

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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The authors are **Min Min**, former Postdoctoral Associate, **Reza Ehsani**, **ASABE Member Engineer**, Assistant Professor, and **Masoud Salyani**, **ASABE Member Engineer**, Professor, University of Florida, IFAS, Agricultural and Biological Engineering Department, Citrus Research and Education Center, Lake Alfred, Florida. **Corresponding author:** Reza Ehsani, University of Florida, IFAS, Agricultural and Biological Engineering Department, Citrus Research and Education Center, 700 Experiment Station Rd, Lake Alfred, FL 33850; phone: 863-956-1151 ext. 1228; fax: 863-956-4631; e-mail: ehsani@ufl.edu.

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.

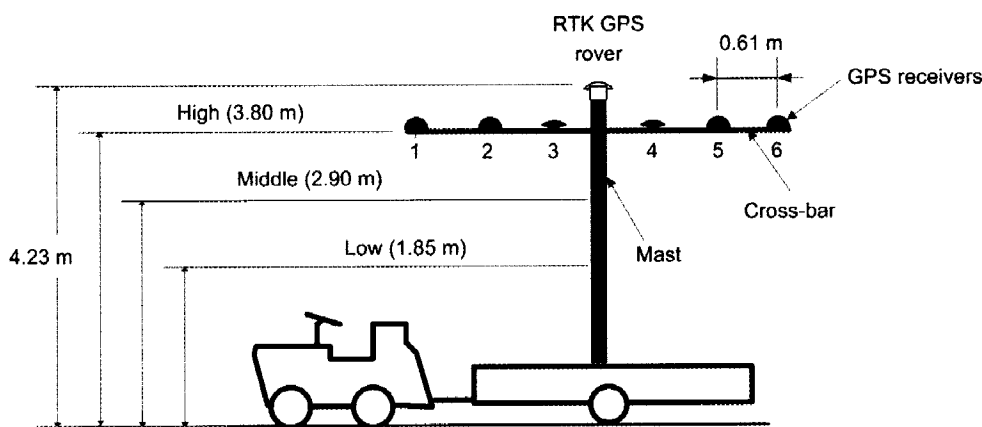


Figure 1. Geometry and height arrangement for GPS antennas used in the static and dynamic tests.

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:

