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I am submitting herewith a thesis written by Timothy Franklin Morrow entitled “Evaluation of DGPS Row Guidance Systems, Analyzing Operator Feedback Methods Based on Accuracy and Operator Insights.” I have examined the final electronic copy of this thesis for form and content and recommend its acceptance in partial fulfillment of the requirements for the degree of Master of Science, with a major in Biosystems Engineering Technology.

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**Evaluation of DGPS Row Guidance Systems, Analyzing Operator Feedback  
Methods Based on Accuracy and Operator Insights**

A Thesis  
Presented for the  
Master of Science  
Degree  
The University of Tennessee, Knoxville

Timothy Franklin Morrow  
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## DEDICATION

This thesis is dedicated to my parents

Mr. Charles W. Morrow

and

Mrs. Bonnie E. Morrow

With their hard work and dedication to their family and careers, they provided me with many wonderful things. They taught me to strive for excellence in all aspects of life. They showed me the endless possibilities that the world could hold, yet let me decide which possibilities the world held for me. They showed me that if a person has pride in the Lord, his family, and his name, then a person can and will overcome any endeavor.

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## ABSTRACT

The study analyzed operator feedback methods of four guidance systems used on agricultural spraying vehicles. One system was the traditional foam marker and the three others were GPS guidance systems, manufactured by Trimble, Satloc®, and Cultiva. Twenty-one drivers participated in this study and ran four tests over a 244 m course. An RTK GPS system provided horizontal center positioning data accurate to within a centimeter. Using the center positioning data, areas of overlap and skip were found using ArcView™ 3.2. In addition, positional error terms of maximum deviation, average maximum deviation, RMS, average, starting, and ending deviation were found. After completing the tests, drivers answered questions regarding the systems. The data set as a whole provided a means for determining differences between guidance systems, evaluating if effects of driver and system explained positional errors, and which systems did the drivers prefer.

Results of overlap and skip were analyzed to determine if differences existed between guidance systems, GPS guidance systems, speeds of high and low, and passes. Analyzing overlap for systems found that GPS systems differed from foam at the 0.05 alpha level, and that systems did not differ for skip. Mean values indicated that foam was higher than GPS guidance systems for both overlap and skip. GPS guidance systems did not differ for overlap and skip at the 0.05 alpha level. Mean values indicated that Cultiva had higher means followed by Satloc and Trimble respectively. Speeds of high and low did not differ for overlap and skip at the 0.05 alpha level. Plots of passes on a per driver

and system basis did not indicate that a learning curve was present. Mean values of speed indicated that high speeds had a greater mean errors than slow speeds.

Results of positional errors were analyzed to study if driver and system affected positional errors and passes. Examination of the data revealed that when found significant, driver explained less than 20 % of the variation. Pass analysis on a per system basis revealed that a learning curve was not evident for Trimble, Satloc®, and Cultiva.

Examination of the survey data revealed that drivers did not prefer one system to the other. Of the twenty-one drivers, seven preferred Trimble's lightbar, six preferred Satloc's lightbar, and eight preferred Cultiva's Marker™. However, drivers did prefer GPS guidance to foam. Fifteen drivers preferred GPS guidance to foam, while sixteen drivers felt that GPS guidance improved their accuracy.

Statistically, guidance systems only differed for overlap; however, mean values indicated that foam had higher mean error values associated with overlap and skip. This indicated that a driver's accuracy improved when using GPS guidance. Statistically, GPS systems did not differ; however, mean values indicated that drivers were less accurate using Marker™, which revealed drivers were more accurate using lightbars as opposed to using a graphical display. Statistically, speeds of high and low did not influence accuracy; however, mean values indicated that high speeds had greater mean errors than slow speeds, and a learning curve was not distinguishable between passes.

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# Chapter I

## Introduction

### Background and Statement of the Problem

A major problem U.S. and Tennessee producers face is the rising cost of agricultural chemicals and commercial fertilizer. Today, a growing number of producers rely on chemicals and fertilizers to obtain maximum yield from their crops. Producers constantly struggle with improving application methods to reduce cost associated with agricultural chemicals and fertilizers. According to the 1997 USDA census, United States producers spent over \$17.1 billion on commercial fertilizers and agricultural chemicals. Tennessee producers spent over \$2.5 billion on commercial fertilizers and agricultural chemicals (USDA, 1997). To say the least these figures are staggering, and in order for producers to realize a profit, chemical and fertilizer cost must be reduced. Palmer and Matheson (1988) reported that producers would see a 10 % decrease of input cost associated with chemicals and fertilizers if producers reduced areas of overlap. Using that report, United States producers would save over \$1.7 billion while producers in Tennessee would save over \$200 million on chemicals and fertilizers. The 10 % projected by Palmer and Matheson (1988) also applies to other cost factors such as fuel, time, labor, etc.; therefore a producer would see a substantial decrease in all cost associated with applying chemicals and fertilizers.

Along with the high cost associated with chemicals and fertilizers, producers must pay particular attention to environmental conditions for areas where chemicals are

applied. Generally, when producers apply chemicals or fertilizer they tend to overlap to make sure an area has had some exposure to the applied product. According to the USDA census of 1997, United States producers applied chemicals to over 100 million hectares, and Tennessee producers applied chemicals to over 1.3 million hectares. Palmer and Matheson (1988) reported that on the average, producers overlap 10 % of a swath width for each pass made. Using that value, US producers double covered over 11 million hectares with chemical. Not only were chemicals wasted, but a lot of soil also had over exposure to chemicals. Tennessee producers exposed over 100 thousand hectares with agricultural chemicals.

Due to the high cost associated with chemicals and fertilizers and the environmental concerns associated with over exposed areas to chemicals, producers are searching and implementing methods to improve application of chemicals and fertilizers. Fortunately, producers spraying chemicals and spreading fertilizers have had the benefit of foam marker systems and dyes to aid in application. Currently, with the aid of Global Positioning Systems (GPS), producers have access to lightbar guidance systems or graphical guidance systems that aid them in correctly applying chemicals and fertilizers. The word “correctly” refers to making a swath without overlapping a previous swath or skipping an area all together. Currently, there are several brands of lightbar and graphical guidance systems on the market, but information pertaining to which system is best in regards to ease of use, ability to aid a driver, cost, etc. is unknown.

Few researchers and manufacturers of guidance systems have reported the capabilities of lightbar and graphical guidance systems. Generally, these tests researched whether a lightbar had the potential to accurately guide an operator (Vetter, 1995; Vetter,

1996; Molin and Ruiz, 1999). Buick (1998) conducted a test to compare a lightbar performance with foam marker performance. These tests concluded that producers would benefit from a GPS lightbar guidance system.

### **Objectives**

The intention of this study was to conduct a comparison between three different Differential GPS (DGPS) guidance systems and a foam marker guidance system. Specifically, the purpose of this study was to conduct a product comparison test using three types of DGPS guidance systems and the industry standard, foam marker. The test used different speeds and drivers in combination with the different guidance systems to determine which method of guidance best suited producers. Specific objectives of the study included:

1. Use experienced agricultural equipment operators to, evaluate the accuracy, ease-of-use, and operator feed back method resulting from the minimization of overlap and skip applications using selected row-guidance systems in a parallel-swathing application.
2. Compare three commercially available DGPS-based row-guidance systems for parallel-swathing applications using the industry standard, foam marker, as the control for evaluating the DGPS guidance systems. Guidance systems were selected to represent the range of current technology and operator interfaces currently available.

## **Chapter II**

### **Review of Literature**

#### **Introduction**

Farmers spend countless hours operating agricultural vehicles. A decrease in time spent operating the vehicle would increase time for other farming tasks. A decrease in operating time and a reduction of both mental and physical stress would also benefit farmers. The development of autonomous and semi-autonomous vehicles has reduced the time and stress factor associated with operating an agricultural vehicle. This development has also increased the precision of spraying and planting tasks associated with agricultural production.

An autonomous vehicle is an automatically controlled vehicle that uses a combination of a guidance sensor or sensors and a steering controller for automation. Computational algorithms produce correction information for the steering controller. Usually, the steering controller is an electrohydraulic valve or some other device used to control the power steering mechanism of the vehicle.

A semi-autonomous vehicle uses a guidance sensor and provides the operator with correct heading information for a desired course. A visual indicator provides heading information to the driver. Indicators range from a monitor type display, to light emitting diodes, or a foam marker indicator.

Various researchers have documented historical overviews of agricultural guidance systems. Tillet (1991) reported the types of guidance sensors available up to

1991. Reid et al. (2000) and Wilson (2000) published reviews covering the guidance systems history from its development to the present. Reid (1998a) reported the advancements of autonomous guidance since the early 1990s to 1998. Reid (1998b) also published the components of an autonomous guidance system using the latest technology of machine vision or GPS sensors and discussed the components required for an autonomous agricultural vehicle.

This review focused on publications that used a testing methodology similar to the testing methodology of this study. The sections on non-GPS and GPS positioning systems report various sensing and testing methods used for controlling and testing either an autonomous or a semi-autonomous system. The lightbar section reports the complete testing methodology used by researchers for lightbar guidance systems.

### **Non-GPS Positioning Systems**

Researchers frequently use non-GPS sensors as positioning instruments. The reason for the sensors popularity is that non-GPS sensors were available for use on agricultural vehicles long before GPS type sensors entered the agricultural market place. Researchers used a variety of sensors for developing algorithms to control steering mechanism or for providing steering information to the operator. Many researchers still rely on non-GPS sensors for guiding agricultural vehicles. Generally, non-GPS positioning sensors are more common on agricultural vehicles primarily used in row crop production. The sensors detect proper vehicle heading by sensing vehicle heading with respect to the row crop. Despite the accuracy, the system has not had a major impact on agricultural production.

This review reports the findings and testing methodology used for researching non-GPS sensors on agricultural vehicles. The sensors' use and function is not a concern, and a paper regarding information about the latest sensors used for agriculture is available (Hague et al., 2000).

Primarily, cameras are the most common non-GPS sensor used for guiding agricultural vehicles. Although sunlight affects image quality, the camera accurately provides guidance information for autonomous and semi-autonomous systems. As noted previously, researchers use these sensors primarily for row crop applications. The camera easily detects vehicle heading with respect to the row. Von Qualen et al. (1991) and Klassen et al. (1993) used a camera as the sole sensor when trying to develop algorithms for an autonomous vehicle. Their test concentrated on a camera detecting foam droplets left by a foam marker system, a demarcation line between tilled and untilled soil, or standing and cut crop. The video camera provided the basis for image analysis and eventually processed the images and provided correct vehicle heading information. The simulation testing performed by Von Qualen et al. (1991) used styrofoam balls for foam and reported offset errors of 7.3 mm with foam ball detection and 11.3 cm with no foam ball detection. Klassen et al. (1993) developed a working algorithm to control the steering mechanism using their vision-based guidance sensor.

Li et al. (1994) developed a steering controller to complement the image analysis performed by Klassen et al. (1993). They studied the effects of implement width, image processing speed, and travel speed on the guidance systems accuracy through a simulated testing environment. They reported that travel speed did not significantly affect the guidance system at speeds ranging from 1.39 m/s and 4.17 m/s. Another study that used

a camera was conducted by Debain et al. (2000). They used a camera as the only sensor to guide a combine harvester to an accuracy better than 10 cm in real-time conditions on a slope of 20%. Their camera also detected crop edge and provided information for algorithms and control laws used for determining correct vehicle heading. Billingsley and Schoenfisch (1997) used a camera as the sensing system for their autonomous vehicle as well. The system studied several crop rows at one time and developed vehicle-heading information from multiple rows instead of one. A significant point from their project was that they provided farmers with guidance systems for six weeks to determine how the system performed under real conditions. Farmers reported that the system was very accurate and reliable, and the system allowed operators to concentrate on other tasks in the cab and not just on driving. In simulation testing, Billingsley and Schoenfisch (1997) reported accuracy measurements of 20 mm, which confirmed the farmers' reports.

To increase the accuracy of vision-based sensors, researchers decided to add other sensors to the vision-based systems. Combining a vision-based sensor with an odometer proved beneficial for researchers at the Silsoe Research Institute. The odometer measured different speeds between two drive wheels, which provided direction information by recording wheel speeds. If the wheels were turning at different speeds, then the test vehicle would turn towards the slower turning wheel. Using a Kalman filter, the odometer information and vision analysis information provided correct heading information for the test vehicle. The team reported a standard deviation of vehicle heading with respect to the row of 20 mm. However, this research used a small plot vehicle and not a production size agricultural machine (Marchant et al., 1997).

Few researchers deviated from using a camera as the sensor for an autonomous vehicle. However, some researchers worked on vehicle guidance with other types of sensors. Chateau et al. (2000) used a laser sensor for guidance information on a windrow harvester and a combine harvester. The same laser provided guidance information for both pieces of equipment; however, laser location on the harvester changed with respect to the head type. For the combine, positioning the laser at one end of the cutter head allowed for crop edge detection, while moving the laser to the cab allowed for windrow detection. The study encountered significant problems with dust, which affected the laser performance. Researchers concluded that a new approach was necessary for accurate vehicle guidance because of dust interference. A proposed idea of using a new laser combined with a video camera resulted from the testing.

Researchers at Iowa State University took a different approach for guiding their autonomous vehicle on a predetermined straight path using a non-GPS sensor. A ground-based spatial positioning system, AGNAV, manufactured by D & N Micro Products, provided X, Y coordinates for the test vehicle. Using the kinematic behavior of the tractor, researchers developed an algorithm for determining steering angle. Reduction of lateral position error occurred in real field conditions. The study concluded with a root mean square error of less than 5 cm at a constant travel speed. Processing speed and better measurements of yaw angle hampered guidance system performance (Choi et al., 1990).

With the introduction of GPS, non-GPS type guidance systems for agriculture equipment are slowly disappearing. However, some researchers still use non-GPS sensors to provide guidance information for autonomous and semi-autonomous systems.

Particular interest was paid to speed, test course, and drivers. These studies did not directly relate because of the lack of GPS and foam markers, but the studies did use speed and a course for testing purposes, which did relate.

### **GPS Positioning Systems**

Researchers have started using GPS technology as the position sensor in an effort to develop a fully autonomous agricultural vehicle. GPS guidance is an obvious choice for obtaining positioning information necessary for precision farming. GPS guidance decreases operation time for any precision farming task, increases guidance accuracy, and is reliable.

Larsen et al. (1988) and Auernhammer et al. (1991) realized the potential of GPS to guide agricultural vehicles. Larsen et al. (1988) recorded vehicle positioning relative to a Geographic Information System (GIS), and Auernhammer et al. (1991) reported the environmental benefits of using GPS for positioning guidance. Both studies concluded that GPS had a future in field navigation. Larsen et al. (1994) confirmed previous results by using carrier-phase GPS and P-code GPS to record and process positioning information necessary for guiding an autonomous vehicle. Larsen et al. (1994) also published the components necessary to construct an autonomous vehicle. Their publication provided a basis for developing an autonomous vehicle using GPS as the positioning sensor.

Many researchers have used different forms of GPS as the positioning sensor for the guidance of their autonomous and semi-autonomous vehicles. One form of GPS guidance, DGPS, is common because of its availability. Because DGPS is less expensive

than RTK-GPS and easier to use, researchers developed an autonomous system using DGPS. Ramalingam et al. (2000) used DGPS as the only position sensor for an autonomous vehicle. Using components already developed for DGPS guidance (lightbar), Ramalingam et al. (2000) and the SATLOC Corporation developed a steering controller that used the correction information produced by the lightbar to steer an agricultural tractor on a parallel pattern. Ramalingam et al. (2000) reported the maximum deviation for cross-track error was 0.6 m.

Another form of GPS commonly used to provide positioning information for autonomous and semi-autonomous vehicles is RTK-GPS. RTK-GPS requires a base station to provide correction information necessary for centimeter level accuracy. Centimeter accuracy is ideal for guiding a fully autonomous system because centimeter accuracy removes concerns regarding vehicle position. The centimeter accuracy makes this particular form of GPS popular among engineers and researchers. Stombaugh et al. (1999) used RTK-GPS to guide a fully autonomous vehicle. The test studied the effectiveness of a steering mechanism in combination with RTK-GPS to guide a test vehicle at high field speeds on parallel patterns. In addition, the test studied accuracy levels produced by GPS when the antenna was on the tractor cab versus the hood. Moving the antenna over the front axel proved to be more accurate than when the antenna was on the cab. Findings revealed that the use of RTK-GPS and a steering controller could provide guidance of an agricultural tractor within 16 cm of a desired path (Stombaugh et al., 1999).

Bell (2000) reported Stanford University results of their fully autonomous tractor using carrier-phase GPS. The test consisted of operating the vehicle through a course

utilizing various patterns (spirals, arcs, curves, and straight) with multiple passes. Not only did Stanford do multiple tests, but they also tested the vehicle pulling an implement. Implement effects did not significantly affect the steering controller. Results stated that carrier-phase GPS could effectively guide a tractor pulling an implement to a 0 cm mean tracking error and a 4-6 cm standard deviation in tracking error.

### **GPS Plus Additional Sensors**

Calculating vehicle heading using a series of GPS points involves differentiation. This calculation introduces error into a system and this error comes from the time series of GPS points (Benson et al., 1998). Instead of making the calculation with time, using a sensor that produces accurate position or direction information without a time variable is ideal (Benson et al., 1998). By combining position and direction sensors with GPS, this error is reduced and guidance systems are more accurate (Benson et al., 1998). There are several different types of position and direction sensors used in conjunction with GPS positioning.

Benson et al. (1998) used a position estimator and a geomagnetic direction sensor combined with GPS to provide steering correction information for a steering controlled guidance system. The test separated the guidance sensors for comparison. Testing included a GPS sensor, GPS sensor with a position estimator, and GPS plus the geomagnetic direction sensor on a straight path at 1.12 m/s. Results revealed that GPS guidance with the addition of the geomagnetic sensor produced less than 1 cm tracking error on a straight path (Benson et al., 1998). Other researchers took this same approach except they used a combination of a vision sensor and a fiber optic gyroscope with RTK-GPS to guide a fully autonomous system. Testing focused on guiding an agricultural

tractor through crop rows and concluded that the combination of a vision sensor, fiber optic gyroscope, and RTK-GPS was satisfactory for guiding a tractor through desired paths (Zhang et al., 1999).

For cost considerations, ideal guidance systems keep the driver involved in the operation (Zhou et al., 2000). The driver's presence requires researchers to develop better semi-autonomous systems. Zhou et al. (2000) developed a guidance system for a sprayer that used GPS and optical encoders as guidance sensors to replace the foam marker system. The system allowed a driver to steer the vehicle to a pre-planned course by viewing a monitor inside the sprayer. Researchers used a camera to track vehicle heading during testing. After multiple tests of the system, Zhou et al. (2000) concluded the lateral error on straight lines to be 300 mm.

In summary, these studies focused on the ability of GPS to guide various autonomous and semi-autonomous systems. Particular interest was paid to testing methodology of test course and speeds when track error was concerned, as well as different operator feedback methods of semi-autonomous systems. Findings revealed that a GPS-based positioning system was capable of providing the necessary information for a steering controller used on autonomous systems, and the guidance sensor was capable of providing position information for precise vehicle guidance.

### **Lightbars**

Several studies have documented the capabilities of a lightbar guidance system to aid an operator in performing an application task. These studies used a testing methodology similar to the methodology used for this study. The testing methodology

consisted of course, drivers, speeds, and error calculation. These studies provided an idea of what to expect from the test results.

The lightbar is the simplest example of a semi-autonomous system. Pilots in the early 1990s reported that the lightbar system's performance was outstanding for aerial applications. Devising a testing method to confirm pilots' reports was difficult. Vetter (1996) conducted a test to confirm the accuracy of aided guidance systems for aerial application of chemicals and fertilizer. The test used a SATLOC AirStar DGPS receiver and lightbar guidance system. Cameras at the end of each pass were equipped with a cross hair generator. The cameras were set at a height of 1 m from the ground, which was the spraying height flown by the pilot. Centering the cross hair to bisect a pass allowed for determination of cross-track error. If the pilot followed the desired heading, then the plane centerline would constantly follow the cross hairs vertical line. Adjacent vertical lines generated by the cross hair generator determined distance of cross-track error. There were 700 lines generated on the monitor with 1.3 mm per line of horizontal resolution. Vetter (1996) concluded that the overall standard deviation of the aircraft from the centerline was 0.38 m.

Because of rising costs of aerial application and the decline of pilots, the lightbar has become prevalent in agricultural production equipment. The lightbar system is a suitable replacement for a foam marker system. Although the lightbar systems introduction in ground-based applications is recent, Vetter tested the idea in 1995. Vetter's aerial applicator research set the protocol for the ground applicator test. The test used the same methodology from the aerial applicator test for conducting a ground applicator test. Vetter (1995) used the same principal to determine cross track error

associated with each pass and concluded with an overall standard deviation from the centerline of 0.42 m.

Vetter's (1995) results proved that the system was suitable for aerial applications and was capable of aiding the driver for ground-based applications as well. Vetter's (1995) test, however, did not prove that the lightbar system was better than the existing foam marker system for ground-based spraying applications. Buick (1998) reported the necessary results for comparing a foam marker performance to a lightbar performance. She recorded center-positioning points with RTK GPS for both the foam marker and DGPS tests. Test course consisted of nine swaths plus the additional A-B swath. Buick (1998) reported overlap and skip as a percentage of the swath area for each pair of passes and for the total area sprayed. Buick and Lange (2000) published the methodology used to determine overlap and skip for the test. Buick (1998) concluded that DGPS guidance showed an average overlap of 1.00% and an average skip of 1.46%, while foam marker guidance concluded with an average overlap of 2.04% and an average skip of 0.35%.

The previous research reported that a lightbar guidance system properly aided the operator in aerial and ground-based spraying applications. Ground-based spreading applications would benefit greatly from the aid of a lightbar guidance system. Molin and Ruiz (1999) realized the potential that a lightbar guidance system would have for ground-based spreading applications. The test objective was to determine the quality of a lightbar guidance system in a ground-based spreading application by comparing a lightbar guidance system and no guidance system. The methodology for determining the tractor track error consisted of a disk marker mounted to the three-point hitch. Tests consisted of an A-B line plus three parallel passes for five drivers at two speeds. The

horizontal distance between furrows left by the disk marker determined tractor track error. Measurements taken every 10 m on the 200 m passes allowed researchers to determine track error. A theodolite established heading lines for each pass. Molin and Ruiz (1999) concluded that the lightbar guidance system had a deviation less than 2.50 m 90% of the time for 2.20 m/s and 1.75 m 90% of the time at 3.75 m/s.

In summary, these studies concluded that the lightbar guidance system would enhance any method of applying pesticides, herbicides, or fertilizer. Producers are confirming the published results in real spraying and spreading situations. Morgan (2000) and Russnogle (2000) reported producers' satisfaction with the lightbar's ability to provide guidance for their spraying and spreading requirements. Producers commented on the reduction of mental stress associated with spraying and spreading applications (Morgan, 2000; Russnogle, 2000). These results show promise for the lightbar guidance system.

## Chapter III

### Materials and Methods

#### Materials

##### Guidance Units

The initial objective was to compare a single lightbar guidance system (Trimble's *AgGPS*® 21 Lightbar) to a foam marker system on a contour pattern at three different speeds. Preliminary testing found that comparing one lightbar with a foam marker might not provide results on which system was better suited for guiding operators in spraying applications. Reasons for that theory was that more than one guidance system was commercially available for producers, and another guidance system might be better suited for guiding operators in spraying applications rather than a single lightbar. In addition, research revealed that no studies compared different operator feedback methods to aid a driver on a straight-line pattern. With preliminary testing and additional information on the research status of guidance systems, a decision was made to acquire additional guidance units and conduct a comparison of different operator feedback methods using three commercially-available row-guidance systems and the industry standard, foam marker. The additional units had to be universal, in that the unit would work with an external DGPS receiver. The reason for using a single receiver was to eliminate variability associated with different receivers. In addition, the new units had to have operator feedback features that Trimble's *AgGPS*® 21 lightbar did not. With this

selection criteria, a Satloc® LiteStar lightbar system and a Cultiva Marker™ graphical display system was acquired. The LiteStar differs from Trimble in that the unit uses two rows of LEDs to provide an operator with feedback information. One row provides course deviation, while the second row provides heading information. Marker™ differs from Trimble and LiteStar in that the unit provides operator feedback information via a graphical display. Details on the different operator feedback methods are discussed in each guidance unit's section. Table 3.1 provides features and specifications for the guidance systems.

### ***Trimble***

A standard *AgGPS®* parallel swathing option package from Trimble Navigation Limited is equipped with an *AgGPS®* 21 lightbar, *AgGPS®* parallel swathing option cable, remote control keypad, *AgGPS®* parallel swathing option operation manual, and audible alarm with baffle. This unit is for interior use and mounts to the ceiling, dash, or window of a vehicle. An *AgGPS®* 21 lightbar weighs 0.45 kg and has dimensions of 23 cm W x 7.5 cm D x 6.4 cm H (with mounting bracket). An *AgGPS®* 21 lightbar requires a supply voltage between 9 to 36 volts direct current (VDC) and an operating temperature range of -20 to 65 °C. The casing consists of cast aluminum and a polycarbonate non-scratch lens, which is dust proof, splash resistant, and shock resistant. The unit provides operator feedback using a single row of LEDs. The LEDs indicate vehicle deviation from desired centerline relaying directional information to the operator for course correction. Figure 3.1 displays the *AgGPS®* 21 Lightbar.

**Table 3.1. Features and specifications of the guidance units used for evaluation.**

	<b>Trimble</b>	<b>Satloc®</b>	<b>Cultiva</b>
<b>Unit Name</b>	AgGPS® 21 Lightbar	LiteStar	Marker™
<b>Guidance Indicators</b>	Single Row LEDs	Double Row LEDs	Graphical
<b>DGPS Receiver Output</b>	LBAR (unique for Trimble lightbar)	NMEA 0183	NMEA 0183
<b>NEMA GPS Strings</b>	LBAR	GGA, VTG	GGA
<b>Baud Rate</b>	38400	9600	9600
<b>Up Date Rate</b>	5 Hz	5 Hz	5 Hz
<b>Display Type</b>	Lightbar	Lightbar	Graphical
<b>Driver Information Display</b>	LCD	LCD	Graphical
<b>Contour Swathing</b>	Yes	Yes	No
<b>Multiple Guidance Patterns</b>	Yes	Yes	No
<b>Capable of Calculating Field Area</b>	Yes	Yes	Yes
<b>Capable of Storing Field Data</b>	No	No	Yes
<b>Capable of Guiding to a Recorded Point</b>	Yes	Yes	Yes



**Figure 3.1. Trimble *AgGPS@21* lightbar equipped with a single row of LED's to provide guidance and correction information to the operator.**

### ***Satloc***

Satloc Inc. in Scottsdale, Arizona manufactures the *LiteStar Ground Application*. The system is equipped with a *LiteStar* display unit, control console, owner's manual, and mounting brackets. Satloc designed the *LiteStar* for external mounting. The display unit consists of a lightbar / central processing unit (CPU) which weighs approximately 5 kg and has dimensions of 35 cm x 5 cm x 17 cm. The CPU is a 386 processor operating at 33 MHz with DR. DOS operating system. *LiteStar* requires a supply voltage of 10 to 30 VDC and operates in various temperatures because of the unit's external design. The housing consists of aluminum and a protective lens. The unit provides operator feed back using a double row of LEDs. The top row indicates vehicle deviation from a desired centerline relaying the direction an operator needs to steer for course correction. The bottom row is a heading indicator. These LEDs indicate what direction the nose of the vehicle is heading in relation to the desired path. Figure 3.2 displays Satloc's® *LiteStar*.



**Figure 3.2. Satloc LiteStar equipped with double row LED's and 7-segement displays to provide guidance and operation information to the operator.**

### ***Cultiva***

Cultiva Electronics Inc. of Beloeil, Qc / Calgary, Alt, Canada manufactures the Marker™ guidance system. Cultiva's Marker™ system includes the Marker™ (course deviation indicator or CDI), processor (guidance control module or GCM), and installation kit (cables, mounting brackets, etc.). Marker™ mounts to a vehicle's dash, has dimensions of 23 cm x 20 cm x 3.8 cm, and weighs 1 kg. Marker™ has a 21.5 cm scratch resistant anti-glare LCD screen, which has a dust proof, splash and shock resistant enclosure. The GCM provides power to the Marker™. The GCM weighs 1 kg and has dimensions of 21.5 cm x 17.5 cm x 11.5 cm and a dust proof, splash and shock resistant enclosure. Marker™ uses a 133 mHz 586 processor for quick system configuration and setup. Marker™ requires a supply voltage of 9 to 18 VDC and both Marker™, and the GCM can operate in a temperature range of -10 to +50 °C. Marker™ provides operator feed back using a graphical display. Two lines on the display indicate deviation from the centerline and relay directional information to the operator for course correction. Figure 3.3 is a photograph of the Cultiva Marker™ display.



**Figure 3.3. Cultiva Marker™ equipped with a graphical display to provide guidance information to the operator.**

### **RTK Unit**

From the onset of this project, the error associated with DGPS was a concern. Error occurs when the time interval (the time for a signal to travel from a satellite to a receiver) increases due to environmental factors such as ionospheric and tropospheric conditions, signal obstructions, multipathing, and radio interference. DGPS receivers used in agricultural applications typically have sub-meter accuracy. Since the main objective was to evaluate operator responses to the guidance systems, an *AgGPS*® 214 Real Time Kinematic (RTK) receiver and base station from Trimble Navigation Limited was used to provide position signals for the guidance units. The *AgGPS*® 214 provides positioning information with centimeter accuracy by applying carrier phase signal processing. The survey grade receiver requires an on-site base station that is located over a reference point and transmits satellite timing information via radio link to a rover receiver (*AgGPS*® 214) placed in a vehicle or, in this case, a sprayer. This centimeter level accuracy removed the concerns associated with DGPS error and with biasing one

guidance system over the other due to errors commonly associated with code-based receivers.

Trimble designed the *AgGPS*® 214 receiver for the harsh conditions (dust, cold, heat, and vibration) associated with precision agricultural practices. An *AgGPS*® 214 is a dual frequency RTK receiver equipped with three RS-232 ports. Design of the *AgGPS*® 214 is similar to the *AgGPS*® receiver family design. The unit weighs 1 kg and has dimensions of 14.5 cm W x 23.9 cm D x 5.1 cm H. An *AgGPS*® 214 requires a supply voltage of 12 to 24 VDC and operates in a temperature range from -20 to + 60°C. The *AgGPS*® 214 receiver utilizes a 33 cm D x 7.2 cm H dual frequency antenna that weighs 1.7 kg and operates in a temperature range of -40 to +70 °C. The receiver has 9 L1 channels and 9 L2 channels with a standard update rate of 10 Hz and uses Compact Measurement Record (CMR) or Radio Technical Commission for Maritime services (RTCM) correction input. The unit outputs numerous NMEA strings with a carrier phase low latency positioning mode accuracy of 2-cm horizontal and 3-cm vertical and has automatic on-the-fly (OTF) initialization capabilities.

An *AgGPS*® 214 receiver provides position information to within a centimeter when a base station linked via radio to the *AgGPS*® 214 provides corrected position information. The base station used with the *AgGPS*® 214 is a Trimble MS750 dual frequency receiver. The base station has the same physical and power characteristics as the *AgGPS*® 214 receiver. This base station has 9 channel tracking capabilities of L1 C/A code and L1/L2 full cycle carrier. Signal processing uses Supertrak™ Multibit Technology and Everest™ Multipath Suppression to provide maximum tracking for low quality satellite singles.

Communication between a base station and rover receiver is essential for RTK surveying. The process of sending real time corrections to a rover receiver requires the use of a wireless data link. This particular RTK setup uses Trimble TrimTalk-900™ radio modems. One modem connects to the base station and the other connects to the rover receiver. Both radio modems are 14 cm W x 19 cm D x 7 cm H and weigh 1 kg. These modems require a supply voltage of 10 to 35 VDC and have an operating temperature range of -20 to +55 °C. An aluminum housing fully seals the radios. The base uses a 7-dB antenna that is 125-cm L x 2.5-cm D and weighs 2 kg, while the rover unit uses a 5-dB antenna that is 84-cm L and weighs 0.45 kg. Each radio utilizes 7-channel capabilities in the 902 – 928 MHz frequency band operating with a maximum output power of 1 watt.

### **Drivers and Site Selection**

Experienced operators were selected to participate in the study. Prior experience with guidance systems was not a requirement. In fact, if an individual expressed an interest in acquiring information on guidance systems, then they were allowed to participate. In addition to conducting research, a service was provided to producers who expressed an interest in guidance systems.

Driver selection was coordinated with the assistance of an extension representative to ask individuals to participate in the test. Drivers varied in age, experience, and knowledge of guidance systems. The majority of the drivers were private producers; however, some were custom applicators for retail suppliers (Southern

States, Miles Farm Supply, and The University of Kentucky). Test sites were selected where producers expressed an interest in using row guidance systems.

## **Sprayers**

With set-up time and running time being a concern, a decision was made to use a common sprayer for all operators at a given site. Self propelled sprayers were selected that had a minimal learning curve for experienced drivers. Sprayers were equipped with metallic hoods for magnetically mounting Satlocs lightbar, minimum of an 18.3-m boom, and a working foam marker system. Meeting those requirements was not difficult and two family-owned operations provided sprayers for this project. The first six drivers operated a John Deere 6500 sprayer, provided by Woodall farms in Franklin County, Tennessee. This sprayer has a standard enclosed cab, utilizes a 70-kW engine, and has an 18.3-m boom. The remaining drivers operated an AgChem RoGator 854, provided by Peterson Farms in Marion County, Kentucky. This sprayer has a roomy standard enclosed cab, utilizes a 149-kW engine, and has a 24.4-m boom.

## **Methods**

### **Testing Criteria**

As previously stated, the initial goal of this study was to compare a foam marker system to a lightbar system on a contour pattern at three different speeds. Due to time constraints and the lightbar's inability to adequately guide on a contour pattern, the decision was made to modify the test and make comparisons with parallel passes.

Devising a testing criteria for meeting these requirements consisted of determining a course length, operating speeds, number of passes, and randomization method for pairing the different drivers with speeds and the guidance systems.

### ***Course Length***

Farmers report that one drawback to using a foam marker system is that as course length increases; the foam has a tendency to disappear. Therefore, the course had to be short enough so the foam would not disappear between passes. However, the course length needed to be long enough to test the operator feedback methods of the different DGPS guidance systems. In addition, finding a field long, wide enough, in Tennessee proved rather difficult during preliminary testing. With those restrictions in mind, a course length of 244 m (800 ft) would properly test the guidance systems operator feedback method and still allow a foam marker to guide the operator near the end of a run.

### ***Speed***

When applying either chemicals or fertilizer, speed of application is an integral factor in the application rate of a product. Similarly, speed contributes to a guidance system's performance because a system has to be capable of providing accurate correction information to the operator at high field speeds. With foam marker systems, the faster a vehicle travels, the more distance exists between each "blob" of foam. This increase in distance usually increases error because the operator has fewer "blobs" of foam to follow and less time to react to course deviation. The same is true for DGPS guidance systems. The systems have to be capable of relaying correction information to the drivers so the driver can stay on course when traveling at high field speeds. To make

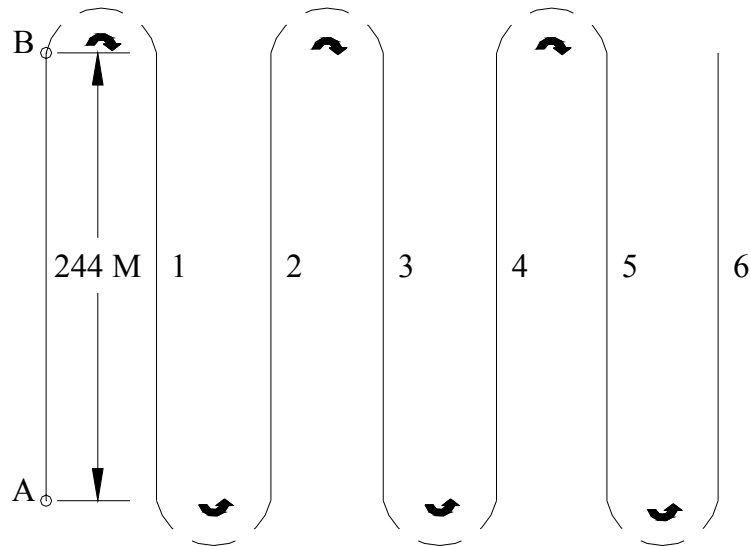
the testing as realistic as possible, the use of common application speeds was desirable. However, defining appropriate operating speeds, prior to test setup, was impractical since this speed is dependent on field surface conditions and test vehicle suspension. Therefore, speeds were defined as high and low and actual speeds were determined at each test site.

### ***Course Layout***

The course was laid out to evaluate each driver's learning curve for the different operator feedback methods. It is hypothesized, that as an operator learns a system, the error of overlap and skip should decrease with the later passes. One limiting factor to the course layout was field width constraints. A sprayer equipped with a ninety-foot boom would cover a number of acres rather quickly. With that restriction, the decision was made to make an initial reference pass (AB pass) and six sequential passes. These passes defined the course layout for testing if a learning curve was present for the different operator feedback methods. Figure 3.4 illustrates the course layout.

### ***Randomization Method***

Speeds and guidance units were randomly assigned to each driver. This randomization placed high statistical power on the guidance units and not on the speeds and drivers. More farmers use foam systems than DGPS systems, thus foam markers were considered the industry standard and used as the control group. The control group consisted of one foam marker test at a slow and high speed. Each driver would run the control group and two or the three DGPS guidance systems. To obtain the desired high statistical power, as many drivers as possible would need to participate in the study.



**Figure 3.4. Course layout illustrating the number of passes and distance between A and B.**

Thus, eighteen drivers were selected to participate in the study, which produced the desired high statistical power for the guidance units.

With the number of restrictions placed on this study, computer randomization was not easily possible. Therefore, driver and guidance system combinations were assigned using “drawing-out-of-a-hat” technique. Each driver was assigned four tests, which consisted of foam marker slow, foam marker fast, guidance unit slow, and guidance unit fast. Testing order consisted of all possible combinations of four (A, B, C, D), which yielded 24 possible combinations of four to draw from. Foam marker slow and fast corresponded to letters A and B respectively, while guidance unit slow and fast corresponded to letters C and D respectively. GPS unit/speed combination consisted of all possible combinations of three (1,2,3) repeated six times, which yielded 18 possible combinations of three to draw from. Trimble’s lightbar corresponded to number 1, Satloc’s Litestar to number 2, and Cultiva’s Marker™ to number 3. Assigning the

guidance unit combinations to the combinations of four simplified this randomization technique.

Selection method consisted of the following steps:

- Select a combination from the guidance units, and then draw a combination from the testing order.
- Join the two combinations and record the testing order for a driver.
- Place the testing order combination back in the “hat”, but do not replace the guidance unit combination.

This method of randomization placed the desired high statistical power on the guidance units.

After completing a test with six drivers, a decision was made to alter the test setup. Instead of running two foam marker tests at a fast and slow speed and two of the three guidance units at a fast and slow speed, it was decided that running three guidance units and one foam marker test at random speeds would provide more useful information for producers and manufacturers. This new testing criteria still kept the desired high statistical power on the guidance units. Randomization of the first six drivers followed the method previously stated, while the last twelve followed a new randomization technique.

Removing the restrictions of having each driver run two foam marker tests and forcing fast and slow speeds for the foam marker and guidance units, computer randomization was possible. The method of randomization consisted of generating random numbers and assigning a condition to each number. Research Randomizer, a web site specifically designed to generate random numbers ([www.randomizer.org](http://www.randomizer.org)), aided

in determining testing order and speeds. Generating the random numbers consisted of the following steps:

- Assign four experimental conditions for numbers from 1 – 4: 1 = Trimble, 2 = Satloc, 3 = Cultiva, and 4 = Foam marker.
- Enter the Research Randomizer web site and fill out the form illustrated in Figure 3.5 using the following format and values.
- With testing order determined, assign two experimental conditions for numbers 1 & 2: 1 = Slow and 2 = Fast.
- Enter the Research Randomizer web site and fill out the form illustrated in Figure 3.6 using the following format and values.
- With testing order and speeds for each guidance unit determined, assign the speeds to the appropriate guidance unit in the testing order results.

### **Equipment Setup**

Proper setup and configuration of the RTK-GPS and the guidance units was essential for accurate data collection. The RTK base station requires an initial setup configuration and cable assembly, and then the unit remains untouched throughout a test period. Although guidance units require one configuration setup at the beginning of a test, the RTK-GPS rover receiver requires a different NEMA string output configuration for each guidance system (Table 3.1). Configuration and setup procedures are described in the following sections.

How many sets of numbers do you want to generate?	<input type="text" value="12"/>
How many numbers per set?	<input type="text" value="4"/>
Number range (e.g., 1-50):	From: <input type="text" value="1"/>
	To: <input type="text" value="4"/>
Do you wish each number in a set to remain unique?	<input type="button" value="Yes"/>
Do you wish to sort your outputted numbers?	<input type="button" value="No"/>
How do you wish to view your outputted numbers?	<input type="button" value="Place Markers Off"/>

**Figure 3.5. Illustration of methodology used on Research Randomizer website (www.randomizer.org) to generate random numbers for determining testing order.**

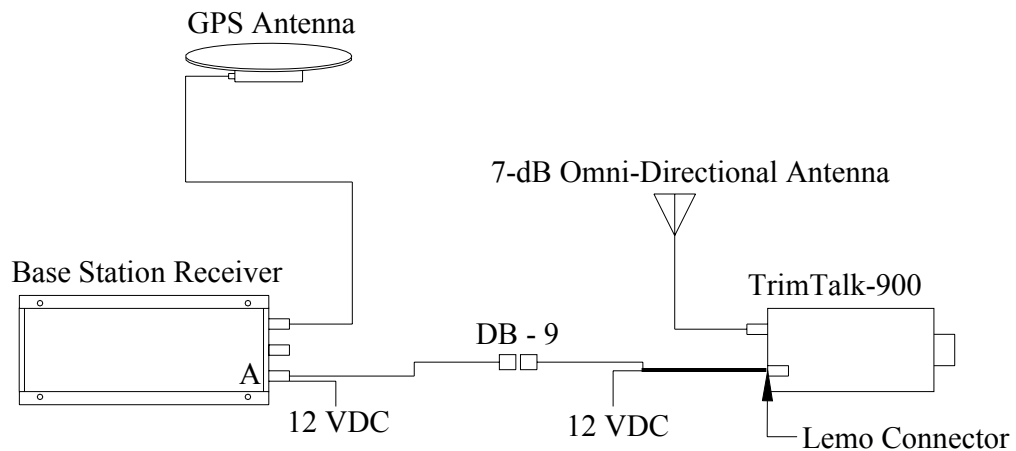
How many sets of numbers do you want to generate?	<input type="text" value="12"/>
How many numbers per set?	<input type="text" value="4"/>
Number range (e.g., 1-50):	From: <input type="text" value="1"/>
	To: <input type="text" value="2"/>
Do you wish each number in a set to remain unique?	<input type="button" value="No"/>
Do you wish to sort your outputted numbers?	<input type="button" value="No"/>
How do you wish to view your outputted numbers?	<input type="button" value="Place Markers Off"/>

**Figure 3.6. Illustration of methodology used on Research Randomizer website (www.randomizer.org) to generate random numbers for determining speed.**

### ***RTK Base Station***

The first step in setting up the base receiver is to connect four cables (two antenna cables and two data/power cables). The GPS antenna cable connects the base receiver to the GPS antenna, while the other antenna cable connects the TrimTalk-900™ to a 7 dB antenna. Data/power cables connect the GPS receiver and TrimTalk-900™ through a DB9 connector (male/female). The power leads on both power cables connect directly to a 12v battery. Figure 3.7 illustrates the wiring diagram for the Base Station.

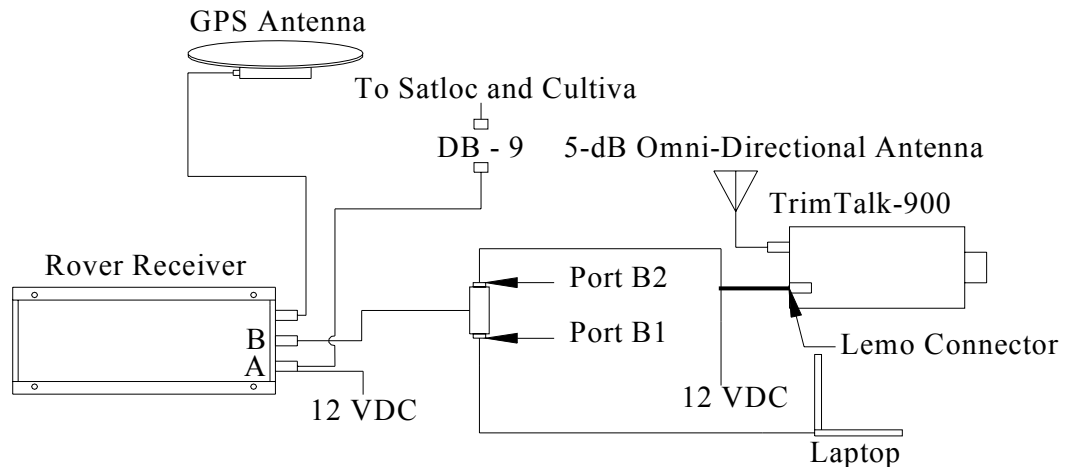
Configuration of the base station requires two steps. First, Port A communication protocol must be set to *9600 8-none-1* in order to communicate with the TrimTalk-900™. Second, the base station location must be established. Accepting the reference point displayed on the base station receiver sets the base point to  $\pm 10$  m of the reference point. Both processes are accomplished by maneuvering through the configuration screens of *configports* and *configbase* respectively.



**Figure 3.7. Schematic illustrating hardware setup for RTK base station.**

### ***RTK Rover Receiver***

The first step in setting up the rover receiver is to connect six cables (two antenna cables, two data/power cables, one split data cable for Port B, and one RS-232 serial cable to connect with the laptop). On the receiver, the GPS antenna cable connects with the antenna, the split Port B cable connects to Port B, and the GPS data/power cable connects to Port A. On the TrimTalk-900™, the antenna cable connects with the 5 dB antenna and the data/power cable connects with the radio and then to Port B2. A serial computer cable connects Port B1 to a serial port on the laptop for data storage. Power leads on both power cables connect to a 12v battery. If available, the rover receiver can be powered through an auxiliary power supply. However, the radio must receive power from a battery at all times, because the unit cannot handle voltage spikes. Figure 3.8 illustrates the wiring diagram for the Rover Receiver. Configuration of the rover receiver requires two steps. Port B1 and B2 require serial communication protocol to be set for *9600 8-none-1*, and set Port B1 to output a GGK



**Figure 3.8. Schematic illustrating hardware setup between rover receiver and TrimmTalk-900™ radio modem and laptop.**

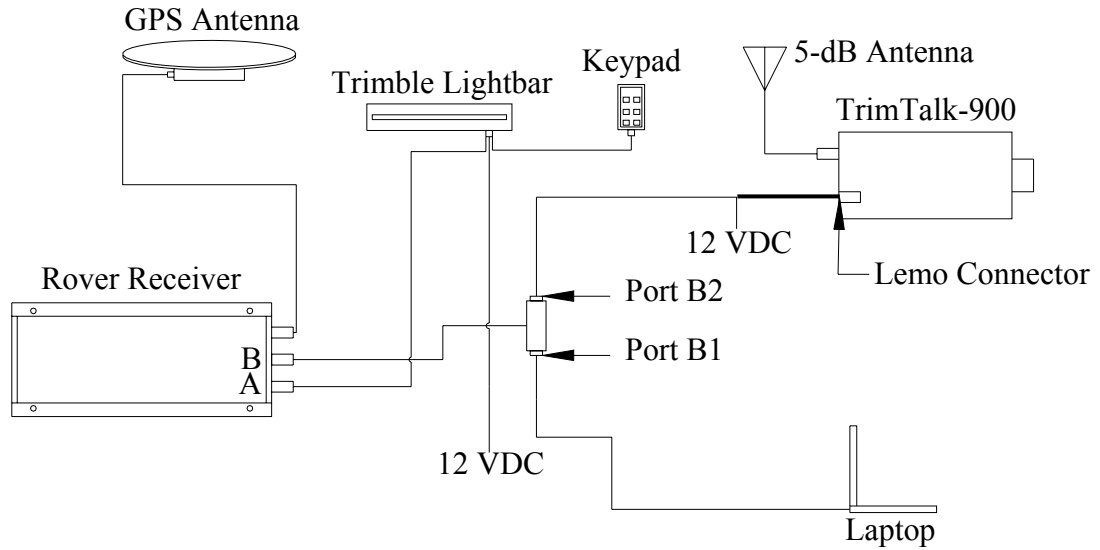
string at 5 Hz. Port B1 configuration is accomplished by maneuvering through the *configports* screen until a *NEMA configuration* screen appears, scroll through the NEMA strings to the *GGK* string, and then set the port to output a 5 Hz output rate.

Configuration of Port A depends on which guidance unit is operating. Accomplishing both processes consists of maneuvering through the configuration screen of *configports*.

### ***Trimble Lightbar***

The rover receiver provides the necessary information for Satloc and Cultiva to operate and operates Trimble's lightbar. The wiring diagram for the rover receiver remains unchanged when using Trimble's lightbar except for the data/power cable connecting to Port A. Trimble's lightbar uses a cable that connects directly to Port A. This cable supplies power to both the receiver and lightbar as well as connecting the lightbar, receiver, and keypad together (keypad controls lightbar functions). The remaining cables on the rover receiver remain unchanged. Refer to figure 3.8 for rover receiver-wiring diagram. Figure 3.9 illustrates the wiring diagram for Trimble's lightbar.

Configuration of Trimble's lightbar requires three steps. The first step is to maneuver through the configuration screens on the rover receiver to a *config lightbar* screen. At this location, lightbar text is set to *-Swath# & Track-*, LED space mode to *-Linear-*, LED spacing to *-0.16 m-*, lightbar mount to *-dash-*, and display mode to *-show correction-*. The second step requires maneuvering to a *config guidance* screen on the rover receiver. At this location, swath width is set according to the distance between step is to maneuver to the *configports* screen, scroll down, and configure the lightbar port foam marker cups. Also, at this location, pattern type is set to *-Basic AB-*, create swath is

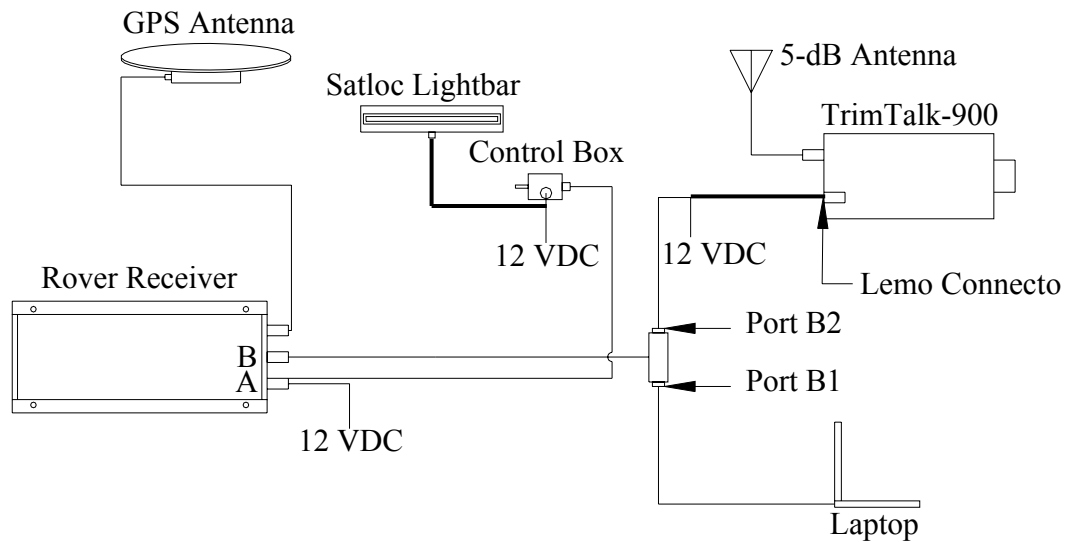


**Figure 3.9. Schematic illustrating hardware connections between Trimble lightbar and rover receiver.**

set to -Snap to Swath-, look ahead to -1 sec-, and position type to -RTK Fix-. The third to -Port A-. The receiver automatically updates the baud rate to 38.4 k at Port A. This baud rate must be changed back to 9600 when using other guidance units. This is the only configuration that requires changing after using Trimble’s lightbar. The settings previously stated remain unchanged until the user physically changes them.

### ***Satloc Lightbar***

Satloc’s lightbar uses a cabling harness equipped with two leads; one connects to the battery, and one connects to the lightbar. The cabling harness originates from the unit’s control box. The rover receiver’s data cable in Port A connects to the control box and outputs NEMA strings. The cabling diagram for the receiver setup remains unchanged from that describe in the Rover Receiver section. Figure 3.10 illustrates the wiring diagram for Satloc’s lightbar. Three steps are required to configure the rover



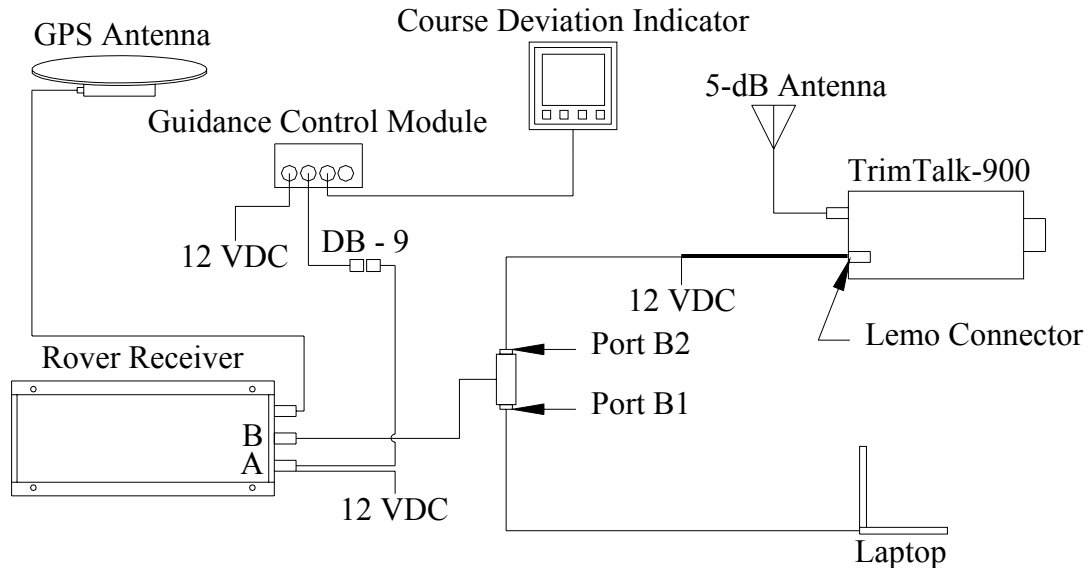
**Figure 3.10. Schematic illustrating hardware connections between Satloc LiteSatr and rover receiver.**

receiver for use with the Satloc lightbar. The first step is to maneuver to *configports* screen, and set serial communication for *Port A* to *9600 8-none-1*. The second step is to scroll down the *configports* screen to *Guidance configuration* and set guidance to *off*. The third step is to scroll down the *configports* screen to *NEMA configuration* and set *Port A* to output *GGA* and *VTG* strings at *5 Hz*. Four variables must be programmed to configure the lightbar for operation. These variables include pattern type, swath width, units, and LiteStar sensitivity. Pattern type is configured to *P0*, which stands for Closest Line Autoswath. Swath width requires a distance between foam cups and the units set to English. LiteStar sensitivity represents the LED spacing for the off track row of LED's. Satloc uses different sensitivity settings depending on the type of guidance. Refer to the operator's manual for list/description of possible settings. This project used the ground sensitivity setting.

## ***Cultiva Marker***

Cultiva uses the GCM (guidance control module) to control the operation of Marker™ and requires setup of three cables for operation. One cable connects the CDI (course deviation indicator) to the GCM. A second, the DGPS cable, connects to Port A on the rover receiver, and a third cable connects to a 12v battery. The cabling diagram for the receiver setup remains unchanged from that describe in the Rover Receiver section. Figure 3.11 illustrates the wiring diagram for Cultiva’s Marker™.

Configuration of the rover receiver to operate Cultiva requires two steps. Step one is to maneuver to the *configports* screen, and set serial communication protocol for Port A to 9600 8-none-1. Step two consists of maneuvering through *configports* screen to *NEMA configuration* and setting *Port A* to output a *GGA* string at 5 Hz.



**Figure 3.11.** Schematic illustrating hardware connections between Cultiva Marker™ and rover receiver.

Before operating Cultiva, the variables units, boom width, and segment width need configured. These variables are accessible by entering the setup section on the CDI. Set measurement units to English and configure the boom width to the distance between foam cups on the sprayer. Segment width is similar to LED spacing on lightbars. This project used a segment width of 0.16 m.

### **Data Collection**

Two types of data are used to determine the results. Type one data utilized the center positioning of the sprayer. Type one data consists of the NEMA GGK string, which provides latitude and longitude information. Latitude and longitude positions make it possible to determine overlap, skip, and off-track distance from the centerline. Type two data was a questionnaire administered to the drivers. The survey consisted of twenty-two questions focusing on driver input regarding the guidance units performance, abilities, and characteristics.

### ***GPS Data***

A Zenith Data Systems laptop s/n 4SSCHV001324 recorded the GGK data string for each test. This particular laptop utilizes a 486DX coprocessor and Windows 3.1 operating system. The only requirement for the data collection device was adequate hard drive space and a serial communications protocol of 9600 n-8-1 at COM1.

Actual data collection of the GGK string consists of executing a program written in BASIC conveniently named LBAR3 (Refer to Appendix A for program). The program structure allows for easy file name and program management. File name structure consists of the following format, D#T#, where D = Driver, # = 1-21, T = Test,

and # = 1-4. Procedures for collecting data consist of naming the file at the beginning of a test and pressing “s” to stop the program upon completing a test.

### ***Questionnaire***

One of the most efficient methods of gathering information regarding new technologies or new and modified equipment is to ask the individuals who use that product. Generally, this focus group offers different ideas that manufactures might not have considered. With this in mind, a survey was taken by the drivers to provide information regarding the guidance units performance, abilities, and characteristics to researchers and manufacturers alike.

The survey provides some historic information regarding the driver’s background, with 90% of the questions focusing on the guidance systems operation. For example, some of these questions ask the driver to rate a particular characteristic in question, while others require a direct answer from a list of possible answers. One critical step in collecting the survey data was that an individual administrated the test and talked with each driver to extract additional information that the survey did not provide. Surveys were administered to each driver immediately after completing their test. Appendix B has a sample survey used during the test.

### **Data Processing**

Many different forms of data processing offer answers to questions that arise during the history of a project. Questions of “what if” constantly surface throughout the data collection and processing procedure. Several processing methods provided different means of viewing the results for this project. Specifically, two measures were used to

evaluate operator performance, area and centerline deviation. Area provides a means for statistically determining which operator feedback method improved a driver's performance. Deviation from centerline data produces different driving patterns for each driver. These results provide maximum deviation from the centerline, average maximum deviation from the centerline, Root Mean Square (RMS) deviation, average deviation, starting deviation, and ending deviation.

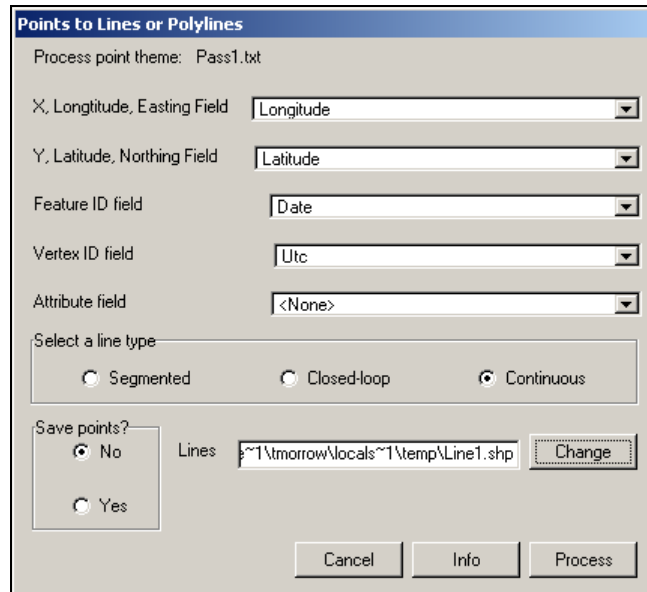
### ***Data Reduction***

Several variables make up a NEMA data string, and these variables range from positional information to satellite information. Not all of the information is relevant to this study; therefore, simplification of the string is acceptable. Eleven variables make up a GGK string, and the first step in processing the data was to simplify the string. A program written in BASIC and named DATACON, simplifies the GGK string to six variables (Refer to Appendix A for the program). The program converts latitude and longitude values to decimal degrees and provides variables of date, UTC time, GPSStat, and DOP. In addition, DATACON converts the file to ASCII (.txt) format and reduces a file to half of the original size, which saves disk space.

### ***GIS Analysis***

Overlap, skip, and deviation from a centerline were determined using the GIS package, ArcView™ 3.2. Also, several ArcView extension files and one script file were utilized in data processing. These files include: *area calculation for polygon* (Guoyun, 2000), *Clip Themes Extension* (Girard, 98), *points to lines or polylines* (Patterson, 2000), *Drawlines by Coordinates* (script file) (Mokraoui, 2000), and *Active Themes 2 Excel* (Bartosh, 2000). ArcView™ data processing required the following steps:

- Add the extensions and set the projection to StatePlan 1983, Type – Tennessee for Tennessee drivers and Kentucky South for drivers from Kentucky. Map units default to meters, and distance units need set to meters.
- From the *Table Screen*, add a raw data text file.
- In the *View Screen* under the *View* tab, add an event theme to bring the text (.txt) file into the view.
- Identify the beginning and ends of a pass, and record the latitude and longitude values. This was accomplished by measuring off approximately 244 m (800 ft) on each pass.
- With the points identified, open the raw data file in Excel. Copy and paste a pass to a new sheet and save that pass as a (.txt) file. This process is necessary because each pass must be a separate file from adjacent passes in order to determine overlap, skip, and offset distance. Note: Only the beginning and end points of pass 1 need recorded for the GPS guidance systems. These points will signify the A and B points.
- Add the passes to the view by following the process previously stated.
- Select a pass and execute the *points to lines or polylines* extension to generate a line. Repeat this process for all passes made with the foam marker and pass 2 through 7 made with each GPS system. Follow the format in Figure 3.12 to generate a line from the points.
- To create a line for pass 1 of the GPS systems, load the Drawlines by Coordinates script file into ArcView™. The script guides a user through the drawing process.



**Figure 3.12. Illustration of process used to generate centerlines for the passes in ArcView™.**

- With the lines created, generate a buffer around each line theme by selecting the *Create Buffers* option under the *View* tab. The buffer distance is half of the boom width for a particular testing location. Note: Do not generate a buffer around pass 1 for any test.
- The next step is to remove the ends of the buffered passes. This is accomplished by selecting the *New Theme* option under the *View* tab and creating two polygon themes. These themes should cover the distance from pass 2 to pass 7 .
- Remove an end by having both a pass theme and an end theme selected. Choose the *clip theme outside* option of the Clip Theme extension to remove an end. Repeat the process to clip all ends.
- Next, determine the areas of overlap by selecting two pass themes, example pass 2 and 3. Choose the *clip theme inside* option of the Clip Theme extension

and clip pass 3 based on pass 2; pass 2 could not overlap pass 3 because pass 2 occurs before pass 3. The new theme is the overlap for pass 2 and 3. Repeat the process for all passes.

- The areas of skip require more work than the areas of overlap. First, a polygon must be created between the edges of two passes. Accomplish this by selecting the *New Theme* option under the *View* tab and creating a polygon. With both the new polygon theme and a pass selected, choose the *clip theme outside* option of the Clip Theme extension, and clip the polygon theme based on the pass theme. Take the new theme generated from that clipping process, choose the *clip theme outside* option, and clip the new theme based on the other pass. The process produces areas of skip between the two passes. Note: Never clip the pass themes when finding areas of skip.
- With the above steps completed, the next process is to calculate the area value for overlap, skip, and the buffered passes. This is accomplished by using the Area calculation for Polygon extension. The extension adds a tab to the *View Screen* tool bar. Individually select the polygons of overlap, skip, and buffered passes; the extension calculates the area of the selected polygon.
- The next process is to determine offset distance error from the centerline for GPS systems passes 2 through 7 using pass 1 as the reference. Open the attribute tables for the line theme of pass 1 and the point theme of pass 2. Join the line theme of pass 1 to the point theme of pass 2. The join will add a field to the point theme titled distance. Values produced are the distances from each point of pass 2 to the line of pass 1. Repeat the process for passes 3 through 7

using pass 1 as the truth. Finding offset distance error for foam marker requires joining the points of a later pass with the line of a previous pass.

Example, the points of pass 4 would join to the line of pass 3.

- After completing the steps described above, the next step is to export the area values and offset distance values from the centerline to Excel. This is accomplished by using the Themes to Excel extension. Having Excel opened before attempting to export the values seems to work better than not having Excel opened. Select the overlap, skip, and buffered passes with the ends clipped polygons, click the “E” on the *View Screen* toolbar, and export the area field associated with each theme. The process exports all the area values to the active Excel worksheet. Export the offset values and UTC time for each pass and save the passes separate from one another.

### ***Excel Procedures***

Excel provides a means for calculating overlap and skip areas as a percentage of two parent passes and total area sprayed. In addition, the program provides a means to determine maximum deviation from the centerline, average maximum deviation from the centerline, Root Mean Square (RMS) deviation, average deviation, starting deviation, and ending deviation using the distance from centerline data. Additionally, Excel provides a means for graphically viewing the driving pattern for a particular driver over time using the offset distance data.

The percentage values of overlap and skip provide an indication of how much area received double application or no application. These values indicate how well a driver performed throughout the course of a test and overall performance. In addition,

these values provided a means for statistically determining the best operator feedback method and studying a learning curve for each driver.

Determining the percentage of overlap and skip for two passes differs from determining the percentage for total area. One equation produces the desired results for both values; however, the area values used in the equation differ for pass-to-pass percentages as opposed to total area percentages. Calculations for determining percent values for overlap and skip use equations (3.1), (3.2), (3.3), and (3.4). Figure 3.13 and Figure 3.14 illustrate the areas of interest for determining percent overlap and skip for swaths and total area.

**% Overlap between Swaths**

$$\% = \frac{\sum (\text{Overlap Area Between Pass}_n \text{ and Pass}_{n+1})}{(\frac{1}{2} \text{Area Pass}_n + \frac{1}{2} \text{Area Pass}_{n+1} - \text{Overlap}_{n\&n+1} + \text{Skip}_{n\&n+1})} \quad (3.1)$$

**% Skip between Swaths**

$$\% = \frac{\sum (\text{Skip Area Between Pass}_n \text{ and Pass}_{n+1})}{(\frac{1}{2} \text{Area Pass}_n + \frac{1}{2} \text{Area Pass}_{n+1} - \text{Overlap}_{n\&n+1} + \text{Skip}_{n\&n+1})} \quad (3.2)$$

**% Overlap for Total Area**

$$\% = \frac{\sum (\text{Overlap Between Pass}_2 \text{ and Pass}_7)}{(\frac{1}{2} \text{Area Pass}_2 + \text{Area Pass}_3 + \dots + \frac{1}{2} \text{Area Pass}_7 - \text{Overlap}_{\text{Total}} + \text{Skip}_{\text{Total}})} \quad (3.3)$$

**% Skip for Total Area**

$$\% = \frac{\sum (\text{Skip Between Pass}_2 \text{ and Pass}_7)}{(\frac{1}{2} \text{Area Pass}_2 + \text{Area Pass}_3 + \dots + \frac{1}{2} \text{Area Pass}_7 - \text{Overlap}_{\text{Total}} + \text{Skip}_{\text{Total}})} \quad (3.4)$$

To determine centerline deviation error, the distance values were subtracted by a boom width or multiple boom widths depending upon which pass was under consideration. GPS systems referenced back to pass 1, while the foam marker system



Figure 3.13. Illustration of area of interest when calculating percent overlap or skip between pass  $n$  and  $n+1$ .

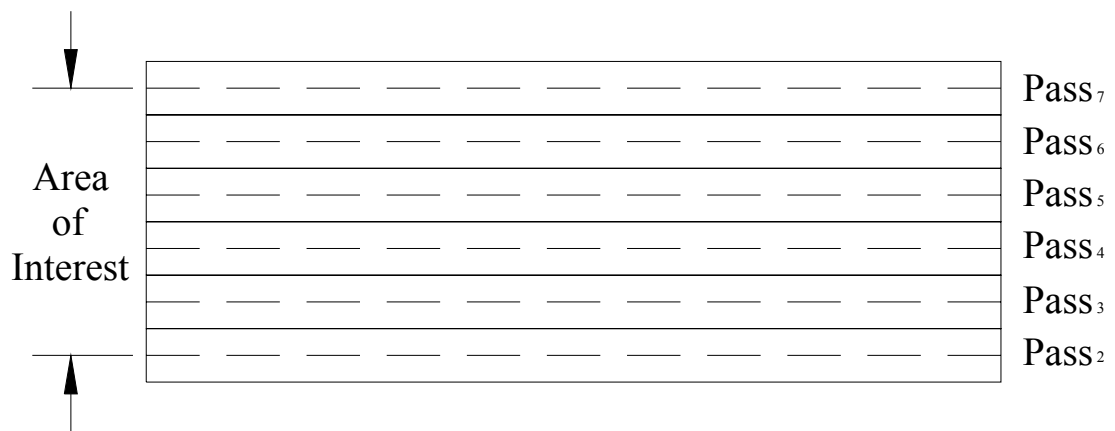


Figure 3.14. Illustration of area of interest when calculating percent overlap or skip for total area between passes 2 and 7.

referenced back to the last completed pass. Figure 3.15 and Figure 3.16 illustrate the procedures used to determine centerline error for GPS systems and foam.

After determining error values, the data was filtered by performing a running average. This filtering process removed error contributed by pitch and sway of the vehicle. In addition, this process strengthens the confidence that the error values represent driver error instead of pitch and sway. Data were filtered using equation (3.5).

**Running Average**

$$Avg = \frac{\sum (Error_1 + Error_2 + Error_3 + Error_4 + Error_5)}{5} \quad (3.5)$$

Another step required for preparing the offset distance data was to convert the UTC time values from hours, minutes, and seconds format to seconds. This step of data processing required two equations because a time value without decimal digits required a different equation. Calculations for converting time data with decimal digits used equation (3.6), while time data without decimal digits used equation (3.7).

**Time Conversion**

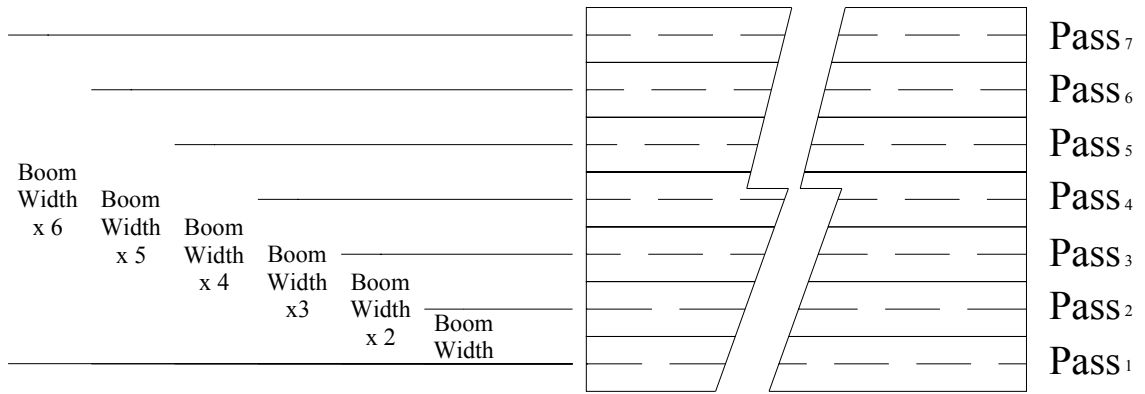
$$Time(sec) = (Left(Cell_n,2) * 3600) + (Mid(Cell_n,2) * 60) + (Right(Cell_n,4)) \quad (3.6)$$

$$Time(sec) = (Left(Cell_n,2) * 3600) + (Mid(Cell_n,2) * 60) + (Right(Cell_n,2)) \quad (3.7)$$

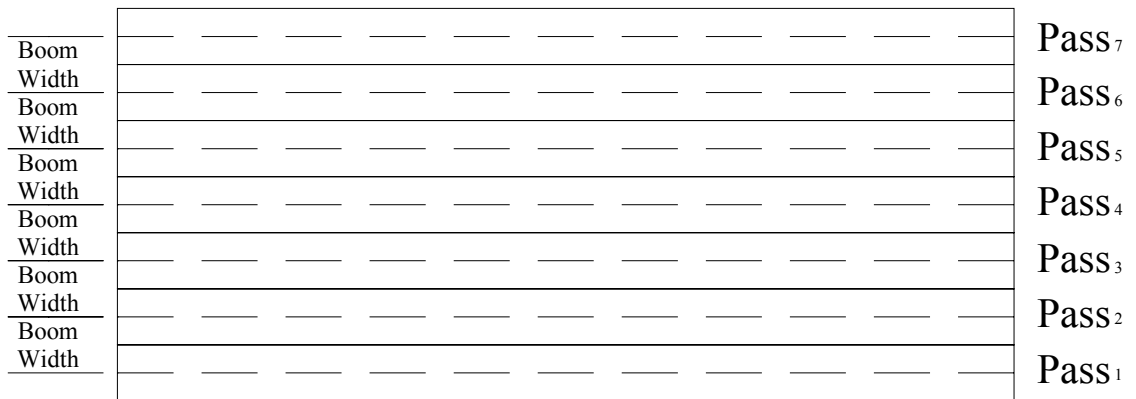
After subtracting a specified boom width, the results have positive or negative values.

The “absolute” function in excel removed the sign value and made the data set unsigned.

Methods for finding maximum deviation consisted of using the “Max” function in Excel



**Figure 3.15. Illustration of passes for determining deviation from a centerline for GPS systems, and how the distance value references back to the centerline of pass 1.**



**Figure 3.16. Illustration of passes for determining deviation from a centerline for foam marker, and how the distance value references back to the centerline of a pervious pass.**

and performing this function on the filtered data set. Average maximum deviation from a centerline consisted of averaging the maximum deviations of the passes in a test.

The next process in analyzing positional errors was to find RMS deviation and average deviation. Average deviation was determined by computing a simple average for the filtered data. Root mean square deviation is a measure of magnitude for the data set, and RMS provides an idea of the typical size for numbers in the data set. A small RMS value indicated that a driver was closer to staying on the centerline during a particular pass, while a large RMS value indicated that a driver was further away from the centerline. Equation (3.8) was used to compute RMS error.

$$RMS = \sqrt{\frac{error_n^2 + \dots + error_{n_i}^2}{N_{Total}}} \quad (3.8)$$

The final step in analyzing positional errors was to find starting deviation and ending deviation. Starting deviation was determined by simply selecting the first point of a data set. Ending deviation was represented by the last point of a data set. Although, this method of selection is simple, the first and last points provided an indication of how far off center the driver was at the start and end of a pass.

## **Chapter IV**

### **Results and Discussion**

Twenty-one drivers participated in the study to evaluate operator feedback methods for four guidance systems used on agricultural spraying and spreading vehicles. Positional data provided the means to determine overlapped and skipped areas as well as course deviation error from a centerline. Survey data presented operator information concerning the guidance systems performance and operator preferences to the guidance systems. Testing took place in the months of August and November of 2001 at two locations. Six drivers from Franklin County, Tennessee, performed the test in August, while fifteen drivers from Marion County, Kentucky, performed the test in November. Appendix C illustrates where the counties lie within the two states. Weather conditions in Franklin County were comfortable. Temperatures were in the mid to upper eighties with little to no breeze. The field was pastureland and had a fescue cover ranging from 6 to 12 inches in height. Corn stover covered the field in Marion County. Temperatures were comfortable and strong winds blew for three days with typical gusts measuring between 16 and 18 mph. Wind conditions were not good for foam marker; however, drivers were able to drive with the wind and effectively use the foam marker system. The following sections present statistical results of overlap and skip error, course deviation error, and descriptive results for the survey information.

## Results for Area Errors

### Source Data

An understanding of the values used in the statistical analysis is necessary when interpreting the results for overlap and skip. The previous chapter explained the processes used to determine overlap and skip, but did not illustrate the results. Figure 4.17 is a representative example for the twenty-one drivers illustrating the results of overlap and skip on a single map. This map provides a view of the total error produced by this particular driver, and was typical for all drivers. Calculations on the data produced percent error of overlap and skip on a per pass basis (equations 3.1 and 3.2) and a total area basis (equations 3.3 and 3.4). Table 4.2 is a representative example for the twenty-one drivers showing results of area values for each pass found in ArcView™ and percent error of overlap and skip.

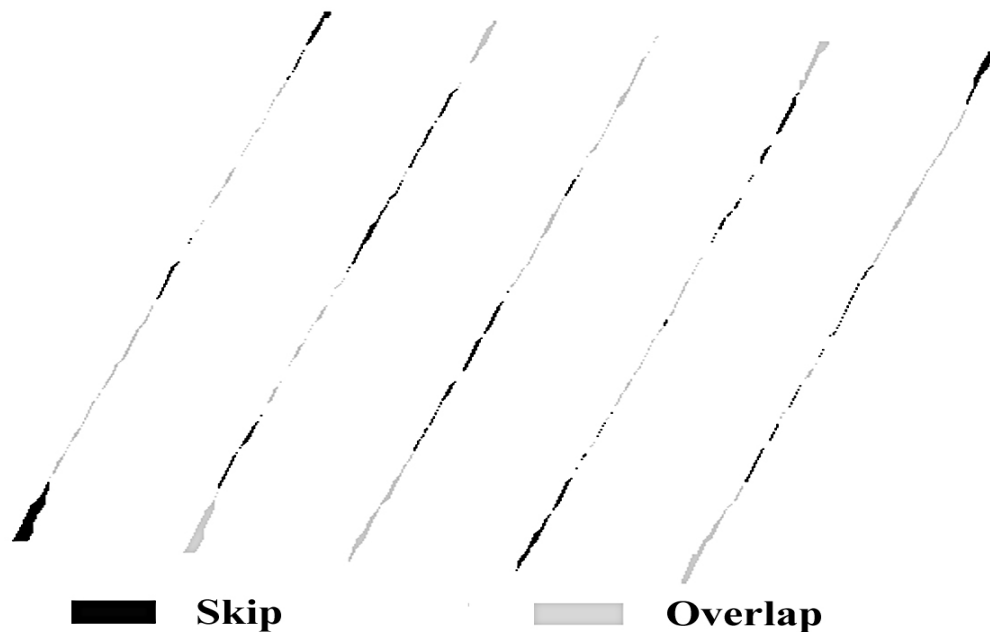


Figure 4.17. Map illustrating areas of overlap and skip using ArcView™.

**Table 4.2. Results of area and percent error calculations used to statistically determine differences among guidance systems and speeds.**

	Area (m)	Overlap (m)	Skip (m)	% Error Overlap	% Error Skip
<b>Run 2</b>	6220.30	33.82	59.08	0.54%	0.95%
<b>Run 3</b>	6230.89				
<b>Run 4</b>	6233.79	59.40	27.03	0.96%	0.44%
<b>Run 5</b>	6241.87	54.61	23.54	0.88%	0.38%
<b>Run 6</b>	6249.53	25.14	41.56	0.40%	0.66%
<b>Run 7</b>	6254.29	48.36	30.49	0.78%	0.49%
<b>Total (m)</b>	37430.67	221.32	181.70	0.71%	0.58%
<b>Total (ha)</b>	3.74	0.02	0.02		

### System Analysis

Using SAS® 8.2, the percent error data was analyzed to determine if systems differed, if speed influenced overlap and skip, and if passes revealed a learning curve. Due to data normality problems, outlier data values for overlap on pass 2&3 and skip on pass 3&4 from driver 11's second test were removed. With normality corrected, statistical analysis of **proc means** and **proc mixed** with least square means produced results for concluding if systems differed, if speed affected overlap and skip, and if a learning curve existed between passes. Table 4.3 presents the results of **proc means** for systems. The information provides a general idea of how the drivers' performed as a whole. Examination of the means revealed that foam has higher overlap and skip values followed by Marker™, then Satloc® and Trimble respectively.

**Table 4.3. Proc mean results of the four guidance systems illustrating the number of observations (N), means, standard deviations, minimum, and maximum values.**

<b>System</b>	<b>Variable</b>	<b>N</b>	<b>Mean</b>	<b>Std. Dev.</b>	<b>Minimum</b>	<b>Maximum</b>
<b>Marker™</b>	Over	90	1.25	1.50	0.048	8.75
	Skip	90	1.04	1.17	0.000	6.81
<b>Foam</b>	Over	125	2.45	2.54	0.000	12.51
	Skip	125	1.10	1.84	0.000	11.23
<b>Satloc®</b>	Over	80	1.19	1.23	0.014	9.51
	Skip	80	0.92	0.72	0.004	2.92
<b>Trimble</b>	Over	99	0.97	0.71	0.131	4.21
	Skip	99	0.80	0.61	0.078	3.43

Results for **proc means** confirmed that GPS guidance systems differed from foam; however, statistical confirmation of differences between GPS systems and foam was necessary. Performing analysis of variance (MIXED procedure, SAS 2001) on the data to determine if statistical differences existed produced the following results. With overlap being the dependent variable, systems differed ( $P=0.0037$ ). Using least square means technique, the **LSD** method found that GPS guidance systems differed from foam at ( $P<0.05$ ). The **Tukey** method found that Marker™ and foam did not differ, and Marker™ did not differ from Satloc and Trimble; however, Satloc and Trimble did differ from foam at the ( $P<0.05$ ) level. Table 4.4 presents results for **LSD** and **Tukey** mean separation techniques. With skip being the dependent variable, systems did not differ ( $P>0.05$ ), and **Tukey** means separation technique substantiated that systems did not differ at the ( $P<0.05$ ) level.

### **System Analysis for GPS Systems**

In order to differentiate differences between GPS systems, a new data set was created by removing the foam marker data. Due to normality problems, outlier data values for overlap were removed from driver 15, pass 2&3 and driver 19, pass 5&6. Table 4.5 presents the results of **proc means** for systems with foam removed.

**Table 4.4 Mean separation results for Guidance systems illustrating Tukey and LSD methods.**

<b>Tukey</b>		<b>LSD</b>	
<b>Foam</b>	A	<b>Foam</b>	A
<b>Marker™</b>	A B	<b>Marker™</b>	B
<b>Satloc®</b>	B	<b>Satloc®</b>	B
<b>Trimble</b>	B	<b>Trimble</b>	B

**Table 4.5. Proc mean results of the GPS guidance systems illustrating the number of observations (N), means, standard deviations, minimum, and maximum values.**

<b>System</b>	<b>Variable</b>	<b>N</b>	<b>Mean</b>	<b>Std. Dev.</b>	<b>Minimum</b>	<b>Maximum</b>
<b>Marker™</b>	Over	89	1.16	1.28	0.048	7.52
	Skip	90	1.04	1.17	0.000	6.81
<b>Satloc®</b>	Over	79	1.08	0.80	0.013	4.12
	Skip	80	0.92	0.72	0.004	2.92
<b>Trimble</b>	Over	99	0.97	0.71	0.129	4.21
	Skip	99	0.80	0.61	0.079	3.43

Examination of the means revealed that Marker™ had higher overlap and skip values followed by Satloc® and Trimble respectively. Performing analysis of variance (MIXED procedure, SAS 2001) on the data to determine if statistical differences existed produced the following results. With overlap as the dependent variable, systems did not statistically differ ( $P > 0.05$ ), and **Tukey** means separation technique confirmed that systems did not statistically differ at the ( $P < 0.05$ ) level. Analyzing the data with skip as the dependent variable also concluded that systems did not statistically differ ( $P > 0.05$ ). The **Tukey** mean separation technique also found that systems did not statistically differ at the ( $P < 0.05$ ) level for skip.

### **Speed Analysis**

The data set used to analysis speed was the same set used to analysis the four guidance systems (Trimble, Satloc®, Marker™, and Foam). Reasons for analyzing speed were to determine how a high and low speed affected error. It was hypothesized that as

speed increased so would the amount of error because a driver could not react quick enough to correct course deviation. Table 4.6 presents the results of **proc means** for high and low speeds. Examination of the means revealed that high speed has higher overlap and skip values than low speed. Performing analysis of variance (MIXED procedure, SAS 2001) on the data to determine if statistical differences existed produced the following results. Speeds did not statistically differ for the dependent variables of overlap and skip ( $P>0.05$ ), and **Tukey** means separation technique concluded that speeds did not statistically differ from one another.

### **Pass Analysis**

A general thought was that as a person repeats a task, the quality of the task should improve. Hence if a learning curve existed, then the means for overlap and skip would decrease with each additional pass. This decrease would indicate that a driver was learning how to respond when a guidance system indicated that a correction was necessary. The data set used to study if a learning curve was present for systems was a new set used for pass analysis. The process used to identify if a learning curve was present was to plot overlap and skip by pass number for each driver and system. Examination of the plots revealed that there was not a decrease in mean values with each additional pass, which suggests that a learning curve was not present.

**Table 4.6. Proc mean results of the speeds illustrating the number of observations (N), means, standard deviations, minimum, and maximum values.**

<b>Speed</b>	<b>Variable</b>	<b>N</b>	<b>Mean</b>	<b>Std. Dev.</b>	<b>Minimum</b>	<b>Maximum</b>
<b>High</b>	Over	210	1.60	1.90	0.0	12.51
	Skip	210	1.00	1.00	0.0	6.10
<b>Low</b>	Over	184	1.49	1.75	0.0	9.12
	Skip	184	0.94	1.51	0.0	11.23

## **Operator Variables Analysis**

A question surfaced dealing with what variables affected overlap and skip. The obvious answer was the driver, but what variables associated with the driver affected overlap and skip. Examination of the information provided by the survey lead to the development of this question: Did age, farming experience, and acres sprayed have an effect on overlap and skip? The overlap and skip values used to answer this question were the total percent error values calculated for each driver. Combining operator variables with overlap and skip created a new data set. Operator variables were classified into three classifications (age <30, between 30&40, over 40; experience <6, between 7&20, over 20; acres <2500, between 2850&6000, over 6000). Performing analysis of variance (GLM procedure, SAS 2001) on the data to determine if statistical differences existed produced the following results. Analyzing the Type III Sums of Squares revealed that age, experience, and acres sprayed were not statistically significant in explaining overlap at the ( $P < 0.05$ ) level. Initial examination of the results for skip revealed that acres sprayed had a statistically significant effect on skip ( $F = 3.72$ ,  $P = 0.0290$  and age and acres sprayed did not ( $P > 0.05$ ). Further investigation of the skip data found an outliers for driver 11 test 1 and 2, and driver 14 test 1, after removing this outliers, the analysis found that acres did not have a statistically significant effect on skip ( $P > 0.05$ ).

## **Results for Positional Errors**

### **Source Data**

The previous chapter described the processes used to determine positional errors of maximum deviation, average maximum deviation, RMS, average, starting, and ending

deviation. An illustration of the error terms helps define the values' origins. Figure 4.18 illustrates positional errors of maximum, starting, and ending deviation for a pass from one of the twenty-one drivers' four tests. The figure does not depict average maximum deviation, RMS, and average deviation because those terms originate from calculations. Table 4.7 presents results for a test from one of the twenty-one drivers four tests. The table is a representative example for the drivers and illustrates the values used for statistical analysis.

One question asked when analyzing positional errors was: Did the positional errors depend solely on the driver or did the guidance system influence positional errors? Separating foam from GPS systems allows for comparisons between the two types of guidance systems and means to answer the question. Performing the separation consisted

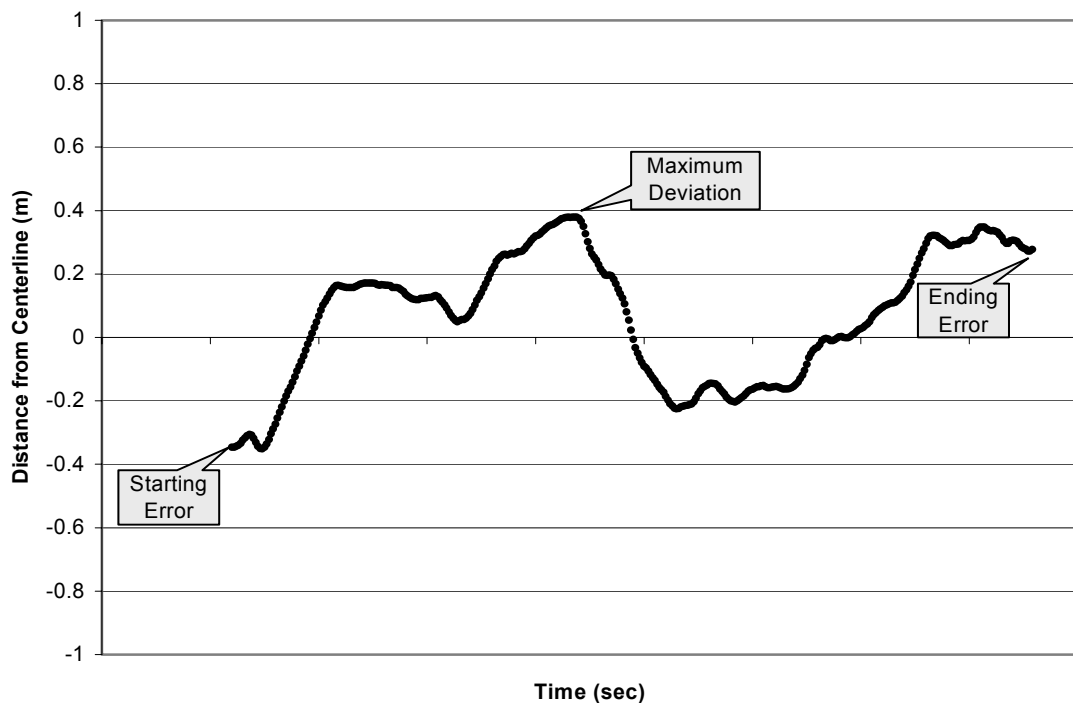


Figure 4.18. Graph illustrating three of the six positional errors found using Excel.

**Table 4.7. Results of positional error values and calculations reporting deviation variables and values.**

	<b>Max Dev</b>	<b>RMS</b>	<b>Average</b>	<b>Starting</b>	<b>Ending</b>
<b>Pass 2</b>	0.37	0.17	0.15	0.37	0.09
<b>Pass 3</b>	2.47	0.56	0.27	2.47	0.44
<b>Pass 4</b>	0.38	0.21	0.19	0.35	0.28
<b>Pass 5</b>	0.49	0.23	0.20	0.39	0.31
<b>Pass 6</b>	1.64	0.41	0.26	1.59	0.34
<b>Pass 7</b>	0.83	0.26	0.20	0.06	0.16
<b>Average</b>	1.03	0.31	0.21	0.87	0.27

### **Analysis of Foam**

of creating two new variables in SAS. The new variables were FOAM and GPSUNIT. Creating these variables allowed for single analysis of foam and single analysis of the GPS units. This analysis concentrated on the variables of driver, FOAM, and the interaction of driver and FOAM. Performing analysis of variance (GLM procedure, SAS 2001) on the data to determine if significant effects existed produced the following results. For maximum deviation, driver was statistically significant ( $F=26.53$ ,  $P<0.0001$ ), while FOAM and the driver/FOAM interaction were not significant. Although driver was statistically significant for maximum deviation, driver explained  $< 6\%$  of the variation in the variable. Driver and the driver/FOAM interaction were statistically significant in explaining RMS ( $P<0.05$ ). Driver was more significant ( $F=28.32$ ) than the interaction ( $F=10.06$ ); however, both variables explained  $< 10\%$  of the variation. FOAM proved not significant in explaining RMS error ( $P>0.05$ ). Driver and the driver/FOAM interaction were statistically significant in explaining average deviation ( $P<0.0001$ ); however, both variables accounted for  $< 16\%$  of the variation. Driver was statistically significant in explaining starting deviation, while FOAM and the driver/FOAM

interaction were not. Although driver was significant, the variable only accounted for < 9 % of the variation. Driver and the driver/FOAM interaction were statistically significant in explaining ending deviation ( $P < 0.05$ ). Although the driver/FOAM interaction appeared more significant ( $F = 18.91$  and  $F = 8.56$ ) respectively, both variables explained < 12 % of the variability.

### **Analysis of GPS Units**

Separating GPS units from foam allowed for comparisons between the two statistical analyses. In addition, this separation allowed for comparison between GPS units. This analysis focused on the variables of driver, GPSUNIT, and the interaction of driver and GPSUNIT. Performing analysis of variance (GLM procedure, SAS 2001) on the data to determine if significant effects existed produced the following results. Driver was statistically significant in explaining maximum deviation ( $P = 0.0005$ ), while GPSUNIT and the driver/GPSUNIT interaction were not. However, driver only explained < 5 % of the variation. Comparing these results to FOAM revealed that maximum deviation had similar results for both FOAM and GPSUNIT. None of the variables were statistically significant in explaining RMS deviation ( $P > 0.05$ ) for GPSUNIT analysis. Comparing these results to FOAM revealed that driver and the driver/FOAM interaction were both statistically significant. None of the variables were statistically significant in explaining average deviation ( $P > 0.05$ ) for GPSUNIT analysis. When compared to FOAM, driver and the driver/FOAM interaction were statistically significant. Driver was statistically significant in explaining starting deviation ( $P < 0.0001$ ), while GPSUNIT and the driver/GPSUNIT interaction were not. Although driver was statistically significant, the variable explained < 7 % of the variation. None of

the variables were statistically significant in explaining ending deviation ( $P>0.05$ ) for GPSUNIT analysis. When compared to FOAM, driver and the driver/FOAM interaction were statistically significant in the FOAM analysis.

### **GPS Unit Comparison**

The final part of the GPSUNIT analysis provided mean comparisons for the three GPS guidance systems. These comparisons revealed if systems differed for maximum deviation, RMS, starting, and ending deviation. Performing **Tukey's** mean separation test on the means produced the following results. GPSUNITS did not differ from one another for variables of maximum deviation, RMS, average deviation, starting and ending deviation.

### **Analysis of Pass**

Another method for determining if a learning curve existed was to analyze the positional errors on a pass basis. The concept for studying a learning curve is similar to the concept stated in the area analysis section, if positional errors decrease with each additional pass, a learning curve exists. Errors were plotted against pass number for each driver and system looking for trends representative of a learning curve. Examination of the plots suggested that a learning curve was not present for drivers and systems when using positional errors.

### **Summary of Guidance Systems**

Descriptive statistics are an effective way to summarize many variables in a data set. A summary of variables maximum deviation, average maximum deviation, RMS, average deviation, starting and ending deviation, overlap, and skip would summarize

each guidance systems' overall accuracy. The data used to produce the descriptive statistics was the total percent values for overlap and skip, highest maximum deviation value per driver per test, and the average totals of average maximum deviation, RMS, average, starting, and ending deviation per driver per test. Refer to table 4.7 to understand the term "average totals." Performing **proc means** on the data (SAS, 2001) produced a set of descriptive statistics for each guidance system. Table 4.8 presents the results of **proc means** for the four guidance systems.

### **Results for Operator Preference Survey**

Examination of the survey data lead to the development of several questions regarding drivers' age, experience, and acres sprayed. The reason behind examining these three variables was to see if the drivers' age, farming experience, and acres sprayed was related to the responses from the survey. For instance, a driver might be more inclined to choose foam over GPS because that is what he or she has the most experience using. Questions regarding age, experience, and acres sprayed lead to the following:

*Did the preference of GPS or foam depend on a driver's age, farming experience, and acres sprayed?*

*Were the responses to "did GPS or foam improve your performance" depend on a driver's age, farming experience, and acres sprayed?*

*Did the preference of LED's or graphical depend on a driver's age, farming experience, and acres sprayed?*

*Did the preference of one row of LED's to two row's of LED's depend on a driver's age, farming experience, and acres sprayed?*

*Did the preference of mounting location of inside the cab to outside on the hood depend on a driver's age, farming experience, and acres sprayed?*

**Table 4.8. Proc mean results for the four guidance systems illustrating total number of tests (N TT), variables of interest, number of tests used (N), means, minimum, and maximum values in meters.**

<b>System</b>	<b>N TT</b>	<b>Variable</b>	<b>N</b>	<b>Mean</b>	<b>Minimum</b>	<b>Maximum</b>
<b>Marker™</b>	21	Maximum Deviation (m)	18	3.96	0.88	11.05
		Avg Maximum Deviation (m)		1.95	0.52	5.27
		Average RMS (m)		0.65	0.20	1.87
		Average Deviation (m)		0.47	0.16	1.17
		Average Starting Deviation (m)		1.15	0.17	2.91
		Average Ending Deviation (m)		0.30	0.004	0.88
		Overlap Error (% m <sup>2</sup> )		1.23	0.50	3.62
		Skip Error (% m <sup>2</sup> )		1.05	0.50	2.70
<b>Foam</b>	27	Maximum Deviation (m)	25	2.51	1.17	6.49
		Avg Maximum Deviation (m)		1.71	0.78	3.77
		Average RMS (m)		0.89	0.35	2.20
		Average Deviation (m)		0.78	0.31	2.02
		Average Starting Deviation (m)		0.65	0.02	1.90
		Average Ending Deviation (m)		0.52	0.02	2.64
		Overlap Error (% m <sup>2</sup> )		2.44	0.00	8.58
		Skip Error (% m <sup>2</sup> )		1.11	0.01	7.89
<b>Satloc®</b>	21	Maximum Deviation (m)	16	3.13	1.01	6.66
		Avg Maximum Deviation (m)		1.71	0.71	3.33
		Average RMS (m)		0.64	0.27	1.28
		Average Deviation (m)		0.49	0.20	1.04
		Average Starting Deviation (m)		0.67	0.01	2.62
		Average Ending Deviation (m)		0.32	0.003	0.95
		Overlap Error (% m <sup>2</sup> )		1.18	0.63	2.97
		Skip Error (% m <sup>2</sup> )		0.93	0.48	1.49
<b>Trimble</b>	21	Maximum Deviation (m)	20	3.68	0.87	14.39
		Avg Maximum Deviation (m)		1.74	0.67	5.28
		Average RMS (m)		0.61	0.21	1.55
		Average Deviation (m)		0.46	0.17	0.96
		Average Starting Deviation (m)		1.02	0.07	3.64
		Average Ending Deviation (m)		0.23	0.001	0.87
		Overlap Error (% m <sup>2</sup> )		1.11	0.43	4.37
		Skip Error (% m <sup>2</sup> )		0.93	0.45	3.29

Chi-square test for independence was used to determine if a relationship existed between operator variables and responses (Proc Freq procedures, SAS 2001). Variables were classified into three classifications for the analysis (age <30, between 30&40, over 40; experience <6, between 7&20, over 20; acres <2500, between 2850&6000, over 6000). Examination of chi-square statistics found that responses to the survey questions were not dependent on a drivers age, farming experience, and acres sprayed.

### **Results of Survey**

A questionnaire is an effective way to extract information concerning products. A research perspective and a non-research perspective provide different responses to different questions. These responses could prove beneficial when products require changes or improvements. In addition, questionnaires are an important tool for gathering information concerning test subjects when the test subjects are people. The following information provided an insight about the drivers and about a driver's observation in reference to the GPS guidance systems. Previously, the Operator Preference section presented responses to eight questions; a summary of the remaining questions is listed below. The value in braces [] represents the number of operators with the same response.

*Do you have prior experience with GPS guidance?*

- No experience [15]
- Less than a year [5]
- 1 to 3 years [1]

*Which guidance system do you feel more comfortable operating?*

- Trimble's lightbar [7]
- Satloc's lightbar [6]
- Marker™ [8]

*Rate your level of confidence that the GPS systems were correctly guiding you?*

- Highly confident [10]
- Moderately highly confident [8]
- Moderately confident [3]

*What lowered your confidence level?*

- Nothing [11]
- Lack of visible indicator [4]
- Not able to follow [2]
- Skeptic [1]
- Validation [1]
- Inexperience [1]

*What raised your level of confidence?*

- Faith in technology [11]
- Information provided by guidance system [4]
- Looking straight ahead [2]
- Nothing [4]
- Published literature on guidance systems[1]

*Rate each GPS guidance system based on display visibility?*

- Trimble excellent visibility [11], very good visibility [5], had good visibility [3]
- Satloc® excellent visibility [8], very good visibility [6], good visibility [1], bad visibility [1]
- Marker™ excellent visibility [9], very good visibility [6], good visibility [1], poor visibility [2]

*What was your confidence level gained in driving a straight line by looking ahead rather than to the side with foam markers?*

- Highly confident [12]
- Moderately highly confidence [3]
- Moderately confident [4]
- Moderately low confidence [1]
- Low level of confidence [1]

*Rate each GPS guidance system based on ease of operation?*

- Trimble easy [9] moderate [7] somewhat easy [4] difficult [0]
- Satloc® easy [9] moderate [3] somewhat easy [3] difficult [1]
- Marker™ easy [12] moderate [4] somewhat easy [2] difficult [0]

*Rate the guidance units method of providing course deviation?*

- Trimble easy [9] moderate [6] somewhat easy [4] difficult [0]
- Satloc easy [8] moderate [4] somewhat easy [2] difficult [2]
- Cultiva easy [9] moderate [5] somewhat easy [2] difficult [1]

*Overall, rate your performance for driving the course?*

- Good [5]
- Above average [8]
- Average [7]
- Below average [1]

*When do you plan to implement row-guidance technology on your operation?*

- Less than a year [9]
- 1 to 5 years [7]
- No response [4]
- Would not implement a guidance system [1]

*What concerns do you have about this technology?*

- Four drivers had no concerns about using the technology [4]
- Cost (included implementing, upgrading, and satellite subscriptions) [3]
- Repairing, servicing, and the down time associated with repairing and servicing [3]
- Reliability of the GPS (including beacon accuracy, DGPS accuracy, and the stability of the GPS system as a whole) [7]
- Lack of a visible indicator [2]
- Guidance systems being able to line a driver up after he or she turns [1]
- Response time of the systems [1]
- Technology going quickly out of date [2]

## **Summary of Comments**

In casual conversation, general comments usually are not noted and the information is lost. However, when evaluating new technology, comments are vital pieces of information because comments are direct thoughts from an individual and not thoughts created from a list of possible answers. During the administration of the questionnaire, the administrator noted any general comments the drivers made. The following information reports these comments on a per system basis.

### ***Trimble***

- Several drivers noticed the response time of the unit and stated that the lightbar stood out for this reason.
- Some drivers reported that the unit was too close and focusing was difficult.
- Some drivers felt that the small LEDs and numeric display was difficult to focus on as well.

- One driver noted that pushing multiple buttons to set the AB line was aggravating.

### ***Satloc®***

Of the first six drivers that ran Satloc®, two stated that pressing the switches after every pass caused a distraction. At that time, the unit's pattern configuration was back to back. After viewing the drivers' difficulties, the pattern configuration was set to closet line auto swath for the remaining drivers. The responses for these drivers are listed below.

- Several drivers commented that the mounting location of Satloc® offered a wider field of view.
- Several drivers stated that the light scheme for the unit was difficult to understand.
- Yellow LED's, indicating whether a driver was on line, were difficult to see.

### ***Marker™***

- There was one device used for configuring the unit, which made it simpler to use.
- Several drivers commented that the refresh rate on the screen was not fast enough. Drivers' noticed when using lightbars, that when they turned the steering wheel LED's would light up, when they steered using Marker™, lines would not move on the screen. This slower response time decreased the drivers' confidence that they were on line.
- The mounting location combined with the screen size caused problems for several drivers as well.
- Drivers' stated that they were concentrating more on the screen and not on driving. Drivers' felt that they were over monitoring themselves instead of driving.
- Visibility became a problem when sun angle changed. Drivers reported a glare on the screen making the unit difficult to follow.
- Some drivers struggled following the unit because of the background clutter on the screen, which made following the lines difficult.

## **“Out of the Box” Assessment**

“Out of the box” in this instance refers to the first time the guidance systems’ were unpacked, assembled, and configured. Assessment refers to whether the manuals provided information that was easy or hard to follow for assembling and configuring, and if any problems occurred when the units were first powered. The following information provides an assessment of unpacking, assembling, and configuration on a per system basis. These assessments are based on the author’s opinion.

The first thought that came to mind when unpacking Trimble’s *AgGPS*® 21 lightbar was “where is the rest of it.” General inspection of the package found that all the components for the unit were present. The manual was easy to follow and offered detailed figures for routing cables and making connections. Cables were labeled which was another added benefit. The manual provided detailed information for configuring the receiver to operate the lightbar. In addition, the manual explained the lightbar configuration steps in detail. The unit booted and ran on the first attempt. Keypad controls were well explained, and an AB line was set on the first attempt as well.

A general inspection of Satloc® found that all components were present. A first reaction to the unit was one of surprise of how heavy the lightbar felt. Overall construction was impressive and instilled a sense of toughness. The manual was easy to read and provided adequate information for connecting the lightbar with a GPS receiver. In addition, the manual provided easy-to-follow information for configuring a receiver to operate the lightbar. The unit booted and ran on the first attempt, but the unit did not recognize something in the GGA string, which caused a LED to blink. A call to Satloc®

technical support found that the unit would do that for receivers not manufactured by Satloc®. The support assured that the unit would function properly. Lightbar configuration was rather difficult. The manual was not hard to follow, but the three switches on the control box were. Changing focus from the lightbar back to the control box did not help when configuring the unit. The provided menu guide offered some relief, but the unit was still difficult to configure. An AB line was set on the first attempt, and the unit guided well.

A general inspection of Cultiva's Marker™ found that all components for using Marker™ were present. The first thought that came to mind was how impressive the course deviation indicator appeared. The manual was easy to follow and read, and system setup was not complicated. Cables were labeled which was an added benefit. In addition to the manual being easy to read, instructions for configuring a receiver was easy as well. The system booted and ran on the first attempt. Configuring Marker™ was simple and very easy to follow in the manual. Of the three guidance systems, Marker™ was simplest to configure. A strike line (AB line) was set on the first attempt and the unit functioned properly when using DGPS. Cultiva sent a new firmware version so that Marker™ would work with the RTK system. Marker™ performed well after receiving the firmware upgrade.

## Chapter V

### Summary and Conclusions

#### Summary

This study compared three GPS guidance systems, specifically evaluating accuracy based on operator responses from the different operator feedback methods. RTK GPS equipment provided guidance information for the systems, and produced positional data for the vehicles. Objectives of the study were to: 1. Using experienced agricultural equipment operators, evaluate the accuracy, ease-of-use, and operator feedback method resulting from the minimization of overlap and skip applications using selected row-guidance systems in a parallel-swathing application. 2. Compare three commercially available DGPS-based row-guidance systems for parallel-swathing applications using the industry standard, foam marker, as the control for evaluating the DGPS guidance systems.

Testing took place in August and November of 2001. Twenty-one drivers, from two locations, participated in the study. A producer from each location provided a test vehicle. Setting up the vehicle for testing consisted of fabricating and installing a mounting bracket over the steering column, and securing a metal strip to the top of the cab for antenna mounting. Installing the guidance systems and the RTK rover receiver completed the vehicle setup.

At both testing sites, field preparation consisted of laying out a course of approximately 244 m and randomly placing flags parallel to the starting and finishing

points of the AB line established course parameters. The RTK base receiver was setup in a location that provided for good satellite coverage from all angles.

Drivers operated through four randomly predefined tests using the four guidance systems, and then answered questions from the survey. The first six drivers operated two foam marker tests and only two GPS guidance systems. In order to conduct adequate comparisons, these six drivers expressed an interest in running all three GPS guidance systems and only one foam marker test. Considering the drivers' interest, the remaining drivers ran three GPS guidance systems tests and one foam marker test. A laptop computer recorded positional data for the test vehicle. Using ArcView and Excel, the positional data provided area error terms of overlap and skip, and positional error terms of maximum deviation, average maximum deviation, RMS, average, starting, and ending deviation. Using SAS® statistical computation software, area and positional error terms provided answers to the objectives listed above.

## **Conclusions**

Statistical analysis of the area and positional error terms as well as answers provided by the survey produced the following conclusions:

1. GPS guidance systems differed from foam marker for overlap, but did not differ from foam marker for skip. Even though guidance systems did not differ for skip, mean values indicated that drivers had higher skip values for foam than with a GPS guidance system. Since foam has higher mean values for overlap and skip, when compared to GPS guidance systems, it was

concluded that drivers were more accurate using GPS guidance systems than using a traditional foam marker system.

2. GPS guidance systems did not statistically differ for overlap and skip. However, examination of the means revealed that Marker™ had higher overlap and skip values, followed by Satloc® and Trimble respectively. Because mean values for Marker™ were higher, it was concluded that drivers were less accurate using Marker™. Another conclusion was that drivers were more accurate using lightbar guidance systems as opposed to using a graphical display guidance system. In addition, drivers were more accurate using a single row of LEDs as opposed to a double row of LEDs.
3. Speeds of high and low did not statistically differ; therefore, speed did not affect accuracy of the guidance systems or the drivers. Mean values were higher for the high speed, but differences between overlap and skip for high and low were 0.10 and 0.06 of a percent respectively. The differences between the means were much lower than expected, but conclude that speeds do not affect system or operator performance.
4. Passes did not differ in a manner exhibiting that a learning curve existed for a driver for both area error terms and positional error terms. This suggests that either a minimal time is required to learn a GPS system, or that test size concerning passes was possibly not large enough.
5. Operator variables age, farming experience, and acres sprayed did not statistically influence overlap error. In addition, age, experience, and acres sprayed did not statistically influence skip error. It was concluded from this

information that more experienced operators do not necessarily perform better than less experienced operators when using a guidance system.

6. When driver was statistically significant in explaining positional error terms for FOAM, driver accounted for less than 16 % of the variation. When driver was statistically significant in explaining positional error terms for GPSUNIT, driver accounted for less than 6 % of the variation. Thus concluding that positional error depended more on a driver than on the guidance system in question.
7. Responses to the survey were not dependent on a driver's age, farming experience, or number of acres sprayed for this study.
8. According to drivers' responses, the best GPS guidance system was not obvious. Drivers identified likes and dislikes for all three GPS units, and these opinions did not favor one system over another. In addition, drivers' responses regarding system performance did not favor one system over another. Therefore, one method of operator feedback did not dominate this study.

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## **APPENDICES**

## **APPENDIX A. PROGRAMS**

## DataCon1

```
REM****Datacon1.bas****
REM****Corrects GPS sentences to a****
REM****GIS-friendly format****

CLS      'Clear the screen

INPUT "Enter the source file name (**Only Root Word, No Extension**). ", file$      'Enter input file
                                                name root word

ffile$ = file$ + ".dat"      'Formulate input file name
gfile$ = file$ + ".txt"      'Formulate output file name

OPEN ffile$ FOR INPUT AS #1      'Open input file
nol = 0                          'This loop counts the
DO WHILE NOT EOF(1)              'number of lines (nol) in the
  LINE INPUT #1, a$              'input file
  nol = nol + 1
LOOP
CLOSE #1
PRINT nol

OPEN ffile$ FOR INPUT AS #1      'Open the input file again
LINE INPUT #1, trash$           'Ignore the first line in the input file

OPEN gfile$ FOR OUTPUT AS #2      'Open the output file
PRINT #2, "Longitude,Latitude,Date,UTC,GPSStat,DOP"      'Print a header line in the output file

FOR i = 1 TO (nol - 2)          'Complete the loop for all but the first and last lines in the input file

  INPUT #1, trash$      Input important values for the GGK sentence, while ignoring non-important values
  INPUT #1, trash$
  INPUT #1, utc
  INPUT #1, date
  INPUT #1, lat#
  INPUT #1, trash$
  INPUT #1, lon#
  INPUT #1, trash$
  INPUT #1, gpsstat
  INPUT #1, numsat
  INPUT #1, dop
  LINE INPUT #1, trash$      'Ignore the remainder of the sentence

  lat$ = LTRIM$(STR$(lat#))      'Convert deg-min lat into decimal deg-lat
  deglat$ = MID$(lat$, 1, 2)
  length = LEN(lat$)
  cc = length - 2
  minlat$ = MID$(lat$, 3, cc)
  deglat# = VAL(deglat$) + (VAL(minlat$) / 60)
  newlat$ = LTRIM$(STR$(deglat#))
  length = LEN(newlat$)
  IF length > 11 THEN
    a$ = MID$(newlat$, 1, 11)
    newlat$ = a$
  END IF
```

```

lon$ = LTRIM$(STR$(lon#))      'Convert deg-min lon into decimal deg-lon
deglon$ = MID$(lon$, 1, 2)
length = LEN(lon$)
cc = length - 2
minlon$ = MID$(lon$, 3, cc)
deglon# = VAL(deglon$) + (VAL(minlon$) / 60)
newlon$ = LTRIM$(STR$(deglon#))
length = LEN(newlon$)
IF length > 11 THEN
a$ = MID$(newlon$, 1, 11)
newlon$ = a$
END IF
a$ = newlon$
newlon$ = "-" + a$          'Add a - sign for west longitude

output$ = newlon$ + "," + newlat$ + "," + LTRIM$(STR$(date)) + ","      'Form an output string
output$ = output$ + LTRIM$(STR$(utc)) + "," + LTRIM$(STR$(gpsstat)) + ","
output$ = output$ + LTRIM$(STR$(dop))
PRINT #2, output$          'Write the output string to a file

NEXT i
CLOSE #1
CLOSE #2
END          'End of program

```

### LBAR3

```
REM****Program file: lbar3.bas****
REM****Logs GPS data to the hard disk****

CLS                                     'Clear the screen
INPUT "Enter the file name. ", file$   'Only enter the file name root word
file1$ = file$ + ".dat"                'Add filename extension
OPEN file1$ FOR OUTPUT AS #1           'Open data file

OPEN "com1:9600,n,8,1,cs,ds" FOR INPUT AS #2   'Initialize com port
LINE INPUT #2, trash$                  'Empty comp buffer
PRINT "Press s To Stop"                'Give the user the option of stopping the program with the "s" key
i = 1                                   'Initialize counter
DO UNTIL INKEY$ = "s"
  LINE INPUT #2, a$                    'Capture one line form com buffer
  PRINT #1, a$                          'Write the line to the disk
  i = i + 1                             'increment counter
  IF i = 21 THEN                        'Reset counter after 20 line captures
    i = 1                                'Reinitialize counter
  END IF
  IF i = 1 THEN                          'Change displayed character to let
    LOCATE 3, 3                          'the user know the program
    PRINT "*"                             'is running
  ELSEIF i = 10 THEN
    LOCATE 3, 3
    PRINT "#"
  END IF
LOOP
CLOSE #1
CLOSE #2
END                                     'End file
```

## SAS Program “Area with Foam”

The Area with Foam program analysis the guidance systems with the dependent variables of overlap and skip. Both dependent variables cannot be analyzed at the same time. To analysis skip, change the dependent variable in the model statement to skip. This is the same program used for GPS unit analysis, except foam marker data was removed from that data set.

```
Data one;
input driver system $ speed $ pass $ over skip;
cards;
Data
.....
.....
proc means; class system;
var over skip;
run;
proc means; class speed;
var over skip;
run;
proc means; class pass;
var over skip;
run;
proc mixed;
class system speed driver pass;
model over=system|speed|pass/outp=rrr ddfm=satterth ;
random driver driver*system*speed;
repeated pass / subject=driver*system*speed type=ar(1);
lsmeans system speed pass/pdiff;
lsmeans system speed pass/ADJUST=Tukey;
ods listing exclude lsmeans diffs;
ods output lsmeans=mmm diffs=ppp;
;
run;
%include 'a:pdmix800.sas';
%pdmix800(ppp,mmm);
proc univariate plot normal data=rrr;
ods listing exclude quantiles;
ods listing exclude testsforlocation;
ods listing exclude basicmeasures;
ods listing exclude moments;
var resid;
run;
```

## SAS Program “Learning Curve for Area”

This program analysis the overlap and skip data to determine if a learning curve existed for each driver and system.

```
data one;
input driver $ pass $ over skip;
cards;
Data
.....
.....
proc sort;
by driver;
proc plot;
by driver;
plot over*pass;
run;
proc plot;
by driver;
plot skip*pass;
run;
```

## SAS Program “Age, Experience, and Acres Sprayed”

The purpose of this program was to determine if age, farming experience, and acres sprayed affected overlap and skip error.

```
data one;
input driver system $ age experience acres over skip;
if age<30 then age=1;
else if 30<=age<=40 then age=2;
else age=3;
if experience<=6 then experience=1;
else if 7<=experience<=20 then experience=2;
else experience=3;
if acres<=2500 then acres=1;
else if 2850<=acres<=6000 then acres=2;
else acres=3;
cards;
Data
.....
.....
proc glm;
class age experience acres;
model over skip=age experience acres;
run;
```

## SAS Program “Positional Error”

This program analyzed the positional data to determine if driver, guidance system, or the driver/guidance system interaction had effects on positional error terms of maximum deviation, rms, average, starting, and ending error, and if a learning curve existed for each driver and system using the positional error terms.

```
data one;
***system 0=foam 1=trimble 2=satloc 3=cultiva***;
***speed 1=low 2=high***;
input driver system pass speed maxdev rms avg starter ender;
  if system=0 then FOAM=1;
  else FOAM=0;
  if system>0 then GPSUNIT=system;
cards;
Data
.....
.....
proc sort;
  by system;
proc glm;
  class FOAM;
  model maxdev rms avg starter ender=driver|FOAM;
run;
proc glm;
  class GPSUNIT system;
  model maxdev rms avg starter ender=driver|GPSUNIT;
  means GPSUNIT/tukey;
run;
proc plot;
  by driver;
  plot maxdev*pass rms*pass starter*pass;
run;
```

## SAS Program “Chi-square”

This program tested for independence between driver variables of age, farming experience, and acres sprayed and responses to questions asked in the survey.

```
data one;
input age experience acres FG $ LG $ TO $ IO $ GF $;
if age<30 then age=1;
  else if 30<=age<=40 then age=2;
  else age=3;
if experience<=6 then experience=1;
  else if 7<=experience<=20 then experience=2;
  else experience=3;
if acres<=2500 then acres=1;
  else if 2850<=acres<=6000 then acres=2;
  else acres=3;
cards;
Data
.....
.....
proc freq data=one;
  tables FG*age FG*experience FG*acres LG*age LG*experience LG*acres TO*age
  TO*experience TO*acres IO*age IO*experience IO*acres GF*age GF*experience GF*acres/
  expected chisq nocol norow nopercnt;
run;
```

## SAS Program “Descriptive”

This program produced descriptive statistics in order to summarize the error variables associated with each guidance system.

```
data one;
input system $ driver maxdev avgmaxdev rms avg starter ender over skip;
cards;
Data
.....
.....
proc sort;
by system;
proc means;
class system;
var maxdev avgmaxdev rms avg starter ender over skip;
run;
```

## **APPENDIX B. QUESTIONNAIRE**

1. How old are you?
2. How long have you been farming?
3. How many acres do you spray per year?
  - a. Personal
  - b. Custom
4. What is your level of experience with GPS guidance systems?
  - a. None
  - b. Less than 1 year
  - c. 1-3 years
  - d. More than 3 years
5. Which guidance units did you operate?
  - a. Trimble (lightbar in the cab)
  - b. Satloc (lightbar on the hood)
  - c. Cultiva (graphical display)
6. Which unit did you feel more comfortable operating during the test?
  - a. Trimble (lightbar in the cab)
  - b. Satloc (lightbar on the hood)
  - c. Cultiva (graphical display)
7. Which guidance system did you prefer? (Omit if the driver operated both lightbars)
  - a. Lightbar
  - b. Graphical display
8. Which guidance system did you prefer? (Omit if the driver operated Cultiva)
  - a. One row of LED's
  - b. Two rows of LED's
9. Which guidance method did you prefer operating?
  - a. Foam Marker
  - b. GPS guidance

10. On a scale of 1 to 5 (1 = low and 5 = high), rate your level of confidence that the GPS systems were correctly guiding you. (Guidance system as a whole)

- a. 1      2      3      4      5

11. What lowered your confidence level?

- a. Lack of visible indicator
- b. Lack of faith in technology
- c. Inability to follow the guidance unit
- d. Nothing lowered my level of confidence
- e. Other \_\_\_\_\_ (What did the driver say)

12. What raised your level of confidence?

- a. The fact that you were looking straight ahead
- b. Faith in the technology
- c. Information provided by the guidance unit
- d. Nothing raised my level of confidence
- e. Other \_\_\_\_\_ (What did the driver say)

13. Which system mounting location did you prefer? (Omit if the driver did not use the Satloc unit)

- a. Inside the cab
- b. On the hood

14. On a scale of 1 to 5 (1 = poor and 5 = best), rate the guidance units level of visibility.

- |             |   |   |   |   |   |
|-------------|---|---|---|---|---|
| a. Trimble, | 1 | 2 | 3 | 4 | 5 |
| b. Satloc,  | 1 | 2 | 3 | 4 | 5 |
| c. Cultiva, | 1 | 2 | 3 | 4 | 5 |

15. On a scale of 1 to 5 (1 = low and 5 = high), how does your confidence in driving a straight line compare in looking straight ahead as to looking reward/to side for foam.

- a. 1      2      3      4      5

16. Were there any guidance system components that distracted you while operating the test?

- a. Control boxes
- b. Input devices (keypad or switch device)
- c. No components caused a distraction
- d. Other \_\_\_\_\_ (What did the driver say)

17. Overall, which guidance system technique do you feel improved your performance?

- a. Foam Marker
- b. GPS guidance

18. On a scale of 1 to 5 (1 = difficult and 5 = easy), rate the ease of operation for the guidance units.

- a. Trimble,      1      2      3      4      5
- b. Satloc,      1      2      3      4      5
- c. Cultiva,      1      2      3      4      5

19. On a scale of 1 to 5 (1 = difficult to understand and 5 = easy to understand), rate the guidance units method of providing course deviation.

- a. Trimble,      1      2      3      4      5
- b. Satloc,      1      2      3      4      5
- c. Cultiva,      1      2      3      4      5

20. On a scale of 1 to 5 (1 bad and 5 good), overall, how do you rate your performance driving the course?

- a. 1      2      3      4      5

21. Do you see yourself implementing this technology in your operation?

- a. Less than 1 year
- b. 1 – 5 years
- c. Not in the foreseen future

22. Do you have concerns about using this technology?

**APPENDIX C. TENNESSEE AND KENTUCY STATE MAP**

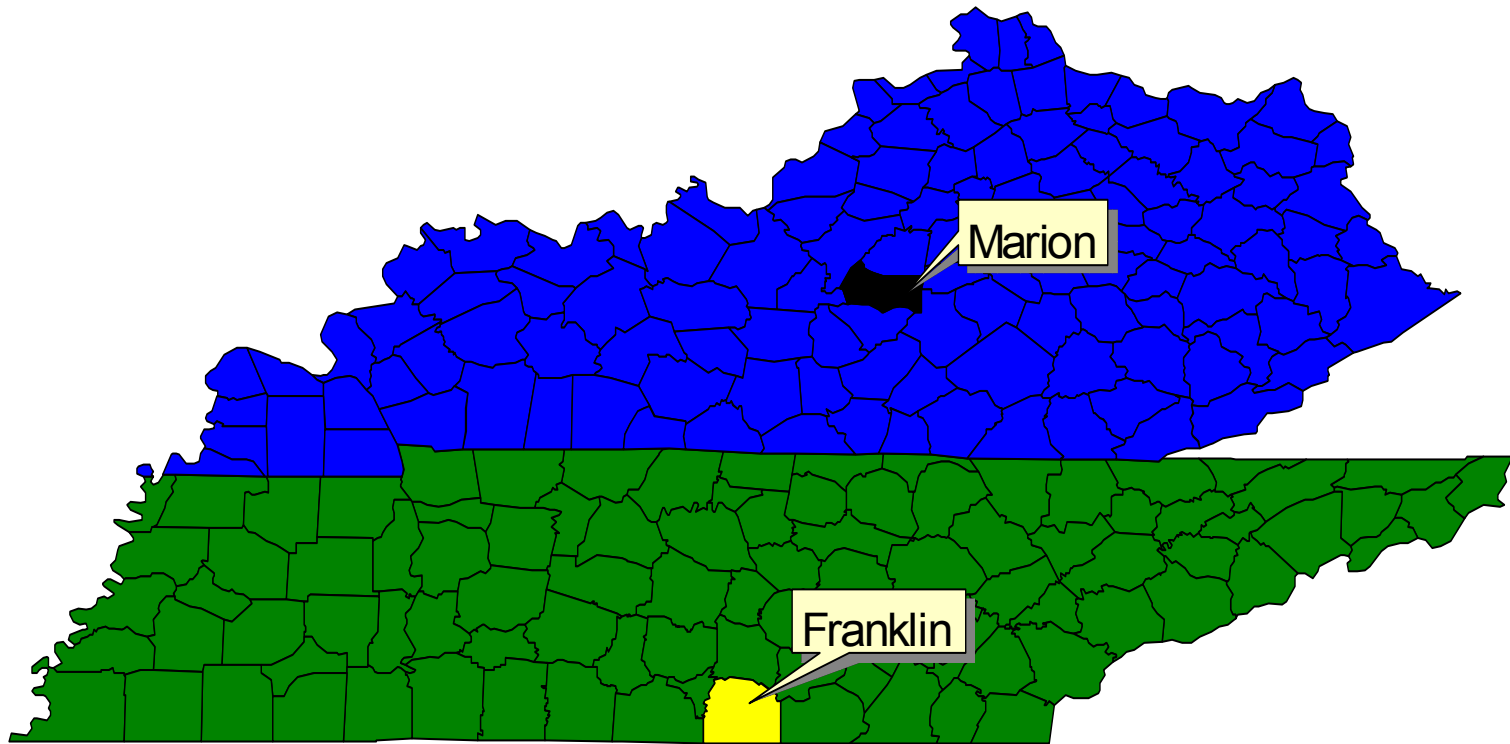


Figure B.1. Map of Tennessee and Kentucky illustrating the counties of Franklin and Marion, which were the test sites for this study.

## VITA

Timothy Franklin Morrow was born on August 31, 1976 in Evansville, Indiana. He attended Soddy-Daisy High School, and graduated in June 1995. In August of 1995 he entered Tennessee Tech University and earned a Bachelor of Science Degree in Agriculture with a concentration in Agricultural Engineering Technology in May of 1999. The following August he entered the Biosystems Engineering Technology Masters program at The University of Tennessee at Knoxville as a Graduate Research Assistant. He completed all requirements for the degree in May of 2002.