COMBINE YIELD MONITOR TEST FACILITY DEVELOPMENT AND INITIAL MONITORING TEST

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ABSTRACT: The Yield Monitor Test Facility’s performance under static grain flow was very good. First, the grain metering system accurately meters grain at varying flow rates to the clean grain elevator over the prescribed time interval. Second, the weigh scale system appears to be very accurate in measuring the accumulated mass flow in the system. However, grain stream dynamics, tank vibration, and load cell sensitivity confounds attempts to measure instantaneous grain flow at low rates of 1 to 4 kg/s. Third, the commercially available yield monitor flow sensor demonstrated excellent accuracy across a wide range of static flow rates from 1.3 to 21.1 kg/s. Percent differences in accumulated mass flow for the yield monitor and the weigh scale were less than 1% at calibration flow rates and approximately 3% for extreme flow rates. Instantaneous mass flow rate variation was observed to be approximately 8% at the mean calibration flow rate.

Keywords. Precision farming, Yield monitor, Test rigs, Site–specific crop management, Combine harvester.

Yield monitor accuracy has been the focus of numerous field investigations over the last several years. Accurate crop yield data must be obtained so that producers can make informed crop production decisions. Several researchers have documented significant spatial variation in crop yield within a given field (Stafford et al., 1991; Yang et al., 1998). Sources of spatial yield variation have been attributed to soil type, nutrient availability, slope, elevation, aspect, moisture availability, and cropping history. Significant errors in crop yield prediction can adversely affect any attempts to manage nutrient availability, slope, elevation, aspect, moisture availability, and cropping history. Significant errors in crop yield prediction can adversely affect any attempts to manage

LITERATURE REVIEW
Shearer et al. (1997) conducted a study in which four combines (two John Deere 9500’s, a Gleaner R70, and a Case IH 1680) were used to harvest wheat within the same field. Each combine was equipped with a yield monitor, the John Deere combines used GreenStar® and the other combines used the Ag Leader 2000. The data from each combine was imported into a popular mapping package to compare the yield estimates. They found that significant differences in measured yield existed between adjacent harvest swathes. These differences were attributed to potential machine/operator variability. In response to these differences, data filtering techniques were developed to help minimize the influence of calibration and machine/operator differences. It was concluded that machine calibration techniques were critical in multiple–combine harvest systems. Strubbe et al. (1996) agreed by stating, “Our investigations show that the accuracy of yield estimates depends greatly on the variability of the harvesting conditions, on the total field area in one grid, and on the range of operating conditions over which a sensor is calibrated.”

Thylen and Murphy (1996) conducted a study of the key factors that cause errors in momentary yield data. They identified five key sources of error. The errors were associated with low yields at the start of a harvest swath, interruptions in crop intake, sudden changes in forward speed, failure to use full cutting width, and the time delay for grain to travel from the cutter bar to the yield sensor. Data filters were evaluated which removed these sources of error. They concluded that removal of data at the start of a harvest swath improves data quality as measured by geostatistical analysis, and that filtered mean instantaneous yield is similar to the mean yield calculated from total grain mass and the harvested area.

In a study conducted by Kettle and Peterson (1998), it was observed that the accuracies of combine yield monitors were significantly affected by hillside conditions and variation in harvest rates. Tests were conducted on two John Deere combines equipped with Greenstar® in the hilly Palouse region of northern Idaho. It was observed that the yield monitor’s response to variation in inflow was exponential rather than linear and suggested that calibration should have been done at several operating points rather than the traditional two–point method. The observed yield monitor...
error was 20.3% when operating the combine at one–third the calibration throughput and 5.7% at half the calibration throughput. They also found that the errors in yield monitor estimates were as high as 18.2% when harvesting uphill and 60.7% when harvesting downhill, on 6 to 9% slopes. Finally, they found a very weak correlation between the yield monitor estimates and hand samples ($R^2 = 0.203$) indicating that the yield monitor is not sensitive to local variation in crop yield.

Arslan and Colvin (1998) reported the development of a test stand for combine grain yield monitors. They constructed a facility to compare the accuracy of a yield monitor to an electronic scale. They found strong correlations between the measured flow in the yield monitor and the electronic scale ($R^2 = 0.99$). They observed stronger agreement when testing at higher flow rates over longer durations.

A test facility has been developed by Kormann et al. (1998) to test multiple clean grain elevator yield monitors simultaneously. A system was built using a Massey Ferguson 38/40 elevator with three reference yield systems installed, the RDS Ceres II (RDS Technology Ltd, Gloucestershire, England) volumetric meter, and the MF Flow–Control and the Ag Leader 2000 mass flow sensors. A second elevator was placed in series with the first elevator and was equipped with the CLAAS Quantimeter II (CLAAS, Harsewinkel, Germany). It should be noted that this system did not use the clean grain elevator fountain auger on either of the elevators. The system was designed so that the elevators could be tilted up to 15° forward or aft with the potential for a simultaneous tilt of 15° to port or starboard. In addition, provision was made to vary mass flow rate from 1 to 35 t/h. They conducted tests varying the inflow rate from 10 to 35 t/h and found mean calibration errors less than 3%. Only at the lowest level did they experience errors of up to 7%. The volumetric sensors tended to perform better under low flow conditions than the mass flow sensors. A second set of tests was conducted by varying the tilt of the elevator system. They found mean errors up to 6% with standard deviations of up to 6%. The radiometric MF Flow–Control device performed the best of all sensors with mean errors less than 2%. Meanwhile the other sensors performed as follows from most to least accurate: CLAAS Quantimeter II (<3%), Ag Leader 2000 (<4%), and RDS Ceres II (<6%).

The ASAE Precision Farming Committee PM–54/01 has been developing a standard for testing yield monitors (Proposed ASAE Standard, Pending). The proposed standard (X578) describes several key design requirements for yield monitor facilities; discusses methods for selecting grain samples; suggests calibration techniques for the yield monitor being tested; describes different grain flow regimes for testing the yield monitor; and outlines procedures for reporting the results of the yield monitor performance test. The proposed standard represents the collective understanding of numerous scientists in precision agriculture research, and thus provides valuable insight into the performance requirements of yield monitor sensing and evaluation.

### FACILITY AND RESEARCH OBJECTIVES

The objectives for the Yield Monitor Test Facility development were:

1. To develop a material handling and weigh tank system capable of storing 17.5 m$^3$ (500 bu) of grain

### COMPONENT AND SYSTEM DESIGN

#### CONCEPTUAL DESIGN

The proposed ASAE X578 Yield Monitor Performance Test Standard played a major role in the design and development of the yield monitor test facility. The proposed standard helped define the performance criteria, while the laboratory facilities established the physical constraints. Several key features guided the development of the yield monitor test facility. First, the test facility should accommodate approximately 17–m$^3$ grain in batch storage and be housed in a laboratory. The system needed to be able to transfer grain from a supply tank to the clean grain elevator and then on to a receiving tank that was equipped with weigh scales. The grain must be re–circulated to the supply tank for further test runs. One of the design criteria for the facility was to dynamically change the elevator inflow rates. The flow rate design range was established at approximately 2 to 160 m$^3$/h for dry grain with a reasonable limit of 95 m$^3$/h for high moisture grain. This wide flow regime is in response to studies by Kormann et al. (1998) where errors up to 7% were observed in force impetus yield monitors under low inflow conditions of 10 t/h. Finally, as reported in the works of Kettle and Peterson (1998), yield monitor performance for hillside operations has been identified as a source of up to 60% yield error when combining downhill on a 6 to 9% slope. As a result, the test facility was designed to accommodate up to 21% slopes (12°) in the forward, aft, port, and starboard directions as well as a combination.
GRAIN HANDLING SYSTEM

The system plan view is shown in figure 1, while a photographic image of the clean grain elevator and material handling system is shown in figure 2. The system consists of a 2.8–m diameter supply tank that stores the grain prior to each test. A receiving tank is supported on a rectangular frame that has a 4500–kg load cell at each corner. A 30–cm supply auger (2.2–kW AC variable speed motor drive) transports grain from the supply tank to the volumetric grain metering device. The meter has a surge hopper and two variable speed flow control turrets. The supply elevator operates at a constant speed of approximately 400 rpm using a 5.6–kW AC motor and is capable of capacities of up to 159 m$^3$/h.

The clean grain elevator is powered by a variable speed 15-kW hydraulic motor (White Hydraulics, Hopkinsville, Ky.). The speed of the hydraulic motor is approximately 400 rpm and is controlled by a laboratory hydraulic test bench. Grain flows through the clean grain elevator and discharges from the top of the fountain auger into a suspended catch hopper. The hopper discharges grain into a 190–rpm 30-cm diameter U–trough, which moves the grain to a discharge point above the grain pump. The 25–cm diameter grain pump (Hutchinson–Mayrath, Clay Center, Kans.) is capable of flow rates up 211 m$^3$/h of dry grain at chain speeds of 100 m/s. The grain pump elevates and discharges the grain into the receiving tank where weight data is sampled once per second.

GRAIN METERING

The grain–metering device consists of a surge hopper and two flow control turrets (fig. 3). The grain meter surge bin is capable of holding up 1 m$^3$ of grain. The first turret is approximately 46 cm long (M1), supplies between 1.8 and 15.9 m$^3$/h, and is powered by a 0.75–kW AC–variable speed drive. The second turret is 91 cm long (M2), powered by a 1.5-kW AC variable speed drive and supplies between 15.9 and 159 m$^3$/h. Each drive system consists of a 1750–rpm motor, a direct coupled 90° gear reducer, and a chain and sprocket drive linkage to provide the final speed reduction. M1 runs at approximately 7 rpm to give 15.9 m$^3$/h and M2 runs at approximately 36 rpm to give 159 m$^3$/h. Meter turret speed is controlled by an Allen–Bradley (Rockwell Automation, Milwaukee, Wis.) AC variable speed drive by a 0 to 10-V speed reference signal from the Allen–Bradley SLC–500 programmable controller. The variable speed drive is capable of a 10:1 speed reduction as the motor frequency is varied from 60 to 6 Hz, with constant torque throughout the speed range.

Grain level is maintained in the hopper between high and low level using 18–mm capacitive proximity switches (Carlo Gavazzi, Steinhausen, Switzerland) located above the turret inlet (low level) and the hopper eave (high level). Turret shaft speed is measured using a 12–mm inductive proximity switch.
(Altech Corp, Flemington, N.J.) with two magnetic pick ups on the drive shaft coupler located 180° apart. Each revolution of the turret motor shaft generates two 24–V DC pulses. This pulse train is conditioned by an optical isolator and a de–bouncing circuit to provide a clean TTL signal. The shaft speed is measured using a Keithley CTM05 (Keithley, Cleveland, Ohio) counter card that runs in the background on the system computer. The shaft speed is used to confirm the volumetric delivery of grain from the meter. Meter flow is calibrated for each specific grain type.

**ELEVATOR SUPPORT AND HILLSIDE SIMULATION FIXTURE**

The clean grain elevator from a John Deere 9600 combine was installed in a fixture designed for simulating hillside conditions. The fixture consisted of the following components: a pitch and yaw pivoting support base, hydraulic cylinder mounting brackets and supports, hydraulic motor assembly to drive the elevator, elevator support tower, elevator infeed hopper, discharge grain collection hopper, and flexible spouting. The base consisted of a steel floor support stand that was rigidly attached to a 10–× 10–× 2.5–cm steel base plate that was in turn fixed to the concrete floor using epoxy adhesive anchor bolts. A fixed 5–cm diameter shaft was located at the top of the floor support stand to allow the elevator to pitch forward to aft. Another shaft was mounted on top of the support frame (rotated 90° from the pitch shaft) to allow yaw rotation port to starboard. The elevator support tower was set on top of the yaw shaft through the use of sleeve bearings. The support tower served to hold the clean grain elevator, the infeed hopper, the hydraulic motor, and the discharge grain collection hopper in place. It was constructed out of structural steel tubing.

The hillside simulation fixture was simultaneously capable of pitch and yaw of 12° in either direction. In its present configuration, the axes are rotated and held in position by turnbuckles. Hydraulic cylinders will be added in the future to allow dynamic testing of hillside conditions.

**CONTROL SYSTEM AND INSTRUMENTATION**

The control system has two levels of operation. First, the system can operate under manual control from the motor control center using a traditional pushbutton switch and relay system. Each motor was provided with an individual circuit breaker and motor starter/heater unit. Emergency stop and motor overload protection was provided to disable the system in the event of motor overheating or an emergency stop. The manual mode of operation was provided for maintenance and emergency operation. The second level of control was developed to provide automated control of the start–up process, level and speed control for the grain meter, systems monitoring, data acquisition, dynamic grain inflow simulation, and dynamic hillside condition simulation. A three–position switch was used to select between manual and automatic system operation. The Yield Monitor Test Facility control system hierarchy is shown in figure 4. It should be noted that the hillside simulation module has not been developed at this point. The automated control system consists of a Allen–Bradley SLC–500 programmable logic controller for machine systems control, and a Pentium–based personal computer (PC) that serves as the User Interface Terminal (UIT) and Data Acquisition System (DAS). The UIT was programmed in Visual Basic 6.0 using Allen–Bradley’s RSTools™, Computer Board’s Universal Library (Measurement Computing, Middleboro, Mass.), and Keithley’s DriverLINX ActiveX controls. The SLC–500 was programmed in ladder logic using Allen–Bradley’s RSLogix 500™.

The primary components of the data acquisition system were the Pentium PC, a Computerboards’ CIO–DAS801 analog card, and a Keithley CTM05 counter card. The PC provided the user interface to the data acquisition system and data storage. The principal data variables were the receiving tank load cell weights, the tare weight prior to grain flow, the grain meter shaft speeds, and an interrupt driven running clock for assisting in data synchronization. A synchronization signal was sent to the yield monitor to initiate data acquisition.

The receiving tank was instrumented with four 4500–kg load cells that supported the bulk tank and its support frame. Each load cell was calibrated at the factory to a response range of 3.0 mV/volt of excitation at full scale loading. The load cells were matched and calibrated in the laboratory with a load cell transmitter. The transmitter provided zero offset and gain adjustment. It also provided a stable 10–V DC excitation voltage to the load cell with line length compensation. Additionally, the transmitter provided a scaled 4– to 20–mA output signal that provided a more robust signal in the presence of potential RF noise produced by the AC inverters. The load cell signals were transmitted to the CIO–DAS801 for data acquisition.

The grain meter shaft speeds were used to determine the volumetric flow rate of grain being supplied to the clean grain elevator. Each turret motor had a shaft speed sensing unit, which consisted of a special dual pick–up shaft coupling and an inductive proximity switch. The pick–up lugs were tapped into the shaft coupling at 180° apart and rotated at the

![Figure 4. Yield monitor test facility control system hierarchy.](image-url)
same rpm as the motor shaft. Therefore each revolution of the motor shaft produced two pulses on the inductive proximity switch. A Keithley CTM05 counter card in the PC monitored this signal. The CTM05 counted pulses per second, calculated turret shaft speed based on the gear ratio, and then determined the delivered volumetric flow.

**EXPERIMENTAL METHODS**

A series of calibration tests were conducted on the Yield Monitor Test Facility system. Since the system will evaluate the accuracy of clean grain elevator yield monitors it must be calibrated to ensure that the results are accurate. All calibration tests reported in this document were conducted using corn at normal storage moisture content of approximately 13%.

**RECEIVING TANK WEIGH SCALE SYSTEM**

The load cells and transmitters were individually calibrated in the laboratory. It was also necessary to calibrate the overall system as installed under the receiving tank. The DAS801 was used to collect a tare weight from the empty receiving tank. Approximately 5.3 m$^3$ of grain was taken to a local feed mill truck scale to determine the net grain weight. The batch of grain was then loaded into the receiving tank and the batch weight was recorded using the DAS801. A second batch of 10.6 m$^3$ was taken to the truck scale for weighing. This method provided a reference weight for two batches independent of each other. As a result, a response curve for 5.3 and 10.6 m$^3$ of grain was generated to confirm system calibration. The percent difference between the mill scale and the receiving tank scale for the 5.3– and 10.6–m$^3$ batches were 0.7 and 1%, respectively. These percent errors were considered to be reasonable for this type of system.

**GRAIN METER SPEED AND VOLUMETRIC DELIVERY**

The grain meter consisted of two turrets which operated separately, the first providing grain flow from 1.8 to 15.9 m$^3$/h (M1) and the second providing flow rates from 15.9 to 159 m$^3$/h (M2). The strategy for calibrating the metering system was to: 1) confirm that the grain meter level control and 30–cm supply auger were maintaining minimum hopper level throughout the flow rate range, and 2) determine the amount of grain moved through the meter to the weight scale at a prescribed flow rate and flow duration. Three discrete flow rates for M1 and six flow rates for M2 were selected for the calibration process. The total grain mass and bulk density of the grain was predetermined. Grain was circulated once through the system to ensure that all trap points were full. The grain batch was then transferred from the supply tank to the receiving tank with the meter running at the prescribed flow rates. The time was recorded for complete transfer, the DAS801 was used to record accumulated grain mass at 1–s intervals and the meter shaft speed was recorded using the CTM05. In addition, a visual check was performed to make sure that the minimum grain level was maintained above each turret during the entire process. The instantaneous and overall variability in flow rate and shaft speed were then determined. This procedure was repeated for all flow set points for both M1 and M2. This information was then used to develop a linear flow set point adjustment relationship that would compensate for error and provide an actual flow within 0.2% of set point at corn flows of 21.1 kg/s and 1.28% at corn flows of 1.3 kg/s. M1 and M2 shaft speeds were found to be fairly stable with a mean of 636 rpm (standard deviation of 12.1 rpm) and 1096 rpm (standard deviation of 15.1 rpm), respectively. It should be noted that the measured rpm varied between two points. For example, the measured turret speed for 21.1–kg/s flow oscillated between 1080 and 1110 rpm. This error was likely due to the sampling rate of 1 Hz being too low. A higher sampling rate should correct this problem and improve the accuracy of this measurement.

**TRANSPORT DELAYS**

Due to long transport distances between the elevator and the receiving tank, it is necessary to determine the time required for grain to move from the clean grain elevator to the receiving tank. The grain transport system downstream from the clean grain elevator ran at a constant speed. Consequently, the transport time should have been fairly independent of the inflow rate to the elevator, as long as, elevator power was sufficient. However, at low flow rates there may be some internal surging as the grain builds up in the inclined section of the U–trough auger and vertical leg of the grain pump. In order to identify these relationships, a series of test were conducted at discrete flow rates between 1.8 and 159 m$^3$/h. During each test, the grain flow was started at the meter with the rest of the system running. The elapsed time required for grain to arrive at the GreenStar sensor and at the receiving tank was documented. The results of the transport delay test are presented in table 1.

<table>
<thead>
<tr>
<th>Target Flow (kg/s)</th>
<th>Flow Run Time (s)</th>
<th>Delay No. 1 Meter to Elevator (s)</th>
<th>Delay No. 2 Meter to Scale (s)</th>
<th>Actual Flow Rate (kg/s)</th>
<th>Instantaneous Meter Flow Rate[^b] (kg/s)</th>
<th>Instantaneous GreenStar[^b] Flow Rate (kg/s)</th>
<th>Instantaneous Scale Flow Rate[^c] (kg/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.3</td>
<td>600</td>
<td>8</td>
<td>1.3</td>
<td>1.2 ± 0.02</td>
<td>1.3 ± 0.6</td>
<td>1.2 ± 0.9</td>
<td></td>
</tr>
<tr>
<td>2.1</td>
<td>420</td>
<td>8</td>
<td>4.6</td>
<td>2.1 ± 0.03</td>
<td>2.2 ± 0.3</td>
<td>2.1 ± 0.3</td>
<td></td>
</tr>
<tr>
<td>4.2</td>
<td>180</td>
<td>6</td>
<td>4.4</td>
<td>4.4 ± 0.3</td>
<td>4.6 ± 0.4</td>
<td>4.6 ± 0.4</td>
<td></td>
</tr>
<tr>
<td>8.4</td>
<td>180</td>
<td>6</td>
<td>8.5</td>
<td>8.5 ± 0.3</td>
<td>8.6 ± 0.5</td>
<td>8.7 ± 0.2</td>
<td></td>
</tr>
<tr>
<td>12.7</td>
<td>180</td>
<td>6</td>
<td>12.7</td>
<td>12.7 ± 0.1</td>
<td>13.0 ± 0.5</td>
<td>13.1 ± 1.3</td>
<td></td>
</tr>
<tr>
<td>16.9</td>
<td>120</td>
<td>5</td>
<td>17.0</td>
<td>16.6 ± 0.3</td>
<td>17.0 ± 0.6</td>
<td>17.0 ± 0.6</td>
<td></td>
</tr>
<tr>
<td>21.1</td>
<td>120</td>
<td>5</td>
<td>212</td>
<td>21.2 ± 0.3</td>
<td>21.2 ± 0.7</td>
<td>21.6 ± 1.2</td>
<td></td>
</tr>
</tbody>
</table>

[^b] Instantaneous flow rate for the grain meter is based on the measured meter shaft and the calculated mass flow using the grain bulk density and the volumetric flow rate for the meter as a function of RPM. Data presented is mean from 60 s of flow ± 1 standard deviation.

[^c] Instantaneous flow rate for the GreenStar system is taken directly from the generated yield map data which provides a 1 s mass flow in lb/s. Data presented is mean from 60 s of flow ± 1 standard deviation.

[^c] Instantaneous flow rate for the Scale is taken from the recorded weigh scale data, using a 5 s running average of the current scale reading and the past four readings. Data presented is mean from 60 s of flow ± 1 standard deviation.
STATIC GRAIN FLOW TESTS

The major impetus of the design of this test facility was to provide a means to determine the response of a yield monitor sensor to variation in inflow rates. Grain meter calibration tests were conducted prior to evaluating the response of the GreenStar® yield monitor. Re-circulation of the 10.6–m³ batch of grain was limited to seven runs. There does not appear to be any effect on the yield monitor performance as a result of the number of grain flow cycles, within the range of cycles used in this test. A list of the static flow test runs is provided in table 2.

The GreenStar® yield monitor system was equipped with the latest hardware and firmware version marketed by John Deere as of June 2000. The system was calibrated using the revised two–point calibration method with a corn flow set point of 12.7 kg/s. The recommended adjustments were made in the calibration factor. Then the system was set to “Low Flow Comp Mode” and was run at 6.3 kg/s adjusting the flow comp number as needed. The remainder of the tests were run with this calibration.

Individual static flow tests were run in the following manner. First, the test corn was transferred from the grain transport trailer into the supply tank. Samples of grain were taken at discrete times in the grain flow for analysis by a Dickey John GAC 2100 grain test unit to determine moisture content.Bulk density, broken corn, and foreign material were evaluated using the recommended practice found in the USDA Grain Inspection Handbook. A small sample of grain was run through the system to fill all void spaces in the flow path from the supply tank to the receiving tank. The SLC–500 grain meter parameters were selected to set the mode of operation and the desired throughput. Data logging with the GreenStar® system was initiated and a new test farm and field number were defined. The grain transport system components were started from the grain pump to the supply elevator. The grain meter was filled with grain. Starting the grain meter and supply auger would begin the flow of grain at the prescribed flow rate. Data was collected for a predetermined test run time based on the number of bushels in the system and the flow rate. Activating grain flow at the meter initiated data acquisition at the weigh scale, grain meter shaft speed sensor, and the GreenStar® system. The grain flow continued until the preset runtime expired. The system was then systematically shut down to allow all grain to move from the grain meter, through the clean grain elevator, and on to the receiving tank. The accumulated data was then saved to a file on the hard drive of the PC and the PC–Card of the GreenStar® system. This data was then used to evaluate the performance of the GreenStar® sensor under variation in inflow rate.

RESULTS AND DISCUSSION

The GreenStar® yield monitor sensor was evaluated for flows ranging from 1.3 to 21.1 kg/s. It was found that the GreenStar® yield sensor performed well across a wide range of static flows as shown in table 1. At calibration flow rates of 12.7 kg/s, the percent difference in total mass flow between the GreenStar® and the weight scale were below 1%, while the difference only increased to 3% at the extreme flow rates of 1.3 and 21.1 kg/s. These results were replicated during the second set of test runs confirming that the GreenStar® sensor is able to predict accumulated grain flow. This conclusion is further confirmed when examining figures 5, 6, and 7, which compare the accumulated mass of the weight scale, GreenStar®, and grain meter. At grain flows of 4.2, 12.7, and 21.1 kg/s, there is minimal observed deviation between the accumulated masses measured and/or predicted by the three devices. In all three cases, the weigh scale ran slightly higher than the grain meter during flow, but seems to home in on the meter value at the end of flow. This trend may be caused by momentum forces in the falling grain stream as it impacts the surface of the grain in the weigh tank and thus transmits a dynamic load into the load cells. The GreenStar® seems to more closely follow the weigh scale at the lower flows, while it more closely follows the meter’s accumulated mass at the high flow rate. However, the difference is still minimal when looking at accumulated mass.

The instantaneous flow rates recorded by GreenStar® exhibited a moderate amount of variability at the calibration flow level of 12.7 kg/s, while higher variation is experienced at low flow rates. Instantaneous flow rates are presented in table 1. Mean GreenStar® instantaneous flow rate was 13.0 kg with a standard deviation of 0.5 kg. At two standard deviations from the mean the variation is less than 8%. Similar results were found for the high–end flow rate of 21.1 kg/s where the instantaneous flow variation is less than 7%. Variability in instantaneous flow becomes high at low flow rates. It is not possible to draw a firm conclusion on the cause of variation at the low flow rates. It could be attributed to sensor error, or it could be the result of actual grain flow variability caused by surging within the material handling

| Table 2. Error in total mass predicted by GreenStar® vs. weigh tank scale. |
|-----------------|-----------------|-----------------|-----------------|
| Target Flow (kg/s) | Run Time (s) | GreenStar® Total Test No. 1 (kg) | Error (%) | Scale Total Test No. 2 (kg) | Error (%) |
| 1.3 | 600 | 795 | 771 | 3.1 | 792 | 770 | 2.8 | 1.28 |
| 2.1 | 420 | 904 | 900 | 0.4 | 906 | 894 | 1.3 | 2.14 |
| 4.2 | 180 | 810 | 798 | 1.5 | 797 | 770 | 0.9 | 4.35 |
| 8.4 | 180 | 1552 | 1554 | 0.1 | 1505 | 1514 | 0.6 | 8.52 |
| 12.7 | 180 | 2322 | 2329 | 0.3 | 2261 | 2248 | 0.6 | 12.71 |
| 16.9 | 120 | 2063 | 2067 | 0.2 | 2038 | 2007 | 1.5 | 16.97 |
| 21.1 | 120 | 2502 | 2573 | 2.7 | 2581 | 2512 | 2.7 | 21.19 |

[a] The actual flow is calculated using the average total mass accumulated at the weigh scale divided by the number of seconds that the meter was delivering grain to the clean grain elevator.

Figure 5. Accumulated mass during last 60 s of a 4.2–kg/s corn flow event.
Weigh Scale

Weigh Scale

GreenStar

GreenStar

was found that the use of a running average filter helped

be momentum force loading from the falling grain stream. It

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minus 2.6 kg under static load. This condition is most likely

First, the load cell measurement is not stable varying plus or

potential sources of variability in the load cell measurements.

Since the turret rpm is fairly stable, the variations in

instaneous flow rates at the meter are minimal, as shown in

table 1. However, high variation in instantaneous flow of

the weigh scale was somewhat unexpected. There are several

potential sources of variability in the load cell measurements.

First, the load cell measurement is not stable varying plus or

minus 2.6 kg under static load. This condition is most likely
due to the sensitivity of the 4500–kg load cells being too large
for the minimum flow levels of 1 to 4 kg/s. A second potential

source of variation in the weigh scale may be vibration from
the grain pump. Although slip joints were provided to isolate
the weigh scale tank from the grain pump, there appears to be
some vibration transmitted by friction in these joints and

through the floor. Another potential cause of variation may
be momentum force loading from the falling grain stream. It
was found that the use of a running average filter helped
minimize the influence of these dynamics. The data present-
ed in table 2 and figures 5, 6, and 7 are unfiltered accumulated
flow values. However, the data presented in table 1 for the
weigh scales are instantaneous 1 s flows filtered with 5 s
averaging filter.

However, it should be remembered that most flow
experienced by an actual combine yield monitor system will
be in the range of 4 and 17 kg/s. Consequently, the main issue
to consider is whether an instantaneous flow rate variation of
approximately 7% is acceptable at calibration flow levels.
More importantly, is the sensed flow variation caused by the
mass flow technique or the yield monitor, or are these flow
variations an artifact of the grain metering and transport
components of the test facility?

**SUMMARY AND CONCLUSIONS**

Yield Monitor Test Facility performance was very good.
It was found that the grain metering system can accurately
meter grain to the clean grain elevator with excellent
accuracy over a prescribed time. A potential concern was

grain flow uniformity to the GreenStar® sensor. Are flow
ripples introduced by the grain handling system? Secondly,
the weigh scale system appears to be very accurate in
measuring the accumulated mass flow in the system. However,

grain stream dynamics, tank vibration and load cell
sensitivity confound attempts to measure instantaneous grain
flow at small flow rates (1 to 2 kg/s). Thirdly, the GreenStar®
sensor demonstrated high accuracy across a range of static
flow rates ranging from 1.3 to 21.1 kg/s. When considering
accumulated mass flow, the percent difference between
GreenStar® and the weigh scale was less than 1% at
calibration flow rates and approximately 3% for extreme
flow rates. However, GreenStar® measured instantaneous
grain flow needs further study. Variations in instantaneous
(1-Hz sampling) grain flow were observed at approximately
8% for calibration flow rates.

Results from these tests indicate that the GreenStar® mass
flow sensor accurately predicts total accumulated mass flow
across a broad range of static inflow rates. However, the
possibility of other sources of error may exist in the overall
combine yield monitor system. For instance, error in ground
speed, measured swath width, transport delays in the
threshing unit, and other issues may still influence the overall
accuracy of the yield map.

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