SEED LOCATION MAPPING USING RTK GPS

M. R. Ehsani, S. K. Upadhyaya, M. L. Mattson

ABSTRACT. *The potential use of a real−time kinematics (RTK) GPS receiver for seed mapping with a high level of accuracy was investigated. High−accuracy seed mapping can potentially be used in weed control and plant−specific crop management. A four−row Salvo 650 vacuum planter was retrofitted with an RTK GPS receiver. Four seed detector sensors (one per planting unit) were mounted directly above the planter shoes. These sensors detected the seeds as they fell through seed tubes. Two low−cost single−board computers were used to acquire data in real time and display it in the tractor cab. The first computer was interfaced to the RTK GPS unit to determine seed location and forward speed. The second computer was interfaced to a display unit mounted in the cab. The first computer obtained the GPS time and UTM coordinates every second and stored them with a reference time (time tag). This computer also monitored the seed detector sensors, time−tagged the seeds from each unit, and stored the information in memory. The second computer monitored the first computer and reported the planter's performance through the display unit mounted in the tractor cab. Field tests were conducted to check the performance of this planter over two growing seasons. The first year test results indicated a need to control the sensitivity of the seed detector sensors used for seed detection. The second year tests showed that the improved system performed very well. The differences between the actual plant and the seed map generated by the RTK GPS based planter were in the range of 30 to 38 mm.*

Keywords. *GPS, Plant map, RTK, Seed map.*

One of the key elements that has aided the development of precision farming techniques is the ability to determine locations accurately within a field using GPS technology. Sub−meter accuracy offered by GPS systems that utilize differential corrections (DGPS) is considered accurate enough for most precision farming applications (yield monitoring, variable rate applications, crop and soil property sensing, etc.). Recent developments in the real−time kinematics (RTK) based GPS system have made it possible to determine positions with a horizontal accuracy of 1 cm. The application of this technology to agriculture can have tremendous economic and environmental benefits.

Since modern agricultural machinery is equipped with many controls, operator fatigue is a serious concern (Tillett, 1991; Noh and Erbach, 1993). Automatic guidance can reduce operator fatigue and improve machinery performance by reducing overlap during field operations (tillage, chemical application, etc.) (Tillett, 1991; Klassen et al., 1993). Many different types of autonomous systems have been attempted for use in agricultural vehicles. Choi et al. (1990) used radio frequency to guide a tractor with an RMS accuracy of less than 5 cm. Zuydam et al. (1994) developed a laser guidance system to achieve an accuracy of less than 6 mm. Tractors equipped with an auto−guidance system can be used to cultivate or spray very close to the plant line (about 5 cm or 2 in) at very high ground speed (up to 11 kph or 7 mph) and chisel or subsoil a field very close to buried drip tapes without damaging them (Abidine et al., 2002). Because of these advantages, auto−guidance tractors are becoming increasingly popular in the U.S., especially in the irrigated western states. Many tractor manufacturing companies are now offering the RTK GPS based auto−steering system as an option on their tractors. These RTK GPS receivers can be used for both guidance and other applications such as seed mapping, controlled traffic, and controlled tillage (Reeder, 2002).

A centimeter−accuracy planting system has the following potential applications in agricultural production:

- Plant−specific pesticide spraying.
- Weed−specific herbicide spraying.
- Plant−specific foliar application of fertilizer.
- Combination of 1 and 2 or 2 and 3 in one field operation.
- Plant thinning (removal of excess plants).
- Mechanical cultivation around the plants.
- Planting seeds at desired locations, resulting in check−row planting that can lend itself to cross cultivation. Moreover, plant population can be controlled to a desired rate based on soil conditions.

Although successful application of RTK GPS technology to auto−guidance tractors is a major accomplishment, the potential use of this technology for other agricultural operations such as plant−specific cultivation is still in its infancy. What this technology offers is a way to move from site−specific (sub−meter accuracy, as in precision farming) to plant−specific farming (centimeter accuracy ultra−precision farming). In the future, a seed mapping system can potentially be used to locate and manage each plant in a field individually. For example, integrating the information from an accurate seed map with plant color (greenness) sensor data

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The authors are **M. Reza Ehsani,** Assistant Professor, Department of Food, Agricultural, and Biological Engineering, Ohio State University, Columbus, Ohio; **Shrinivasa K. Upadhyaya, ASAE Member Engineer,** Professor, Department of Agricultural and Biological Engineering, University of California, Davis, California; and **Mark L. Mattson, ASAE Member Engineer,** Design Engineer, John Deere Worldwide Combine Product Development Center, East Moline, Illinois. **Corresponding author:** M. Reza Ehsani, 590 Woody Hayes Drive, Columbus, OH 43210; phone: 640−292−2540; fax: 640−292−4490; e−mail: ehsani.2@osu.edu.

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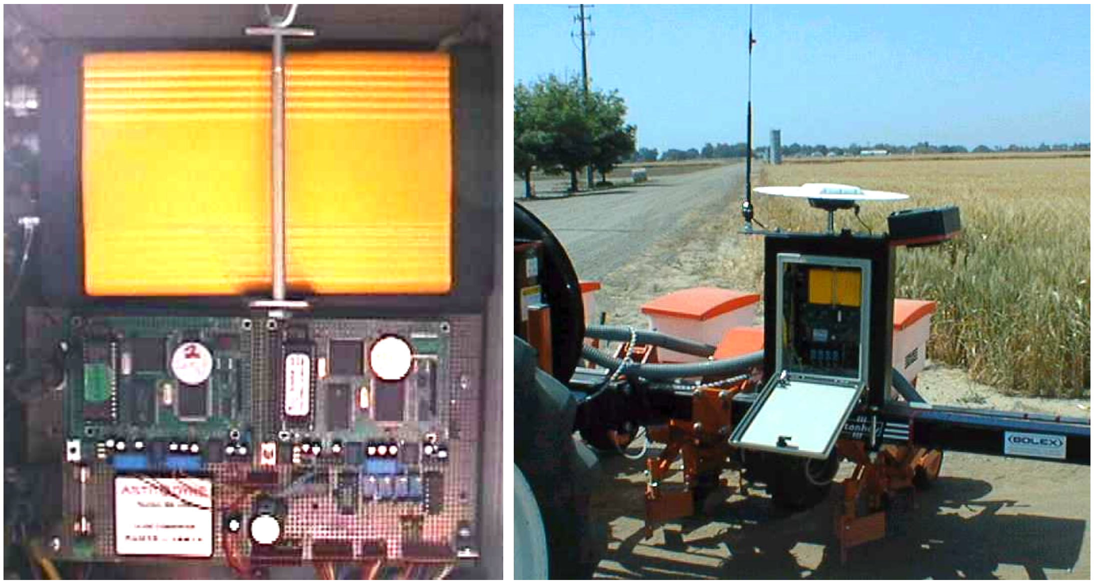

Figure 1. RTK GPS based precision planter. The data acquisition boards along with the RTK GPS receiver used as the rover are shown in the left image, and the complete assembly consisting of RTK GPS receivers and data acquisition boards (housed in a weatherproof box), GPS antenna, and radio receiver antenna are shown in the right image.

could be used for plant−specific herbicide or pesticide applications. This approach to target spraying is potentially faster than current computer vision and pattern recognition approaches because it requires less computation.

Objectives

The specific objectives of this research were:

- To retrofit a Salvo 650 four−row vacuum planter with a centimeter−accuracy GPS unit and to map the seed delivery.
- To compare the actual plant map to the seed delivery map to determine the error in seed placement.

Methods and Procedure

Planter Instrumentation

A four−row Salvo 650 vacuum planter (Solex Corporation, Dixon, Cal.) was retrofitted with a complete 4700 Series centimeter−accuracy surveying and mapping system consisting of a base unit, a rover, radio link, and other accessories donated by Trimble Navigation, Ltd. (Sunnyvale, Cal.). Two low−cost, low−power AE−P single−board computers (Tern, Inc., Davis, Cal.) were used to acquire data in real time and display it in the tractor cab. The first computer was interfaced to the centimeter−accuracy GPS unit to obtain location information and to an encoder to obtain wheel speed. The second computer was interfaced to a display unit mounted in the cab. The two computers and the GPS receiver were mounted in a rugged, weatherproof metal box and secured to the planter frame. The GPS antenna was installed on the top of the frame (fig. 1). The GPS antenna was directly ahead of planter unit 1. Four optical sensors (Keyence, Woodcliff, N.J.) were used to detect the seed. The signals from the optical sensors were amplified through amplifiers (Keyence, Woodcliff, N.J.). It was possible to adjust the sensitivity of detection based on the size of the seed using the seed sensor amplifiers. Optical sensors (one per planter unit) were mounted directly above the planter shoes and detected seeds as they fell through the seed tubes (fig. 2). Note that U.S. patent numbers 6,516,271 B2 and 6,553,312 B2 cover these inventions.

The first computer obtained the GPS time and UTM coordinates every second and stored them with a reference time (time tag). This computer also monitored the optical sensors, time−tagged the seeds, and stored the information in RAM. The second computer monitored the first data logger and reported the quality of RTK−GPS data (fix−float) and the

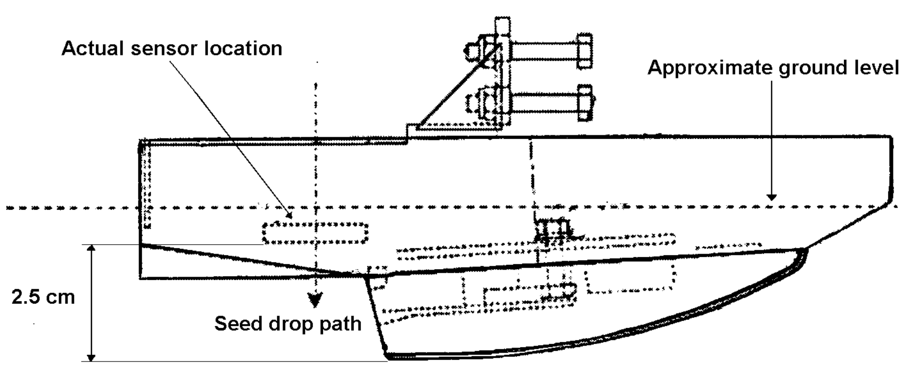

Figure 2. Runner−opener layout showing sensor location.

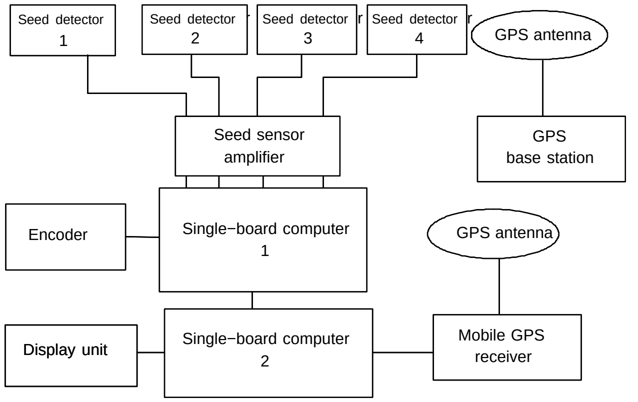

Figure 3. Schematic diagram of the planter instrumentation and data acquisition system.

planter's seed dropping performance through the display unit mounted in the tractor cab. Initially, a radar gun was included to measure planter travel speed. However, it was found that the radar speed sensor was not accurate enough for this purpose, especially at low speed. The radar gun was replaced with a wheel encoder that was capable of producing 256 pulses per revolution of the wheel. The encoder was mounted on the planter frame and was connected to the left planter wheel to measure its rotation. Figure 3 is a schematic diagram of the data acquisition system used in this study.

A permanent base station was installed in the field. It consisted of a punch mark on top of a machined metal rod embedded in concrete located near the experimental plots. A surveyed point at the nearby Davis airport was used to determine the exact location of the base station.

Data Acquisition Program

Two main GPS data strings (PJK and VTG) contained the data used in this study. The PJK string contained the UTC time, northing, easting, and GPS quality. The system used UTC time for both the GPS coordinates and the seed events. The northing and easting gave the global coordinates of the GPS receiver on the tractor. The GPS quality indicated the quality (RTK fixed, float, etc.) of the GPS data being recorded. The VTG string gave the velocity in units of knots and kph, although only speed in kph was recorded. A flowchart of the program is shown in figure 4.

Determination of Seed Location

An interpolation technique, which utilizes time tags, was used for determining GPS antenna locations during seed events. Let (X_i,Y_i), (X_j,Y_j), and (X_k,Y_k) be the RTK GPS positions (RTK−fixed) and let t_i, t_j, and t_k be the time tags corresponding to these RTK−fixed GPS positions, respectively. A linear regression line can be drawn through these three locations using the following model:

$$x_l = a\tau_l \tag{1}$$

$$y_l = b\tau_l \tag{2}$$

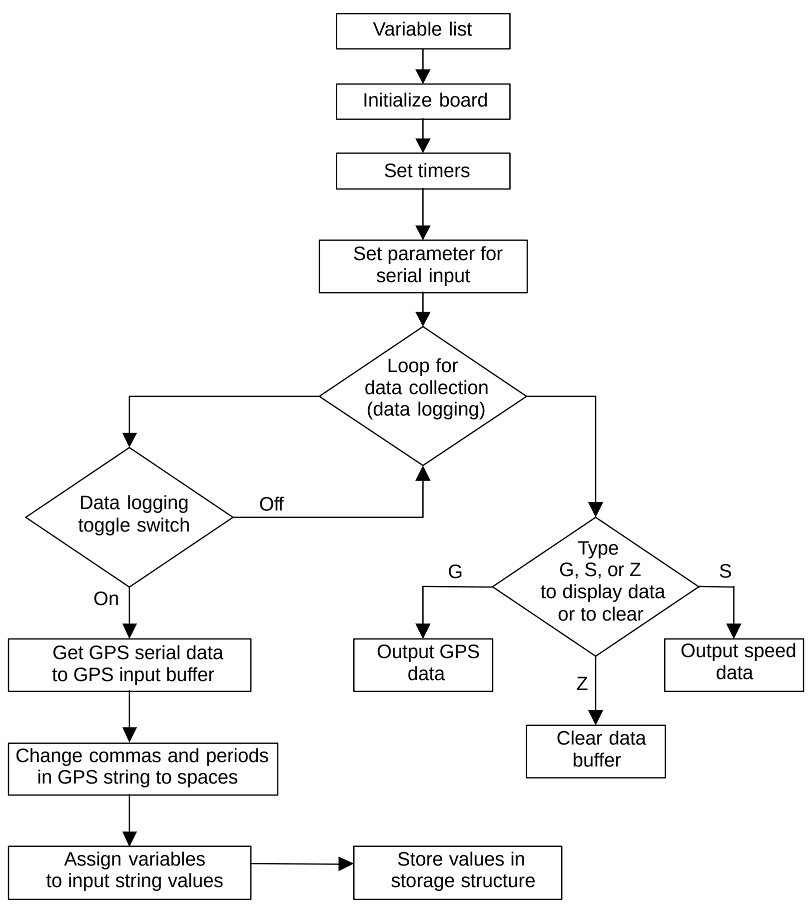

Figure 4. Flowchart for the data acquisition program.

$$v = \alpha N \text{ or } N = \beta v \tag{3}$$

where

$$x_l = X_l - \bar{X};\ \bar{X} = \frac{\sum X_l}{3}$$

$$y_l = Y_l - \bar{Y};\ \bar{Y} = \frac{\sum Y_l}{3}$$

$$\tau_l = t_l - \bar{t};\ \bar{t} = \frac{\sum t_l}{3}$$

subscript l = i, j, or k
Σ = sum over i, j, and k
a, b, α = regression parameters
β = $1/\alpha$
N = wheel rpm
v = forward speed of the planter (ms^{-1}).

Note that the regression parameters a and b represent velocities along northing and easting directions. The regression parameter β is related to α, which represents the instantaneous wheel calibration constant. The regression parameters a, b, and α can be determined by minimizing the sum of squared error (SSE), which is given by:

$$\text{SSE} = \sum (x_l - a\tau_l)^2 + \sum (y_l - b\tau_l)^2 + \sum (N_l - \beta\sqrt{a^2+b^2})^2 \tag{4}$$

Note that $v = \sqrt{a^2+b^2}$. The minimization of SSE is equivalent to taking partial derivatives of SSE with respect to a, b, and β and equating them to zero, i.e., $\frac{\partial \text{SSE}}{\partial a} = 0, \frac{\partial \text{SSE}}{\partial b} = 0, \text{and } \frac{\partial \text{SSE}}{\partial \beta} = 0.$ This process results in following equations for a, b, and β:

$$a = \frac{\sum x_l \tau_l}{\sum \tau_l^2} \tag{5}$$

$$b = \frac{\sum y_l \tau_l}{\sum \tau_l^2} \tag{6}$$

$$\beta = \frac{\sum N_l}{3\sqrt{a^2+b^2}} \tag{7}$$

Once a and b are known, positions (x_l, y_l) corresponding to any time tag t_l such that $t_i < t_l < t_k$, which represents a seed location, can be determined by equations 1 and 2. The regression parameter β, which is equal to $1/\alpha$, can provide some check on the accuracy. It may also be useful to locate (X_k,Y_k), if RTK GPS quality corresponding to t_k is not fixed. Moreover, $\tan(\phi) = b/a$ is a measure of the direction or heading in which the antenna is moving. This information is essential to determine the seed location from the antenna location.

Seed Location Based on GPS Antenna Location

Let XY (fig. 5) be a right−handed, global, Cartesian coordinate system that gives us the UTM coordinates of the RTK GPS antenna located at point O on the planter.

Let the UTM coordinates of the antenna be (X_0,Y_0). In addition, let X′Y′ be another coordinate system located at point O, which is parallel to the global coordinate system XY.

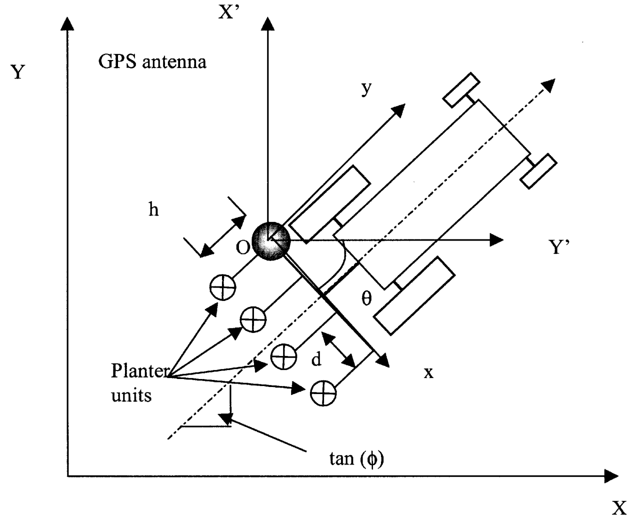

Figure 5. Locating of seeds from the antenna location using Eulerian transformation.

Moreover, let xy be a right−handed, local, Cartesian coordinate system such that its origin is at O and its y−axis is parallel to the direction of travel of the tractor. The heading of the tractor (ϕ) is the angle the direction of travel makes with the global X−axis. To locate the seeds in the global coordinate system (UTM coordinates), the coordinates of the planting units need to be determined. The coordinates of these units in the local coordinate system are ($-h$, 0), ($-h$, d), ($-h$, $2d$), and ($-h$, $3d$), respectively, for units 1, 2, 3, and 4. This local coordinate system is related to the X′Y′ coordinate system by a rotation angle (θ), which is related to the heading (ϕ). Once the rotation angle is known, the coordinates of the planting units can be determined by Eulerian transformation, as follows:

$$\begin{Bmatrix} X' \\ Y' \end{Bmatrix} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix} \begin{Bmatrix} x \\ y \end{Bmatrix} \tag{8}$$

where (x, y) is the coordinate of the seed in the local coordinate system and (X′,Y′) is the coordinate of the seed in the X′Y′ coordinate system. The coordinates of the seed in the global coordinate system is given by:

$$X = X_0 + X' \tag{9a}$$

$$Y = Y_0 + Y' \tag{9b}$$

where (X,Y) is the global or UTM coordinates of the seed. The relationship between rotation angle (θ) and heading (ϕ) depends on the particular quadrant in which the tractor is located and its travel direction. Equations 10a through 10d define the relationship:

$$\text{Both } v_x \text{ and } v_y \text{ are positive: } \theta = -(90 - \phi) \tag{10a}$$

$$\text{Both } v_x \text{ and } v_y \text{ are negative: } \theta = (90 + \phi) \tag{10b}$$

$$v_x > 0 \text{ and } v_y < 0\text{: } \theta = (90 - \phi) \tag{10c}$$

$$v_x < 0 \text{ and } v_y > 0\text{: } \theta = -(90 + \phi) \tag{10d}$$

where v_x (i.e., a) andv_y (i.e., b) are components of the velocity along the local coordinate system, xy.

A Visual Basic program that implements the above scheme to locate seeds was developed. The flowchart of the program is shown in figure 6.

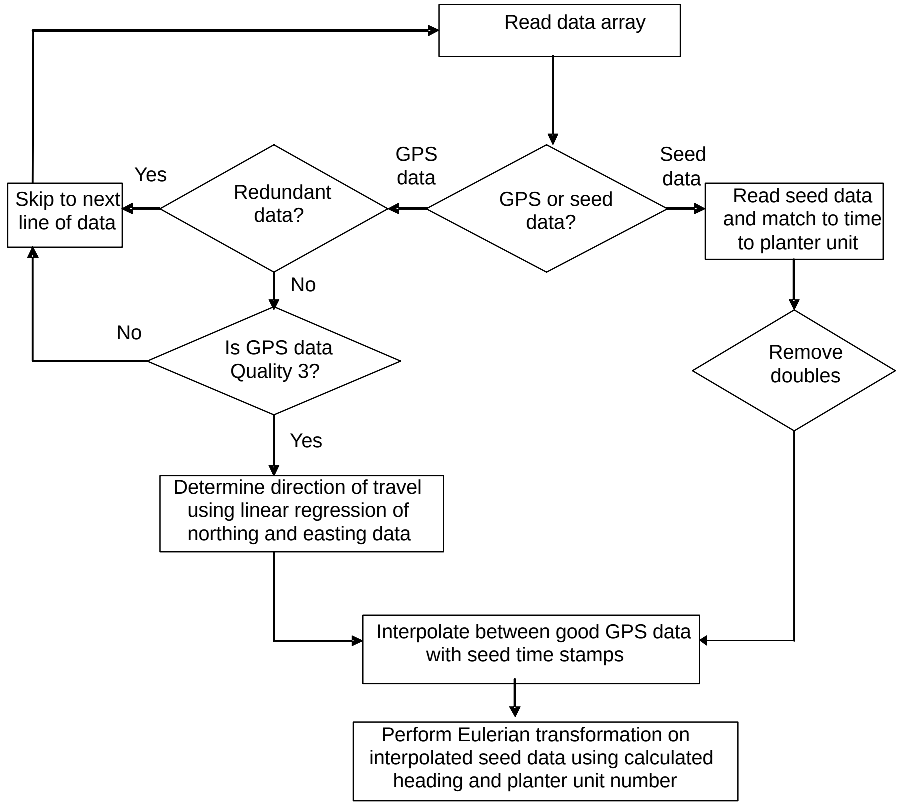

Figure 6. Flowchart of seed mapping program.

Field Experiments

Following the preliminary tests to make sure all components of the system were operational, field tests were conducted over two planting seasons to check the performance of the plant mapping system. In the first year, a 50 m (165 ft) long test plot was planted using the instrumented four−row planter. Corn seeds (hybrid: Pioneer 3162 R24) were planted at a depth of 5 cm (2 in.) and an operating speed of 3 kph (2 mph). In each row, 0.46 m (15 ft) sections were marked consecutively. Three of the eleven 4.6 m sections were selected at random for analysis. The location of each plant within these selected sections was measured using the Trimble RTK surveying equipment. Prior to the second year field tests, the sensitivity of the optical sensors was modified, by changing the sensitivity level on the optical sensor amplifier, such that particles of the size of a corn seed were detected as seeds whereas small clods and dust particles were ignored. In addition, the algorithm for determining the seed location was improved. In the second year, field tests were repeated in the same manner as the first year tests to evaluate the planter performance.

Results and Discussion

A summary of the field test results of this study is presented in table 1, and figure 7 is an example of a seed map. During the first year of experiments, a seed map accuracy of 0.043 to 0.053 m (1.7 to 2.1 in) with respect to the actual plant map was achieved. There was a need to correct the along−track error. It was hypothesized that if the true ground speed of the planter were known, it may be possible to minimize the along−track error using statistical techniques. It was found that the radar gun was not providing a sufficiently accurate speed measurement, especially at low ground speeds. Moreover, the velocity value of the VTG string that was output from the RTK GPS did not have enough accuracy at low ground speeds; therefore, it was decided to replace the radar gun with a wheel encoder, as mentioned earlier. However, subsequent trials in the second year indicated that as long as RTK GPS quality was fixed, centimeter accuracy was guaranteed. A new algorithm was developed that utilized only fixed GPS signals and continuously performed instantaneous ground wheel calibration, which could be used for prediction purposes if a fixed GPS signal was unavailable.

In evaluating the performance of the planter, two distinct cases were addressed:

- A seed was seen by the optical sensor, but no plant ever germinated in the vicinity of that site. This could be due to oversensitivity of the optical sensor, seed viability, and birds and/or rodents eating the seed. In general, roughly 10% of seeds never germinate due to these factors.
- A seed was not seen at a location, but a plant germinated there. This is due to the error in detecting seeds.

Table 1. Mean errors and standard deviation for all rows during plantings in two years of testing.

Planter Unit	Year 1 Mean Error (cm)	Year 1 Std. Dev. (cm)	Year 2 Mean Error (cm)	Year 2 Std. Dev. (cm)
1	4.56	4.2	3.84	2.09
2	4.39	3.1	3.16	2.18
3	4.99	4.8	2.92	1.98
4	5.27	5	2.91	1.66

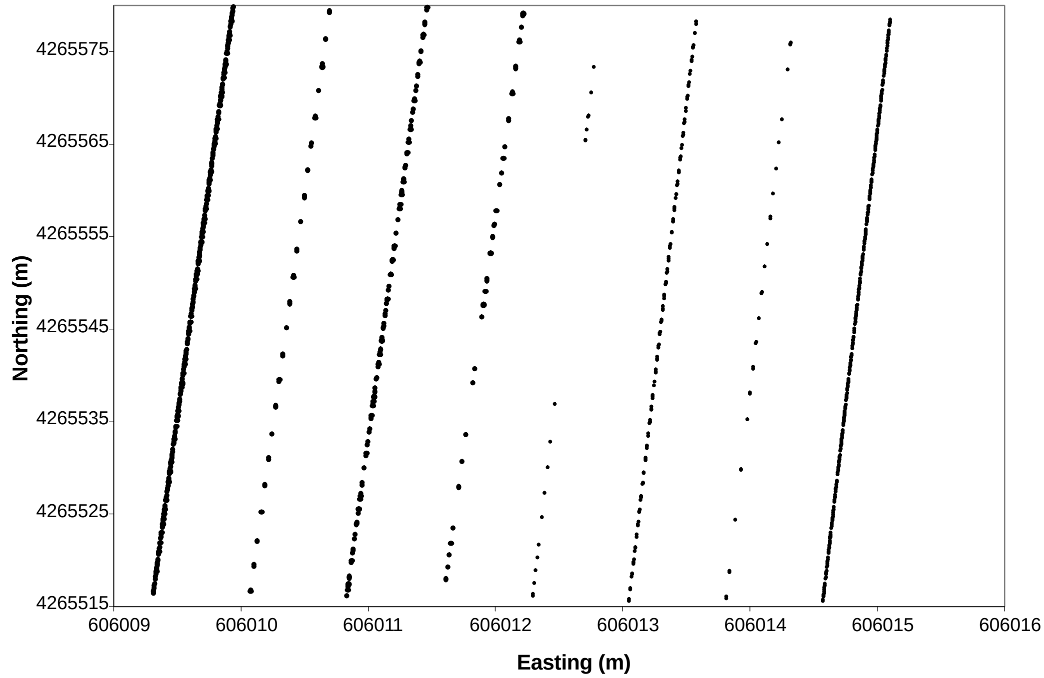

Figure 7. Sample seed map for a short segment of a field. The gaps in the seed map are intentionally made by blocking off various holes on the singulator plate to ensure correct measurement of germinated plants.

It is preferable to have a small amount of first type of error. This type of error, if not excessive, provides a certain degree of protection against mistaking a plant as a weed and killing it. However, it is preferable that the second type of error be negligible. A plant seen at a location near which no seeds were seen would be treated as a weed and eliminated. So, the second criterion was used as a measure of planter performance. In other words, we looked for the closest seed to a germinated plant and used this distance as a measure of our accuracy; the smaller this distance, the better the accuracy.

In the second year of testing, seed detection accuracy improved to a range of 3.0 to 3.8 cm (1.2 to 1.5 in.), and was considered very good taking into account the error due to the accuracy of RTK GPS and other factors that influence the seed placement and seed dynamics. This makes it possible to produce plant maps for use in subsequent cultivation.

Conclusions

Based on this study, the following conclusions were reached:

- We were able to successfully integrate a centimeter−accuracy RTK GPS system with a four−row Salvo 650 vacuum planter and map seeds as they were being planted.
- An algorithm was developed to convert time−tagged RTK GPS data into seed location data of individual planting units of the four−row planter.
- Field tests using this RTK GPS instrumented planter revealed that on an average, mapped seeds were within 3.4 cm of a germinated plant.

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