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Evaluating the Ability to Defect Foreign Objects in Crops Using Laser Range Scanners Mounted on Agricultural Vehicles

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# Evaluating the Ability to Detect Foreign Objects in Crops Using Laser Range Scanners Mounted On Agricultural Vehicles

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A thesis submitted to the faculty of Graduate and Postdoctoral Studies in partial fulfillment of the requirements for the degree of

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In Mechanical Engineering

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**Abstract.**

The general objective of this work was to evaluate the effectiveness of a Laser Measurement Systems (LMS) mounted on an agricultural vehicle at detecting foreign objects in standing crops such as Hay, Wheat, Soy, and Oats. More specifically, to evaluate the effectiveness of various algorithms and evaluating the affect of various test parameters. A SICK LMS 291-S14 scanner was placed on an agricultural tractor to scan different standing crops in which standard test objects were placed.

A high rate of detection was found for objects that were significantly taller than crops. Crop density or foliage cover had a negative impact on the detection rate for shorter test objects. Increasing vehicle speed was also found to reduce detection rates due to lower field scan resolution. The average height and density methods had greater success rates of 72.4% and 49.4%. The discontinuity and connectivity methods had a success rate of 20.6% and 18% respectively.

This system, with the conjunction of other safety systems, may be useful for ensuring safe field operation of autonomous agricultural vehicles.

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# Table of Contents

# List of Figures

# List of tables

# Introduction

An increase in the size, field capacity, and power requirements of machines have marked the evolution of agricultural mechanization in developed countries since its beginning (Stout and Cheze, 1999; Srivastava, 2006). These changes were made necessary by significant reductions in the number of agricultural workers and associated increased labour costs. Despite the many advantages that they offer on the productivity front, larger agricultural machines also have a number of drawbacks: high fixed and variable costs, increased risks of excessive soil compaction due to their mass, and important productivity losses in cases of breakdowns.

Smaller vehicles can alleviate many of these problems in addition to offering better manoeuvrability during field operations. An important goal for the future developments in agricultural machinery engineering is to rely on multiple smaller autonomous vehicles where humans are placed in a supervisory position (N.B Power, 2005). They have also concluded that the automation of agricultural vehicles offers the ability to increase driving precision compared to that currently found with human drivers.

An important step in that evolution is "developing a sensor suited for object detection and avoidance, a major step in creating safe automata." (N.B Power, 2005). Obstacle detection and avoidance issues must be addressed in the development of autonomous agricultural vehicles because of obvious safety concerns. Implementation of safety controls as well as obstacle detection and avoidance are a must for any autonomous system to be widely accepted.

The primary goal of this research project was to evaluate the effectiveness of a Lidar (i.e. **Li**ght **d**etection **a**nd **r**anging) system at detecting foreign objects placed within standing crops throughout the growing season. End use applications of such a system could include the detection of inanimate objects, animals, or humans. The end purpose of the system will be to detect any object or element that may cause damage to either the agricultural equipment or the obstacles present in a field during the operation of autonomous agricultural vehicles.

This thesis includes five sections including this introduction. Chapter 1 presents a review of the relevant literature in the areas of autonomous agricultural vehicles and machine vision as applied to the detection of obstacles in agricultural fields. The equipment and experimental methods used in this study are presented in Chapter 2. The results obtained from the four methods used to analyze the raw experimental data provided by the laser scanning apparatus are presented in Chapter 3. The final section is comprised of the conclusions and recommendations that resulted from this study.

# Chapter 1. Literature Review

## *1.1. Autonomous Agricultural Vehicles*

Similar to what is observed in other sectors of the transportation industry one can note a growing interest for agricultural applications of autonomous vehicles. Current technologies and research for autonomous agricultural vehicles include global positioning systems (GPS), fibre optic gyroscopes (FOG), near infra-red (NIR) image sensing, Doppler radar, microwave, acoustic, and other optical position and vision technologies (Reid, 2002). GPS constitutes one of the more popular solutions for field equipment positioning with accuracies narrowed to 2 cm or less with onsite Real-Time Kinematics GPS systems (Heraud and Lange, 2009). Manual control is still needed for headland operations at the end of fields. Fully autonomous agricultural vehicles will ultimately have to be responsible for their complete operation as well as for the overseeing of the field operations to ensure the safety of the machines as well as of its surroundings (Reid, 2002).

Many challenges are expected to be encountered while developing accurate object detection systems in agricultural environments:

1. Need to isolate potential dangers within path, off of field objects, field inclinations, weather (rain, fog), and lighting changes.
2. Filtering through biological foliage
3. Tractor vibration noise
4. Distinguishing rocks from clods (reflectivity)
5. Detecting Water Hazards
6. Trajectory forecasting of moving objects
7. Appropriate actions after detection (stopping or altering trajectory)

## 1.2. Soil Compaction

Previous studies have identified the need to reduce vehicle mass as a primary method of reducing deep subsoil compaction (J. Kirby and Raper, 2006). Similarly, computer models determined that the axle load was also the prime factor in deep soil compaction. As opposed to surface compaction, which can mostly be eliminated with surface tillage or management system, subsoil compaction is longer lasting and may be (J. Kirby and Raper, 2006). Another potential benefit of using lighter agricultural vehicles is the elimination of the requirements for large horsepower tractors for subsoiling, due to the improved soil structure (J. Kirby and Raper, 2006). Thus, the use of fleets of smaller autonomous agricultural vehicles in place of larger human-operated machines should result in decreasing soil compaction risks. By further restricting axle loads to 6 Mg or less, it should be possible to only deal with manageable topsoil compaction issues.

## 1.3. Economics

Here are a few characteristics that will likely be involved in the use of autonomous agricultural vehicles. A larger crop area can be managed by one human supervising a fleet of smaller autonomous vehicles. The amount of downtime will be greatly decreased when removing the human factor (e.g. no breaks, no daylight restrictions, etc), which may lead to 24 h/day operation. Comparing the field capacity of an autonomous operation (130 – 1 950 ha/day) to that of an 8-hour working day (43 – 805 ha/day) the area covered may be increased by a factor of 2.5 to 3 (Goense, 2005).

It can also be economically viable for larger and often used equipment such as combines, forage harvesters, and sprayers with a production cost greater than $170,000 to be made autonomous before smaller agricultural vehicles (Reid, 2002). This author also suggested that the research be conducted on smaller and less expensive vehicles such as utility vehicles.

## 1.4. Safety Emphasis

Three factors must be considered when considering obstacle detection methods. The first is the safety of humans near autonomous vehicles. The second is to avoid damage to the surrounding environment, and the third is the safety of the vehicle itself (Stentz *et al.*, 2002). The vehicle must avoid contact with any object in which it could cause damage to, or be damaged by. A categorized list of such obstacles or barriers is provided below (Hollnagel, 1999).

- Material barriers such as buildings, walls, fences.
- Functional barriers that can impede the work to be conducted, usually pre-conditions.
- Symbolic barriers such as reflective posts, road signs, visual or auditory.
- Immaterial barriers such as rules, guidelines, laws, property lines.

Safety for autonomous vehicles is not a simple approach. (Wardziński, 2008) states that the "safety analysis methods for situation awareness model and dynamic risk assessment are not mature and are the subject of further research."

## 1.5. Tractor Vibrations

Considering the environment in which tests will be conducted, tractor vibration is expected to cause range data noise introducing outliers. "The vibration conditions to which tractor operators are subjected are complex and varied with multi axis translation and rotational vibration inputs to different parts of the body" (Muzammil *et al.*, 2004). These vibrations are expected during our tests due to the similar un-even terrain and lack of stabilization system for the Laser Measurement System (LMS). Possible solutions include the installation of a stabilization system for the LMS to reduce the amplitude of any vibrations as well as the keeping the pitch and roll of the LMS to a constant. Installing an Inertial Navigation System (INS) or accelerometer on the LIDAR scanner may allow us to measure the vibration of the Lidar and allow a correction to the measurements taken.

## 1.6. Sensing Systems

As an object detection system, many sensing systems are available such as radar, Lidar, thermal imaging, sonar (ultrasonic), stereo vision, and camera vision. Because of the specific conditions encountered in agricultural field environments, many of these may be omitted such as sonar, stereo vision, and camera vision. Sonar does offer some advantages that typical time of flight techniques do not. These include frequency modulation, the ability to use the Doppler effect, and amplitude based interpretation. Sonar is dismissed because of its general lack of accuracy and typical need for a medium (other than air) for efficient sonic or ultrasonic wave propagation. Atmospheric conditions such as temperature variations and wind may also have effect on accuracy. Typical sonar devices for robotic use have slower response time and lower measurement frequency compared to laser range finder (Aboshosha and Zell, 2003).

Millimetre wave radars as well as SICK LIDARs are commonly used in current off-highway obstacle detections systems, especially for the Defense Advanced Research Projects Agency (DARPA) organized Grand Challenge. Both systems are simultaneously used to profit from each others advantages and reduce disadvantages. The millimetre wave radar is used for a range of 50m while the short range bumper-mounted SICK LIDAR has an approximately 25m range, depending on the specific sensor used (Johnston, 2006). (Sugimoto *et al.*, 2004) were able to use a millimetre wave radar with a CCD camera for obstacle detection. A calibration was required to synchronize the camera and radar frame of references. They found that it was "extremely difficult to detect (objects) and measure their accurate position by radar with low directional resolution".

It was also found that when using radar, the "intensity of radar backscatter returns is a pour indicator of danger to a vehicle despite the attempt of several projects to show otherwise" (Johnston, 2006). It was also found that objects such as guard rails, fences and posts create a small backscatter and could cause intense damage to agricultural machinery if undetected and struck by the machinery.

Stereo vision consists of two cameras with the same field of view and is capable of evaluating its 3D properties. Often this method is used to determine object distances using multiple images taken from different viewpoints (Payeur, 2004). Because vision "is much more sensitive to environmental conditions, in particular for outdoor applications" (Hebert, 2000), there are limitations of this technology for practical use in agricultural applications. Stereo and Camera Vision are both dismissed for the same reasons, including reduced visibility in low light, fog, and rain. Stereo vision requires high computation processing for accurate object positioning.

LMS or Laser Scanners have become a common tool in obstacle detection, mapping, and navigation in agricultural applications (Lee and Ehsani, 2008). "New techniques for robust operation of range sensors in hostile environmental conditions have substantially increased the possibilities in field robotics" (Hebert, 2000).

### 1.6.1. Machine Vision Algorithms

Specific algorithms have to be used to filter out typical foliage feedback in order to accurately identify foreign objects. Filter calibration will most likely be required due to the various crop densities and scanner locations. With Lidar scanners, the data returned are in 3D spatial points also known as range data. The data points returned from a typical crop are expected to be a random scatter because of the small surface area of each plant. Signals returned from an object of significant size should be composed of a dense cluster of points. As the vehicle travels forward, a greater area of the object is scanned and thus a 3D model can be rendered. It should be noted that because only one side of the objects are scanned, 3D information on the back side is unknown.

## *1.7. Range Data Mean and Standard Deviation*

The first analysis that can be done from the range data is analysing the mean and standard deviation of the results as the scan plane passes over the objects. If there is no significant change in either mean or standard deviation, than that may mean that the foliage is too dense or the objects too small for detection. Range data may need to have a calibration process to set-up an upper and lower limit for both the mean and variance values.

The scanning plane may also be sectioned and analyzed per section. The mean and standard deviation of each section may be compared to each other as well as the overall values. If one or many of these sections do not comply with the overall average, the section in question may need to be further examined.

## *1.8. Prior knowledge Input/ Space Clipping*

This type of process can allow the user to greatly simplify the processing requirements and data management (Gong and Caldas, 2008). A typical example used to explain this process includes the prior knowledge of the floor or ground position. Floor position is the relative distance of the ground to the LMS. This allows the user to "filter out ground-floor-related data points" (Gong and Caldas, 2008). With a reduced number of data points, the detection algorithm may have quicker processing time to detect objects. This method can be used to eliminate data points caused by known obstacles or fluctuating terrain slopes.

## 1.9. Stopping Requirements

From ASABE Standards 2006, typical operating speeds for agricultural field operations may range from 5 to 15 km/h depending on the operation itself as well as specific field conditions (Appendix A). If obstacles are detected in the vicinity of autonomous agricultural machines during operation, the vehicle may be required to stop. It is important that the maximum distance at which an obstacle can be detected be at least equal to the maximum vehicle stopping distance.

Table 1-1 presents the maximum stopping distances for agricultural vehicles according to ASABE Standard 9.1.2 Stopping performance as well as the corresponding maximum scanning angle for different types of agricultural vehicles and different field operating speeds. Maximum stopping distance for various categories are shown below, (ASABE, 2006).

**Table 1-1: Classification of Agricultural Vehicles(ASABE, 2006)**

| **Classifications of agricultural field equipment** | |
|---|---|
| Category-I | Agricultural Tractors |
| Category-IIa | Self-Propelled Agricultural Machines |
| Category-IIb | Special Self-Propelled Agricultural Machines |
| Category-III | Agricultural Trailers |
| Category-IV | Towed Agricultural Machines |

Below are the stopping distance equations for the various agricultural vehicle categories listed above.

$$S = \frac{V^2}{6.27} + \frac{V}{3} \tag{1}$$

S = stopping distance for categories I, IIa, III, and IV [m]

V = initial velocity [m/s]

$$S = \frac{V^2}{3.52} + \frac{V}{3} \tag{2}$$

S = maximum stopping distance for category IIb and combination of braked and un-braked machines of categories I and III, I and IV, IIa and III, IIa and IV [m]

V = initial velocity [m/s]

From , we find that for tillage and planting the average speed is 9.3km/h, for harvesting the average speed is 7km/h and 8.5 for others.

For each of the machine categories and maximum stopping distances, it is possible to calculate the maximum scan angle at which an object must be detected to be able to stop before a collision occurs (Equation (3)).

$$\theta = \tan^{-1}\left(\frac{LMS\ Height}{stopping\ dist}\right) \tag{3}$$

$\theta$ = max required scan angle

Stopping dist = minimum braking distance from equation (1) and (2) [m]

LMS Height = Height of scanner on vehicle [m]

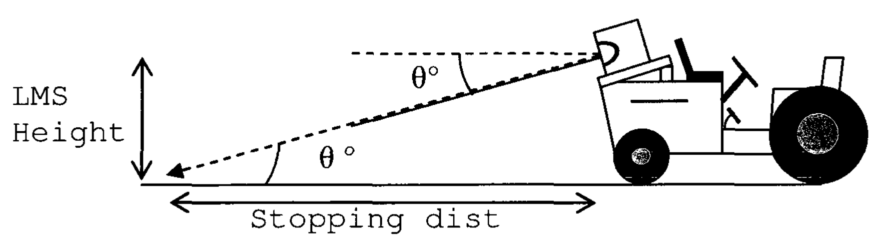



**Figure 1.1: Stopping Dist and Scan angle diagram**

Table 1-2 presents values of maximum scan angles for different travel speeds and different categories of agricultural vehicles.

**Table 1-2: Minimum braking distance and required scanning angle**

| | **V = 5 km/h** | **V = 7.0 km/h** | **V = 9.3 km/h** | **V = 15 km/h** |
|---|---|---|---|---|
| Maximum braking distance for categories I,IIa, III, and IV [m] | 0.77 | 1.25 | 1.93 | 4.16 |
| **Max Req. scan angle [°]** | 56.63 | 43.08 | 31.28 | 15.72 |
| Maximum braking distance for category IIb and combinations of braked and un-braked machines of categories I and III, I and IV, Iia and III, Iia and IV [m] | 1.01 | 1.72 | 2.76 | 6.32 |
| **Max Req. scan angle [°]** | 49.17 | 34.19 | 22.99 | 10.49 |

For the purpose of this work, no importance is given to the distance, from the tractor, at which an object is detected. This is because of two reasons. The first being the fact that we did not place the test objects in the path of the vehicle. The second reason is because we did not analyzing the field data in real time. As we will explain in Chapter 2, we have analyzed the data as a whole field. We evaluated the potential of the LMS to distinguish between objects and the crops and not evaluating whether it can evaluate the objects in time to avoid collisions.

## *1.10. Specific Objectives*

As indicated in the Introduction, the primary goal of this research project was to evaluate the effectiveness of a Lidar system at detecting foreign objects placed within standing crops throughout the growing season. Two specific objectives were pursued in this work. The first was to evaluate the effectiveness of four different signal-processing algorithms at detecting foreign objects placed within crops in order to identify the most promising ones. The second specific objective was to identify the effects of various field test parameters (type of crop, plant growth stages, object type and size, scan angle, and travel speed) on the effectiveness of each algorithm and on the object detection rates. It is not expected to design a reliable detection system solely with the use of an LMS. We evaluated whether or not an LMS has a place in a greater obstacle detection system that may use a variety of sensors. Such a system can use the information from many sensors to evaluate the probably and tracking of other in field objects.

# Chapter 2. Equipment and Methodology

## *2.1. Field Experiments*

### 2.1.1. Scanner, Scanner Location and Tractor

A delicate balance is required to establish an appropriate location for the scanners. Positioning the device near the center of gravity (CG) of a vehicle generally reduces the vibration noise during operation. It is very difficult to place the scanners at the CG on most agricultural vehicles, and consequently finding the next best appropriate location should be attempted for each vehicle.

Placing a Lidar scanner above the crop and oriented downwards is expected to provide a better view angle through the foliage for object detection but at a consequence. At this position the vibration noise is expected to be amplified and harder to compensate. A stabilization system could be used to mitigate this movement. Installing an Inertial Navigation System (INS) or accelerometer on the LIDAR scanner may allow us to measure the vibration of the Lidar and allow a correction to the measurements taken. The forward view is also limited as we increase the scan angle.

An alternate position is near the front end bumper of the vehicle. This allows for a field of view parallel to the ground. In this configuration, the field of view is not limited by the ground and scan angle but by the crop density. Positioning the LIDAR to scan through the crop will most likely reduce its range. As the crop density increases the LIDAR's range of view will decrease because the LIDAR is based on a line of site method.

For the purpose of this research, the Laser Scanner was placed on the front hood of a commercial agricultural tractor (*Kubota B6200)* above the crop line. The scanning plane was oriented down from the horizon at 20° and 30°. With our maximum test scan angle of 30° we are below the maximum allowable stopping distance for our max speed of 7km/h, which is 43.08°. The 90° scan plane was also oriented to the left to cover the second quadrant of the Cartesian plane with 90° being the direction of travel. The scanner was oriented in this direction to minimize the scanning of the vehicle tracks as well as maximizing the view of the crop. It should be noted that the vehicle track was placed along the side of crops to avoid any crop damage caused during the tests.

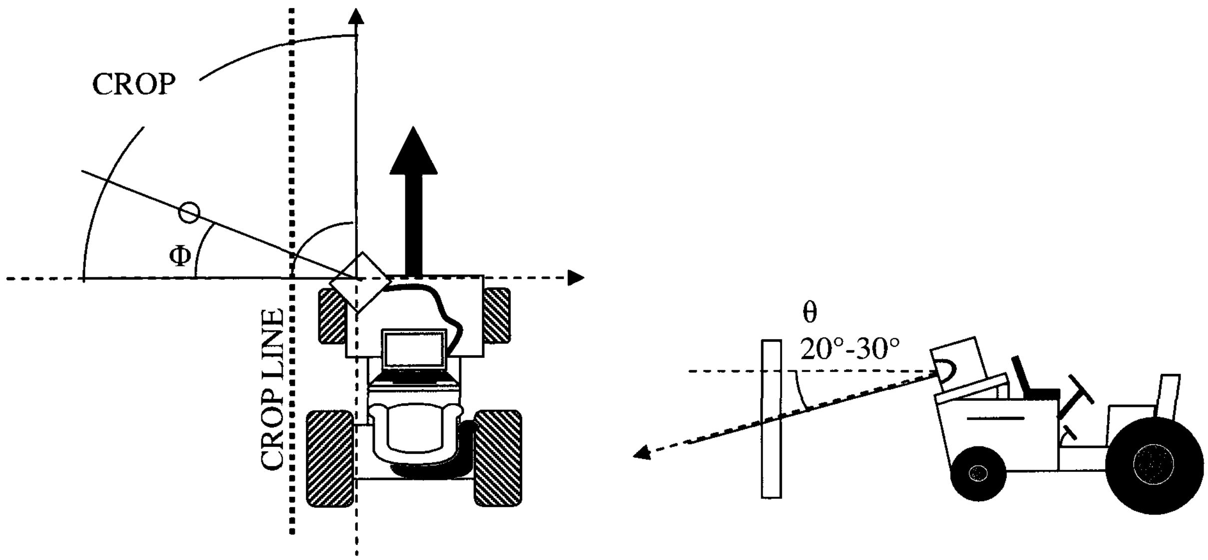



**Figure 2.1: Laser Scanner Location**

The SICK LMS 291-S14 model is a laser measurement system that sends and receives infra-red beams in a 90° sweep and uses time of flight to return range data. This product is often used in autonomous robot navigation and obstacle detection. Examples of such applications include the DARPA challenge, terrain mapping (Wong), and other agricultural robot applications (Blackmore *et al.*, 2004).

The LMS are typically used for:

- Area monitoring
- Object measurement and detection
- Determining positions

Below are some of the key features and advantages that this product provides (Sensor Intelligence, 2006):

- Rapid scanning times, thus measurement objects can move at high speeds
- No special target-object reflective properties necessary (no reflectors required)
- Background and surroundings have little or no influence on measurements

- Data are available in real-time and can be used for further processing or control tasks
- No illumination required
- Simple mounting
- Completely weatherproof

The model used for the experimentation is the LMS 291-S14, also known as the LMS-FAST manufactured by SICK Inc. This model is intended for an outdoor function with an indoor housing, has a 90° scan angle, a 0.5° resolution, and a 13.3 ms response time (75Hz)(Sensor Intelligence, 2006). This model will also return the range data as well as the reflectivity for each range set. There are 181 values returned starting from 0°, 0.5°, to 90°. The data received from the scanner are represented in polar coordinates with the scanner as the origin. Included in the scanner software is the ability for the scanner to correct the data in the presence of fog.


**Figure 2.2: Picture of SICK LMS**

#### 2.1.1.1. Agricultural Machinery:

The tractor used for this experimentation was a Kubota B6200 with the approximate front end dimensions shown in Figure 2.3.

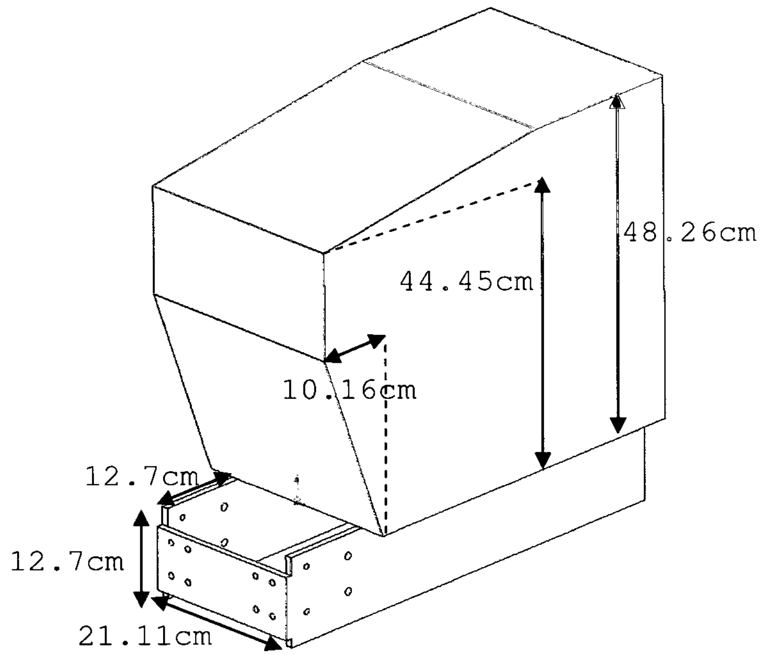



**Figure 2.3: Approximate Front end Kubota Dimensions**

**Figure 2.4: Kubota B6200 with SICK LMS291-S14 and Laptop**

#### 2.1.1.2. Vehicle Speed

Because the Kubota tractor had no accurate speedometer, the speed was tested and calibrated at various engine speeds and gears on a 30 m track where we measured transit time and calculated average speed. The three test speeds used during the study were 2, 4, and 7 km/h.

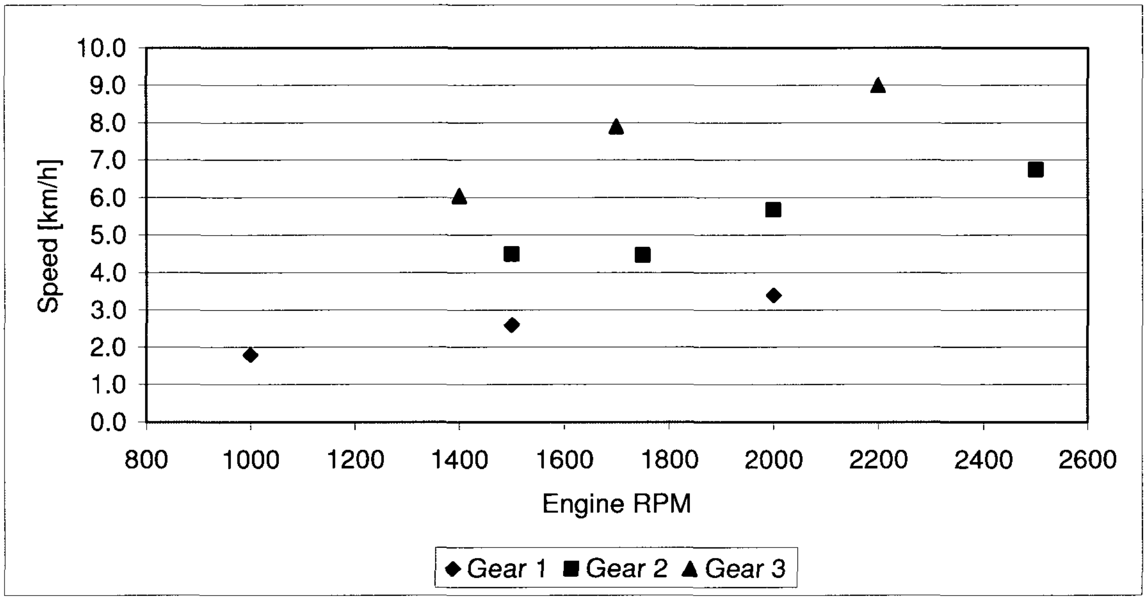



**Figure 2.5: Kubota Speeds**

For a slow speed of 2 km/h we had the engine turning at 1100 rpm in First Gear. For a medium speed of 4 km/h the engine ran at 1700 rpm in Second Gear. For a speed of 7 km/h, the engine ran at 1500 rpm in Third Gear.

The power requirements for the SICK LMS 291-S14 are very specific and thus we used a 9-18V to 24V power converter. The LMS 291 requires 24V±15 % and a power consumption ≤ 20W (Sensor Intelligence, 2006). We installed an SD-50A-24 Converter to draw power from the tractor's 12V battery and provide 12V for the LMS.

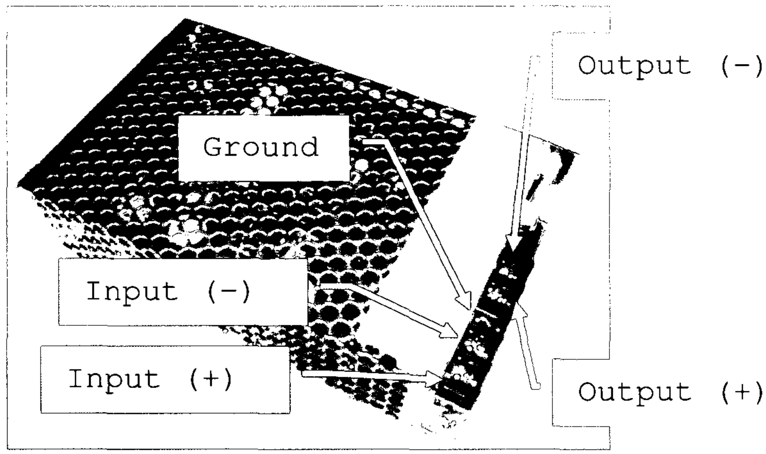



**Figure 2.6: Power Converter**

A power switch was also installed between the converter and the Kubota tractor to reduce the battery load when the LMS is not in being used and/or the tractor is not being operated. The Red and Brown wires from the LMS were connected to the V+ and V- (Outputs) of the converter respectively. The Brown wires corresponds to the GND(ground) from the power supply and the Red for the 24V DC ±15% as seen in Table 7-2 of the Technical Description Guide (Sensor Intelligence, 2006). Note that the other wires from the LMS were not used.

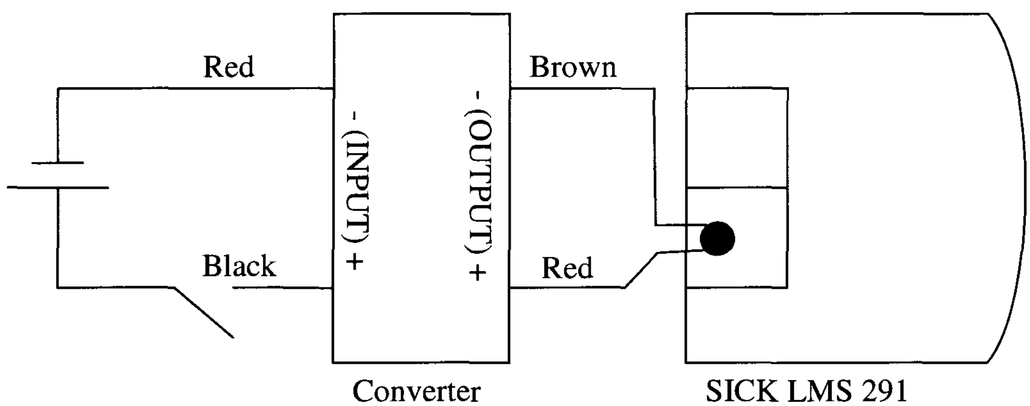



**Figure 2.7: Power Source Set-up**

#### 2.1.1.3. Data Interface Installation

The SICK LMS 291-S14 was connected via RS-422 Serial connection which was then converted to USB using the USB-COMi-M serial to USB converter. The LMS factory setting was wired for an RS-232 connection. The wiring was then converted to RS-422 for increase baud rates (Miller and Derenick, 2008).

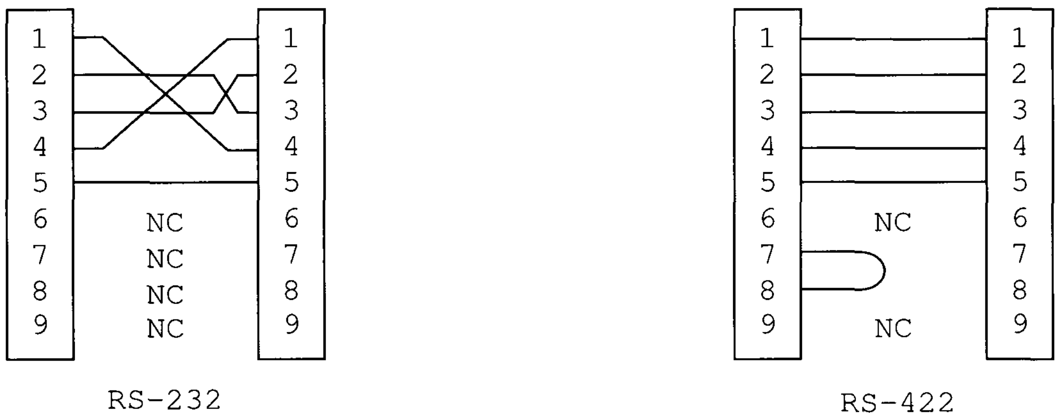



**Figure 2.8: RS-232 and RS-422 serial configuration**

### 2.1.2. Experimental Site and Crops

Due to practical limitation, initial development of this system was limited to four specific types of crops: wheat, hay, soybeans, and oats. These limitations include availability of field sites and available time. These four crops are considered representative of the many crops that a tractor is used for.

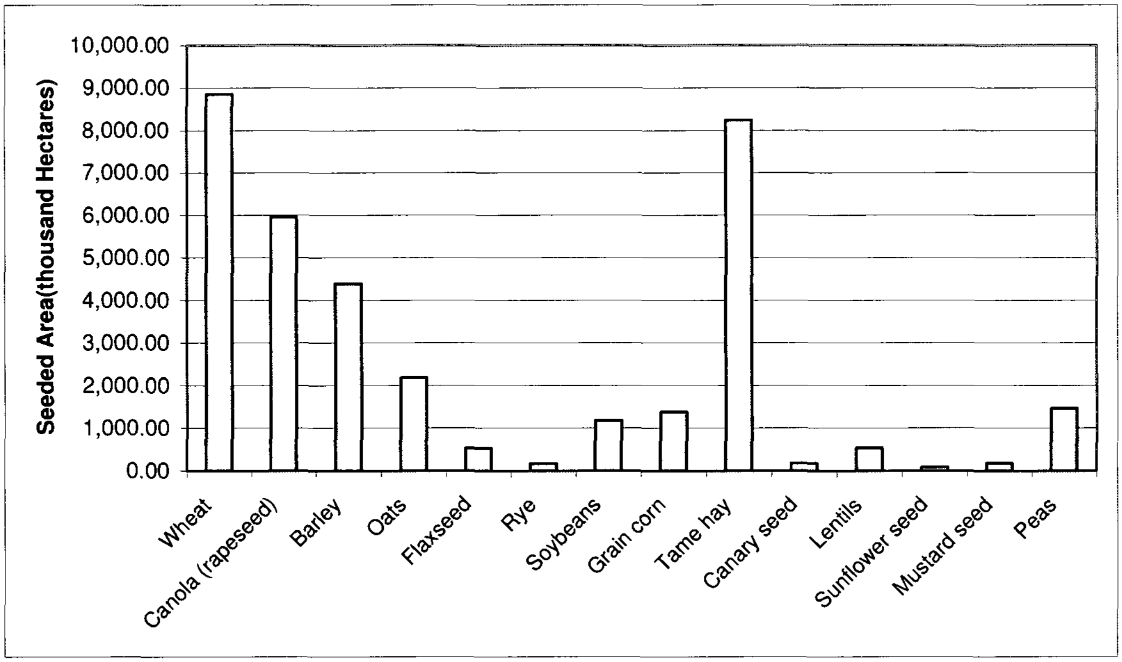



**Figure 2.9: Field and specialty crops (Seeded area),(StatsCan, 2007)**

Testing took place in August and September 2008. Due to our late season arrival to the experimental site; we were only able to obtain test results for one growth stage of the wheat. The measured height for the wheat field was 75-cm and was our tallest crop. The oat crop was tested with a measured height of approx 60-cm during a single growth stage. The hay fields were tested at two growth stages, 20-cm and 40-cm. The hay field had a much wider range of height where tuffs of grass were significantly taller than other areas. The hay had a much lower uniformity in height and density compared to the other fields. The soybeans field's height was a constant 70-cm with varying canopy density for the two growth stages. In the first growth stage, the soy leaves were full and un-withered leaving a full and dense canopy. In the second stage, most leaves had withered leaving a visible plant stem.

The experimental site was located at the Eastern Cereal and Oilseed Research Center, Ottawa, Ontario. The crops used were located on the south east corner of the site. Each crop was conveniently located along Morningside Lane which allowed easy travel between sites. Figure 2.10 shows the exact location for each crop as well as an arrow representing the tractors test path.

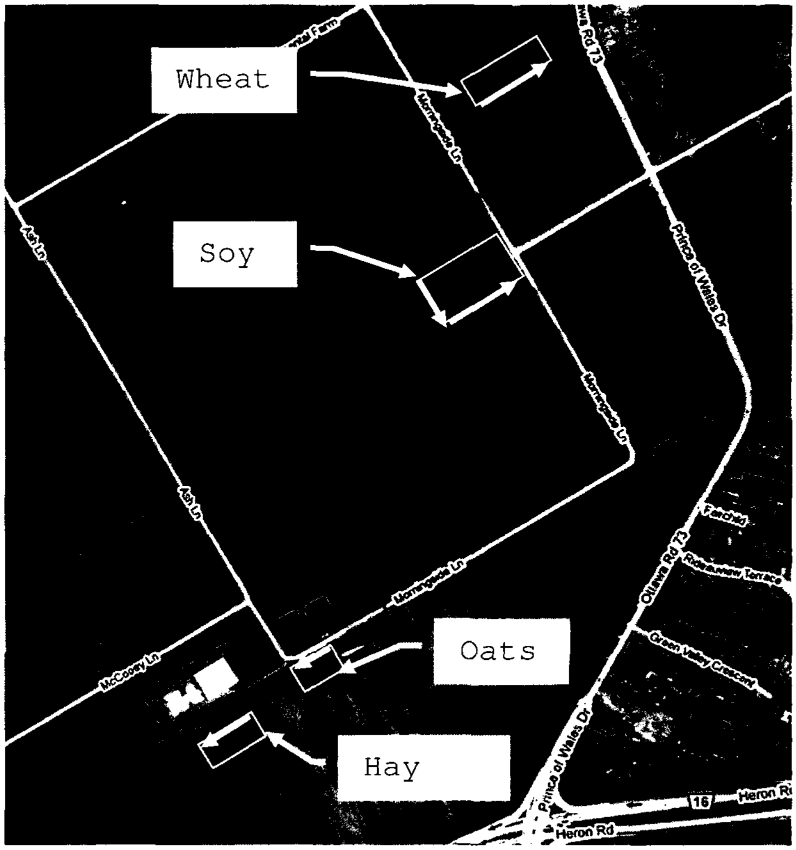



**Figure 2.10: Satellite view of experimental sites at the Central Experimental Farm, Ottawa, ON (Google, 2009)**

### 2.1.3. Test Objects

Three types of test objects were used, the first was a tall rectangular shaped box. The second was a tall cylindrical shaped box. Both were 1.83 m tall and were respectively 17 cm wide and 14 cm in diameter. The third is similar to the cylindrical object but at a height of 0.6 m. The smaller test object was used to test the ability of the system to scan and detect objects that were approximately the same height or shorter than the average crop canopy. The tall square test object is labelled (TS), the tall cylindrical test object is labelled (TC), and the short cylindrical object is labelled (SC).

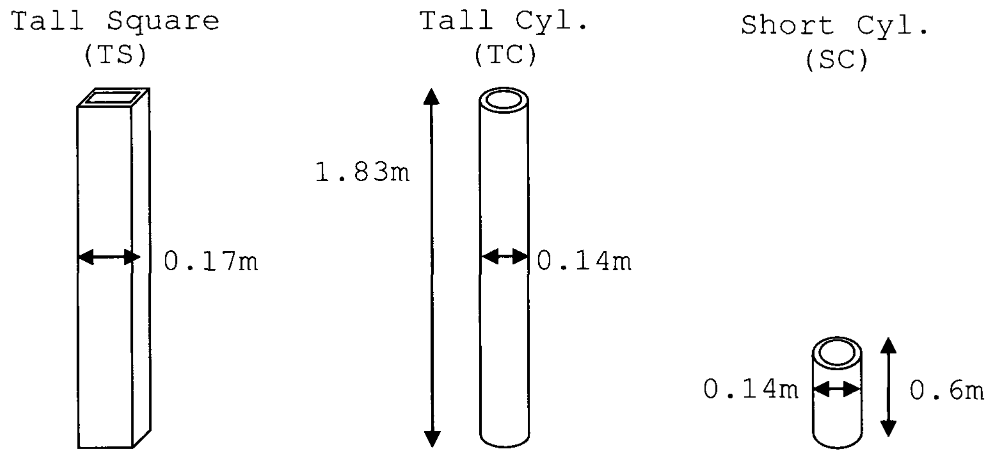



**Figure 2.11: Test Objects**

The reflectivity of the objects has a significant effect on the ability of the Laser scanners to return a data point at greater distances (ex: 10 m). To stay within the scope of this research project, the test objects were made from builder's tubing (Cardboard) and wood which has a reflectivity of 20% and 40% respectively (Sensor Intelligence, 2006). Because we did not expect to obtain range data greater than 10 m, which requires a minimum of approx 10% reflectivity (Sensor Intelligence, 2006), the reflectivity of the object material should not have a significant effect on the results.

A reference flag was placed 10m behind the objects along the crop edge and was used as a reference point for each field scan. Because the tractor and LMS passed directly in front of the flag, causing very low range data values, its location could be used to find the theoretical object location within the map matrix.

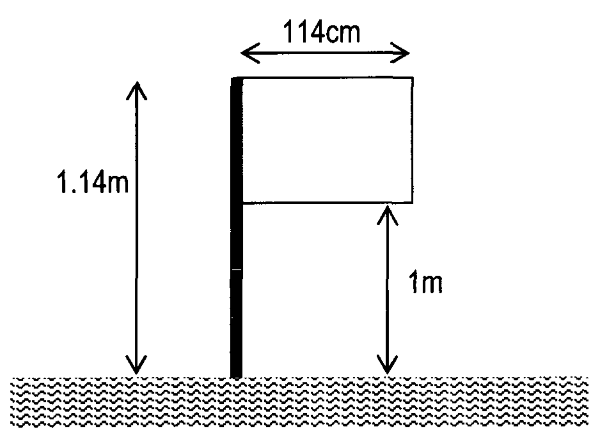



**Figure 2.12: Reference Flag and Dimensions**

### 2.1.4. Experimental Design

Testing was attempted during three crop growing periods; initial crop development, mid-season, and late season. Actual field experimentation focussed on the later stages of the growing season due to the increased difficulty to distinguish between test objects and crops.

**Required Equipment List**

1. Laser Scanner
2. Agricultural Vehicle
3. Three test objects
4. Mounting plate for scanner
5. Computer
6. Speedometer/odometer
7. Power Supply & Converter/Regulator
8. Serial to USB converter

The total number of tests required to for each of the parameters listed below is 648, including three tests for each setup. For each growth period 144 tests are required and for each crop there are 48. Due to time restrictions not all tests were performed. As explained in section 2.1.2 we were not able to test in all growth stages. Only for the Soy and Hay crops was a second seasons tests performed. This greatly reduced our total number of tests to a total of 292. For the complete test list please refer to the appendix B.

**Table 2.1: Test Parameters and planned number of tests**

| Parameter | Variables | Planned | Actual |
|---|---|---|---|
| Season | Early season | 3 | 1.5 |
| | Mid-season | | |
| | Late season | | |
| Crop | Wheat | 4 | 4 |
| | Hay | | |
| | Soybean | | |
| | Oats | | |
| Object | Cylindrical | 3 | 3 |
| | Square | | |
| | Short | | |
| Scanner Angle | 20 | 2 | 2 |
| | 30 | | |
| Speed of Vehicle | Slow, 2km/h | 3 | 3 |
| | Medium, 4km/h | | |
| | Fast, 7km/h | | |
| # of Tests | 3 | 3 | 3 |
| | **Total # of Setups** | 216 | 108 |
| | **Total # of Tests** | 648 | 324 |

The slight discrepancy between table value (324) and final actual tests performed (292) is because not all slow, 2km/h tests were performed in the wheat and oat field as well as in the first season of the hay field.

The results for each test are labelled in accordance to all the test parameters listed in . Each test is named as such (C_S#_O_SA_V_T). The C is either H(hay), S(Soy), O(Oats), and W for (Wheat).

**Table 2-1: Test name labelling**

| | |
|---|---|
| C | H = Hay<br>O = Oats<br>S = Soy<br>W = Wheat |
| S# | Growth Stage 1 = S1, S2, S3 |
| O | Tall Square(TS) = S<br>Tall Cylindrical(TC) = C<br>Short Cylindrical(SC) = L |
| SA | Scan angle = 20° or 30° |
| V | Travel Speed = 2, 4, or 7 |
| T | Test Number = 1, 2, or 3 |

As an example for a test where the Hay crop was tested in its first growth stage, with the tall square object, at 20°, with a travel speed of 7km/h, and on the third test, the annotation is H_S1_S_20_7_3.

## 2.2. Data Acquisition and Analysis

This project aimed at identifying foreign objects in a field using LIDAR placed on a moving vehicle. The objects were embedded within the crop, thus resulting in the need to scan through the crop to identify the object. Multiple tests were conducted with varying parameters as indicated in Section 2.1 above.

With successful object detection, visual spike of values, the level of success was also based on the matrix values at the object location for each method. These results will help gauge the ability for an autonomous vehicle to detect objects embedded in the crops.

Two of the test objects were fabricated to be taller than the average crop height. An evaluation of the scanner's ability to penetrate the "crop height line" could be conducted after the data recordings. Objects of various sizes were also used to evaluate the scan resolution. To simplify our system, testing and modeling were conducted with the assumption of a flat terrain. The introduction of variable terrain gradient would greatly increase the number of system variables. Thus, for the purpose of this research project, tests were conducted on relatively flat terrain.

### 2.2.1. Data Acquisition

Multiple software methods are available for data acquisition such as Matlab, C++, and other software toolboxes (Derenick, 2009). We were able to keep the programming and data acquisition language in Matlab. Research at Carnegie Mellon found that "While Matlab allows rapid prototyping of complex software systems, it is fundamentally unfit to run real-time field applications"(Wong). Because the purpose of this research was not to run a real-time system but more to analyze the ability to detect objects with Laser scanners, Matlab was deemed to be a suitable program.

The MST demo program provided by SICK was used to record the range data directly from the LMS and convert the data into text files for later analysis. We used Matlab to read the data from text files and inserted them into data matrices.

Figure 2.2.1 presents the first few lines of a text file example of the data recorded using the MST demo program:

```
Filename;StartAngle[°];StopAngle[°];Resolution[°*100];ScanStepWidth;ExportChannelNumber;Date[mm/dd/yyyy];Time[hh:mm:ss]
LMSData.dat;45;135;50;1;0;07/28/2008;15:18:30
Record Number;Scan Index;Telegram Index;Interlaced Scan Number;Begin Data
1;0;0;0;8047;7966;7900;7839;7775;7715;7633;7593;7539;7478;7388;6311;6441;6281;6143;6011;5838;5688;5630;5496;5450;...
2;0;0;0;8045;7973;7902;7832;7779;7705;7645;7597;7535;7468;7390;6318;6438;6295;6133;6012;5845;5699;5631;5498;5442;...
3;0;0;0;8038;7971;7902;7827;7766;7711;7631;7584;7533;7479;7386;6753;6439;6296;6127;6014;5846;5697;5631;5498;5433;...
```

**Figure 2.13: Range Data text file example**

Matlab was then used to open each file, ignoring the first 3 lines and the first 4 columns that are separated by semi-colons. The subsequent values which are delimitated by semi-colons are placed into a matrix. Each value represents the distance recorded with the column number corresponding to each scan angle value increasing by 0.5° for each column. The polar points are then converted into Cartesian values.

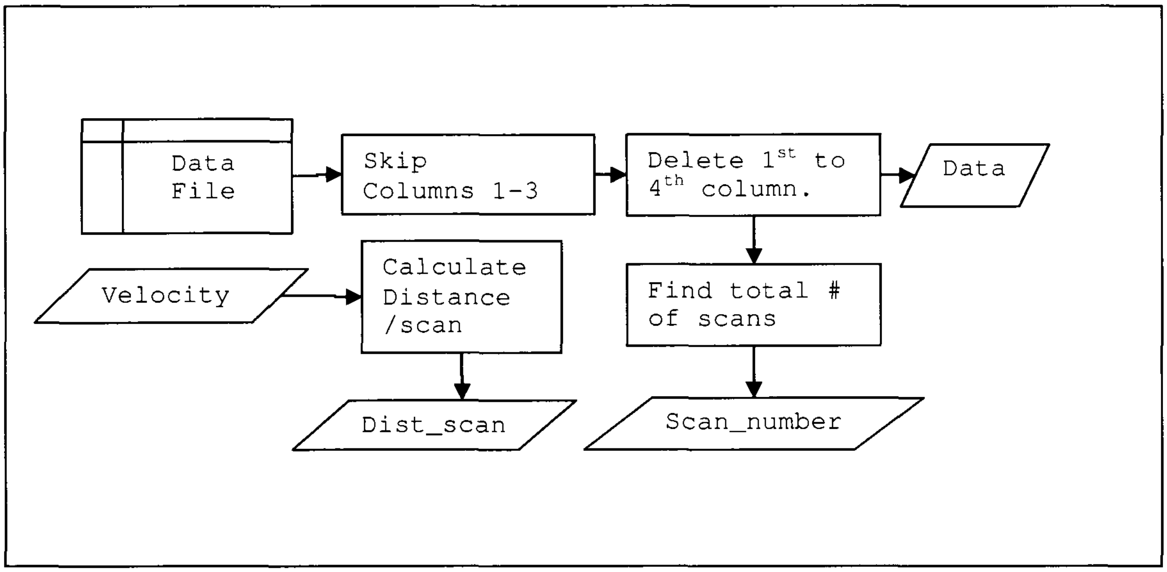



**Figure 2.14: Data Import Flow Chart**

### 2.2.2. Occupancy Grid

For the purpose of this research, occupancy grids are represented using $n \times m$ matrices from the range data provided by the SICK LMS291-S14. Each row and column represents a distance range. This distance value can be changed to any value wanted. For example each row may represent range values that fall between 100 mm and 110 mm, thus representing an occupancy grid of 10 mm for each scan angle. The grid size can be varied in both the X and Y direction.

$$\text{y grid} \begin{bmatrix} 0 & 0 & 1 & 0 \\ 1 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 1 \end{bmatrix}$$

X grid

**Figure 2.15: Occupancy Example**

The Occupancy matrix is made up of 1's and 0's with the first representing a range data point being represented by its location in the matrix. All matrix entries that do not have values of one are populated with zeros.

The occupancy matrix or grid method was used as the basis for data fusion of each range data scan as well as for reducing the computational requirements associated to the analysis of the data. As the range data are converted into an occupancy grid, they can be manipulated and analyzed in matrix form. Even though the occupancy grid data may be less accurate than the original range data due to the greater grid size, they allow for easier data analysis at a much greater processing speed. (Payeur, 2004; R.Murphy, 2000)

### 2.2.3. Raster Scan

A raster scan is the method of covering a specified area by scanning rows from left to right and from top to bottom. Within the context of this work, a raster scan of a matrix will begin at cell [1, 1] and analyze along the row until the last column is reached. At this point the analysis will resume on the next row, i.e. [2, 1] and follow that row until the last column is reached.

### 2.2.4. Labelling

This is a simple connectivity algorithm requiring 2 Raster scans (Spong *et al.*, 2006). This process checks the connectivity of each occupied node and labels them accordingly. Two raster scans are performed; each pixel or node is checked from left to right, top to bottom. With 4-connectivity "a pixel with image pixel coordinates (r,c) is adjacent to four pixels, those with image coordinates (r-1,c), (r+1,c), (r,c+1), and (r,c-1)"(Spong *et al.*, 2006). The 8-connectivity method also introduces the (r-1,c-1), (r-1,c+1), (r+1,c-1), and (r+1,c+1) pixels or nodes.

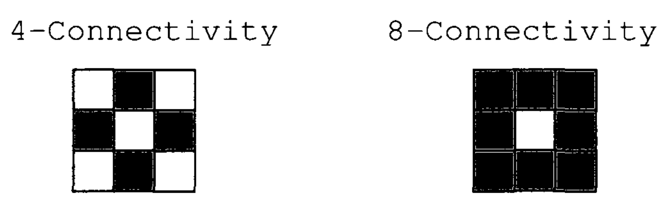



**Figure 2.16: 4-8 Connectivity**

The first raster scan labels each pixel or occupied node in an ascending order while also checking for connectivity to previously labelled nodes. When previously labelled nodes are found to be connected, the current node is then labelled the same as the previously labelled node. When multiple previous nodes are found to be connected, then the new node is labelled the same as the lowest connected label.

$$\text{Range}\begin{bmatrix} 0 & 0 & 1 & 0 \\ 2 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 \\ 3 & 3 & 0 & 4 \end{bmatrix}$$

Angle

**Figure 2.17: 1st scan labelled example**

$$\text{Range}\begin{bmatrix} 0 & 0 & 1 & 0 \\ 1 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 \\ 3 & 3 & 0 & 4 \end{bmatrix}$$

Angle

**Figure 2.18: 2nd scan labelled example**

The second scan performs the same type of scan as the first one except that it will check for connectivity for all 8 surrounding pixels or nodes of all previously identified pixels or nodes. This will then reduce the number of different labels and group nodes that should be labelled the same that were not done so in the first scan.

A secondary algorithm to the connectivity algorithm is the group size of each connected component. This method calculates the size of each labelled group of connected cells and replaces the cell values of each component with the size of the component itself. After the connectivity process, the cells in each connected component are assigned numerical values corresponding to their label. After the group size process, each cell with a label is replaced with a numerical value corresponding to its group size.

### 2.2.5. Hough Transform

The Hough transform is a relatively simple tool for edge detection using data points. This transform offers multiple advantages including the ability to detect contours using multiple range data points, noisy data are filtered out, and range data points are not required to be equally spaced along the whole edge (Payeur, 2004).

The Hough transform is based on the principle that a line can be represented by a point in a polar coordinates system as seen in Figure 2.19

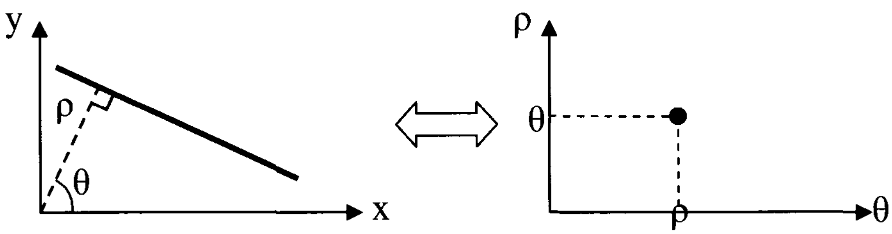



**Figure 2.19: Line representation in Polar coordinate system.**

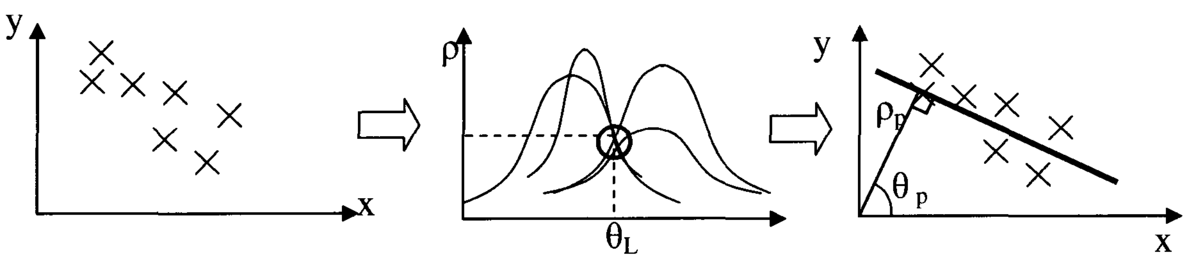
To put the transform in use, each range datum point was used to create a sinusoidal curve using its X and Y values as constants in the equation (4)..

$$\rho = x_p \cos\theta + y_p \sin\theta \qquad (4)$$

$x_p, y_p$ = range data point coordinate

$\rho$ = distance value

Multiple sinusoidal curves are then created and superimposed, using a max and min θ for each data point.




$$\rho = x_p \cos\theta + y_p \sin\theta$$

**Figure 2.20: Hough Transform Process**

The overlapping curves are plotted on a matrix so that the values in each of the cells where there are intersection of curves are increased.

$$\begin{bmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix} + \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 1 \\ 0 & 0 & 2 & 0 \\ 0 & 1 & 0 & 1 \\ 1 & 0 & 0 & 0 \end{bmatrix}$$

**Figure 2.21: Summing of intersecting curves**

Using a threshold or max value finder, we can find the location of cells with high values. The coordinates of these cells ($\rho_p$,$\theta_p$) represent the infinite lines of the image or range data points, see Figure 2.20.

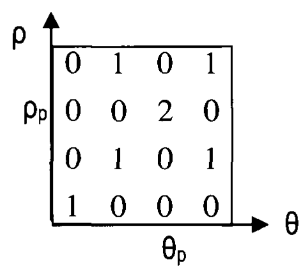



Figure 2.22 is an example given by the Matlab Help guide showing the Hough transform matrix for an image of a crane truss.

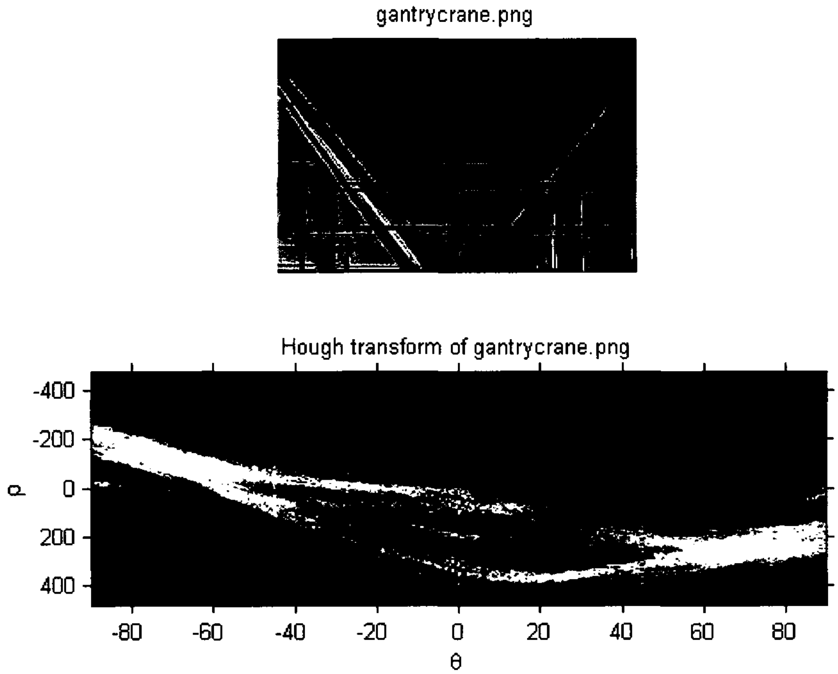



**Figure 2.22: Image and Hough Transform Matrix Example**

As illustrated in Figure 2.22, the colour intensity/matrix value is greater where the curve lines have overlapped. Matrix locations that have the highest cell values are then used to represent the contour lines using $\rho$ and $\theta$. For more information on the Hough Transform please see (Kiryati *et al.*, 1991)

### 2.2.6. Filter Outliers

An outlier is a data point found at a significant distance away from its neighbours. It is a type of noise that is easy to detect and filter (Payeur, 2004). These data points are typically removed from the rest of the data. One must be careful not to remove data points that are representing a small object that is located in an area with small angular resolution. This can easily happen near the sides and far distances of the scan plane where the resolution is reduced because of the distance from the scanner.

Objects that are scanned at a far distance and that are represented by a single data point could inadvertently be removed or ignored. As the scanner approaches the objects, the resolution will increase, thus increasing the number of range points representing the object and size within the occupancy grids.

The problem may present itself when objects are low to the ground or oriented perpendicular to the travel direction. This will increase the overall and sectioned range data averages and only be represented by a minimal number of scans because of the quick pass of the scanning plane over the object.

A few filters such as the Kalman filter, Mean filter, Gaussian filter, and Median filter are available to help reduce noise. The Kalman filter "provides an efficient computational (recursive) means to estimate the state of process, in a way that minimizes the mean of the squared error." (Welch and Bishop, 2006). The main advantage of this filter is that it considers past, present, and future estimations to provide new filtered data. Knowing the theoretical trajectory of the vehicle, future work could include Kalman filtering to help reduce noise caused by vibrations and changes in actual vehicle trajectory. Kalman filtering could be used in navigation and object tracking especially when the system model is known.

Mean filtering or averaging, is a simple filter where the cell values take on the average of the surrounding cells. Weighting schemes can also be used where the values of closer cells are valued of higher influence. The size of surrounding area, in which values are considered, has an effect on the filtering. When the surrounding area is greater, there is a greater degree of filtering. One disadvantage of this filtering method is the reduction of sharp details (Payeur, 2004). This could cause a problem for our final map results because the peak in cell values, due to the object, are not represented by many cells and thus could easily be filtered out. One could either increase the resolution of the occupancy grid or reduce the size of the averaging area to ensure that the cell values for the objects are still detectable. The Gaussian filter is similar to the Mean filtering but the weights of the surrounding cells are determined by the shape of the standard Gaussian function.(Payeur, 2004)

The Median filter uses the median of the surrounding cells to replace the values of the cell in question. This is a nonlinear filter which allows for better preservation of data details.

In this work, filtering only occurs in two of our methods. The first is the average height method where the average old and new data for each cell is used. When new values are available for a specific cell, the average between the old and new value is used. The second data filtering occurs in the crop discontinuity method when the Hough Transform is used. The Hough Transform provides its own filtering technique that helps filter out points that do not correspond well with the others.

### 2.2.7. Object Reflectivity

The LMS 291-S14 also returns reflectivity data and we can use these data in conjunction with the range data to increase the ability to detect foreign objects and reduce false alarms. With this knowledge, we can have the detection algorithm "pay more attention" to areas in which the reflectivity is higher than the crop and ground average. A situation where this type of analysis may be worthless is when the detection algorithm is attempting to detect a biological object such as wood, animals, or people where the reflectivity is similar or lower than that of the crops..

**Table 2-2: Typical material reflectivity (Sensor Intelligence, 2006)**

| Material | Reflectivity |
|---|---|
| Cardboard, matt black | 10% |
| Cardboard, grey | 20% |
| Wood (raw pine, dirty) | 40% |
| PVC, grey | 50% |
| Paper, matt white | 80% |
| Aluminum, anodised, black | 110%-150% |
| Steel, rust-free shiny | 120%-150% |
| Steel, very shiny | 140%-200% |
| Reflectors | >2 000% |

### 2.2.8. Average Height Method

Attempting to identify field locations where the scanned height was different than average crop height we used the average height method. This method was intended to identify objects that are greater or lower in height than the average crop height.

Using the 181 Cartesian points for each scan, an occupancy grid was created and the points were fitted into the grid. The size of each grid could change depending of the speed of the vehicle as well as the time between each scan. In the y-direction (perpendicular to direction of travel), the grid size was kept constant at 10 cm. In the x-direction (parallel to direction of travel) we used the distance per scan. To calculate the distance per scan we simply divided the vehicle velocity V(m/s) by the scan frequency(Hz).

$$dist\_scan = \frac{V}{f} \tag{5}$$

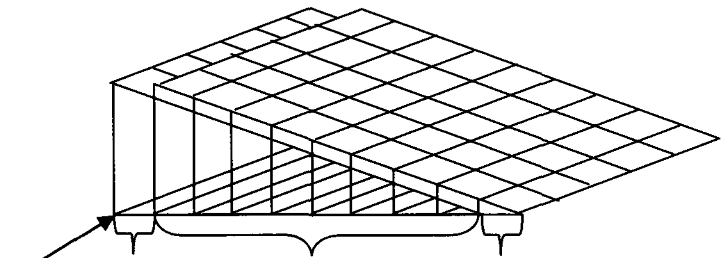
| | |
|---|---|
| *dist_scan* = | distance travelled during each scan [m] |
| $V$ = | vehicle velocity [m/s] |
| $f$ = | scan frequency [Hz] |

Knowing the height and orientation of the LMS, we calculated and associated a predicted height for each point. The measured height of the mounted scanner was 1.17m, and the scan angle being either 20 or 30 degrees depending on the type of test.

$$Z_{pts} = H - Y_{pts} * \sin(theta) \tag{6}$$

| | |
|---|---|
| $Z_{pts}$ = | calculated height of range data point |
| $Y_{pts}$ = | range data value from LMS |
| *theta* = | scan angle, 20° or 30° |
| $H$ = | measured height of the LMS |

We now have an occupancy grid matrix with height values in grids where points were detected and a value of zero for all others. For each scan, an occupancy grid is created and then superimposed on an overall Map matrix. Because each cell size is equal to that of the distance travelled between scans, each occupancy matrix is overlapped by one column. This means that a new column is then added to the Map matrix with each additional scan. For all other columns, where there is an overlap with previous values, the new and old values are averaged for a new cell value, corresponding to an average calculated height.



$$\text{Map} = S1 + \frac{(S1+S2)}{2} + S2 \qquad (7)$$

Equation 7 is used to create and increase the size of the map. S1 represents the sections of the map where there was no new information to be added. (S1+S2)/2 is the middle section where new information is being added to the map where we already had some data. The final S2 section represents a completely new section of the map where we had no known information. The process is repeated for every new scan with the S1 section growing by one row with every scan.

It should be noted that the cell values for each method are calculated prior to the data fusion. The middle section for the connectivity and density method is slightly different because the sum of the values are used and not the average. The middle section is then represented by (S1+S2). The final map matrices are then plotted using a contour style which highlights higher cell values.

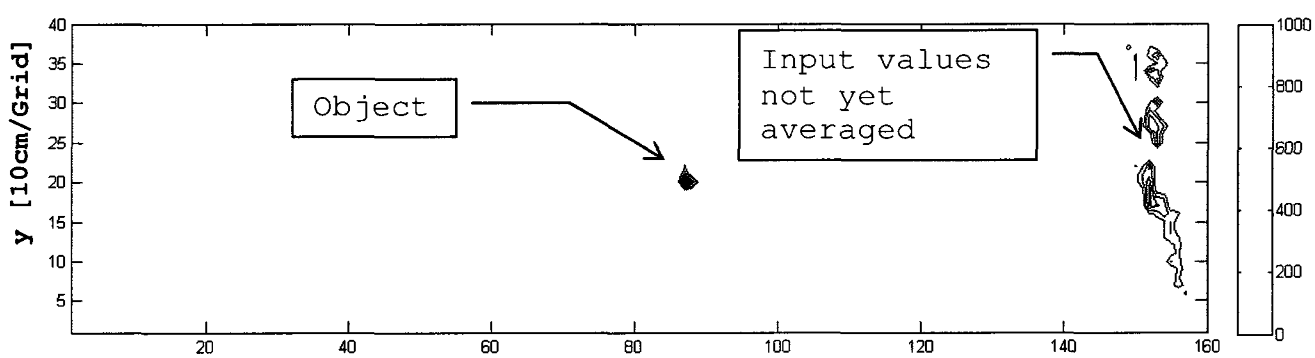



**Figure 2.23: Average height method example H_S1_S_20_7_3**

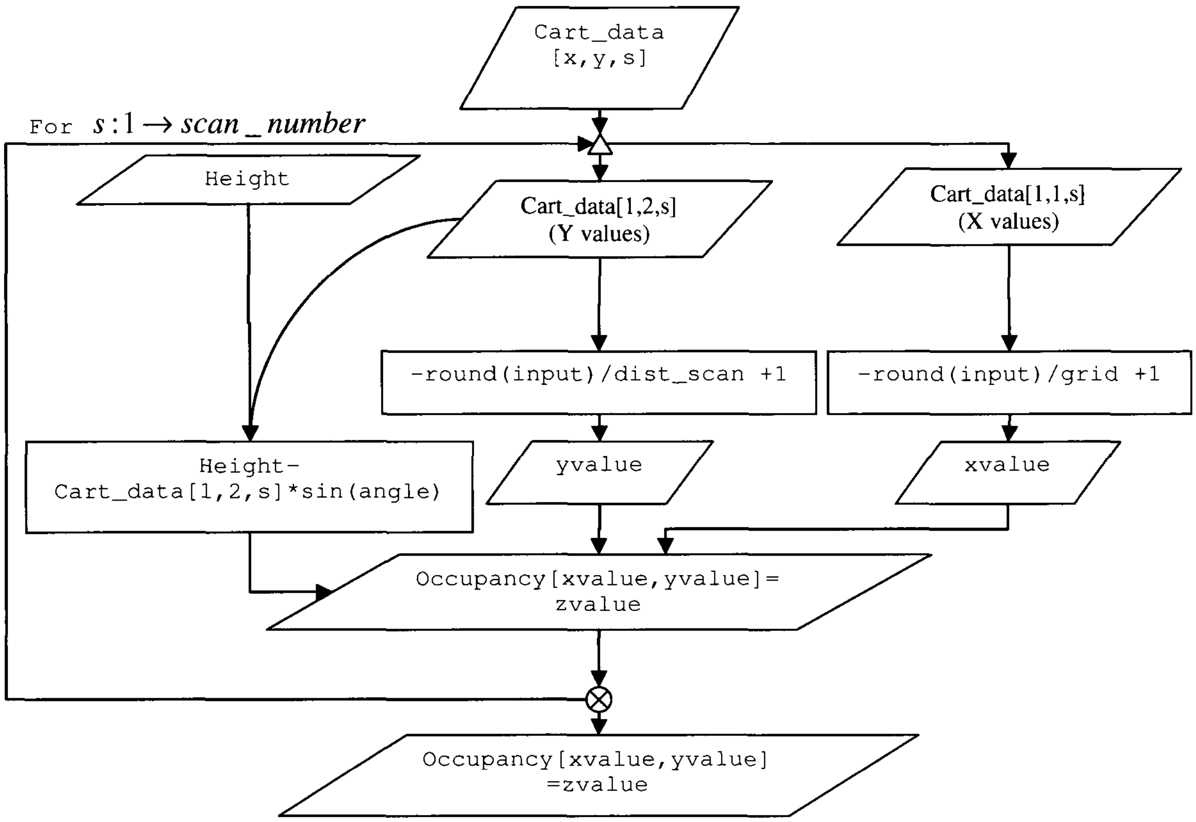



**Figure 2.24: Occupancy Grid and Height Value Flow Chart**

### 2.2.9. Occupancy Grid Density Method

Using crop density we attempted locating the test objects based on the density of range data points within each occupancy cell. It was predicted that the test objects would create a large density region within the crops.

This method starts very similar to the average height method where the Cartesian points are sorted into their appropriate grid values. The primary difference for this method is that the cell values for each occupancy cell now corresponds to the number of datum points found in each cell from the data in Cartesian form. Each cell value represents the density of data points found within that specific grid area. The cell value in the Occupancy matrix is increased by one for every new range data point found within the grid.

$$Occupancy[x, y] = Occupancy[x, y] + 1 \quad (8)$$

$Occupancy[x, y]$ = Occupancy matrix for density method

The map matrix is created using a slightly different method as the average height method. In this method the density values are summed and not averaged.

### 2.2.10. Occupancy Grid Density and Connectivity Method

Building on the density method, another algorithm is added, which we have called the connectivity method. When multiple grid squares are found to be attached, either by side or diagonal, their connectivity factor is increase. Figure 2.25 shows a basic example of how the cell values are labelled in accordance to the size of their connectivity.

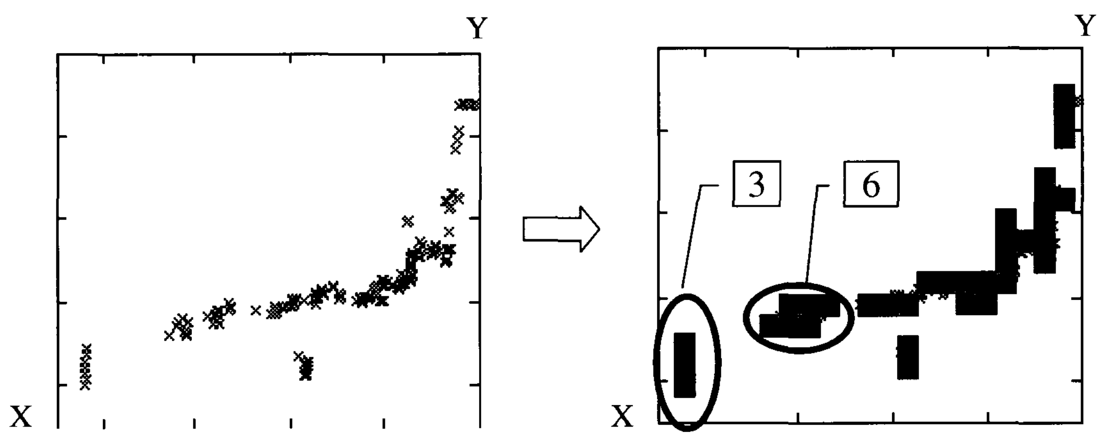



**Figure 2.25: Occupancy and connectivity grid**

This method multiplies the density values found in the previous section by each cells connectivity value. This increases the value of each cell by a factor that corresponds to its group size. Two raster scans are required for this labelling process as described in section 2.2.3 and 2.2.4.

Hoping for a diffusion of range points into the fields and clustering of points near the objects, we evaluated the increase of connectivity near the objects compared to that of the field. With a larger and dense object in the field, a large connectivity of adjacent cells in the occupancy grid was expected.

### 2.2.11. Crop Discontinuity (Hough Transform)

In this method we are trying to detect any crop foliage discontinuities formed on the scan line. From the Figure 2.25, one can see a discontinuity in the crop line created by the test object near the bottom. Using the Hough transform to form contour lines based on the data points, we are able to create a generalized contour of the crops. When a height discontinuity is found, the difference in Y values for two adjacent contour lines are greater than the specified threshold, the location is noted and plotted on the map matrix of the overall pass. Because the scan plan is 20 and 30 degrees, typical thresholds used to identify discontinuities are much greater than the actual size of the discontinuities in the vertical directions. The threshold is also based on the distance between two adjacent points on the occupancy grid, whose grid size is dependant on the vehicle speed. Similar to the cell values in other methods, the threshold values used here do not represent any real physical values; it is used for a comparative analysis.

Data points from the occupancy grid are used to create contour lines within 3 grid wide strips, approximately 30cm. One contour line is created within each 3 column wide strip outputting 2 data points representing the start and finish points of the line. The Y-values of each adjacent point are compared and put into a discontinuity matrix if the differences in values are greater than a specified threshold.

Matlab offers multiple Hough transform functions that facilitate the range data analysis.

- `[H, theta, rho] = hough(BW)`
  This function computes the Standard Hough Transform from a black and white (BW) image. In our case the BW images are sectioned off into strips. From this function, H is the Hough transform matrix. Theta(in degrees) and rho is the angle and distance representing lines (see section 2.2.5, Hough Transform in Machine Vision section).(Matlab, 2008)

- `Peaks = houghpeaks(H,numpeaks)`

The houghpeaks function finds the peaks in the Hough transform matrix. Numpeaks is the number of peaks that are returned for each Hough transform matrix given. In our case we only want one edge detection for each section thus keeping this value at one. (Matlab, 2008)

- `Lines = houghlines(BW, theta, rho, peaks)`
  From this function, a lines array is returned which constitutes point1, point 2, theta, and rho. Point1 and point2 are of most interest to us, giving the [X Y] coordinates of the end-point of the line.(Matlab, 2008)

Figure 2.26 illustrates the edge contour created by the Hough transform based on range data. For this example the field scan is paused at scan number 131 to show the discontinuity caused by the object.

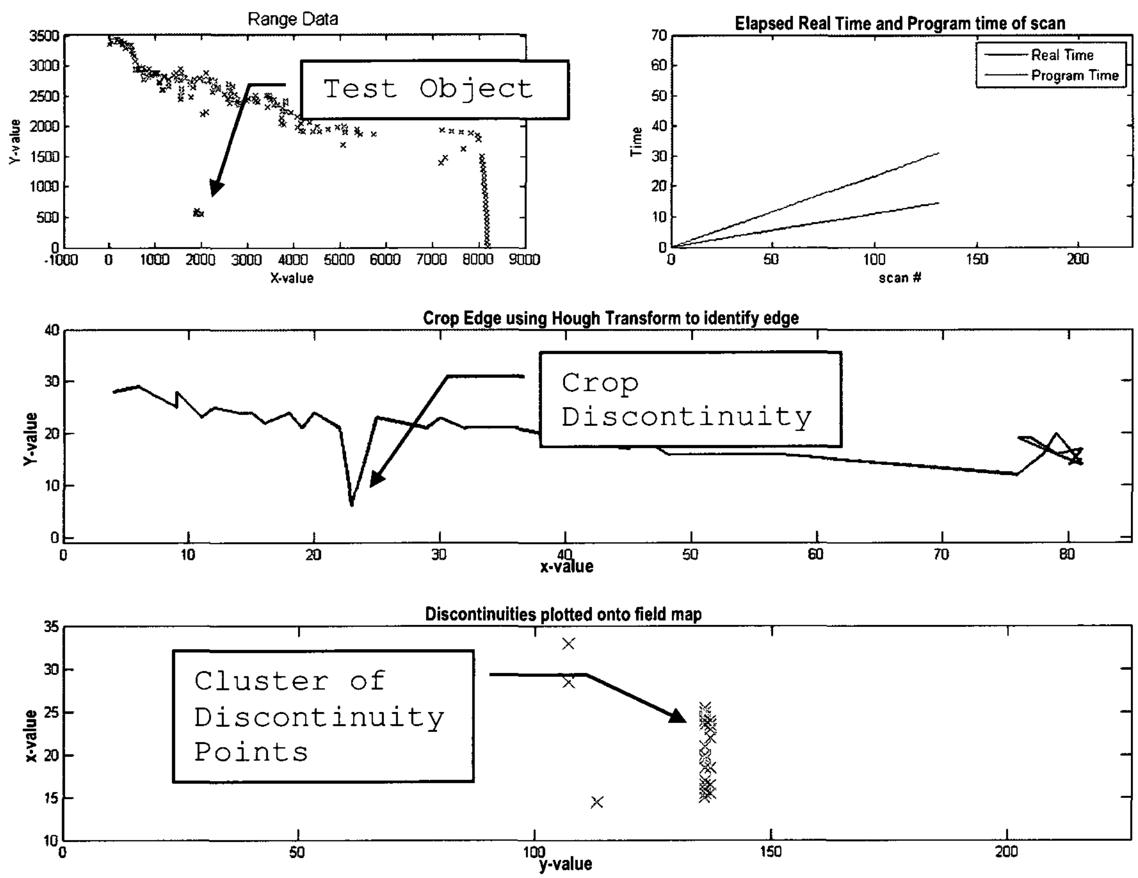



**Figure 2.26: Hough Transform example using field data**

### 2.2.12. Matlab GUI

Using Matlab as our primary data analysis program and having multiple m-files for the various analysis techniques, we were able to consolidate these methods into one GUI (Graphic User Interface).

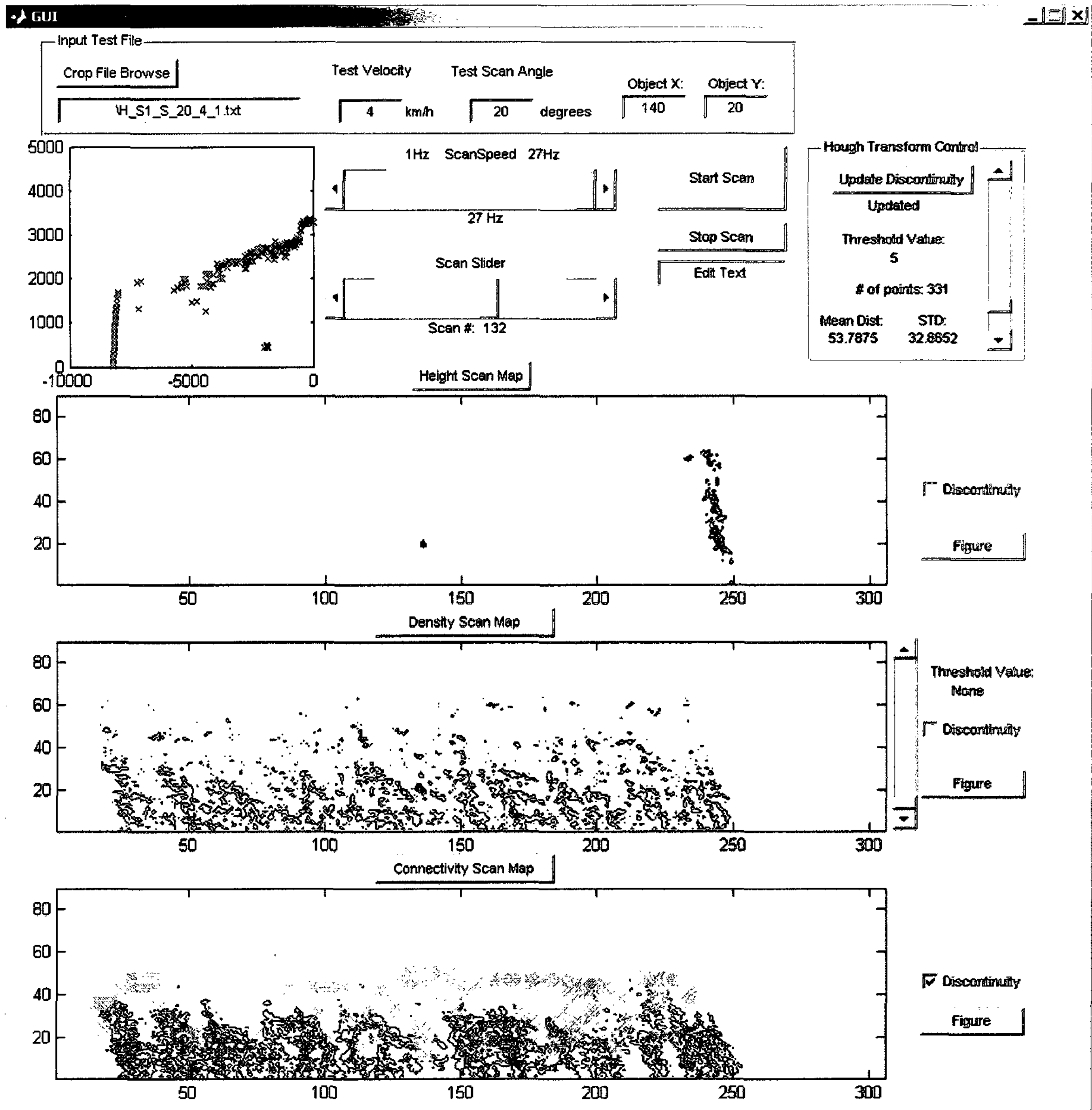



**Figure 2.27: GUI**

To view a scan file, the "Crop File Browser" button is used to select the folder in which the test files are located. The specific test name is then typed in the test box below the browse button. It is important to input the correct test velocity and test scan angle in their appropriate text boxes.

The user can also view the test scan at any point through out the scan or can see the play back at a desired frequency by pressing the "Start Scan" button. This is accomplished with the sliders labelled "Scan Speed" and "Scan Slider". The "Scan Speed" slider allows the user the speed at which he/she the scan is played back. If the user wishes to see a specific scan number, they may use the "Scan Slider" or the text box below the "Stop Scan" button. The GUI includes Average Height Method, Density Method, and Connectivity Method presented in three different frames.

To plot the values for Average Height, Density, and Connectivity methods, simply press on the appropriate button above each figure. The user may vary the density and discontinuity threshold as well as choose the location on the map to which the mean distance and standard deviation is evaluated. Once evaluated for a specific threshold, by using the "Update Discontinuity" button, the discontinuity points can be plotted on any of the three other map results for visual inspection. To plot these points, simply ensure that the discontinuity points have been updated and check the boxes beside the desired figure.

# Chapter 3. Results and Discussion

The experimental data collected during the field trials were analyzed using the four methods presented in Chapter 2: average height, connectivity, density, and discontinuity. The results obtained from these different analyses were then compared using the following parameters: cell values at each object location, average cell values and standard deviations in the area surrounding the objects, and the presence of false detections or excessive noise.

For these methods, the results were considered successful when peaks in cell values were found near the known object location. When observing the final field map and no peak in cell value was found, the test was noted as unsuccessful. The mean distance of the discontinuities to the known object location and visual inspection of clustering were used to distinguish successful tests for the discontinuity method. If the mean distance of discontinuities diminished with an increase in threshold and clustering of discontinuities around the flag or objects were found, the test was marked as successful.

## *3.1. Average Height Method Results*

The average height method consistently yielded the best results in four different crops that were used during the experiments. This method yielded very high cell values at the grid location of the objects with an average cell value of 1014 and a standard deviation of 201. This method also found very little noise with cell values around the object to be in the order of 1.0 or three orders of magnitude lower. A typical example of results obtained from the average height analysis is presented on Figure 3.1 (Hay, Season 1, Square object, 20 Degrees, 7 km/h, and test # 3). For that particular experiment, the object was placed near cell (87, 20) as indicated on the figure. Cell values for the entire scanned area were very low with the exception of the last section (i.e. x > 15.0 m) for which the scan values have not yet been averaged out. This phenomenon was present in most results obtained by this method.

Though the cell values do not represent the actual height of objects or of the crop, the average height method does yield the desired large differences between the location of objects of higher heights and the rest of the field.

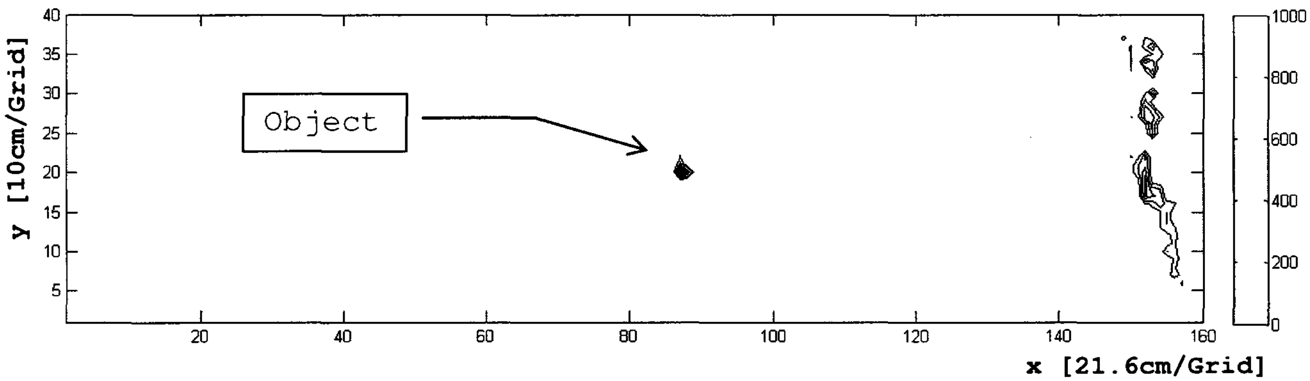



**Figure 3.1: Average Height Method Results H_S1_S_20_7_3**

Although this method had the best overall results, it was not capable of detecting the shorter objects. None of the short object tests were able to successfully identify the object locations using the average height method. Figure 3.1 is an example of the composed map view of a test run. The tractor travelled along the x-axis below the matrix.

### 3.1.1. Effects of Travel Speed

Figure 3.2 represents the average cell values and their standard deviations at the location of the object obtained with the average height method. The average cell values decreased with increasing travel speed from 1142 at 2 km/h to 934.3 at 7 km/h. This is caused by the decrease of field resolution with an increase in vehicle speed. Because of the decreased number of datum points having higher average height cell values, the cell values at the object location have less of an opportunity to be averaged higher than their surroundings. It should also be noted that the standard deviation of height results increased with increasing travel speed, from 23.75 at 2 km/h to 227.5 at 7 km/h.

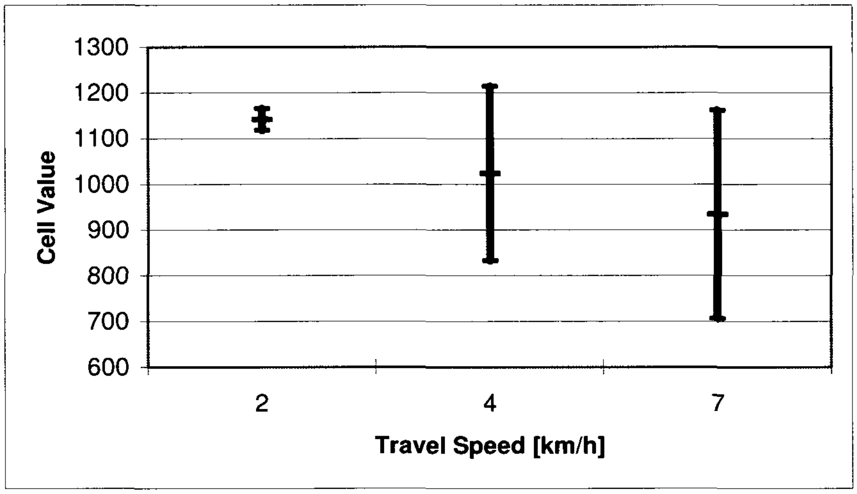



**Figure 3.2: Average Height results at different speeds**

### 3.1.2. Effects of Crop

The cell values at the object location as determined using the average height method also varied depending on the type of crop present in the experimental plots. As shown on Figure 3.3, the average cell values as well as the standard deviations for the tests completed in hay, oats, and soy values were very similar with a difference of only 59.44 between the average cell values for soy and oats. The wheat average detection values were slightly lower at 730.1 and had a greater standard deviation at 256.8.

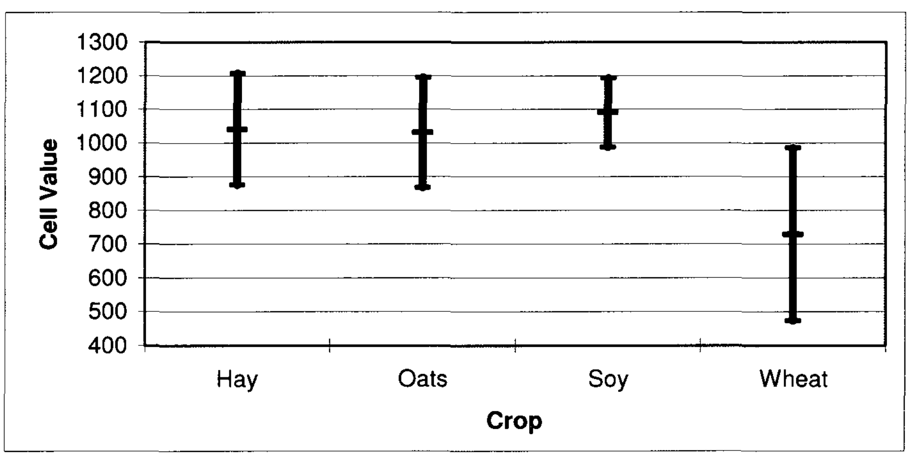



**Figure 3.3: Average Height Method Values vs. Crop Type**

### 3.1.3. Effects of Scanner Angle

The differences in the results obtained for the two scanner angles used during the field experiments were very small. The results obtained from the 20-degree tests yielded a higher average cell value (+3.4%) and a lower standard deviation (-8.9%) at the object location than those from the 30-degree tests.

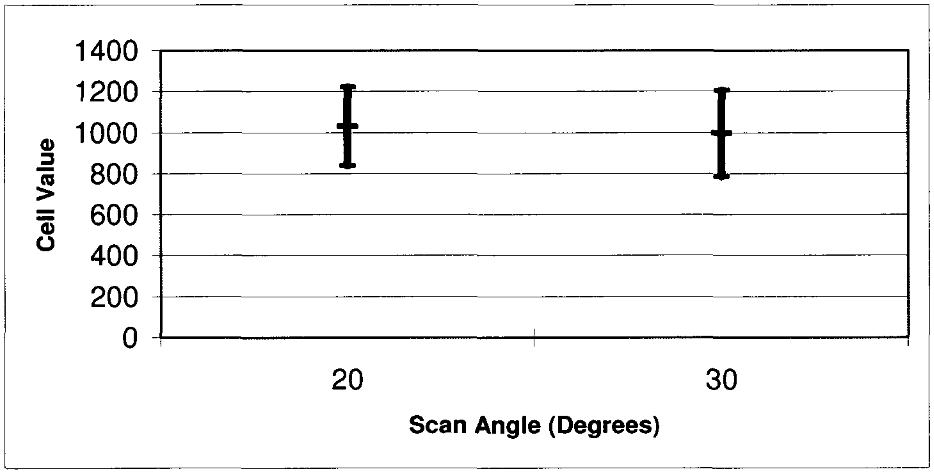



**Figure 3.1.4: Average Height Method Values vs. Scan Angle**

This shows that the 20° scan angle provided a slightly greater distinction between the objects and the surrounding fields.

### 3.1.4. Effects of Objects Type and Height

As mentioned before and as indicated on Figure 3.1., the analysis of the experimental data using the average height method did not allow for the identification of the short 60-cm objects that were placed in the experimental plots. All of the cell values for the short cylindrical object, at the known object location, were between 0-1.0 which was the same values as the rest of the field. In short, there was no increase in cell values for the short cylindrical object. Figure 3.1.also shows that the results yielded for the two tall objects having square and cylindrical cross sections were very similar with slightly higher average cell value and smaller standard deviation for the cylindrical one.

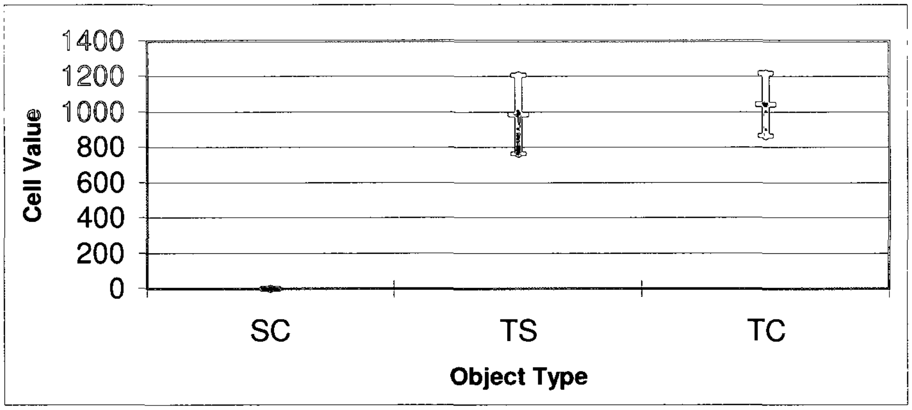



**Figure 3.1.5: Average Height Method Values vs. Object Type**

### 3.1.5. Effect of Growth Stage of the Crops

We were also able to test the detection values at different stages of growth for the soy and hay crops.

For the soy crop, we found that the only significant change in values was the standard deviation, which doubled in value for the end of season tests (Figure 3.1.). This may be caused by the loss of leaves near the end of the season, which allowed for greater range penetration into the foliage. In the early season tests, the soy canopy was dense and did not allow for much line of sight penetration as shown in Figure 3.1..

**Figure 3.1.6: Soy Field in first growth stage**

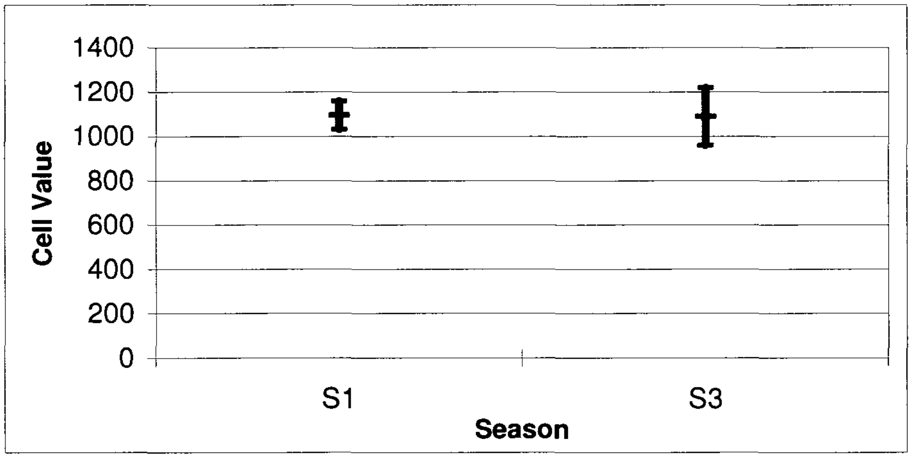



**Figure 3.1.7: Soy Seasonal Average Height Method Results**

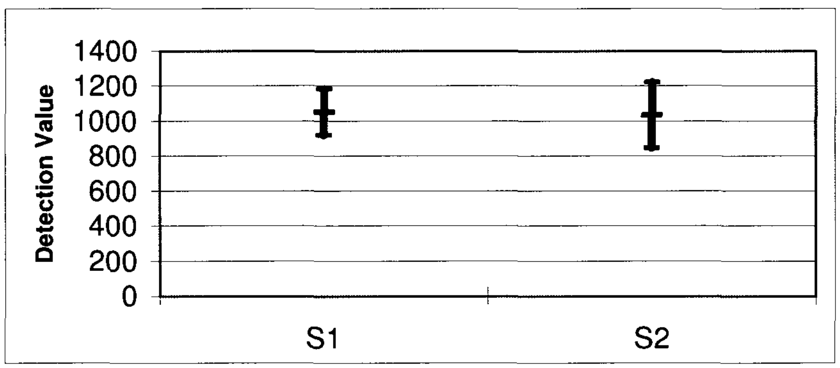



**Figure 3.1.8: Hay Seasonal Average Height Method Results**

As mentioned before, the detection rate was high for the 180-cm tall test objects and non-existent for the short 60-cm object. In the case of the tall objects, the average height method allowed for the identification of the object 178 times of the 182 tests for a detection rate of 97.8%. However, when the 64 unsuccessful short object tests are included, the detection rate obtained with the average height method drops to 72.4%.

## 3.2. Density Method Results

The density method yielded good object detection rates, similar to the average height method, but with slightly higher noise as seen in Figure 3.4 – H_S1_S_20_7_3. The noise values were found to be generally below the object values, suggesting the ability to establish a threshold value that could eliminate much of the false detections.

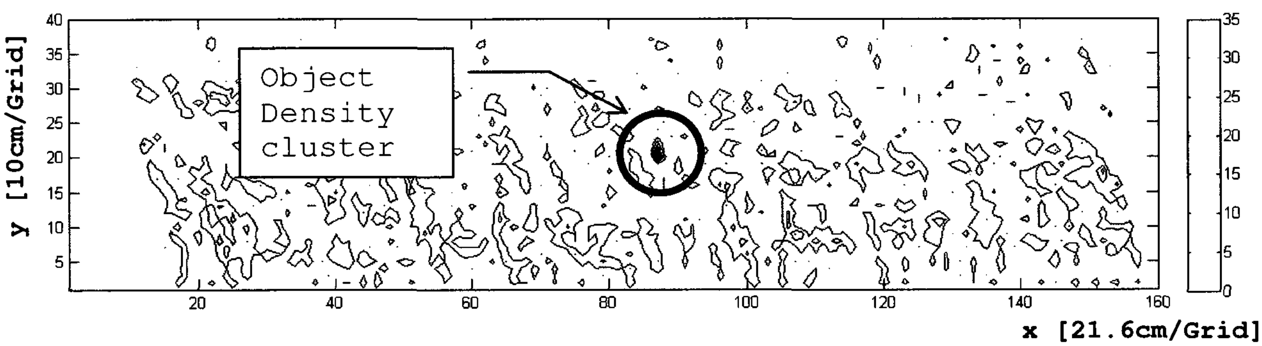



**Figure 3.4: Example of Density Method Result, H_S1_S_20_7_3**

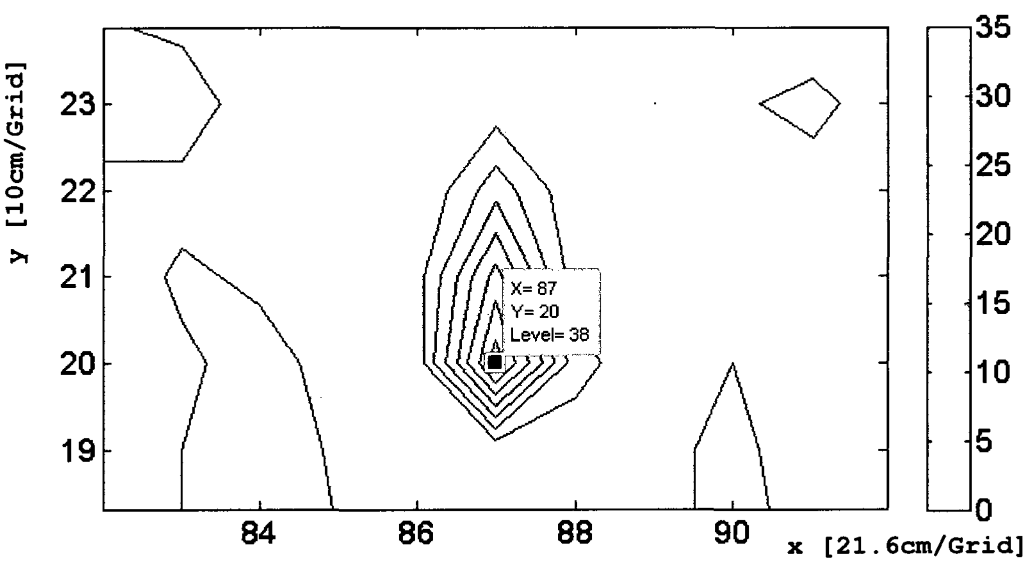



**Figure 3.5: Example of Density Method Result, H_S1_S_20_7_3- Zoomed**

With the data analysis methods described above, there were very few successful object detection for the shorter test object. Only six unconfirmed peaks were measured in the oat and hay crops; three in each the oat and hay crops with five of the tests run at 4 km/h and the other at 7 km/h.

### 3.2.1. Effects of Travel Speed

We also found the density method to be more effective at detecting the objects at slower speeds. As expected, because of the higher crop resolution, the grid density at the locations of the test objects was higher at slower speeds. The average density found at 2 km/h was 46.76 range data points. For 4 km/h and 7 km/h the average density was 38.27 and 30.68 points respectively at the grid location of the test objects.

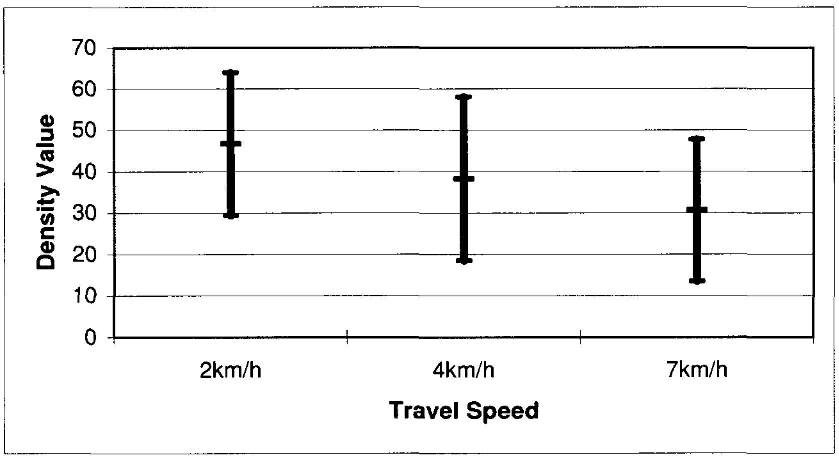



**Figure 3.6: Density Method Values vs. Speed**

### 3.2.2. Effects of Crop

In Figure 3.7 the density values for each crop type is shown. The hay crop density varied the most with a standard deviation of 21.29 points but with the highest average density of 48.38. The Hay crops provided the highest density because of the shorter crop height at 0.20m and 0.40m. The LMS had a longer view of the objects during each field test thus providing greater data points at the object location.

The wheat field provided the lowest amount of density at the object locations with an average density of 25.77. Because of the greater density and greater crop height, 0.75m, the LMS had less of a view of the objects during each field run. The overall object location density for all tests had an average of 37.02 and a standard deviation of 19.14.

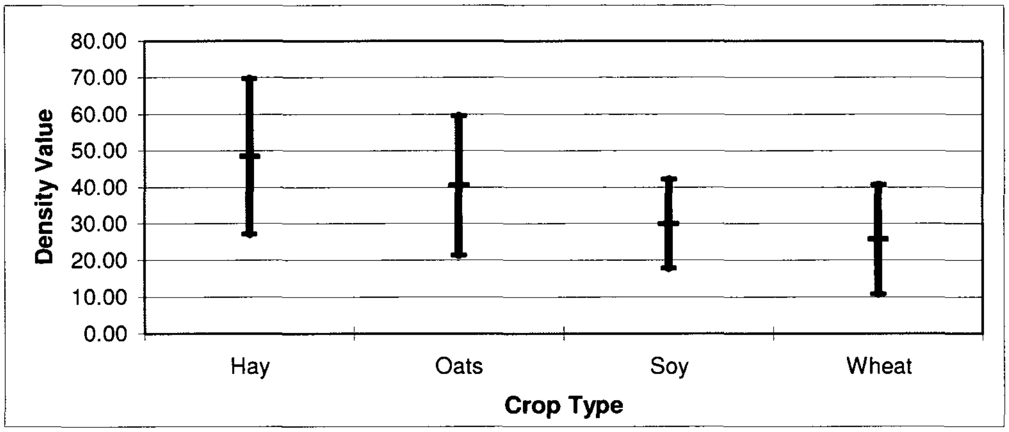



**Figure 3.7: Density Method Values vs. Crop Type**

The hay crop provided the clearest values showing a clear peak in density at the object locations on the map matrix. Unfortunately we found very little success with the shorter 60-cm object. Less than 10% of the short object tests provided any distinguishable change in the density around the object location. The table below presents the percentage of the tests, excluding short object tests, which provided a large and distinguishable density peak at the object location.

**Table 3-1: Percentage of tests showing density peaks excluding short objects**

| | % of tests showing density peaks |
|---|---|
| Hay | 87% |
| Oats | 58% |
| Wheat | 58% |
| Soy | 56% |

### 3.2.3. Effects of Scanner Angle

There is very little overall difference when comparing the density values for the two scan angles of 20 and 30 degrees.

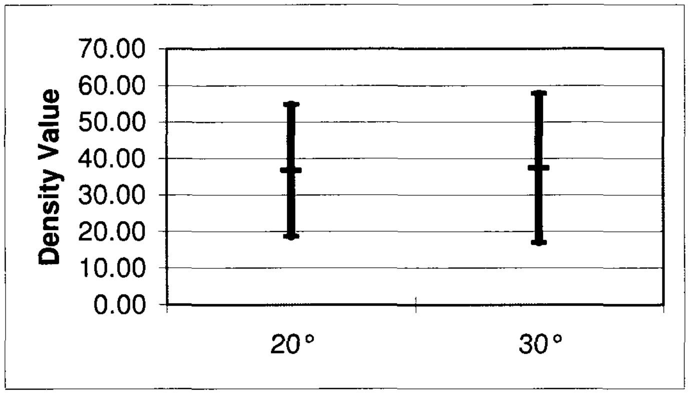



**Figure 3.8: Density Values per Scan Angle**

### 3.2.4. Effects of Object

It should be noted that only six density values were available to calculate the average and distribution for the short cylindrical object type due to its low detection rate. With this in mind we have concentrated our analysis of the density values, not success rate, on the square and cylindrical objects.

For an unknown reason, the density values for the cylindrical object were significantly higher than for the square objects. The cylindrical density average is 45.81 where the square average value is 28.72 being only 62.7% of the cylindrical object. There are respectively 90 and 94 values for each of the square and cylindrical tests.

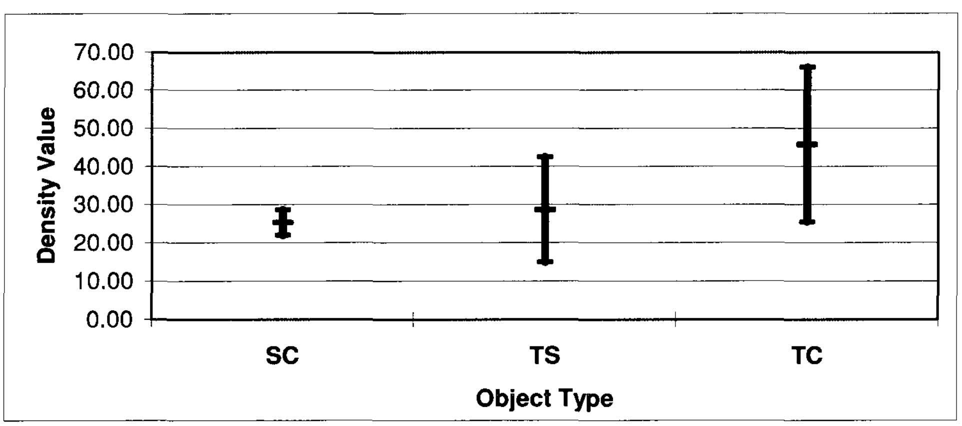



**Figure 3.9: Density Values vs. Object Type**

When observing the number of cylinder and square tests for each crop type, we can see that there is little difference in the number of tests for each object. This may have been a source for the higher values found for the cylinder test object.

**Table 3-2: Count of object type tests vs crop type**

| Crop | Object | |
|---|---|---|
| | Cylinder | Square |
| Hay | 30 | 30 |
| Oats | 12 | 12 |
| Soy | 38 | 36 |
| Wheat | 14 | 12 |
| Grand Total | 94 | 90 |

When looking at the density values for each object type within each crop (3-3), it was noticed that the cylinder (TC) values were consistently higher than the square (TS) object values.

**Table 3-3: Density Values of Cylinder and Square objects within each crop**

| Crop | TC | TS | TC/TS | Total AVG |
|---|---|---|---|---|
| Hay | 59.93 | 39.03 | 1.54 | 49.48 |
| Oats | 57.33 | 28.75 | 1.99 | 43.04 |
| Soy | 35.26 | 24.42 | 1.44 | 29.99 |
| Wheat | 34.29 | 15.83 | 2.17 | 25.77 |
| Total AVG | 45.81 | 28.72 | | 37.45 |

### 3.2.5. Effects of Growth Stage of the Crops

For the Soy crops the density values increase slightly from 28.56 to 31.57 points when going from the first growth stage to the third. It is believed that the crop canopy had an effect on these values similarly to the average height method, (see Effect of Growth Stage of the , Section 3.1.5.) With a decreased crop canopy, the LMS may have had greater success in reaching the objects below the average crop height which would increase the number of data points at the object locations.

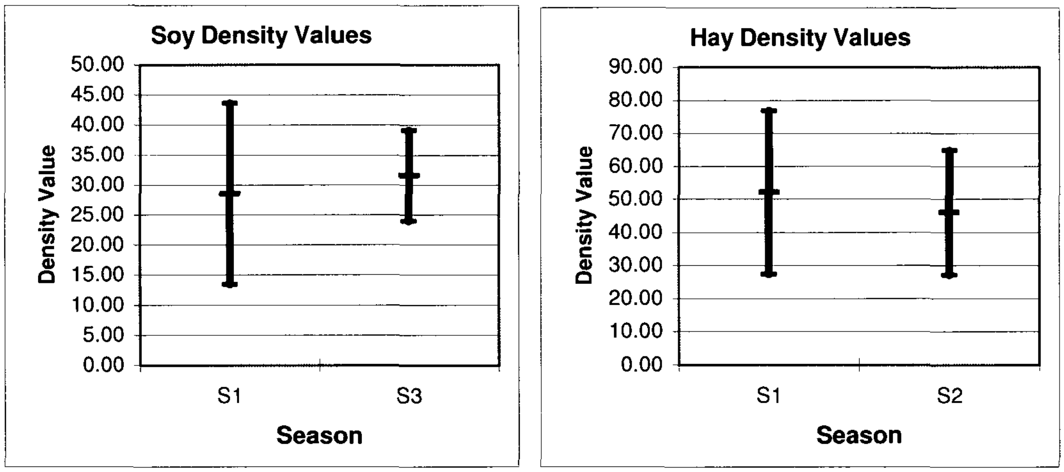



**Figure 3.10: Soy and Hay Density Values vs. Season**

In the second growth stage of the Hay field, the crop height and density had increased, contrary to the soy fields. This may explain the slight decrease in density values in the Hay fields.

## 3.3. Connectivity Method Results

The detection rates of the objects were very low for the connectivity method. The primary reason for this low success rate is due to the increased noise caused by the connectivity algorithm itself (see Figure 3.11). The connectivity algorithm connects much of occupancy grids that were created by the crop foliage. Because the connected foliage or crop components are greater than the connected object grids, greater values were placed around the objects. The expected connection values caused by the objects were less or similar that that caused by the crop canopy. It was expected to have a diffusion of range data points through the crop and a large clustering and high connection and/or clustering for the objects.

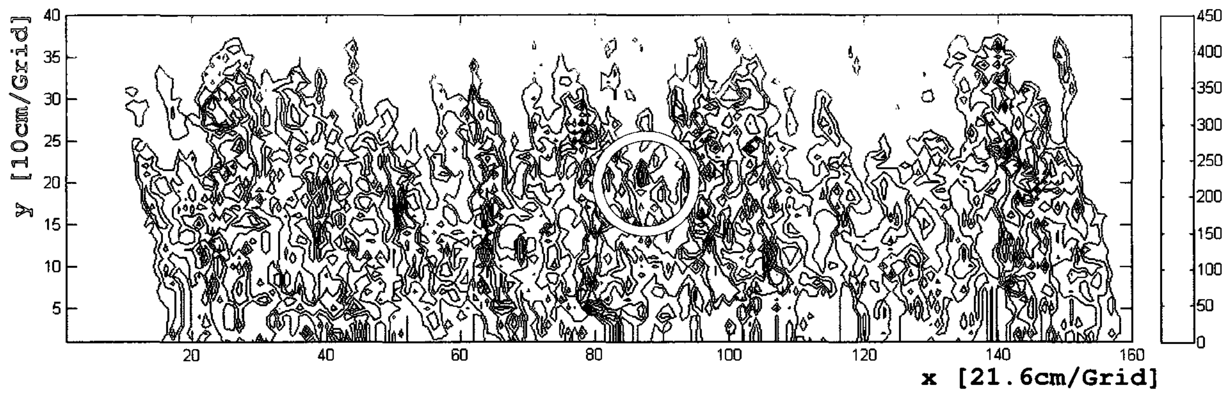



**Figure 3.11: Connectivity Method Result**

Figure 3.12 represents the overall detection rates, excluding the short test object tests.. In nearly two thirds of the tests, no peak in cell values were found at the known test object locations. In another 16% of the tests, a weak potential peak was found at or near the known object location. Significant peaks in cell values at the object location were obtained in only 18% of the tests.

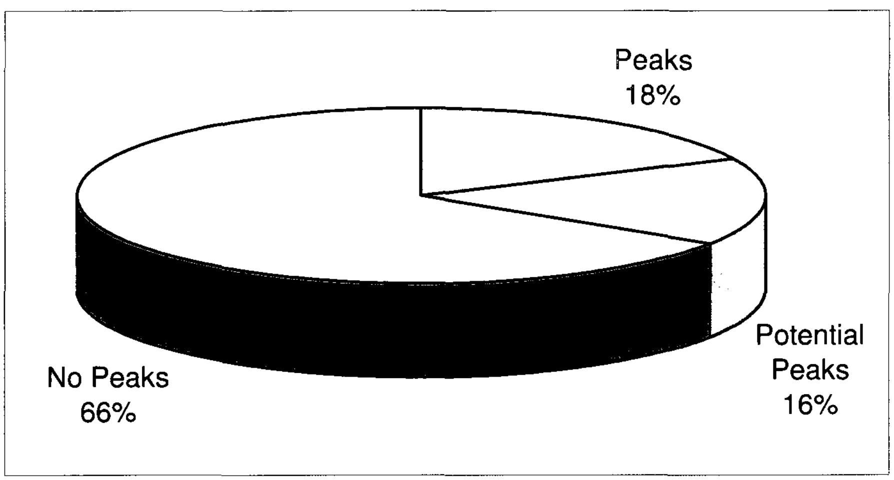



**Figure 3.12: Overall Connectivity Detection Rates**

We have also compared the average cell values of the map to the cell values of our test object locations. In all of the results with significant peaks, the peak values were all above the average cell values for the field. For the potential peaks only 1 of 28 tests had a peak value lower than the field average. In the tests where no peaks were detected, approximately half of the object location values were greater than the field average.

Because of the general ineffectiveness of this method of data analysis in detecting the objects placed in the experimental plots, detailed analyses relative to the effects of speed, scanner angle, type of crops, type of objects, and growth stage of the crops have not been completed.

### 3.4. Discontinuity Method Results

In order to analyze the ability of the Hough transform at detecting crop and object edges, the edge variance threshold was varied with the threshold value representing the allowable distance between two adjacent Hough transform points. The average distances of each discontinuity point to the object location for a varying threshold were compared. The Matlab function used to determine the distance between two points uses the map grid locations and not actual distances. Thus, the mean distance and standard deviation do not accurately represent in field distance values. Preliminary results suggest a decrease in distance to the object with an increasing threshold value. The results also suggest that the average distances to the object as the threshold values are increased do not reach zero but rather stabilize at a given distance.

Due to the increased computational and time requirements of the discontinuity tests, this method was not used for all the recorded tests. At least one of each type of test was used for this method for a total of 63 different test types. Each one of those scan results were tested at various thresholds. The threshold was increased until clustering occurred or only a few discontinuities remained.

The analyzed data are for each 2-D scan that was obtained at either 20 or 30 degrees. This provides discontinuities found on a 20 or 30 degrees to the horizon. This helps to explain why large threshold values are used. For example, a threshold of 7 locates discontinuities that are greater than 0.7 m.

In the sections below, when analyzing the effect of the threshold on the average distance, we were hoping to find overall trends that converge to a common threshold that uniquely identifies either the objects or the reference flag.

### 3.4.1. Overall Discontinuity Results

The discontinuity results that are considered successful are presented in Figure 3.13. In these cases, both the mean distance and standard deviation were reduced with an increase in threshold because of the clustering of discontinuity points near a known object location. Out of 63 discontinuity tests, only 13 were deemed to be successful yielding a success rate of 20.6% when considering the mean and standard deviation of the distance values.

The data series labelled with the mention "Flag" are the results of that particular field test when analyzing the mean distance and standard deviation to the flag location rather than to the object location. These tests have been chosen as successful because of the reduction of mean distance as well as a low standard deviation with an increase in threshold. The final standard deviations for the successful results are all below 5 for Wheat and Hay and below 10 for the Soy fields.

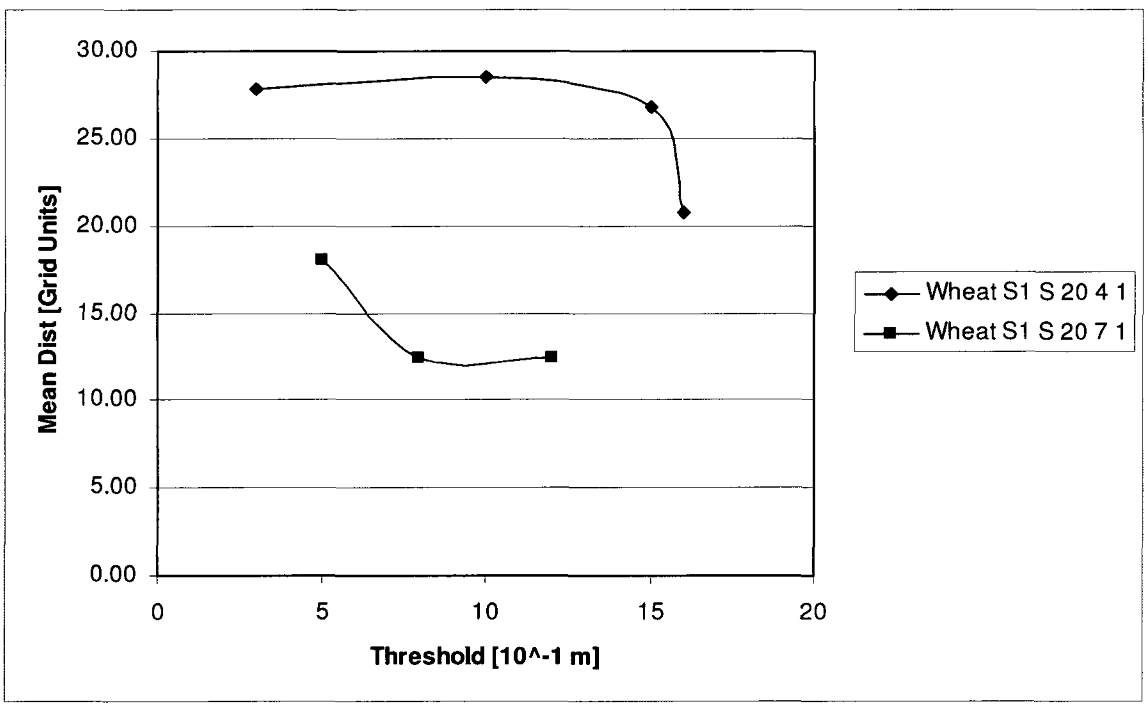



**Figure 3.13: Successful Wheat Discontinuity Results**

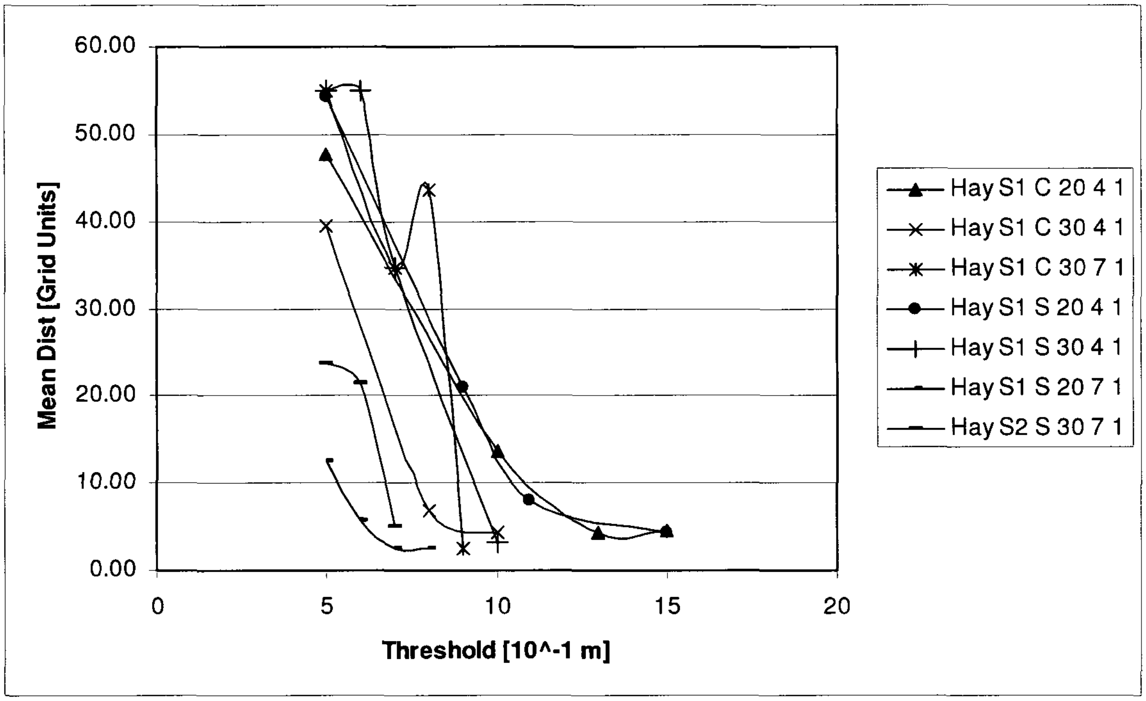



**Figure 3.14: Successful Hay Discontinuity Results**

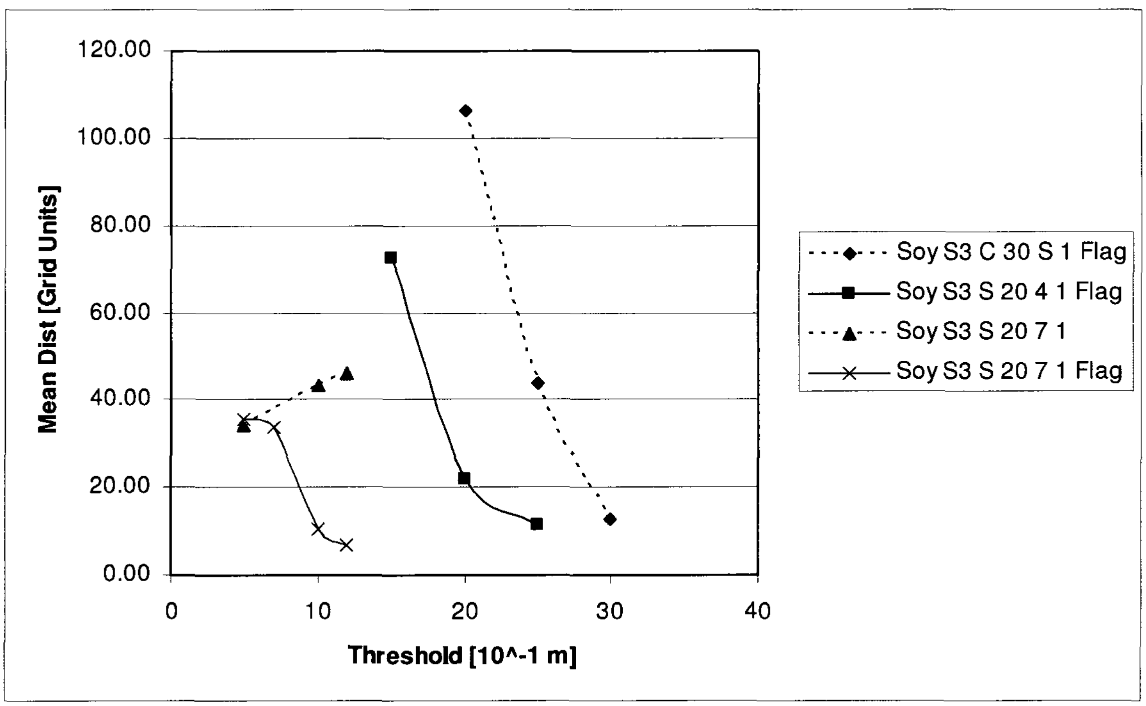



Figure 3.15 is an image of the GUI (Graphic User Interface) used to obtain discontinuity results. The slider on the right is used to select the desired threshold with

the update button located on its left. The number of points, mean distance, and standard deviation results are returned within the same Control box. The image posted in the bottom section of the GUI comprises of the Discontinuity Points plotted over the Average Height Results. Here we can see a good example of a cluster of points located around the known object location.

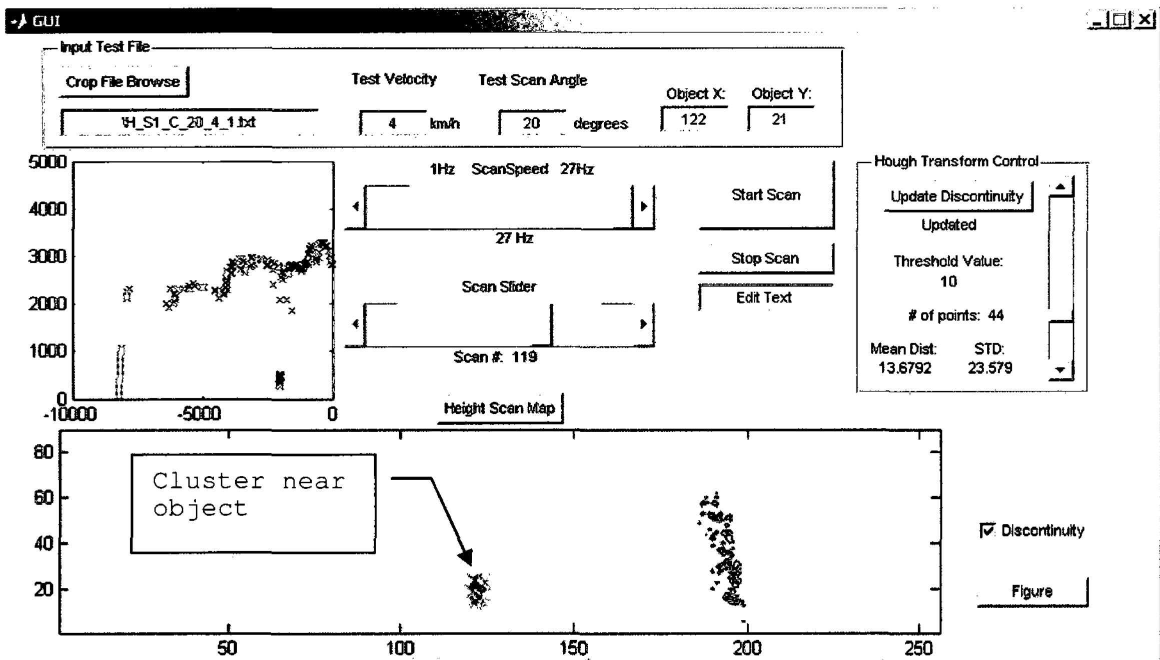



**Figure 3.15: Example of successful clustering of discontinuity points**

### 3.4.2. Effect of Reference Flag on Discontinuity Results

The figures below illustrate the effect of the flag located at the edge of the crop on the location and number of discontinuity points. In Figure 3.17, with a threshold of 15, there are many point clusters some of which are located on the objects, on the flag, as well as other areas.

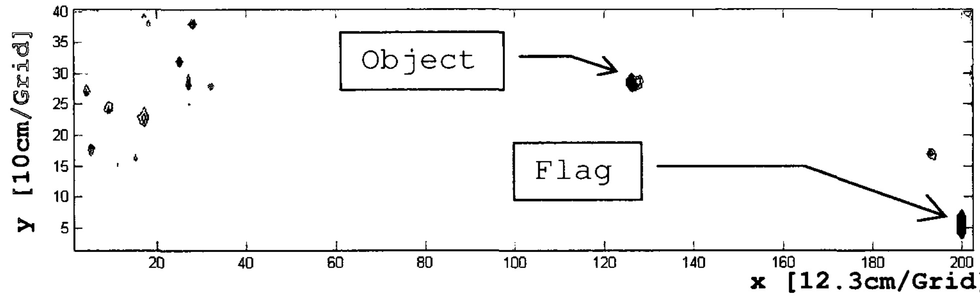



**Figure 3.16: Height Results S_S3_S_20_4_1**

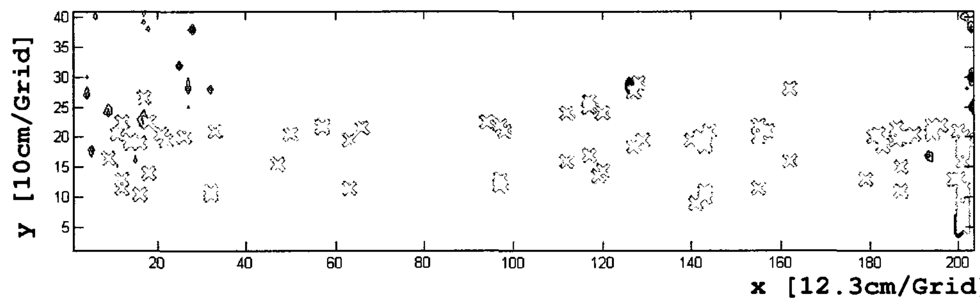



**Figure 3.17: Height Results S_S3_S_20_4_1 with discontinuity points, threshold = 15**

When the threshold was increased to 20, many of the clusters disappeared leaving a few points near the flag location (Figure 3.18). This may have been caused by the greater discrepancy in height between the flag and the ground compared to that of the object and the crop canopy.

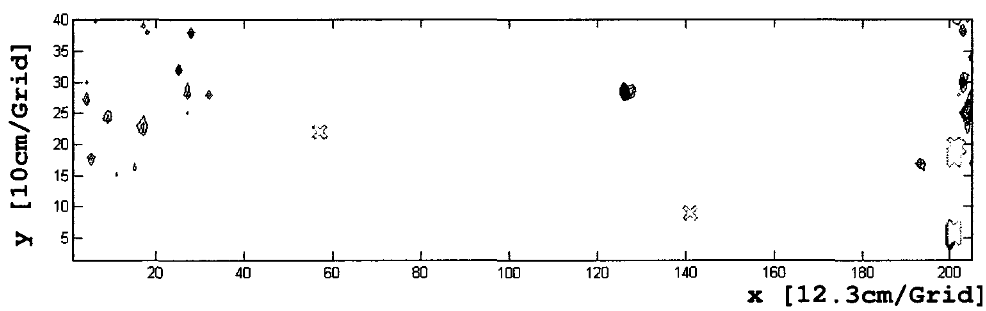



**Figure 3.18: Height results S_S3_S_20_4_1 with discontinuity points, threshold = 20**

Figure 3.19 shows the decrease in average distance when evaluating the flag location and an increase when evaluating the object location. In both situations, the standard deviation was reduced with the increase of the threshold because of the point clustering near the flag.

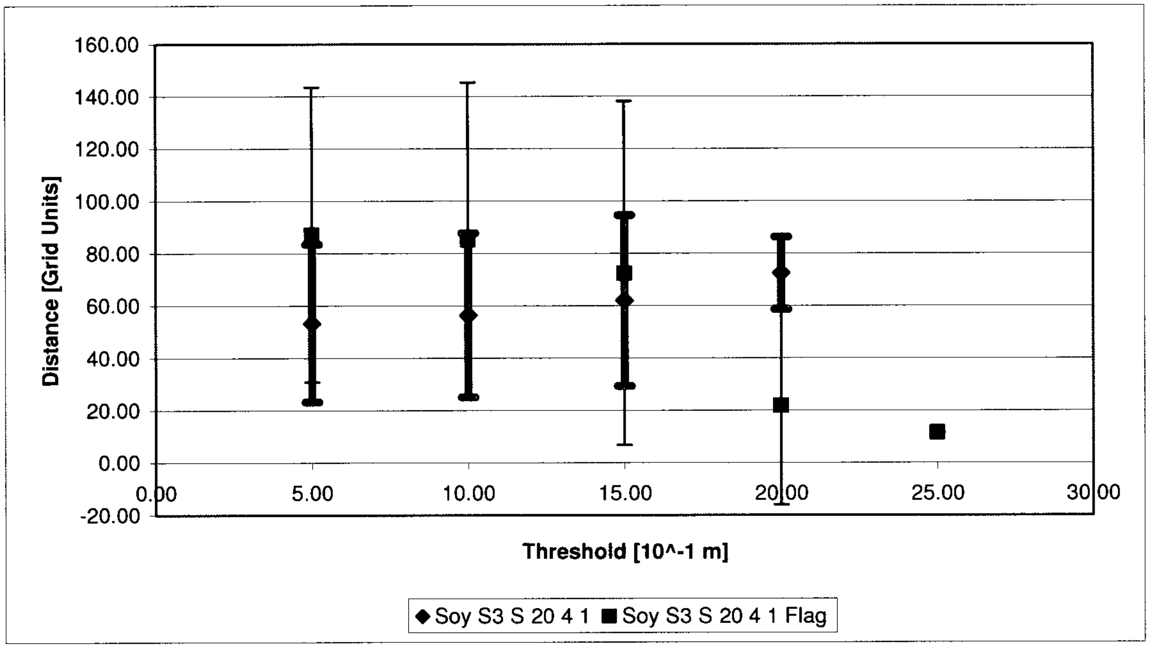



**Figure 3.19: Distance Results for S_S3_S_20_4_1**

### 3.4.3. Effects of Travel Speed

Evaluating for the number of discontinuity points for various thresholds, it was found that at slower speeds the number of discontinuities were much greater than using the same threshold at a faster speed. This may be attributed to the fact that there are many more scans during a 2 km/h test run than a 7 km/h test. Linearly extrapolating the number of points at 7 km/h we can find an expected number of points at 4 and 2 km/h. These theoretical values consider only the increase of points based on the increase of scans per test based on the speed of the test.

**Table 3-4: Average number of points for various test speeds**

| Speed | Data | Grand Total | Theoretical |
|---|---|---|---|
| | Average of Mean Dist | 75.24 | |
| 2 | Average of # Points | 731.36 | 234.89 |
| | Average of Mean Dist | 47.15 | |
| 4 | Average of # Points | 236.99 | 117.44 |
| | Average of Mean Dist | 28.82 | |
| 7 | Average of # Points | 67.11 | 67.11 |
| Total Average of Mean Dist | | 47.28 | |
| Total Average of # Points | | 290.51 | |

From theoretical values located in table 3-4, we see that the average number of points are still much smaller than the experimental values. The experimental values are two to three times greater than the linear increased values based on speed alone. The algorithm was able to detect more discontinuities per scan at lower speeds.

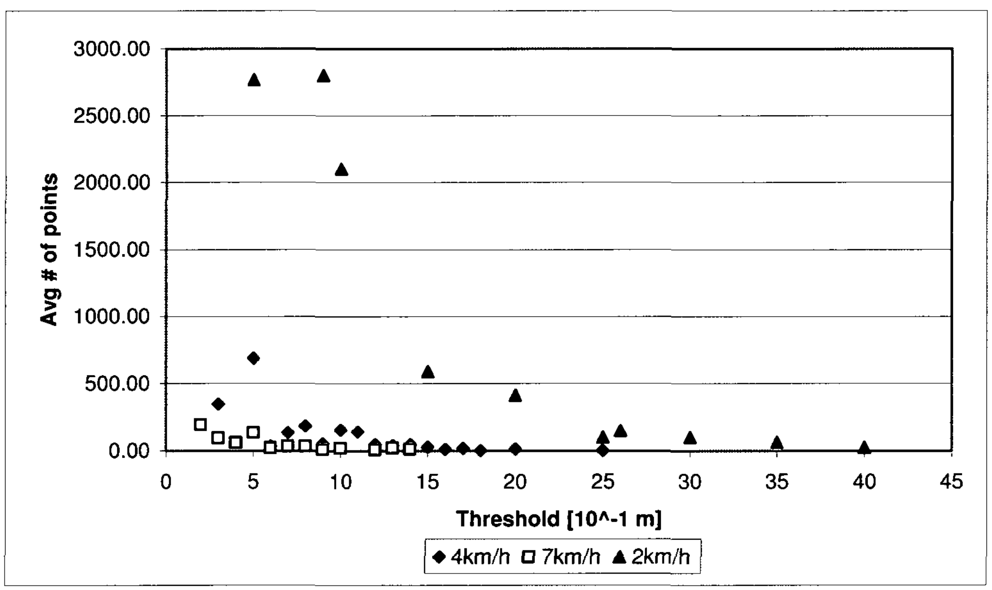



**Figure 3.20: Average number of points vs. Threshold**

Evaluating the number of successful test runs on their speed and the total number of tests for each speed category, we find that 26.9% of 7 km/h tests had discontinuity clustering near the object and/or the flag. The 4 km/h test runs yielded the second best results with 21.43% and this was reduced to 8.33% when testing at 2 km/h.

### 3.4.4. Effects of Crop

The average distances found between the discontinuities and the object locations varied greatly depending on the threshold used. Figure 3.21 to Figure 3.24 inclusively present the average distances for each crop for varying thresholds. The overall average distances for Hay, Oats, Soy, and Wheat were 40.97, 52.54, 54.57, and 24.13 respectively.

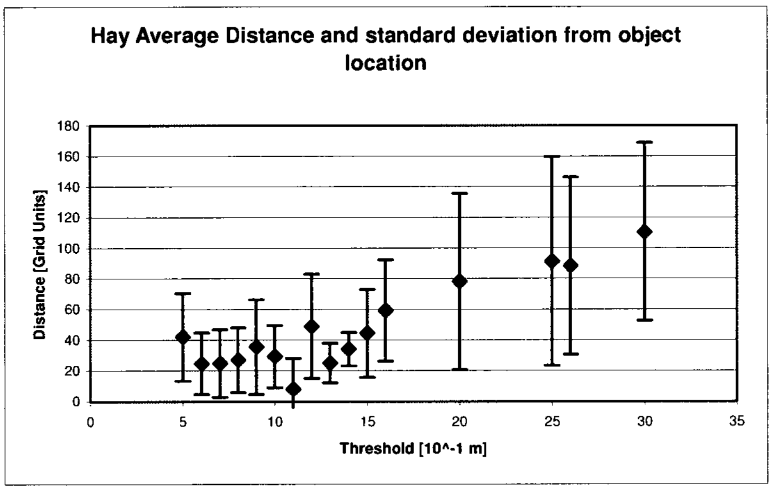



**Figure 3.21: Hay Discontinuity Results**

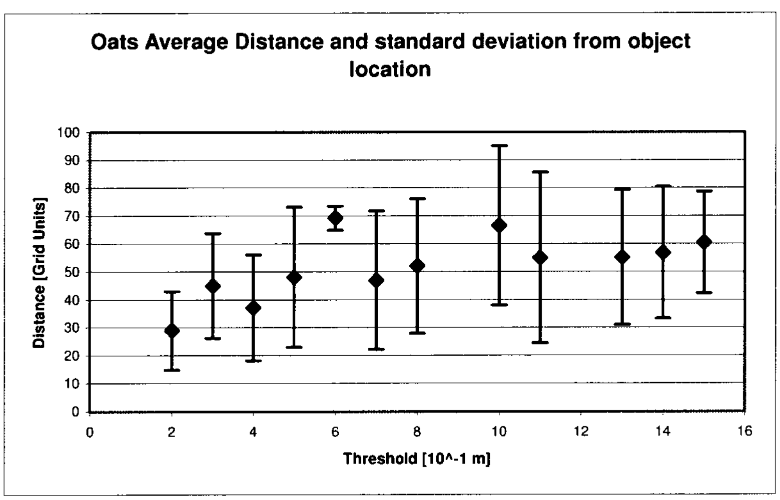



**Figure 3.22: Oats Discontinuity Results**

The results obtained in the Hay and Oat fields show that the distance increased proportionally with the threshold. Especially for the Hay fields, as the threshold reaches upwards of 20, the mean distance increased and the standard deviation of these distances are also increased suggesting that the discontinuities found do not cluster near any specific area.

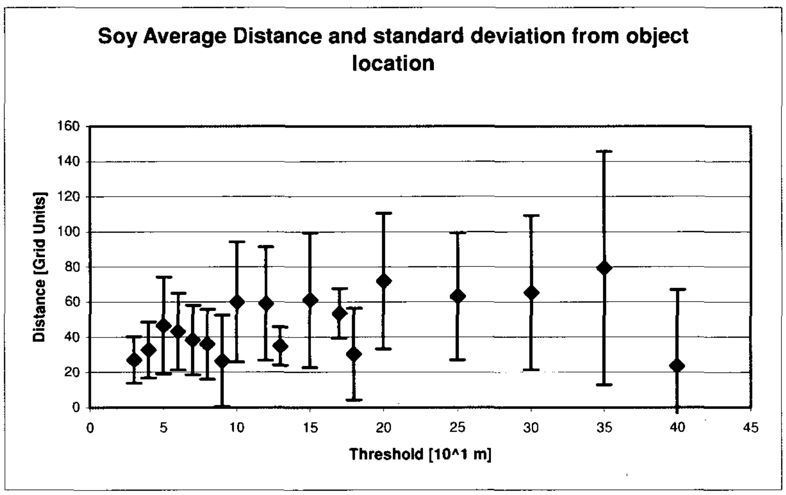



**Figure 3.23: Soy Discontinuity Results**

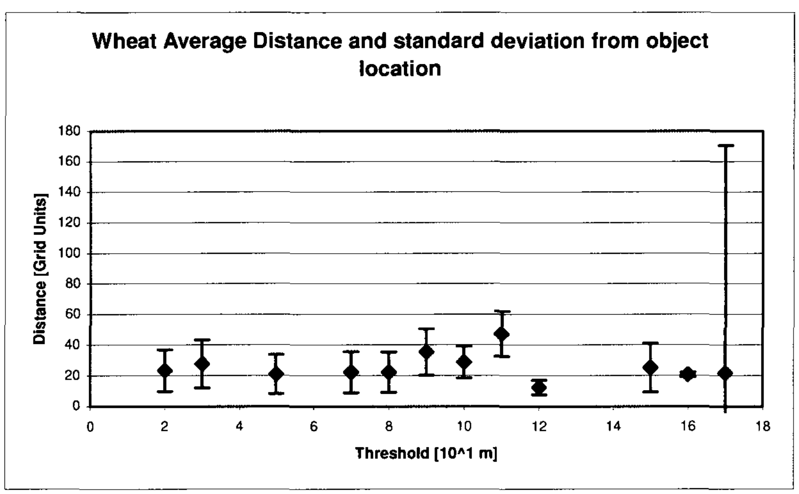



**Figure 3.24: Wheat Discontinuity results**

Wheat had the lowest overall distance between discontinuities and the object. There is also little variation among the results when comparing to the other crops. The small standard deviations observed with a threshold of 12 and 16 were due to the successful clustering of points around the object.

### 3.4.5. Effects of Scanner Angle

There is no significant difference in the two data series as shown by the average of the mean distances and standard deviations for both 20 and 30 degrees.

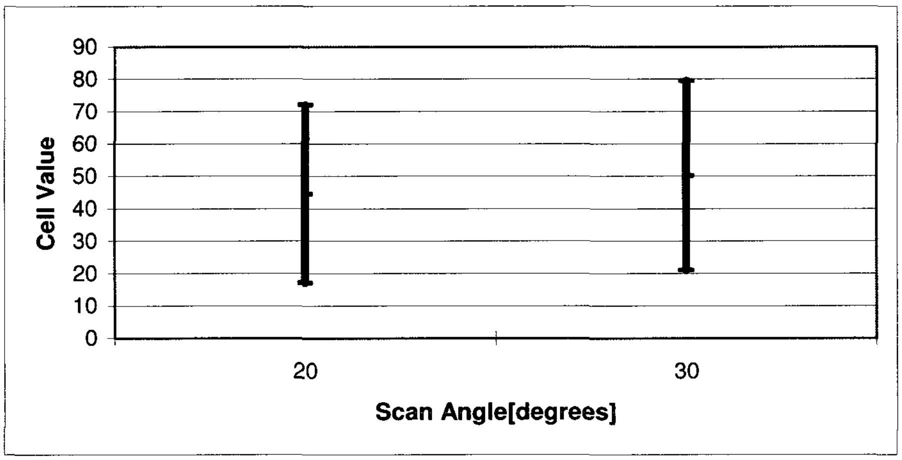



**Figure 3.25: Scan angle discontinuity results**

No significant changes in values were found when comparing 20 and 30 degree scan angles. The 20 degree scan angle tests yielded slightly better overall mean distances as well as 26.66% success rates. The 30 degree tests yielded 15.15% success rate.

### 3.4.6. Effects of Object

Observing the average of the mean distances and standard deviations for both tall cylindrical (TC) and tall square (TS) objects, there is no significant difference in the two data series.

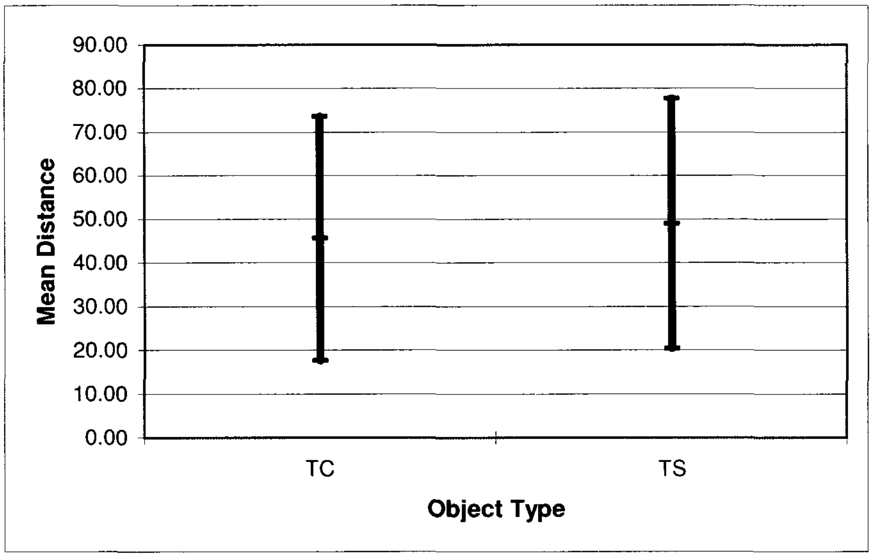



**Figure 3.26: Object Type discontinuity results**

### 3.4.7. Effects of Growth Stage of the Crops

The higher height of soy field, compared to other test fields, impaired the field of view and increased the scanning resolution near the edge of the field. This may help to explain why the reference flags were detectable in the Soy fields. The height difference between the scanner and the crop height was the smallest for the wheat and soy crops at 42-cm and 47-cm respectively. The dense soy canopy in the first season may have also helped to reduce the field of view. Observing the plotted discontinuity points, we can see that many points represent the crop edge. During the second growth stage of the Soy crop (S3), the plant leaves had dried and withered leaving much of the plan stem and a greatly reduced crop canopy. This allowed greater crop penetration for the LMS.

We believe that the increased crop height for the Wheat and Soy reduced the field of view and range data resolution away from the crop edge. This could then have reduced the ability for this method to identify discontinuities farther in to the crop, were the objects were located.

### 3.4.8. Effect of Crop Edge

Because the tests were run along the sides of crops, the end of crop edges were constantly scanned. Many of the discontinuity tests showed an increase in discontinuity density along the crop edge. Though this can cause increased error in detecting objects within the fields, we found that this method has the ability to detect the crop edge which may have many advantages in precision agriculture. Crop edge detection has the ability to complement an autonomous navigation system to ensure they are on track with the crop. This may also be used for precision weeding or application of pesticides, herbicides, watering, etc.

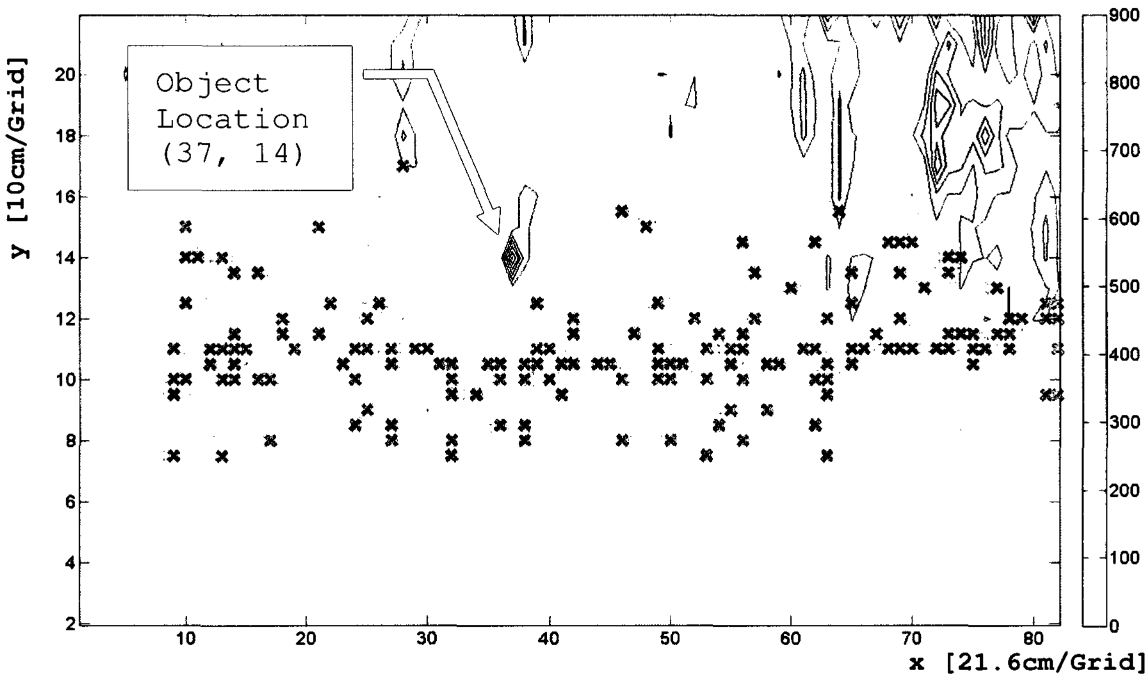



**Figure 3.27: Discontinuities of W_S1_S_30_7_1(threshold = 2) plotted over averaged height values**

In Figure 3.27 we notice many discontinuity points at the position Y=11. The test object was located at (37, 14) where there is a peak in average height value. In this situation, most of the points at Y = 11 represent the crop edge.

### 3.4.9. Discontinuity Density

Observing the density distribution of the discontinuity points, while the mean and standard deviation values did not yield good results, there may be potential in evaluating the point density. This may provide valuable information on the characteristic of the field.

In Figure 3.28 we can see a cluster near the object location of (128, 28) and another near the flag at (202, 5). There are also many discontinuities along the crop edge between $10 \leq Y \leq 25$. Thus, evaluating this data series at a threshold of 1.5m in a density method could provide us information on the location of three separate field characteristics. The first being the test object, the second being the flag and the third being the crop edge.

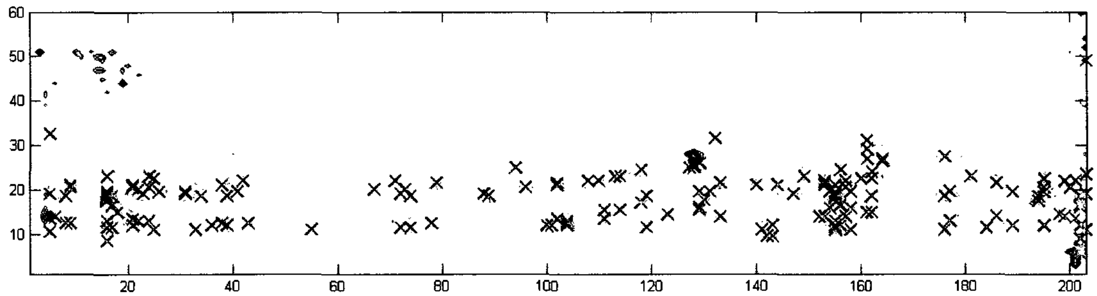



**Figure 3.28: Example of crop discontinuity density, S_S3_C_20_4_2, threshold = 1.5m**

Future work should evaluate the higher discontinuity density locations to help identify areas of interest while using a constant threshold relative to the speed of travel. It should be noted that the difference in height between the crops and of the taller test objects was in the order of 1m.

## 3.5. Overall Success Assessment

Each proposed detection method yielded a different overall object detection rate. The greatest success was achieved with the Average Height method which resulted in an overall 72.4% object detection rate. The least successful was the Connectivity Method which could only provide higher peak values for 18% of the tests.

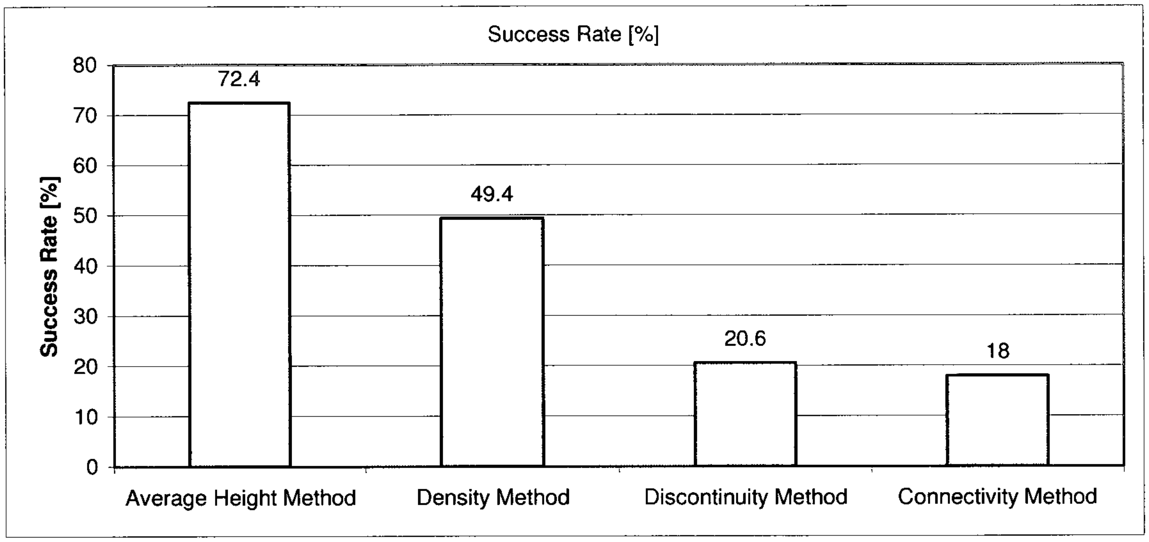



**Figure 3.29: Overall Method Success Rates**

The success rates in Figure 3.29 omit the "possible detection" cases where peak values were present but could not be attributed solely to the object. Noise and false detections were present in these results thus not allowing us to categorize these results as a successful detection. The Discontinuity values are based on previously known locations and mean distance convergence.

## *3.6. Computational Requirements of the Different Methods*

To evaluate the computational requirements/abilities of the different algorithms used in this study, we compared the average computational time to the field scan times assuming a consistent 9Hz scan rate. We ran each detection program three times for four different crop tests. Initially, the computational time per scan is calculated.

$t_p$ : Time required for Matlab program to evaluate scan file

$s$ : Number of scans in file

$f_s$ : Lidar scan frequency, 9Hz

$$1/f_p = t_p/s \tag{9}$$

$1/f_p$ = Time per scan [sec]

$$R = {f_s}/{f_p} = {9Hz}/{f_p} \qquad (10)$$

$R$ = Lidar and Program frequency ratio

**Table 3-5: R Values for various field tests**

| R values for various field tests | | | | |
|---|---|---|---|---|
| | H_S1_S_20_7_3 | O_S1_S_20_4_1 | S_S3_C_30_S_1 | W_S1_C_20_4_1 |
| Height, | 0.0489 | 0.0489 | 0.0540 | 0.0495 |
| Density | 0.0073 | 0.0086 | 0.0108 | 0.0074 |
| Connectivity | 0.0157 | 0.0166 | 0.0203 | 0.0159 |
| Hough Transform | 1.5872 | 1.4807 | 1.3034 | 1.2238 |

Detailed results can be found in Appendix A

Reviewing the results from table 3-5, the first three methods have a programming frequency greater than the Lidar scan frequency yielding R values lower than 1. Essentially what we are looking for is to have the $f_p$ (program frequency) to be greater than the Lidar frequency. In this case, the computer algorithms are, for the most part, able to keep up with the incoming data. The Height, Density, and Connectivity methods have much less computational requirements than the Hough Transform. These three methods should be able to easily keep up with any incoming scan data with a frequency of 9Hz. The Discontinuity method, that uses the Hough transform, was slower at processing the data. No attempts were made to reduce the discontinuity method computational requirements due to the scope of this work.

# Conclusions

The end goal of the overarching research program is to evaluate the feasibility of using this particular type of LMS on future autonomous agricultural vehicles. It was found that this system, with the conjunction of other safety systems, may be useful in ensuring the safe field operation of autonomous agricultural vehicles.

With the LMS placed on a tractor, oriented downwards and towards the crops and test objects placed within the crops, the range data were recorded and later analysed with various algorithms. These algorithms included the average height method, range data point density, connectivity, and crop discontinuity analyses.

Each analysis method provided different detection rates. The connectivity method yielded the lowest detection rate with only 18% of the results showing peak values at the known object location. The discontinuity method, when analysing the relative mean and standard deviation of the discontinuities to the known object location, yielded converging results for 20.6% of the tests. The density and average height method were shown to have the greatest success rates of 49.4% and 72.4% respectively. The density method had greatest noise. There was very little success with the shorter test object.

Both the Average Height and Density method cell values decreased with an increase of speed. No evaluation was performed for the connectivity method due to poor success rates. The Discontinuity method had greater success at higher speeds. A total of 26.9% of high speed tests yielded good results where as only 8.33% for the slower travel speed.

The average height method yielded the best results with the Hay, Oats, and Soy crops with the Wheat crop providing the lowest cell values. Using the density method the highest cell values were obtained from the Hay crops and the lowest from the Wheat. The Discontinuity method experienced consistently low average distance results with the wheat crops.

For all methods the tall cylindrical (TC) object yielded slightly higher values than the tall square object. Little or no success was found with the short cylindrical (SC) object. Also comparing the results for the 20 and 30 degree tests, no significant differences were recorded.

Evaluating the processing time for each method it was found that the average height method, the connectivity method, and the density method could process the range data faster than the scanning rate. Due to the higher computational requirements associated with the Hough transform, the discontinuity method was slower at processing the data than the scan rate.

Using a Laser Measurement System and the detection algorithms we were able to detect objects with various degrees of success. Laser Measurement Systems with object detection algorithms has the potential to have significant role in future autonomous agricultural vehicles. This type of system could contribute to the navigation and safety of agricultural vehicles and to precision farming systems.

## Recommendations for Future Work

With little previous work conducted in this type of research, this study was meant to identify potential object identification methods. Future work is recommended to improve these methods and better test their abilities. Recommendations are divided into two categories, the testing stages and the range data analysis methods.

For in-field testing the LMS should be installed on a stabilization system. This is expected to greatly increase the consistency of the data. When observing the range data in 3D format inconsistencies were found and believed to be caused by the changing pitch of the tractor. Included in this stabilization system can also be an Inertial Navigation System (INS) that records the pitch, yaw, and roll of the scanner. This information could help correct any data that has been affected by tractor and LMS vibrations. A secondary axis of rotation for the LMS, oscillating the LMS in one axis would give a much greater field of view. This could give multiple view angles of the same object. Various height discrepancies between the test object and crops could also provide better performance results of each method.

To reduce the future number of field tests, testing can be done on a unique crop. Oats and Wheat crops are suggested because their height and density are more consistent over time when compared to Soy and Hay.

Work can also begin on trying to integrate a navigation system such as GPS and auto-steering. Real-time analysis should also be implemented considering the end purpose of this type of research.

For the data analysis methods, future work includes evaluating the effect of varying grid size and how it affects the detection rates. Test object recognition algorithms may be included. End of crop discontinuities analysis can be performed to evaluate its usefulness in crop management and evaluating the discontinuity points on a density basis can also be examined. To compare detection rates at various scan frequencies, the original field scan can be done at a higher frequency and the analysis can be done while omitting every second scan.

## References

Aboshosha, A. & Zell, A. 2003. Robust Mapping and Path Planning for Indoor Robots based on Sensor Integration of Sonar and a 2D Laser Range Finder. IEEE 7th International Conference on Intelligent Engineering Systems.

ASABE 2006. ASABE STANDARDS 2006. St. Joseph, MI: ASABE.

Blackmore, B. S., Fountas, S., Vougioukas, S., Tang, L., Sørensen, C. G. & Jørgensen, R. 2004. A method to define agricultural robot behaviours. In Automation Technology for Off-Road Equipment. Kyoto, Japan: ASAE.

Derenick, J. 2009. the Sick LIDAR Matlab/C++ toolbox, http://sicktoolbox.sourceforge.net. Accessed August 2009.

Goense, D. 2005. The Economics of Autonomous Vehicles in Agriculture. In 2005 ASAE Annual International Meeting Sponsored by ASAE. Tampa Convention Center Tampa, Florida.

Gong, J. & Caldas, C. H. 2008. Data processing for real-time construction site spatial modeling. Automation in Construction Vol. 17(Issue 5): p.526-535.

Google. 2009.Imagery 2009 DigitalGlobe, GeoEye, Map data, www.maps.google.com. Accessed July 2009.

Hebert, M. 2000. Active and Passive Range Sensing for Robotics. In International Conference on Robotics & Automation San Francisco, CA: The Robotics Institute, Carnegie Mellon University.

Heraud, J. A. & Lange, A. F. 2009. Agricultural Automatic Vehicle Guidance from Horses to GPS: How we got here, and where we are going. In 2009 Agricultural Equipment Technology Conference Louisville, Kentucky, USA: American Society of Agricultural and Biological Engineers.

Hollnagel, E. 1999. Accidents and barriers. In Proceedings of lex valenciennes, Vol. 28, 175-182.

J. Kirby & Raper, R. 2006. SOIL COMPACTION: HOW TO DO IT, UNDO IT, OR AVOID DOING IT. In 2006 Agricultural Equipment Technology Conference

Louisville, Kentucky, USA: American Society of Agricultural and Biological Engineers, Publication Number 913C0106.

Johnston, J. 2006. Off-highway obstacle detection. Vol. 9, p16-24: Institute of Electrical and Electronics Engineers.

Kiryati, N., Eldar, Y. &Bruckstein, A. M. 1991. A Probabilistic Hough Transform. Pattern Recognition Vol. 24: p.303-316.

Lee, K.-H. & Ehsani, R. 2008. Comparison of two 2D laser scanners for sensing object distances, shapes, and surface patterns. Computers and Electronics in Agriculture Vol. 60(Issue 2): p.250-262.

Matlab (2008).Matlab Help Guide. In Version 7.3.0 (R2006b): MathWorks, Inc.

Miller, T. H. & Derenick, J. C. 2008. The Sick LIDAR Matlab/C++ Toolbox: Enabling RS-422 Communication via USB-COMi-M. 10 Bethlehem, PA: Lehigh University, Computer Science and Engineering.

Muzammil, M., Siddiqui, S. & Hasan, F. 2004. Physiological Effect of Vibrations on Tractor Drivers under Variable Ploughing Conditions. Journal of Occupational Health Vol. 46(Issue 5): p.403-409.

N.B Power, M. B. B. 2005. A sensor Integration Method for Autonomous Equipment. In ASABE, Paper #051137 Tampa, Florida.

Payeur, P. 2004. Machine Vision ELG5163. In Course Notes: University of Ottawa.

R.Murphy, R. 2000. Introduction to AI Robotics. Cambridge, MA: MIT Press.

Reid, W. S. 2002. An Assessment of the Control and Safety Needs of Autonomous Agricultural Vehicles and Implement Systems on Farm Property. In Automation Technology for Off-Road Equipment, 422-431 (Ed Q. Zhang.). Chicago, Illinois, USA: ASAE.

Sensor Intelligence, S. 2006. LMS200/211/221/291 Laser Measurement Systems. (Ed T. Description). Waldkirch: SICK.

Spong, M. W., Hutchinson, S. & Vidyasagar, M. 2006. Robot modeling and control. Hoboken, NJ: John Wiley & Sons.

Srivastava, A. K. 2006. Engineering principles of agricultural machines. American Society of Agricultural and Biological Engineers St. Joseph, Mich.

StatsCan 2007. Field and specialty crops, table (for fee) 001-0010 and Catalogue no. 22-002-X, www.statscan.gc.ca. Accessed December 2007.

Stentz, A., Dima, C., Wellington, C., Herman, H. &Stager, D. 2002. A System for Semi-Autonomous Tractor Operations. Autonomous Robots Vol. 13: p.87-104.

Stout &Cheze 1999. GIGR Handbook of Agricultural Engineering. St. Joseph, Mich: ASABE.

Sugimoto, S., Tateda, H., Takahashi, H. &Okutomi, M. 2004. Obstacle Detection Using Millimeter-wave Radar and Its Visualization on Image Sequence. In 17th International Conference on Pattern Recognition: IEEE.

Wardziński, A. 2008. Safety Assurance Strategies for Autonomous Vehicles. Springer Berlin / Heidelberg.

Welch, G. &Bishop, G. 2006. An Introduction to the Kalman Filter. (Ed D. o. C. Science). Chapel Hill: University of North Carolina.

Wong, U. Terrain Obstacle Detection and Analysis using LIDAR. Carnegie Mellon University, Robotics Institute.

# Appendix A. Crop and Equipment Information and Data

**Table A.1: Field and specialty crops in Canada (StatsCan, 2007)**

| **Field and specialty crops** (Seeded area) | | | | | | |
|---|---|---|---|---|---|---|
| | **2003** | **2004** | **2005** | **2006** | **2007** | **Percentage (2007)** |
| | Seeded area | | | | | |
| | thousand hectares | | | | | |
| **Field crops** | | | | | | |
| Wheat | 10,413.30 | 9,885.10 | 9,653.90 | 9,852.20 | 8,849.50 | 25% |
| Canola (rapeseed) | 4,735.70 | 5,218.20 | 5,369.90 | 5,283.30 | 5,959.50 | 17% |
| Barley | 4,989.40 | 4,432.10 | 4,142.60 | 3,689.90 | 4,396.80 | 12% |
| Oats | 2,033.20 | 1,924.10 | 1,767.90 | 2,063.50 | 2,188.40 | 6% |
| Flaxseed | 744.6 | 700 | 760.8 | 804.8 | 528 | 1% |
| Rye | 246.4 | 258.2 | 207.6 | 276.2 | 171.9 | 0% |
| Soybeans | 1,052.80 | 1,223.00 | 1,172.40 | 1,213.50 | 1,180.10 | 3% |
| Grain corn | 1,264.60 | 1,184.80 | 1,113.10 | 1,093.10 | 1,391.50 | 4% |
| Tame hay | 7,879.00 | 8,024.50 | 8,169.90 | 8,237.00 | 8,239.20 | 23% |
| **Specialty crops** | | | | | | |
| Canary seed | 250.9 | 347.9 | 184.2 | 135.6 | 178.1 | 1% |
| Lentils | 513.4 | 738.4 | 802.8 | 516.3 | 540.2 | 2% |
| Sunflower seed | 108.4 | 80.9 | 87 | 77 | 80.9 | 0% |
| Mustard seed | 339.8 | 298.6 | 194.1 | 133.8 | 176 | 0% |
| Peas | 1,169.30 | 1,282.90 | 1,303.00 | 1,260.50 | 1,469.00 | 4% |
| **Total** | **35,740.80** | **35,598.70** | **34,929.20** | **34,636.70** | **35,349.10** | |

**Source:** Statistics Canada, CANSIM, table (for fee) 001-0010 and Catalogue no. 22-002-X.
Last modified: 2007-12-06.
* 1 hect = 10 000 m² = 100m x 100m

**Table A-1: ASABE Typical Operating Speeds**

| *From :ASABE Standards 2006, 53rd Edition, Standards Engineering Practices Data, p.395, Table 3, Typical operating speeds* | | | | | |
|---|---|---|---|---|---|
| ***Tillage and Planting*** | ***km/h*** | ***Harvesting*** | ***km/h*** | ***Misc.*** | ***km/h*** |
| Moldboard Plow | 7 | Corn picker sheller | 4 | Fertilizer Spreader | 11 |
| Heavy-duty disk | 7 | Combine | 5 | Boom-type sprayer | 10.5 |
| tandem disk harrow | 10 | Combine (SP) | 5 | Air-carrier sprayer | 5 |
| (Coulter) chisel plow | 8 | Mower | 8 | Bean puller-windrower | 8 |
| Field cultivator | 11 | Mower (rotary) | 11 | Beet topper/stalk chopper | 8 |
| Spring tooth harrow | 11 | Mower-Conditioner | 8 | | |
| Roller-Packer | 10 | Mower-Conditioner (rotary) | 11 | | |
| Mulcher-Packer | 8 | Windrower | 8 | | |
| Rotary Hoe | 19 | Side Delivery take | 10 | | |
| Row crop cultivator | 8 | Rectangular baler | 6.5 | | |
| Rotary tiller | 5 | Large rectanguler baler | 8 | | |
| Row crop planter | 9 | Large round baler | 8 | | |
| Grain drill | 8 | Forage Harvester | 5 | | |
| | | Forage Harvester (SP) | 5.5 | | |
| | | Sugar beet harvester | 8 | | |
| | | Potato Harvester | 4 | | |
| | | Cotton picker | 4.5 | | |
| **AVG** | 9.3 | | 7.0 | | 8.5 |
| **Overall Avg** | 8.3 | | | | |

**Table A-2: Minimum braking performance criteria(ASABE, 2006) Section 9.1.2**

| ***Stopping performance for service braking systems*** | |
|---|---|
| Category | Maximum stopping distance |
| I,IIa, III, IV | $S = \frac{V^2}{6.27} + \frac{V}{3}$ |
| IIb and combinations of braked and un-braked machines I and III, I and IV, Iia and III, IIa and IV | $S = \frac{V^2}{3.52} + \frac{V}{3}$ |

(V=initial velocity, m/s)

**Table A-3: Kubota 30M time trials**

| ***Time Trials*** | | | | |
|---|---|---|---|---|
| Distance[m] | 30 | Terrain: | Grass | |
| RPM | Gear | Time[s] | m/s | km/h |
| 1000 | 1 | 60 | 0.5 | 1.8 |
| 1500 | 1 | 42 | 0.7 | 2.6 |
| 2000 | 1 | 32 | 0.9 | 3.4 |
| 2000 | 2 | 19 | 1.6 | 5.7 |
| 2500 | 2 | 16 | 1.9 | 6.8 |
| 1750 | 2 | 24.18 | 1.2 | 4.5 |
| 1500 | 2 | 24.17 | 1.2 | 4.5 |
| 1400 | 3 | 17.3 | 1.7 | 6.2 |
| 1700 | 3 | 13.71 | 2.2 | 7.9 |
| 1400 | 3 | 18.27 | 1.6 | 5.9 |
| 2200 | 3 | 12 | 2.5 | 9.0 |

**Table A-4: Computational Time Requirements**

| Computational Requirements (Time/Scan) | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | test: | H_S1_S_20_7_3 | | | O_S1_S_20_4_1 | | | S_S3_C_30_S_1 | | | W_S1_C_20_4_1 | | |
| Height Averaging | | time(s) | scans | time/scan | time(s) | scans | time/scan | time(s) | scans | time/scan | time(s) | scans | time/scan |
| | 1 | 0.78 | 143 | 0.01 | 0.99 | 184 | 0.01 | 1.72 | 302 | 0.01 | 0.81 | 146 | 0.01 |
| | 2 | 0.78 | 143 | 0.01 | 1.01 | 184 | 0.01 | 1.77 | 302 | 0.01 | 0.80 | 146 | 0.01 |
| | 3 | 0.77 | 143 | 0.01 | 0.99 | 184 | 0.01 | 1.73 | 302 | 0.01 | 0.81 | 146 | 0.01 |
| | avg | 0.78 | 143 | 0.01 | 1.00 | 184 | 0.01 | 1.74 | 302 | 0.01 | 0.80 | 146 | 0.01 |
| Prog.(Hz)/ Scan(Hz) | | | | 0.05 | | | 0.05 | | | 0.05 | | | 0.05 |
| | | | | | | | | | | | | | |
| Density | | time(s) | scans | time/scan | time(s) | scans | time/scan | time(s) | scans | time/scan | time(s) | scans | time/scan |
| | 1 | 0.12 | 143 | 0.00 | 0.19 | 184 | 0.00 | 0.34 | 302 | 0.00 | 0.12 | 146 | 0.00 |
| | 2 | 0.11 | 143 | 0.00 | 0.17 | 184 | 0.00 | 0.40 | 302 | 0.00 | 0.12 | 146 | 0.00 |
| | 3 | 0.11 | 143 | 0.00 | 0.17 | 184 | 0.00 | 0.34 | 302 | 0.00 | 0.11 | 146 | 0.00 |
| | avg | 0.12 | 143 | 0.00 | 0.18 | 184 | 0.00 | 0.36 | 302 | 0.00 | 0.12 | 146 | 0.00 |
| Prog.(Hz)/ Scan(Hz) | | | | 0.01 | | | 0.01 | | | 0.01 | | | 0.01 |
| | | | | | | | | | | | | | |
| Connectivity | | time(s) | scans | time/scan | time(s) | scans | time/scan | time(s) | scans | time/scan | time(s) | scans | time/scan |
| | 1 | 0.24 | 143 | 0.00 | 0.34 | 184 | 0.00 | 0.65 | 302 | 0.00 | 0.27 | 146 | 0.00 |
| | 2 | 0.24 | 143 | 0.00 | 0.34 | 184 | 0.00 | 0.65 | 302 | 0.00 | 0.24 | 146 | 0.00 |
| | 3 | 0.27 | 143 | 0.00 | 0.35 | 184 | 0.00 | 0.74 | 302 | 0.00 | 0.27 | 146 | 0.00 |
| | avg | 0.25 | 143 | 0.00 | 0.34 | 184 | 0.00 | 0.68 | 302 | 0.00 | 0.26 | 146 | 0.00 |
| Prog.(Hz)/ Scan(Hz) | | | | 0.02 | | | 0.02 | | | 0.02 | | | 0.02 |
| | | | | | | | | | | | | | |
| Hough Transform | | time(s) | scans | time/scan | time(s) | scans | time/scan | time(s) | scans | time/scan | time(s) | scans | time/scan |
| | 1 | 25.08 | 143 | 0.18 | 30.33 | 184 | 0.16 | 43.72 | 302 | 0.14 | 19.78 | 146 | 0.14 |
| | 2 | 25.34 | 143 | 0.18 | 30.40 | 184 | 0.17 | 43.87 | 302 | 0.15 | 19.91 | 146 | 0.14 |
| | 3 | 25.23 | 143 | 0.18 | 30.09 | 184 | 0.16 | 43.62 | 302 | 0.14 | 19.86 | 146 | 0.14 |
| | avg | 25.22 | 143 | 0.18 | 30.27 | 184 | 0.16 | 43.74 | 302 | 0.14 | 19.85 | 146 | 0.14 |
| Prog.(Hz)/ Scan(Hz) | | | | 1.59 | | | 1.48 | | | 1.30 | | | 1.22 |

# Appendix B. Complete Experimental Results

## B.1 Average Height Method Results

**Average Height Method Results**

*NF: object not found*

| Crop | Season | Object | Scanner Angle [degrees] | Speed [km/h] | Test # | Peak-X | Peak-Y | Cell Value | Flag-X | peak-peak dist [m] | dist/scan [mm] | #scan/10m | Crop height [cm] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Wheat | S1 | SC | 20 | 4 | 1 | NF | | | | | 123 | 81.30 | 75 |
| Wheat | S1 | SC | 20 | 4 | 2 | NF | | | | | 123 | 81.30 | 75 |
| Wheat | S1 | SC | 20 | 4 | 3 | NF | | | | | 123 | 81.30 | 75 |
| Wheat | S1 | SC | 20 | 7 | 1 | NF | | | | | 216 | 46.30 | 75 |
| Wheat | S1 | SC | 20 | 7 | 2 | NF | | | | | 216 | 46.30 | 75 |
| Wheat | S1 | SC | 20 | 7 | 3 | NF | | | | | 216 | 46.30 | 75 |
| Wheat | S1 | SC | 20 | 2 | 1 | NF | | | | | 62 | 161.29 | 75 |
| Wheat | S1 | SC | 20 | 2 | 2 | NF | | | | | 62 | 161.29 | 75 |
| Wheat | S1 | SC | 20 | 2 | 3 | NF | | | | | 62 | 161.29 | 75 |
| Wheat | S1 | SC | 30 | 4 | 1 | NF | | | | | 123 | 81.30 | 75 |
| Wheat | S1 | SC | 30 | 4 | 2 | NF | | | | | 123 | 81.30 | 75 |
| Wheat | S1 | SC | 30 | 4 | 3 | NF | | | | | 123 | 81.30 | 75 |
| Wheat | S1 | SC | 30 | 7 | 1 | NF | | | | | 216 | 46.30 | 75 |
| Wheat | S1 | SC | 30 | 7 | 2 | NF | | | | | 216 | 46.30 | 75 |
| Wheat | S1 | SC | 30 | 7 | 3 | NF | | | | | 216 | 46.30 | 75 |
| Wheat | S1 | SC | 30 | 2 | 1 | NF | | | | | 62 | 161.29 | 75 |
| Wheat | S1 | SC | 30 | 2 | 2 | NF | | | | | 62 | 161.29 | 75 |
| Wheat | S1 | SC | 30 | 2 | 3 | NF | | | | | 62 | 161.29 | 75 |
| Wheat | S1 | TS | 20 | 4 | 1 | 57 | 15 | 482.86 | | -7.01 | 123 | 81.30 | 75 |
| Wheat | S1 | TS | 20 | 4 | 2 | 61 | 15 | 583.18 | | -7.50 | 123 | 81.30 | 75 |
| Wheat | S1 | TS | 20 | 4 | 3 | 83 | 13 | 585.63 | | -10.21 | 123 | 81.30 | 75 |
| Wheat | S1 | TS | 20 | 7 | 1 | 53 | 17 | 465.15 | | -11.45 | 216 | 46.30 | 75 |
| Wheat | S1 | TS | 20 | 7 | 2 | 40 | 14 | 686.38 | | -8.64 | 216 | 46.30 | 75 |
| Wheat | S1 | TS | 20 | 7 | 3 | 47 | 14 | 1059.34 | | -10.15 | 216 | 46.30 | 75 |
| Wheat | S1 | TS | 30 | 4 | 1 | 65 | 14 | 853.08 | | -7.995 | 123 | 81.30 | 75 |
| Wheat | S1 | TS | 30 | 4 | 2 | 64 | 14 | 413.11 | | -7.872 | 123 | 81.30 | 75 |
| Wheat | S1 | TS | 30 | 4 | 3 | 61 | 15 | 519.19 | | -7.503 | 123 | 81.30 | 75 |
| Wheat | S1 | TS | 30 | 7 | 1 | 37 | 14 | 611.47 | | -7.992 | 216 | 46.30 | 75 |
| Wheat | S1 | TS | 30 | 7 | 2 | 31 | 14 | 299.29 | | -6.696 | 216 | 46.30 | 75 |
| Wheat | S1 | TS | 30 | 7 | 3 | 39 | 14 | 592.45 | | -8.424 | 216 | 46.30 | 75 |
| Wheat | S1 | TC | 20 | 4 | 1 | 85 | 13 | 1002.78 | | -10.455 | 123 | 81.30 | 75 |
| Wheat | S1 | TC | 20 | 4 | 2 | 67 | 14 | 584.21 | | -8.241 | 123 | 81.30 | 75 |
| Wheat | S1 | TC | 20 | 4 | 3 | 34 | 14 | 871.41 | | -4.182 | 123 | 81.30 | 75 |

## Average Height Method Results

*NF: object not found*

| Crop | Season | Object | Scanner Angle [degrees] | Speed [km/h] | Test # | Peak-X | Peak-Y | Cell Value | Flag-X | peak-peak dist [m] | dist/scan [mm] | #scan/10m | Crop height [cm] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Wheat | S1 | TC | 20 | 7 | 1 | 18 | 14 | 1006.38 | | -3.888 | 216 | 46.30 | 75 |
| Wheat | S1 | TC | 20 | 7 | 2 | 30 | 14 | 587.38 | | -6.48 | 216 | 46.30 | 75 |
| Wheat | S1 | TC | 20 | 7 | 3 | 15 | 13 | 592.06 | | -3.24 | 216 | 46.30 | 75 |
| Wheat | S1 | TC | 20 | 2 | 1 | 51 | 13 | 1151.85 | | -3.162 | 62 | 161.29 | 75 |
| Wheat | S1 | TC | 30 | 4 | 1 | 54 | 14 | 1108.82 | | -6.64 | 123 | 81.30 | 75 |
| Wheat | S1 | TC | 30 | 4 | 2 | 47 | 14 | 875.58 | | -5.781 | 123 | 81.30 | 75 |
| Wheat | S1 | TC | 30 | 4 | 3 | 53 | 14 | 869.94 | | -6.519 | 123 | 81.30 | 75 |
| Wheat | S1 | TC | 30 | 7 | 1 | 25 | 13 | 303.70 | | -5.4 | 216 | 46.30 | 75 |
| Wheat | S1 | TC | 30 | 7 | 2 | 27 | 14 | 885.68 | | -5.832 | 216 | 46.30 | 75 |
| Wheat | S1 | TC | 30 | 7 | 3 | 22 | 14 | 847.43 | | -4.752 | 216 | 46.30 | 75 |
| Wheat | S1 | TC | 30 | 2 | 1 | 43 | 14 | 1145.08 | | -2.666 | 62 | 161.29 | 75 |
| Hay | S1 | TC | 20 | 4 | 1 | 122 | 21 | 1136.01 | | -15.006 | 123 | 81.30 | 20 |
| Hay | S1 | TC | 20 | 4 | 2 | 155 | 21 | 1137.06 | | -19.065 | 123 | 81.30 | 20 |
| Hay | S1 | TC | 20 | 4 | 3 | 127 | 21 | 1128.68 | | -15.621 | 123 | 81.30 | 20 |
| Hay | S1 | TC | 20 | 7 | 1 | 63 | 21 | 1088.06 | | -13.608 | 216 | 46.30 | 20 |
| Hay | S1 | TC | 20 | 7 | 2 | 85 | 21 | 1098.98 | | -18.36 | 216 | 46.30 | 20 |
| Hay | S1 | TC | 20 | 7 | 3 | 107 | 21 | 1110.54 | | -23.112 | 216 | 46.30 | 20 |
| Hay | S1 | TC | 30 | 4 | 1 | 149 | 20 | 1122.47 | | -18.327 | 123 | 81.30 | 20 |
| Hay | S1 | TC | 30 | 4 | 2 | 144 | 19 | 1122.39 | | -17.712 | 123 | 81.30 | 20 |
| Hay | S1 | TC | 30 | 4 | 3 | 170 | 20 | 1117.27 | | -20.91 | 123 | 81.30 | 20 |
| Hay | S1 | TC | 30 | 7 | 1 | 69 | 21 | 1055.61 | | -14.904 | 216 | 46.30 | 20 |
| Hay | S1 | TC | 30 | 7 | 2 | 82 | 21 | 1078.50 | | -17.712 | 216 | 46.30 | 20 |
| Hay | S1 | TC | 30 | 7 | 3 | 93 | 19 | 1074.89 | | -20.088 | 216 | 46.30 | 20 |
| Hay | S1 | TS | 20 | 4 | 1 | 136 | 20 | 1132.38 | | -16.728 | 123 | 81.30 | 20 |
| Hay | S1 | TS | 20 | 4 | 2 | 146 | 20 | 1126.34 | | -17.958 | 123 | 81.30 | 20 |
| Hay | S1 | TS | 20 | 4 | 3 | 123 | 20 | 1121.01 | | -15.129 | 123 | 81.30 | 20 |
| Hay | S1 | TS | 20 | 7 | 1 | 82 | 20 | 996.29 | | -17.712 | 216 | 46.30 | 20 |
| Hay | S1 | TS | 20 | 7 | 2 | 73 | 21 | 827.98 | | -15.768 | 216 | 46.30 | 20 |
| Hay | S1 | TS | 20 | 7 | 3 | 87 | 20 | 1071.73 | | -18.792 | 216 | 46.30 | 20 |
| Hay | S1 | TS | 30 | 4 | 1 | 188 | 20 | 1114.33 | | -23.124 | 123 | 81.30 | 20 |
| Hay | S1 | TS | 30 | 4 | 2 | 156 | 20 | 862.85 | | -19.188 | 123 | 81.30 | 20 |
| Hay | S1 | TS | 30 | 4 | 3 | 159 | 20 | 1110.25 | | -19.557 | 123 | 81.30 | 20 |
| Hay | S1 | TS | 30 | 7 | 1 | 96 | 21 | 1052.93 | | -20.736 | 216 | 46.30 | 20 |

## Average Height Method Results

*NF: object not found*

| Crop | Season | Object | Scanner Angle [degrees] | Speed [km/h] | Test # | Peak-X | Peak-Y | Cell Value | Flag-X | peak-peak dist [m] | dist/scan [mm] | #scan/10m | Crop height [cm] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hay | S1 | TS | 30 | 7 | 2 | 92 | 20 | 559.97 | | -19.872 | 216 | 46.30 | 20 |
| Hay | S1 | TS | 30 | 7 | 3 | 68 | 20 | 1008.86 | | -14.688 | 216 | 46.30 | 20 |
| Hay | S2 | SC | 20 | 4 | 1 | NF | | | | | 123 | 81.30 | 35 |
| Hay | S2 | SC | 20 | 4 | 2 | NF | | | | | 123 | 81.30 | 35 |
| Hay | S2 | SC | 20 | 4 | 3 | NF | | | | | 123 | 81.30 | 35 |
| Hay | S2 | SC | 20 | 7 | 1 | NF | | | | | 216 | 46.30 | 35 |
| Hay | S2 | SC | 20 | 7 | 2 | NF | | | | | 216 | 46.30 | 35 |
| Hay | S2 | SC | 20 | 7 | 3 | NF | | | | | 216 | 46.30 | 35 |
| Hay | S2 | SC | 20 | 2 | 1 | NF | | | | | 62 | 161.29 | 35 |
| Hay | S2 | SC | 20 | 2 | 2 | NF | | | | | 62 | 161.29 | 35 |
| Hay | S2 | SC | 30 | 4 | 1 | NF | | | | | 123 | 81.30 | 35 |
| Hay | S2 | SC | 30 | 4 | 2 | NF | | | | | 123 | 81.30 | 35 |
| Hay | S2 | SC | 30 | 4 | 3 | NF | | | | | 123 | 81.30 | 35 |
| Hay | S2 | SC | 30 | 7 | 1 | NF | | | | | 216 | 46.30 | 35 |
| Hay | S2 | SC | 30 | 7 | 2 | NF | | | | | 216 | 46.30 | 35 |
| Hay | S2 | SC | 30 | 7 | 3 | NF | | | | | 216 | 46.30 | 35 |
| Hay | S2 | SC | 30 | 2 | 1 | NF | | | | | 62 | 161.29 | 35 |
| Hay | S2 | SC | 30 | 2 | 2 | NF | | | | | 62 | 161.29 | 35 |
| Hay | S2 | SC | 30 | 2 | 3 | NF | | | | | 62 | 161.29 | 35 |
| Hay | S2 | TC | 20 | 4 | 1 | 85 | 27 | 863.65 | 139 | 6.642 | 123 | 81.30 | 40 |
| Hay | S2 | TC | 20 | 4 | 2 | 85 | 28 | 1099.62 | 139 | 6.642 | 123 | 81.30 | 40 |
| Hay | S2 | TC | 20 | 4 | 3 | 84 | 28 | 1038.05 | 139 | 6.765 | 123 | 81.30 | 40 |
| Hay | S2 | TC | 20 | 7 | 1 | 48 | 28 | 585.00 | 82 | 7.344 | 216 | 46.30 | 40 |
| Hay | S2 | TC | 20 | 7 | 2 | 38 | 28 | 472.88 | 69 | 6.696 | 216 | 46.30 | 40 |
| Hay | S2 | TC | 20 | 7 | 3 | 41 | 28 | 861.09 | 76 | 7.56 | 216 | 46.30 | 40 |
| Hay | S2 | TC | 20 | 2 | 1 | 120 | 27 | 1146.28 | 290 | 10.54 | 62 | 161.29 | 40 |
| Hay | S2 | TC | 20 | 2 | 2 | 57 | 28 | 1152.33 | 222 | 10.23 | 62 | 161.29 | 40 |
| Hay | S2 | TC | 20 | 2 | 3 | 90 | 28 | 1149.96 | 260 | 10.54 | 62 | 161.29 | 40 |
| Hay | S2 | TC | 30 | 4 | 1 | 113 | 15 | 1116.07 | 192 | 9.717 | 123 | 81.30 | 40 |
| Hay | S2 | TC | 30 | 4 | 2 | 121 | 16 | 1113.51 | 200 | 9.717 | 123 | 81.30 | 40 |
| Hay | S2 | TC | 30 | 4 | 3 | 108 | 16 | 1117.56 | 189 | 9.963 | 123 | 81.30 | 40 |
| Hay | S2 | TC | 30 | 7 | 1 | 54 | 15 | 562.29 | 102 | 10.368 | 216 | 46.30 | 40 |
| Hay | S2 | TC | 30 | 7 | 2 | 51 | 16 | 1058.16 | 99 | 10.368 | 216 | 46.30 | 40 |

## Average Height Method Results

*NF: object not found*

| Crop | Season | Object | Scanner Angle [degrees] | Speed [km/h] | Test # | Peak-X | Peak-Y | Cell Value | Flag-X | peak-peak dist [m] | dist/scan [mm] | #scan/10m | Crop height [cm] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hay | S2 | TC | 30 | 7 | 3 | 55 | 16 | 1060.83 | 105 | 10.8 | 216 | 46.30 | 40 |
| Hay | S2 | TC | 30 | 2 | 1 | 63 | 15 | 1145.02 | 231 | 10.416 | 62 | 161.29 | 40 |
| Hay | S2 | TC | 30 | 2 | 2 | 78 | 15 | 1145.38 | 237 | 9.858 | 62 | 161.29 | 40 |
| Hay | S2 | TC | 30 | 2 | 3 | 89 | 15 | 1143.62 | 255 | 10.292 | 62 | 161.29 | 40 |
| Hay | S2 | TS | 20 | 4 | 1 | 97 | 27 | 1073.95 | 180 | 10.209 | 123 | 81.30 | 40 |
| Hay | S2 | TS | 20 | 4 | 2 | 82 | 28 | 1130.71 | 165 | 10.209 | 123 | 81.30 | 40 |
| Hay | S2 | TS | 20 | 4 | 3 | 94 | 28 | 1129.18 | 178 | 10.332 | 123 | 81.30 | 40 |
| Hay | S2 | TS | 20 | 7 | 1 | 51 | 28 | 1068.57 | 101 | 10.8 | 216 | 46.30 | 40 |
| Hay | S2 | TS | 20 | 7 | 2 | 40 | 28 | 1097.64 | 86 | 9.936 | 216 | 46.30 | 40 |
| Hay | S2 | TS | 20 | 7 | 3 | 51 | 28 | 1095.65 | 101 | 10.8 | 216 | 46.30 | 40 |
| Hay | S2 | TS | 20 | 2 | 1 | 71 | 26 | 1151.02 | 232 | 9.982 | 62 | 161.29 | 40 |
| Hay | S2 | TS | 20 | 2 | 2 | 94 | 27 | 1151.22 | 259 | 10.23 | 62 | 161.29 | 40 |
| Hay | S2 | TS | 20 | 2 | 3 | 74 | 27 | 1151.26 | 240 | 10.292 | 62 | 161.29 | 40 |
| Hay | S2 | TS | 30 | 4 | 1 | 49 | 17 | 585.01 | 128 | 9.717 | 123 | 81.30 | 40 |
| Hay | S2 | TS | 30 | 4 | 2 | 106 | 15 | 1110.67 | 184 | 9.594 | 123 | 81.30 | 40 |
| Hay | S2 | TS | 30 | 4 | 3 | 95 | 16 | 1115.46 | 176 | 9.963 | 123 | 81.30 | 40 |
| Hay | S2 | TS | 30 | 7 | 1 | 47 | 15 | 1033.87 | 99 | 11.232 | 216 | 46.30 | 40 |
| Hay | S2 | TS | 30 | 7 | 2 | 52 | 16 | 1054.81 | 98 | 9.936 | 216 | 46.30 | 40 |
| Hay | S2 | TS | 30 | 7 | 3 | 50 | 15 | 1047.46 | 97 | 10.152 | 216 | 46.30 | 40 |
| Hay | S2 | TS | 30 | 2 | 1 | 54 | 15 | 1145.45 | 216 | 10.044 | 62 | 161.29 | 40 |
| Hay | S2 | TS | 30 | 2 | 2 | 79 | 15 | 1145.21 | 243 | 10.168 | 62 | 161.29 | 40 |
| Hay | S2 | TS | 30 | 2 | 3 | 68 | 15 | 1144.42 | 238 | 10.54 | 62 | 161.29 | 40 |
| Soy | S1 | TC | 20 | 4 | 1 | 101 | 20 | 1131.58 | | -12.423 | 123 | 81.30 | 70 |
| Soy | S1 | TC | 20 | 4 | 2 | 82 | 19 | 1133.84 | | -10.086 | 123 | 81.30 | 70 |
| Soy | S1 | TC | 20 | 4 | 3 | 112 | 20 | 1134.24 | | -13.776 | 123 | 81.30 | 70 |
| Soy | S1 | TC | 20 | 7 | 1 | 58 | 21 | 1098.29 | | -12.528 | 216 | 46.30 | 70 |
| Soy | S1 | TC | 20 | 7 | 2 | 84 | 20 | 1103.88 | | -18.144 | 216 | 46.30 | 70 |
| Soy | S1 | TC | 20 | 7 | 3 | 71 | 19 | 1084.75 | | -15.336 | 216 | 46.30 | 70 |
| Soy | S1 | TC | 20 | 2 | 1 | 93 | 20 | 1153.30 | | -5.766 | 62 | 161.29 | 70 |
| Soy | S1 | TC | 20 | 2 | 2 | 103 | 19 | 1153.77 | | -6.386 | 62 | 161.29 | 70 |
| Soy | S1 | TC | 20 | 2 | 3 | 71 | 19 | 1152.04 | | -4.402 | 62 | 161.29 | 70 |
| Soy | S1 | TC | 30 | 4 | 1 | 99 | 19 | 1105.00 | | -12.177 | 123 | 81.30 | 70 |
| Soy | S1 | TC | 30 | 4 | 2 | 94 | 19 | 1114.00 | | -11.562 | 123 | 81.30 | 70 |

## Average Height Method Results

*NF: object not found*

| Crop | Season | Object | Scanner Angle [degrees] | Speed [km/h] | Test # | Peak-X | Peak-Y | Cell Value | Flag-X | peak-peak dist [m] | dist/scan [mm] | #scan/10m | Crop height [cm] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Soy | S1 | TC | 30 | 4 | 3 | 107 | 19 | 1115.00 | | -13.161 | 123 | 81.30 | 70 |
| Soy | S1 | TC | 30 | 7 | 1 | 78 | 19 | 1069.00 | | -16.848 | 216 | 46.30 | 70 |
| Soy | S1 | TC | 30 | 7 | 2 | 67 | 19 | 1041.00 | | -14.472 | 216 | 46.30 | 70 |
| Soy | S1 | TC | 30 | 7 | 3 | 67 | 19 | 1069.00 | | -14.472 | 216 | 46.30 | 70 |
| Soy | S1 | TC | 30 | 2 | 1 | 121 | 19 | 1146.00 | | -7.502 | 62 | 161.29 | 70 |
| Soy | S1 | TC | 30 | 2 | 2 | 76 | 20 | 1145.45 | | -4.712 | 62 | 161.29 | 70 |
| Soy | S1 | TC | 30 | 2 | 3 | 64 | 20 | 1145.00 | | -3.968 | 62 | 161.29 | 70 |
| Soy | S1 | TS | 20 | 4 | 1 | 134 | 19 | 1121.00 | | -16.482 | 123 | 81.30 | 70 |
| Soy | S1 | TS | 20 | 4 | 2 | NF | | | | | 123 | 81.30 | 70 |
| Soy | S1 | TS | 20 | 4 | 3 | 92 | 20 | 1058.00 | | -11.316 | 123 | 81.30 | 70 |
| Soy | S1 | TS | 20 | 7 | 1 | NF | | | | | 216 | 46.30 | 70 |
| Soy | S1 | TS | 20 | 7 | 2 | NF | | | | | 216 | 46.30 | 70 |
| Soy | S1 | TS | 20 | 7 | 3 | NF | | | | | 216 | 46.30 | 70 |
| Soy | S1 | TS | 20 | 2 | 1 | 121 | 20 | 1134.92 | | -7.502 | 62 | 161.29 | 70 |
| Soy | S1 | TS | 20 | 2 | 2 | 120 | 20 | 1148.00 | | -7.44 | 62 | 161.29 | 70 |
| Soy | S1 | TS | 20 | 2 | 3 | 118 | 19 | 1050.00 | | -7.316 | 62 | 161.29 | 70 |
| Soy | S1 | TS | 30 | 4 | 1 | 69 | 20 | 1041.00 | | -8.487 | 123 | 81.30 | 70 |
| Soy | S1 | TS | 30 | 4 | 2 | 94 | 20 | 1076.24 | | -11.562 | 123 | 81.30 | 70 |
| Soy | S1 | TS | 30 | 4 | 3 | 90 | 20 | 1107.18 | | -11.07 | 123 | 81.30 | 70 |
| Soy | S1 | TS | 30 | 7 | 1 | 65 | 20 | 948.64 | | -14.04 | 216 | 46.30 | 70 |
| Soy | S1 | TS | 30 | 7 | 2 | 60 | 20 | 868.36 | | -12.96 | 216 | 46.30 | 70 |
| Soy | S1 | TS | 30 | 7 | 3 | 70 | 20 | 1062.06 | | -15.12 | 216 | 46.30 | 70 |
| Soy | S1 | TS | 30 | 2 | 1 | 146 | 20 | 1145.00 | | -9.052 | 62 | 161.29 | 70 |
| Soy | S1 | TS | 30 | 2 | 2 | 133 | 21 | 1038.22 | | -8.246 | 62 | 161.29 | 70 |
| Soy | S1 | TS | 30 | 2 | 3 | 133 | 20 | 1142.13 | | -8.246 | 62 | 161.29 | 70 |
| Soy | S3 | SC | 20 | 4 | 1 | NF | | | | | 123 | 81.30 | 70 |
| Soy | S3 | SC | 20 | 4 | 2 | NF | | | | | 123 | 81.30 | 70 |
| Soy | S3 | SC | 20 | 4 | 3 | NF | | | | | 123 | 81.30 | 70 |
| Soy | S3 | SC | 20 | 2 | 1 | NF | | | | | 62 | 161.29 | 70 |
| Soy | S3 | SC | 20 | 2 | 2 | NF | | | | | 62 | 161.29 | 70 |
| Soy | S3 | SC | 20 | 2 | 3 | NF | | | | | 62 | 161.29 | 70 |
| Soy | S3 | SC | 30 | 4 | 1 | NF | | | | | 123 | 81.30 | 70 |
| Soy | S3 | SC | 30 | 4 | 2 | NF | | | | | 123 | 81.30 | 70 |

**Average Height Method Results**

*NF: object not found*

| Crop | Season | Object | Scanner Angle [degrees] | Speed [km/h] | Test # | Peak-X | Peak-Y | Cell Value | Flag-X | peak-peak dist [m] | dist/scan [mm] | #scan/10m | Crop height [cm] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Soy | S3 | TS | 30 | 4 | 3 | 139 | 28 | 1119.40 | 213 | 9.102 | 123 | 81.30 | 70 |
| Soy | S3 | TS | 30 | 7 | 1 | 74 | 28 | 1079.00 | 118 | 9.504 | 216 | 46.30 | 70 |
| Soy | S3 | TS | 30 | 7 | 2 | 73 | 30 | 1044.00 | 118 | 9.72 | 216 | 46.30 | 70 |
| Soy | S3 | TS | 30 | 7 | 3 | 64 | 28 | 1051.00 | 108 | 9.504 | 216 | 46.30 | 70 |
| Soy | S3 | TS | 30 | 2 | 1 | 141 | 28 | 1144.00 | 296 | 9.61 | 62 | 161.29 | 70 |
| Soy | S3 | TS | 30 | 2 | 2 | 75 | 28 | 1142.00 | 234 | 9.858 | 62 | 161.29 | 70 |
| Soy | S3 | TS | 30 | 2 | 3 | 93 | 28 | 1144.00 | 252 | 9.858 | 62 | 161.29 | 70 |
| Oats | S1 | TC | 20 | 4 | 1 | 102 | 15 | 1130.22 | | -12.546 | 123 | 81.30 | 60.00 |
| Oats | S1 | TC | 20 | 4 | 2 | 103 | 15 | 1136.62 | | -12.669 | 123 | 81.30 | 60.00 |
| Oats | S1 | TC | 20 | 4 | 3 | 82 | 16 | 1130.93 | | -10.086 | 123 | 81.30 | 60.00 |
| Oats | S1 | TC | 20 | 7 | 1 | 47 | 16 | 1088.62 | | -10.152 | 216 | 46.30 | 60.00 |
| Oats | S1 | TC | 20 | 7 | 2 | 58 | 16 | 1099.64 | | -12.528 | 216 | 46.30 | 60.00 |
| Oats | S1 | TC | 20 | 7 | 3 | 50 | 15 | 1103.94 | | -10.8 | 216 | 46.30 | 60.00 |
| Oats | S1 | TC | 30 | 4 | 1 | 104 | 15 | 1097.72 | | -12.792 | 123 | 81.30 | 60.00 |
| Oats | S1 | TC | 30 | 4 | 2 | 112 | 15 | 1121.19 | | -13.776 | 123 | 81.30 | 60.00 |
| Oats | S1 | TC | 30 | 4 | 3 | 100 | 15 | 1120.12 | | -12.3 | 123 | 81.30 | 60.00 |
| Oats | S1 | TC | 30 | 7 | 1 | 57 | 16 | 1060.05 | | -12.312 | 216 | 46.30 | 60.00 |
| Oats | S1 | TC | 30 | 7 | 2 | 57 | 16 | 1040.64 | | -12.312 | 216 | 46.30 | 60.00 |
| Oats | S1 | TC | 30 | 7 | 3 | 50 | 16 | 1063.48 | | -10.8 | 216 | 46.30 | 60.00 |
| Oats | S1 | TS | 20 | 4 | 1 | 93 | 16 | 1119.70 | | -11.439 | 123 | 81.30 | 60.00 |
| Oats | S1 | TS | 20 | 4 | 2 | 96 | 15 | 1133.29 | | -11.808 | 123 | 81.30 | 60.00 |
| Oats | S1 | TS | 20 | 4 | 3 | 96 | 15 | 1068.18 | | -11.808 | 123 | 81.30 | 60.00 |
| Oats | S1 | TS | 20 | 7 | 1 | 42 | 16 | 1078.46 | | -9.072 | 216 | 46.30 | 60.00 |
| Oats | S1 | TS | 20 | 7 | 2 | 51 | 16 | 1033.68 | | -11.016 | 216 | 46.30 | 60.00 |
| Oats | S1 | TS | 20 | 7 | 3 | 48 | 16 | 590.57 | | -10.368 | 216 | 46.30 | 60.00 |
| Oats | S1 | TS | 30 | 4 | 1 | 115 | 17 | 1053.83 | | -14.145 | 123 | 81.30 | 60.00 |
| Oats | S1 | TS | 30 | 4 | 2 | 128 | 17 | 1101.00 | | -15.744 | 123 | 81.30 | 60.00 |
| Oats | S1 | TS | 30 | 4 | 3 | 116 | 18 | 836.13 | | -14.268 | 123 | 81.30 | 60.00 |
| Oats | S1 | TS | 30 | 7 | 1 | 64 | 18 | 1043.19 | | -13.824 | 216 | 46.30 | 60.00 |
| Oats | S1 | TS | 30 | 7 | 2 | 65 | 17 | 492.39 | | -14.04 | 216 | 46.30 | 60.00 |
| Oats | S1 | TS | 30 | 7 | 3 | 58 | 18 | 1026.20 | | -12.528 | 216 | 46.30 | 60.00 |
| Oats | S1 | SC | 20 | 4 | 1 | NF | | | | | 123 | 81.30 | 60.00 |
| Oats | S1 | SC | 20 | 4 | 2 | NF | | | | | 123 | 81.30 | 60.00 |

## Average Height Method Results

*NF: object not found*

| Crop | Season | Object | Scanner Angle [degrees] | Speed [km/h] | Test # | Peak-X | Peak-Y | Cell Value | Flag-X | peak-peak dist [m] | dist/scan [mm] | #scan/10m | Crop height [cm] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Oats | S1 | SC | 20 | 4 | 3 | NF | | | | | 123 | 81.30 | 60.00 |
| Oats | S1 | SC | 20 | 7 | 1 | NF | | | | | 216 | 46.30 | 60.00 |
| Oats | S1 | SC | 20 | 7 | 2 | NF | | | | | 216 | 46.30 | 60.00 |
| Oats | S1 | SC | 20 | 2 | 1 | NF | | | | | 62 | 161.29 | 60.00 |
| Oats | S1 | SC | 20 | 2 | 2 | NF | | | | | 62 | 161.29 | 60.00 |
| Oats | S1 | SC | 20 | 2 | 3 | NF | | | | | 62 | 161.29 | 60.00 |
| Oats | S1 | SC | 30 | 4 | 1 | NF | | | | | 123 | 81.30 | 60.00 |
| Oats | S1 | SC | 30 | 4 | 2 | NF | | | | | 123 | 81.30 | 60.00 |
| Oats | S1 | SC | 30 | 4 | 3 | NF | | | | | 123 | 81.30 | 60.00 |
| Oats | S1 | SC | 30 | 7 | 1 | NF | | | | | 216 | 46.30 | 60.00 |
| Oats | S1 | SC | 30 | 7 | 2 | NF | | | | | 216 | 46.30 | 60.00 |
| Oats | S1 | SC | 30 | 7 | 3 | NF | | | | | 216 | 46.30 | 60.00 |
| Oats | S1 | SC | 30 | 2 | 1 | NF | | | | | 62 | 161.29 | 60.00 |
| Oats | S1 | SC | 30 | 2 | 2 | NF | | | | | 62 | 161.29 | 60.00 |
| Oats | S1 | SC | 30 | 2 | 3 | NF | | | | | 62 | 161.29 | 60.00 |

## *B.2 Density Method Results*

Density Method Results

NF: object not found, Peak: Peak value found, and "-": Potential detection

| Crop | Season | Object | Scanner Angle [degrees] | Speed [km/h] | Test # | Peak-X | Peak-Y | Cell Value | Avg Surrounding Value | Detection | Crop height [cm] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Wheat | S1 | SC | 20 | 4 | 1 | | | | | NF | 75 |
| Wheat | S1 | SC | 20 | 4 | 2 | | | | | NF | 75 |
| Wheat | S1 | SC | 20 | 4 | 3 | | | | | NF | 75 |
| Wheat | S1 | SC | 20 | 7 | 1 | | | | | NF | 75 |
| Wheat | S1 | SC | 20 | 7 | 2 | | | | | NF | 75 |
| Wheat | S1 | SC | 20 | 7 | 3 | | | | | NF | 75 |
| Wheat | S1 | SC | 20 | 2 | 1 | | | | | NF | 75 |
| Wheat | S1 | SC | 20 | 2 | 2 | | | | | NF | 75 |
| Wheat | S1 | SC | 20 | 2 | 3 | | | | | NF | 75 |
| Wheat | S1 | SC | 30 | 4 | 1 | | | | | NF | 75 |
| Wheat | S1 | SC | 30 | 4 | 2 | | | | | NF | 75 |
| Wheat | S1 | SC | 30 | 4 | 3 | | | | | NF | 75 |
| Wheat | S1 | SC | 30 | 7 | 1 | | | | | NF | 75 |
| Wheat | S1 | SC | 30 | 7 | 2 | | | | | NF | 75 |
| Wheat | S1 | SC | 30 | 7 | 3 | | | | | NF | 75 |
| Wheat | S1 | SC | 30 | 2 | 1 | | | | | NF | 75 |
| Wheat | S1 | SC | 30 | 2 | 2 | | | | | NF | 75 |
| Wheat | S1 | SC | 30 | 2 | 3 | | | | | NF | 75 |
| Wheat | S1 | TS | 20 | 4 | 1 | 59 | 14 | 20.00 | 4.04 | NF | 75 |
| Wheat | S1 | TS | 20 | 4 | 2 | 62 | 15 | 25.00 | 3.96 | - | 75 |
| Wheat | S1 | TS | 20 | 4 | 3 | 83 | 14 | 23.00 | 3.93 | - | 75 |
| Wheat | S1 | TS | 20 | 7 | 1 | 53 | 17 | 5.00 | 3.90 | NF | 75 |
| Wheat | S1 | TS | 20 | 7 | 2 | 40 | 14 | 13.00 | 3.30 | Peak | 75 |
| Wheat | S1 | TS | 20 | 7 | 3 | 47 | 14 | 3.00 | 3.79 | NF | 75 |
| Wheat | S1 | TS | 30 | 4 | 1 | 65 | 14 | 14.00 | 4.07 | - | 75 |
| Wheat | S1 | TS | 30 | 4 | 2 | 64 | 14 | 10.00 | 4.04 | NF | 75 |
| Wheat | S1 | TS | 30 | 4 | 3 | 61 | 15 | 34.00 | 4.05 | Peak | 75 |
| Wheat | S1 | TS | 30 | 7 | 1 | 37 | 14 | 7.00 | 4.08 | NF | 75 |
| Wheat | S1 | TS | 30 | 7 | 2 | 32 | 14 | 14.00 | 2.77 | - | 75 |
| Wheat | S1 | TS | 30 | 7 | 3 | 40 | 14 | 22.00 | 4.16 | Peak | 75 |
| Wheat | S1 | TC | 20 | 4 | 1 | 86 | 13 | 28.00 | 4.14 | Peak | 75 |
| Wheat | S1 | TC | 20 | 4 | 2 | 68 | 14 | 55.00 | 3.98 | Peak | 75 |
| Wheat | S1 | TC | 20 | 4 | 3 | 36 | 14 | 35.00 | 3.93 | Peak | 75 |

Density Method Results

NF: object not found, Peak: Peak value found, and "-": Potential detection

| Crop | Season | Object | Angle [degrees] | Speed [km/h] | Test # | Peak-X | Peak-Y | Cell Value | Avg Surrounding Value | Detection | Crop height [cm] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Wheat | S1 | TC | 20 | 7 | 1 | 18 | 14 | 23.00 | 2.39 | Peak | 75 |
| Wheat | S1 | TC | 20 | 7 | 2 | 31 | 14 | 28.00 | 3.12 | Peak | 75 |
| Wheat | S1 | TC | 20 | 7 | 3 | 16 | 14 | 35.00 | 2.12 | Peak | 75 |
| Wheat | S1 | TC | 20 | 2 | 1 | 52 | 13 | 45.00 | 3.44 | Peak | 75 |
| Wheat | S1 | TC | 30 | 4 | 1 | 54 | 14 | 56.00 | 4.17 | Peak | 75 |
| Wheat | S1 | TC | 30 | 4 | 2 | 47 | 14 | 21.00 | 4.11 | - | 75 |
| Wheat | S1 | TC | 30 | 4 | 3 | 55 | 14 | 29.00 | 4.11 | Peak | 75 |
| Wheat | S1 | TC | 30 | 7 | 1 | 26 | 14 | 20.00 | 2.55 | - | 75 |
| Wheat | S1 | TC | 30 | 7 | 2 | 28 | 14 | 22.00 | 3.20 | Peak | 75 |
| Wheat | S1 | TC | 30 | 7 | 3 | 23 | 14 | 25.00 | 2.73 | Peak | 75 |
| Wheat | S1 | TC | 30 | 2 | 1 | 44 | 14 | 58.00 | 3.90 | Peak | 75 |
| Hay | S1 | TC | 20 | 4 | 1 | 121 | 22 | 63.00 | 2.94 | Peak | 20 |
| Hay | S1 | TC | 20 | 4 | 2 | 153 | 22 | 68.00 | 2.94 | Peak | 20 |
| Hay | S1 | TC | 20 | 4 | 3 | 127 | 21 | 92.00 | 2.99 | Peak | 20 |
| Hay | S1 | TC | 20 | 7 | 1 | 62 | 22 | 42.00 | 1.98 | Peak | 20 |
| Hay | S1 | TC | 20 | 7 | 2 | 85 | 21 | 74.00 | 2.84 | Peak | 20 |
| Hay | S1 | TC | 20 | 7 | 3 | 107 | 21 | 85.00 | 2.69 | Peak | 20 |
| Hay | S1 | TC | 30 | 4 | 1 | 149 | 20 | 82.00 | 3.40 | Peak | 20 |
| Hay | S1 | TC | 30 | 4 | 2 | 144 | 19 | 96.00 | 3.39 | Peak | 20 |
| Hay | S1 | TC | 30 | 4 | 3 | 169 | 21 | 82.00 | 3.44 | Peak | 20 |
| Hay | S1 | TC | 30 | 7 | 1 | 69 | 21 | 44.00 | 2.09 | Peak | 20 |
| Hay | S1 | TC | 30 | 7 | 2 | 82 | 21 | 69.00 | 2.75 | Peak | 20 |
| Hay | S1 | TC | 30 | 7 | 3 | 93 | 19 | 67.00 | 2.56 | Peak | 20 |
| Hay | S1 | TS | 20 | 4 | 1 | 135 | 21 | 29.00 | 3.03 | Peak | 20 |
| Hay | S1 | TS | 20 | 4 | 2 | 146 | 20 | 33.00 | 3.03 | Peak | 20 |
| Hay | S1 | TS | 20 | 4 | 3 | 123 | 20 | 60.00 | 3.02 | Peak | 20 |
| Hay | S1 | TS | 20 | 7 | 1 | 81 | 21 | 14.00 | 2.50 | - | 20 |
| Hay | S1 | TS | 20 | 7 | 2 | 73 | 21 | 31.00 | 2.62 | Peak | 20 |
| Hay | S1 | TS | 20 | 7 | 3 | 87 | 20 | 38.00 | 2.68 | Peak | 20 |
| Hay | S1 | TS | 30 | 4 | 1 | 188 | 20 | 30.00 | 3.44 | Peak | 20 |
| Hay | S1 | TS | 30 | 4 | 2 | 156 | 22 | 32.00 | 3.39 | Peak | 20 |
| Hay | S1 | TS | 30 | 4 | 3 | 159 | 21 | 41.00 | 3.45 | Peak | 20 |
| Hay | S1 | TS | 30 | 7 | 1 | 96 | 21 | 33.00 | 3.13 | Peak | 20 |

## Density Method Results

NF: object not found, Peak: Peak value found, and "-": Potential detection

| Crop | Season | Object | Angle [degrees] | Speed [km/h] | Test # | Peak-X | Peak-Y | Cell Value | Avg Surrounding Value | Detection | Crop height [cm] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Hay | S1 | TS | 30 | 7 | 2 | 93 | 21 | 26.00 | 2.80 | Peak | 20 |
| Hay | S1 | TS | 30 | 7 | 3 | 68 | 21 | 20.00 | 2.51 | Peak | 20 |
| Hay | S2 | SC | 20 | 4 | 1 | 126 | 21 | 31.00 | 3.18 | - | 35 |
| Hay | S2 | SC | 20 | 4 | 2 | 119 | 22 | 26.00 | 3.12 | - | 35 |
| Hay | S2 | SC | 20 | 4 | 3 | | | 22.00 | 3.19 | NF | 35 |
| Hay | S2 | SC | 20 | 7 | 1 | | | | | - | 35 |
| Hay | S2 | SC | 20 | 7 | 2 | | | | | NF | 35 |
| Hay | S2 | SC | 20 | 7 | 3 | | | | | NF | 35 |
| Hay | S2 | SC | 20 | 2 | 1 | | | | 2.73 | NF | 35 |
| Hay | S2 | SC | 20 | 2 | 2 | | | | 2.76 | NF | 35 |
| Hay | S2 | SC | 30 | 4 | 1 | | | | | NF | 35 |
| Hay | S2 | SC | 30 | 4 | 2 | | | | | NF | 35 |
| Hay | S2 | SC | 30 | 4 | 3 | | | | | NF | 35 |
| Hay | S2 | SC | 30 | 7 | 1 | | | | 2.74 | NF | 35 |
| Hay | S2 | SC | 30 | 7 | 2 | | | | 2.66 | NF | 35 |
| Hay | S2 | SC | 30 | 7 | 3 | | | | 2.89 | NF | 35 |
| Hay | S2 | SC | 30 | 2 | 1 | | | | 3.23 | NF | 35 |
| Hay | S2 | SC | 30 | 2 | 2 | | | | 3.26 | NF | 35 |
| Hay | S2 | SC | 30 | 2 | 3 | | | | 3.24 | NF | 35 |
| Hay | S2 | TC | 20 | 4 | 1 | 87 | 28 | 41.00 | | Peak | 40 |
| Hay | S2 | TC | 20 | 4 | 2 | 84 | 28 | 42.00 | | Peak | 40 |
| Hay | S2 | TC | 20 | 4 | 3 | 83 | 28 | 36.00 | | - | 40 |
| Hay | S2 | TC | 20 | 7 | 1 | 48 | 28 | 19.00 | 2.47 | - | 40 |
| Hay | S2 | TC | 20 | 7 | 2 | 36 | 28 | 4.00 | 2.03 | NF | 40 |
| Hay | S2 | TC | 20 | 7 | 3 | 42 | 29 | 25.00 | 3.32 | - | 40 |
| Hay | S2 | TC | 20 | 2 | 1 | 121 | 28 | 73.00 | 2.66 | Peak | 40 |
| Hay | S2 | TC | 20 | 2 | 2 | 57 | 28 | 75.00 | 2.82 | Peak | 40 |
| Hay | S2 | TC | 20 | 2 | 3 | 89 | 28 | 70.00 | 2.81 | Peak | 40 |
| Hay | S2 | TC | 30 | 4 | 1 | 113 | 16 | 77.00 | 3.62 | Peak | 40 |
| Hay | S2 | TC | 30 | 4 | 2 | 121 | 16 | 59.00 | 3.63 | Peak | 40 |
| Hay | S2 | TC | 30 | 4 | 3 | 108 | 16 | 50.00 | 3.64 | Peak | 40 |
| Hay | S2 | TC | 30 | 7 | 1 | 55 | 16 | 47.00 | 3.20 | Peak | 40 |
| Hay | S2 | TC | 30 | 7 | 2 | 51 | 16 | 52.00 | 2.90 | Peak | 40 |

**Density Method Results**

**NF: object not found, Peak: Peak value found, and "-": Potential detection**

| Crop | Season | Object | Angle [degrees] | Speed [km/h] | Test # | Peak-X | Peak-Y | Cell Value | Avg Surrounding Value | Detection | Crop height [cm] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Hay | S2 | TC | 30 | 7 | 3 | 54 | 16 | 42.00 | 3.50 | Peak | 40 |
| Hay | S2 | TC | 30 | 2 | 1 | 62 | 16 | 86.00 | 3.42 | Peak | 40 |
| Hay | S2 | TC | 30 | 2 | 2 | 77 | 16 | 84.00 | 3.36 | Peak | 40 |
| Hay | S2 | TC | 30 | 2 | 3 | 89 | 16 | 52.00 | 3.32 | Peak | 40 |
| Hay | S2 | TS | 20 | 4 | 1 | 98 | 28 | 31.00 | 3.33 | - | 40 |
| Hay | S2 | TS | 20 | 4 | 2 | 81 | 29 | 41.00 | 3.29 | Peak | 40 |
| Hay | S2 | TS | 20 | 4 | 3 | 93 | 28 | 34.00 | 3.33 | Peak | 40 |
| Hay | S2 | TS | 20 | 7 | 1 | 51 | 29 | 38.00 | 2.97 | Peak | 40 |
| Hay | S2 | TS | 20 | 7 | 2 | 40 | 29 | 29.00 | 3.03 | Peak | 40 |
| Hay | S2 | TS | 20 | 7 | 3 | 51 | 29 | 32.00 | 3.31 | - | 40 |
| Hay | S2 | TS | 20 | 2 | 1 | 70 | 28 | 56.00 | 2.94 | Peak | 40 |
| Hay | S2 | TS | 20 | 2 | 2 | 95 | 28 | 56.00 | 2.76 | Peak | 40 |
| Hay | S2 | TS | 20 | 2 | 3 | 75 | 28 | 41.00 | 2.81 | Peak | 40 |
| Hay | S2 | TS | 30 | 4 | 1 | 50 | 17 | 27.00 | 3.67 | - | 40 |
| Hay | S2 | TS | 30 | 4 | 2 | 106 | 16 | 49.00 | 3.63 | Peak | 40 |
| Hay | S2 | TS | 30 | 4 | 3 | 95 | 16 | 52.00 | 3.66 | Peak | 40 |
| Hay | S2 | TS | 30 | 7 | 1 | 47 | 16 | 46.00 | 3.07 | Peak | 40 |
| Hay | S2 | TS | 30 | 7 | 2 | 52 | 16 | 36.00 | 2.85 | Peak | 40 |
| Hay | S2 | TS | 30 | 7 | 3 | 50 | 16 | 33.00 | 3.14 | Peak | 40 |
| Hay | S2 | TS | 30 | 2 | 1 | 55 | 16 | 62.00 | 3.39 | Peak | 40 |
| Hay | S2 | TS | 30 | 2 | 2 | 80 | 16 | 49.00 | 3.35 | Peak | 40 |
| Hay | S2 | TS | 30 | 2 | 3 | 69 | 15 | 72.00 | 3.34 | Peak | 40 |
| Soy | S1 | TC | 20 | 4 | 1 | 101 | 20 | 38.00 | | Peak | 70 |
| Soy | S1 | TC | 20 | 4 | 2 | 82 | 19 | 50.00 | | Peak | 70 |
| Soy | S1 | TC | 20 | 4 | 3 | 112 | 20 | 51.00 | | Peak | 70 |
| Soy | S1 | TC | 20 | 4 | 1_Long | 64 | 34 | 13.00 | 4.09 | - | 70 |
| Soy | S1 | TC | 20 | 4 | 2_Long | 73 | 34 | 10.00 | 4.09 | NF | 70 |
| Soy | S1 | TC | 20 | 4 | 3_Long | 64 | 34 | 15.00 | 3.11 | - | 70 |
| Soy | S1 | TC | 20 | 7 | 1 | 58 | 21 | 54.00 | 3.72 | Peak | 70 |
| Soy | S1 | TC | 20 | 7 | 2 | 84 | 20 | 29.00 | 4.02 | Peak | 70 |
| Soy | S1 | TC | 20 | 7 | 3 | 71 | 19 | 44.00 | 3.94 | Peak | 70 |
| Soy | S1 | TC | 20 | 2 | 1 | 92 | 20 | 47.00 | 3.82 | Peak | 70 |
| Soy | S1 | TC | 20 | 2 | 2 | 102 | 19 | 57.00 | 3.90 | Peak | 70 |

**Density Method Results**

**NF: object not found, Peak: Peak value found, and "-": Potential detection**

| Crop | Season | Object | Angle [degrees] | Speed [km/h] | Test # | Peak-X | Peak-Y | Cell Value | Avg Surrounding Value | Detection | Crop height [cm] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Soy | S1 | TC | 20 | 2 | 3 | 70 | 20 | 45.00 | 3.84 | Peak | 70 |
| Soy | S1 | TC | 30 | 4 | 1 | 98 | 19 | 28.00 | 4.08 | Peak | 70 |
| Soy | S1 | TC | 30 | 4 | 2 | 94 | 19 | 30.00 | 4.18 | Peak | 70 |
| Soy | S1 | TC | 30 | 4 | 3 | 107 | 19 | 33.00 | 4.09 | Peak | 70 |
| Soy | S1 | TC | 30 | 7 | 1 | 78 | 19 | 36.00 | 4.05 | Peak | 70 |
| Soy | S1 | TC | 30 | 7 | 2 | 67 | 20 | 16.00 | 4.08 | - | 70 |
| Soy | S1 | TC | 30 | 7 | 3 | 67 | 19 | 41.00 | 3.93 | Peak | 70 |
| Soy | S1 | TC | 30 | 2 | 1 | 121 | 19 | 38.00 | 3.90 | Peak | 70 |
| Soy | S1 | TC | 30 | 2 | 2 | 74 | 20 | 45.00 | 3.97 | Peak | 70 |
| Soy | S1 | TC | 30 | 2 | 3 | 63 | 20 | 55.00 | 4.07 | Peak | 70 |
| Soy | S1 | TS | 20 | 4 | 1 | 134 | 20 | 18.00 | 4.00 | - | 70 |
| Soy | S1 | TS | 20 | 4 | 2 | 87 | 19 | 13.00 | 4.09 | - | 70 |
| Soy | S1 | TS | 20 | 4 | 3 | 93 | 20 | 22.00 | 4.08 | - | 70 |
| Soy | S1 | TS | 20 | 7 | 1 | 48 | 20 | 20.00 | 3.13 | - | 70 |
| Soy | S1 | TS | 20 | 7 | 2 | 73 | 21 | 16.00 | 3.95 | - | 70 |
| Soy | S1 | TS | 20 | 7 | 3 | 56 | 20 | 15.00 | 3.55 | - | 70 |
| Soy | S1 | TS | 20 | 2 | 1 | 123 | 20 | 26.00 | 3.71 | - | 70 |
| Soy | S1 | TS | 20 | 2 | 2 | 121 | 21 | 12.00 | 3.71 | - | 70 |
| Soy | S1 | TS | 20 | 2 | 3 | 118 | 20 | 35.00 | 3.78 | Peak | 70 |
| Soy | S1 | TS | 30 | 4 | 1 | 70 | 21 | 12.00 | 3.87 | - | 70 |
| Soy | S1 | TS | 30 | 4 | 2 | 94 | 22 | 13.00 | 4.16 | - | 70 |
| Soy | S1 | TS | 30 | 4 | 3 | 90 | 20 | 21.00 | 4.12 | Peak | 70 |
| Soy | S1 | TS | 30 | 7 | 1 | 65 | 20 | 7.00 | 3.67 | - | 70 |
| Soy | S1 | TS | 30 | 7 | 2 | 60 | 20 | 8.00 | 3.60 | NF | 70 |
| Soy | S1 | TS | 30 | 7 | 3 | 70 | 20 | 13.00 | 4.16 | - | 70 |
| Soy | S1 | TS | 30 | 2 | 1 | 146 | 20 | 30.00 | 3.71 | Peak | 70 |
| Soy | S1 | TS | 30 | 2 | 2 | 133 | 21 | 19.00 | 3.71 | - | 70 |
| Soy | S1 | TS | 30 | 2 | 3 | 133 | 20 | 39.00 | 3.78 | Peak | 70 |
| Soy | S3 | SC | 20 | 4 | 1 | | | | | NF | 70 |
| Soy | S3 | SC | 20 | 4 | 2 | | | | | NF | 70 |
| Soy | S3 | SC | 20 | 4 | 3 | | | | | NF | 70 |
| Soy | S3 | SC | 20 | 2 | 1 | | | | | NF | 70 |
| Soy | S3 | SC | 20 | 2 | 2 | | | | | NF | 70 |

| Density Method Results | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| NF: object not found, Peak: Peak value found, and "-": Potential detection | | | | | | | | | | | |
| Crop | Season | Object | Angle [degrees] | Speed [km/h] | Test # | Peak-X | Peak-Y | Cell Value | Avg Surrounding Value | Detection | Crop height [cm] |
| Soy | S3 | SC | 20 | 2 | 3 | | | | | NF | 70 |
| Soy | S3 | SC | 30 | 4 | 1 | | | | | NF | 70 |
| Soy | S3 | SC | 30 | 4 | 2 | | | | | NF | 70 |
| Soy | S3 | SC | 30 | 4 | 3 | | | | | NF | 70 |
| Soy | S3 | SC | 30 | 2 | 1 | | | | | NF | 70 |
| Soy | S3 | SC | 30 | 2 | 2 | | | | | NF | 70 |
| Soy | S3 | SC | 30 | 2 | 3 | | | | | NF | 70 |
| Soy | S3 | TC | 20 | 4 | 1 | 121 | 28 | 39.00 | 3.54 | - | 70 |
| Soy | S3 | TC | 20 | 4 | 2 | 128 | 28 | 38.00 | 3.60 | - | 70 |
| Soy | S3 | TC | 20 | 4 | 3 | 131 | 28 | 42.00 | 3.57 | - | 70 |
| Soy | S3 | TC | 20 | 7 | 1 | 72 | 28 | 28.00 | 3.59 | Peak | 70 |
| Soy | S3 | TC | 20 | 7 | 2 | 76 | 28 | 26.00 | 3.50 | Peak | 70 |
| Soy | S3 | TC | 20 | 7 | 3 | 83 | 28 | 42.00 | 3.59 | Peak | 70 |
| Soy | S3 | TC | 20 | 2 | 1 | 122 | 28 | 44.00 | 3.08 | Peak | 70 |
| Soy | S3 | TC | 20 | 2 | 2 | 93 | 28 | 38.00 | 3.27 | Peak | 70 |
| Soy | S3 | TC | 20 | 2 | 3 | 79 | 28 | 38.00 | 3.28 | Peak | 70 |
| Soy | S3 | TC | 30 | 4 | 1 | 133 | 28 | 32.00 | 3.82 | - | 70 |
| Soy | S3 | TC | 30 | 4 | 2 | 136 | 28 | 29.00 | 3.76 | Peak | 70 |
| Soy | S3 | TC | 30 | 4 | 3 | 138 | 28 | 33.00 | 3.77 | Peak | 70 |
| Soy | S3 | TC | 30 | 7 | 1 | 83 | 28 | 23.00 | 3.77 | - | 70 |
| Soy | S3 | TC | 30 | 7 | 2 | 64 | 27 | 30.00 | 3.54 | Peak | 70 |
| Soy | S3 | TC | 30 | 7 | 3 | 77 | 28 | 17.00 | 3.75 | - | 70 |
| Soy | S3 | TC | 30 | 2 | 1 | 148 | 28 | 35.00 | 3.52 | Peak | 70 |
| Soy | S3 | TC | 30 | 2 | 2 | 84 | 27 | | 3.67 | NF | 70 |
| Soy | S3 | TC | 30 | 2 | 3 | 115 | 27 | 31.00 | 3.54 | Peak | 70 |
| Soy | S3 | TS | 20 | 4 | 1 | 127 | 28 | 26.00 | 3.59 | Peak | 70 |
| Soy | S3 | TS | 20 | 4 | 2 | 117 | 28 | 35.00 | 3.55 | Peak | 70 |
| Soy | S3 | TS | 20 | 4 | 3 | 115 | 28 | 33.00 | 3.58 | Peak | 70 |
| Soy | S3 | TS | 20 | 7 | 1 | 63 | 29 | 21.00 | 3.60 | - | 70 |
| Soy | S3 | TS | 20 | 7 | 2 | 79 | 28 | 31.00 | 3.64 | - | 70 |
| Soy | S3 | TS | 20 | 7 | 3 | 71 | 28 | 20.00 | 3.62 | - | 70 |
| Soy | S3 | TS | 20 | 2 | 1 | 149 | 29 | 33.00 | 3.14 | - | 70 |
| Soy | S3 | TS | 20 | 2 | 2 | 110 | 28 | 28.00 | 3.18 | Peak | 70 |

**Density Method Results**

**NF: object not found, Peak: Peak value found, and "-": Potential detection**

| Crop | Season | Object | Scanner Angle [degrees] | Speed [km/h] | Test # | Peak-X | Peak-Y | Cell Value | Avg Surrounding Value | Detection | Crop height [cm] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Soy | S3 | TS | 20 | 2 | 3 | 121 | 28 | 44.00 | 3.16 | Peak | 70 |
| Soy | S3 | TS | 30 | 4 | 1 | 143 | 28 | 26.00 | 3.83 | - | 70 |
| Soy | S3 | TS | 30 | 4 | 2 | 132 | 28 | 22.00 | 3.83 | - | 70 |
| Soy | S3 | TS | 30 | 4 | 3 | 139 | 28 | 35.00 | 3.86 | Peak | 70 |
| Soy | S3 | TS | 30 | 7 | 1 | 74 | 28 | 35.00 | 3.79 | Peak | 70 |
| Soy | S3 | TS | 30 | 7 | 2 | 74 | 29 | 23.00 | 3.82 | - | 70 |
| Soy | S3 | TS | 30 | 7 | 3 | 64 | 28 | 16.00 | 3.78 | - | 70 |
| Soy | S3 | TS | 30 | 2 | 1 | 141 | 28 | 38.00 | 3.53 | Peak | 70 |
| Soy | S3 | TS | 30 | 2 | 2 | 76 | 28 | 34.00 | 3.62 | Peak | 70 |
| Soy | S3 | TS | 30 | 2 | 3 | 92 | 28 | 40.00 | 3.65 | Peak | 70 |
| Oats | S1 | TC | 20 | 4 | 1 | 101 | 16 | 62.00 | 3.25 | Peak | 60.00 |
| Oats | S1 | TC | 20 | 4 | 2 | 103 | 15 | 79.00 | 3.25 | Peak | 60.00 |
| Oats | S1 | TC | 20 | 4 | 3 | 82 | 16 | 39.00 | 3.90 | Peak | 60.00 |
| Oats | S1 | TC | 20 | 7 | 1 | 46 | 17 | 49.00 | 1.97 | Peak | 60.00 |
| Oats | S1 | TC | 20 | 7 | 2 | 58 | 16 | 52.00 | 2.35 | Peak | 60.00 |
| Oats | S1 | TC | 20 | 7 | 3 | 49 | 16 | 52.00 | 3.40 | Peak | 60.00 |
| Oats | S1 | TC | 30 | 4 | 1 | 105 | 15 | 57.00 | 3.57 | Peak | 60.00 |
| Oats | S1 | TC | 30 | 4 | 2 | 111 | 15 | 83.00 | 3.72 | Peak | 60.00 |
| Oats | S1 | TC | 30 | 4 | 3 | 100 | 15 | 61.00 | 3.61 | Peak | 60.00 |
| Oats | S1 | TC | 30 | 7 | 1 | 57 | 16 | 54.00 | 3.11 | Peak | 60.00 |
| Oats | S1 | TC | 30 | 7 | 2 | 57 | 16 | 35.00 | 3.11 | Peak | 60.00 |
| Oats | S1 | TC | 30 | 7 | 3 | 50 | 16 | 65.00 | 2.94 | Peak | 60.00 |
| Oats | S1 | TS | 20 | 4 | 1 | 93 | 16 | 39.00 | 3.35 | - | 60.00 |
| Oats | S1 | TS | 20 | 4 | 2 | 96 | 15 | 52.00 | 3.32 | - | 60.00 |
| Oats | S1 | TS | 20 | 4 | 3 | 96 | 15 | 33.00 | 3.33 | - | 60.00 |
| Oats | S1 | TS | 20 | 7 | 1 | 42 | 15 | 25.00 | | - | 60.00 |
| Oats | S1 | TS | 20 | 7 | 2 | 51 | 17 | 30.00 | | Peak | 60.00 |
| Oats | S1 | TS | 20 | 7 | 3 | 49 | 17 | 29.00 | | Peak | 60.00 |
| Oats | S1 | TS | 30 | 4 | 1 | 114 | 12 | 45.00 | 3.52 | - | 60.00 |
| Oats | S1 | TS | 30 | 4 | 2 | 128 | 17 | 26.00 | 3.64 | - | 60.00 |
| Oats | S1 | TS | 30 | 4 | 3 | 116 | 17 | 18.00 | 3.58 | - | 60.00 |
| Oats | S1 | TS | 30 | 7 | 1 | 64 | 18 | 14.00 | 3.60 | - | 60.00 |
| Oats | S1 | TS | 30 | 7 | 2 | 65 | 17 | 17.00 | 3.64 | - | 60.00 |

| Density Method Results | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| NF: object not found, Peak: Peak value found, and "-": Potential detection | | | | | | | | | | | |
| Crop | Season | Object | Scanner Angle [degrees] | Speed [km/h] | Test # | Peak-X | Peak-Y | Cell Value | Avg Surrounding Value | Detection | Crop height [cm] |
| Oats | S1 | TS | 30 | 7 | 3 | 57 | 18 | 17.00 | 3.65 | - | 60.00 |
| Oats | S1 | SC | 20 | 4 | 1 | | | | | NF | 60.00 |
| Oats | S1 | SC | 20 | 4 | 2 | 56 | 15 | | | NF | 60.00 |
| Oats | S1 | SC | 20 | 4 | 3 | 80 | 17 | | | NF | 60.00 |
| Oats | S1 | SC | 20 | 7 | 1 | | | | | NF | 60.00 |
| Oats | S1 | SC | 20 | 7 | 2 | | | | | NF | 60.00 |
| Oats | S1 | SC | 20 | 2 | 1 | | | | | NF | 60.00 |
| Oats | S1 | SC | 20 | 2 | 2 | | | | | NF | 60.00 |
| Oats | S1 | SC | 20 | 2 | 3 | | | | | NF | 60.00 |
| Oats | S1 | SC | 30 | 4 | 1 | 105 | 13 | 25.00 | | - | 60.00 |
| Oats | S1 | SC | 30 | 4 | 2 | 93 | 11 | 26.00 | | - | 60.00 |
| Oats | S1 | SC | 30 | 4 | 3 | 86 | 12 | 22.00 | | - | 60.00 |
| Oats | S1 | SC | 30 | 7 | 1 | | | | | NF | 60.00 |
| Oats | S1 | SC | 30 | 7 | 2 | | | | | NF | 60.00 |
| Oats | S1 | SC | 30 | 7 | 3 | | | | | NF | 60.00 |
| Oats | S1 | SC | 30 | 2 | 1 | | | | | NF | 60.00 |
| Oats | S1 | SC | 30 | 2 | 2 | | | | | NF | 60.00 |
| Oats | S1 | SC | 30 | 2 | 3 | | | | | NF | 60.00 |

## *B.3 Connectivity Method Results*

**Connectivity Method Results**

**NF: object not found, Peak: Peak value found, and "-": Potential detection**

| Crop | Season | Object | Scanner Angle [degrees] | Speed [km/h] | Test# | Detection | Peak-X | Peak-Y | Cell Value | Avg | CellValue-AVGValue | Crop height [cm] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Wheat | S1 | SC | 20 | 4 | 1 | | | | | | | 75 |
| Wheat | S1 | SC | 20 | 4 | 2 | | | | | | | 75 |
| Wheat | S1 | SC | 20 | 4 | 3 | | | | | | | 75 |
| Wheat | S1 | SC | 20 | 7 | 1 | | | | | | | 75 |
| Wheat | S1 | SC | 20 | 7 | 2 | | | | | | | 75 |
| Wheat | S1 | SC | 20 | 7 | 3 | | | | | | | 75 |
| Wheat | S1 | SC | 20 | S | 1 | | | | | | | 75 |
| Wheat | S1 | SC | 20 | S | 2 | | | | | | | 75 |
| Wheat | S1 | SC | 20 | S | 3 | | | | | | | 75 |
| Wheat | S1 | SC | 30 | 4 | 1 | | | | | | | 75 |
| Wheat | S1 | SC | 30 | 4 | 2 | | | | | | | 75 |
| Wheat | S1 | SC | 30 | 4 | 3 | | | | | | | 75 |
| Wheat | S1 | SC | 30 | 7 | 1 | | | | | | | 75 |
| Wheat | S1 | SC | 30 | 7 | 2 | | | | | | | 75 |
| Wheat | S1 | SC | 30 | 7 | 3 | | | | | | | 75 |
| Wheat | S1 | SC | 30 | S | 1 | | | | | | | 75 |
| Wheat | S1 | SC | 30 | S | 2 | | | | | | | 75 |
| Wheat | S1 | SC | 30 | S | 3 | | | | | | | 75 |
| Wheat | S1 | TS | 20 | 4 | 1 | NF | 57 | 15 | 266.00 | 180.00 | 86.00 | 75 |
| Wheat | S1 | TS | 20 | 4 | 2 | NF | 61 | 15 | 328.00 | 172.00 | 156.00 | 75 |
| Wheat | S1 | TS | 20 | 4 | 3 | NF | 83 | 15 | 66.00 | 190.00 | -124.00 | 75 |
| Wheat | S1 | TS | 20 | 7 | 1 | NF | 53 | 17 | 49.00 | 144.00 | -95.00 | 75 |
| Wheat | S1 | TS | 20 | 7 | 2 | NF | | | 347.00 | 140.00 | 207.00 | 75 |
| Wheat | S1 | TS | 20 | 7 | 3 | NF | | | 102.00 | 144.00 | -42.00 | 75 |
| Wheat | S1 | TS | 30 | 4 | 1 | NF | | | 283.00 | 194.00 | 89.00 | 75 |
| Wheat | S1 | TS | 30 | 4 | 2 | NF | | | 211.00 | 201.00 | 10.00 | 75 |
| Wheat | S1 | TS | 30 | 4 | 3 | NF | | | 386.00 | 187.00 | 199.00 | 75 |
| Wheat | S1 | TS | 30 | 7 | 1 | NF | | | 37.00 | 147.00 | -110.00 | 75 |
| Wheat | S1 | TS | 30 | 7 | 2 | NF | | | 211.00 | 137.00 | 74.00 | 75 |
| Wheat | S1 | TS | 30 | 7 | 3 | NF | | | 104.00 | 147.00 | -43.00 | 75 |
| Wheat | S1 | TC | 20 | 4 | 1 | NF | | | 213.00 | 172.00 | 41.00 | 75 |
| Wheat | S1 | TC | 20 | 4 | 2 | NF | | | 134.00 | 151.00 | -17.00 | 75 |
| Wheat | S1 | TC | 20 | 4 | 3 | NF | | | 165.00 | 141.00 | 24.00 | 75 |

## Connectivity Method Results

**NF: object not found, Peak: Peak value found, and "-": Potential detection**

| Crop | Season | Object | Angle [degrees] | Speed [km/h] | Test# | Detection | Peak-X | Peak-Y | Cell Value | Avg | CellValue-AVGValue | Crop height [cm] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Wheat | S1 | TC | 20 | 7 | 1 | NF | | | 155.00 | 130.00 | 25.00 | 75 |
| Wheat | S1 | TC | 20 | 7 | 2 | NF | | | 14.00 | 139.00 | -125.00 | 75 |
| Wheat | S1 | TC | 20 | 7 | 3 | NF | | | 145.00 | 115.00 | 30.00 | 75 |
| Wheat | S1 | TC | 20 | S | 1 | NF | | | 118.00 | 127.00 | -9.00 | 75 |
| Wheat | S1 | TC | 30 | 4 | 1 | Peak | | | 496.00 | 158.00 | 338.00 | 75 |
| Wheat | S1 | TC | 30 | 4 | 2 | NF | | | 88.00 | 155.00 | -67.00 | 75 |
| Wheat | S1 | TC | 30 | 4 | 3 | NF | | | 191.00 | 165.00 | 26.00 | 75 |
| Wheat | S1 | TC | 30 | 7 | 1 | NF | | | 202.00 | 133.00 | 69.00 | 75 |
| Wheat | S1 | TC | 30 | 7 | 2 | NF | | | 165.00 | 121.00 | 44.00 | 75 |
| Wheat | S1 | TC | 30 | 7 | 3 | NF | | | 37.00 | 130.00 | -93.00 | 75 |
| Wheat | S1 | TC | 30 | S | 1 | Peak | | | 343.00 | 130.00 | 213.00 | 75 |
| Hay | S1 | TC | 20 | 4 | 1 | NF | | | 122.00 | 99.00 | 23.00 | 20 |
| Hay | S1 | TC | 20 | 4 | 2 | NF | | | 21.00 | 105.00 | -84.00 | 20 |
| Hay | S1 | TC | 20 | 4 | 3 | NF | | | 158.00 | 99.00 | 59.00 | 20 |
| Hay | S1 | TC | 20 | 7 | 1 | NF | | | 168.00 | | | 20 |
| Hay | S1 | TC | 20 | 7 | 2 | NF | | | 170.00 | | | 20 |
| Hay | S1 | TC | 20 | 7 | 3 | NF | | | 107.00 | | | 20 |
| Hay | S1 | TC | 30 | 4 | 1 | Peak | | | 430.00 | 100.00 | 330.00 | 20 |
| Hay | S1 | TC | 30 | 4 | 2 | Peak | | | 484.00 | 97.00 | 387.00 | 20 |
| Hay | S1 | TC | 30 | 4 | 3 | NF | | | 128.00 | 101.00 | 27.00 | 20 |
| Hay | S1 | TC | 30 | 7 | 1 | Peak | 69 | 20 | 228.00 | 76.00 | 152.00 | 20 |
| Hay | S1 | TC | 30 | 7 | 2 | - | | | 190.00 | 75.00 | 115.00 | 20 |
| Hay | S1 | TC | 30 | 7 | 3 | Peak | | | 225.00 | 70.00 | 155.00 | 20 |
| Hay | S1 | TS | 20 | 4 | 1 | NF | | | 63.00 | 106.00 | -43.00 | 20 |
| Hay | S1 | TS | 20 | 4 | 2 | NF | | | 132.00 | 113.00 | 19.00 | 20 |
| Hay | S1 | TS | 20 | 4 | 3 | Peak | | | 284.00 | 112.00 | 172.00 | 20 |
| Hay | S1 | TS | 20 | 7 | 1 | NF | | | 116.00 | 95.00 | 21.00 | 20 |
| Hay | S1 | TS | 20 | 7 | 2 | - | | | 168.00 | 93.00 | 75.00 | 20 |
| Hay | S1 | TS | 20 | 7 | 3 | Peak | | | 251.00 | 100.00 | 151.00 | 20 |
| Hay | S1 | TS | 30 | 4 | 1 | NF | | | 70.00 | 116.00 | -46.00 | 20 |
| Hay | S1 | TS | 30 | 4 | 2 | NF | | | 119.00 | 116.00 | 3.00 | 20 |
| Hay | S1 | TS | 30 | 4 | 3 | NF | | | 200.00 | 112.00 | 88.00 | 20 |
| Hay | S1 | TS | 30 | 7 | 1 | - | | | 190.00 | | | 20 |

**Connectivity Method Results**

**NF: object not found, Peak: Peak value found, and "-": Potential detection**

| Crop | Season | Object | Angle [degrees] | Speed [km/h] | Test# | Detection | Peak-X | Peak-Y | Cell Value | Avg | CellValue-AVGValue | Crop height [cm] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hay | S1 | TS | 30 | 7 | 2 | NF | | | 2.00 | | | 20 |
| Hay | S1 | TS | 30 | 7 | 3 | - | 68 | 22 | 245.00 | | | 20 |
| Hay | S2 | SC | 20 | 4 | 1 | | | | | | | 35 |
| Hay | S2 | SC | 20 | 4 | 2 | | | | | | | 35 |
| Hay | S2 | SC | 20 | 4 | 3 | | | | | | | 35 |
| Hay | S2 | SC | 20 | 7 | 1 | | | | | | | 35 |
| Hay | S2 | SC | 20 | 7 | 2 | | | | | | | 35 |
| Hay | S2 | SC | 20 | 7 | 3 | | | | | | | 35 |
| Hay | S2 | SC | 20 | S | 1 | | | | | | | 35 |
| Hay | S2 | SC | 20 | S | 2 | | | | | | | 35 |
| Hay | S2 | SC | 30 | 4 | 1 | | | | | | | 35 |
| Hay | S2 | SC | 30 | 4 | 2 | | | | | | | 35 |
| Hay | S2 | SC | 30 | 4 | 3 | | | | | | | 35 |
| Hay | S2 | SC | 30 | 7 | 1 | | | | | | | 35 |
| Hay | S2 | SC | 30 | 7 | 2 | | | | | | | 35 |
| Hay | S2 | SC | 30 | 7 | 3 | | | | | | | 35 |
| Hay | S2 | SC | 30 | S | 1 | | | | | | | 35 |
| Hay | S2 | SC | 30 | S | 2 | | | | | | | 35 |
| Hay | S2 | SC | 30 | S | 3 | | | | | | | 35 |
| Hay | S2 | TC | 20 | 4 | 1 | NF | | | 41.00 | 109.00 | -68.00 | 40 |
| Hay | S2 | TC | 20 | 4 | 2 | NF | | | 22.00 | 109.00 | -87.00 | 40 |
| Hay | S2 | TC | 20 | 4 | 3 | NF | | | 0.00 | 118.00 | -118.00 | 40 |
| Hay | S2 | TC | 20 | 7 | 1 | NF | | | 3.00 | 109.00 | -106.00 | 40 |
| Hay | S2 | TC | 20 | 7 | 2 | NF | | | 76.00 | 107.00 | -31.00 | 40 |
| Hay | S2 | TC | 20 | 7 | 3 | NF | | | 7.00 | 109.00 | -102.00 | 40 |
| Hay | S2 | TC | 20 | S | 1 | | | | | | | 40 |
| Hay | S2 | TC | 20 | S | 2 | | | | | | | 40 |
| Hay | S2 | TC | 20 | S | 3 | | | | | | | 40 |
| Hay | S2 | TC | 30 | 4 | 1 | - | 113 | 16 | 448.00 | 117.00 | 331.00 | 40 |
| Hay | S2 | TC | 30 | 4 | 2 | Peak | | | 336.00 | 112.00 | 224.00 | 40 |
| Hay | S2 | TC | 30 | 4 | 3 | NF | | | 56.00 | 111.00 | -55.00 | 40 |
| Hay | S2 | TC | 30 | 7 | 1 | NF | | | 112.00 | 88.00 | 24.00 | 40 |
| Hay | S2 | TC | 30 | 7 | 2 | NF | | | 178.00 | 83.00 | 95.00 | 40 |

## Connectivity Method Results

**NF: object not found, Peak: Peak value found, and "-": Potential detection**

| Crop | Season | Object | Angle [degrees] | Speed [km/h] | Test# | Detection | Peak-X | Peak-Y | Cell Value | Avg | CellValue-AVGValue | Crop height [cm] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hay | S2 | TC | 30 | 7 | 3 | NF | | | 66.00 | 89.00 | -23.00 | 40 |
| Hay | S2 | TC | 30 | S | 1 | NF | | | 158.00 | 97.00 | 61.00 | 40 |
| Hay | S2 | TC | 30 | S | 2 | NF | | | 180.00 | 102.00 | 78.00 | 40 |
| Hay | S2 | TC | 30 | S | 3 | Peak | 90 | 16 | 438.00 | 96.00 | 342.00 | 40 |
| Hay | S2 | TS | 20 | 4 | 1 | NF | | | 40.00 | 109.00 | -69.00 | 40 |
| Hay | S2 | TS | 20 | 4 | 2 | NF | | | 46.00 | 109.00 | -63.00 | 40 |
| Hay | S2 | TS | 20 | 4 | 3 | NF | | | 50.00 | 118.00 | -68.00 | 40 |
| Hay | S2 | TS | 20 | 7 | 1 | NF | | | 8.00 | 109.00 | -101.00 | 40 |
| Hay | S2 | TS | 20 | 7 | 2 | NF | | | 10.00 | 107.00 | -97.00 | 40 |
| Hay | S2 | TS | 20 | 7 | 3 | NF | | | 6.00 | 109.00 | -103.00 | 40 |
| Hay | S2 | TS | 20 | S | 1 | NF | | | 131.00 | 56.00 | 75.00 | 40 |
| Hay | S2 | TS | 20 | S | 2 | NF | | | 0.00 | 48.00 | -48.00 | 40 |
| Hay | S2 | TS | 20 | S | 3 | NF | | | 0.00 | 52.00 | -52.00 | 40 |
| Hay | S2 | TS | 30 | 4 | 1 | - | 50 | 18 | 456.00 | 117.00 | 339.00 | 40 |
| Hay | S2 | TS | 30 | 4 | 2 | NF | | | 218.00 | 112.00 | 106.00 | 40 |
| Hay | S2 | TS | 30 | 4 | 3 | - | | | 371.00 | 111.00 | 260.00 | 40 |
| Hay | S2 | TS | 30 | 7 | 1 | NF | | | 139.00 | 88.00 | 51.00 | 40 |
| Hay | S2 | TS | 30 | 7 | 2 | NF | | | 175.00 | 83.00 | 92.00 | 40 |
| Hay | S2 | TS | 30 | 7 | 3 | NF | | | 74.00 | 89.00 | -15.00 | 40 |
| Hay | S2 | TS | 30 | S | 1 | NF | | | 140.00 | 97.00 | 43.00 | 40 |
| Hay | S2 | TS | 30 | S | 2 | NF | | | 123.00 | 102.00 | 21.00 | 40 |
| Hay | S2 | TS | 30 | S | 3 | NF | | | 119.00 | 96.00 | 23.00 | 40 |
| Soy | S1 | TC | 20 | 4 | 1 | NF | | | 250.00 | 114.00 | 136.00 | 70 |
| Soy | S1 | TC | 20 | 4 | 2 | Peak | | | 392.00 | 120.00 | 272.00 | 70 |
| Soy | S1 | TC | 20 | 4 | 3 | Y | | | 418.00 | 116.00 | 302.00 | 70 |
| Soy | S1 | TC | 20 | 4 | 1_Long | | | | | | | 70 |
| Soy | S1 | TC | 20 | 4 | 2_Long | | | | | | | 70 |
| Soy | S1 | TC | 20 | 4 | 3_Long | | | | | | | 70 |
| Soy | S1 | TC | 20 | 7 | 1 | Peak | | | 347.00 | 95.00 | 252.00 | 70 |
| Soy | S1 | TC | 20 | 7 | 2 | Peak | | | 339.00 | 88.00 | 251.00 | 70 |
| Soy | S1 | TC | 20 | 7 | 3 | NF | | | 180.00 | 85.00 | 95.00 | 70 |
| Soy | S1 | TC | 20 | S | 1 | Peak | | | 537.00 | 113.00 | 424.00 | 70 |
| Soy | S1 | TC | 20 | S | 2 | Peak | | | 513.00 | 119.00 | 394.00 | 70 |

## Connectivity Method Results

**NF: object not found, Peak: Peak value found, and "-": Potential detection**

| Crop | Season | Object | Angle [degrees] | Speed [km/h] | Test# | Detection | Peak-X | Peak-Y | Cell Value | Avg | CellValue-AVGValue | Crop height [cm] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Soy | S1 | TC | 20 | S | 3 | NF | | | 114.00 | 112.00 | 2.00 | 70 |
| Soy | S1 | TC | 30 | 4 | 1 | - | 97 | 19 | 313.00 | 106.00 | 207.00 | 70 |
| Soy | S1 | TC | 30 | 4 | 2 | NF | | | 244.00 | 103.00 | 141.00 | 70 |
| Soy | S1 | TC | 30 | 4 | 3 | Peak | | | 392.00 | 105.00 | 287.00 | 70 |
| Soy | S1 | TC | 30 | 7 | 1 | Peak | 77 | 19 | 285.00 | 79.00 | 206.00 | 70 |
| Soy | S1 | TC | 30 | 7 | 2 | - | 66 | 20 | 234.00 | 82.00 | 152.00 | 70 |
| Soy | S1 | TC | 30 | 7 | 3 | NF | | | 164.00 | 81.00 | 83.00 | 70 |
| Soy | S1 | TC | 30 | S | 1 | Peak | | | 586.00 | 125.00 | 461.00 | 70 |
| Soy | S1 | TC | 30 | S | 2 | Peak | | | 573.00 | 122.00 | 451.00 | 70 |
| Soy | S1 | TC | 30 | S | 3 | - | | | 434.00 | 116.00 | 318.00 | 70 |
| Soy | S1 | TS | 20 | 4 | 1 | NF | | | 193.00 | 11.00 | 182.00 | 70 |
| Soy | S1 | TS | 20 | 4 | 2 | | | | | 118.00 | -118.00 | 70 |
| Soy | S1 | TS | 20 | 4 | 3 | NF | | | 22.00 | 112.00 | -90.00 | 70 |
| Soy | S1 | TS | 20 | 7 | 1 | | | | | | | 70 |
| Soy | S1 | TS | 20 | 7 | 2 | | | | | | | 70 |
| Soy | S1 | TS | 20 | 7 | 3 | | | | | | | 70 |
| Soy | S1 | TS | 20 | S | 1 | NF | | | 344.00 | 119.00 | 225.00 | 70 |
| Soy | S1 | TS | 20 | S | 2 | NF | | | 38.00 | 113.00 | -75.00 | 70 |
| Soy | S1 | TS | 20 | S | 3 | NF | | | 71.00 | 113.00 | -42.00 | 70 |
| Soy | S1 | TS | 30 | 4 | 1 | NF | | | 131.00 | 119.00 | 12.00 | 70 |
| Soy | S1 | TS | 30 | 4 | 2 | NF | | | 0.00 | 116.00 | -116.00 | 70 |
| Soy | S1 | TS | 30 | 4 | 3 | NF | | | 164.00 | 112.00 | 52.00 | 70 |
| Soy | S1 | TS | 30 | 7 | 1 | NF | | | 100.00 | 88.00 | 12.00 | 70 |
| Soy | S1 | TS | 30 | 7 | 2 | NF | | | 13.00 | 83.00 | -70.00 | 70 |
| Soy | S1 | TS | 30 | 7 | 3 | NF | | | 143.00 | 83.00 | 60.00 | 70 |
| Soy | S1 | TS | 30 | S | 1 | NF | | | 295.00 | 133.00 | 162.00 | 70 |
| Soy | S1 | TS | 30 | S | 2 | NF | | | 193.00 | 134.00 | 59.00 | 70 |
| Soy | S1 | TS | 30 | S | 3 | NF | | | 239.00 | 132.00 | 107.00 | 70 |
| Soy | S3 | SC | 20 | 4 | 1 | | | | | | | 70 |
| Soy | S3 | SC | 20 | 4 | 2 | | | | | | | 70 |
| Soy | S3 | SC | 20 | 4 | 3 | | | | | | | 70 |
| Soy | S3 | SC | 20 | S | 1 | | | | | | | 70 |
| Soy | S3 | SC | 20 | S | 2 | | | | | | | 70 |

## Connectivity Method Results

**NF: object not found, Peak: Peak value found, and "-": Potential detection**

| Crop | Season | Object | Angle [degrees] | Speed [km/h] | Test# | Detection | Peak-X | Peak-Y | Cell Value | Avg | CellValue-AVGValue | Crop height [cm] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Soy | S3 | SC | 20 | S | 3 | | | | | | | 70 |
| Soy | S3 | SC | 30 | 4 | 1 | | | | | | | 70 |
| Soy | S3 | SC | 30 | 4 | 2 | | | | | | | 70 |
| Soy | S3 | SC | 30 | 4 | 3 | | | | | | | 70 |
| Soy | S3 | SC | 30 | S | 1 | | | | | | | 70 |
| Soy | S3 | SC | 30 | S | 2 | | | | | | | 70 |
| Soy | S3 | SC | 30 | S | 3 | | | | | | | 70 |
| Soy | S3 | TC | 20 | 4 | 1 | NF | | | 88.00 | 69.00 | 19.00 | 70 |
| Soy | S3 | TC | 20 | 4 | 2 | NF | | | 121.00 | 66.00 | 55.00 | 70 |
| Soy | S3 | TC | 20 | 4 | 3 | NF | | | 73.00 | 73.00 | 0.00 | 70 |
| Soy | S3 | TC | 20 | 7 | 1 | NF | | | 178.00 | 118.00 | 60.00 | 70 |
| Soy | S3 | TC | 20 | 7 | 2 | NF | | | 27.00 | 103.00 | -76.00 | 70 |
| Soy | S3 | TC | 20 | 7 | 3 | NF | | | 65.00 | 113.00 | -48.00 | 70 |
| Soy | S3 | TC | 20 | S | 1 | - | | | 146.00 | 28.00 | 118.00 | 70 |
| Soy | S3 | TC | 20 | S | 2 | - | | | 96.00 | 27.00 | 69.00 | 70 |
| Soy | S3 | TC | 20 | S | 3 | Peak | | | 167.00 | 27.00 | 140.00 | 70 |
| Soy | S3 | TC | 30 | 4 | 1 | - | | | 111.00 | 98.00 | 13.00 | 70 |
| Soy | S3 | TC | 30 | 4 | 2 | NF | | | 83.00 | 98.00 | -15.00 | 70 |
| Soy | S3 | TC | 30 | 4 | 3 | NF | | | 59.00 | 95.00 | -36.00 | 70 |
| Soy | S3 | TC | 30 | 7 | 1 | NF | | | 46.00 | 124.00 | -78.00 | 70 |
| Soy | S3 | TC | 30 | 7 | 2 | NF | | | 70.00 | 127.00 | -57.00 | 70 |
| Soy | S3 | TC | 30 | 7 | 3 | - | | | 163.00 | 131.00 | 32.00 | 70 |
| Soy | S3 | TC | 30 | S | 1 | Peak | | | 142.00 | 42.00 | 100.00 | 70 |
| Soy | S3 | TC | 30 | S | 2 | Peak | | | 148.00 | 41.00 | 107.00 | 70 |
| Soy | S3 | TC | 30 | S | 3 | Peak | | | 154.00 | 41.00 | 113.00 | 70 |
| Soy | S3 | TS | 20 | 4 | 1 | - | | | 115.00 | 72.00 | 43.00 | 70 |
| Soy | S3 | TS | 20 | 4 | 2 | NF | | | 97.00 | 66.00 | 31.00 | 70 |
| Soy | S3 | TS | 20 | 4 | 3 | NF | | | 78.00 | 74.00 | 4.00 | 70 |
| Soy | S3 | TS | 20 | 7 | 1 | - | | | 113.00 | 103.00 | 10.00 | 70 |
| Soy | S3 | TS | 20 | 7 | 2 | NF | | | 31.00 | 118.00 | -87.00 | 70 |
| Soy | S3 | TS | 20 | 7 | 3 | NF | | | 31.00 | 108.00 | -77.00 | 70 |
| Soy | S3 | TS | 20 | S | 1 | - | | | 148.00 | 29.00 | 119.00 | 70 |
| Soy | S3 | TS | 20 | S | 2 | Peak | | | 144.00 | 26.00 | 118.00 | 70 |

**Connectivity Method Results**

**NF: object not found, Peak: Peak value found, and "-": Potential detection**

| Crop | Season | Object | Angle [degrees] | Speed [km/h] | Test# | Detection | Peak-X | Peak-Y | Cell Value | Avg | CellValue-AVGValue | Crop height [cm] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Soy | S3 | TS | 20 | S | 3 | Peak | | | 185.00 | 28.00 | 157.00 | 70 |
| Soy | S3 | TS | 30 | 4 | 1 | NF | | | 80.00 | 98.00 | -18.00 | 70 |
| Soy | S3 | TS | 30 | 4 | 2 | NF | | | 22.00 | 97.00 | -75.00 | 70 |
| Soy | S3 | TS | 30 | 4 | 3 | - | | | 140.00 | 91.00 | 49.00 | 70 |
| Soy | S3 | TS | 30 | 7 | 1 | - | | | 174.00 | 132.00 | 42.00 | 70 |
| Soy | S3 | TS | 30 | 7 | 2 | NF | | | 61.00 | 128.00 | -67.00 | 70 |
| Soy | S3 | TS | 30 | 7 | 3 | NF | | | 86.00 | 122.00 | -36.00 | 70 |
| Soy | S3 | TS | 30 | S | 1 | - | | | 85.00 | 44.00 | 41.00 | 70 |
| Soy | S3 | TS | 30 | S | 2 | - | | | 125.00 | 40.00 | 85.00 | 70 |
| Soy | S3 | TS | 30 | S | 3 | - | | | 157.00 | 41.00 | 116.00 | 70 |
| Oats | S1 | TC | 20 | 4 | 1 | NF | | | 129.00 | 109.00 | 20.00 | 60.00 |
| Oats | S1 | TC | 20 | 4 | 2 | - | | | 314.00 | 117.00 | 197.00 | 60.00 |
| Oats | S1 | TC | 20 | 4 | 3 | - | | | 288.00 | 108.00 | 180.00 | 60.00 |
| Oats | S1 | TC | 20 | 7 | 1 | NF | | | 70.00 | 122.00 | -52.00 | 60.00 |
| Oats | S1 | TC | 20 | 7 | 2 | NF | | | 154.00 | 106.00 | 48.00 | 60.00 |
| Oats | S1 | TC | 20 | 7 | 3 | | 49 | 16 | 522.00 | 117.00 | 405.00 | 60.00 |
| Oats | S1 | TC | 30 | 4 | 1 | - | | | 577.00 | 131.00 | 446.00 | 60.00 |
| Oats | S1 | TC | 30 | 4 | 2 | Peak | | | 608.00 | 139.00 | 469.00 | 60.00 |
| Oats | S1 | TC | 30 | 4 | 3 | Peak | | | 480.00 | 132.00 | 348.00 | 60.00 |
| Oats | S1 | TC | 30 | 7 | 1 | Peak | | | 362.00 | 100.00 | 262.00 | 60.00 |
| Oats | S1 | TC | 30 | 7 | 2 | - | | | 192.00 | 93.00 | 99.00 | 60.00 |
| Oats | S1 | TC | 30 | 7 | 3 | Peak | | | 447.00 | 98.00 | 349.00 | 60.00 |
| Oats | S1 | TS | 20 | 4 | 1 | Peak | | | 571.00 | 106.00 | 465.00 | 60.00 |
| Oats | S1 | TS | 20 | 4 | 2 | - | | | 571.00 | 109.00 | 462.00 | 60.00 |
| Oats | S1 | TS | 20 | 4 | 3 | - | | | 571.00 | 109.00 | 462.00 | 60.00 |
| Oats | S1 | TS | 20 | 7 | 1 | Peak | 42 | 17 | 525.00 | 104.00 | 421.00 | 60.00 |
| Oats | S1 | TS | 20 | 7 | 2 | NF | | | 149.00 | 110.00 | 39.00 | 60.00 |
| Oats | S1 | TS | 20 | 7 | 3 | NF | | | 90.00 | 107.00 | -17.00 | 60.00 |
| Oats | S1 | TS | 30 | 4 | 1 | NF | | | 71.00 | 131.00 | -60.00 | 60.00 |
| Oats | S1 | TS | 30 | 4 | 2 | NF | | | 221.00 | 138.00 | 83.00 | 60.00 |
| Oats | S1 | TS | 30 | 4 | 3 | NF | | | 41.00 | 133.00 | -92.00 | 60.00 |
| Oats | S1 | TS | 30 | 7 | 1 | NF | | | 32.00 | 100.00 | -68.00 | 60.00 |
| Oats | S1 | TS | 30 | 7 | 2 | NF | | | 0.00 | 106.00 | -106.00 | 60.00 |

**Connectivity Method Results**

**NF: object not found, Peak: Peak value found, and "-": Potential detection**

| Crop | Season | Object | Angle [degrees] | Speed [km/h] | Test# | Detection | Peak-X | Peak-Y | Cell Value | Avg | CellValue-AVGValue | Crop height [cm] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Oats | S1 | TS | 30 | 7 | 3 | NF | | | 136.00 | 101.00 | 35.00 | 60.00 |
| Oats | S1 | SC | 20 | 4 | 1 | | | | | | | 60.00 |
| Oats | S1 | SC | 20 | 4 | 2 | | | | | | | 60.00 |
| Oats | S1 | SC | 20 | 4 | 3 | | | | | | | 60.00 |
| Oats | S1 | SC | 20 | 7 | 1 | | | | | | | 60.00 |
| Oats | S1 | SC | 20 | 7 | 2 | | | | | | | 60.00 |
| Oats | S1 | SC | 20 | S | 1 | | | | | | | 60.00 |
| Oats | S1 | SC | 20 | S | 2 | | | | | | | 60.00 |
| Oats | S1 | SC | 20 | S | 3 | | | | | | | 60.00 |
| Oats | S1 | SC | 30 | 4 | 1 | | | | | | | 60.00 |
| Oats | S1 | SC | 30 | 4 | 2 | | | | | | | 60.00 |
| Oats | S1 | SC | 30 | 4 | 3 | | | | | | | 60.00 |
| Oats | S1 | SC | 30 | 7 | 1 | | | | | | | 60.00 |
| Oats | S1 | SC | 30 | 7 | 2 | | | | | | | 60.00 |
| Oats | S1 | SC | 30 | 7 | 3 | | | | | | | 60.00 |
| Oats | S1 | SC | 30 | S | 1 | | | | | | | 60.00 |
| Oats | S1 | SC | 30 | S | 2 | | | | | | | 60.00 |
| Oats | S1 | SC | 30 | S | 3 | | | | | | | 60.00 |

## *B.4 Crop Discontinuity Results*

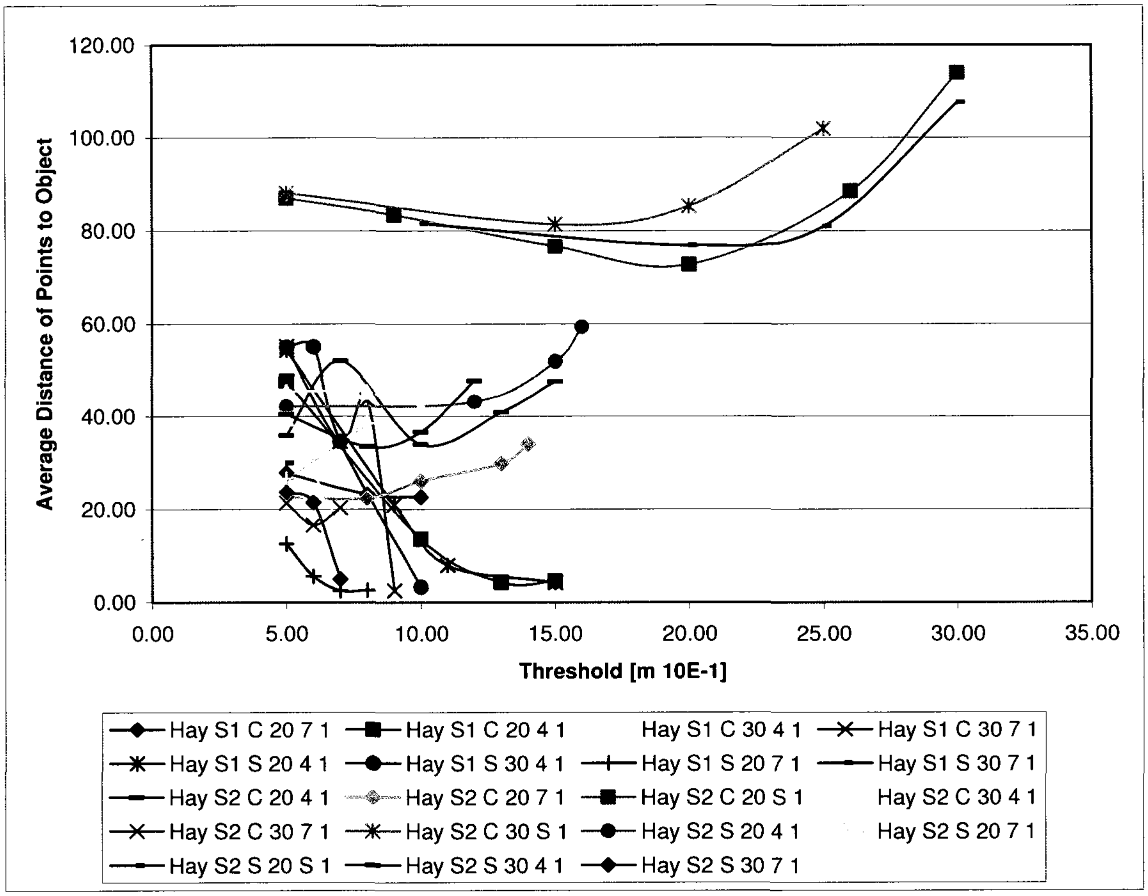



**Figure B.1: Hay Discontinuity Average Distance to object vs. Threshold**

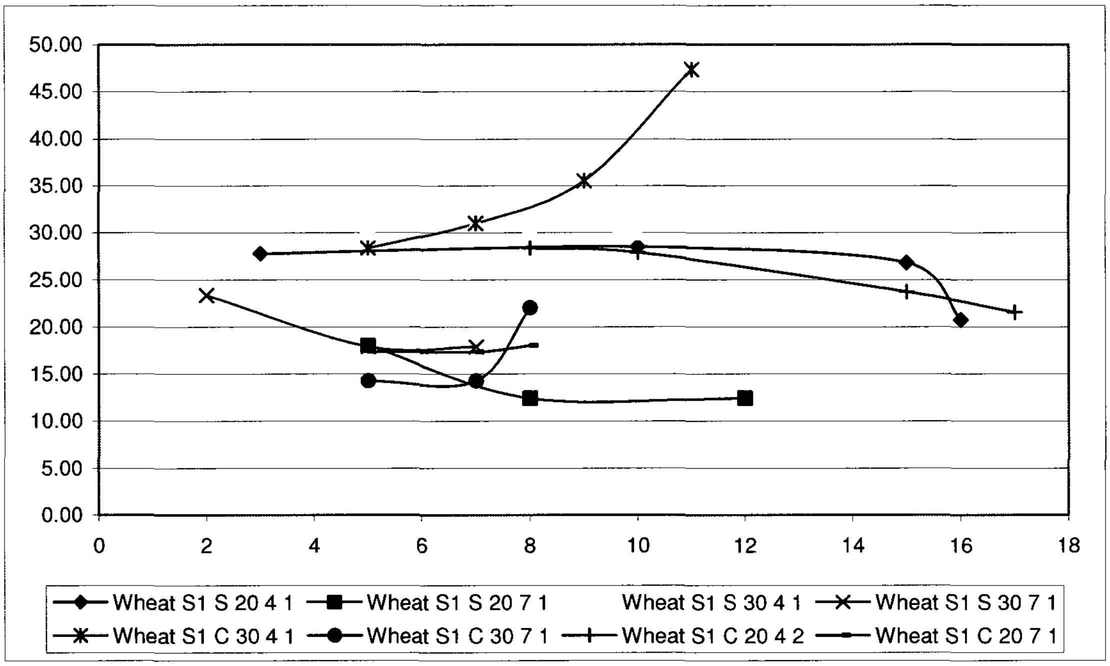



**Figure B.2: Wheat Discontinuity Average Distance to object vs. Threshold**

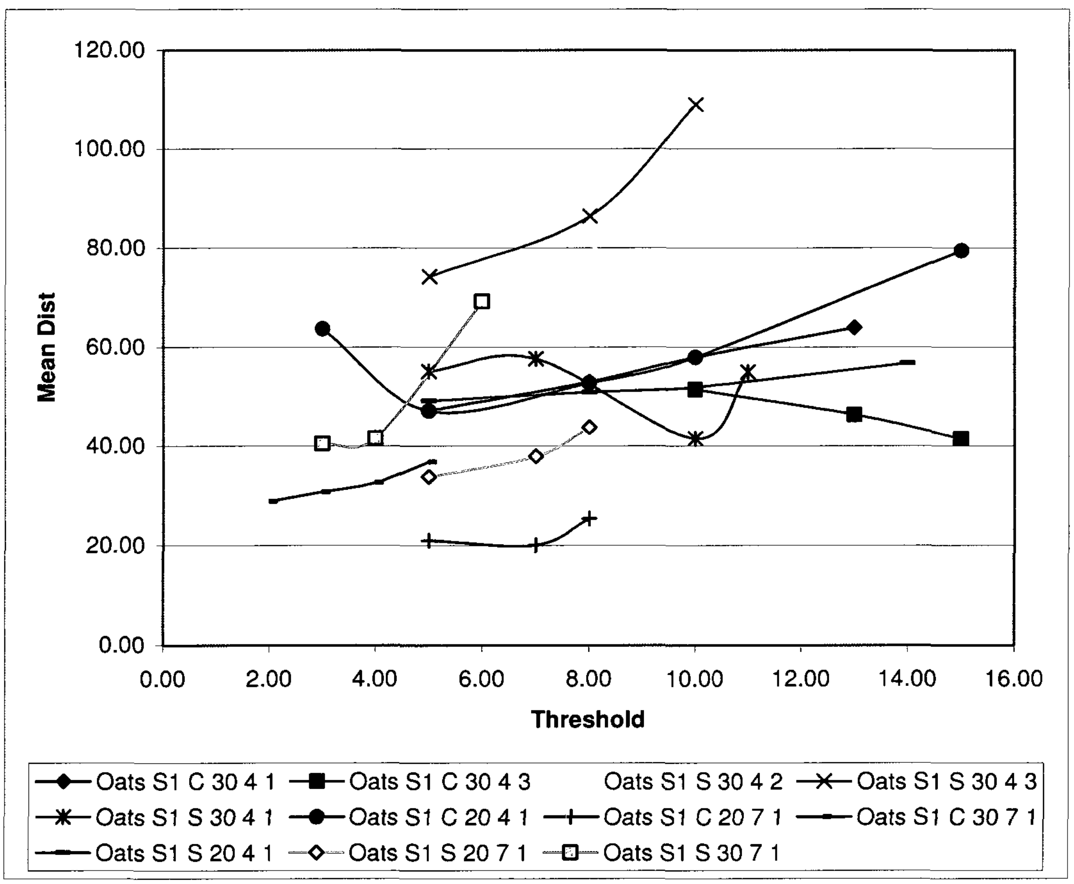



**Figure B.3: Oat Field Discontinuity Average Distance to object vs. Threshold**

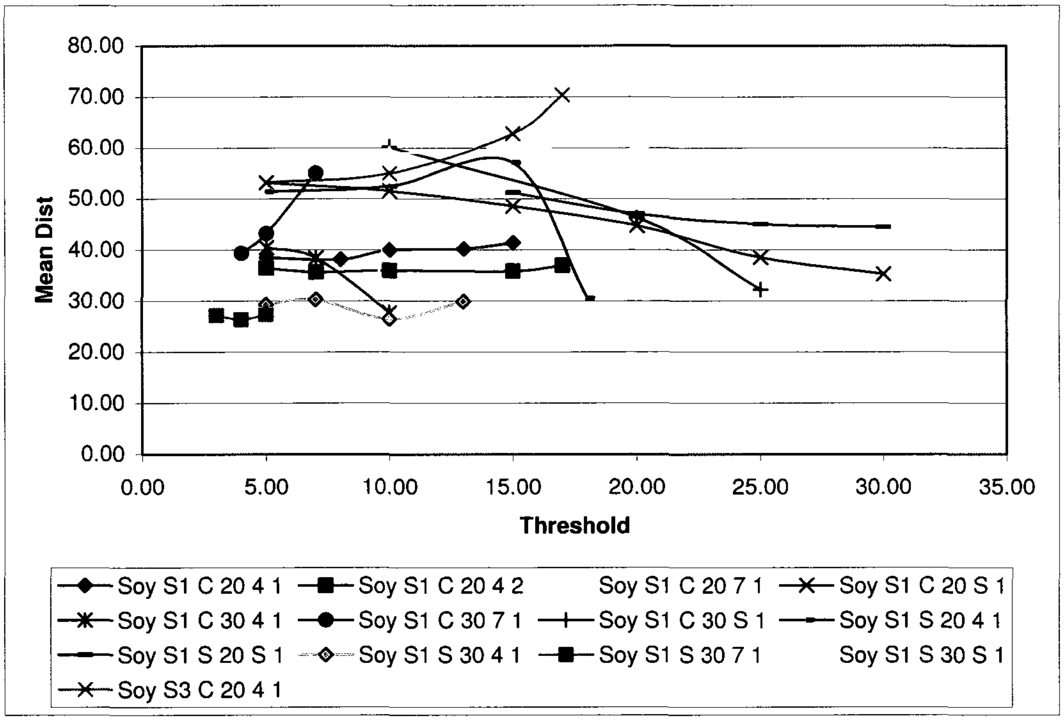



**Figure B.4 : Soy Field Discontinuity Avg Dist to object vs. Threshold Part-1**

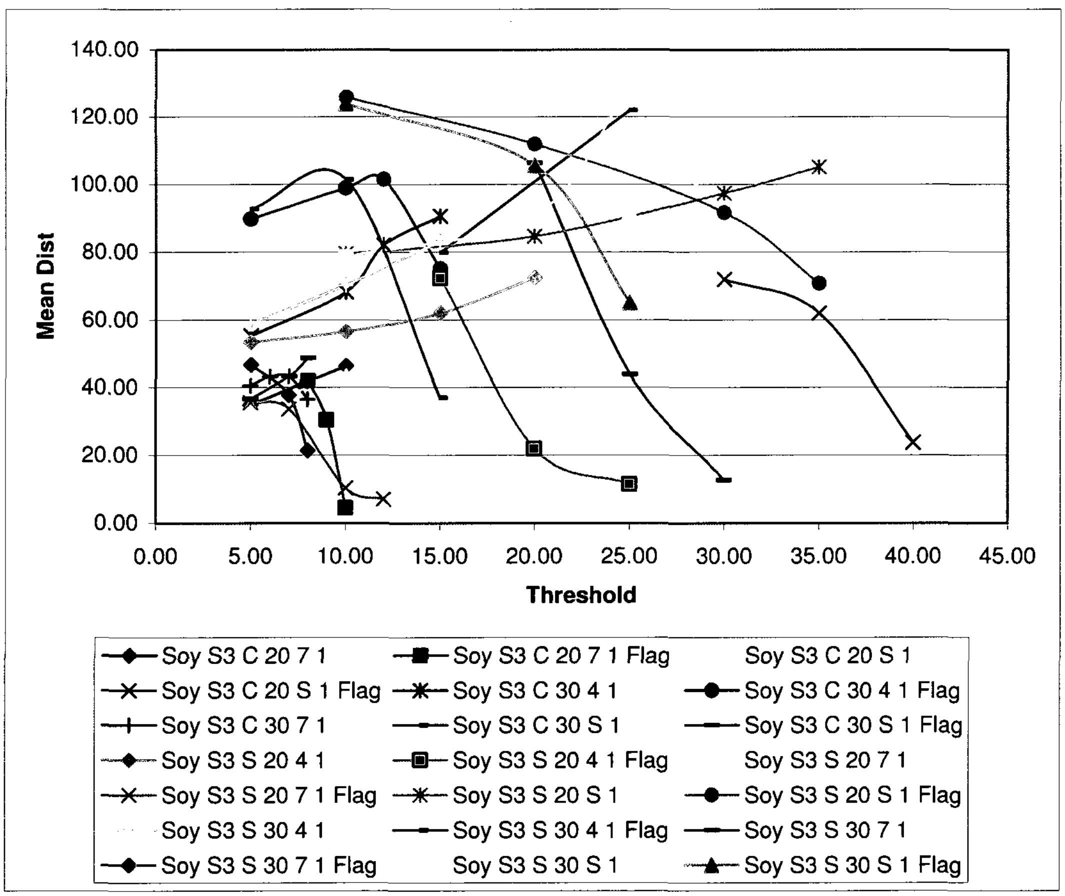



**Figure B.4: Soy Field Discontinuity Avg Dist to object vs. Threshold Part-2**

| Discontinuity Method Results | | | | | | |
|---|---|---|---|---|---|---|
| File | Peak 1 X | Peak 1 Y | Threshold | Mean Dist | Standard Deviation | # Points |
| Wheat S1 S 20 4 1 | 57 | 15 | 3 | 27.82 | 15.66 | 651 |
| Wheat S1 S 20 4 1 | 57 | 15 | 10 | 28.53 | 15.135 | 141 |
| Wheat S1 S 20 4 1 | 57 | 15 | 15 | 26.8 | 15.213 | 8 |
| Wheat S1 S 20 4 1 | 57 | 15 | 16 | 20.76 | 1.58 | 4 |
| Wheat S1 S 20 7 1 | 53 | 17 | 5 | 18.05 | 10.86 | 117 |
| Wheat S1 S 20 7 1 | 53 | 17 | 8 | 12.43 | 4.66 | 12 |
| Wheat S1 S 20 7 1 | 53 | 17 | 12 | 12.43 | 4.66 | 12 |
| Wheat S1 S 30 4 1 | 65 | 14 | 5 | 30.67 | 18.55 | 198 |
| Wheat S1 S 30 4 1 | 65 | 14 | 7 | 31.1671 | 19.45 | 87 |
| Wheat S1 S 30 4 1 | 65 | 14 | 8 | 30.6 | 20 | 50 |
| Wheat S1 S 30 4 1 | 65 | 14 | 10 | 30 | 0 | 2 |
| Wheat S1 S 30 7 1 | 37 | 14 | 2 | 23.3592 | 13.5 | 200 |
| Wheat S1 S 30 7 1 | 37 | 14 | 5 | 17.89 | 11.09 | 11 |
| Wheat S1 S 30 7 1 | 37 | 14 | 7 | 17.89 | 11.09 | 11 |
| Wheat S1 C 30 4 1 | 54 | 14 | 5 | 28.39 | 15.89 | 237 |
| Wheat S1 C 30 4 1 | 54 | 14 | 7 | 31.02 | 15.67 | 153 |
| Wheat S1 C 30 4 1 | 54 | 14 | 9 | 35.51 | 15.18 | 68 |
| Wheat S1 C 30 4 1 | 54 | 14 | 11 | 47.37 | 14.76 | 8 |
| Wheat S1 C 30 7 1 | 25 | 13 | 5 | 14.29 | 7.9 | 30 |
| Wheat S1 C 30 7 1 | 25 | 13 | 7 | 14.28 | 9 | 30 |
| Wheat S1 C 30 7 1 | 25 | 13 | 8 | 22.05 | 14.38 | 28 |
| Wheat S1 C 20 4 2 | 67 | 14 | 8 | 28.373 | 15.15 | 294 |
| Wheat S1 C 20 4 2 | 67 | 14 | 10 | 27.9 | 15.84 | 245 |
| Wheat S1 C 20 4 2 | 67 | 14 | 15 | 23.72 | 16.49 | 36 |
| Wheat S1 C 20 4 2 | 67 | 14 | 17 | 21.59 | 149 | 2 |
| Wheat S1 C 20 7 1 | 18 | 14 | 5 | 17.39 | 11.98 | 96 |
| Wheat S1 C 20 7 1 | 18 | 14 | 7 | 17.38 | 11.73 | 61 |
| Wheat S1 C 20 7 1 | 18 | 14 | 8 | 18.05 | 11.62 | 28 |
| Hay S1 C 20 7 1 | 63 | 21 | 5 | 27.85 | 15.2 | 123 |
| Hay S1 C 20 7 1 | 63 | 21 | 8 | 23.2 | 15.61 | 26 |
| Hay S1 C 20 7 1 | 63 | 21 | 10 | 22.65 | 0 | 2 |
| Hay S1 C 20 4 1 | 122 | 21 | 5 | 47.75 | 32.46 | 246 |
| Hay S1 C 20 4 1 | 122 | 21 | 10 | 13.68 | 23.57 | 44 |
| Hay S1 C 20 4 1 | 122 | 21 | 13 | 4.3 | 1.62 | 32 |
| Hay S1 C 20 4 1 | 122 | 21 | 15 | 4.6 | 1.93 | 21 |
| Hay S1 C 30 4 1 | 149 | 20 | 5 | 39.57 | 38.13 | 56 |
| Hay S1 C 30 4 1 | 149 | 20 | 8 | 6.95 | 15.88 | 20 |
| Hay S1 C 30 4 1 | 149 | 20 | 10 | 4.24 | 2.79 | 12 |
| Hay S1 C 30 7 1 | 69 | 21 | 5 | 55.089 | 41.1 | 61 |
| Hay S1 C 30 7 1 | 69 | 21 | 7 | 34.65 | 44.33 | 19 |
| Hay S1 C 30 7 1 | 69 | 21 | 8 | 43.672 | 47.32 | 12 |
| Hay S1 C 30 7 1 | 69 | 21 | 9 | 2.52 | 2.31 | 5 |
| Hay S1 S 20 4 1 | 136 | 20 | 5 | 54.35 | 32.91 | 331 |

**Discontinuity Method Results**

| File | Peak 1 X | Peak 1 Y | Threshold | Mean Dist | Standard Deviation | # Points |
|---|---|---|---|---|---|---|
| Hay S1 S 20 4 1 | 136 | 20 | 9 | 20.98 | 33.38 | 40 |
| Hay S1 S 20 4 1 | 136 | 20 | 11 | 7.98 | 20.22 | 24 |
| Hay S1 S 20 4 1 | 136 | 20 | 15 | 4.26 | 1.76 | 18 |
| Hay S1 S 30 4 1 | 188 | 20 | 5 | 55 | 41.09 | 61 |
| Hay S1 S 30 4 1 | 188 | 20 | 6 | 55.05 | 45.6 | 36 |
| Hay S1 S 30 4 1 | 188 | 20 | 7 | 34.64 | 44.33 | 19 |
| Hay S1 S 30 4 1 | 188 | 20 | 10 | 3.29 | 3.26 | 3 |
| Hay S1 S 20 7 1 | 82 | 20 | 5 | 12.66 | 18.92 | 29 |
| Hay S1 S 20 7 1 | 82 | 20 | 6 | 5.622 | 12.52 | 16 |
| Hay S1 S 20 7 1 | 82 | 20 | 7 | 2.53183 | 1.974 | 12 |
| Hay S1 S 20 7 1 | 82 | 20 | 8 | 2.59 | 2.29 | 9 |
| Hay S1 S 30 7 1 | 96 | 21 | 5 | 30.07 | 27.05 | 21 |
| Hay S1 S 30 7 1 | 96 | 21 | | | | |
| Hay S1 S 30 7 1 | 96 | 21 | | | | |
| Hay S1 S 30 7 1 | 96 | 21 | | | | |
| Hay S2 C 20 4 1 | 85 | 27 | 5 | 35.9 | 21.33 | 1017 |
| Hay S2 C 20 4 1 | 85 | 27 | 7 | 52.05 | 26.95 | 124 |
| Hay S2 C 20 4 1 | 85 | 27 | 10 | 34.04 | 20.19 | 299 |
| Hay S2 C 20 4 1 | 85 | 27 | 13 | 40.94 | 23.97 | 49 |
| Hay S2 C 20 4 1 | 85 | 27 | 15 | 47.6 | 21.11 | 18 |
| Hay S2 C 20 7 1 | 48 | 28 | 5 | 22.65 | 11.13 | 568 |
| Hay S2 C 20 7 1 | 48 | 28 | 8 | 22.39 | 11.21 | 243 |
| Hay S2 C 20 7 1 | 48 | 28 | 10 | 26.19 | 12.82 | 96 |
| Hay S2 C 20 7 1 | 48 | 28 | 13 | 29.93 | 12.94 | 24 |
| Hay S2 C 20 7 1 | 48 | 28 | 14 | 34.05 | 10.95 | 14 |
| Hay S2 C 20 S 1 | 120 | 27 | 5 | 87.01 | 57.85 | 4808 |
| Hay S2 C 20 S 1 | 120 | 27 | 9 | 83.37 | 56.77 | 2802 |
| Hay S2 C 20 S 1 | 120 | 27 | 15 | 76.65 | 53.02 | 1230 |
| Hay S2 C 20 S 1 | 120 | 27 | 20 | 72.74 | 51.72 | 647 |
| Hay S2 C 20 S 1 | 120 | 27 | 26 | 88.5 | 57.8 | 152 |
| Hay S2 C 20 S 1 | 120 | 27 | 30 | 114 | 63 | 51 |
| Hay S2 C 30 4 1 | 113 | 15 | 5 | 45.46 | 27.07 | 511 |
| Hay S2 C 30 4 1 | 113 | 15 | 8 | 45.37 | 29.624 | 142 |
| Hay S2 C 30 4 1 | 113 | 15 | 10 | 41.77 | 30.84 | 55 |
| Hay S2 C 30 4 1 | 113 | 15 | 12 | 55.89 | 38.6 | 18 |
| Hay S2 C 30 7 1 | 54 | 15 | 5 | 21.4 | 12.01 | 28 |
| Hay S2 C 30 7 1 | 54 | 15 | 6 | 16.68 | 9.04 | 15 |
| Hay S2 C 30 7 1 | 54 | 15 | 7 | 20.32 | 13.61 | |
| Hay S2 C 30 S 1 | 63 | 15 | 5 | 88.13 | 57.58 | 2418 |
| Hay S2 C 30 S 1 | 63 | 15 | 15 | 81.41 | 62.43 | 263 |
| Hay S2 C 30 S 1 | 63 | 15 | 20 | 85.3 | 67.33 | 96 |
| Hay S2 C 30 S 1 | 63 | 15 | 25 | 102 | 80.42 | 36 |
| Hay S2 S 20 4 1 | 97 | 27 | 5 | 42.21 | 25.57 | 1118 |
| Hay S2 S 20 4 1 | 97 | 27 | 12 | 43.25 | 26.74 | 116 |
| Hay S2 S 20 4 1 | 97 | 27 | 15 | 51.9 | 31.27 | 29 |

## Discontinuity Method Results

| File | Peak 1 X | Peak 1 Y | Threshold | Mean Dist | Standard Deviation | # Points |
|---|---|---|---|---|---|---|
| Hay S2 S 20 4 1 | 97 | 27 | 16 | 59.35 | 33.05 | 19 |
| Hay S2 S 20 7 1 | 51 | 28 | 5 | 26.69 | 15.1 | 161 |
| Hay S2 S 20 7 1 | 51 | 28 | 8 | 38.49 | 20.41 | 20 |
| Hay S2 S 20 S 1 | 71 | 26 | 10 | 81.59 | 60.04 | 1926 |
| Hay S2 S 20 S 1 | 71 | 26 | 20 | 76.83 | 53.52 | 419 |
| Hay S2 S 20 S 1 | 71 | 26 | 25 | 81 | 55.88 | 170 |
| Hay S2 S 20 S 1 | 71 | 26 | 30 | 107.58 | 53.23 | 65 |
| Hay S2 S 30 4 1 | 49 | 17 | 5 | 40.468 | 27.38 | 446 |
| Hay S2 S 30 4 1 | 49 | 17 | 8 | 33.53 | 25.74 | 103 |
| Hay S2 S 30 4 1 | 49 | 17 | 10 | 36.69 | 29.43 | 43 |
| Hay S2 S 30 4 1 | 49 | 17 | 12 | 47.77 | 36.56 | 19 |
| Hay S2 S 30 7 1 | 47 | 15 | 5 | 23.7 | 13 | 34 |
| Hay S2 S 30 7 1 | 47 | 15 | 6 | 21.49 | 12.68 | 8 |
| Hay S2 S 30 7 1 | 47 | 15 | 7 | 5 | 0 | 2 |
| Hay S2 S 30 S 1 | 54 | 15 | | | | |
| Hay S2 S 30 S 1 | 54 | 15 | | | | |
| Hay S2 S 30 S 1 | 54 | 15 | | | | |
| Hay S2 S 30 S 1 | 54 | 15 | | | | |
| Oats S1 C 20 4 1 | 102 | 15 | 3 | 63.7 | 20.87 | 46 |
| Oats S1 C 20 4 1 | 102 | 15 | 5 | 47.16 | 24.88 | 507 |
| Oats S1 C 20 4 1 | 102 | 15 | 8 | 52.77 | 24.67 | 259 |
| Oats S1 C 20 4 1 | 102 | 15 | 10 | 57.96 | 24.08 | 154 |
| Oats S1 C 20 4 1 | 102 | 15 | 15 | 79.47 | 9.826 | 14 |
| Oats S1 C 20 7 1 | 47 | 16 | 5 | 21.02 | 8.91 | 57 |
| Oats S1 C 20 7 1 | 47 | 16 | 7 | 20.15 | 8.35 | 18 |
| Oats S1 C 20 7 1 | 47 | 16 | 8 | 25.46 | 3.65 | 4 |
| Oats S1 C 30 4 1 | 104 | 15 | 5 | 47.25 | 25.21 | 507 |
| Oats S1 C 30 4 1 | 104 | 15 | 8 | 53.02 | 25.19 | 259 |
| Oats S1 C 30 4 1 | 104 | 15 | 10 | 58 | 25 | 154 |
| Oats S1 C 30 4 1 | 104 | 15 | 13 | 63.95 | 22.4 | 46 |
| Oats S1 C 30 4 3 | 100 | 15 | | | | |
| Oats S1 C 30 4 3 | 100 | 15 | 10 | 51.45 | 24.5 | 155 |
| Oats S1 C 30 4 3 | 100 | 15 | 13 | 46.37 | 25.93 | 37 |
| Oats S1 C 30 4 3 | 100 | 15 | 15 | 41.57 | 26.5 | 13 |
| Oats S1 C 30 7 1 | 57 | 16 | 2 | 28.95 | 14.12 | 196 |
| Oats S1 C 30 7 1 | 57 | 16 | 3 | 30.85 | 14.7 | 72 |
| Oats S1 C 30 7 1 | 57 | 16 | 4 | 32.66 | 15.18 | 37 |
| Oats S1 C 30 7 1 | 57 | 16 | 5 | 36.86 | 8.87 | 10 |
| Oats S1 S 20 4 1 | 93 | 16 | 5 | 49.24 | 28.63 | 671 |
| Oats S1 S 20 4 1 | 93 | 16 | 8 | 50.98 | 27.16 | 329 |
| Oats S1 S 20 4 1 | 93 | 16 | 10 | 51.97 | 26.7 | 238 |
| Oats S1 S 20 4 1 | 93 | 16 | 14 | 56.8 | 23.57 | 48 |
| Oats S1 S 20 7 1 | 42 | 16 | 5 | 33.86 | 17.8 | 110 |
| Oats S1 S 20 7 1 | 42 | 16 | 7 | 37.96 | 19.02 | 40 |
| Oats S1 S 20 7 1 | 42 | 16 | 8 | 43.8 | 16.95 | 16 |

**Discontinuity Method Results**

| File | Peak 1 X | Peak 1 Y | Threshold | Mean Dist | Standard Deviation | # Points |
|---|---|---|---|---|---|---|
| Oats S1 S 30 4 2 | 128 | 17 | 5 | 67.37 | 38.05 | 382 |
| Oats S1 S 30 4 2 | 128 | 17 | 7 | 71.98 | 40.03 | 226 |
| Oats S1 S 30 4 2 | 128 | 17 | 10 | 96.18 | 32.28 | 34 |
| Oats S1 S 30 4 3 | 116 | 18 | 5 | 74.23 | 43.06 | 405 |
| Oats S1 S 30 4 3 | 116 | 18 | 8 | 86.4 | 47.07 | 175 |
| Oats S1 S 30 4 3 | 116 | 18 | 10 | 108.99 | 35.97 | 38 |
| Oats S1 S 30 4 1 | 116 | 18 | 5 | 55.17 | 30.6 | 398 |
| Oats S1 S 30 4 1 | 116 | 18 | 7 | 57.68 | 31.9 | 205 |
| Oats S1 S 30 4 1 | 116 | 18 | 10 | 41.54 | 30.88 | |
| Oats S1 S 30 4 1 | 116 | 18 | 11 | 55 | 30.6 | 398 |
| Oats S1 S 30 7 1 | 64 | 18 | 3 | 40.55 | 20.83 | 135 |
| Oats S1 S 30 7 1 | 64 | 18 | 4 | 41.66 | 22.76 | 79 |
| Oats S1 S 30 7 1 | 64 | 18 | 6 | 69.26 | 4.28 | 3 |
| Soy S1 C 20 4 1 | 101 | 20 | 5 | 38.47 | 23.53 | 422 |
| Soy S1 C 20 4 1 | 101 | 20 | 8 | 38.18 | 23.34 | 232 |
| Soy S1 C 20 4 1 | 101 | 20 | 10 | 39.96 | 22.31 | 146 |
| Soy S1 C 20 4 1 | 101 | 20 | 13 | 40.22 | 21.15 | 80 |
| Soy S1 C 20 4 1 | 101 | 20 | 15 | 41.42 | 21.54 | 25 |
| Soy S1 C 20 4 2 | 82 | 19 | 5 | 36.49 | 20.646 | 313 |
| Soy S1 C 20 4 2 | 82 | 19 | 7 | 35.67 | 21.22 | 200 |
| Soy S1 C 20 4 2 | 82 | 19 | 10 | 35.9861 | 22.3 | 85 |
| Soy S1 C 20 4 2 | 82 | 19 | 15 | 35.816 | 27.05 | 6 |
| Soy S1 C 20 4 2 | 82 | 19 | 17 | 37 | 0 | 16 |
| Soy S1 C 20 7 1 | 58 | 21 | 5 | 28.4 | 13.76 | 130 |
| Soy S1 C 20 7 1 | 58 | 21 | 7 | 28.12 | 13.98 | 58 |
| Soy S1 C 20 7 1 | 58 | 21 | 8 | 23.34 | 10.1 | 25 |
| Soy S1 C 20 7 1 | 58 | 21 | 9 | 22.74 | 11.75 | 10 |
| Soy S1 C 20 7 1 | 58 | 21 | 10 | 50.42 | 0 | 2 |
| Soy S1 C 20 S 1 | 93 | 20 | 5 | 53.13 | 35.27 | 1082 |
| Soy S1 C 20 S 1 | 93 | 20 | 10 | 51.53 | 35.9 | 549 |
| Soy S1 C 20 S 1 | 93 | 20 | 15 | 48.57 | 33.89 | 363 |
| Soy S1 C 20 S 1 | 93 | 20 | 20 | 44.69 | 31.8 | 259 |
| Soy S1 C 20 S 1 | 93 | 20 | 25 | 38.56 | 27.04 | 156 |
| Soy S1 C 20 S 1 | 93 | 20 | 30 | 35.3 | 24.41 | 58 |
| Soy S1 C 30 4 1 | 99 | 19 | 5 | 40.48 | 23.9 | 239 |
| Soy S1 C 30 4 1 | 99 | 19 | 7 | 38.4 | 23.53 | 121 |
| Soy S1 C 30 4 1 | 99 | 19 | 10 | 27.7 | 18.39 | 13 |
| Soy S1 C 30 7 1 | 78 | 19 | | | | |
| Soy S1 C 30 7 1 | 78 | 19 | | | | |
| Soy S1 C 30 7 1 | 78 | 19 | 4 | 39.32 | 19.45 | 72 |
| Soy S1 C 30 7 1 | 78 | 19 | 5 | 43.21 | 19.2 | 27 |
| Soy S1 C 30 7 1 | 78 | 19 | 7 | 55.05 | 0.54 | 3 |
| Soy S1 C 30 S 1 | 121 | 19 | 10 | 60.22 | 35.85 | 423 |
| Soy S1 C 30 S 1 | 121 | 19 | 20 | 46.3 | 27.63 | 85 |
| Soy S1 C 30 S 1 | 121 | 19 | 25 | 32.22 | 24.95 | 18 |

**Discontinuity Method Results**

| File | Peak 1 X | Peak 1 Y | Threshold | Mean Dist | Standard Deviation | # Points |
|---|---|---|---|---|---|---|
| Soy S1 S 20 4 1 | 134 | 19 | 5 | 51.37 | 34.06 | 423 |
| Soy S1 S 20 4 1 | 134 | 19 | 10 | 52.47 | 33.81 | 153 |
| Soy S1 S 20 4 1 | 134 | 19 | 15 | 57.05 | 37.51 | 20 |
| Soy S1 S 20 4 1 | 134 | 19 | 18 | 30.5 | 26.16 | 3 |
| Soy S1 S 20 S 1 | 121 | 20 | 15 | 51.19 | 25.94 | 343 |
| Soy S1 S 20 S 1 | 121 | 20 | 20 | 47.02 | 23.28 | 233 |
| Soy S1 S 20 S 1 | 121 | 20 | 25 | 45.0156 | 22.15 | 131 |
| Soy S1 S 20 S 1 | 121 | 20 | 30 | 44.46 | 23.67 | 47 |
| Soy S1 S 30 4 1 | 69 | 20 | 5 | 29.27 | 15.17 | 136 |
| Soy S1 S 30 4 1 | 69 | 20 | 7 | 30.31 | 14.58 | 77 |
| Soy S1 S 30 4 1 | 69 | 20 | 10 | 26.45 | 11.8 | 15 |
| Soy S1 S 30 4 1 | 69 | 20 | 13 | 29.92 | 0.69 | 3 |
| Soy S1 S 30 7 1 | 65 | 20 | 3 | 27.14 | 13.19 | 87 |
| Soy S1 S 30 7 1 | 65 | 20 | 4 | 26.38 | 12.76 | 60 |
| Soy S1 S 30 7 1 | 65 | 20 | 5 | 27.34 | 15.8 | 25 |
| Soy S1 S 30 S 1 | 146 | 20 | 10 | 58.89 | 32.82 | 437 |
| Soy S1 S 30 S 1 | 146 | 20 | 15 | 59.87 | 31.04 | 222 |
| Soy S1 S 30 S 1 | 146 | 20 | 20 | 60.09 | 23.55 | 58 |
| Soy S1 S 30 S 1 | 146 | 20 | 25 | 53.83 | 19.05 | 7 |
| Soy S3 C 20 4 1 | 121 | 28 | 5 | 53.19 | 28.77 | 2059 |
| Soy S3 C 20 4 1 | 121 | 28 | 10 | 54.93 | 29.99 | 583 |
| Soy S3 C 20 4 1 | 121 | 28 | 15 | 62.84 | 30.16 | 78 |
| Soy S3 C 20 4 1 | 121 | 28 | 17 | 70.38 | 28.21 | 37 |
| Soy S3 C 20 7 1 | 72 | 28 | 5 | 34.77 | 15.9 | |
| Soy S3 C 20 7 1 | 72 | 28 | 8 | 41.837 | 15.92 | 59 |
| Soy S3 C 20 7 1 | 72 | 28 | 10 | 46.42 | 1.41 | 8 |
| Soy S3 C 20 7 1 | 72 | 28 | | | | |
| Soy S3 C 20 7 1 | 115 | 6 | 8 | 42.08 | 39.82 | 59 |
| Soy S3 C 20 7 1 | 115 | 6 | 9 | 30.42 | 40.39 | 20 |
| Soy S3 C 20 7 1 | 115 | 6 | 10 | 4.511 | 2.95 | 8 |
| Soy S3 C 20 S 1 | 123 | 27 | 10 | 76.33 | 49.33 | 3280 |
| Soy S3 C 20 S 1 | 123 | 27 | 25 | 91.96 | 54.98 | 376 |
| Soy S3 C 20 S 1 | 123 | 27 | 30 | 104.832 | 58.3663 | 127 |
| Soy S3 C 20 S 1 | 281 | 6 | | | | |
| Soy S3 C 20 S 1 | 281 | 6 | 30 | 72 | 65.07 | 127 |
| Soy S3 C 20 S 1 | 281 | 6 | 35 | 62 | 74.89 | 49 |
| Soy S3 C 20 S 1 | 281 | 6 | 40 | 23.72 | 43.41 | 25 |
| Soy S3 C 30 4 1 | 133 | 28 | 5 | 55.36 | 32.57 | 1469 |
| Soy S3 C 30 4 1 | 133 | 28 | 10 | 68.212 | 37.8 | 195 |
| Soy S3 C 30 4 1 | 133 | 28 | 12 | 82.119 | 32.6633 | 44 |
| Soy S3 C 30 4 1 | 133 | 28 | 15 | 90.74 | 18.305 | 11 |
| Soy S3 C 30 4 1 | 206 | 5 | 5 | 89.86 | 58.6 | 1469 |
| Soy S3 C 30 4 1 | 206 | 5 | 10 | 99 | 69.25 | 195 |
| Soy S3 C 30 4 1 | 206 | 5 | 12 | 101.5 | 77.73 | 44 |
| Soy S3 C 30 4 1 | 206 | 5 | 15 | 75.14 | 80.08 | 11 |

**Discontinuity Method Results**

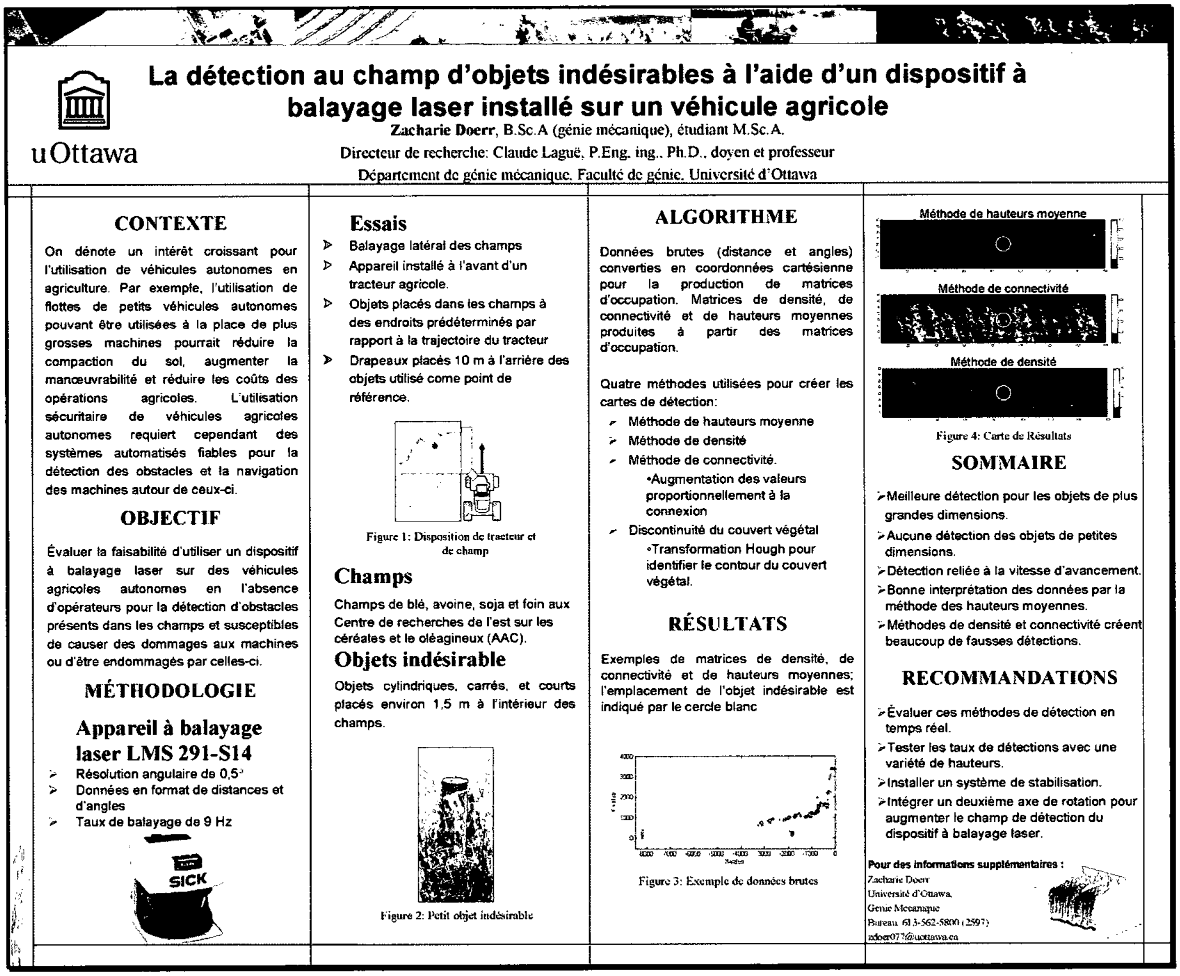
| File | Peak 1 X | Peak 1 Y | Threshold | Mean Dist | Standard Deviation | # Points |
|---|---|---|---|---|---|---|
| Soy S3 C 30 7 1 | 83 | 28 | 5 | 40.522 | 20.14 | 193 |
| Soy S3 C 30 7 1 | 83 | 28 | 6 | 43.29 | 21.86 | 73 |
| Soy S3 C 30 7 1 | 83 | 28 | 7 | 43.39 | 22.59 | 20 |
| Soy S3 C 30 7 1 | 83 | 28 | 8 | 36.47 | 14.46 | 3 |
| Soy S3 C 30 S 1 | 148 | 28 | 15 | 79.94 | 45.83 | 1121 |
| Soy S3 C 30 S 1 | 148 | 28 | 25 | 121.991 | 45.74 | 51 |
| Soy S3 C 30 S 1 | 148 | 28 | 20 | 106.405 | 78.8 | 329 |
| Soy S3 C 30 S 1 | 148 | 28 | 25 | 44.001 | 50.09 | 51 |
| Soy S3 C 30 S 1 | 148 | 28 | 30 | 12.71 | 9.61 | 14 |
| Soy S3 S 20 4 1 | 126 | 29 | 5 | 53.409 | 30.08 | 2108 |
| Soy S3 S 20 4 1 | 126 | 29 | 10 | 56.519 | 31.36 | 645 |
| Soy S3 S 20 4 1 | 126 | 29 | 15 | 62.049 | 32.57 | 102 |
| Soy S3 S 20 4 1 | 126 | 29 | 20 | 72.533 | 13.88 | 15 |
| Soy S3 S 20 4 1 | 200 | 6 | 5 | 87.279 | 56.25 | 2108 |
| Soy S3 S 20 4 1 | 200 | 6 | 10 | 85.216 | 60.062 | 645 |
| Soy S3 S 20 4 1 | 200 | 6 | 15 | 72.44 | 65.65 | 102 |
| Soy S3 S 20 4 1 | 200 | 6 | 20 | 21.93 | 37.93 | 15 |
| Soy S3 S 20 4 1 | 200 | 6 | 25 | 11.54 | 0 | 2 |
| Soy S3 S 20 7 1 | 63 | 29 | 5 | 34.31 | 14.53 | 487 |
| Soy S3 S 20 7 1 | 63 | 29 | 10 | 43.42 | 11.11 | 17 |
| Soy S3 S 20 7 1 | 63 | 29 | 12 | 46.02 | 9.2 | 10 |
| Soy S3 S 20 7 1 | 63 | 29 | | | | |
| Soy S3 S 20 7 1 | 108 | 5 | 5 | 35.55 | 27.3 | 487 |
| Soy S3 S 20 7 1 | 108 | 5 | 7 | 33.62 | 26.65 | 160 |
| Soy S3 S 20 7 1 | 108 | 5 | 10 | 10.36 | 10.89 | 17 |
| Soy S3 S 20 7 1 | 108 | 5 | 12 | 7.03 | 9.42 | 10 |
| Soy S3 S 20 S 1 | 150 | 28 | 10 | 79.57 | 47.5 | 3688 |
| Soy S3 S 20 S 1 | 150 | 28 | 20 | 84.79 | 49.22 | 1118 |
| Soy S3 S 20 S 1 | 150 | 28 | 30 | 97.45 | 50.35 | 212 |
| Soy S3 S 20 S 1 | 150 | 28 | 35 | 105.19 | 60.66 | 71 |
| Soy S3 S 20 S 1 | 304 | 6 | 10 | 125.82 | 79.69 | 3688 |
| Soy S3 S 20 S 1 | 304 | 6 | 20 | 112 | 78.15 | 1118 |
| Soy S3 S 20 S 1 | 304 | 6 | 30 | 91.73 | 75.69 | 212 |
| Soy S3 S 20 S 1 | 304 | 6 | 35 | 70.79 | 63.74 | 71 |
| Soy S3 S 30 4 1 | 143 | 28 | 5 | 58.96 | 34.91 | 1632 |
| Soy S3 S 30 4 1 | 143 | 28 | 10 | 70.33 | 38.68 | 218 |
| Soy S3 S 30 4 1 | 143 | 28 | 15 | 83.32 | 14.28 | 7 |
| Soy S3 S 30 4 1 | 218 | 5 | 5 | 92.77 | 62.7 | 1632 |
| Soy S3 S 30 4 1 | 218 | 5 | 10 | 101.467 | 72.49 | 218 |
| Soy S3 S 30 4 1 | 218 | 5 | 15 | 36.998 | 73.93 | 7 |
| Soy S3 S 30 7 1 | 74 | 28 | 5 | 36.62 | 17.02 | 171 |
| Soy S3 S 30 7 1 | 74 | 28 | 7 | 43.32 | 16.24 | 25 |
| Soy S3 S 30 7 1 | 74 | 28 | 8 | 48.86 | 3.25 | 10 |
| Soy S3 S 30 7 1 | 74 | 28 | | | | |
| Soy S3 S 30 7 1 | 118 | 5 | 5 | 46.79 | 35.1 | 171 |

**Discontinuity Method Results**

| File | Peak 1 X | Peak 1 Y | Threshold | Mean Dist | Standard Deviation | # Points |
|---|---|---|---|---|---|---|
| Soy S3 S 30 7 1 | 118 | 5 | 7 | 37.72 | 38.77 | 25 |
| Soy S3 S 30 7 1 | 118 | 5 | 8 | 21.37 | 32.99 | 10 |
| Soy S3 S 30 7 1 | 118 | 5 | | | | |
| Soy S3 S 30 S 1 | 141 | 28 | 10 | 78.65 | 46.81 | 2466 |
| Soy S3 S 30 S 1 | 141 | 28 | 20 | 90.96 | 52.97 | 310 |
| Soy S3 S 30 S 1 | 141 | 28 | 25 | 128.67 | 58.94 | 61 |
| Soy S3 S 30 S 1 | 141 | 28 | | | | |
| Soy S3 S 30 S 1 | 141 | 28 | 10 | 123.98 | 78.6 | 2466 |
| Soy S3 S 30 S 1 | 141 | 28 | 20 | 105.66 | 7.25 | 310 |
| Soy S3 S 30 S 1 | 295 | 5 | 25 | 65.125 | 58.84 | 61 |

# Appendix C. Presentations and Papers

## C.1 ACFAS 2009 Poster Presentation



uOttawa

**La détection au champ d'objets indésirables à l'aide d'un dispositif à balayage laser installé sur un véhicule agricole**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**CONTEXTE**

On dénote un intérêt croissant pour l'utilisation de véhicules autonomes en agriculture. Par exemple, l'utilisation de flottes de petits véhicules autonomes pouvant être utilisées à la place de plus grosses machines pourrait réduire la compaction du sol, augmenter la manœuvrabilité et réduire les coûts des opérations agricoles. L'utilisation sécuritaire de véhicules agricoles autonomes requiert cependant des systèmes automatisés fiables pour la détection des obstacles et la navigation des machines autour de ceux-ci.

**OBJECTIF**

Évaluer la faisabilité d'utiliser un dispositif à balayage laser sur des véhicules agricoles autonomes en l'absence d'opérateurs pour la détection d'obstacles présents dans les champs et susceptibles de causer des dommages aux machines ou d'être endommagés par celles-ci.

**MÉTHODOLOGIE**

**Appareil à balayage laser LMS 291-S14**

- Résolution angulaire de 0,5°
- Données en format de distances et d'angles
- Taux de balayage de 9 Hz

SICK

**Essais**

- Balayage latéral des champs
- Appareil installé à l'avant d'un tracteur agricole.
- Objets placés dans les champs à des endroits prédéterminés par rapport à la trajectoire du tracteur
- Drapeaux placés 10 m à l'arrière des objets utilisé come point de référence.

Figure 1: Disposition de tracteur et de champ

**Champs**

Champs de blé, avoine, soja et foin aux Centre de recherches de l'est sur les céréales et le oléagineux (AAC).

**Objets indésirable**

Objets cylindriques, carrés, et courts placés environ 1,5 m à l'intérieur des champs.

Figure 2: Petit objet indésirable

**ALGORITHME**

Données brutes (distance et angles) converties en coordonnées cartésienne pour la production de matrices d'occupation. Matrices de densité, de connectivité et de hauteurs moyennes produites à partir des matrices d'occupation.

Quatre méthodes utilisées pour créer les cartes de détection:

- Méthode de hauteurs moyenne
- Méthode de densité
- Méthode de connectivité.
  - Augmentation des valeurs proportionnellement à la connexion
- Discontinuité du couvert végétal
  - Transformation Hough pour identifier le contour du couvert végétal.

**RÉSULTATS**

Exemples de matrices de densité, de connectivité et de hauteurs moyennes; l'emplacement de l'objet indésirable est indiqué par le cercle blanc

Figure 3: Exemple de données brutes

Méthode de hauteurs moyenne
Méthode de connectivité
Méthode de densité

Figure 4: Carte de Résultats

**SOMMAIRE**

- Meilleure détection pour les objets de plus grandes dimensions.
- Aucune détection des objets de petites dimensions.
- Détection reliée à la vitesse d'avancement.
- Bonne interprétation des données par la méthode des hauteurs moyennes.
- Méthodes de densité et connectivité créent beaucoup de fausses détections.

**RECOMMANDATIONS**

- Évaluer ces méthodes de détection en temps réel.
- Tester les taux de détections avec une variété de hauteurs.
- Installer un système de stabilisation.
- Intégrer un deuxième axe de rotation pour augmenter le champ de détection du dispositif à balayage laser.


**Pour des informations supplémentaires :**
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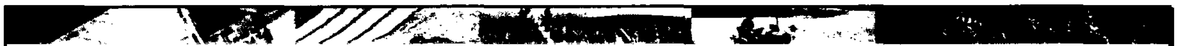
## C.2 Faculty of Engineering Research Day Poster Presentation



uOttawa

# Detecting Foreign Objects in Crops Using Laser Range Scanners Mounted On Agricultural Vehicles

By: Zacharie Doerr, B.A.Sc Mechanical Engineering
Supervisor: Dr. Claude Laguë, P.Eng., Ing

## ABSTRACT

The general objective of this work is to evaluate the effectiveness of a Laser Measurement Systems (LMS), mounted on an agricultural vehicle, at detecting foreign objects in standing crops.

## BACKGROUND

With increased labour costs, smaller vehicles with higher manoeuvrability, and less soil compaction, N.B Power and M.B Boyette[1] have found that the goal for many agricultural developers is to have multiple vehicles with humans in a supervisory position.

With safety concerns as the next logical step in the development of autonomous agricultural vehicles, obstacle detection & avoidance problems need to be addressed. Implementation of safety controls & obstacle detection and avoidance are a must.

## OBJECTIVE

The end purpose of the system will be to detect *any object or element that may cause damage to* the agricultural equipment or the objects itself while using a fully autonomous tractor system.

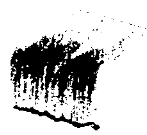


Figure 1: Range data in 3D format

## METHODS

### LMS 291-S14


- 0.5° Angular resolution
- Scanner returns Range Data
- Scan rate of 9 Hz

### Field Testing

- Scanning crops along side of fields
- Objects are placed within crop at a measured distance from test track
- Flag markers placed 10m behind test objects

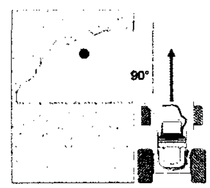



Figure 2: Tractor and field layout

### Crops

Wheat, Hay, Soy, and Oat crops at the Eastern Cereal and Oilseed Research Centre (ECORC)

### Test Objects

Square, Cylindrical, & Short Posts placed within the crops at approx 1.5m from the test track

## RESULTS

Each planar scan is converted from polar coordinates to Cartesian coordinates. From this, Density, Occupancy and Avg. Height matrices are created.

Currently comparing 3 field mapping and object detections methods

- Occupancy, density, & group size probability matrix
- Height averaging matrix
- Crop line discontinuity analysis using the Hough transform

Figure 3: 2D Mapping

## CONCLUSION

The end goal of the research is to create and evaluate the feasibility of using this type of LMS for future autonomous agricultural vehicles. This system, with the conjunction of other safety systems, may be useful for ensuring safe field operation of autonomous vehicles.

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## *C.3 ASABE Conference Paper*

The following document, "*Evaluating the Ability to Detect Foreign Objects in Crops Using Laser Range Scanners Mounted On Agricultural Vehicles*", was presented at the 2009 ASABE Annual International Meeting at the Grand Sierra Resort and Casino, Reno, Nevada, June21-24$^{th}$, 2009. Paper # 095878

# Appendix D. Programs

## D.1 Average Height Program

```
function [ map ] = Height_scan( file_name,theta,velocity )
%HEIGHT_SCAN Summary of this function goes here
% 2DANALYSIS Summary of this function goes here
% Detailed explanation goes here
% Data file has no units removed and follows the format provided

%% Input Data

distperscan=velocity*5/18/9*1000;                %% in mm
Height = 1170;                                   %% Height of scanner [mm]
scan_filter = 1;                                 %% use every # of scans
xmax = 8000;         xmin = 0;
grid = 100;
threshold = 0;
distribution_xlimit=160; distribution_ylimit=40;
real_time(1)=0;
real_time(2)=0;
%close all;

tic
%% Header Data Line 1
% Filename;StartAngle[°];StopAngle[°];Resolution[°*100];ScanStepWidth;...
%...ExportChannelNumber;Date[mm/dd/yyyy];Time[hh:mm:ss]
%% Header Data Line 2
% Actual Header Data

%% Data = [ Record Number;Scan Index;Telegram Index;Interlaced Scan
Number;Begin Data(45°-->135°)]
%         [   1,                2,               3,               4,
5,...]

%% Import all scans

M = dlmread(file_name, ';',3,0);
data=M;
data(:, 2) = [];                                 %% Deleting Row 2
data(:, 2) = [];                                 %% Deleting Row 3
data(:, 2) = [];                                 %% Deleting Row 4
scan_number = max(data(:,1));                    %% number of scans
data(:, 1) = [];                                 %% Deleting Scan number


%% Convert to Cartesian
c=1;
for i=90:0.5:180                                 %% Preparing RHO matrix
    THETA(1,c)=i*pi/180;
    c=c+1;
end
var=0;
for s=1:1:scan_number

    %% [x-value, y-value, scan number]
    [cart_data(:,1,s) , cart_data(:,2,s)] = pol2cart(THETA,data(s,:));
    var=var+1;
end
scan_number = var;                                %% new scan_number
```

```
%% Visualize in 2D
%% range Data 2D


for s=1:1:scan_number

    occupancy=zeros(90,90);                         %% Initial Occupancy grid
    occupancy_density=occupancy;

    for i=1:1:181

       %%% First Occupancy Grid with Value = # of points in 10cm grids %%%

        %% xvalue in 10cm sections for occupancy matrix address
        xvalue = -round(cart_data(i,1,s)/grid)+1;
        %% yvalue in 10cm sections for occupancy matrix address
        yvalue =  round(cart_data(i,2,s)/distperscan)+1;
        zvalue = Height-cart_data(i,2,s)*sind((20));

       %%% Side clipping if wanted %%%
        %% Framing xvalues //Clipping xvalues
        if (xvalue < xmax/distperscan    && xvalue > xmin/distperscan)
            occupancy(xvalue,yvalue)=zvalue;        %% Occupancy Matrix
        end
    end

 occupancy;

%% density matrix values X connectivity matrix values

    probability_matrix=occupancy;

%% Creation of map
if s==1;
    map=probability_matrix;
else
    map(1:80,s+80)=zeros(80,1);
    map(1:80,s:s+79)=(map(1:80,s:s+79)+probability_matrix(1:80,1:80))/2;
    map(:,s+79)=probability_matrix(:,80);
end

%% Visuals

end
prog_time(:,2)=0;
real_time(:,1)=0;

%% Map analysis
map_mean = mean(mean(map))
map_std = std(std(map))
[m,n] = size(map);
max1(1)=threshold;
max1(2)=0; max1(3)=0;
max2(1)=threshold;
max2(2)=0; max2(3)=0;
for s=1:1:n
    for r=1:1:m
        if map(r,s)<threshold
            map(r,s)=0;

        end
```

```
    end
end
toc
scan_number
toc/scan_number
end
```

## D.2 Density Method Program

```
function [ map ] = occupancy_density( file_name, theta, velocity, threshold )
% [output] = occupancy_density(input)
% Density matrix of LMS Scan
% Data file has no units removed and follows the format provided
% by the .csv file created by MST software

%% Input Data
distperscan=velocity*5/18/9*1000;                       %% in mm
Height = 1170;                                          %% LMS Height [mm]
xmax = 8000;        xmin = 0;
grid = 100;
distribution_xlimit=160;
real_time(1)=0;
real_time(2)=0;

tic
%% Header Data Line 1
% Filename;StartAngle[°];StopAngle[°];Resolution[°*100];ScanStepWidth;...
...ExportChannelNumber;Date[mm/dd/yyyy];Time[hh:mm:ss]
%% Header Data Line 2
% Actual Header Data

%% Import all scans

M = dlmread(file_name, ';',3,0);
data=M;
data(:, 2) = [];                                        %% Deleting Row 2
data(:, 2) = [];                                        %% Deleting Row 3
data(:, 2) = [];                                        %% Deleting Row 4
scan_number = max(data(:,1));                           %% number of scans
data(:, 1) = [];                                        %% Deleting Scan #


%% Convert to Cartesian
c=1;
for i=90:0.5:180                                    %% Preparing RHO matrix
    THETA(1,c)=i*pi/180;
    c=c+1;
end
var=0;

for s=1:1:scan_number                   %% [x-value, y-value, scan number]
    [cart_data(:,1,s) , cart_data(:,2,s)] = pol2cart(THETA,data(s,:));
    var=var+1;
end
scan_number = var;                                      %% new scan_number

%% Visualize in 2D
%% range Data 2D

for s=1:1:scan_number

    occupancy=zeros(90,90);                 %% Initialize Occupancy grid
    occupancy_density=occupancy;            %% Ininitalize Density grid

    for i=1:1:181

        %%% First Occupancy Grid with Value = # of points in 10cm grids %%%

        %% xvalue in 10cm sections for occupancy matrix address
```

```
        xvalue = -round(cart_data(i,1,s)/grid)+1;

        %% yvalue in 10cm sections for occupancy matrix address
        yvalue =  round(cart_data(i,2,s)/distperscan)+1;

        %%% Side clipping if wanted %%%
        if (xvalue < xmax/distperscan    && xvalue > xmin/distperscan)
            %% Density Matrix

occupancy_density(xvalue,yvalue)=occupancy_density(xvalue,yvalue)+1;
        end

    end

%% density matrix values == probability matrix

    probability_matrix=occupancy_density;

%% Creation of map
if s==1;
    map=probability_matrix;
else
    map(1:80,s+80)=zeros(80,1);
    map(1:80,s:s+79)=map(1:80,s:s+79)+probability_matrix(1:80,1:80);
    map(:,s+79)=probability_matrix(:,80);
end

end

%% Map analysis
map_mean = mean(mean(map));
[m,n] = size(map);

%% if threshold is used eliminating values < threshold
max1(1)=threshold;
max1(2)=0; max1(3)=0;
max2(1)=threshold;
max2(2)=0; max2(3)=0;

for s=1:1:n
    for r=1:1:m
        if map(r,s)<threshold
            map(r,s)=0;
        elseif (map(r,s)>max2(1)) && (map(r,s)>max1(1))
            max2=max1(:);
            max1(1)=map(r,s);
            max1(2)=r;
            max1(3)=s;
        elseif (map(r,s)>max2(1)) && (map(r,s)<max1(1))
            max2(1)=map(r,s);
            max2(2)=r;
            max2(3)=s;
        end
    end
end

toc
scan_number

end
```

### D.3 Connectivity Program

```
function [ output_args ] = one_occupancy_matrix( input_args )
% [output] = convertMST(input)
% Connectivity analysis of Range Data
% Using 8-connectivity, cell values are related to size of connection
% between adjacent cells
% Data file has no units removed and follows the format provided
% by the .csv file created by MST software

%% Input Data
%user_entry = input('Range Data File name: ','s');           %% Input
File Name
%file_name = user_entry;


for trial=1:1:3
    if trial ==1;
file_name = 'C:\Documents and Settings\lague\Desktop\Thesis\Field
Data\Hay\H_S1_S_20_7_3.txt';
    end
    if trial ==2;
file_name = 'C:\Documents and Settings\lague\Desktop\Thesis\Field
Data\Oats\O_S1_L_30_4_2.txt';
    end
    if trial ==3;
file_name = 'C:\Documents and Settings\lague\Desktop\Thesis\Field
Data\Hay\H_S1_S_20_7_3.txt';
    end
velocity = 7;

theta = 20;
distperscan=velocity*5/18/9*1000;                          %% in mm
Height = 1170;                                                  %% Height
of scanner [mm]
scan_filter = 1;                                                 %% use
every # of scans
clipping = 0;                              %% =1 if Yes =0 if No,
gclearance in [mm]
xmax = 8000;        xmin = 0;
grid = 100;
threshold = 0;
visualization=0;
distribution_xlimit=150;
real_time(1)=0;
real_time(2)=0;
close all;

tic

%% Import all scans

M = dlmread(file_name, ';',3,0);
data=M;
data(:, 2) = [];                        %% Deleting 2,3,4th columns
data(:, 2) = [];
```

```
data(:, 2) = [];
scan_number = max(data(:,1));              %% number of scans in file
data(:, 1) = [];                           %% Deleting Scan number

%% Convert to Cartesian
c=1;
for i=90:0.5:180                            %% Preparing RHO matrix
    THETA(1,c)=i*pi/180;
    c=c+1;
end
var=0;
    %% Reducing number of scans used with "scan_filter"
for s=1:scan_filter:scan_number
    %% [x-value, y-value, scan number]
    [cart_data(:,1,s) , cart_data(:,2,s)] = pol2cart(THETA,data(s,:));
    var=var+1;
end
scan_number = var;                            %% new scan_number

%% Visualize in 2D
%% range Data 2D

for s=1:1:scan_number

    occupancy=zeros(90,120);          %% Initialize size of Occupancy
grid
    occupancy_density=occupancy;

    for i=1:1:181

       %%%% First Occupancy Grid with Value = # of points in 10cm grids
%%%

        %% xvalue in 10cm sections for occupancy matrix address
        xvalue = -round(cart_data(i,1,s)/grid)+1;
        %% yvalue in 10cm sections for occupancy matrix address
        yvalue =  round(cart_data(i,2,s)/distperscan)+1;

       %%%%%%%%%%%%%%%%% Side clipping %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

       %% Framing xvalues //Clipping xvalues
        if (xvalue < xmax/distperscan    && xvalue > xmin/distperscan)
            %% Density Matrix

occupancy_density(xvalue,yvalue)=occupancy(xvalue,yvalue)+1;
            %% Occupancy Matrix
            occupancy(xvalue,yvalue)=1;
        end


    end

%% Connectivity Matrix, Cell values represent size of connected block
    occupancy;
```

```
    label=[1,0];                          %% declair label matrix
    occupancy = bwlabeln(occupancy);  %% Labels connected components 1
to n

    %% Makes list with name and size of connected groups
    for k=1:1:80
        for p=1:1:80
            if occupancy(k,p)~=0
                group_id = occupancy(k,p);
                label(group_id,1)=group_id;
                label(group_id,2)=label(group_id,2)+1;
            end
        end
    end
 label;

    %% Makes cell value size of block
    for k=1:1:80
        for p=1:1:80
            if occupancy(k,p)~=0
                occupancy(k,p) = label(occupancy(k,p),2) ;
            end
        end
    end
 occupancy;

%% density matrix values X connectivity matrix values

    probability_matrix=occupancy_density.*occupancy;

%% Creation of map
if s==1;
    map=probability_matrix;
else
    map(1:80,s+80)=zeros(80,1);

map(1:80,s:s+79)=(map(1:80,s:s+79)+probability_matrix(1:80,1:80))/2;
    map(:,s+79)=probability_matrix(:,80);
end

%% Visuals
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% Visualize in 2D Range Data
 if visualization ==1;
    subplot(3,2,1)
    plot(cart_data(:,1,s),cart_data(:,2,s),'x')
    axis([-8500 0 -500 4000])
    title('Range Data','fontsize',12)
    xlabel('X-value')
    ylabel('Y-value')

    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% Occupancy Grid Visual
    subplot(3,2,2)
    %pcolor(occupancy_density')
    %contourf(occupancy')
```

```
    title('Density')
    %xlabel('Scan number')
    %ylabel('Pts out of range & Outliers')
    %legend('# Out of Range)','# outliers')


    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%  Size of groups
    subplot(3,2,3)
    %pcolor(occupancy')
    %contourf(probability_matrix')
    %bwareaopen(occupancy2',2,8)
    title('Connected Groups')
    %axis([-8000 0 -500 4000])
    %xlabel('X mean value')
    %ylabel('Y mean & Std Dev value')


    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%  Probability Matrix
    subplot(3,2,4)
    pcolor(probability_matrix')
    %contourf(probability_matrix')
    %bwareaopen(occupancy2',2,8)
    title('Probability Matrix(density,connectivity)')
    %axis([-8000 0 -500 4000])
    %xlabel('X mean value')
    %ylabel('Y mean & Std Dev value')

    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%  Probability Matrix
    subplot(3,2,6)
    %pcolor(probability_matrix_2')
    %contourf(probability_matrix')
    %bwareaopen(occupancy2',2,8)
    %title('Final Probability Matrix')
    %axis([-8000 0 -500 4000])
    %xlabel('X mean value')
    %ylabel('Y mean & Std Dev value')

    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% Time Data
    prog_time(s,1)=s;
    if s==1;
        prog_time(s,2)=toc;
    else
    prog_time(s,2)=toc;
    end
    real_time(s,1)=s;
    real_time(s,2)=s/9;

    subplot(3,2,5)

plot(real_time(:,1),real_time(:,2),prog_time(:,1),prog_time(:,2),s,scan
_number)
    xlabel('scan #')
    ylabel('Time')
    axis([0 scan_number 0 70])
    legend('Real Time','Program Time')
```

```
    %pause();
    pause(1/(3*9))

end
end
%% Map analysis
map_mean = mean(mean(map));
[m,n] = size(map);
max1(1)=threshold;
max1(2)=0; max1(3)=0;
max2(1)=threshold;
max2(2)=0; max2(3)=0;
for s=1:1:n
    for r=1:1:m
        if map(r,s)<threshold
            map(r,s)=0;
        elseif (map(r,s)>max2(1)) && (map(r,s)>max1(1))
            max2=max1(:);
            max1(1)=map(r,s);
            max1(2)=r;
            max1(3)=s;
        elseif (map(r,s)>max2(1)) && (map(r,s)<max1(1))
            max2(1)=map(r,s);
            max2(2)=r;
            max2(3)=s;
        end

    end
end

%% X-axis distribution analysis
distribution = sum(map);
(mean(distribution)+std(distribution));
avg=mean(distribution);
uplimit=std(distribution);

i=1;
while i<=scan_number
    sector(i)=0;
        if distribution(i)>(avg+uplimit)
            sector(ceil(i/25))=sector(ceil(i/25))+1;
        end
i=i+1;
end

%%
    if trial ==1;
map1 = map;
distribution1= distribution;
maps_sectors1=sector;
'map1';
scan_number1=scan_number;
    end
    if trial ==2;
map2 = map;
distribution2= distribution;
```

```
maps_sectors2=sector;
'map2';
scan_number2=scan_number;
    end
    if trial ==3;
map3 = map;
distribution3= distribution;
maps_sectors3=sector;
'map3';
scan_number3=scan_number;
    end
%%
end %% end of trial loop

figure
%    if trial ==1;
    subplot(3,1,1)
        contourf(map1)
        xlim([1 distribution_xlimit]);
        ylim([1 40]);
%    end
%    if trial ==2;
    subplot(3,1,2)
        contourf(map2)
        xlim([1 distribution_xlimit]);
        ylim([1 40]);
%    end
%    if trial ==3;
    subplot(3,1,3)
        contourf(map3)
        xlim([1 distribution_xlimit]);
        ylim([1 40]);
%    end

    max1
    max2

distperscan
file_name
mean_x_start=20;
mean(mean(map1(1:30,20:scan_number1)))
mean(mean(map2(1:30,20:scan_number2)))
mean(mean(map3(1:30,20:scan_number3)))
end
```

## D.4 Crop Discontinuity Program

```
function [ disc_global,avg_dist,std_dist,dis_count ] = Hough_transform2(
file_name, velocity, threshold, object_x, object_y )
% Hough Transform and line discontinuity
% Data file has no units removed and follows the format provided
% by the .csv file created by MST software

%% Input Data
object_x;
object_y;
distperscan=velocity*5/18/9*1000                       %% in mm
Height = 1170;                                         %% LMS Height [mm]
scan_filter = 1;                                       %% use every # of scans
grid = 100;
%threshold = 5;           %% allowable cells of difference between points
clipping_x = 0;
visualization=0;
distribution_xlimit=200;
discons=1;
dis_count=1;
x=0;
h=waitbar(x,'Updating Discontinuity from File')

tic
%% Header Data Line 1
% Filename;StartAngle[°];StopAngle[°];Resolution[°*100];ScanStepWidth;...
...ExportChannelNumber;Date[mm/dd/yyyy];Time[hh:mm:ss]
%% Header Data Line 2
% Actual Header Data

%% Import all scans

M = dlmread(file_name, ';',3,0);
data=M;
data(:, 2) = [];                                               %% Delete Row 2
data(:, 2) = [];                                               %% Delete Row 3
data(:, 2) = [];                                               %% Delete Row 4
scan_number = max(data(:,1));                                  %% scan #
data(:, 1) = [];                                               %% Delete scan#

%% Convert to Cartesian
c=1;
for i=90:0.5:180                                       %% Preparing RHO matrix
    THETA(1,c)=i*pi/180;
    c=c+1;
end
var=0;
for s=1:1:scan_number                  %% [x-value, y-value, scan number]
    [cart_data(:,1,s) , cart_data(:,2,s)] = pol2cart(THETA,data(s,:));
    var=var+1;

    %% Initialize size of Occupancy grid
    occupancy=zeros(80,160);

    for i=1:1:181

       %%% First Occupancy Grid with Value = # of points in 10cm grids %%%

       %% xvalue in 10cm sections for occupancy matrix address
        xvalue = -round(cart_data(i,1,s)/grid)+1;

        %% yvalue in 10cm sections for occupancy matrix address
```

```
        yvalue =  round(cart_data(i,2,s)/distperscan)+1;

        %% Occupancy Matrix
        occupancy(xvalue,yvalue)=1;

    end
    occupancy=occupancy';

secsize=3;
sections=floor(80/secsize);
counter=1;
%% Section analysis for each scan

    for k = 1:1:sections

        section=occupancy(:,1+secsize*(k-1):secsize*k);
        empty = sum(sum(section));

        %% if matrix requires at least 3 occupied cells in the section
        if empty >=3
            BW=section;

            %% Compute the Hough transform of the image using the hough
function.
            [H,theta,rho] = hough(BW);

            %%%%% Find the Peak of the hough transform
            P = houghpeaks(H,1);
            %%%%% Find the lines in the image
            lines = houghlines(BW,theta,rho,P,'FillGap',50,'MinLength',1);

            xy(2*counter-1,:) = [lines(1).point1];
            xy(2*counter,:)=[ lines(1).point2];

            xy(2*counter-1,1)=xy(2*counter-1,1)+k*secsize;
            xy(2*counter,1)=xy(2*counter,1)+k*secsize;

        else
            counter=counter-1;
        end
        counter=counter+1;

    end
    var1=size(xy,1);

%% Locating discontinuity
    for k=2:1:var1
        if abs(xy(k,2)-xy(k-1,2))>threshold && xy(k,1)>clipping_x

            disc_global(dis_count,1)=s+min(xy(k,2),xy(k-1,2));
            disc_global(dis_count,2)=(xy(k,1)+xy(k-1,2))/2;

Discontinuity_location=[disc_global(dis_count,1),disc_global(dis_count,2)];
            object_location=[object_x,object_y];

            [Discontinuity_location;object_location];
            distance = pdist([Discontinuity_location;object_location]);
            disc_global(dis_count,3)=distance;

            dis_count=dis_count+1;
            var3=1;

        end
```

```
    end

%% Create a plot that superimposes the lines on the original image.
 %{
if visualization ==1;

        subplot(3,2,3:4)
        plot(xy(:,1),xy(:,2),'LineWidth',2,'Color','blue')
        xlim([0 85])
        ylim([-1 40])

%% Visuals
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% Visualize in 2D Range Data
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% Time Data
    prog_time(s,1)=s;
    if s==1;
        prog_time(s,2)=toc;
    else
    prog_time(s,2)=toc;
    end
    real_time(s,1)=s;
    real_time(s,2)=s/9;

    subplot(3,2,2)

plot(real_time(:,1),real_time(:,2),prog_time(:,1),prog_time(:,2),s,scan_number)
    xlabel('scan #')
    ylabel('Time')
    axis([0 scan_number 0 70])
    legend('Real Time','Program Time')

    %Plot Discon's locations

    if var3==1;
    subplot(3,2,5:6)
        plot(disc_global(:,1),disc_global(:,2),'xr','MarkerSize',12)
        xlim([0 scan_number])
    end

    %pause();
    %pause(1/(3*9))
end
    %}
    x = s/scan_number;
    waitbar(x)

end
    close(h)
%disc_global;
avg_dist=mean(disc_global(:,3));
std_dist=std(disc_global(:,3));
toc
scan_number
end
```