EVALUATION OF APPLICATION ACCURACY AND PERFORMANCE OF A HYDRAULICALLY OPERATED VARIABLE-RATE AERIAL APPLICATION SYSTEM

S. J. Thomson, L. A. Smith, J. E. Hanks

ABSTRACT. *An aerial variable-rate application system consisting of DGPS (Differential Global Positioning System)-based guidance, an automatic flow controller, and a hydraulically controlled pump was evaluated for response to rapidly changing flow requirements and accuracy of application. Spray deposition position error was evaluated by direct field observation of water-sensitive paper (WSP) cards while traveling east to west and north to south across rate change boundaries. Data from the flow controller and a custom-built flowmeter monitor were used to evaluate flow controller error and variable-rate system error while making applications to a series of four management zones (28, 47, 56, and 37 L ha^{-1}; each 81 m long). 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. Flow controller error and variable-rate system error were evaluated from data collected while making applications to a series of four management zones (each zone required approximately 1.2 s) with application rates of 28, 47, 56, and 37 L ha^{-1}. Areas under time plots of required and actual flow rates were compared and indicated flow controller error ranging from -1.0% to 2.1%. Variable-rate system error due to rate change timing was evaluated by comparing required rates from the system to required rates from the prescription. Area under time plots of these variables showed that average rate timing error for six application passes ranged from -9.1% to 1.4% with an average of -3.04%. Considering the speed at which changes have to be made for aircraft typically flying at 65 m s^{-1}, the hydraulically operated variable-rate system performed well for location accuracy of deposition, response to changing flow rates, and accuracy of application amounts for the prescription.*

Keywords. *Aerial application, Automatic flow control, Precision agriculture, Site-specific management, Variable-rate application.*

Prescription application with agricultural aircraft requires flow control and application systems that can change rates rapidly according to a field prescription and apply the correct rates of spray material within a management zone. Although variable-rate aerial application systems are in their comparative infancy, early work with ground-driven variable sprayers demonstrated that good accuracy could be obtained for targeted spraying and variable-rate application (Shearer and Jones, 1991; Hanks, 1996; Tian et al., 1999). Variable-rate ground application systems have long since been successfully commercialized (Raven, 2008), and precise application is possible from ground rigs that typically travel at ground speeds of 3 m s^{-1}. However, accurate application of material at the proper field location can be quite a challenge for aircraft that typically travel at ground speeds near 65 m s^{-1}. Automatic flow control and global positioning system receivers must respond rapidly to effect changes in spray rates at desired field boundaries.

Recently, fast-responding hydraulic flow systems for agricultural aircraft have demonstrated potential for effecting rapid flow changes based on input from swath guidance Global Positioning System (GPS) receivers. These GPS-based guidance systems can also read "prescription" files that define management zones and their associated properties (i.e., application rate and boundaries) within fields being sprayed. Prescription files are generated by marking field locations with desired spray rates within each specified polygon in a Geographic Information System (GIS). Software supplied by the guidance system manufacturer then converts the GIS shape file to prescription format, which can be interpreted by the swath guidance system. All system components (the GPS receiver, automatic flow controller, hydraulic actuators, and spray system plumbing) can contribute to application accuracy errors and response delays for a given flow control signal.

GROUND-BASED APPLICATION

The dynamic performance of GPS receivers has been studied by Taylor et al. (2004) and Han et al. (2004), but the emphasis was on cross-track error for ground-driven systems.

Submitted for review in October 2008 as manuscript number PM 7775; approved for publication by the Power & Machinery Division of ASABE in April 2009.

Mention of a trade name, proprietary product, or specific equipment does not constitute a guarantee or warranty by the USDA and does not imply approval of the product to the exclusion of others that may be available.

The authors are **Steven James Thomson, ASABE Member Engineer,** Research Agricultural Engineer, **Lowrey A. Smith,** Agricultural Engineer (retired), and **James E. Hanks,** Agricultural Engineer, USDA-ARS Application and Production Technology Research Unit, Stoneville, Mississippi. **Corresponding author:** Steven J. Thomson, USDA-ARS APTRU, P.O. Box 36, Stoneville, MS 38776; phone: 662-686-5240; fax: 662-686-5372; e-mail: steve.thomson@ars.usda.gov.

This aspect of position error was evaluated since the majority of applications for GPS systems in agriculture are related to machine guidance along parallel tracks. These studies used a real-time kinematic (RTK) GPS system with centimeter-level position accuracy as a reference for comparison to other GPS receivers mounted on the same platform as it was traversed over a test track. Taylor et al. (2004) compared a GPS receiver with dual-frequency correction to a receiver operated in autonomous mode (no differential correction) over a 24 h period at two different speeds and in opposite directions of travel on a fixed fixture (railroad). Differential correction reduced mean cross-track error from 1.348 m to 0.171 m. Han et al. (2004) compared the cross-track position error of eight GPS receivers as the test platform was driven on a straight line in the north-south direction to make six parallel passes that were 305 m (1000 ft) long. A total of 68 tests were made at different dates, different times of day, and at four different ground speeds (1.34, 2.24, 3.58, and 5.36 m s^{-1}). Four of the systems evaluated used the wide area augmentation signal (WAAS) for differential correction. Average cross-track error for the WAAS-corrected units ranged from 8 to 39 cm with a mean error of 16.5 cm. The lowest-speed test required approximately 30 min for completion, compared to approximately 9 min for the highest speed. Cross-track error tended to be larger for the lowest speed, and this was attributed to the greater time required for these tests.

Many studies have shown that application rate errors associated with boom injection systems result from transport lag (Zhu et al., 1998; Tompkins et al., 1990; and Miller and Smith, 1992). Transport lag is a function of the solution velocity and the volume of liquid in the hose between the injection point and the nozzle (Rockwell and Ayers, 1996). In pressure-based systems, transport lag refers to the time lapse between the request for change in application rate and the attainment of the new rate. Al-Gaadi and Ayers (1994) also classified the influence of lag on system response as delay time, which is the time required for the system to reach 10% of a step input, and response time, which is the time required to go from 10% to 90% of a step input. The sum of delay and response times is classified as reaction time (Rockwell and Ayers, 1996). Anglund and Ayers (2003) investigated the performance of a ground sprayer applying chemicals at constant and variable rates. Tests were performed on pressure-based spray systems as well as injection systems. Transport lag for pressure-based variable-rate systems was approximately 2 s due to GPS signal lag and control valve response lag. On injection-type variable-rate technology, the active ingredient lag time varied for each nozzle and ranged from 15 to 55 s. Results showed an average application rate within 2.25% of the desired rate.

Aerial Application

Accurately identifying where management zone boundaries are crossed by the spray plane is critical for aerial variable-rate application. Rate changes occur at these positions as the plane typically travels at high ground speeds ranging from 58 to 67 m s^{-1} (130 to 150 mph). Smith and Thomson (2005) evaluated position latency of the GPS receiver used in the Satloc Airstar M3 swath guidance system (Hemisphere GPS, Calgary, Alberta, Canada), which is an integral component of the variable-rate aerial application system. A light-sensing circuit was mounted on the plane and interfaced to the swath guidance system such that a record was logged as the plane passed over a vertical light beam emanating from a reference point on the ground with known position coordinates. The data log containing plane position coordinates associated with the light beam was then compared to the reference point position, and the distance between the points (measured longitudinally, in the direction of flight) was considered to be the position latency. Cross-track error was not considered because the airplane could not be confined to a specified flight line. This study found that the dynamic position latency (based on logged data from the system) was 7.9 m on average when traveling north or south and −4.5 m when traveling east or west. Increasing ground speed by 12% tended to increase the magnitude of position latency less than 1 m.

Many systems for variable-rate aerial application have been summarized by Barber (2007). In addition to dynamic GPS accuracy and overall system response time, accuracy of application at management zone boundaries can be assisted by calculation of spray release distance offset, which depends largely on meteorological factors (wind), spray release height, and droplet spectrum interactions. The Ag-Nav Flightmaster (Ag-Nav, Inc., Newmarket, Ontario, Canada) uses a drift compensation module to optimally determine flight line offset, and this is being marketed primarily for aerial adulticide sprays. Their system allows interfacing with several flow controller brands. ADAPCO (ADAPCO, Inc., Sanford, Fla.) offers an integrated system that also includes real-time meteorology and AgDISP (Continuum Dynamics, Inc., Ewing, N.J.) spray fate modeling onboard the aircraft, permitting real-time acquisition of data and instantaneous optimization of offset distance for spraying. Flow control makes use of meteorology data such as that obtained from an on-board Aircraft Integrated Meteorological Management System (AIMMS-20, Aventech, Inc., Barrie, Ontario, Canada). Distance offsets and altitudes for spraying are then resolved.

Hemisphere GPS (Calgary, Alberta, Canada) acquired Del Norte Technology, Inc., in early 2006 and has consolidated the two brands: its own brand (Satloc) and the Del Norte guidance and variable-rate flow control systems. Thus, many compatible options can be configured. The standard Satloc M3 (now simply called the Air M3) can be used with AirTrac software and with the AerialAce flow controller to effect variable-rate application. The Del Norte system components include the Air Flying Flagman and the Air Intelliflow variable-rate option. Both systems are similar in that they require a flowmeter, a GPS receiver, and an electric ball-valve to control boom flow rate.

The AutoCal II flow controller (Houma Avionics, Houma, La.) uses different technology to control flow rate, and can interface with all swath guidance systems. The AutoCal II controls boom flow rate by controlling the spray pump output. The spray pump is driven hydraulically from an engine-driven hydraulic power pack, and an electrically operated servo-valve controls the speed/output of the spray pump with a signal from the AutoCal II. A spray valve is actuated with an electrically controlled hydraulic cylinder operated by the pilot. The spray valve is fully opened (no bypass flow) when the plane enters the field to be sprayed, and the flow control adjusts the pump's output to the required flow rate for the application rate specified for each management zone.

The research reported on herein is the first known experimental evaluation of a hydraulically operated variable-rate aerial application system. Aerial applicators have begun, however, to document their field experiences with variable-rate aerial application. It was noted for one case study (Robinson, 2005) that a GPS updating interval of 0.2 s could only resolve rate changes to greater than 13 m distance on the ground, but this distance was still smaller than the grid size used to establish the variable-rate zones. In practice, spraying for a variable-rate aerial application system needs to be initiated before the boundary is reached to account for GPS lags and delays in hydraulic system response. A lead time of 0.75 s was used to compensate for this largely systematic error and was found to work well for an AirTractor 802 airplane traveling about 65 m s^{-1} perpendicular to the wind (Riddell, 2004). Riddell's airplane used a very similar complement of system components as those evaluated herein.

Variable-rate technology has been available to aerial applicators for several years but, as indicated, very little performance information on this technology has yet been published. Rate-change position error includes the uncertainty of the GPS system's capability for locating the zone boundary under dynamic conditions, the uncertainty of the variable-rate system for initiating rate change at the proper time, and the uncertainty of the application parameters, which include release height, ground speed, wind speed, and wind direction. The system must coordinate the processing and recording of information from the GPS receiver, prescription file, flowmeter, and spray system parameter values set by the pilot in order to implement control commands in a timely way that results in a successful spray job. GPS receiver performance is one component of the variable-rate system performance, but it may not reflect the overall performance of the system.

Objectives

The objectives of this study were to:

1. Evaluate position error of spray deposits relative to management zone boundaries where rate changes occur.
2. Evaluate response time of the variable-rate controller to step changes in flow rate.
3. Evaluate variable-rate flow accuracy by comparison with target prescription amounts.

To meet these objectives, experiments or methods are summarized for each objective as follows:

1. Position error of application was evaluated using water-sensitive paper (WSP) positioned at 2 m intervals in the field so the location of spray rate changes (from zero flow to a predetermined rate) could be determined by observation of WSP.
2. Response time of the flow controller to step changes in flow was determined by flying a pre-set field prescription. Target rates were compared with flowmeter output rates over six spray passes in alternating directions.
3. Required amounts as defined by the variable-rate system were obtained by integrating the area under flow rate vs. time curves. These amounts were compared with target prescription amounts over the same intervals.

Materials and Methods

The swath guidance system described herein used a GPS receiver to determine the current position and ground speed of the spray plane and then accessed the prescription file to determine the required application rate at that position. Speed and required rate were then communicated to the flow controller, which computed the required boom flow rate and adjusted the actual flow to the required rate. The GPS receiver was used to guide the pilot along the proper spray swath, monitor ground speed, and identify management zone boundaries where application rates should change. The aerial variable-rate system used in this study consisted of the Hemisphere Satloc M3 swath guidance system running AirTrac software that was designed to implement variable-rate application. The Satloc GPS receiver used WAAS for differential correction and updated position at 5 Hz. 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 spray system on the Air Tractor 402B was set with a special configuration of CP-09 deflector nozzles to extend the range of operating flow rates. This setup was needed to accommodate the wide range of pressures encountered when changing flow rates from 28 to 56 L ha^{-1} (3 to 6 gal $acre^{-1}$). The final setup was 57 total nozzles (centers off) consisting of nineteen 0.078 orifices and thirty-eight 0.125 orifices. The spray system was customized by installing 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. The spray valve was also operated electrically with a toggle switch mounted on the aircraft control stick. Variable-rate operation required the development of a prescription file that specified the areas of the field to receive different application rates.

Flow Control and Data Acquisition

Performance of the system was evaluated using data generated by the automatic flow control system, data from flowmeter circuitry (hereafter called FMC) to read the flowmeter at 10 Hz and time-stamp each record using a real-time clock, and data from water-sensitive cards to physically define the where spray was deposited relative to rate-change boundaries marked off in the field. The FMC, designed by the second author, was added because the AutoCal flow controller in its present form generates data records (serial output) at irregular time intervals depending on which of two control loops is running within the controller software. However, the time intervals for each loop (fractions of a second) are known, and a status flag in the AutoCal output data file indicates which of the two loops is running, so the number of readings of target flow rate (received by the Satloc and logged by the AutoCal) can be counted within each timeframe and matched one-to-one to actual flow rate obtained directly from the flowmeter at 10 Hz for comparison. It should be noted that comparisons could also have been made between the readings without circuitry and using actual flow rate (logged via the AutoCal at irregular time intervals), but reading the flowmeter directly at 10 Hz (0.1 s) improved resolution, which was found to be especially important during rapid rate changes.

Flowmeter readings by the FMC were based on the measurement of elapsed time between consecutive turbine-wheel blade passes through the magnetic field of the flowmeter proximity sensor. This time was measured by gating a 250 kHz signal generated by a crystal-controlled oscillator to a counter during this period. Simulating the flowmeter signal with equivalent output from a signal generator demonstrated that the circuit was accurate within 1 period of the 250 kHz signal; therefore, the interval between blade passes was measured with an accuracy of 4 μs. The time required for one blade pass could be converted to gallons per minute by using the calibration constant of 45.47 blade passes per gallon. A Basic Stamp micro-controller (BS2p-24, Parallax, Inc., Rocklin, Cal.) was used to read the flowmeter and real-time-clock. The raw data were converted to desired units and then output through a serial port at a 10 Hz rate for capture by an HP IPAQ HX-4700 Pocket-PC. A 10 Hz timing signal, generated by the oscillator, was applied to an input pin of the microcontroller to control the output interval of the data records. These records were captured to the hard drive of a notebook computer using Windows Hyperterminal software and included values of actual flow rate, required flow rate, and ground speed. The FMC produced records at 0.1 s intervals that included the current time and flow rate to the boom, and this output was captured with a Pocket-PC using ZTERM CE software (www.tsreader.com/legacy/). The apparatus is illustrated in figure 1, and circuit diagrams are available from the first author by request.

Description of Test Area for All Experiments

The test area used for evaluating the aerial variable-rate system was established on a field that measured approximately 506 × 271 m (1660 × 890 ft). This area was seeded to Bermuda grass such that spray test sampler lines could be established relative to any wind direction. A prescription was established for testing purposes that included management zone sizes ranging from 81 to 162 m in length and application rates ranging from 0 to 56 L ha^{-1} (fig. 2). A 0 L ha^{-1} rate was assigned to buffer zones on both ends of the prescription area to provide time for the spray boom to be turned on/off by the pilot when entering or exiting the prescription area. Corners

Figure 1. Data acquisition equipment on the airplane.

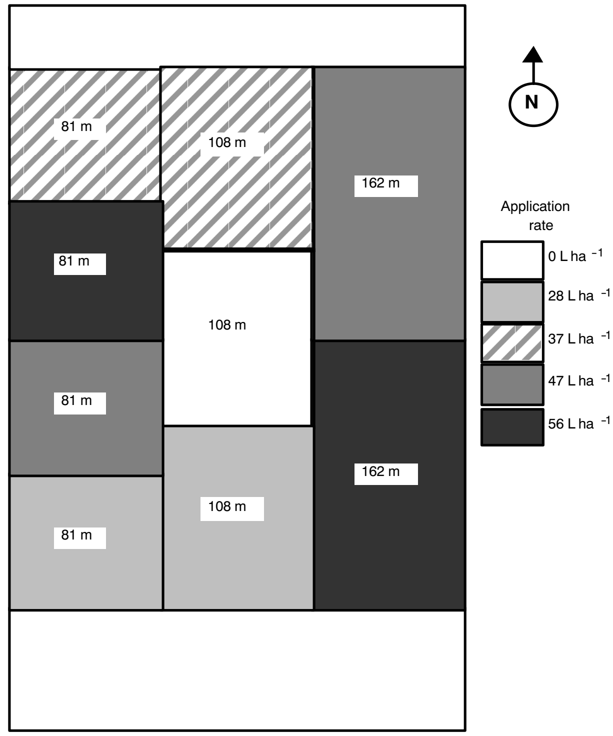

Figure 2. Layout of management zones in test area used for aerial variable-rate performance testing. The test area (324 × 255 m) includes nine management zones laid out in three lanes (85 m wide) with lengths as indicated in the figure. Application rates ranging from 0 to 56 L ha^{-1} were assigned to zones as indicated in the legend. Buffers across the north and south ends of the test area served to give uniform initial conditions for entering the test area from either direction.

of the rectangular management zones were located on the ground using Trimble MS-750 RTK receivers with Sitenet 900 radio (cm level accuracy) referenced to a base station positioned over U.S. Coast and Geodetic Survey Satellite Triangulation Station No. 133, which is established 3.68 km from the test area. After locating the management zone corners, steel rods were driven into the ground to permanently mark them.

Aircraft and Field Setup for Evaluating Accuracy of Spray Deposition

WSP cards (3 × 5 cm) were supported on 12 horizontal samplers positioned at 2 m intervals on either side of a chosen rate change boundary, for a total of 25 samplers at ground level (fig. 3). Droplets on the WSP were observed visually to evaluate position error. Preliminary testing showed that a defined boundary (spray or no spray) could be easily determined in this way. The WSP cards were positioned in either east-west or north-south directions, depending on the flight direction required for evaluation. Position error was also estimated from FMC timing data and ground speed data from the AutoCal II.

Visual observation of several north-south runs with the flow controller turned on indicated that a lead time for spray initiation of 0.5 s was required. This value was set in the Air-Trac software to account for the combined effects of inherent flow system delays and GPS lags after initiation of liquid flow. We initially used the 0.75 s lead time as a starting point (Riddell, 2004) and trimmed it back until we obtained a suitable setting for our airplane. Riddell (2004) used a larger Air

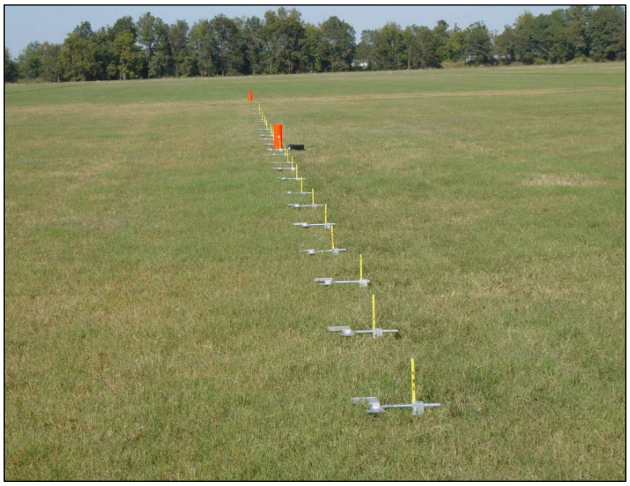

Figure 3. Layout of WSP and target marker at the field boundary.

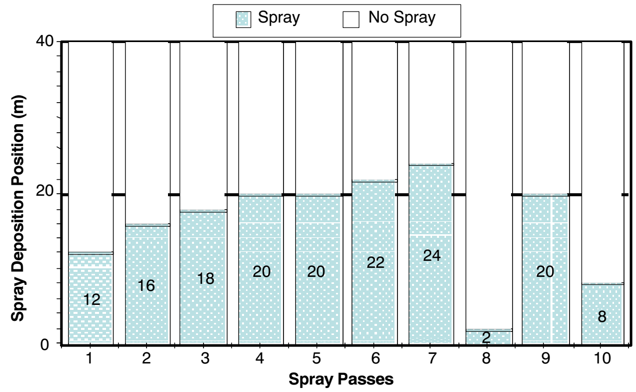

Figure 4. Spray deposition relative to a rate change boundary located at the 20 m position as determined with 25 WSP spaced at 2 m intervals. Application rate was 56 L ha^{-1} at positions less that 20 m and 0 L ha^{-1} at positions greater than 20 m. The direction of travel for all spray passes was from east to west (0 to 56 L ha^{-1}).

Tractor 802, so it stands to reason that his system may have required a longer lead time to overcome additional lag due to more extensive plumbing of a larger airplane.

The deposition accuracy experiment was conducted over two days, 13 October 2005 (east to west runs) and 26 October 2005 (north to south runs). Flight direction was set perpendicular to the prevailing wind so that the wind-induced component of spray offset error would be minimized. East-west spray passes (13 Oct. 2005) were conducted in the afternoon between 14:04 to 14:41; the prevailing wind was from the N-NE. The north-south spray passes (26 Oct. 2005) were made from 13:16 to 13:58, when the prevailing wind was from the east. The aerial variable-rate system was tested by making application passes over a rate-change boundary between two of the management zones shown in the prescription layout (fig. 2). Blocks in the prescription layout were chosen for application rate changes of 0 to 56 L ha^{-1} for east-west runs and 0 to 28 L ha^{-1} for north-south runs. Spray deposition on the WSP was observed as flow automatically switched between zero flow and the desired rate. Locations where “no flow” vs. “full rate” occurred could easily be seen on the cards, as there was a well-defined demarcation. The east-west test used 25 samplers (ten applications), and the north-south test used 21 samplers (five applications). Previous test results (Smith and Thomson, 2005) demonstrated differences in dynamic GPS position latency with respect to direction of flight, so we were interested to see if observed differences were propagated to affect deposition accuracy.

Results and Discussion

Accuracy of Spray Deposition

Ten spray passes were made with identical setup parameters to evaluate the variability and magnitude of deposition position error. Figure 4 shows spray deposition position relative to the rate change boundary (20 m position) when making applications in an east to west direction. Application rate automatically changed from 0 to 56 L ha^{-1} when the boundary was reached. Deposition position error ranged from −18 m to +4 m, where the negative error denotes spray initiation after reaching the rate change boundary and the positive error denotes early initiation of spray. Absolute position error averaged 5.0 m for the ten spray passes; standard deviation of error magnitude was 6.9 m. The algebraic average (including sign) of deposition position error was −3.8 m, indicating a system response lag. Average ground speed for these spray passes was 63.9 m s^{-1}; therefore, the system tended to delay spray initiation by 0.05 s, on average.

A 0.5 s lead time set for spraying appears to be appropriate, as evidenced by the results in figure 4. If the largest difference (pass 8, which is greater than two standard deviations from the mean) is removed, the algebraic average reduces to −2.2 m. The GPS position updating interval of 0.2 s limits the usable grid size within which changes can be made. An interval of 0.2 s corresponds to an approximate travel distance of 12.8 m, so a portion of the larger errors observed for three of the spray passes (−8, −18, and −12 m) may be due to this updating interval limitation. Rate change communication and response of the flow controller to the rate change are other possible sources of this error. With the current setup, there is no way to evaluate the time required for the flow controller to respond to a new application rate communicated to it by the Satloc system.

Results from the second test (north-south) are shown in figure 5. Spray deposition position error ranged from −8 m to 6 m with an algebraic average of −2.8 m and an absolute aver-

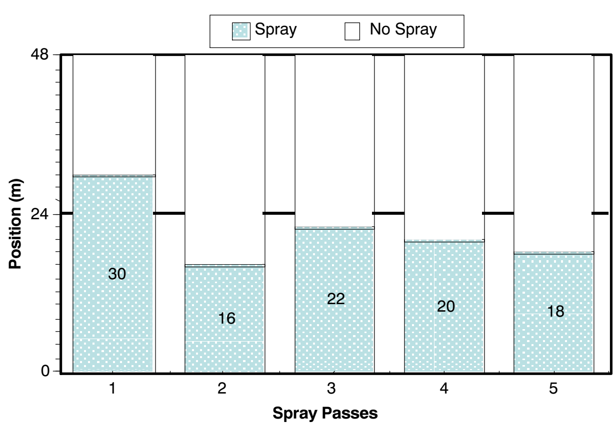

Figure 5. Spray deposition position relative to a rate change boundary located at the 24 m position as determined with 25 WSP spaced at 2 m intervals. Application rate was 28 L ha^{-1} at positions 0 to 24 m and 0 L ha^{-1} at positions 24 to 48 m. The direction of travel for all spray passes was from the 48 m position toward the 0 m position (north to south).

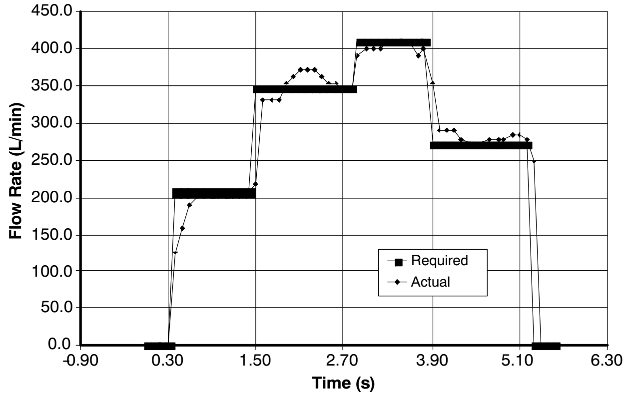

Figure 6. Typical response of actual boom flow rate to step changes in the required flow rate. These data were captured while spraying a series of four management zones with application rates of 28, 47, 56, and 37 L ha^{-1} (209, 350, 418, and 276 L min^{-1}) in the west lane of the prescription area (fig. 2) from south to north. Ground speed during this spray pass was 67.9 m s^{-1} (152 mph), and a 0.5 s lead time was used. Vertical grid lines represent management zone boundaries based on time required to travel 81 m.

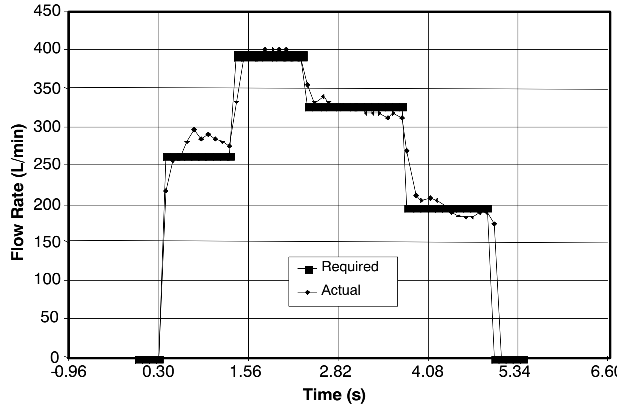

Figure 7. Typical response of actual boom flow rate to step changes in the required flow rate. These data were captured while spraying a series of four management zones with application rates of 37, 56, 47, and 28 L ha^{-1} (209, 350, 418, and 276 L min^{-1}) in the west lane of the prescription area (fig. 2) from north to south. Ground speed during this spray pass was 64.3 m s^{-1} (144 mph), and a 0.5 s lead time was used. Vertical grid lines represent management zone boundaries based on time required to travel 81 m.

age of 5.2 m. The standard deviation of deposition position error magnitude was 2.3 m.

Statistical analysis of deposition position error magnitude from these tests (north-south versus east-west) showed no significant differences in treatment means (F = 1.78; P = 0.2528). This indicates the similarity of variable-rate system response to rate change boundaries for all flight directions; therefore, a constant lead time irrespective of flight direction can be used. The effect of flight direction on dynamic GPS position latency may have been influenced by availability of satellites in the north (Thomson et al., 2007) or direction-specific distortions in the Universal Transverse Mercator (UTM) WGS84 ellipsoid model approximating the geoid (Ewing and Mitchell, 1970). It should be noted that our UTM Zone 15 is very close to the edge of Zone 16, so edge distortions influencing the ellipsoid model could have been a factor in geo-positioning accuracy. Data logging logistics associated with software execution could also be a factor in GPS latency, but it is not clear how this could influence direction-specific differences.

Flow Controller Response and Accuracy

Data from the FMC and the AutoCal II (captured while spraying the west lane of the prescription) were combined to plot the required and actual flow rate versus time. A total of six spray passes were made in alternating directions. Representative plots while traveling in each direction are presented in figures 6 and 7. The required application rates are mirror images of each other since the applications were made from opposite directions. Flow controller response to the 0 to 28 L ha^{-1} (3 gal acre^{-1}) rate change was overdamped (fig. 6), but the response to the 0 to 37 L ha^{-1} (4 gal acre^{-1}) rate change did not show this characteristic (fig. 7). If anything, the response shown in figure 7 was slightly underdamped.

A likely explanation for the overdamped response (fig. 6) is the combined effect of the control approach used and the type of spray pump. The approach used by the flow controller was to adjust the pump output to achieve the required flow rate. As the prescription area was entered, the pilot manually toggled a switch on the flight control stick to completely open the boom valve. Pump output was controlled by the application of voltages (proportional to the flow rate required) to a hydraulic servo valve that controlled the flow rate of hydraulic fluid to the hydraulic motor driving the spray pump. With the system configured this way, a zero application rate requirement caused the pump to be turned off, but the boom valve remained in the open position. Rate change to a non-zero value required the spray pump to overcome static condition of the spray mix and get it moving through the plumbing and out of the boom. A centrifugal pump was used to pump the spray mix, and the efficiency of this type of pump increases as its rotational speed increases. Therefore, more time would be required to achieve a change (from zero) of 200 L min^{-1} (fig. 6) than to achieve a change of 250 L min^{-1} (fig. 7) due to the lower efficiency associated with the lower rotational pump speed. The overdamped response was not apparent at flow rates of 250 L min^{-1} and above. These results have prompted the manufacturer to consider a revised approach for flow control that keeps the pump operating and closes the boom valve to achieve zero-flow requirements. With the boom valve in the closed position, flow to the boom is shut off and the pump output recirculates to the hopper. This approach has the advantages of maintaining fluid momentum through the pump and having non-zero pressure available for initiating spray when the boom valve is opened.

Direct measures of the average flow controller accuracy were made by numerically integrating the area under the time plots of required flow rate and actual flow rate. Two such time plots are illustrated in figures 6 and 7. Table 1 presents the areas under the curves and the average flow control error for each of six spray passes. Average error for each pass ranged from −1.0% to 2.1%, and the overall average error over the six passes was 0.75%. Average error not considering sign was 1.08%. Considering that the four management zones were traversed in approximately 1.2 s each and that required rates for each zone ranged from 28 to 56 L ha^{-1}, an average application error of 1.08% was excellent.

Variable-Rate System Accuracy

Flow controller accuracy is a major component of variable-rate system accuracy, but all systems including the flow controller, guidance system, and hydraulic pump and

Table 1. Area under flow rate vs. time curves comparing accuracy of flow controller response to step changes in required flow rate as defined by the variable-rate system. Data were collected while making six spray passes over a series of four management zones (each 81 m in length, requiring approximately 1.2 s) with application rates of 28, 47, 56, and 37 L ha^{-1}. Area values represent the average response for each pass and were computed by numerical integration techniques using 0.1 s time intervals.

Pass	Actual Flow Rate Area [(L min^{-1}) × s]	Variable-Rate System Required Flow Rate Area [(L min^{-1}) × s]	Percent Error (%)
1	1517	1506	0.7
2	1373	1349	1.8
3	1458	1429	2.1
4	1402	1416	-1.0
5	1480	1472	0.5
6	1481	1474	0.4
Average			0.75
|Average|			1.08

Table 2. Area under flow rate vs. time curves comparing the required flow rate defined by the variable-rate system to the required flow rate defined by the prescription. Data were collected while making six spray passes over a series of four management zones (each 81 m in length, requiring approximately 1.2 s) with application rates of 28, 47, 56, and 37 L ha^{-1}. This comparison is an indication of the error in the variable-rate system relative to synchronizing rate changes with the management zone boundaries.

Pass	Variable-Rate System Required Flow Rate Area [(L min^{-1}) × s]	Prescription Required Flow Rate Area [(L min^{-1}) × s]	Percent Error (%)
1	1506	1485	1.4
2	1349	1485	-9.1
3	1429	1490	-4.1
4	1416	1483	-4.5
5	1472	1490	-1.2
6	1474	1485	-0.7
Average			-3.04
|Average|			3.50

actuators work together to ensure that the correct rates are applied at the correct field location. Timing associated with determination of position and ground speed, determination of prescription file application rates for approaching management zone boundaries, and communication of rate changes to the flow controller are all factors that influence application and position accuracy. If all processes are performed within a consistent time frame, then lead time in the software can be used to help compensate for them and allow rate changes to be synchronized with the physical boundaries of the management zones.

Required amounts as defined by the variable-rate system were compared with amounts required by the prescription (table 2). Application amounts required by the prescription in each management zone were calculated by:

$$\frac{\text{Length of prescription zone (m)} \times \text{Required rate (L min}^{-1})}{\text{Ground speed (m s}^{-1})}$$

These amounts for each of four zones were added together, and the final result was compared with the variable-rate system required rate (table 1) as numerically integrated from the AutoCal plot (as illustrated in fig. 6). A comparison of prescription rates to the variable-rate system rates communicated to the flow controller revealed that rate error ranged from −9.1% to 1.4% for the six spray passes. Average error across the six passes was −3.04%. This error was almost four times the magnitude of the flow controller error and represented the combined influence of factors mentioned above that affected the timing of rate changes relative to the management zone boundary. One possible source of additional error that is included in this type of error, but could not be evaluated with the current setup, was delay in flow controller response to rate changes communicated to it by the system. No indication of controller delay was observed in the captured data; however, some delay could have been present.

Summary and Discussion

The performance of a hydraulically operated variable-rate system consisting of a Hemisphere Satloc M3 with AirTrac software with WAAS-corrected DGPS, an AutoCal II automatic flow controller, and Kawak Aviation Technologies hydraulically controlled spray pump/valve package was evaluated for application accuracy. This system was installed on an Air Tractor 402B agricultural aircraft. Spray deposition position error was evaluated by direct field observation of WSP while traveling east to west and north to south across rate change boundaries. Data from the AutoCal automatic flow controller and a custom-designed flowmeter circuit that permitted a constant data sampling rate were used to evaluate flow controller error and variable-rate system error while making applications to the west lane of the test area prescription (four zones, 81 m long; 28, 47, 56, and 37 L ha^{-1}).

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 spray deposition position error magnitude. Flow controller and variable-rate system errors were evaluated from data collected while making applications to a series of four management zones (each zone required approximately 1.2 s) with application rates of 28, 47, 56, and 37 L ha^{-1}. Areas under time plots of required and actual flow rates were compared and indicated flow controller error ranging from −1.0% to 2.1% with an average of 1.08%. Variable-rate system error due to rate change timing was evaluated by comparing required rates from the system to required rates from the prescription. Area under time plots of these variables showed that average rate timing error for six application passes ranged from −9.1% to 1.4% with an average of −3.04%.

Considering the ground speed at which rate changes need to be made, performance of the variable-rate system was very good. For the ground positioning tests, larger errors observed for three of the spray passes (−8, −18, and −12 m) may have been due to limitation in the 0.2 s updating interval (corresponding to 12.8 m) as indicated.

Hemisphere GPS now has guidance systems that update position at up to 20 Hz and algorithms for increasing accuracy of GPS position. Some firmware options for increasing accuracy require a base station, rover, and transmission of corrections. Many guidance system manufacturers now have 10 Hz updating as standard.

A GPS receiver with faster updating could possibly improve the timing for application at rate-change boundaries over the 5 Hz updating used herein, since the flow controller as presently designed depends on GPS position updating to effect rate changes. However, utilizing position interpolation between 5 Hz updates might be just as effective, since the airplane travels at an essentially constant ground speed between updates. Although not documented by Hemisphere GPS, we suspect that position interpolation is used to log flow events at 0.01 s intervals (100 Hz) in the Satloc data file.

A limitation of any aerial variable-rate application system is that conventional nozzles will be operating outside their optimal pressure ranges at some flow rates. This could adversely affect droplet size distribution, causing either a higher propensity for off-target drift (too many fines) or lower application efficacy (too many large droplets). Controller response could also be affected at different operating pressures. A nozzle is available for ground applicators that is designed to keep a consistent droplet spectrum regardless of pressure (SprayTarget, 2009), but no nozzle seems to be available to accommodate the different flow/pressure relationships for aerial application. This would not be an issue for "on/off" control, which is also a likely mode of operation for a variable-rate system. Along with system flow rates that are available in the guidance system log file, it would also be useful to continuously monitor fluid pressure at various places along the flow path for controller and spray system diagnostics. For this purpose, we are developing self-contained pressure transducer and logging monitors that can be placed anywhere along the boom.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the assistance of Phelesia Foster, Roger Bright, Earl Franklin, Lindsey Sheffield, and Andrea McNeal for field layout and data collection. We also greatly appreciate the dedication of David Poythress in piloting the aircraft according to the requirements of the research plan.

REFERENCES

Al-Gaadi, K. A., and P. D. Ayers. 1994. Monitoring controller-based field sprayer performance. *Applied Eng. in Agric.* 10(2): 205-208.

Anglund, E. A., and P. D. Ayers. 2003. Field evaluation of response times for a variable-rate (pressure-based and injection) liquid chemical applicator. *Applied Eng. in Agric.* 19(2): 273-282.

Barber, L. 2007. Precision ag: The future of aerial application. *Agric. Aviation* 34(2): 16-20. Available at: www.agaviation.org/MagazineFeatures/Mar%20Apr%20Precision%20Agriculture.pdf.

Ewing, C. E., and M. M. Mitchell. 1970. *Introduction to Geodesy.* New York, N.Y.: American Elsevier.

Han, S., W. Zhang, H. Noh, and B. Shin. 2004. A dynamic performance evaluation method for DGPS receivers under linear parallel-tracking applications. *Trans. ASAE* 47(1): 321-329.

Hanks, J. E. 1996. Smart sprayer selects weeds for elimination. *Agric. Res.* 44(4): 15.

Miller, M. S., and D. B. Smith. 1992. A review of application error for sprayers. *Trans. ASAE* 35(3): 787-791.

Raven. 2008. Raven precision solutions–Application controls. Sioux Falls, S.D.: Raven International. Available at: www.ravenprecision.com/us/Products/productCat1.jsp?cat1=4.

Riddell, P. 2004. Personal communication. West Helena, Ariz.: Riddell Flying Service.

Robinson, E. 2005. Aerial variable-rate applications proving their worth. *Delta Farm Press* (April 28). Available at: http://deltafarmpress.com/news/050428-aerial-vr/.

Rockwell, A.D., and P. D. Ayers. 1996. A variable rate, direct nozzle injection field sprayer. *Applied Eng. in Agric.* 12(5): 531-538.

Shearer, S. A., and P. T. Jones. 1991. Selective application of postemergence herbicides using photoelectrics. *Trans. ASAE* 34(4): 1661-1666.

Smith, L. A., and S. J. Thomson. 2005. GPS position latency determination and ground speed calibration for the Satloc Airstar M3. *Applied Eng. in Agric.* 21(5): 769-776.

SprayTarget. 2009. VariTarget variable-rate nozzle. Rosemount, Minn.: SprayTarget. Available at: www.spraytarget.com.

Taylor, R. K., M. D. Schrock, J. Bloomfield, G. Gora, G. Brockmeier, W. Burton, B. Carlson, J. Gattis, R. Groening, J. Kopriva, N. Oleen. J. Ney, C. Simmelink, and J. Vondracek. 2004. Dynamic testing of GPS receivers. *Trans. ASAE* 47(4): 1017-1025.

Thomson, S. J., L. A. Smith, and J. E. Hanks. 2007. An instrumentation platform and GPS position latency issues for remote sensing on agricultural aircraft. *Trans. ASABE* 50(1): 13-21.

Tian, L., J. F. Reid, and J. W. Hummel. 1999. Development of a precision sprayer for site-specific weed management. *Trans. ASAE* 42(4): 893-900.

Tompkins, F. D., K. D. Howard, C. R. Mote, and R. S. Freeland. 1990. Boom flow characteristics with direct chemical injection. *Trans. ASAE* 18(3): 439-443.

Zhu, H., R. D. Fox, H. E. Ozkan, R. D. Brazee, and R. C. Derksen. 1998. A system to determine lag time and mixture uniformity for inline injection sprayers. *Applied Eng. in Agric.* 14(2): 103-110.