1996

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EVALUATION OF GPS FOR APPLICATIONS IN PRECISION AGRICULTURE

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ABSTRACT. *Location coordinate information is needed in precision agriculture to map in-field variability, and to serve as a control input for variable rate application. Differential global positioning system (DGPS) measurement techniques were compared with other independent data sources for sample point location and combine yield mapping operations. Sample point location could be determined to within 1 m (3 ft) 2dRMS using C/A code processing techniques and data from a high-performance GPS receiver. Higher accuracies could be obtained with carrier phase kinematic positioning methods, but this required more time and was a less robust technique with a greater potential for data acquisition problems. Data from a DGPS C/A code receiver was accurate enough to provide combine position information in yield mapping. However, distance data from another source, such as a ground-speed radar or shaft speed sensor, was needed to provide sufficient accuracy in the travel distance measurements used to calculate yield on an area basis.* ***Keywords.*** *GPS, Global positioning system, Precision farming, Site specific crop management, Combine harvesting, Soil sampling.*

Knowing the location of a field operation or a data collection point is important for precision agriculture implementation. Location accuracy requirements are variable, based on the intended use of the information. For variable rate application and referencing of soil and yield data, an accuracy of one to several meters is generally sufficient. More accurate systems would be useful for vehicle guidance, to eliminate skips and overlaps with a chemical applicator, or for precision cultivation operations (Auernhammer and Muhr, 1991). Most current precision agriculture efforts use Global Positioning System (GPS) technology to provide location data.

The Navstar Global Positioning System (GPS) is a satellite-based radionavigation system developed and operated by the U.S. Department of Defense that allows users to determine three-dimensional position and velocity anywhere in the world with a high degree of accuracy (Tyler, 1992).

GPS satellites transmit both a standard C/A (coarse acquisition) code and a precise P code (restricted to U.S. government use) on each of two frequencies. System designers have developed navigation and positioning solutions based on processing the C/A code, the P code, and/or the underlying carrier wave from one or both frequencies.

The pseudo-range positioning technique compares the coded signal transmitted from the satellites with an exact replica of the code generated in the receiver. The time delay between the two signals provides a measurement of the distance to each satellite. Pseudo-range measurements from at least four satellites allow for the computation of receiver position and a clock offset. When the pseudo-ranging procedure is employed with a single receiver, an absolute position is computed. Errors due to atmospheric delays, orbit deviations, etc., yield an expected 2dRMS accuracy of 100 m (330 ft) with the C/A code. The 2dRMS accuracy specification indicates that the measured position will be within the stated distance from the true position 95% of the time. The accuracy of pseudo-range positioning can be increased substantially by placing one receiver in a fixed position and using the GPS information from that fixed receiver to compensate for inaccuracies in the GPS position of the roving receiver. This procedure, called differential GPS (DGPS), yields improved 2dRMS accuracies of 5 m (16 ft) or better with C/A code (Leick, 1990). C/A code DGPS receivers with horizontal accuracy claims of 1 m (3.3 ft) are now available. DGPS positions can be calculated either in real-time or through post-processing of the signal. Real-time differential positioning requires a communications link, such as VHF-FM radio, to transmit the correction signal from the fixed receiver to the roving receiver.

The carrier phase positioning technique is an alternative to using the coded GPS data from the satellites. By directly observing the phase of the carrier wave on one or both frequencies, maximum accuracies are attainable. Because of complexities in the required measurement techniques, carrier phase measurements require much greater attention to detail during data collection. Therefore, although carrier phase measurements result in higher location accuracies (ranging from sub-centimeter to a few centimeters), the techniques

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Article was submitted for publication in March 1996; reviewed and approved for publication by the Power and Machinery Div of ASAE in September 1996 Presented as ASAE Paper No. 92-3615

Contribution from the Missouri Agricultural Experiment Station Journal Series No 12,450. Names are necessary to report factually on available data; however, the University of Missouri and the USDA neither guarantee nor warrant the standard of the product, and the use of the name implies no approval of the product to the exclusion of others that may be suitable

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are less robust and require greater attention to field methods than do pseudo-range techniques (Leick, 1990).

Two DGPS techniques using carrier phase solutions are the static and kinematic positioning methods. Static positioning is used to locate stationary points with a high degree of accuracy, such as for primary control networks. Repeated measures from several satellites to the stationary receiver provide a sub-centimeter level of position accuracy. Static positioning data can be processed either real-time or post-mission. Static positioning sessions typically require one or more hours of data collection per point, with longer sessions resulting in better accuracies. Kinematic positioning is used when the rover receiver is moving. The receiver maintains continuous lock on the signals from four or more satellites during the survey, and points are generally occupied for at least one minute each. The resulting positions can be obtained in real-time or can be post-processed, using computer-assisted smoothing operations to improve the quality of the data. The kinematic process is more rigorous than the static process, in that phase ambiguities are resolved at the beginning of the survey. These solved ambiguities are then carried through the survey, and the survey is closed by returning to the starting point.

Accuracy requirements of the application determine the appropriate GPS capability and technique. Low accuracy applications require only one receiver with the coordinates determined in real-time. A variety of hand-held, low-accuracy GPS receivers are on the market. The procedures can be conducted whenever three or more satellites are in view. Usually, this technique is not accurate enough for precision agriculture applications. Equipment tracking and mapping applications, such as determination of combine location or the location of soil sampling points, require medium accuracy techniques. The procedures are more rigorous than those for determining low-accuracy, stand-alone locations and require DGPS capabilities. If point locations must be determined with higher accuracy, kinematic GPS techniques may be appropriate.

GPS technology has been applied to soil mapping and production agriculture. Long et al. (1991) reported that using GPS in a soil survey provided sufficiently accurate results for positioning and navigating in the field and for digitizing of soil boundaries, and allowed greater in–field efficiencies than conventional methods. Shropshire et al. (1993) used post-processed DGPS to locate sample points and real-time DGPS for fertilizer application rate control. Muhr et al. (1994) used real-time DGPS to monitor forage chopper position during harvest with an accuracy of better than 2.25 m (7.4 ft). Eliason et al. (1995) obtained sub-meter accuracies on-the-go by applying a robust carrier phase smoothing technique to GPS C/A code data.

OBJECTIVES

Although researchers have reported the uses and assumed accuracies of GPS location data for precision agriculture applications, few have evaluated GPS accuracies in comparison to other sources of location information. Therefore, the purpose of this study was to evaluate GPS performance in precision agriculture applications by comparing the GPS information with other independent data sources. The applications evaluated included: (1) location of discrete points for soil sampling or other static data collection; and (2) distance and velocity determination during dynamic data collection, such as combine-based grain yield mapping.

GEOREFERENCING OF SAMPLE LOCATIONS

Collection of samples or data, such as soil samples or weed pressure ratings, on some type of spatial grid is a basic task in precision agriculture. To map variability patterns based on the collected data or samples, locations of the collection points must be determined. The use of various GPS procedures for this georeferencing process was evaluated for accuracy.

Two separate evaluations were carried out, using two different sets of DGPS equipment. The first evaluation (Test One) used two self-contained survey-type receivers of 1991 vintage as the rover and base. The second evaluation (Test Two) used two GPS receivers operating on expansion cards in personal computers. These cards were acquired in 1994 and used narrow correlator spacing technology, which provided improved accuracy levels compared to the older receivers (Van Dierendonck et al., 1992).

MATERIALS AND METHODS

Test One evaluated the use of two Ashtech M-XII GPS receivers equipped with L_1-L_2 geodetic antennas. A bar code reader was attached to the rover receiver, and the rover antenna was attached to a bipod and pole. Bar codes to identify each sampling site were made before the survey. A Nikon Topgun A20LG total station surveying instrument was used to provide another position measurement for GPS data comparison. This total station instrument was essentially an electronic theodolite containing an integral electronic distance meter.

Location data were collected in three 18 m × 190 m (60 ft × 620 ft) research plots. A 31-sample transect was located lengthwise in each plot, with individual sample sites approximately 6 m (20 ft) apart. Data were collected using kinematic survey procedures to allow processing of the same data set by both carrier phase and code processing methods. The kinematic survey was initialized using standard GPS antenna swap procedures to resolve carrier phase ambiguities (Remondi, 1985). After initialization, the rover receiver was set up over the temporary point used for the antenna swap and its antenna was attached to a bipod and pole for ease of handling while moving through the experimental plots. The rover receiver was hand-carried to the research plots and set up over each soil sample point for 60 s of data collection. Relevant point descriptive data for each soil sample point were entered into the receiver via the barcode reader.

During the Test One data collection process, the satellite constellation visible by the GPS receivers was less than optimal, varying between four and six satellites. On several occasions while surveying points near a tree line, the number of visible satellites dropped below four, causing loss of satellite lock. Loss of satellite lock required reinitialization of the survey by returning a previously measured point to collect another 60 s of data.

Following data collection at all soil sample points, the survey was closed by returning the rover receiver to the temporary point for a final 60 s data collection. By closing the survey, processing could be initiated from both ends of the survey, to aid data recovery if a loss of satellite lock occurred during the survey. Processing data from both ends of the survey also allowed for reduction of cumulative measurement errors. After the GPS survey was completed, the receiver measurement data were transferred into a computer. Data were then processed and the results were incorporated into the existing survey network. Total project time for data collection and processing was 3.5 h.

Georeferencing of soil sampling points by the total station was accomplished following standard surveying procedures. A project benchmark previously established through a static GPS survey was used to align the GPS kinematic survey with the conventional survey by total station. Data collector files were downloaded to a computer and processed to determine coordinates. Total project time was 2.5 h.

Test Two evaluated the use of two NovAtel 951R GPSCard receivers equipped with survey-quality antennas. This receiver was designed to be mounted in a standard card slot of a personal computer, and had pseudo-range, carrier phase, and real time differential capabilities. The base receiver antenna was placed over a known point, previously located through a static GPS survey. For efficient traversing of the sample point grid, the rover receiver GPSCard was installed in a portable computer affixed to the front carrier of an all-terrain vehicle (ATV), with the antenna mounted to a mast located in front of the operator.

Location data were collected for a set of 149 soil sampling points on a 40 m (130 ft) square grid in a 24 ha (60 ac) research field. GPS antenna swap procedures were used to resolve initial carrier phase ambiguities. After survey initialization, the ATV was driven to position the rover GPS antenna over each sampling point. As with Test One, data were collected in a kinematic survey, with each sample point occupied for a minimum of 60 s (6 location measurements, 10 s apart). Some inaccuracy in sample point location was introduced through the antenna mast not being positioned directly over sample point and/or the mast not being vertical, due to ATV pitch. The estimated error of positioning the antenna over the sampling point was generally less than 15 cm (6 in.). Sample point identification was entered through the keyboard of the portable computer.

GPS data were post-processed using both kinematic (carrier phase) and pseudo-range (C/A code) processing methods. Pseudo-range positions were computed both for a single reading at each point and by averaging of the six individual readings collected at each location. After processing, it was discovered that a loss of lock occurred partway through the initial survey, requiring the re-survey of approximately 40% of the sample points. Data collection and processing required approximately 6 h for the initial survey, and 2.5 h for the re-survey.

Comparison position data were collected with the same Nikon total station instrument used for Test One. Due to line-of-sight obstructions, valid comparison data were obtained for only 143 of the sample points. Time for total station survey and data processing was approximately 3.5 h.

Results and Discussion

Test One (Ashtech M-XII) kinematically processed carrier phase data exhibited approximately 0.1 m (4 in.) offset in both northing and easting from the total station data (table 1). These differences were greater than the errors expected in a kinematic survey (Leick, 1990), and were likely due to an alignment inaccuracy between the total station survey initial coordinates and the local GPS benchmark used for differential correction. Positioning accuracy was evaluated after removing the mean offset from the GPS data, based on the assumption that the mean differences were due to a systematic error in the total station positions. This resulted in a standard deviation of less than 3 cm (1.2 in.) in northing and easting, and less than 6 cm (2.4 in.) in elevation. These differences were consistent with data reported in the literature for kinematic survey precision (Leick, 1990).

Processing of the Test One C/A code data yielded dRMS positional errors of less than 1.9 m (6.2 ft) in all dimensions (table 1). These data were obtained as the average of six individual readings at each sample point. Again, a significant offset (mean difference) was observed between the GPS positions and the total station positions.

Test Two (NovAtel) data were collected using the same benchmark as the reference point for both the GPS and the total station surveys. Mean position differences between GPS and total station data were less in this test than in Test One (table 1). Kinematic processing of the GPS data provided horizontal dRMS accuracies of within 17 cm (6.7 in.). These accuracies were worse than expected from GPS kinematic analysis, but part of the error was attributable to mis-alignment of the GPS antenna on the ATV relative to the sampling point. It was estimated that this positioning error could have been as much as 15 cm (6 in.) in some cases.

Processing of the C/A code data from Test Two yielded horizontal dRMS errors of 39 cm (15.4 in.) when averaging the six individual readings at each sample point. If only a single reading at each point was used, the dRMS error was 45 cm (18 in.) (fig. 1). Thus, the 2dRMS error would be 90 cm (3 ft), meaning that 95% of the time, a single C/A code reading would be expected to be within 90 cm (3 ft) of the true position. Cannon and Lachapelle (1992) reported dRMS errors of less than 1 m (3.3 ft) in each of three dimensions when using similar NovAtel equipment. They noted that their data were collected under suboptimal conditions and expected that better results would be possible once the full GPS constellation of satellites was deployed.

These tests document the accuracy and utility of GPS techniques for locating sampling points. Processing of a single C/A code reading at each point provided 2dRMS errors of less than 0.7 m (2.3 ft) in the northing and easting dimensions, and less than 1.2 m (3.9 ft) in elevation with a high precision, narrow correlator receiver. Errors were reduced by only 15 to 20% when six readings were averaged at a single point. These results indicate that a high-precision C/A code GPS receiver can provide accuracies better than required for many precision agriculture location tasks, without the need for collecting multiple readings at a single point or resorting to more difficult kinematic, carrier phase analysis techniques. However, the GPS user must be aware that position errors much greater than the 2dRMS level can and do occur (fig. 1), and take appropriate steps to minimize the effect of these outliers, if necessary.

The Test One survey exhibited considerably larger C/A code position errors than did the Test Two survey. Part of this difference may have been due to older technology in the

Table 1. Comparison of GPS-derived sample point positions to positions calculated from total station measurements

Test No	Receiver/Transport	Processing Method	Dimension	Mean Difference (m)*	Std Dev About Zero, or dRMS Error (m)†	Std. Dev About Mean (m)‡
1	Ashtech M-XII, hand carried	Kinematic	Northing	–0.100	0.104	0 028
			Easting	–0.120	0 123	0 029
			Horizontal§	0 160	0 161	0.022
			Vertical	–0 010	0 113	0 054
1	Ashtech M-XII, hand carried	C/A code, avg 6 rdgs	Northing	0.804	1 442	1 197
			Easting	–0 259	0 878	0 839
			Horizontal	1 278	1 688	1 103
			Vertical	0 004	1 846	1 846
2	NovAtel 951R, ATV‖	Kinematic	Northing	–0 077	0 142	0 119
			Easting	0 025	0 088	0.084
			Horizontal	0 146	0 167	0 082
			Vertical	–0 118	0 122	0 030
2	NovAtel 951R, ATV	C/A code, avg 6 rdgs.	Northing	–0.051	0 270	0 265
			Easting	0.005	0 283	0 283
			Horizontal	0 337	0 391	0 199
			Vertical	–0 064	0 472	0 468
2	NovAtel 951R, ATV	C/A code, single rdg	Northing	–0 039	0 332	0 330
			Easting	0 006	0 309	0 309
			Horizontal	0 362	0 454	0 273
			Vertical	–0 136	0 588	0 572

* Mean difference between GPS derived position and position computed from total station survey

† Standard deviation referenced to total station positions, also termed dRMS error

‡ Standard deviation referenced to mean GPS position, a measure of precision

§ Horizontal differences computed from northing and easting differences

‖ GPS receiver and antenna were affixed to an all-terrain vehicle (ATV)

Ashtech receivers. Another factor was the weak satellite constellation in effect at the time of the survey. At the time of the Test One survey, the complete GPS satellite constellation was not yet deployed, and the number of satellites visible ranged from 4 to 6 during data collection. The Test Two survey was conducted under a much better satellite constellation, and 6 to 10 satellites were always visible.

Kinematic survey methods provided much higher accuracies in these tests than did the C/A code methods. However, kinematic methods should only be employed when higher accuracies are needed, due to the additional difficulties involved. Kinematic position determinations take considerably more time and require more attention to detail than do positions obtained with C/A code methods. Even when considerable care is taken, a loss of satellite lock can occur, requiring a repeat of portions of the survey. If accuracies better than those possible with standard code positioning are needed, it may be worthwhile to investigate enhancement techniques, such as carrier phase smoothed code processing, or "on-the-fly" carrier phase processing, which does not require static initialization (Cannon and Lachapelle, 1992).

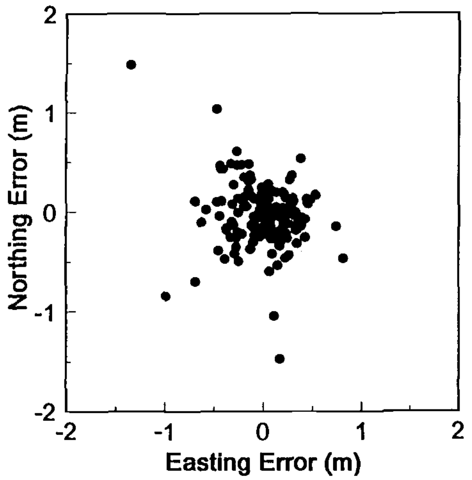

Figure 1–Error in sampling point location with a C/A code GPS-determined positions as compared to positions obtained by total station surveying measurements for 143 points.

GPS DISTANCE AND VELOCITY DETERMINATION DURING YIELD MAPPING

The determination of combine location and area harvested is an integral part of yield mapping. GPS has become the standard method for combine location. The GPS position can be used to determine the travel distance between successive readings. However, the accuracy of the GPS positions relative to the distance to be calculated must be considered.

MATERIALS AND METHODS

An instrumented, 8-row Gleaner R62 combine was used to map crop yield data in a soybean field. The combine was instrumented with an impact-based AgLeader Yield Monitor 2000. The sensor measured the force of grain impacting against a plate situated at the top of the clean grain elevator. Grain force, elevator speed, and other measured parameters were used in the Yield Monitor 2000 to determine mass grain flow rates. The AgLeader system included a monitor displaying instantaneous values and cumulative totals of yield, grain moisture, grain flow, speed, distance and other parameters. The monitor internally stored cumulative parameter totals for each load of grain and all measured instantaneous parameters were output to a serial port at one second intervals.

The factory-installed magnetic pick-up speed sensor on the combine was used to determine speed and distance traveled. The sensor was calibrated by comparing the cumulative distance recorded by the sensor to the known distance between the beginning and end of a straight harvest transect. This procedure was repeated several times and a least squares regression was used to obtain the linear calibration slope with the intercept forced to zero.

A Starlink DNAV-212 real-time DGPS system was used during harvest. The receiver consisted of a high performance 12-channel Ashtech GPS Sensor II GPS receiver, integrated with a Starlink MRB-2A MSK radio beacon receiver. The Ashtech receiver consisted of 12 separate, parallel channels for C/A code and carrier phase measurements on the L_1 frequency band, with real-time differential capability. The MRB-2A was a two-channel, fully automatic scanning receiver capable of receiving the RTCM SC-104 format DGPS correction signal broadcast by the U.S. Coast Guard Differential GPS stations in the frequency range 283.5-325.0 kHz.

The Coast Guard DGPS system is a network of GPS reference stations that generate and broadcast pseudo-range corrections for all satellites in view using the RTCM SC-104 format. Each station consists of two all-in-view GPS receivers, the primary receiver and an automatic backup receiver, linked to a broadcast transmitter. All stations are connected to two computerized control systems for system level monitoring and configuration control. The broadcast signal includes RTCM messages, reference station parameters, constellation health and radio beacon almanac information, and a system integrity message. The DGPS correction beacon used during this study was located at St. Louis, Missouri, approximately 240 km (150 mi) from the harvest area.

The combine data acquisition system was a portable computer running a QuickBASIC program. The computer received the differentially-corrected GPS position and GPS time through one serial port and the yield parameters via a second serial port. The relevant GPS data was matched to the yield data and logged to disk on one second intervals.

Results and Discussion

The accuracy of the GPS for combine location was adequate for yield mapping, particularly when considering the uncertainties in the grain flow dynamics through the combine (Birrell et al., 1996). As expected, the deviation of the GPS position from the actual position appear minor (fig. 2), since the nominal error of the GPS system (1 to 3 m, 3 to 10 ft) was small compared to the scale of the field. However, if the results are compared on a smaller scale, the errors become significant, although still within the nominal error of the GPS system. The small-scale accuracy of the GPS system was evaluated along a series of harvest transects. During analysis, the ends of the field were ignored, to remove the effects of combine turns on the results.

The GPS-determined distance traveled by the combine between successive GPS position readings (every second) was compared with the distance measured using the combine speed sensor. Figure 3 shows a single data transect including a period when the combine was stationary. The GPS distance measurement exhibited a periodic component fluctuating about the mean distance measured by the speed sensor. In most cases the amplitude of these fluctuations was less than 0.25 m (0.8 ft), but in several cases the excursions were as large as 2 m (6.5 ft). The GPS data also indicated a movement of up to 0.25 m/s (0.8 ft/s) while the combine was stationary. Therefore, the GPS readings could not be used to accurately calculate the distance between two points that were relatively close together. Similarly, if the total distance traveled was calculated by the accumulation of the distance between successive points, distance error accumulated (fig. 4). This was particularly noticeable when the vehicle was stationary, since the GPS position calculated at any instant varied about the true position, thus indicating a false relative movement.

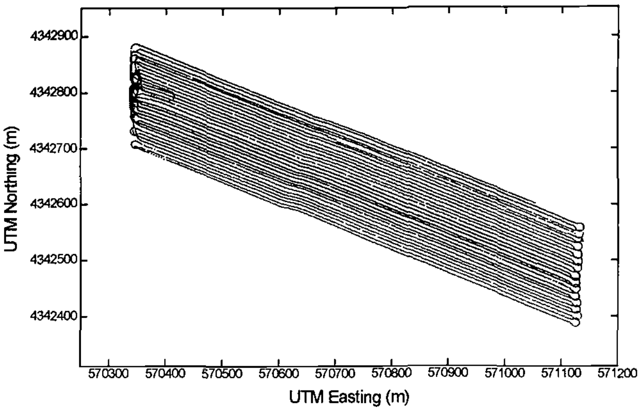

Figure 2–Combine travel pattern during harvest, as determined by real-time C/A code differential GPS.

Table 2 shows the effect of increasing the spacing between the points used to calculate the distance covered. The mean distance between points and the difference between the speed sensor and GPS distances were calculated. This was done for every point and then repeated using every second, fourth, eighth, sixteenth and thirty-second point. The mean distances traveled were proportional to the number of points used. However, the calculated differences between the speed sensor and GPS

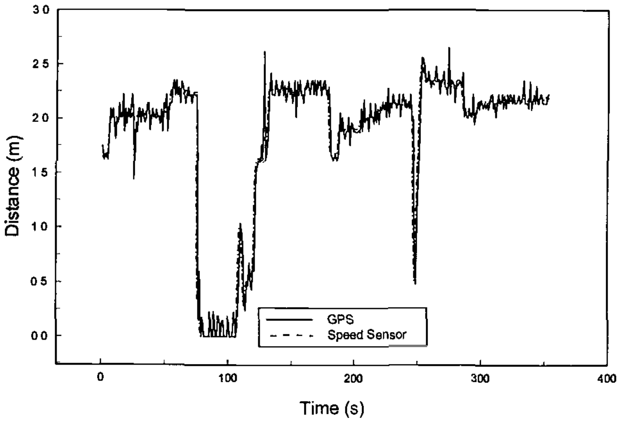

Figure 3–Distance traveled in each 1-second interval between position readings, as determined using combine speed sensor and GPS position data.

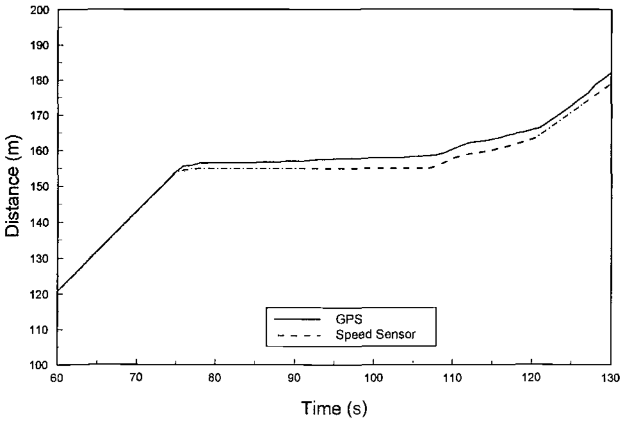

Figure 4–Cumulative distance traveled during harvest of a single transect, as determined using combine speed sensor and GPS position data.

Table 2. Comparison of GPS-derived distances to magnetic speed sensor measurements, using different calculation intervals (1-32 s)

		Statistics of GPS Distance vs Actual Travel Distance					
Calcu-lation Interval (s)	Number of Observations	Mean Travel Distance (m)	Mean Difference (m)	Median Difference (m)	Std Dev of Difference (m)	Maximum Difference (m)	Maximum Error (%)
1	4452	2 47	0 07	0 06	0 07	1 80	73
2	2216	4 93	0 09	0 07	0 10	2 82	57
4	1099	9 85	0 11	0 09	0 13	2 75	28
8	538	19 67	0 17	0 14	0 19	3 03	15
16	260	39 21	0 27	0 22	0 26	3 08	8
32	120	78 05	0 43	0 37	0 32	2 11	3

distances were not proportional to the spacing between calculation points. The mean and median error only increased by a factor of approximately 5, whereas the distance traveled increased by a factor of 32 (table 2). If every point was used to calculate the distance traveled over a period, the maximum error could be larger than 100%, whereas if every 32nd point was used, the error would normally be less than 3%. The use of GPS positions to calculate travel distance, and therefore area, must be questioned unless the distance between calculation points is much larger than the approximately 1 to 3 m (3 to 10 ft) error of the GPS system. A C/A code differential GPS system is not suitable for instantaneous distance (or velocity) measurements, and should not be used to provide an instantaneous distance parameter for any continuous sensor However, the GPS system could be used with an integrating, batch type sensor, if the area covered was sufficiently large.

SUMMARY

The use of GPS technology is an efficient and effective method of providing location data for precision agriculture applications. GPS signal selection (C/A code or carrier phase) should be determined by the accuracy required for a particular project.

Tests showed that standard C/A code receivers could be used when accuracy requirements were about 1 m (3 ft) or less. A high-performance C/A code GPS receiver provided better than 1 m (3 ft) accuracy for sampling positions. Accuracy levels could be improved somewhat by averaging multiple code readings obtained at each point. Even higher accuracies could be obtained with a kinematic positioning method, although this required more data collection and was a less robust technique (greater potential for data acquisition problems).

Carrier phase receivers provided accuracy resolutions of approximately 2 mm (0.1 in.) and should be considered when accuracies better than 1 m are required. Carrier phase receivers are more expensive then C/A code receivers and data collection procedures must be rigorous to provide the theoretically possible accuracies.

C/A code receivers do not provide sufficient accuracy for the calculation of combine travel distance and harvested area based on GPS position. The potential error in distance calculation over short distances is great, introducing a high-frequency noise component into yield calculations that could sometimes result in significant errors (> 100%) in the calculated yield. The determination of swath width using GPS-derived trajectories would also require much higher GPS accuracy than was possible using standard C/A code receivers.

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