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Progress on Field Evaluation of Aerial Variable-Rate Systems for Liquid Application

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Abstract. *Flow control systems for aerial spraying have been evaluated at the USDA, ARS, CPSRU over the past 12 years. Early experiments were designed to evaluate the ability of flow controllers to provide a desired application rate regardless of changes in ground speed. More recent testing has focused on variable-rate aerial application. Experiments have been conducted to determine flow response to changing rates and the accuracy of material placement in the field as the system was switched from zero to full flow. New results are presented from evaluation of the integrated AutoCal II flow controller, Kawak Aviation Technologies hydraulic power pack, and Satloc Airstar M3 guidance system. A special flow monitor was designed to increase resolution of data acquisition from the flowmeter when comparing actual to desired flowrates as the system changed rates automatically over a georeferenced field prescription. Since a flowmeter monitor might not be readily available to those wanting to evaluate their own systems, comparative flow results are presented with and without the flowmeter monitor activated. Results from 2005 experiments showed that good responses to changing rates could be assessed with or without the flowmeter monitor, but that data acquisition resolution was visibly improved when using the monitor. Integrated areas under the flowrate curves that signify total amounts applied to each prescription area showed good agreement with target-rate results*

for six passes over the prescription zone. Errors between required and actual flow rate areas ranged from -1.0% to 2.1% using the flowmeter monitor. Calculated timing for the entire run based on ground speed was about 4.8s, and flow response results accumulated both with and without the monitor were very close to that value. For 2008 tests however, time intervals for individual flow rates over the prescription polygons varied between 1.2 and 1.66 seconds and total time for the entire run was represented as 5.6s, or 0.9s greater than that using the flow monitor. Inconsistencies in timing for 2008 might be attributable to modifications to loop-timing portions of the AutoCal II control algorithm by the system manufacturer since the 2005 runs were conducted. These results further support the utility of the flowmeter monitor in providing consistent results for analysis regardless of possible changes to the AutoCal II data acquisition and control program. A new system that allows switching of two different flow control systems for testing is described, which presently allows the Ag-Nav and Autocal II systems to be interchanged.

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Keywords. variable-rate application, site specific management, precision agriculture, aerial application

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Introduction[1]

Evaluation of flow control for aerial application at the USDA, ARS, APTRU (now CPSRU) in Stoneville, MS, USA has progressed from early testing of the AutoCal (Houma Avionics, Houma, LA) flow controller (Smith, 1997; 2001) to the present-day variable-rate (VR) application system. The VR system has been evaluated for application accuracy with respect to known georeferenced ground positions (Thomson et al., 2009a) and refined to improve its response to changing application rates (Thomson et al., 2009b).

A new aircraft setup for an Air Tractor 402B has been designed to allow manual switching of flowmeters and guidance systems depending on which configuration is under test. The present setup includes the AutoCal II flow controller paired with Hemisphere Satloc Airstar M3 (Hemisphere GPS, Calgary, AB, Canada) and the Ag-Nav Guía guidance system (Ag-Nav Inc., Newmarket, Ontario, Canada) with in-line ball valve for flow control.

Flow controllers for aerial application have been evaluated for their ability to adjust flow accommodating changes in ground speed. This assures that the same rate of material is applied per unit field area. Kirk and Tom (1996) evaluated an early version of the Satloc automatic flow control system over 1600 m runs. Performance was evaluated from data logged during the flight describing performance of the controller relative to the information received from the flow sensor and GPS receiver. Several aircraft runs were made upwind and downwind at four different wind speed levels. Without the flow controller, errors ranged from 6.4 to 14.3%. Spray rate errors ranged from 0 to 4.4% over the eight treatments with flow control switched on. Smith (1997) evaluated an early version of the AutoCal I automatic flow controller using a combination of logged flight data and measurements of actual water volume sprayed. Results from spraying 19 L/ha (2 gal/acre) on a 40–ha (100-acre) plot revealed that application error with the system operating was 0.48%. Without flow control, error was 7.25%. Average upwind speed during the application was 209 km/h (130 mph), and average downwind speed was 234 km/h (145 mph). Evaluation of performance over a range of application rates indicated that the calibration code and sensitivity values for this version of the controller required adjustment for the application rate being applied.

Martin et al. (2004) evaluated a variable-rate system mounted in an agricultural aircraft that used a propeller-driven spray pump on an Ayers Thrush aircraft, similar to the pump used by Smith (2001). However, instead of controlling a ball valve or

[1] Mention of trademark, vendor, or proprietary product does not constitute a guarantee or warranty of the product by the USDA and does not imply its approval to the exclusion of other products that may also be suitable.

bypass return valve, a servo-controlled actuator was connected directly to the pump propeller to achieve variable fluid rates. Propeller pitch was controlled by the AutoCal I flow controller, and a Trimble AgGPS® TrimFlight™ 3 was used for guidance and position georeferencing. A 1-mm cotton string was placed along the spray path to determine where spray with a fluorescent dye tracer started or stopped relative to a target positions measured on the ground. Preliminary tests showed that on-off control could be achieved within 16-m of the target. A follow-up study evaluated the system's ability to vary flowrate in-flight. The aircraft was flown through six application rate zones of 0, 45, 0, 34, 23, and 0 L/ha and water sensitive papers were used to collect deposition samples in each of the zones. Results indicated a delayed response of the system to the input requests and an overall inability of the system to achieve the desired application rates. This was attributed to the turbulent fluid dynamics of the system using a conventional hydraulic nozzle, where a doubling of the flow rate required a quadrupling of the pressure in the system.

Objectives

Our objectives are:

1. To summarize progression of our work with aerial flow control at the USDA, ARS, CPSRU.
2. To present results from recent evaluation of the variable-rate aerial application system.
3. To describe a new system that allows selection between two different controllers and associated guidance systems for experimentation.

AutoCal Flow Control Configurations

Early Systems (1997-2001)

Smith (1997) evaluated an early version of the AutoCal I. Four years later, the system progressed into a versatile controller with improvements in the ability to read the flowmeter and calibrate (Smith, 2001). Two versions of the AutoCal flow controller were available at the time. The AutoCal I adjusted a boom–valve to control boom flow, and the AutoCal II adjusted a bypass valve between the pump outlet and inlet to control boom flow (Fig. 1). The AutoCal I controlled flow directly by mechanically adjusting a valve in the flow path (Fig. 2). A servo–controlled linear actuator extended or retracted in response to commands from the control unit in the cockpit. The setup consisted of a control unit and display, Satloc Airstar GPS receiver with a one second position updating, a servo driven linear actuator, spray valve, and flow sensor. The control unit had provisions for setting application rate, swath width, calibration code, and sensitivity by using toggle switches. Two modes could be selected with a switch on the control unit: a calibration mode for performing calibrations and an operating mode for normal flowrate control. Calibration mode deactivated automatic control functions and

made provision for calibrating the system by displaying flow meter output and activating calibration code setting functions. Operating mode activated the automatic control function and displayed the required flowrate, actual flowrate, servo position, ground speed, swath width, application rate, and system sensitivity. Calibration consisted of determining the calibration code value to convert the flow meter output signal to actual flowrate passing through the meter. User controls for the AutoCal II version in use today are essentially the same as those used in 2001.

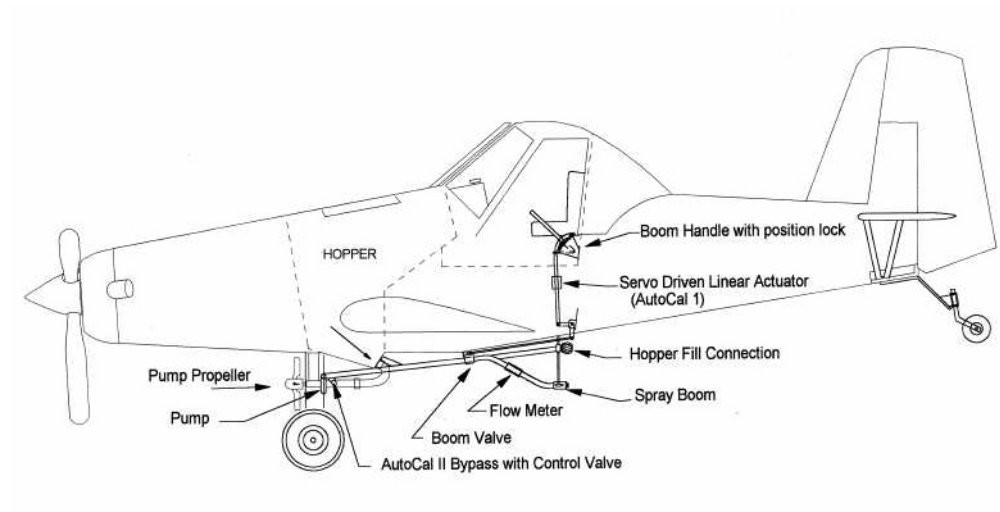
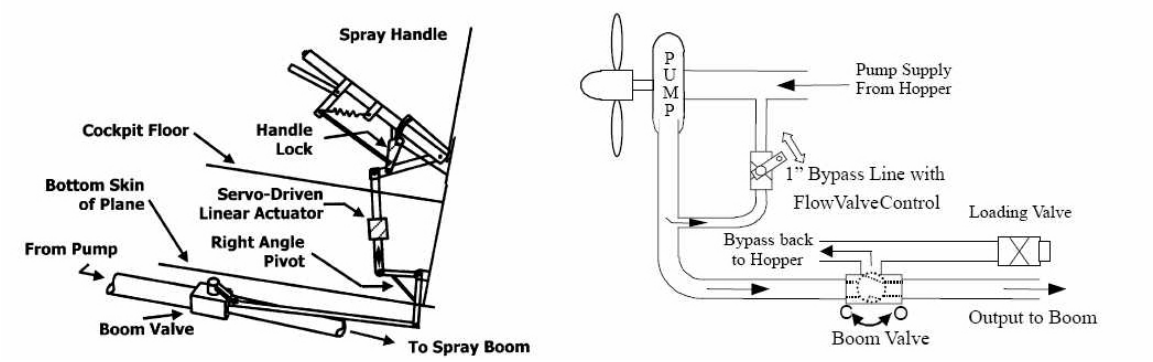


Figure 1. Components of the Air Tractor 402B spray system equipped with automatic flow control. When the AutoCal I was implemented, flowrate was controlled by adjustment of the boom valve. The AutoCal II controlled flowrate to the boom by bypassing some of the pump discharge back to the pump inlet (from Smith, 2001).



a. b.

Figure 2. Servo-driven control actuator for the AutoCal I (Fig. 2a) was positioned in the linkage between the boom valve handle in the cockpit and the right angle pivot. Bypass line and flow control valve for the AutoCal II flow control system (Fig 2b.) is illustrated by schematic diagram. A cable (not shown) from a servo–

driven linear–actuator mounted beneath the cockpit operated the flow control valve (from Smith, 2001).

Recent Configurations (2005-2009)

In 2005, 2008 and 2009, evaluations of an updated AutoCal II flow control system were made to determine potential to perform variable-rate aerial application (Smith and Thomson, 2006; Thomson et al., 2009a). Flow data from the AutoCal II were logged using Hyperterminal on a notebook computer mounted in the airplane and an HP IPAQ HX-4700 Pocket-PC was used to log flowmeter data directly at 0.1-s intervals using a monitor designed by Dr. Lowrey A. Smith (retired).

The aircraft system had been altered since the 2001 experiments were conducted by installation of a Kawak Aviation hydraulic power pack that featured an engine-driven hydraulic pump, a hydraulic motor for driving the spray pump, and a hydraulic cylinder to actuate the spray valve. Hydraulic power to the spray pump was controlled with an electrically operated hydraulic servo valve from signals generated by the flow controller.and Satloc Airstar M3. The Satloc implemented AirTrac software to implement variable-rate application and used the Wide Area Augmentation System (WAAS) for differential correction. A prescription map was developed to test the variable-rate system and points were georeferenced on the map in the field using a Trimble MS750 RTK system. Pre-defined rates were specified on the map using Arcview 3.2a and converted to a format that the Satloc M3 could understand for delivering prescriptions. The Hemisphere Mapstar application mapping software program was used to accomplish this. Details of how this field layout was georeferenced and how the prescription was generated using ArcView and ArcGIS can be found in Bright et al. (2009).

Experimental Procedures

Early Evaluations (ca. 2001)

Performance of the flow controllers was tested by Smith (2001) under controlled conditions to evaluate the ability of the controller to determine and apply the correct application rate. Multiple pass applications were made to evaluate the controller under conditions that incorporated variable speeds and different application rates. All tests were applied with the controllers installed on a turbine–powered Air Tractor 402B. The volume sprayed could be determined by subtracting the volume drained from the hopper after the run from the amount loaded for the test. The data stream transmitted by the AutoCal II to notebook computer mounted in the baggage compartment included application rate, swath width, calibration code, sensitivity, required flowrate, actual flowrate, ground speed, servo position, and status code. An early version of the Satloc AirStar

swath guidance system provided guidance to the pilot while spraying and logged flight information to a user accessible log file. Logged data of interest for this study was collected at one second intervals and included ground speed, time, and spray activation flags. At the end of the test day, the logs were downloaded to a PC and converted to an ASCII text file. The AirStar system also provided a display of accumulated spray time and sprayed area.

Initial tests on the AutoCal I were designed to evaluate the ability of the controller to apply water at a prescribed application rate while ground speed was maintained at a near constant value. The plane was loaded with the required volume of water as measured with a calibrated flow meter. The pilot then made two 45 second spray runs while maintaining a ground speed of approximately 217 km/h (135 mph) before returning to the loading area. The unsprayed water remaining in the hopper was then drained through the fill–tube and weighed to the nearest 45 g (0.1 lb). Experimental error was computed as the percentage difference between the required volume for the run and the sprayed volume. For these tests, the required volume was computed from application rate, swath width, average ground speed, and spray time. The volume sprayed was computed as the difference between the volume loaded and the volume drained from the hopper at the completion of the test run.

Dynamic performance of the AutoCal I was then evaluated with a test requiring application of water on 23 ha (57 acre) plots with varying ground speeds. The ability of the AutoCal I to keep up with ground speed changes while spraying was evaluated, along with the effect of spray initiation on controller error. The effect of spray initiation was evaluated by using 5, 10, 15, and 20 spray passes to spray the 23–ha (57–acre) plots. Each test run consisted of approximately 180–s total spray time divided among the number of passes required for that run. The test run was terminated when the target area, as determined by the Airstar ‘acres’ display, had been sprayed. Four replicates of each treatment were applied in a randomized complete block design while maintaining a consistent application rate of 18.7 L/ha (2 gal/acre). Experimental error was determined by the difference between the actual volume of water sprayed on the area and the required volume, which was computed as the product of area sprayed and application rate.

The AutoCal II was tested only under dynamic application conditions. This test was similar to the plot sprays for the AutoCal I except that a range of application rates were used and the number of passes per plot remained constant for all treatments. Ground speed was purposely varied during each test run to evaluate the ability of the controller to track the changing flowrates due to changing speeds. Each test run was comprised of 10 spray passes of about 10–s duration. Each test run was initiated with the spray system plumbing full of water and the hopper loaded with a volume of water equal to the expected volume to be sprayed plus about 76 L (20 gal) to maintain proper spray system operation at the end of the spray run. After spraying, the unsprayed water from the hopper

was drained and weighed. The sprayed volume was then computed as the difference between the initial volume loaded and the unsprayed volume. The actual volume sprayed was then compared to the volume required (application rate × area sprayed) for the test run to evaluate experimental error. Four replicates of each application rate were run to complete the study.

Recent Evaluations (2005 - 2009)

In 2005, tests were conducted to determine how closely to a pre-defined ground position that rate changes occur. This is obviously the most important evaluation for a GPS-triggered aerial flow control system since rate changes must occur at correct field boundaries in practice to prevent off-target application.

The AutoCal II automatic flow controller received ground speed and application rate from the Satloc system and adjusted the spray pump output to deliver the required flow to the boom based on speed, rate, and swath width. The flow controller was operated in automatic mode over a field prescription of four pre-set rates. The controller was set to control a hydraulically operated spray pump and was integrated with Satloc Airstar M3 guidance GPS set to update position every 0.2 sec. WSP cards were placed every 2-m along the flight path, and visual observation was used to determine where rate changes were made over several runs. A lead time of 0.5-s was used to trigger rate changes with respect to the system boundary to account for response lags inherent in the aircraft plumbing and GPS.

The spray system on the Air Tractor 402B was set with a special configuration of CP-09 deflector nozzles (CP Products Inc., Tempe AZ) to extend the range of operating flow rates. The final setup was fifty seven total nozzles (centers off) consisting of nineteen 0.078 orifices and thirty-eight 0.125 orifices.

In 2008, three sets of flights over the field prescription were made in both South-North and North-South directions; the AutoCal II was set to automatic mode. Flow responses by the AutoCal II to changing rates were observed and quantified. To make comparisons between the desired and actual flow rates, data from the AutoCal II output file were analyzed for each spray run. A conventional nozzle complement of fifty-seven CP-09 deflector spray nozzles with 0.078 orifices was set up on spray booms. The west side of the prescription field was used to test system response to changing rates on 18 August 2008. Results are represented both with and without the flowmeter monitor activated.

Results and Discussion

Early Experiments (ca. 2001)

AutoCal I performance was evaluated under controlled conditions (Smith, 2001). The results reflected ability of the system to identify and apply the desired

application rate. Ground speed during spray runs was maintained at 217 km/h (135 mph). Spray was initiated twice during each spray run, which covered about 11.6 ha (29 acres). All application rates were applied with the same calibration code and sensitivity settings. Experimental errors were computed from the measurements of water volume sprayed during the run. Experimental errors ranged from 0.78 to 1.55% and were not statistically different at the 0.05 level of probability. The maximum experimental error was 1.55% and occurred while applying the 37.4 L/ha (4 gal/acre) application rate.

Dynamic performance of the AutoCal I was also evaluated for accuracy in spraying field areas of varying length. All runs were made at the 18.7 L/ha (2 gal/acre) application rate. The maximum difference in ground speed that occurred while spraying replications of each treatment ranged from 35.4 km/h (22.0 mph) for the 15–pass treatment to 74.0 km/h (46.0 mph) for the 10–pass treatment. This level of speed variation was used in the test to evaluate the ability of the flow controller to track dynamic variations in flow requirements. Error in this test increased with number of spray passes, as would be expected. Every time the spray was initiated, there was a short time interval required for the flowrate to settle down to the required value. The experimental errors were not significantly different and had values ranging from 0.51 to 1.08% with the smallest value occurring for the five–pass treatment. Spray initiation was characterized by very little overshoot of required flowrate as actual flowrate increased from zero to 135 L/min (35.7 gal/min). Error between the required and actual flowrate curves was very small over duration of flight, and time constants of 0.28 to 0.32 s indicated that error for the spray run was reduced to 36.8% of its total algebraic sum in about 0.3 s. The AutoCal I tracked changes in ground speed from 154 to 228 km/h (95.7 to 142 mph).

Experimental error for the AutoCal II ranged from 0.64 to 1.60% for the treatments tested. In this test, application rate was varied from 9.4 to 88.9 L/ha (1 to 9.5 gal/acre). Ten spray passes were used to perform the application on 12.9 ha (31.8 acre) plots for each treatment. Controller response was similar to that of the AutoCal I as shown by the error–decay time–constant values. No significant difference was observed between treatments for experimental error.

New Experiments (2005-2009)

Figure 3 illustrates how well the flow control system tracked changing rates using the flow monitor at 0.1-s logging intervals. Tracking was quite good between the rates illustrated, but a lag in response like that shown for the initial rate change was typical. For a north-south run, an opposite and underdamped response was observed (Thomson et al., 2009a). Response seemed to depend on both the magnitude of initial flowrates and the flowrate differences. Integrated areas under the flowrate curves that signify total amounts applied to each prescription area showed good agreement with target-rate results for six passes over the prescription

zone. Errors between required and actual flow rate areas ranged from -1.0% to 2.1% with an absolute average (not considering sign) of 1.08%.

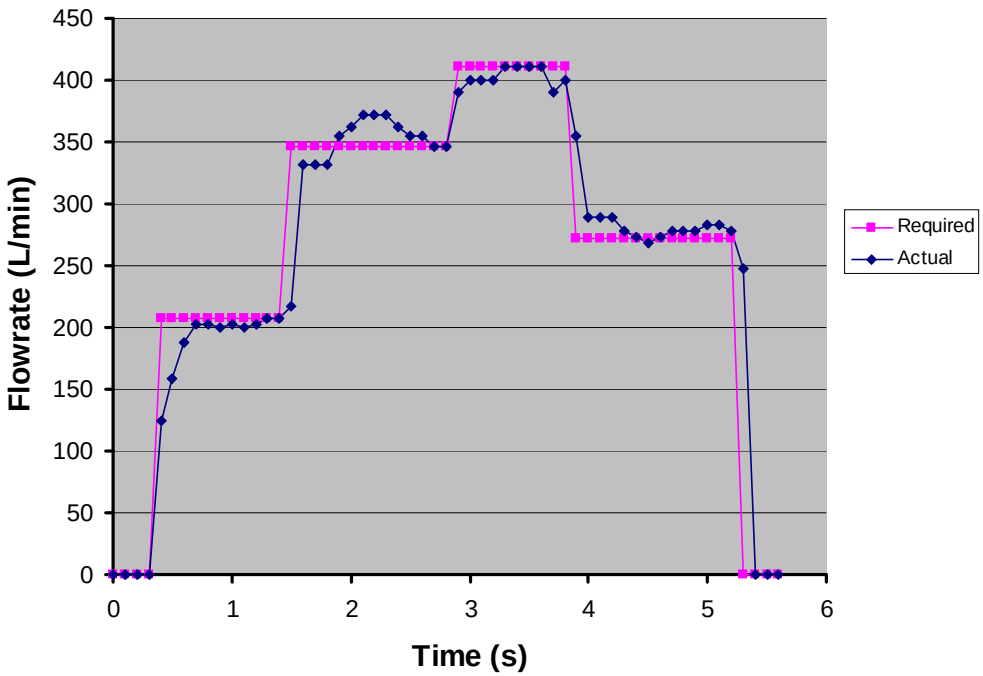


Figure 3. Typical system response to changing rates (south-north runs). Sensitivity 45; Ground speed 68 m/s (152 mph). Test was conducted 30 November 2005. Flow rates were logged by the flow monitor.

Observations of WSP showed that average spray deposition position error magnitude was 5.0 m when traveling east to west and 5.2 m when traveling north to south. Statistical analysis indicated that direction of travel had a non-significant effect on the magnitude of spray deposition position error. Placement variability over all runs was rather high for some runs (standard deviation ranging from 2.3 to 6.9 m), and this was attributed to limitations in the GPS updating interval. An updating interval of 0.2 s (5 Hz) translates into about 14-m at 70 m/s ground speed.

The AutoCal II has provisions for easy logging of flow data via serial port connection. This allows a user to compare as-applied flowrate to user-defined flowrate that is set manually or by field prescription. The high resolution flowmeter monitor used to generate Fig. 3 was designed mainly for research purposes and to allow greater resolution for analysis. Although monitor circuitry can be constructed, it would not be readily available to most users for logging flow controller data. For this reason, it is instructive to observe data as obtained only from the AutoCal II. Figure 4 illustrates both required and actual flowrates obtained and processed directly from the AutoCal II data file. Rate of data acquisition seemed to depend on the rate-of-change of flow readings, and flowmeter readings were averaged over those intervals. A status flag is also set in the output data file that indicates

which data acquisition interval (0.11 or 0.33 seconds) is active. It is clear that resolution of data acquisition was not as good as that illustrated in Fig. 3 but appears to be good enough to yield information for system evaluation. Calculated duration for the entire run based on ground speed was about 4.8s, and data represented by both Figs. 3 and 4 were very close to that value.

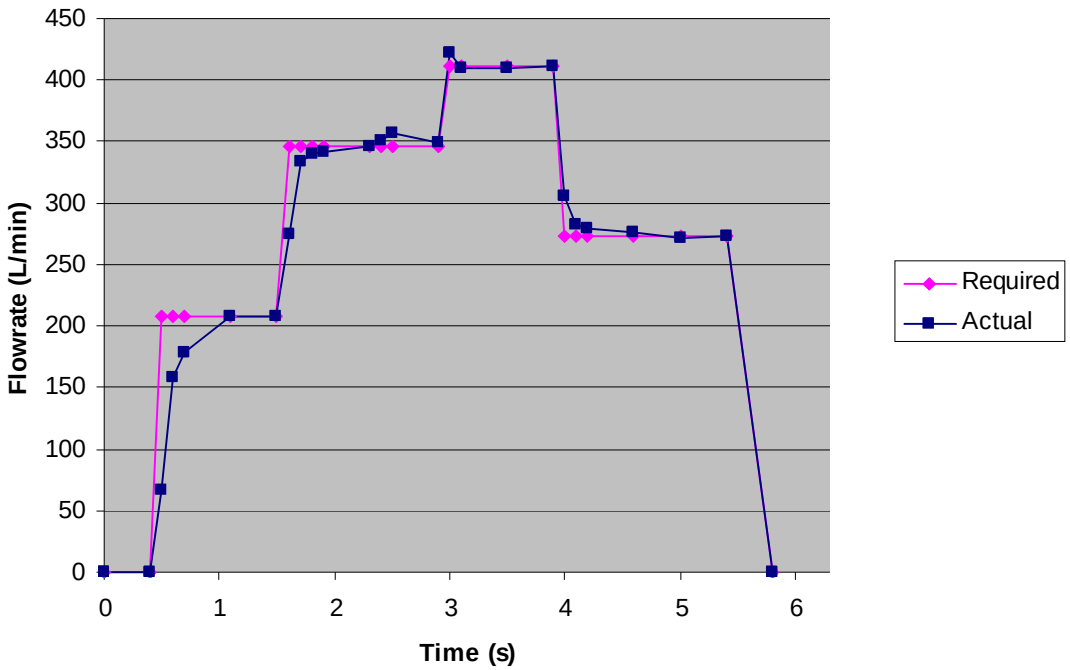


Figure 4. Typical system response to changing rates (south-north runs). Sensitivity 45; Ground speed 68 m/s (152 mph). Test was conducted 30 November 2005.

For runs conducted in 2008, timing over the entire run was not represented correctly when using the AutoCal II alone at irregular sampling intervals. Time intervals for individual flow rates varied between 1.2 and 1.66 seconds and total time for an entire run (Fig. 5) was represented as about 5.6s. This is 0.9s greater than the calculated interval represented correctly in Fig. 6 using the flow monitor. Timing intervals did not change in actuality; they were simply mis-represented in Fig. 5. It should be noted that flow capability was exceeded at the highest rate shown, as actual flow did not quite approach required flow. This was due to limited capacity of the nozzle configuration at the high ground speed.

Data from 2005 runs (Figs. 3 and 4) might help illustrate reasons for differences between the two flow counting methods. To reiterate, both the AutoCal II and flowmeter monitor represented integration times properly in these figures as timing for both matched expected values based on ground speed. Thus, inconsistencies in AutoCal II timing for the 2008 runs (Fig. 5) might be attributable to modifications to loop-timing portions of the AutoCal II control algorithm since the 2005 runs were conducted. These results indicate the utility of the flowmeter monitor for providing

consistent results on a temporal basis regardless of changes to firmware. This is in addition to its affording higher temporal resolution in representing flow data.

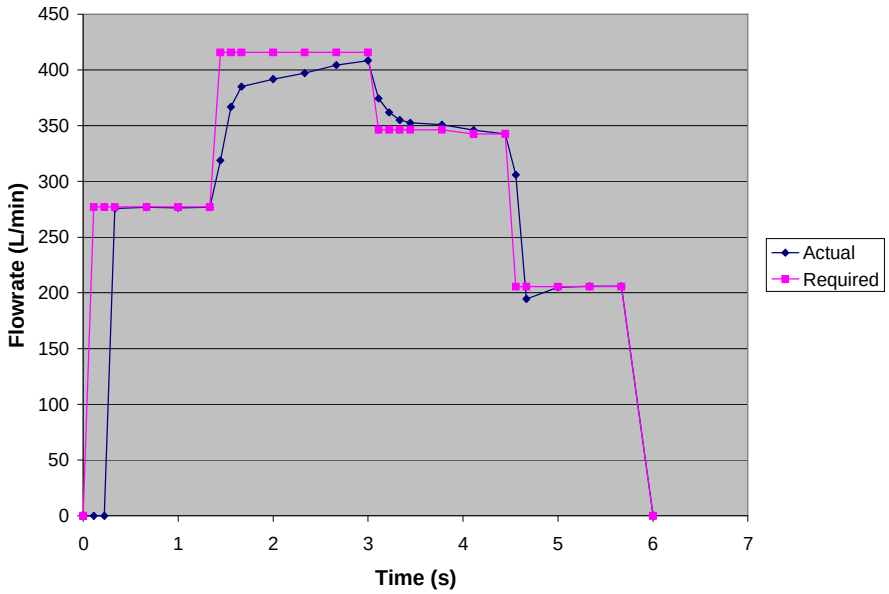


Figure 5. Typical system response to changing rates (north-south runs). Sensitivity 45; Ground speed 67 m/s (150 mph). Test was conducted 18 August 2008.

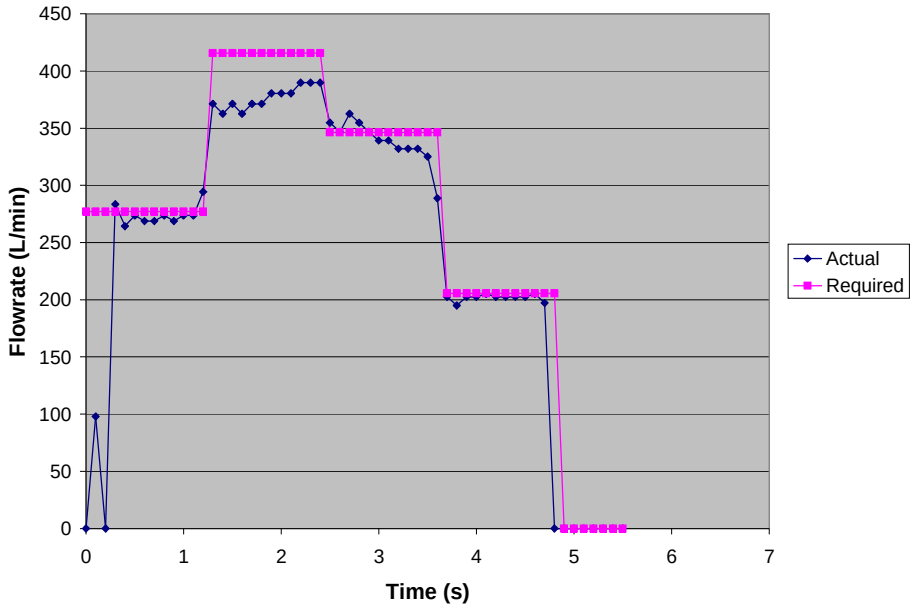


Figure 6. Typical system response to changing rates (north-south runs). Sensitivity 45; Ground speed 67 m/s (150 mph). Test was conducted 18 August 2008. Flow rates were logged by the flow monitor.

To help quantify improvements to control algorithms, areas under the flow rate-time curves were determined for each rate under the prescription and compared with each other before and after changes to the control algorithms were made by

the manufacturer. Changes in the algorithm were meant to smooth out responses and provide tighter control over a wide range of operating pressures (Graves, 2008). Percentage differences between actual and desired flow rate areas were consistently lower after program modification, and this can be illustrated by a typical controller response (Figs. 7 and 8) and integrated areas (Thomson et al., 2009b). There was also more variability between these integrated areas before program modification than after modification (Thomson et al., 2009b). Any ground speed differences between runs in the same direction would influence the calculated areas, but speed differences for all runs in the same direction were small (average difference = 2.2 %).

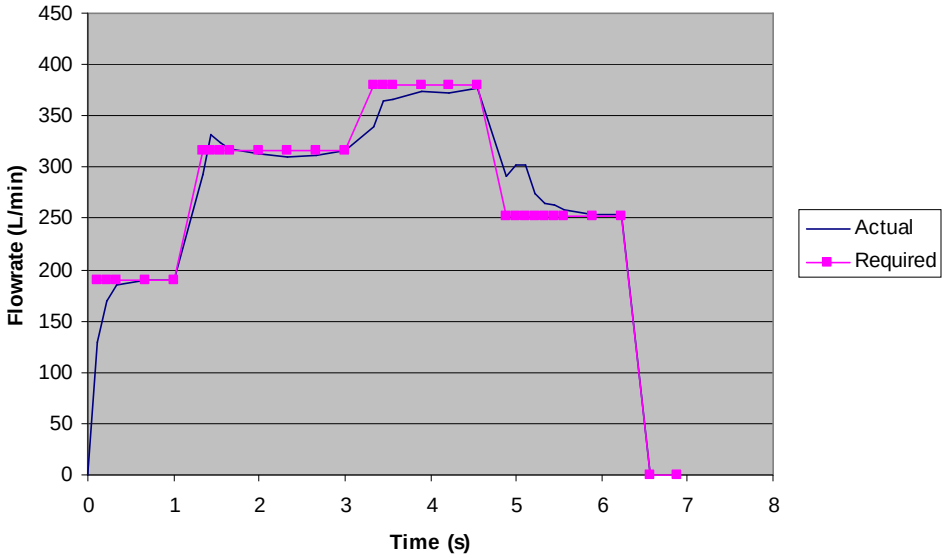


Figure. 7. Typical response of actual boom flow rate to step changes in required rate before control program modification. These data were captured by the AutoCal II while spraying a series of four management zones in the west lane of the prescription area from south to north. Sensitivity setting 46; Ground speed 62 m/s (139 mph). Test was conducted 18 August 2008.

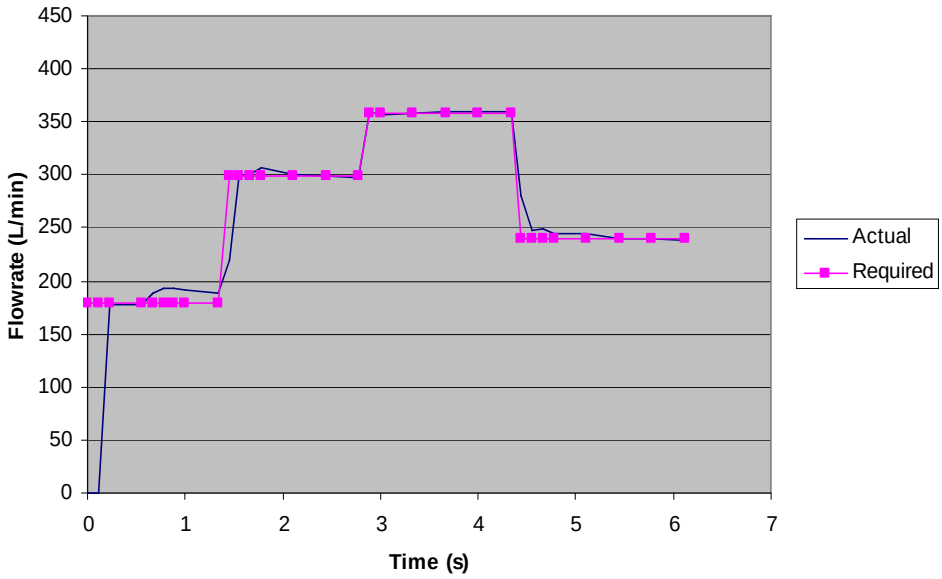


Figure 8. Typical system response to changing rates (south-north runs) after control program modification. Sensitivity setting 48; Ground speed 59 m/s (131 mph). Test was conducted 18 August 2008.

New Switchable Flow Routing System

Testing of flow controllers at the CPSRU thus far has involved the Satloc guidance system and AutoCal flow controller in various configurations. However, we are also interested in testing other guidance and flow control systems, so a switchable flow routing system was devised to permit this. Figure 9 depicts the first such installation for our Air Tractor 402B. For this setup, the Ag-Nav flow control valve w/flowmeter and AutoCal II flowmeter could be interchanged by un-hitching two clamps and installing the alternate system for testing purposes. Installation of the AutoCal II flow assembly required only a flowmeter and long adapter pipe since it controlled the spray pump hydraulically (Fig. 10). This system was rather cumbersome and prone to water leakage, however. Slight misalignment of pipes necessitated frequent readjustment to reduce the leaks.

Figure 9. Piping arrangement for interchanging flowmeters and valves. Ag-Nav flowmeter and valve are illustrated.

Figure 10. Hydraulically operated spray pump

Problems with the interchangeable setup required us to develop a dual-routed system with simple manually operated flow valves to allow routing of flow through one side or the other (Fig. 11). Our current requirements specify evaluation of only one system at a time, so automatic cockpit-controlled valves that would allow “hot switching” were not required although this could be considered as future needs arise. For our installation, the Satloc M3 is coupled with the AutoCal II and the Ag-Nav Guía guidance system uses its own in-line flow valve and flowmeter. The cockpit allows access to either guidance system and light-bar combination depending upon which system is being evaluated.

Figure 11. Dual piping system to allow switching of multiple flowmeters for different flow controllers

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