed higher maximum errors than the others. These results appeared to be correlated with the average HDOP and average number of satellites in use.
- Receiver type and antenna mounting height had significant effects on GPS accuracies; however, the effects varied in different orchards (tree sizes). The T132 receivers showed the least amount of absolute error in small tree orchard, which agree with the static test results. Since T106 receivers lost a considerable percentage of data points, their performance under orchard conditions could be questionable. The number of satellites used by the G18W receivers was more than the others, but they used only 6-decimals to report the location information, which could have some impact on their accuracy levels. While absolute error values were not significantly different at three antenna mounting heights in any orchard, relative error could generally increase at lower antenna heights in orchards with mid-size and large trees.
- Comparison of differential correction sources for Trimble AgGPS®132 revealed that the WAAS system could generally provide an accuracy level comparable to the Beacon in most central Florida orchard conditions.

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