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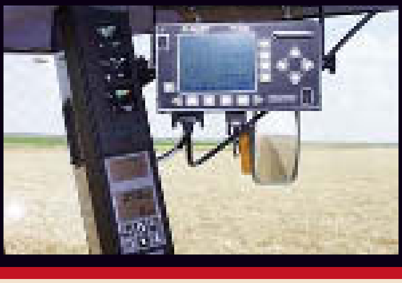

Precision Agriculture Research

Special Publication

Kansas State University Agricultural Experiment Station and Cooperative Extension Service

Comparison of Differentially Corrected GPS Sources for Support of Site-Specific Management in Agriculture

by
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Chapter 1: Static Test. Static assessment of the relative performance of three differential correction sources for global positioning systems (GPS) available to users of precision agriculture technology in the Hays, KS area.

Chapter 2: Dynamic Test. Dynamic assessment of three differential correction sources for global positioning systems (GPS) to determine suitability for precision agriculture applications in the vicinity of Hays, KS.

Keywords. Precision agriculture, Differential global positioning system (DGPS), Dilution of precision (DOP), Beacon, OmniSTAR, WAAS, Real Time Kinematic (RTK).

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CHAPTER 1: STATIC TEST

Abstract. Autonomous GPS and three differentially corrected GPS (DGPS) sources were tested under static conditions to assess suitability for precision agriculture applications in the vicinity of Hays, KS. DGPS sources included the U.S. Coast Guard Beacon, Wide Area Augmentation System (WAAS), and OmniSTAR, a commercial service. Both WAAS and OmniSTAR broadcast correction messages from geostationary satellites and cover wide areas. The ground-based Beacon currently is more restricted in area of coverage. The standard for absolute accuracy in this study was RTK (Real Time Kinematic) GPS. Horizontal absolute accuracy (referenced to RTK) as measured by the root mean square error was 0.46, 0.49, 1.13, and 1.71 m for Beacon, OmniSTAR, WAAS, and Autonomous GPS, respectively. Corresponding values for horizontal relative accuracy (each mode referenced to its own mean) were 0.41, 0.47, 0.32, and 0.92 m, respectively. The rather significant improvement in relative performance of WAAS compared to its absolute accuracy resulted from the DGPS correction being based on a different geodetic datum than RTK, Beacon and OmniSTAR. This resulted in a northwest quadrant bias for WAAS compared to RTK. Performance of all three DGPS sources met or exceeded design specifications. Availability for the period of the test ranged from 99.2% (Beacon, WAAS) to greater than 99.9% (OmniSTAR), indicating all the DGPS sources tested provided dependable service.

Farmers are expanding their use of precision agriculture or site-specific management technologies to optimize inputs and reduce negative environmental impact. Position accuracy required to consistently implement site-specific management normally exceeds that attainable from the autonomous (uncorrected) Global Positioning System (GPS) even with selective availability disabled. Differentially corrected GPS (DGPS) is a common method for correcting some of the inherent errors and provides submeter accuracy. Consistent realization of centimeter accuracy requires survey-grade or Real Time Kinematic (RTK) GPS. Users of DGPS today have access to alternative differential correction sources that vary in cost as well as suitability or reliability depending on location.

Numerous comparisons of accuracy of GPS receivers for precision agriculture applications have been made. Recent examples include evaluation of cross-track error in parallel tracking operations (Han et al., 2002) and analysis of errors in GPS-based automatic guidance systems (Ehsani et al., 2002, Gan-Mor et al., 2002). Stombaugh et al. (2002), in search of standards for dynamic GPS accuracy tests, noted the frustrations of assessing relative GPS receiver performance among commercial options using manufacturer specifications because reporting formats vary and because of differences in data filtering or smoothing. They also lamented that accuracy specifications are generally for static conditions, which may have minimal relevance to the mobile world of precision agriculture. They concluded that the Institute of Navigation had developed a static test standard suitable for characterizing performance of GPS receivers used in precision agriculture, but that dynamic test standards were not yet well defined.

Quantification of and standards for GPS accuracy are application dependent. Some applications require high absolute accuracy; others depend on high relative accuracy. Buick (2002) provided an analysis of the meaning of those terms as they apply to static and dynamic conditions and to mapping, swathing, and automated guidance applications. Buick also explored the causes of reduced GPS performance external to the GPS receiver.

This study compared absolute and relative accuracy of position fixes determined by autonomous GPS and three DGPS sources referenced to RTK GPS in response to clientele seeking recommendations on the suitability of specific DGPS services. To avoid confounding results, we made concurrent comparisons using a common antenna and a single make, model, and firmware of GPS receiver. Static test results are reported here. Dynamic results are reported in Chapter 2.

METHODS

This static test was conducted at Hays, KS and compared differences in position fixes derived from autonomous GPS (no correction) and three differentially corrected GPS (DGPS) sources referenced to RTK GPS coordinates. The DGPS sources were the U.S. Coast Guard Beacon, the U.S. Federal Aviation Agency Wide Area Augmentation System (WAAS), and OmniSTAR, a commercial subscription service. The Beacon correction signal was received from the Kansas City tower (39.1173° N, 95.4088° W; ~340 km due east of Hays; 305 kHz). WAAS and OmniSTAR correction messages were received from geostationary satellites.

Instrumentation

The signal from a single antenna (Trimble AgGPS 214 dual-frequency RTK antenna with 13-inch ground plane) was connected to four Trimble AgGPS 132 (Model 33302-01) GPS receivers (one for each GPS/DGPS mode) through a splitter (GPS Networking, Inc., Part No. ALDCBS1X8) with 1 in-port and 6 out-ports (Figure 1-1). One out-port allowed DC power to flow from the autonomous GPS receiver to the antenna; the other five out-ports were DC-blocked. Using a single antenna for all GPS receivers eliminated potential variability related to correcting data from multiple antennas to a common location.

Receiver configuration is shown in Table 1-1 and was selected based on consultation with the manufacturer. The settings for DGPS age limit (Table 1-1) conformed to those determined by the manufacturer to optimize performance for the specified firmware at the time this study was conducted.

The common antenna was mounted on the roof of a two-story building on a steel mast anchored to a flat slab of concrete (4.0 m x 2.7 m) that constituted the top of the building elevator shaft. The building roof was pitched and made of tile. The antenna mount was higher than the roof gable. The location of the antenna was established prior to the start of the test by a licensed surveyor using RTK GPS and four NGS control points. The RTK coordinates were 99.335196194° W, 38.857939278° N, and 625.41 m above MSL (14.4 m above the ground level and 2.1 m above the concrete slab).

The AgGPS 214 primary antenna could receive OmniSTAR and WAAS correction signals, but not Beacon signals. Therefore, a second antenna (AgGPS 132) was mounted below and away from the common antenna for that purpose. The specific location of this secondary antenna had no effect on calculated position fixes. The secondary antenna lead was connected to a fifth AgGPS 132 receiver and the Beacon correction information relayed by RS-232 interface to the Beacon receiver wired to the splitter.

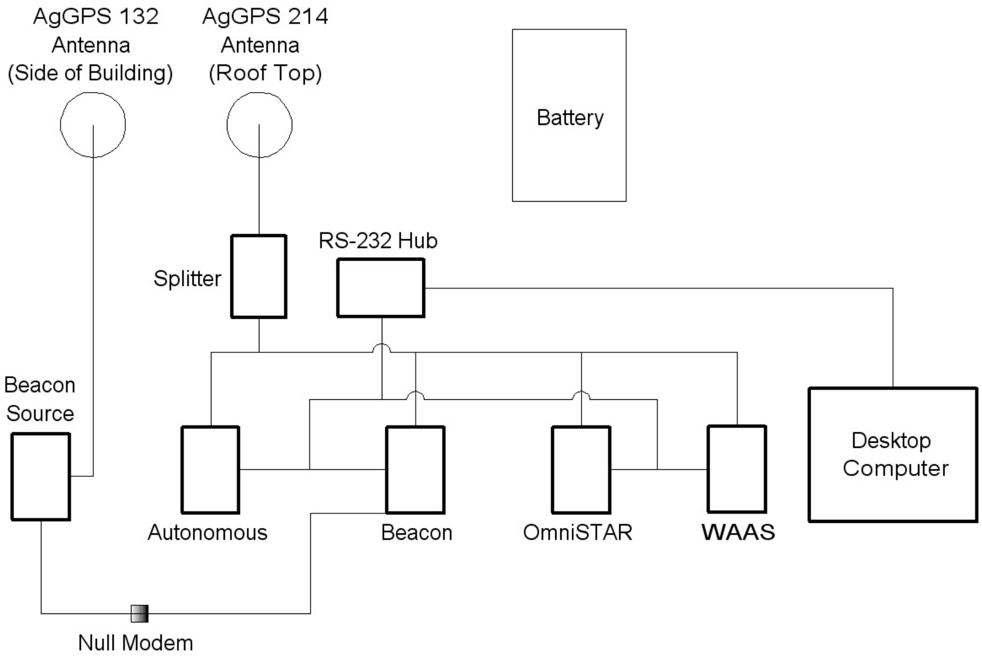

Figure 1-1. Schematic of static test layout.

Table 1-1: AgGPS 132 receiver configuration for four GPS/DGPS modes.

Parameter	Autonomous GPS	Beacon DGPS	OmniSTAR DGPS	WAAS DGPS
Firmware Version	*1.58.03*	*1.58.03*	*1.58.03*	*1.58.03*
PDOP Mask	*13*	*13*	*13*	*13*
PDOP Switch	*11*	*11*	*11*	*11*
PV Filter / Level	*D&S / High*	*D&S / High*	*D&S / High*	*D&S / High*
DGPS Source	*Beacon*	*Beacon*	*Satellite only*	*WAAS only*
DGPS Mode	*Manual DGPS off*	*Auto DGPS/GPS*	*Auto DGPS/GPS*	*Manual DGPS req'd*
DGPS Age Limit	*30 seconds*	*30 seconds*	*30 seconds*	*250 seconds*
WAAS Backup	*Off*	*Off*	*Off*	*Off*
WAAS T2 Remap	*Off*	*Off*	*Off*	*On*
Frequency or PRN	*N/A*	*Ch0 305 kHz, Ch1 305 kHz*	*1554.497 MHz*	*PRN 122*

The common antenna signal was routed approximately 20 m from the roof through a grounded lightning arrester (Polyphaser MR50LNZ+15, 1.2 to 2.0 GHz) to the top floor of the building via coaxial cable. The GPS receivers, splitter, and computer were located at that level. Antenna mountings and GPS receivers for the static test are shown in Figures 1-2 and 1-3.

GPS fixes are referenced to the World Geodetic System 1984 (WGS-84) datum, which is based on the WGS-84 ellipsoid. However, there are currently four WGS-84 reference frames: original, G730, G873, and G1150 (Milbert, 2002). WGS-84 (original) is identical to the North American Datum 1983 (NAD-83, Date Tag 1986), which is based on the Geodetic Reference System 1980 (GRS-80) ellipsoid, within the coterminous United States. WGS-84 (G873) differs from NAD-83 (86) by about 2 m. WGS-84 (G873) is equivalent to the International Terrestrial Reference Frame ITRF94 (1997.0) within a few centimeters.

In this study, autonomous GPS, Beacon DGPS, OmniSTAR DGPS, and RTK GPS were referenced to the NAD-83 (86) Datum, i.e., WGS-84 (original). WAAS DGPS was referenced to the WGS-84 (G873) datum. Because of datum differences, corresponding DGPS position fixes from WAAS were expected to be approximately 1.4 m north and 0.5 m west of DGPS position fixes from Beacon and OmniSTAR at the Hays location. These values were estimated with the National Geodetic Survey (2002) program HTDP using the RTK static coordinates as input.

Treatments were the four GPS/DGPS modes referenced to a single RTK point over a period of about 7 days. Because a common antenna was used, only the assignment of GPS receiver to GPS/DGPS mode was randomized.

Data Collection

All dates are for the year 2002; all times are CST (0000 to 2400). Static performance data were collected from approximately 1100 on 14 June to 1930 on 20 June, except for periods with the potential for lightning, during which time the system was shut down and the antenna removed from the roof. The GPS receivers were active for about 118 of the possible 152 hours during this period. Total data records (N) for each GPS receiver were greater than 420,000.

Data, consisting of the National Marine Electronics Association (NMEA) standard output sentences $GPGGA and $GPGSA, were recorded at 1-second intervals by a single desktop computer operating under MS Windows 2000 using a separate HyperTerminal window for each GPS receiver. Serial output (9600,8,N,1) from the four GPS receivers was routed through a multiplexer (QualTech QSU-100 with four serial ports and USB interface) and written to separate disk files using the “Capture Text” feature of HyperTerminal.

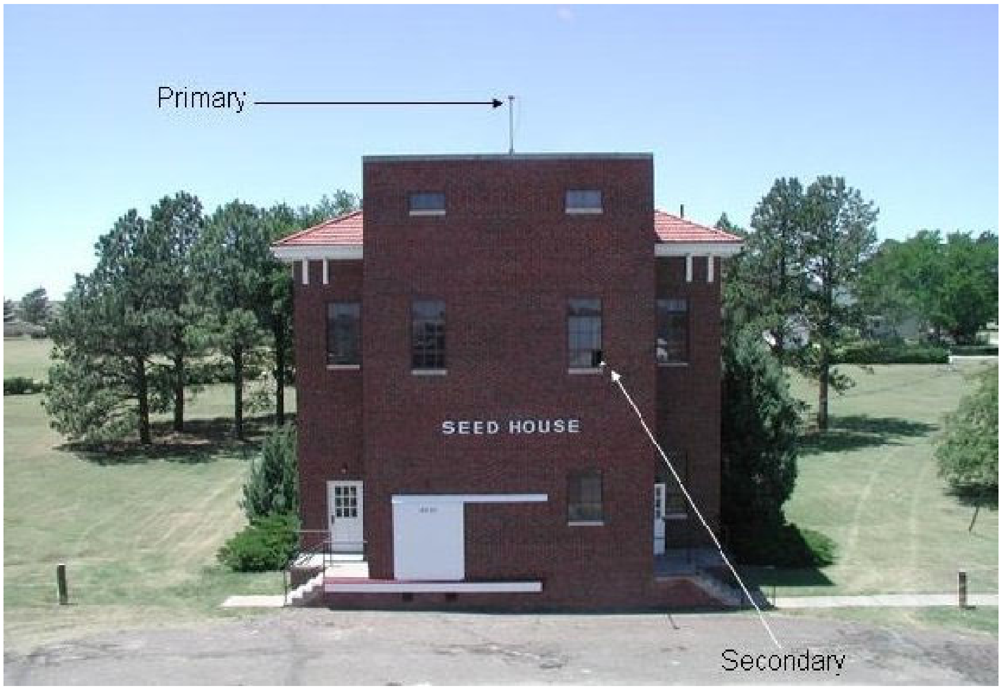

Figure 1-2. Deployment of primary (roof top) and secondary (window) GPS antennas for the static test. Building faces east.

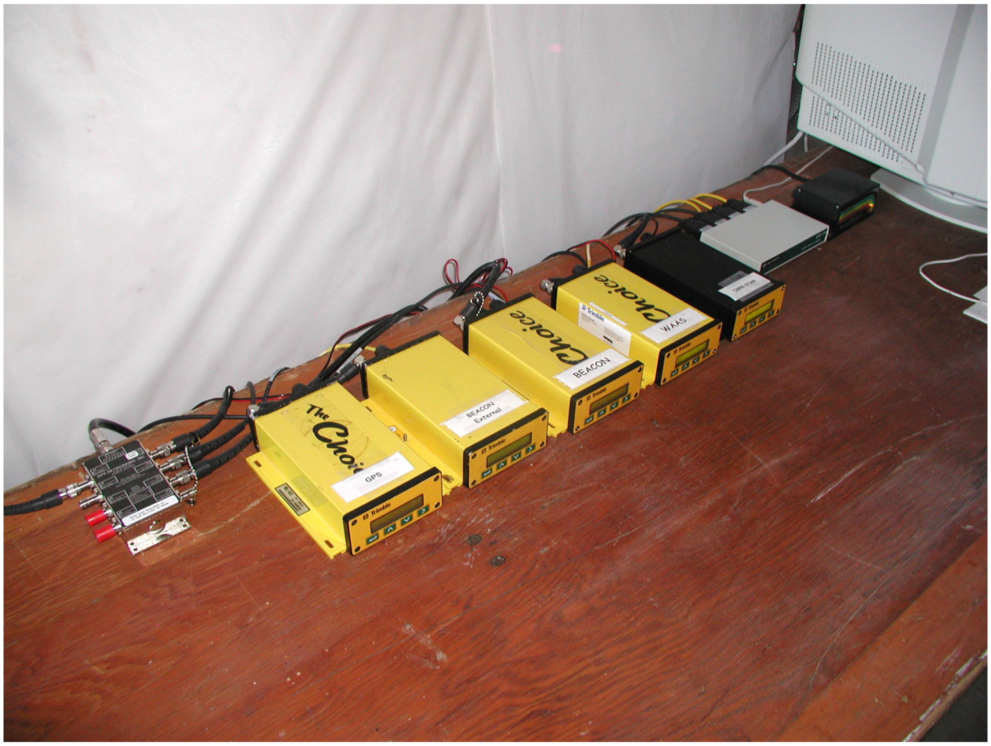

Figure 1-3. Antenna splitter, GPS receivers, and RS-232 multiplexer arrayed for the static test.

Quality of a position fix based on GPS depends on the geometry of the space vehicle (SV) constellation. In general, quality increases with angular separation between SVs. A dimensionless parameter, called Dilution of Precision (DOP), quantifies the quality of a GPS position fix. It is based solely on the geometry of the SVs; the smaller the number, the higher the quality. DOP is frequently divided into horizontal (HDOP) and vertical (VDOP) components. The position dilution of precision (PDOP) is equivalent to $(HDOP^2+VDOP^2)^{0.5}$. VDOP and HDOP were extracted from the NMEA GSA sentence.

Data Processing

Raw data files were preprocessed by an auditing algorithm that checked for potential errors—specifically, variations in field content from the expected, or field width arising from receiver or logging issues (e.g., occasional buffer overrun). Less than 20 records out of each 420,000 record subset had any error issues. Following the audit and subsequent editing of flagged fields, or deletion of unintelligible records, fields required for the analysis were extracted from NMEA sentence couplets (GGA, GSA) and formatted into a single record. Longitude and latitude were converted from degrees-decimal minutes (DDMM.MMMM) to decimal degrees (DD.DDDD), longitude was multiplied by -1 to designate distances west of the prime meridian, and the synthesized record was written to a new disk file. Records not meeting specific quality or availability criteria (Table 1-2) were filtered out. Additional algorithms read the preprocessed files and computed distances of test position fixes from the RTK coordinates in the XYZ directions, as described below.

Differences between a test system position fix and a reference position, both expressed in the geographic coordinates of longitude and latitude in decimal degrees and altitude in meters, were converted to 3-dimensional Cartesian coordinates (X_i,Y_i,Z_i) in meters. The reference position (Lon_0, Lat_0, Alt_0) was either external (RTK) or internal (GPS/DGPS mode means). The internal reference provided a check on the relative accuracy of a GPS/DGPS mode. The differences in altitude fixes between the test and reference system were determined by subtraction. The conversion method used for X,Y was described by Kirvan (1997) and summarized below.

The north-south distance per degree of latitude is approximately the same regardless of geodetic position and ranges from 110.57 km at the equator to 111.69 km at the poles. For example, at 40° N, 1 degree of geodetic latitude is 111.04 km. Because meridians of longitude are not parallel, distance per degree of arc varies with latitude. Let R be the radius of the earth at the equator (6,378.166 km) and r be the radius of a parallel circle of latitude at latitude Φ. The circumference of the earth at the equator is $2\pi R$ or 40,075.199 km. Therefore, the circumference of a parallel of latitude in km at latitude Φ is $2\pi r = 2\pi R*COS(\Phi) = 40{,}075.199*COS(\Phi)$. Dividing by 360 gives the distance per degree of longitude, i.e., the length of a 1 degree arc of longitude in km at latitude Φ is $2\pi r/360 = 2\pi R*COS(\Phi)/360 = 40{,}075.199/360*COS(\Phi) = 111.320*COS(\Phi)$. Thus, at 40°N, a 1 degree arc of longitude is 111.320*COS(40)=111.320*0.766 = 85.276 km.

Table 1-2. Data record filtering retention criteria based on select NMEA fields.

Sentence	Field	Autonomous	Beacon	OmniSTAR	WAAS	RTK
GGA	Fix Quality: 1=GPS, 2=DGPS	1	2	2	2	4
GGA	No. Space Vehicles	>3	>3	>3	>3	>4
GSA	Mode: 1D, 2D, 3D	3	3	3	3	3

Within a limited geographical area, and considering the expectation of very small distances (a few meters or less) between a test value and its reference, the curvature of the earth can be ignored when projecting Cartesian (flat surface) on geodetic (curved surface) coordinates. Accordingly, in this discussion, the values delta X_i (or δX_i), delta Y_i (or δY_i), and delta Z_i (or δZ_i) describe the straight-line distances in the XYZ directions between a point (Lon_i,Lat_i,Alt_i) fixed by one of the test GPS/DGPS modes and the external or internal reference point (Lon_0,Lat_0,Alt_0), when using the Cartesian coordinate system.

The following equations were used (all δ values are in meters):

$$\delta X_i = (Lon_i - Lon_0)*111320*COS[(Lat_i + Lat_0)/2]$$
$$\delta Y_i = (Lat_i - Lat_0)*111040$$
$$\delta Z_i = (Alt_i - Alt_0)$$

The straight line distance, δR_i (R=resultant or radius), from the reference point to the test point is a measure of horizontal accuracy and was calculated by the Pythagorean theorem:

$$\delta R_i = \sqrt{\delta X_i^2 + \delta Y_i^2}$$

GPS/DGPS modes were compared based upon the relative magnitude of their summary statistics for δX, δY, δZ or δR, where smaller was considered better.

GPS Error Analysis

Accuracy in positions fixed by GPS or DGPS involves a statistical measure of performance. In this analysis, it is assumed that errors in vertical (1-D) position follow a normal linear distribution; errors in the geodetic (2-D) position follow a normal circular distribution, and errors in spatial (3-D) position follow a normal spherical distribution. Horizontal and vertical differences between observed and benchmark or reference positions are commonly analyzed using the root mean square error (RMSE) statistic. RMSE measures the departure from a null (reference) value (Buick, 2002). The National Standard for Spatial Data Accuracy or NSSDA (FGDC-STD-007.3-1998) adopted RMSE to estimate positional accuracy. The standard defines RMSE as the square root of the average of the set of squared differences between dataset coordinate values and coordinate values from an independent source of higher accuracy for identical points. The RMSE for a univariate population of values (X or Y or Z), referenced to a benchmark (Lon_0 or Lat_0 or Alt_0), is described by:

$$\sigma_x = RMSE_X = \sqrt{\frac{1}{N}\sum \delta X_i^2}\;;$$
$$\sigma_y = RMSE_Y = \sqrt{\frac{1}{N}\sum \delta Y_i^2}\;;$$
$$\sigma_z = RMSE_Z = \sqrt{\frac{1}{N}\sum \delta Z_i^2}\;;$$

where $RMSE_X$, $RMSE_Y$, and $RMSE_z$ represent 1σ (read 1-sigma) for δX, δY, and δZ, respectively. Approximately 68% of the observations fall within ±1σ linear standard error of the mean (U.S. Army Corps of Engineers, 1994). RMSE and the standard deviation (SD) converge as the average values of Lon, Lat, or Alt for a GPS/DGPS mode, and their respective reference values (Lon_0 or Lat_0 or Alt_0), converge.

Horizontal position errors are bivariate, i.e., they have both X (easting) and Y (northing) components. The concept of standard error becomes somewhat nebulous because this statistic could be σ_x, σ_y, or some combination of both standard errors. Whereas a univariate distribution is depicted graphically as a 2-D bell-shaped or normalized curve, a bivariate distribution is depicted as a 3-D mound. Any horizontal slice through this distribution or mound yields an ellipse. This ellipse will have standard deviations σ_x, σ_y, and correlation (σ_{xy}) unless the axes of the ellipse are oriented parallel with the coordinate system axes. In that case, the ellipse is rotated in a principal plane with no correlation, i.e., no covariance (U.S. Army Corps of Engineers, 1994).

The resultant RMSE for a series of replicated X,Y coordinate pairs, i.e., the circular standard error (CSE=1σ$_c$) is defined (NSSDA FGDC-STD-007.3-1998) as:

$$\sigma_c = RMSE_r = \sqrt{\frac{1}{N}\sum \delta R_i^{\,2}} = \sqrt{RMSE_x^2 + RMSE_y^2}$$

Assuming a circular normal distribution for the resultant δR, the probability that the error in an X-Y position fix is 1σ$_c$ or less is 0.394. This is found by setting r in the probability density function for a circular normal distribution equal to σ$_c$ and solving for P$_c$.

$$P_c = 1 - e^{-(r^2/2\sigma_c^2)}$$

$$P_c = 1 - e^{-(\sigma_c^2/2\sigma_c^2)}$$

$$P_c = 1 - e^{-0.5}$$

$$P_c = 1 - 0.6065 = 0.394$$

Other commonly used statistics are derived from σ$_c$. For example, substituting 1.1774σ$_c$ for r gives a probability of 0.500 and is called the circular error probable (CEP), substituting 1.4142σ$_c$ for r yields a probability of 0.632 and is called 1DRMS (one deviation RMS). Likewise, substituting 2.8346σ$_c$ for r gives a probability of 0.982 and is called 2DRMS (U.S. Army Corps of Engineers, 1994).

While RMSE is commonly used to compare GPS position fixes, the RMSE and SD statistics assume data independence and normal distribution. Neither assumption was satisfied by our data. The δR data were not normally distributed, but were skewed to the right. Lack of independence resulted from a sampling frequency of 1 Hz, which caused the data to be highly and positively correlated. For highly correlated data, the estimate of the variance is generally too small, so the values of RMSE and SD underestimate the true parameters. Thus, in this discussion, these estimates are used as indices of variability in comparing the performance of the GPS/DGPS modes.

RESULTS AND DISCUSSION

Mean values from the static test for HDOP, VDOP, and number of SVs used in the position solutions are given in Table 1-3. DOP values less than 3 are considered very good. In this study, all HDOP values for autonomous GPS and OmniSTAR DGPS were less than 3. HDOP exceeded 3 in 0.019% and 0.006% of the values for Beacon DGPS and WAAS DGPS, respectively. VDOP is commonly higher than HDOP. Approximately 0.5% of the VDOP values exceeded 3 in all the GPS/DGPS modes. The datasets were not filtered to remove records for which VDOP and HDOP were greater than 3 in order to reflect real-world, end-user conditions. Beacon DOP values were expected to be slightly greater than the other three modes and this was the case (Table 1-3) with both HDOP and VDOP. This relates to the fact that the Beacon DGPS correction only supports a maximum of 9 SVs in the solution. There were times when the number of SVs exceeded 9 (Table 1-3). Thus, even though autonomous, OmniSTAR, and WAAS used 11 SVs at times, the Beacon only reported using 9. Signal availability is an important consideration for DGPS end users. Not only must the signal from a DGPS source be detectable, but it needs to have a high level of availability to support precision agriculture. All three DGPS sources were available over 99% of the time that the static test was running (Table 1-3). This indicates that any of these sources should work at Hays, KS. Even though Hays is 340 km from the Beacon tower, availability was close to the specified 99.7% experience of this source. The Beacon system is expected to expand its tower network, so availability should improve in the future.

Summary static statistics are provided in Table 1-4. The values for δX, δY, δZ, and δR represent distances in meters from the RTK reference coordinates in the X, Y, Z, and R directions, respectively.

Table 1-3. Static test GPS quality data for autonomous GPS and three DGPS sources.

Variable	Statistic	Autonomous GPS	Beacon DGPS	OmniSTAR DGPS	WAAS DGPS
Sample Size	N	423,700	420,270	423,648	420,353
HDOP*	Mean	1.1	1.2	1.1	1.1
	SD	0.2	0.3	0.2	0.2
	Min	0.7	0.8	0.7	0.7
	Max	2.7	5.7	2.8	4.1
VDOP*	Mean	1.7	1.9	1.7	1.7
	SD	0.4	0.5	0.5	0.5
	Min	1.0	1.2	1.0	1.0
	Max	5.7	8.4	5.8	5.7
Number of Space Vehicles	Mean	8.0	7.5	7.9	8.0
	SD	1.4	1.0	1.4	1.4
	Min	5	4	5	4
	Max	11	9	11	11
Availability (seconds)	Potential	423,700	423,675	423,671	423,651
	Actual	423,700	420,270	423,648	420,353
	Act/Pot	1.0000	0.9920	0.9999	0.9922

*HDOP, VDOP: horizontal and vertical dilution of precision, respectively.

Note that when the mean static offset from the RTK coordinates is close to zero, SD and RMSE are of similar magnitude. All static $\delta X, \delta Y$ data points were plotted as target diagrams (Figure 1-4) to show relative scatter and offsets from RTK coordinates, i.e., the origin. The autonomous GPS position fixes tended to wander or drift. A bias for the NW and NE quadrants was evident and δR was as large as 4 m. Position fixes based on DGPS were tightly clustered. Beacon data were the most concentrated and evenly distributed about the origin. OmniSTAR data indicated a slight bias for the NE and SW quadrants. WAAS data were predominantly in the NW quadrant (mean δX and δY were -0.8 and 0.8 m, respectively; Table 1-4). This NW bias was expected since WAAS is based on a different geodetic datum, as previously explained. Most of the DGPS data could be contained within a circle of approximately 1 m radius.

Scatter plots in Figure 1-4 show absolute accuracy. For many precision agriculture applications, relative accuracy (repeatability) is sufficient (Buick, 2002). In those cases, low variance, an indicator of internal consistency, is of primary importance. In Figure 1-5a, circles of $1\sigma_c$ radius (RMSE) centered on the RTK coordinates reveal that Beacon and OmniSTAR performed the best, in an absolute sense, followed by WAAS and autonomous GPS (Table 1-4: RMSE values for δR). In Figure 1-5b, data were adjusted for their X and Y static offsets from the RTK coordinates before calculating the RMSE (Table 1-4: adjusted RMSE values for δR). These circles are shown centered on their respective static X,Y offsets from RTK. In the relative case (Figure 1-5b), WAAS had the lowest RMSE, but its NW quadrant bias is clearly shown.

Table 1-4. Summary statistics for the static test referenced to RTK coordinates.

Variable		Statistic	Autonomous GPS	Beacon DGPS	OmniSTAR DGPS	WAAS DGPS
Sample Size		N	423,700	420,270	423,648	420,353
δX (m)		Mean	-0.52	0.06	-0.04	-0.77
		SD	0.54	0.29	0.25	0.19
		RMSE	0.75	0.29	0.25	0.79
δY (m)		Mean	1.35	0.18	-0.13	0.77
		SD	0.74	0.30	0.40	0.26
		RMSE	1.54	0.35	0.42	0.81
δZ (m)		Mean	0.98	-0.02	-0.11	-0.51
		SD	1.13	0.62	0.61	0.47
		RMSE	1.50	0.62	0.62	0.69
δR (m)		Mean	1.67	0.40	0.43	1.12
		SD	0.39	0.23	0.23	0.20
	*	RMSE	1.71	0.46	0.49	1.13
	#	RMSE	0.92	0.41	0.47	0.32

* Referenced to RTK.

\# Adjusted for mean offset from RTK.

Table 1-5. Static mean values of δR referenced to RTK for autonomus GPS and three DGPS sources at three percentiles.

	Percentile		
Mode	75th	95th	99th
	-------------------- m --------------------		
Autonomous GPS	1.917	2.251	2.952
Beacon DGPS	0.507	0.825	1.073
OmniSTAR DGPS	0.566	0.862	1.069
WAAS DGPS	1.240	1.434	1.542

To summarize the static data, estimates of the 75th, 95th, and 99th percentiles are provided for each of the GPS/DGPS modes (Table 1-5). The similarity in absolute accuracy relative to RTK is demonstrated for Beacon and OmniSTAR. About 75%, 95%, and 99% of the observations for these two DGPS sources fell within 0.5, 0.8, and 1.1 m of the RTK reference point, respectively. WAAS values would converge on Beacon and OmniSTAR if corrected for the offset due to its geodetic datum.

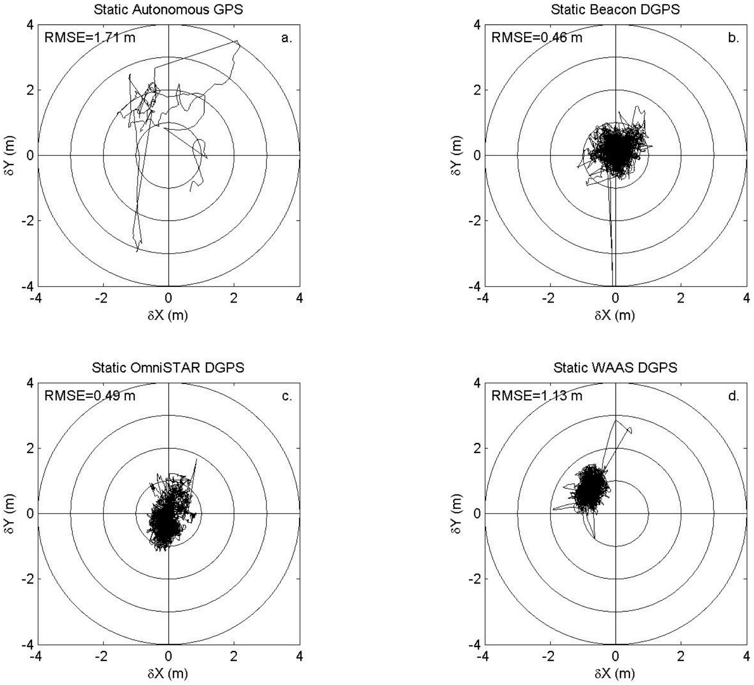

Figure 1-4. Plots of static position fixes in the X (east-west) and Y (north-south) directions for autonomous GPS and three DGPS sources referenced to the RTK coordinates. RMSE values represent 1-sigma circular error. The probability that a position fix lies within 1 RMSE of the origin is 0.394.

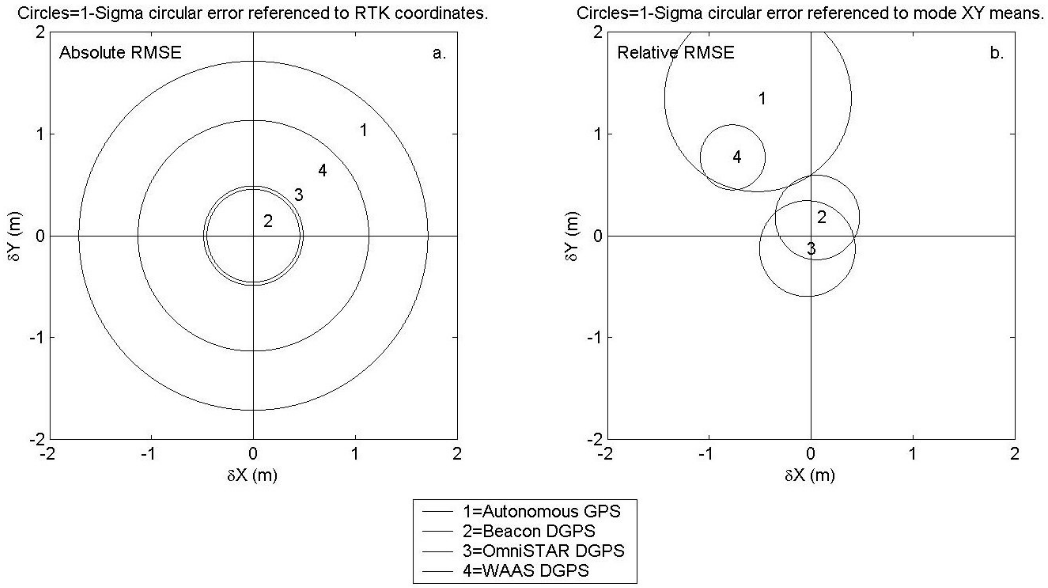

Figure 1-5. Variation in static performance among autonomous GPS and three DGPS sources as measured by the RMSE. Circle diameters are 1 RMSE. Absolute values (Figure 1-5a) were referenced to the RTK coordinates and show the absolute error in position fixes from a fixed point. Relative values (Figure 1-5b) were referenced to the mode means and estimate relative error in position fixes over time or internal consistency for a specific mode. Circle centers in 1-5b represent the average static offset of a specific mode from the origin (RTK coordinates).

CONCLUSIONS

Estimates of absolute horizontal accuracy, based on RMSE referenced to RTK, were 0.46, 0.49, 1.13, and 1.71 m for Beacon, OmniSTAR, WAAS, and Autonomous, respectively. Corresponding values for relative accuracy with RMSE referenced to the GPS/DGPS mode means were 0.41, 0.47, 0.32, and 0.92 m, respectively. Beacon and OmniSTAR had high absolute and relative accuracy. However, relative accuracy for WAAS was 3.5 times greater than the absolute accuracy. This result reflects the difference in geodetic datum used by WAAS, which resulted in a NW quadrant bias relative to RTK and the other DGPS sources. This does not prevent WAAS from being useful in applications requiring high absolute accuracy. It does mean that in such applications, WAAS position fixes may require correction for geodetic datum differences when navigating to map points established by RTK, Beacon DGPS, or OmniSTAR DGPS. General performance and availability data met or exceeded design specifications during the period of the test and relative accuracy was similar across the three DGPS sources under static conditions. Therefore, we conclude that any of these DGPS sources should work well in many site-specific management applications in the vicinity of Hays, KS. However, static performance does not necessarily predict dynamic performance. Dynamic performance is compared in Chapter 2.

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CHAPTER 2: DYNAMIC TEST

Abstract. Performance comparisons of autonomous GPS and three differentially corrected GPS (DGPS) sources were made under dynamic conditions to evaluate suitability for precision agriculture applications in the vicinity of Hays, KS. DGPS sources included the U.S. Coast Guard Beacon, the Wide Area Augmentation System (WAAS), and a commercial service, OmniSTAR. Beacon availability depends on distance to the nearest broadcast tower. Both WAAS and OmniSTAR offer wide-area coverage via geostationary satellites. Survey-grade Real Time Kinematic (RTK) GPS served as the standard for absolute accuracy. As expected, autonomous GPS was not sufficiently accurate to support most site-specific management operations. The three DGPS sources had comparable relative accuracy (repeatability), but, as compared to the RTK standard, Beacon>OmniSTAR>WAAS for absolute accuracy. Absolute accuracy of OmniSTAR and WAAS appeared to decrease as ground speed increased, but Beacon data were not similarly affected. This trend was considered an artifact caused by differences in the way the position-velocity filter algorithm of the GPS receivers processed correction messages from OmniSTAR and WAAS compared to Beacon. Because Beacon and WAAS signals are available at no direct cost, these two DGPS sources are attractive options for the location of this study, with Beacon preferred over WAAS providing that the signal is reliable and availability is equivalent to WAAS or OmniSTAR.

Precision agriculture, or site-specific management technologies, has great potential to optimize production inputs and thereby enhance profitability, reduce environmental risk, and document compliance with regulations pertaining to the use of agricultural chemicals. Positioning accuracy consistent with site-specific management requires that GPS signals be differentially corrected. Farmers now have access to multiple sources of DGPS correction messages that vary in cost, suitability, or reliability depending on location in the United States. DGPS is capable of submeter accuracy and consists of two or more receivers that observe a common set of satellites. A reference receiver, at a certified point, compares its known location to a position fix provided by the satellite constellation. Discrepancies between these two values quantify the measurement error, which is broadcast to compatible GPS receivers for use in correction algorithms.

Real Time Kinematic (RTK) GPS is survey-grade and capable of centimeter accuracy. RTK has primary application in site-specific management for automated guidance of implements, but also for various other mapping functions. RTK consists of two or more GPS receivers and two or more radio-modems. One receiver occupies a known location (reference or base station) and broadcasts a correction message (Compact Measurement Record or CMR2) to one or more roving receivers via a radio link. The roving receiver(s) processes this information to produce an accurate position relative to the base station. A local RTK base station must be on site within 10-20 km of a rover to ensure carrier phase initialization. This is a very limited range compared to the wide-area coverage of OmniSTAR and WAAS, or even a radio beacon that may be usable at distances from 160 to 400 km or more from the transmitter. The range of RTK systems can be expanded by installing a network of base stations.

Precision agriculture is not about static conditions. The power of this technology is the ability to track moving equipment and to implement management decisions in real time based on geographic position. Other research has shown that static performance of GPS receivers is not necessarily indicative of dynamic performance and that few standards exist for testing GPS performance under dynamic conditions (Stombaugh et al. 2002).

The objective of this study was to compare the performance of autonomous GPS and three DGPS modes under dynamic conditions using a test protocol that was representative of field maneuvers and ground speeds, and which minimized experimental errors resulting from variations in GPS receivers and antennas. Real Time Kinematic GPS was used as the standard for accuracy. This study is one of two that compared DGPS alternatives available to support site-specific management near Hays, KS. Reported here are results of the dynamic test. Static test results were reported in Chapter 1.

METHODS

We tested three DGPS sources: the U.S. Coast Guard's maritime DGPS radio beacon system (Beacon), the U.S. Federal Aviation Agency's Wide-Area Augmentation System (WAAS), and OmniSTAR, a commercial subscription service. Autonomous or uncorrected GPS was also included in the test. The Beacon correction signal was received from the Kansas City tower (39.1173° N, 95.4088° W; ~340 km due east of Hays; 305 kHz).

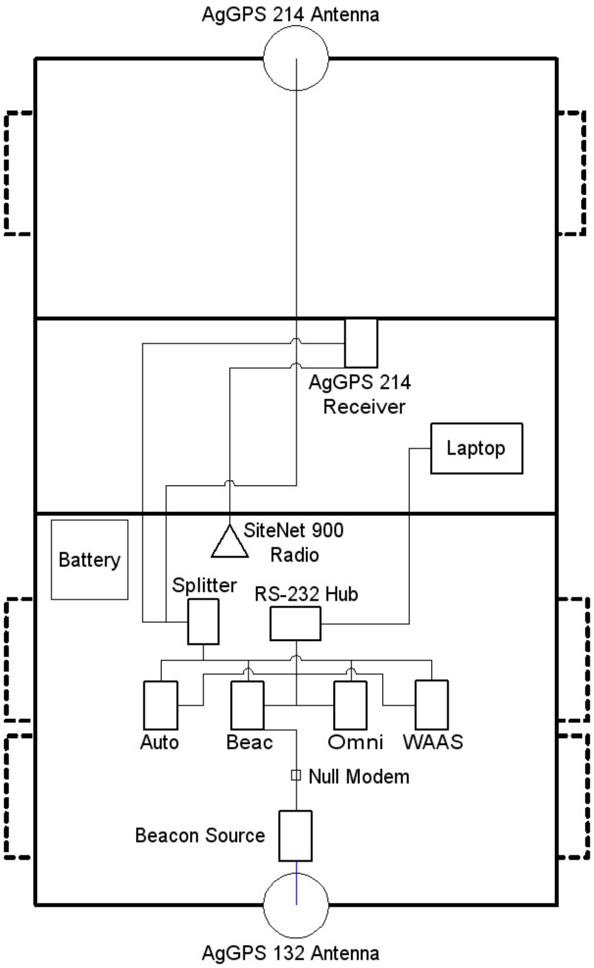


Figure 2-1. Schematic of dynamic test layout. The SiteNet 900 is a radio modem that communicates with a similar modem attached to the RTK base station.

Instrumentation

The signal from a single Trimble AgGPS 214, dual-frequency, RTK antenna, with a 13-inch ground plane, was connected to four Trimble AgGPS 132 (Model 33302-01) GPS receivers (one for each GPS/DGPS mode) and a Trimble RTK receiver (AgGPS 214) through a splitter (GPS Networking, Inc., Part No. ALDCBS1X8) with 1 in-port and 6 out-ports (Figure 2-1). One out-port allowed DC power to flow from the autonomous GPS receiver to the antenna; the other 5 out-ports were DC-blocked. The common antenna was mounted on a mast at the front centerline of the rover vehicle. Using a single antenna for all GPS receivers eliminated having to correct positions, based on multiple antennas, to a single location. The primary antenna could monitor OmniSTAR and WAAS correction signals, but not that of the Beacon. Therefore, a separate secondary antenna, connected to a dedicated AgGPS 132 receiver, was mounted at the rear centerline of the rover for this purpose. Output from this receiver was fed via RS-232 interface to the Beacon receiver connected to the common antenna. AgGPS 132 receiver configuration was described in Chapter 1. The AgGPS 214 (RTK) high-accuracy receiver was equipped with firmware version 1.37. The base station and rover were configured as specified by Trimble Navigation (2000). The RTK base station was positioned on the same point used as the static test benchmark (99.335196194° W, 38.857939278° N, and 625.41 m above MSL) as described in Chapter 1.

Figure 2-2 (left). Rover vehicle used for the dynamic test showing primary (front) and secondary (rear) antennas.

Figure 2-3 (right). GPS receivers installed on the rover vehicle for the dynamic test. The RTK receiver is in front of the operator, others are mounted behind.

Treatments

Treatments were the four GPS/DGPS modes referenced to the RTK track at four ground speeds of approximately 5, 8, 11, and 15 km/h (km/h x 0.621 = miles/h). Treatments were replicated five times. Ground speeds were randomized within a replication and consisted of five revolutions around a test track. Direction of travel around the closed loop track was alternated among replications, but held constant within a replication. The test track was a flattened figure "8" covering a plane of approximately 140 m by 140 m oriented N-S by E-W in a perennial shortgrass pasture (Figure 2-4). A Polaris Ranger 6x6 ATV equipped with the AgGPS 214 RTK (reference) system and the AgGPS 132 (test) systems repeatedly navigated the course to evaluate each GPS/DGPS mode simultaneously. Total distance traveled was 5 reps x 5 revolutions/rep x 4 speeds x 644 m/revolution = 64.4 km or 16.1 km per GPS/DGPS mode-ground speed combination. Because distance traveled per treatment was held constant, sample size decreased as speed increased.

An additional dynamic test was conducted to assess the effect of the PV (Position-Velocity) filter on accuracy and variance. This filter algorithm smoothes position data when the antenna is moving and attempts to reduce the effects of position disturbances, which include reflected signals and short-term outages of DGPS corrections (Rev C. AgGPS 132 Operation Manual, Feb 1998). Only the Beacon and OmniSTAR position fixes were compared to RTK. The two DGPS receivers were configured exactly as described previously (Chapter 1), except the PV filter was set to "Off/Normal." Conduct of this test was the same as described above except the four ground speeds were replicated three times rather than five.

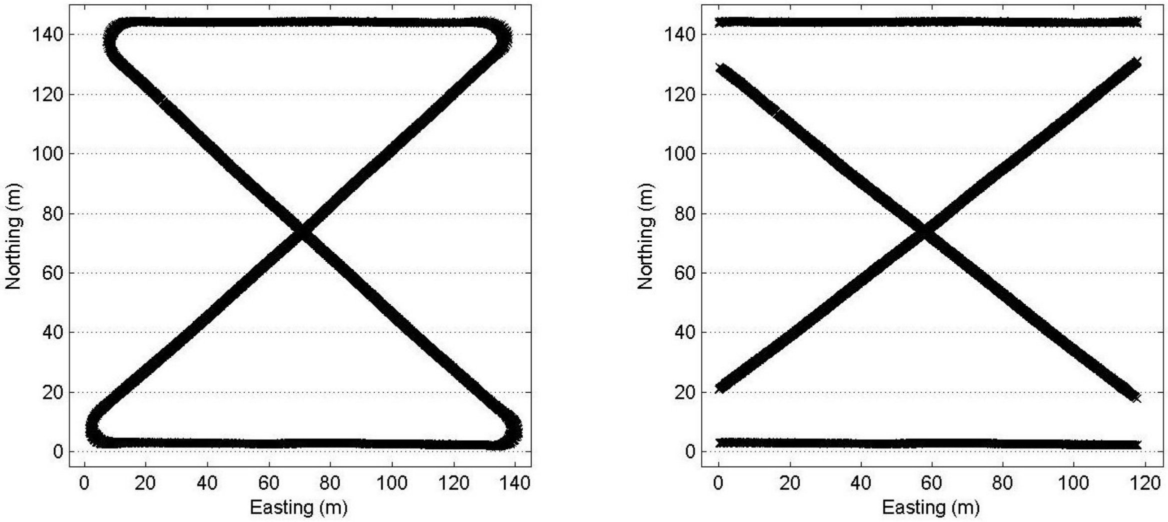


Figure 2-4. Dynamic test track with (left) and without (right) corners. The right version, with corners filtered out, was used for cross-track error analysis. The RTK coordinates for the southwest corner of the complete track were 99.3337° W and 38.8583° N.

Data Collection

All dates are for the year 2002. All times are CST (0000 to 2400 hours). Dynamic performance data were collected during the periods 1200 to 1700 on 21 June (replications 1 and 2), 0800 to 1400 on 22 June (replications 3 and 4), and 1000 to 1200 on 27 June (replication 5). Total data records (N) for which all GPS/DGPS receivers were simultaneously available was 27,171. The scaled-down dynamic test to determine PV filter effects was conducted on 4 September between 0700 and 1400 hours. Sample size for the Beacon and OmniSTAR receivers was 17,010.

Data, consisting of the National Marine Electronics Association (NMEA) standard output sentences $GPGGA, $GPGSA, and $VTG, were recorded at one second intervals by a single laptop computer operating under MS Windows XP. A separate HyperTerminal window was attached to each of the five GPS receivers. Serial output (9600,8,N,1) from the four AgGPS 132 receivers was routed through a multiplexer (QualTech QSU-100 with four serial ports and USB interface). The AgGPS 214 (RTK) serial output was routed to the COM1 port. All output was written to separate disk files using the “Capture Text” feature of HyperTerminal. The RTK output consisted of the GGA and VTG sentences with VTG used to monitor ground speed. The GPS/DGPS output consisted of the GGA and GSA sentences.

Data Processing

Raw data files were preprocessed by an auditing algorithm that checked for potential errors—specifically variations in field content from the expected, or field width arising from receiver or logging issues (e.g., occasional buffer overrun). Following the audit and subsequent editing of flagged fields, or deletion of unintelligible records, fields required for the analysis were extracted from NMEA sentence couplets (GGA, GSA for the GPS/DGPS modes; GGA, VTG for RTK) and formatted into a single record. Longitude and latitude were converted from degrees-decimal minutes (DDMM.MMMM) to decimal degrees (DD.DDDD), longitude was multiplied by -1 to designate distances west of the prime meridian, and the synthesized record was written to a new disk file. Additional algorithms read the preprocessed files and computed the distances of the test position fixes from the RTK track in the XYZ directions. Records not meeting specific criteria were filtered out before computations as described in Chapter 1. In addition to those filtering criteria for the test GPS/DGPS modes, RTK data records were filtered to retain records with Fix Quality=4 (RTK), Space Vehicles>4, Mode=3-Dimensional, and ground speeds ≥3.2 km/h. Conversion from geographical to Cartesian coordinates followed the same procedures as for the static test (Chapter 1).

Horizontal and vertical dilution of precision (HDOP, VDOP), which are dimensionless values broadcast by the Space Vehicles (SV), are related to the configuration of the SV constellation. Quality of a position fix is inversely related to the magnitude of the DOP values. For the GPS/DGPS modes, HDOP and VDOP were extracted from the NMEA GSA sentence. Only HDOP was available for RTK (GGA sentence) because the AgGPS 214 receiver could not output GSA.

In this discussion, δX_i for (X_i-X_0), δY_i for (Y_i-Y_0), and δZ_i for (Z_i-Z_0) describe the straight-line distances in meters for the X (E-W), Y (N-S), and Z (vertical) directions between a test point (Lon_i,Lat_i,Alt_i) fixed by one of the GPS/DGPS modes and the corresponding point on the RTK track (Lon_0,Lat_0,Alt_0), when using the Cartesian coordinate system. The straight line distance, δR_i (R=resultant or radius), from the test point to the RTK reference point, was calculated as $(\delta X_i^2+ \delta Y_i^2)^{0.5}$. Performance of the GPS/DGPS modes was compared using the relative magnitude of their means, root mean square errors (RMSE), and standard deviations (SD) for δX, δY, δZ or δR, where smaller was considered better. The basis for the dynamic test GPS error analysis was the same as for the static test (Chapter 1).

To minimize the effects of autocorrelation in the datasets (see Chapter 1), analysis of variance was used to compare three percentiles from each DGPS distribution of δR values. The Shapiro-Wilk test for normality was used to evaluate the distributions of residuals. The experimental design conformed to a randomized complete block with five replications of four treatments. The 75th, 95th, and 99th percentiles were determined within replications. These percentiles were largely uncorrelated because the replications occurred hours to days apart. The analysis of variance included DGPS source and ground speed as fixed effects and replication as a random effect. Autonomous GPS data were excluded from this analysis because the variance was much larger compared to the DGPS datasets. We wanted to evaluate the DGPS-ground speed interaction without the influence of autonomous GPS data.

RESULTS AND DISCUSSION

Even though the antennas were in motion and mounted closer to the ground, quality did not deteriorate relative to the static condition (see Chapter 1). Both the mean and maximum number of SVs used by RTK were lower than those used by the GPS/DGPS modes (Table 2-1). This relates to a requirement of RTK that both the base and rover stations use the same SV set in a position solution. The base station antenna was 18 m higher than the rover antenna and located approximately 150-200 m SW of the rover with a row of mature trees between the two stations. In addition, a tree row to the north of the test track likely increased the effective elevation mask of the rover station in a northerly direction. These factors would increase the probability that the base station would see some satellites that were blocked from the view of the rover station.

Table 2-1. Dynamic test GPS quality data for autonomous GPS and three DGPS sources.

		GPS	DGPS			
Variable	Statistic	Autonomous	Beacon	OmniSTAR	WAAS	RTK
Sample Size	N	271,171	271,171	271,171	271,171	271,171
HDOP	Mean	1.1	1.2	1.1	1.1	1.2
	SD	0.2	0.2	0.2	0.2	0.2
	Min	0.8	0.9	0.8	0.8	0.9
	Max	3.4	3.4	3.4	3.4	3.3
VDOP	Mean	1.6	1.9	1.6	1.6	N/A
	SD	0.4	0.5	0.4	0.4	N/A
	Min	1.0	1.2	1.0	1.0	N/A
	Max	4.7	5.7	4.7	4.7	N/A
Number of Space Vehicles	Mean	8.9	8.2	8.9	8.9	8.0
	SD	1.2	0.9	1.2	1.2	1.0
	Min	6	5	6	6	5
	Max	11	9	11	11	9
Availability (seconds)	Potential	27,418	27,418	27,418	27,418	27,418
	Actual	27,418	27,185	27,405	27,418	27,418
	Act/Pot	1.0000	0.9915	0.9995	1.0000	1.0000

HDOP, VDOP: horizontal and vertical dilution of precision, respectively.

The lower elevation of the secondary antenna used to monitor the Beacon correction message was expected to reduce dynamic Beacon availability (0.9915) relative to static availability (0.9920). In fact, our data showed this to be the case, but the effect was very small, if real.

Summary statistics for the dynamic test are presented within and across ground speed treatments in Table 2-2. Note that SD and RMSE values converge as the mean δX, δY, and δZ offsets from the RTK track approach zero. The entire dataset collected at all speeds ranging from about 3 to 16 km/h is graphed by GPS/DGPS mode in Figure 2-5. The quadrant biases noted in the static test (Chapter 1) were also evident in the dynamic test. There was an unexpected increase in scatter for OmniSTAR and WAAS data as a function of ground speed compared to Beacon, suggesting a speed effect on position fix accuracy. Note the larger standard deviations for OmniSTAR and WAAS compared to Beacon (Table 2-2). To better analyze the interaction of speed and position accuracy, data were stratified by ground speed treatment and plotted by GPS/DGPS mode in Figures 2-6 to 2-9. Each ground speed treatment represented a range of speeds contingent upon the rover vehicle operator's ability to hold speed constant. Ground speed means and standard deviations are indicated on each mode-by-ground speed graph. Because autonomous GPS data were not differentially corrected, the effects of changes in the SV constellation with time were more evident than with the three DGPS modes. This clustering effect was particularly apparent in Figures 2-6a and 2-6c. Scatter in the Beacon data was not affected by increasing ground speed (Figure 2-7). However, for OmniSTAR (Figure 2-8) and WAAS (Figure 2-9), the position fix variability increased with ground speed. This trend is quantified by the standard deviations, which were fairly consistent across ground speeds for Beacon, but had a tendency to increase with speed for OmniSTAR and WAAS (Table 2-2). In addition, the resultant (δR) for OmniSTAR increased with ground speed indicating the distance of position fixes from the origin (RTK track) increased as speed increased (Table 2-2).

Analysis of variance indicated that the distributions of the residuals were not significantly different from a normal distribution ($p \leq 0.64$, 0.25, and 0.62 for 75th, 95th, and 99th percentiles, respectively), and there was no evidence of unequal variances. There was a significant DGPS source by ground speed interaction for each of the percentiles ($p \leq 0.0131$, 0.0002, and 0.0010 for the 75th, 95th, and 99th percentiles, respectively), which showed that OmniSTAR and WAAS reacted differently to ground speed than Beacon. This is demonstrated by comparing the δR means within percentiles for each DGPS source and ground speed combination (Table 2-3). Estimates of the Beacon percentiles were not affected by the ground speed, while estimates of the percentiles for OmniSTAR and WAAS tended to increase as ground speed increased. Beacon percentiles were smaller than those for OmniSTAR and WAAS at all ground speeds.

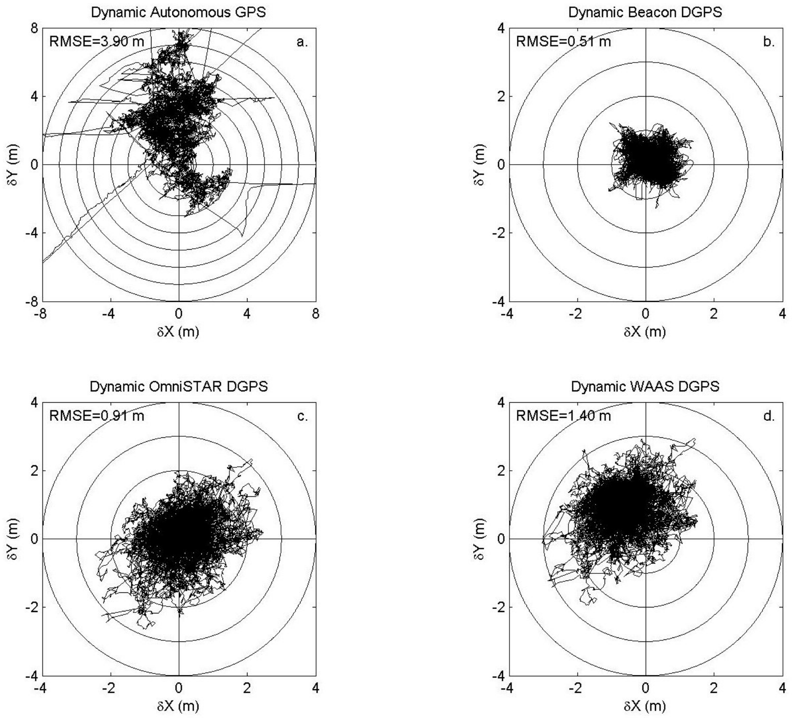


Figure 2-5. Plots of dynamic position fixes in the X (east-west) and Y (north-south) directions for autonomous GPS and three DGPS sources referenced to the RTK track. RMSE values represent 1-sigma circular error. The probability that a position fix lies within 1 RMSE of the origin is 0.394. Values plotted are for all ground speeds. Mean ground speed=8.5 ± 3.5 km/h.

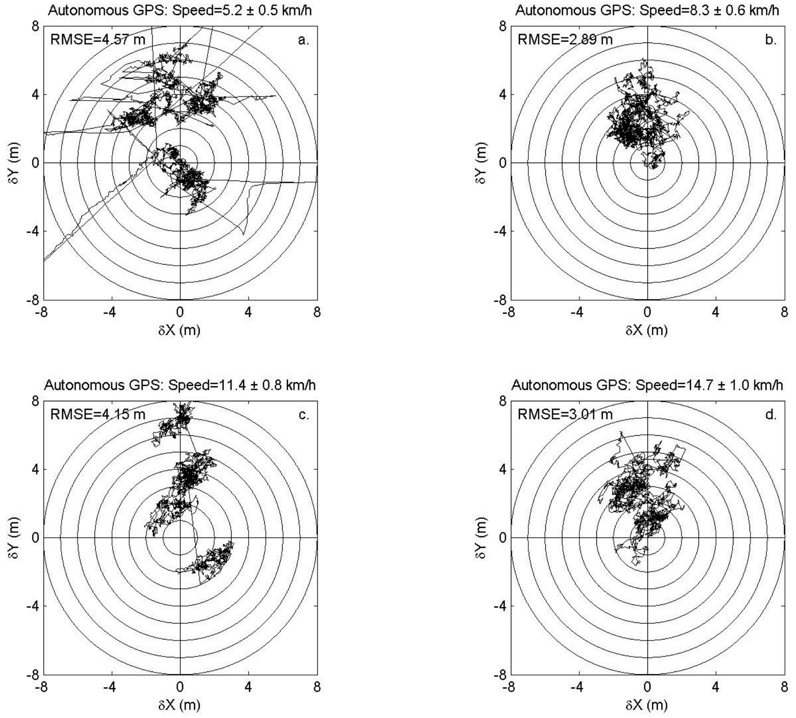


Figure 2-6. Plots of dynamic position fixes in the X (east-west) and Y (north-south) directions for autonomous GPS at four mean ground speeds referenced to the RTK track. RMSE values represent 1-sigma circular error. The probability that a position fix lies within 1 RMSE of the origin is 0.394.

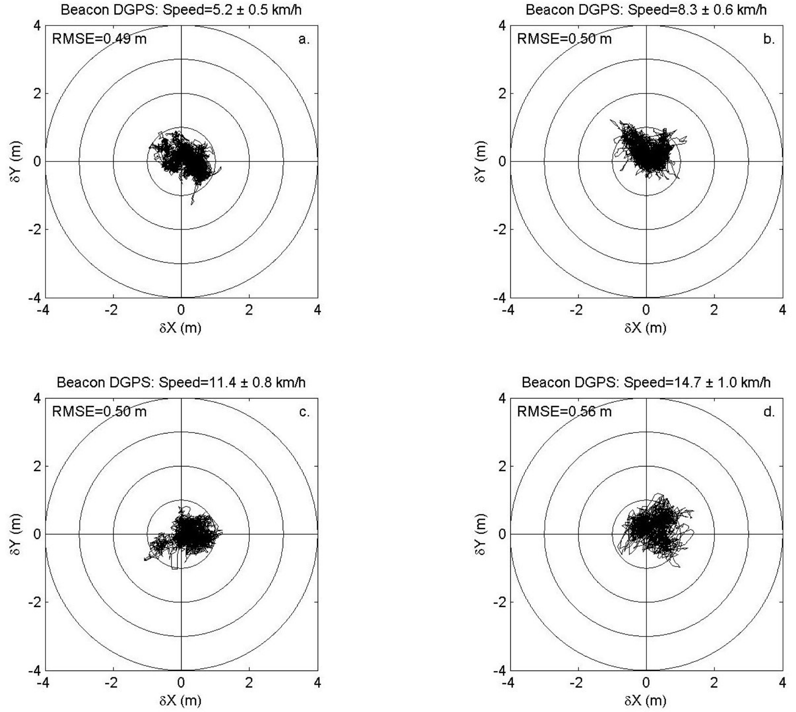


Figure 2-7. Plots of dynamic position fixes in the X (east-west) and Y (north-south) directions for Beacon DGPS at four mean ground speeds referenced to the RTK track. RMSE values represent 1-sigma circular error. The probability that a position fix lies within 1 RMSE of the origin is 0.394.

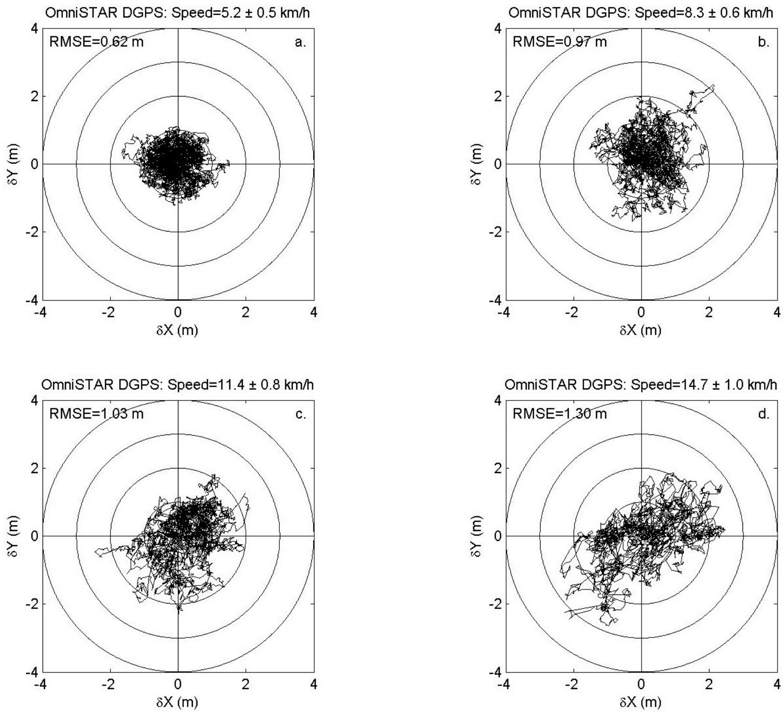


Figure 2-8. Plots of dynamic position fixes in the X (east-west) and Y (north-south) directions for OmniSTAR DGPS at four mean ground speeds referenced to the RTK track. RMSE values represent 1-sigma circular error. The probability that a position fix lies within 1 RMSE of the origin is 0.394.

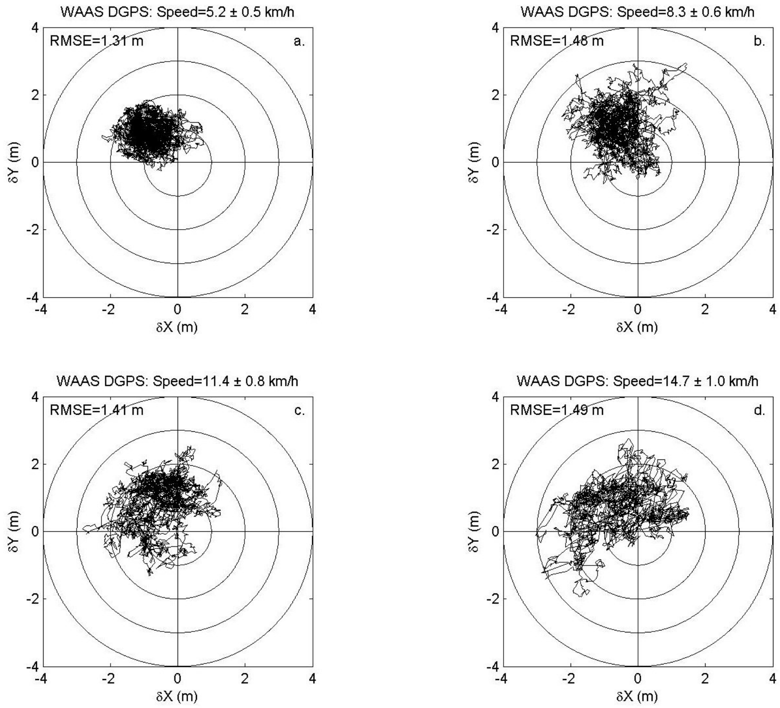


Figure 2-9. Plots of dynamic position fixes in the X (east-west) and Y (north-south) directions for WAAS DGPS at four mean ground speeds referenced to the RTK track. RMSE values represent 1-sigma circular error. The probability that a position fix lies within 1 RMSE of the origin is 0.394.

Table 2-2. Summary statistics for the dynamic test referenced to the RTK track.

Variable	Statistic	Autonomous GPS	Beacon DGPS	OmniSTAR DGPS	WAAS DGPS
Ground speed= 5.2 ± 0.5 km/h; N=11,097.					
δX (m)	Mean	-0.53	0.23	-0.09	-0.81
	SD	2.65	0.33	0.44	0.44
	RMSE	2.70	0.40	0.45	0.93
δY (m)	Mean	1.87	0.01	0.04	0.85
	SD	3.17	0.28	0.41	0.36
	RMSE	3.68	0.28	0.42	0.93
δZ (m)	Mean	0.67	-0.08	-0.07	-0.09
	SD	3.15	0.58	0.71	0.83
	RMSE	3.22	0.58	0.72	0.83
δR (m)	Mean	3.49	0.45	0.55	1.25
	SD	2.95	0.19	0.28	0.39
	RMSE	4.57	0.49	0.62	1.31
Ground speed=8.3 ± 0.6 km/h; N=7,061.					
δX (m)	Mean	-0.50	0.06	0.22	-0.55
	SD	0.91	0.34	0.59	0.59
	RMSE	1.03	0.34	0.63	0.80
δY (m)	Mean	2.42	0.26	0.26	1.06
	SD	1.18	0.27	0.69	0.64
	RMSE	2.70	0.37	0.74	1.24
δZ (m)	Mean	0.10	0.03	0.30	-0.03
	SD	2.92	0.55	0.70	0.63
	RMSE	2.92	0.55	0.76	0.63
δR (m)	Mean	2.67	0.44	0.84	1.35
	SD	1.11	0.25	0.47	0.59
	RMSE	2.89	0.50	0.97	1.48
Ground speed=11.4 ± 0.8 km/h; N=5,133.					
δX (m)	Mean	0.47	0.27	0.22	-0.58
	SD	1.07	0.34	0.69	0.68
	RMSE	1.16	0.43	0.73	0.89
δY (m)	Mean	2.88	-0.01	-0.03	0.85
	SD	2.75	0.25	0.72	0.68
	RMSE	3.98	0.25	0.72	1.09
δZ (m)	Mean	0.46	0.06	-0.29	-0.55
	SD	2.77	0.47	1.05	1.04
	RMSE	2.81	0.48	1.09	1.17
δR (m)	Mean	3.74	0.45	0.92	1.33
	SD	1.79	0.23	0.45	0.46
	RMSE	4.15	0.50	1.03	1.41

Table 2-2. (continued)

Variable	Statistic	Autonomous GPS	Beacon DGPS	OmniSTAR DGPS	WAAS DGPS
Ground speed=14.7 ± 1.0 km/h; N=3,880.					
δX (m)	Mean	-0.34	0.22	0.13	-0.61
	SD	1.04	0.36	1.03	0.96
	RMSE	1.09	0.42	1.04	1.13
δY (m)	Mean	2.41	0.20	-0.06	0.64
	SD	1.45	0.31	0.78	0.71
	RMSE	2.81	0.37	0.78	0.96
δZ (m)	Mean	1.87	0.11	0.04	-0.13
	SD	2.04	0.52	1.46	1.50
	RMSE	2.77	0.53	1.46	1.51
δR (m)	Mean	2.70	0.50	1.14	1.37
	SD	1.34	0.25	0.62	0.58
	RMSE	3.01	0.56	1.30	1.49
Grand Values. Ground speed=8.5 ± 3.5 km/h; N=27,171.					
δX (m)	Mean	-0.31	0.19	0.08	-0.67
	SD	1.89	0.35	0.66	0.64
	RMSE	1.92	0.40	0.66	0.92
δY (m)	Mean	2.28	0.10	0.07	0.88
	SD	2.52	0.30	0.63	0.58
	RMSE	3.40	0.31	0.63	1.05
δZ (m)	Mean	0.65	0.00	0.00	-0.17
	SD	2.94	0.55	0.94	0.97
	RMSE	3.01	0.55	0.94	0.99
δR (m)	Mean	3.21	0.45	0.78	1.31
	SD	2.22	0.23	0.48	0.49
	RMSE	3.90	0.51	0.91	1.40

Table 2-3. Dynamic mean values of δR referenced to RTK for three DGPS sources at four mean ground speeds (GS).

GS (km/h)	Beacon (m)	OmniSTAR (m)	WAAS (m)
75th Percentile			
5.2	0.563 a1	0.730 a2	1.502 a2
8.3	0.549 a1	1.158 b2	1.734 b3
11.4	0.537 a1	1.165 b2	1.533 b3
14.7	0.634 a1	1.521 b2	1.702 b2
SE of each mean=0.099; SE of difference of two means=0.134			
95th Percentile			
5.2	0.771 a1	1.015 a2	1.818 a3
8.3	0.761 a1	1.638 b2	2.284 b3
11.4	0.722 a1	1.663 b2	1.928 a3
14.7	0.844 a1	2.188 c2	2.243 b2
SE of each mean=0.115; SE of difference of two means=0.145			
99th Percentile			
5.2	0.880 a1	1.229 a2	2.048 a3
8.3	0.949 a1	1.878 b2	2.585 b3
11.4	0.892 a1	2.007 b2	2.106 a2
14.7	1.116 a1	2.618 c2	2.639 b2
SE of each mean=0.181; SE of difference of two means=0.142			

Means followed by a common letter within a column or common number within a row are not different (p≤0.05).

The appearance of decreasing performance of OmniSTAR and WAAS as ground speed increased was not attributable to the quality of correction information provided by OmniSTAR and WAAS. We believe this effect resulted from differences in the way the AgGPS 132 receivers calculate position fixes from the Beacon Type 9 partial correction message versus the Type 1 full correction message broadcast by OmniSTAR and WAAS. While the PV filter is proprietary, we understand that these variations in correction messages lead to different paths through the PV filter smoothing algorithm. The flow control of the PV filter, depending on the correction message type, may result in behavior that resembles or mimics a time offset in the calculation of the OmniSTAR and WAAS DGPS position fixes compared to RTK such that the effect is exacerbated as ground speed increases. Stombaugh et al. (2002) also reported an example of data filtering that reduced dynamic performance of a GPS receiver.

Because the PV filter algorithm is predicted to vary across GPS receiver manufacturers, we expect the filtering effect will also vary depending on the brand of GPS receiver used. A precautionary note is that results of studies comparing dynamic DGPS performance may be further confounded unless receiver brand, model, and firmware version are standardized across DGPS sources, as was done in this study.

An alternative approach to determine relative performance of DGPS sources in the presence of the PV filter effects is to compare cross-track errors, i.e., the indicated perpendicular distance of a mobile GPS receiver antenna from the RTK track. In automated or manual guidance systems, the cross-track error is more important than the along-track error and the former should be least sensitive to time offsets whether real or apparent. Cross-track data, therefore, should minimize PV filter smoothing effects. Perpendicular distances to the RTK track were computed after the dataset was filtered to remove data points located geographically in the turns of the test track (Figure 2-4) so that only straight line segments remained. Scatter plots of the data against ground speed (Figure 2-10) showed that using cross-track errors did not remove the apparent speed effect from OmniSTAR (Figure 2-10c) and WAAS (Figure 2-10d) data compared to Beacon (Figure 2-10b.) Cross-track error means and standard deviations are shown in Table 2-4 as a function of mean ground speed. Standard deviations for the cross-track errors of OmniSTAR and WAAS increased with ground speed indicating that increasing speed reduced relative accuracy. This was not the case for Beacon.

To further resolve the apparent speed dependency issue for OmniSTAR and WAAS, an additional three replications of the dynamic test protocol were carried out using only Beacon and OmniSTAR DGPS sources with the PV filter turned off. These two DGPS sources were selected because position fixes based on their correction messages were apparently affected differently by increases in ground speed and because they are both referenced to the same geodetic datum. WAAS and OmniSTAR reacted similarly, so only one of the two was included in this clarification test. To compare performance with and without the smoothing effects, the RMSE for data collected with the PV filter on was divided by the RMSE for corresponding condition of PV filter off. These ratios were plotted against mean ground speed (Figure 2-11).

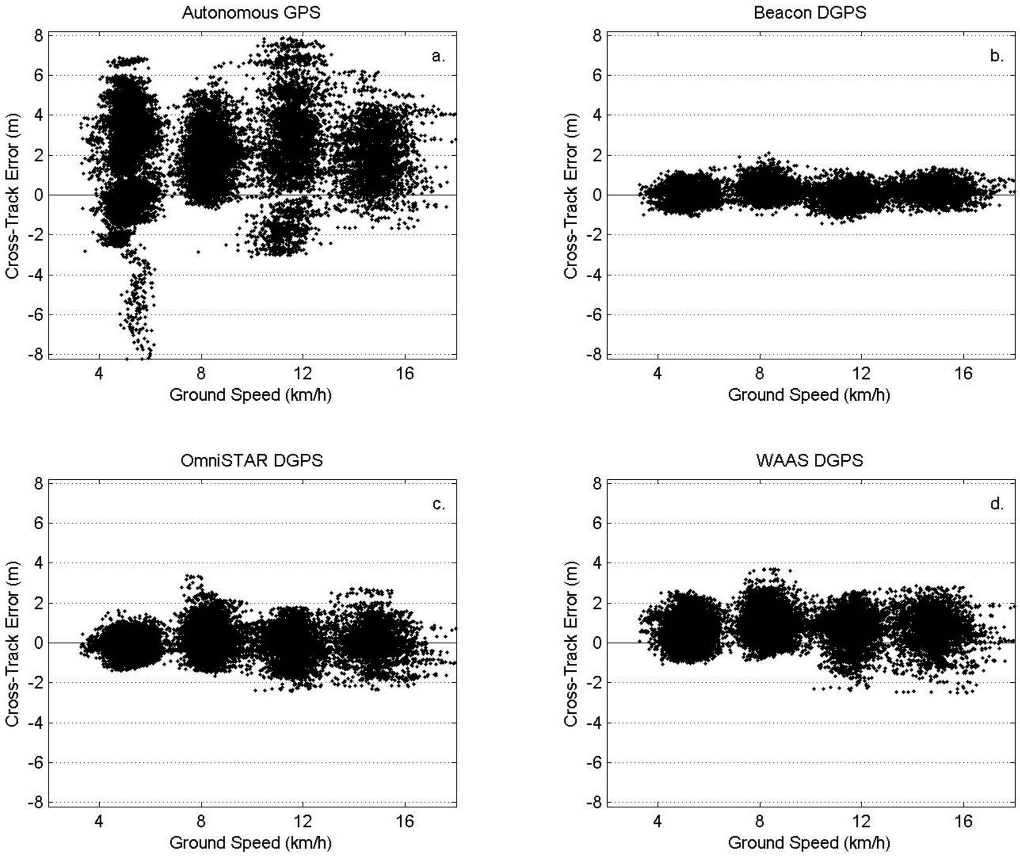
Ratios less than 1 indicate that turning the PV filter off increased RMSE (decreased accuracy) relative to the condition of PV filter on. This was the case for the Beacon DGPS values at the three slowest ground speeds. PV filter on/off had no effect on the Beacon RMSE at the highest ground speed. In contrast, the ratios for the OmniSTAR DGPS were 20 to 60% greater than 1 for all but the slowest ground speed. These results indicate that turning the PV filter off actually increased positional accuracy of OmniSTAR relative to the RTK track at the three highest ground speeds. While we cannot document the actual manner in which the PV filter reduced OmniSTAR DGPS accuracy as speed increased, it seems clear from this analysis that the effect is real. OmniSTAR and WAAS DGPS corrections are not inferior to Beacon DGPS, providing that the PV filter used by the GPS receiver has the same smoothing effect on all three DGPS corrections. For this reason, designers of auto guidance systems may prefer unfiltered GPS-based position fixes as input to their controller circuitry. Any smoothing requirements specific to the controller can be relegated to the guidance algorithms.

Table 2-4. Results of the cross-track error (XTE) analysis for autonomous GPS and three DGPS sources at four ground speeds*.

	Autonomous GPS		Beacon DGPS		OmniSTAR DGPS		WAAS DGPS	
Ground Speed	XTE	SD	XTE	SD	XTE	SD	XTE	SD
km/h				-m-				
5.2	1.60	2.39	0.01	0.35	0.00	0.46	0.69	0.63
8.3	2.01	1.21	0.26	0.37	0.27	0.75	0.95	0.76
11.4	2.40	2.46	0.00	0.39	-0.06	0.79	0.75	0.82
14.7	1.99	1.39	0.19	0.39	0.03	0.83	0.63	0.88

* Values for ground speed and XTE are means.

The question of whether OmniSTAR and WAAS are reliable DGPS correction sources for precision agriculture applications remains. The requirements for such uses include repeatability over time and high internal consistency (low scatter). The increase in deviation from the RTK track as a function of increasing ground speed for OmniSTAR and WAAS, under the conditions of this study, became an issue only if these DGPS positions were referenced to the RTK or Beacon tracks. That this is true is demonstrated by referencing WAAS position data to the OmniSTAR track (Figure 2-12), rather than the RTK track, and then correcting for geodetic datum differences between these two DGPS sources by subtracting the static X-Y offsets from RTK. This centered the data cloud on the origin and resulted in uniform values for the standard deviations thereby demonstrating internal consistency. The uniformity in the RMSE values (referenced to OmniSTAR) as ground speed increased showed that OmniSTAR and WAAS reacted similarly to increasing ground speed and that both correction messages were processed the same way by the PV filter. Referencing OmniSTAR to the WAAS track produced results similar to those presented in Figure 2-12, so those data were not included here. In summary, OmniSTAR and WAAS, like Beacon, do conform to precision agriculture requirements that require submeter accuracy.



Autonomous GPS

Beacon DGPS

OmniSTAR DGPS

WAAS DGPS

Figure 2-10. Scatter plots of cross-track errors derived from autonomous GPS and three DGPS sources measured as the perpendicular distance from the RTK track versus ground speed.

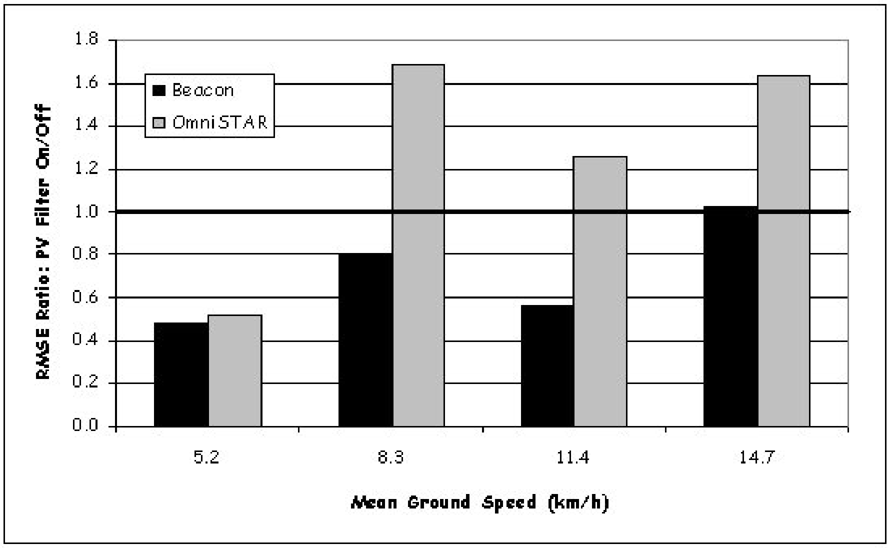


Figure 2-11. RMSE for δR from Beacon DGPS and OmniSTAR DGPS for the configurations of PV filter on and PV filter off. Data are expressed as a ratio of on/off.

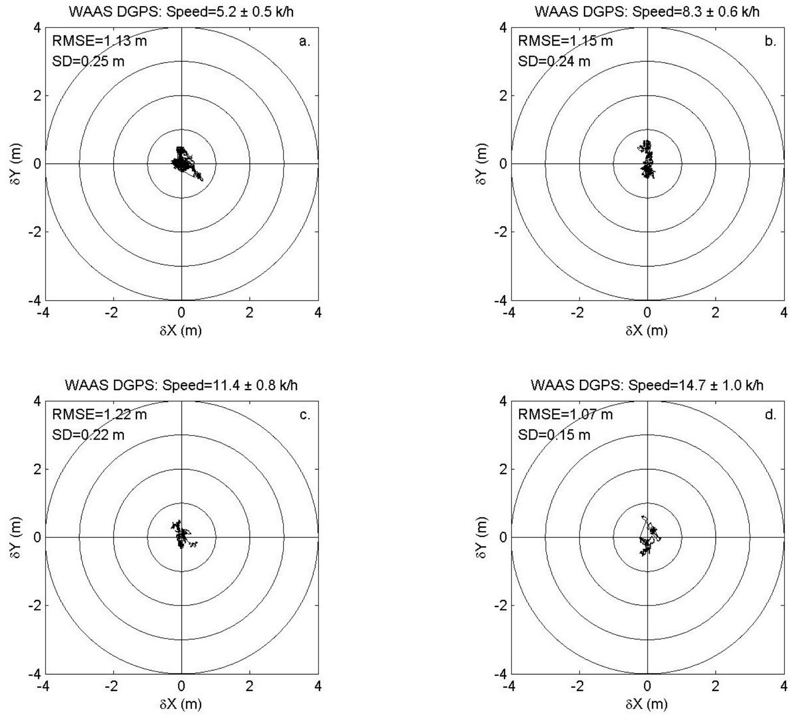


Figure 2-12. Plots of dynamic position fixes in the X (east-west) and Y (north-south) directions for WAAS DGPS at four mean ground speeds referenced to the OmniSTAR track. RMSE values represent 1-sigma circular error from the OmniSTAR track. SD values show the internal consistency of the position fixes across ground speeds. Note: The coordinates were translated by subtracting the WAAS static RTK X-Y offsets to adjust for differences in reference datum between OmniSTAR and WAAS. This removed the northwest quadrant bias of WAAS.

CONCLUSIONS

This research was implemented to answer questions from users of precision agriculture technology concerning relative dynamic performance of DGPS sources in our research center's geographical region of focus anchored at Hays, KS. Not surprisingly, it is clear that autonomous GPS is not a reliable solution. Among the three DGPS sources tested, all had comparable relative accuracy and availability and performed at levels that met or exceeded published specifications. If repeatable accuracy is required in order to return to previously marked locations, or to accurately and repeatedly retrace tracks through a field, then it is advisable to use the same source of differential corrections with the same geodetic datum for all field work. Changing the source of DGPS is not recommended unless the position data are corrected for differences due to reference datum. Multiple vehicles working in the same field that are not standardized on DGPS source or geodetic datum could lead to incompatibilities.

Users of OmniSTAR and WAAS need to be aware of the potential for the PV filter to decrease performance as ground speed increases. This is important if attempting to revisit points or tracks established with RTK or Beacon, and that this effect will likely vary with brand of GPS receiver and with time as new models and firmware upgrades are deployed. The fact that the Beacon and WAAS are delivered to the end user at no direct cost makes them attractive alternatives in this region of Kansas, although Hays is currently on the fringe for reliable Beacon service. Beacon signal access will improve when the federal government implements plans for augmenting the Beacon tower network.

For automated guidance systems, RTK clearly provides the best performance and would be the obvious choice if the significantly higher cost can be justified by economies of scale. If RTK is cost prohibitive, then Beacon DGPS would seem the best choice where the signal is reliable, because the SD and RMSE values for X, Y, R, and cross-track error were approximately half those of OmniSTAR and WAAS, and the DGPS correction is apparently not degraded by the PV filter algorithm as it is currently deployed in the AgGPS 132 receivers.

These conclusions apply to the region around Hays, KS. Some validation is recommended if extrapolating to other locations.

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500