

USING LOW-COST GPS RECEIVERS FOR DETERMINING FIELD POSITION OF MECHANIZED IRRIGATION SYSTEMS

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ABSTRACT. *As the accuracy of GPS receivers improves and the costs decrease, more applications for GPS become feasible. One such application is reporting center-pivot and lateral-move field position. Accurate knowledge of center-pivot or lateral-move position in real time is critical for site-specific irrigation. On center pivots, a traditional resolver can only report the location of the first interior tower while a GPS receiver can more precisely show the location of the end of the pivot. This advantage over traditional resolvers becomes more pronounced with longer center pivots. Lateral-move systems do not have a readily available mechanism for reporting their position as they travel over the field. GPS is potentially an ideal method for position and alignment reporting on lateral-moves. The resolver on a three tower center pivot was tested using a survey grade, sub-meter-accuracy GPS receiver. The resolver-reported angular position had errors up to ± 5 degrees. Fitting a sine curve and subtracting the modeled errors from the reported measurements corrected these errors to plus or minus one degree. A low-cost GPS receiver was tested in a stationary location on the same center pivot to determine its fitness for reporting field position for mechanized or self-propelled irrigation systems. This low-cost receiver was accurate to within 2.1 m 95% of the time. However, the remaining 5% of points showed errors up to 6.6 m. Outlying errors this large can present problems for precision or site-specific irrigation. Suggestions are offered for mitigating these errors.*

Keywords. *Global positioning system (GPS), Precision irrigation, Site-specific irrigation, Center pivot, Lateral move, Linear move, Resolver.*

In 1994 the U.S. Department of Defense finished deploying an improved global positioning system (GPS) composed of a constellation of 24 active satellites for military purposes. Civilian uses were permitted but with degraded accuracy by periodically shifting “reported” satellite positions or randomly switching off satellite signals briefly. In May of 2000, President Clinton announced the removal of this selective availability (SA), which increased the accuracy of publicly available GPS positioning from approximately 100 to 10 m. In July of 2003, the Wide-Area Augmentation System (WAAS) was certified by the Federal Aviation Administration (FAA) to meet the basic requirements for aviation navigation, providing a publicly available method for differentially correcting GPS signals to further increase accuracy to less than 3 m. Along with increased accuracy, the cost of differentially corrected GPS receivers has been decreasing, making possible their use in many additional applications. One such application includes precision farming where GPS systems are used to guide tractors and to create yield maps. There has been additional interest in using GPS technology for center-pivot or lateral-move positioning for site-specific irrigation (also known as precision irrigation).

Most modern center pivots use a small instrument called a resolver to report angular position. However, these are often subject to errors. A major limitation of using resolvers for site-specific irrigation work is that they only report the position of the first tower from the center point. Center pivots often have a slight bow in them as they travel around the circle. Also, the intermittent movement of interior towers for system alignment results in position errors as the end tower moves far more often than the first interior tower. The resolver-reported angular position of the first tower may not translate into an accurate representation of the position of the end tower. Other site-specific irrigation research has found errors in the reported resolver angle and identified correction algorithms to get accurate field positions (e.g. Sadler et al., 2002). Though these errors are not a cause for concern for most irrigators, accurate pivot position is required for site-specific irrigation. A low-cost GPS receiver mounted near the end of the pivot could provide a more accurate representation of the pivot’s position. The GPS receiver could also be used as a safeguard for the resolver-reported angular position.

Site-specific irrigation with lateral-move irrigation systems also requires accurate reporting of the real-time position in the field. This is especially difficult to obtain on lateral-move systems since most do not have a mechanism for reporting field position. Heermann et al. (1997) discussed the position reporting alternatives and concluded that GPS was the most viable method for determining field position for lateral-move systems. Applying GPS positioning to lateral-move systems could provide significant cost savings over buried cable, or other alignment and control systems in use.

Heermann et al. (1997) investigated non-differentially corrected GPS positioning on a lateral-move irrigation system for site-specific irrigation work. They determined

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potential position with dead reckoning based on travel speed and known initial position. This was then corrected with an averaging algorithm applied to the GPS receiver reported positions. The demonstrated accuracy was within ± 7 m. Kostrzewski et al. (2002) briefly described a lateral-move system with a differentially corrected GPS unit mounted on one end for reporting system position. In this experiment the position accuracy was described by fitting a regression curve to the measured points from a moving system and the variance from the regression was discussed. Reinke Manufacturing Inc. (Deshler, Nebr.) has applied for a patent (Barker, 2004) for a GPS control system for mechanized irrigation systems, and GPS units are being tested on cornering systems (Robinson, 2003). However, few data are available on the accuracy of low-cost GPS units as applied to center-pivot or lateral-move irrigation systems. The objective of this project was to evaluate the fitness of a typical center-pivot resolver and low-cost GPS receivers for reporting center-pivot angular position and lateral-move field position for site-specific irrigation.

MATERIALS AND METHODS

A survey grade GPS receiver (Trimble GPS Pathfinder Pro XRS, Sunnyvale, Calif.) with sub-meter accuracy was mounted on the end of a three-span experimental center pivot to evaluate the angular accuracy of the resolver. The center pivot was configured to log the pivot status and resolver position every minute (Peters and Evett, 2004). The center-pivot control panel clock was synchronized with the GPS clock, and the pivot was sent around in a complete circle at 100% of its potential speed while logging both the center-pivot angular position as reported by the resolver and the end point position as reported by the Trimble GPS receiver. These data were used to determine the accuracy of the resolver angle.

In a separate test, a low-cost (US \$169) GPS receiver (Garmin, model 16HVS, Olathe, Kans.) was mounted approximately 6 m beyond the last tower of a three-tower, 127-m center-pivot system. This receiver was WAAS enabled and had a reported position accuracy of 95% less than 3 m when differentially corrected and 95% less than 15 m if not differentially corrected. The output NMEA (National Marine Electronics Association) sentence (\$GPGGA), which used the RS-232 protocol, was recorded on 1-min intervals by a datalogger (Campbell Scientific CR10X, Logan, Utah) mounted on the last tower.

Two separate trials were run in the spring of 2004 where the pivot was left in a stationary position for an extended period of time to analyze the variability of the measurements. The first trial ran for almost 63 h beginning on day-of-year (DOY) 96, 2004 at 1645 h. The second trial ran for almost 137 h beginning on DOY 119 at 1608 h. The two trials were performed in different locations in the field.

GPS receivers report global position in terms of longitude and latitude. Translating these parameters into a pivot's angular position requires more than simple trigonometry. One degree of longitude translates to various distances from about 111 km (69 miles) at the equator to 0 km at the poles. One degree of latitude on the earth's surface also does not stay constant because of the elliptical shape of the earth resulting from the earth's spin. The pivot's center position in latitude

and longitude was measured accurately with the sub-meter Trimble GPS receiver. A series of equations, as described by Carlson (1999), were used to convert the center-pivot point and the measured pivot end point into an east-west and north-south distance difference. These equations use the WGS-84 (World Geodetic Survey 1984) reference datum to determine the earth's spheroid model. This model was used to calculate the true angles, which account for the elliptical nature of the earth. The plot's elevation was then used with the spheroid model to calculate the true radius from the earth's center point. The pivot center point was set as the axis origin of a theoretical field level grid. Trigonometry was then used with the calculated true angles and with the earth's radius to determine the north-south and east-west differences between the center point and the pivot end point. These differences were used as X, Y points to plot the location of the end of the pivot on the theoretical field level grid. Using this point, trigonometry was again used to give the angular position of the center pivot. For a lateral-move system the latitude and longitude of a corner of the field would be measured accurately. This would be set as the field level grid origin and all other points were determined in relation to it.

RESULTS AND DISCUSSION

The resolver position error was determined using the survey-grade, sub-meter-accuracy GPS receiver mounted on the end of the center pivot for one complete revolution (fig. 1). The resolver error changed as the pivot moved around the circle. The error was as large as ± 5 degrees. This is unacceptably large for site-specific irrigation even on a short three-tower center pivot. Resolver errors make end tower location estimates worse on longer pivots. For example this 5-degree error on the shorter 217-m pivot would mean that the end tower location estimate could be off by more than 11 m, while on a 400-m ($\frac{1}{4}$ -mile) pivot the end tower location estimate could be off by more than 35 m. This would require a greater buffer between management zones in the field, or if necessary, more accurate positions using other methods.

Resolvers produce signals that are in proportion to the sine or cosine of their rotor angle (Admontec, 2004). This can be seen in the sinusoidal nature of the resolver error. Least squares regression was used to fit a sine curve to the error

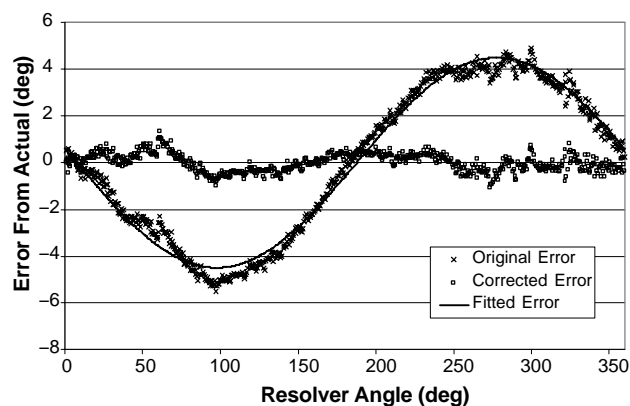


Figure 1. Center pivot resolver-reported, fitted and corrected angular errors determined by a survey grade GPS receiver mounted outside the end tower for one revolution.

(fig. 1). The resolver angle was then corrected by subtracting this error from the reported resolver angle as:

$$\theta_t = \theta_r + 3.7 \sin(\theta_r - 5.1) - 3.7 \quad (1)$$

where θ_t is the estimated true angle (degrees), and θ_r is the resolver angle (degrees). When this correction was applied the error approached the zero-error line such that the errors were ± 1 degree (fig. 1).

The data collected from the two trials of the low-cost GPS receiver are shown in figures 2 and 3. During both trials all points were differentially (WAAS) corrected. The X and Y position is the GPS receiver position in the field level grid with the pivot center point as the origin. The mean point is shown in each of these graphs along with the circle that includes 95% of all of the points collected. This circle radius was 2.07 m for Trial 1 (fig. 2) and 1.42 m for Trial 2 (fig. 3). From these plots it can be seen that, although most points are within the stated tolerance for the low-cost receiver of 95% less than 3 m, the points that do go outside tend to go far out. In this case points further than 6 m away from the mean were measured. This maximum error would translate into an error of 3.0 degrees at the pivot point on our center pivot, 0.9 degrees on a 402-m (1/4-mile) pivot, and 0.5 degrees on a 805-m (1/2-mile) pivot. All of these errors are less than the 5-degree error found on our resolver, less than even the corrected resolver angle on a pivot that is 400 m (1/2 mile) or longer.

The mean number of satellites acquired for all points during both trials was 9.59 satellites. The maximum of 10 satellites were acquired for Trial 1 and 11 for Trial 2. Although there were times during both trials when as few as six satellites were acquired by the receiver, greater than 93% of the points used nine or more satellites. Greater than 65% of the points for both trials used 10 or more satellites. When all data points with fewer than 10 satellites were excluded, the radius of the 95% inclusion circle was reduced from 2.07 to 2.01 m for trial one and from 1.42 to 1.23 m for Trial 2. These are not large improvements.

The effect that the GPS outlying points had on the calculated center-pivot angular position for Trial 1 can be seen in figure 4. The plot for Trial 2 was similar. Although 95% of the points were within a range of 1.55° for Trial 1 and

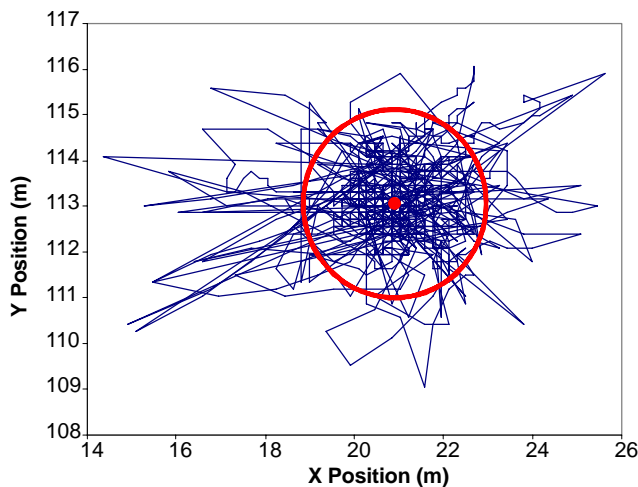


Figure 2. A plot of the points recorded by the low-cost GPS receiver in Trial 1. The mean position and a circle enclosing 95% of the position readings are also shown.

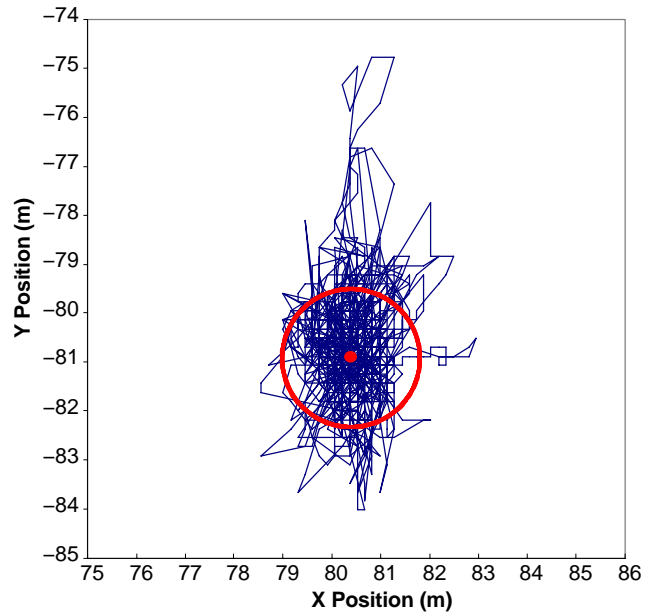


Figure 3. A plot of the points recorded by a low-cost GPS receiver in Trial 2. The mean position and a circle enclosing 95% of the position readings are also shown.

1.08° for Trial 2, the outliers created a range of errors of 5.55° for Trial 1 and 3.94° for Trial 2. These angular position errors are larger for the short, three-tower center pivot used for this experiment than would be calculated for a typical, longer center pivot. On a seven-tower, 400-m (1/4 mile) center pivot these errors would translate to a 95% range of 0.49° for Trial 1 and 0.34° for Trial 2, and a maximum range of 1.77° for Trial 1 and 1.25° for Trial 2. For even longer pivots the angular position errors would reduce further.

The probability that the low-cost GPS receiver would give an error outside of a given distance is summarized for both trials in figure 5. The mean error, the root mean square error (RMSE), the 50% and 95% probability errors, and the maximum errors are also shown for each trial. Although 95% of the position measurements were within about 2 m, the remaining 5% of measurements showed errors as high as 6 m. This is a significant concern if accurate position is always required as tends to be the case in precision control of moving center pivots or lateral-moves for site-specific irrigation. These high outlying errors have been largely ignored by previous publications on the use of GPS positioning for

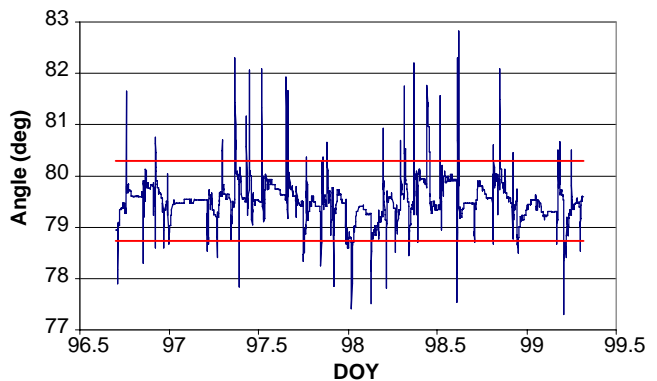


Figure 4. Calculated angular position of the center pivot over the time period of Trial 1. The upper 97.5 percentile and lower 2.5 percentile lines are shown such that 95% of all measurements are between the two lines.

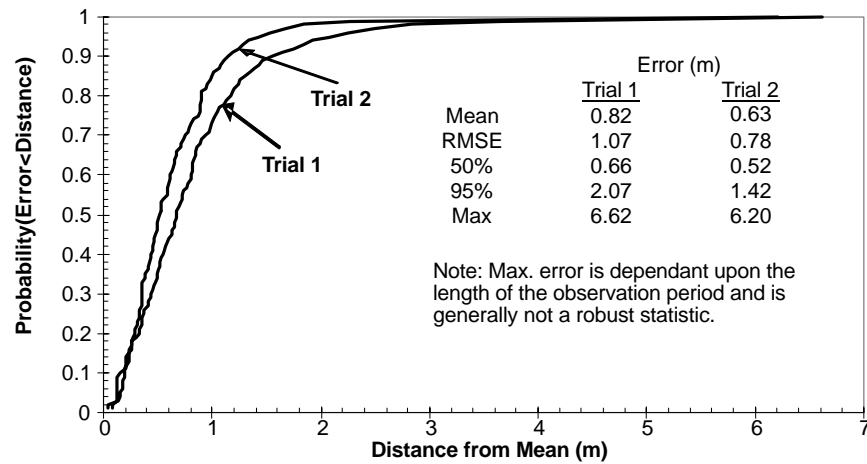


Figure 5. The cumulative probability curve that the GPS position error will be greater than the given distance.

mechanized irrigation systems. The probable causes for GPS position error include interferences in the ionosphere, the ephemeris and the troposphere, as well as multi-path errors and problems with the GPS clock and receiver. Because of these many possible error sources, it is difficult to know exactly what caused the error differences between Trial 1 and Trial 2. Rolling averaging schemes would provide little help since site-specific irrigation systems may need to respond immediately as they move over the field, and because most GPS errors are caused by atmospheric interferences (Garmin, 2004), which tend to change slowly. Although this can be seen in figure 2, figure 3 more clearly demonstrates how outliers tend to follow each other in time, thereby diminishing the effectiveness of averaging algorithms. To demonstrate this, instead of using individual points, the 5- and 10-min running averages were similarly tested from Trial 2. The 95% radius was only reduced from 1.42 m for individual points to 1.37 m with 5-min averages and to 1.30 m with 10-min averages. The maximum error was reduced from 6.2 m for individual points to 5.8 m with 5-min averages and to 5.1 m with 10-min averages. Averaging algorithms would also greatly complicate real-time position estimates of a moving system.

Incorporating the use of a second GPS receiver positioned in a known location might compensate for the errors caused by atmospheric differences. This might either be at the pivot point or at a nearby location for lateral-move systems. Atmospheric conditions that would cause errors in one receiver would also cause similar errors in the other receiver. For pivot angular position the position reported by a receiver located at the pivot center point and the pivot end point would be compared to each other to calculate angular position. The absolute position errors would be less of a problem when compared with doing the calculation using a predefined center-pivot point. For lateral-moves, the position as reported by the receiver mounted on the irrigation platform might be corrected by subtracting the error between the position as reported by the second receiver from its known location. This is similar to the way that differential GPS correction is done. Although this would double the equipment costs and require additional complexity in arranging for real-time or near-real-time communication between the two receivers, errors might be significantly reduced. Research on this method is currently being conducted.

CONCLUSIONS

An advantage of the GPS receiver is that it can show the location of the center pivot end point whereas resolvers can only indicate the location of the first tower. This advantage becomes more pronounced with longer center pivots. GPS is also an ideal method for determining lateral-move field position for site-specific irrigation. On the center pivot that was tested, the resolver angle had to be corrected to give angular position of sufficient accuracy for site-specific irrigation. The low-cost GPS receiver that was tested conformed to the stated specifications of an accuracy of 95% of points less than 3 m. In fact, an accuracy of 95% less than 2.1 m was measured. However, the remaining 5% of points showed errors as large as 6.6 m. These outlying points are a cause for concern when using GPS for pivot or lateral-move positioning under site-specific irrigation that has not been previously discussed in published literature. Using an additional GPS in a known location might mitigate the GPS position errors caused by atmospheric interferences.

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