EFFECTS OF TIME-VARYING INFLOW RATES ON COMBINE YIELD MONITOR ACCURACY

T. F. Burks, S. A. Shearer, J. P. Fulton, C. J. Sobolik

ABSTRACT. The Yield Monitor Test Facility (YMTF) was used to evaluate the GreenStar® mass flow sensor in a 9600 clean grain elevator under dynamically varying inflow rates. It was found that the GreenStar® yield sensor predicted accumulated mass with less than 4% error (under dynamically varying step and ramp flow rates) within normal operating conditions of 4.2 to 16.9 kg/s (10 to 40 bu/min) and predicts flow at upper limits of 20 kg/s with a 7.3% error. The yield sensor followed ASAE Draft Standard X578 variable step flow rates, while operating under 20 kg/s, but exhibited significant errors for flows above 20 kg/s. The maximum error in accumulated mass for the variable step profile was less than 2%, while the approximate average instantaneous flow error at steady state was approximately 4.4% with a 3.4% standard deviation. It was found that transient flow had maximum accumulated flow errors of approximately 5%, while oscillating flow had errors around 2.5%. These errors were attributed to the fact that the transient flow maintains flow at the extremity of the GreenStar® operation range (based on 12.7 kg/s calibration) for longer periods.

Additionally, 2−s time averaging of flow readings smoothed noise in the original signal with minimal loss of signal definition.

Keywords. Precision farming, Yield monitoring, Mass flow sensor, Site−specific crop management, Grain harvester, Test stand.

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 crop production. Perez−Munoz and Colvin (1996) noted that yield monitors tend to overestimate crop yield in regions of low yield. Kormann et al. (1998) reported that errors up to 7% were observed in force impetus yield monitors under low inflow conditions of 2.77 kg/s. As a result of actual in−field variability of crop yield and the questions surrounding yield monitor accuracies under dynamically varying field conditions, the Yield Monitor Test Facility was developed at the University of Kentucky to assess clean grain elevator yield monitor sensing technology.

LITERATURE REVIEW

A study conducted by Shearer et al. (1997) found that significant differences in measured yield existed between adjacent harvest swaths. The study used four combines (two John Deere 9500's, a Gleaner R70, and a Case IH 1680) to harvest wheat within the same field. Each combine was equipped with a yield monitor; the 9500's used GreenStar® and the other combines used the Ag Leader® Yield Monitor 2000. Differences in yield estimates 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. Shearer et al. (1997) concluded that machine calibration techniques were critical in multiple−combine harvest systems. Strube 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: low yields at the start of harvest transects, 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 in an attempt to compensate for these errors. Thylen and Murphy concluded that the removal of the start of harvest transects improves data quality as measured by geostatistical analysis, and that filtered mean instantaneous yield is similar to mean yield calculated from total grain mass and the harvested area.

A case study was conducted between the University of Nebraska. Successful Farming, and three corn farmers to assess the impact of yield monitor calibration and combine
operational conditions on yield monitor accuracy (Grisso et al., 2002). Two combines were operated at three different travel velocities and one combine was operated under varying slope conditions. They found that calibration differences can result in errors up to 10% between yield monitor wet weight estimates and weigh wagon results.

Kettle and Peterson (1998) observed that the accuracy of combine yield monitors was significantly affected by hillside conditions and variation in harvest rates. They observed that the yield monitor’s response to inflow variation was exponential rather than linear, and suggested that calibration should be done at several operating points rather than the traditional two-point method. Tests were conducted on two John Deere combines equipped with Greensear® yield monitors in the hilly Palouse region of northern Idaho. 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 error in yield monitor estimates were as high as 18.2% when harvesting uphill and 60.7% when harvesting downhill, on 6% to 9% slopes. A very weak correlation between the yield monitor’s estimated yield and hand samples ($R^2 = 0.203$) indicated that the yield monitor did not track local variation in crop yield.

As a result of the wide variability of field conditions and the difficulty of accurately testing yield monitors in the field, several researchers construct elaborate laboratory test stands, which can isolate the performance of the yield monitor sensor. This approach has several benefits, such as accurate in-flow control, controlled sensor inclination, and redundant flow sensing to confirm sensor accuracy. Arslan and Colvin (1998) 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 was developed by Kormann et al. (1998) to test multiple clean grain elevator yield monitors simultaneously. A system was fabricated using a Massey Ferguson 38/40 elevator with three reference yield monitoring systems installed: the RDS Ceres II (RDS Technology Ltd, Gloucestershire, England) volumetric meter, 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 CLASS 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, provisions were made to vary mass flow rate from 2.8 to 9.7 kg/s. They conducted tests varying the inflow rate from 2.8 to 9.7 kg/s and found mean calibration errors of 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 did the mass flow sensors. A second set of tests conducted by varying the tilt of the elevator system found mean errors up to 6% with standard deviations of up to 6%. The radiometric MF Flowcontrol device performed the best of all sensors with mean errors less than 2%, while the other sensors performed as follows from most to least accurate: CLASS 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 grain yield monitors (Proposed ASAE Standard, Pending). The proposed ASAE 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 knowledge of numerous scientists in precision agriculture research, and thus provides valuable insight into the performance requirements of yield monitor sensing and evaluation.

**OBJECTIVES**

The goal for this research was to compare mass flow measurement capability of the yield monitor test facility, reported by Burks et al. (2003), with that of a commercially available yield monitor system under dynamic variations in grain flow rates. The specific research objectives were:

- To develop control algorithms, which will generate step, ramp, square wave, triangle wave, and the proposed X578 grain flow profiles from the facility grain meter to the clean grain elevator.
- To evaluate the performance of the YMTF with respect to generating dynamic flow profiles and compare these profiles with the yield monitor’s predicted flows.
- To evaluate the data acquisition methodology and recommend data analysis techniques that will enhance the utility of the YMTF.

**TEST FACILITY SYSTEM DESIGN**

The YMTF at the University of Kentucky was used for this research project. Additional details pertaining to the system development and calibration were reported by Burks et al. (2003).

**GRAIN HANDLING SYSTEM**

The grain handling system was designed to hold up to 18 m³ of grain and is capable of flow rates up to 31.7 kg/s of dry grain. The system plan view is shown in figure 1. The system consists of two 2.8–m diameter supply tanks. The supply tank stores the grain prior to each test. The receiving tank is mounted on a rectangular frame, which has four 4500–kg load cells, one at each corner. A 30–cm supply auger (2.2–kW Allen–Bradley AC variable speed motor drive) transports grain from the supply tank to the volumetric grain–metering device. Grain level sensors control surge hopper filling rates by varying supply auger speed and on/off operation. The supply elevator operates at a constant speed of approximately 400 rpm using a 5.6–kW AC motor and is capable of achieving flow capacities of up to 31.7 kg/s.

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 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 41.6 kg/s 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 digitized once per second.

**GRAIN METERING**

The grain–metering device consists of a surge hopper and two flow control turrets. The first turret is approximately 46 cm in length (M1), runs between 0.4 and 3.2 kg/s, 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 runs between 3.2 and 31.7 kg/s. 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 3.2 kg/s and M2 runs at approximately 36 rpm to give 31.7 kg/s. Meter turret speed is controlled by an Allen–Bradley AC variable speed drive by a 0– to 10– V speed reference signal from the Allen–Bradley (Rockwell Automation, Milwaukee, Wis.) 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 levels using 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 inductive proximity switch (Altech Corp, Flemington, N.J.) with two 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 (Cleveland, Ohio) CTM05 counter card, which runs in the background on the system PC. The shaft speed is used to confirm the volumetric delivery of grain from the meter to the clean grain elevator. Meter flow was calibrated for the specific grain type used in this test, confirming that the accumulated mass flow measured by the receiving tank and the flow predicted by the turret shaft speed sensors were closely matched over the range of delivery rates, with less than 1% error.

**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 push button switch and relay system. The second level of control provides 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. The automated control system consists of an Allen–Bradley SLC–500 programmable logic controller for machine systems control, and a Pentium–based personal computer that serves as the user interface terminal (UIT) and data acquisition system (DAS).

The primary components of the data acquisition system are the Pentium PC, a Computerboards' (Measurement Computing, Middleboro, Mass.) CIO–DAS801 analog card, and a Keithley CTM05 counter card. The PC provides the user interface to the data acquisition system and data storage. The pertinent data include receiving tank load cell weights, tare weight prior to grain flow, grain meter shaft speeds, and an interrupt–driven running clock for assisting in data synchronization. A synchronization signal is sent to the yield monitor to initiate data acquisition.

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

**EXPERIMENTAL METHODS**

A series of calibration tests were conducted on the YMTF system (Burks et al., 2003). All calibration and test procedures were conducted using corn stored at average moisture content of 15.3% with a 0.1% standard deviation. The grain used in these tests had been dried and stored for sufficient time to reach moisture equilibrium, thus minimizing moisture content variability. Moisture content was measured using a Dickey–John GAC 2100 (Auburn, Ill.). The clean grain elevator yield monitor sensor was re–calibrated before running the dynamic flow test using the standard two–point calibration technique recommended by the manufacturer. This system utilized the GreenStar® self zero feature. It was calibrated at a grain flow rate of 12.7 kg/s, and the recommended adjustments were made in the calibration factor via the user interface. The system was then set to "Low Flow Comp Mode” and run at 6.3 kg/s, while the low–flow comp number was adjusted at the GreenStar® user interface.
**Dynamic Flow Tests**

The YMTF control system parameters were selected to set the grain meter flow rate and profile, and data acquisition method. The yield monitor display was configured and a test farm and field number were defined. Grain delivery was initiated by automatically starting the various components from the grain pump to the supply elevator in sequence. Once the supply auger filled the meter to the minimum grain level, thereby starting the meter, the auger initiated the flow of grain to the clean grain elevator. Data was collected for a predetermined test duration time, which was based on the volume of grain 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. Samples of grain were taken at random times during grain flow to determine moisture content and assess grain quality. The grain flow continued until the preset runtime expired. The system was then sequentially shut down to allow all grain to move from the grain meter through the clean grain elevator and onto the receiving tank weight scale. The accumulated weigh scale and meter speed data were saved to a file on the hard drive of the PC, while the yield sensor saved its data to the PC card of the GreenStar® system. These data were then used to evaluate the performance of the GreenStar® sensor under varying inflow rate.

There were two types of test runs performed during this experiment. First, the grain meter was used to supply two basic dynamic grain flow profiles to the clean grain elevator, a step change and a ramp change, to determine if dynamic variations affected the yield sensor’s accumulated mass flow.

A minimal flow of 4.2 kg/s was provided until steady state conditions were achieved, and then the grain meter began to change the flow rate based on the selected flow profile and the target flow rates. In each case, the flow was varied from the initial value of 4.2 kg/s to one of four values (8.4, 12.7, 16.9, and 21.1 kg/s). Two repetitions of each flow profile and target flow combination were conducted to evaluate the relative accuracy of the grain flow profiles and the yield monitor sensor.

The second type of test in this experiment used the PLC controller to produce the X578 grain flow profiles suggested by the proposed ASAE X578 yield monitor test Standard. This standard proposes three flow profiles: 1) transient flow (ramp up from 50% maximum flow to maximum flow – hold – ramp back down to 50%), oscillating flow (triangle wave between 50% maximum flow and maximum flow), and the variable step flow (step down from 90% maximum flow to 75%, back to 90%, down to 50%, back to 90%, down to 0%, back to 90%, and then repeat). The objectives of these tests were to evaluate the accumulated flow accuracies, to assess the ability of the grain meter to accurately produce the X578 profiles, and to monitor the yield sensor’s ability to track the flow profile provided by the grain meter. Two repetitions of each profile were conducted to evaluate the relative accuracy of the grain flow profiles and the yield monitor sensor. It is recommended that at least three repetitions be conducted when evaluating a specific yield monitor for sensing accuracy. Two repetitions were selected for these test, since the purpose was primarily to evaluate the YMTF.

<table>
<thead>
<tr>
<th>Target Flow Rate (kg/s)</th>
<th>Run Time (s)</th>
<th>Actual Flow (kg/s)</th>
<th>Sensor (kg)</th>
<th>Scale (kg)</th>
<th>Maximum Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.2</td>
<td>180</td>
<td>803</td>
<td>799</td>
<td>771</td>
<td>3.1</td>
</tr>
<tr>
<td>8.4</td>
<td>180</td>
<td>1529</td>
<td>1534</td>
<td>2289</td>
<td>0.6</td>
</tr>
<tr>
<td>16.9</td>
<td>120</td>
<td>2051</td>
<td>2037</td>
<td>2037</td>
<td>1.5</td>
</tr>
<tr>
<td>21.1</td>
<td>120</td>
<td>2542</td>
<td>2543</td>
<td>2543</td>
<td>2.7</td>
</tr>
</tbody>
</table>

[a] The actual flow is calculated using the average total mass accumulated at the weigh scale divided by run time.
[b] The listed accumulated mass flows are the means of two observations.
[c] Maximum Error = 100% × |(Accumulated yield sensor reading − Net weigh scale reading)/(Net weigh scale reading)|.

**Results and Discussion**

In an earlier study by Burks et al. (2003), the GreenStar® yield monitor sensor was evaluated for variation in measured flow ranging from 1.3 to 21.1 kg/s. The GreenStar® yield sensor performed well across a wide range of uniform flow rates, 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 weigh scale were less than 1%, which increased to 3% at the extreme flow rates of 1.3 and 21.1 kg/s.

The results of the test for variation in accumulated mass flow under step and ramp flow conditions demonstrated that moderate changes in flow rates had minimal effect on accumulated mass flow. Table 2 shows that for both step and ramp flow changes between 4.2 and 16.9 kg/s or less, the errors in accumulated mass between the yield sensor and the weigh scales were less than 3%. However, for a step change between 4.2 and 21.1 kg/s the error jumped to 7.3%. It should be noted that the sensor was calibrated at an upper flow of 12.7 kg/s. Thus it appears that flow rates above the calibration point increase the risk of error. The ramp flow seemed to maintain a reasonable error of 4% over the range observed. In general, the mass–flow sensor tended to over–predict mass flow when compared to the weigh scales.

The differences in accumulated mass flow between the yield mass–flow sensor, grain meter, and weigh tank as a function of time (fig. 2a and 2b). Figure 2a shows accumulated mass versus time for a single test run using step flow.

<table>
<thead>
<tr>
<th>Target Flow Range (kg/s)</th>
<th>Run Time (s)</th>
<th>Step Change Flow (kg)</th>
<th>Step Change Error (%)</th>
<th>Ramp Change Flow (kg)</th>
<th>Ramp Change Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.2 to 8.4</td>
<td>90</td>
<td>625</td>
<td>610</td>
<td>2.5</td>
<td>569</td>
</tr>
<tr>
<td>4.2 to 12.7</td>
<td>90</td>
<td>855</td>
<td>872</td>
<td>0.7</td>
<td>756</td>
</tr>
<tr>
<td>4.2 to 16.9</td>
<td>90</td>
<td>1110</td>
<td>1118</td>
<td>0.7</td>
<td>941</td>
</tr>
<tr>
<td>4.2 to 21.1</td>
<td>90</td>
<td>1456</td>
<td>1356</td>
<td>7.3</td>
<td>1163</td>
</tr>
</tbody>
</table>

[a] The flow ranges represent the starting flow rate and the target flow rates for both the step and ramp flow profile. The step flow begins at initial flow and then instantaneously changes to the target flow rate, while the ramp incrementally changes over the flow duration.
[b] The listed accumulated mass flows are the means of two observations.
[c] Error = 100% × |(Accumulated yield sensor reading − Net weigh scale reading)/(Net weigh scale reading)|.
a) Step flow with 21 kg/s maximum.

b) Ramp flow with 21 kg/s maximum.

Figure 2. Accumulated flow comparison between sensor, meter, and scales. Sensor calibrated using two-point method at 6.3 and 12.7 kg/s.

input, while figure 2b shows similar results for ramp flow input. The slope of all measurement methods are similar, with the meter and scale equilibrating at the end of the run, and the mass–flow sensor over–predicting in both cases. It makes sense that the meter and scale would equilibrate, since the meter flow rate is determined by dividing the total mass delivered to the weigh tank by the number of turret revolutions, thus providing an average grain bulk density per turret compartment. Earlier calibration tests justified this approach. In general, it can be concluded that the yield sensor accurately predicts (less than 4% error) accumulated mass under varying flow rates within normal operating conditions of 4.2 to 16.9 kg/s, and does a reasonable job of predicting flow at the upper limits of 21.1 kg/s.

The series of tests conducted using the X578 profiles provided several interesting discoveries. First, figure 3a and 3b show the instantaneous flow measurements of the yield sensor and meter for the variable step profile. In both cases, noise can be observed in the sensor’s predicted flow. Figure 3a demonstrates an X578 flow profile generated using the recommended 90% of a maximum flow, with 26 kg/s being selected as maximum flow. This resulted in a peak flow of 23 kg/s. The yield sensor closely followed the meter for flow rates under 20 kg/s, but exhibited significant error for flows above 20 kg/s. Once the flow exceeded a certain threshold above the calibration point, the accuracy began to deteriorate. In figure 3b, the sensor closely tracked the meter throughout the entire flow profile. This profile was based on a maximum flow of 21 kg/s (90% flow is 19 kg/s). It is clear from these figures that sensor performance can be enhanced by accurately selecting the calibration points based on the average and maximum expected flow rate. In this case, instantaneous predicted flow near the set point of 12.7 kg/s is good. Sensor predictions at flows nearly 70% above the upper calibration set point still provide acceptable results.

The error in 1−s readings is very difficult to predict, since there is not an accurate means to register the two data streams and thus perfectly align the step transitions. However, when observing a 5−s segment of the grain flow profile, at steady state grain metering, the average error between corresponding 1−s readings was found to be 4.4% with a standard deviation of 3.4%. If adjacent sensor readings are averaged to yield a running 2−s time average, the error drops to 3.2% with a 2.6% standard deviation. The error in accumulated mass between the yield sensor and the weigh scale is given in table 3. The maximum error in accumulated mass for the variable step profile is less than 2%. This speaks well for the accuracy of predicted grain yield at flows within the

Table 3. Accumulated mass flow comparison for proposed ASAE Standard X578 flow profiles.

<table>
<thead>
<tr>
<th>Flow Type</th>
<th>Flow Range[a] (kg/s)</th>
<th>Run Time (s)</th>
<th>Sensor (kg)</th>
<th>Scale (kg)</th>
<th>Maximum Error[b] (%)</th>
<th>RMS Error [b] (kg/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transient</td>
<td>11 − 21</td>
<td>60</td>
<td>768</td>
<td>739</td>
<td>3.9</td>
<td>1.4</td>
</tr>
<tr>
<td>Oscillating</td>
<td>11 − 21</td>
<td>180</td>
<td>1199</td>
<td>1179</td>
<td>1.7</td>
<td>1.1</td>
</tr>
<tr>
<td>Variable step</td>
<td>0 − 21</td>
<td>180</td>
<td>2618</td>
<td>2624</td>
<td>0.2</td>
<td>1.4</td>
</tr>
</tbody>
</table>

[a] The flow range represents the theoretical minimum and maximum flows based on the X578 flow profile definitions.
[b] The maximum error is the greater of two unique observations, while the RMS error provides a measure of fit between the two flow profiles. Maximum Error = 100% × |(Accumulated yield sensor reading – Net weigh scale reading)/Net weigh scale reading|. RMS Error = |(Accumulated yield sensor reading – Net weigh scale reading)/Net weigh scale reading|.
The filtering technique of averaging adjacent values in a data stream has been used successfully for reducing signal noise. It does however result in a loss of signal information as a result of smoothing. The influence of time averaging on adjacent sensor readings can be observed in figure 4a and 4b. They are from the same data stream, but for different time durations. In figure 4a, it can be seen that the 2− and 3−s average followed the original signal, but with two noticeable differences. First, filtered data had less noise (smoother), but also had a loss of definition at the transitions. In figure 4b, it can be seen that the 3−s average had less pronounced corners or transitions.

The results of the remaining two X578 flow profiles can be seen in figure 5a and 5b. Figure 5a shows the transient flow condition, which demonstrates excellent tracking of the ramp up and ramp down portion of the flow. However, it does show higher error at flows of 21 kg/s (50 bu/min). Figure 5b shows the oscillating flow that maintains good tracking of the meter flow at all levels. When looking at the error in accumulated mass flow for the profiles, it is found that the transient flow has maximum errors of approximately 5%, while the oscillating flow has errors around 2.5%. This may be attributed to the fact that the transient flow profile maintains flow at the maximum level for the greatest period of time. The greater error results from the yield sensor operating at the extremity of its calibrated operation range for longer periods.

When considering the RMS error associated with the three X578 flow profiles, as shown in table 3, it is found that the oscillating flow has a very low RMS error of 1.1 kg/s, while the variable−step and the transient flow profiles have similar performance at 1.4 kg/s. Figures 3b demonstrate the closeness of fit of the oscillating profile once flow begins, while figures 5a and 5b show the increased variability between meter flow and the yield sensor predicted flow. Potential causes for this variability were previously discussed.

**SUMMARY AND CONCLUSIONS**

Grain flow control algorithms were developed for the grain meter’s Allen−Bradley SLC 500 controller to provide step, ramp, and the proposed X578 grain flow profiles to the clean grain elevator. The Yield Monitor Test Facility flow profiles were then monitored using a GreenStar® mass flow sensor in a 9600 clean grain elevator, and the YMTF scales. The GreenStar® yield sensor closely predicted (less than 4% error) accumulated mass (for step and ramp flow rates) within normal operating conditions of 4.2 to 16.9 kg/s (10 to 40 bu/min), while predicting flows with 7% error at upper flow limits of 21 kg/s. The yield sensor accurately followed X578 variable step flow rates while operating below 20 kg/s, but exhibited errors for flows above 20 kg/s. The maximum error in accumulated mass for the variable step profile was less than 2%, while the average instantaneous flow error during steady state grain metering was estimated at 4.4% with a 3.4% standard deviation. Time averaging adjacent readings reduced the error to 3.2%. It was found that transient flow had maximum errors of approximately 5%, while oscillating flow had errors around 2.5%. This was due to the operational flow range, which is in the range of 4.2 to 20 kg/s at these calibration settings.
fact that transient flow maintained flow at the extremity of the GreenStar® operation range (based on 12.7–kg/s calibration) for longer periods.

The results from these tests indicated that the GreenStar® mass flow sensor closely predicted total accumulated mass flow across a broad range of time–varying inflow rates and demonstrated good instantaneous flow prediction when operated within an acceptable flow range. Additionally, 2–s time averaging of adjacent flow readings smoothed noise in the original signal with minimal loss of signal definition. However, this study was limited to laboratory test of a stationary clean grain elevator. Consequently, potential error sources, such as shock and vibration, measured swath width, transport delays in the threshing unit, GPS position fixes, and other factors, may still influence the overall accuracy of the yield map.

REFERENCES

