

# Technology to Improve Sprayer Accuracy

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A number of new technologies have been introduced over the last several years aimed at improving the accuracy of spray application, but do they really work? The purpose of this document is to highlight the most common causes of application errors then discuss the array of new sprayer technologies that are becoming available, how they might affect application accuracy, and pitfalls involved in using them.



## What are we really trying to do?

Before talking about gizmos and gadgets, all operators should really understand what they are trying to accomplish in the field. The main goal of any spray application is to apply a certain amount of a concentrated chemical product to a field as uniformly as possible within the target area. Along with that goal, it is often critical to precisely control the dilution of that product as well as the droplet size of the diluted product as it is deposited on plants or soil. These together will affect the efficacy or effectiveness of the chemical that is applied. This all must be done while minimizing the amount of material that does not hit the target either by drift or errant placement.

The fundamental mathematical relationship that governs application rate is shown in Figure 1.

**Application rate**, which is the amount of material we want to apply, is often expressed as gallons per acre or quarts per acre. **Flow rate** is the amount of material that is coming out of a nozzle per unit of time; it is typically measured with a cup and a stopwatch during calibration pro-

cedures and is reported in units such as gallons per minute. Flow rate is a function primarily of the size of the orifice (hole) in the nozzle and the fluid pressure at the nozzle. **Speed** is simply how fast the machine is moving. Flow rate and speed must be controlled together to maintain accuracy, e.g. slowing the machine without reducing flow rate will cause an over-application of chemical.

Flow rate can be increased by increasing the pressure, but that also decreases the droplet size in the spray pattern. Smaller droplets are sometimes needed. For example, many contact fungicides and herbicides are more effective with lots of small droplets covering as much of the surface of the target as possible while some soil-applied herbicides are still effective with fewer larger drops. The problem with smaller droplets is that they are more susceptible to drift. Because of all these conflicting factors, the configuration of the sprayer in terms of nozzle type and size, operating pressure, and forward speed is often challenging and expensive. Several of the new technological developments are meant to help give the operator more flexibility in

controlling droplet sizes, flow rates, and operating speeds.

## Causes of Application Errors

Five fundamental issues cause inaccuracy of spray applications:

1. System calibration
2. Off-target application
3. Response of flow controllers to on/off and rate change commands
4. Speed differential across the boom during turns
5. Boom height

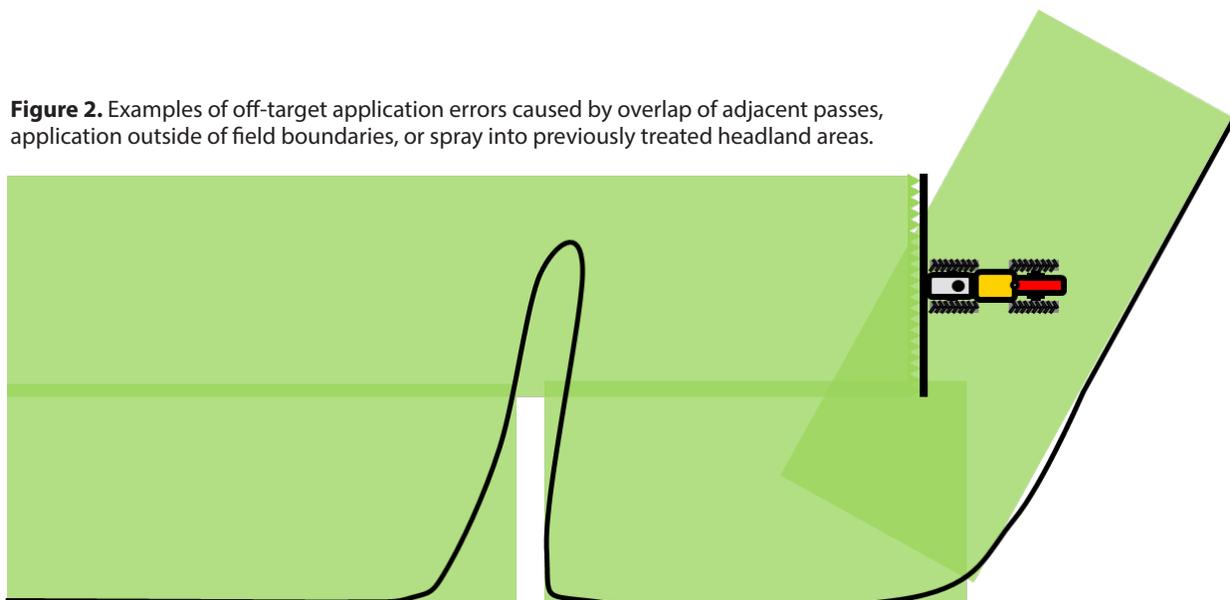
### 1. System Calibration

Calibrating the sprayer is the first and most fundamental step that should be taken to insure accurate application. The goal when calibrating a sprayer is to correlate the actual flow rate and speed with machine settings and/or sensor outputs. Sprayer controller manufacturers typically give clear explanations of calibration procedures, and there are a number of good resources to help with calibration techniques and calculations. In general, the calibration will involve measuring the actual flow rate from the nozzles with a "bucket" and stopwatch and measuring the actual machine speed with a tape measure and stopwatch. The calibration should be periodically checked as nozzles and other components will wear and change performance over time.

Figure 1. Application rate equation.

$$\text{ApplicationRate} = \frac{\text{FlowRate} \times \text{ApplicationWidth}}{\text{Speed}}$$

**Figure 2.** Examples of off-target application errors caused by overlap of adjacent passes, application outside of field boundaries, or spray into previously treated headland areas.



## 2. Off-Target Application

Most farmers do not have the luxury of working in perfectly rectangular fields with no internal obstructions, so most everyone must deal with point rows. Especially as machinery gets bigger, field irregularities will cause some kind of off-target application of material. Off-target application (Figure 2) could be double coverage into a previously treated area that might occur when spraying into an angled headland or when overlapping adjacent swaths because of imprecise steering control. It could also be application outside the field boundary into an area such as a waterway, access road, or fencerow.

Off-target application is obviously a waste of input, which represents a direct cost to producers or service providers. One study showed that off-target applications could be as much as 25 percent of the field area in small and irregularly shaped fields. Beyond that, off-target application can have a detrimental effect on the crop since double application of some chemicals can damage plants. Extra chemical not used by the cropping system could adversely impact the environment. Application outside boundaries could damage vegetative buffers and other critical protective features.

## 3. Response of Flow Controllers to On/Off and Rate Change Commands

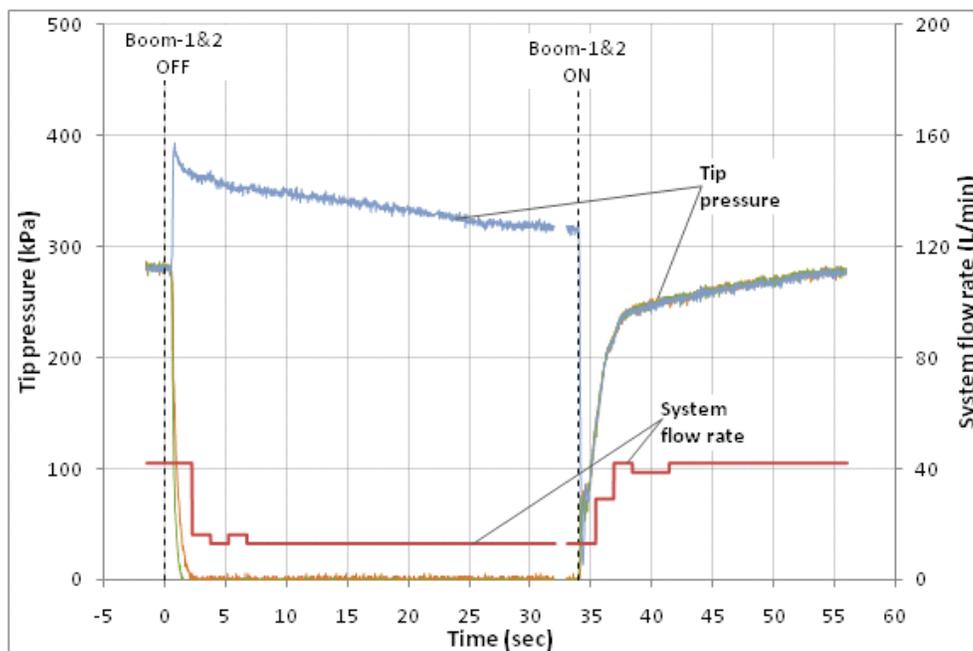
Another major cause of application inaccuracy lies in the performance of the flow control system on the sprayer. Most modern flow control systems are capable of automatically compensating for a number of factors that affect desired flow rate such as vehicle speed or desired application rate, but sometimes there is a time delay in the response. For example, if a boom section is turned on or off, there will often be an abrupt pressure change throughout the rest of the boom that will cause the output to change, and it may take some time for the control system to settle back to the desired flow rate. An abrupt speed change will cause the same kind of behavior because the system must adjust to a new operating flow rate that matches the new speed.

The article “Real-time Pressure and Flow Dynamics Due to Boom Section and Individual Nozzle Control on Agricultural Sprayers” evaluated the response time of various flow controllers to abrupt system changes by installing extra pressure sensors near different nozzles across a boom to estimate actual flow rates through the nozzles. They showed several examples of control performance, one of which was presented in Figure 3. When part of the boom was turned off at time 0, there was an immediate pressure increase in the rest of the boom and it took almost 30 seconds for that pressure to settle back to the desired value. While this particular

example may be one of the more extreme examples, in general there will be a pressure spike or dip in the rest of the boom when a boom section is turned off or back on, and the system will take some time to settle back to the correct operating point. Overall, they observed flow rate increases of 3.7 percent to 10.6 percent that lasted up to 25 seconds when turning boom sections off. The percentage of rate increase was roughly proportional to the percentage of the boom that was turned off, i.e. if more of the boom is shut off, the rest of the boom will see a higher rate increase spike.

Different controllers will respond differently—some will settle more quickly than others, some may allow larger spikes than others. The magnitude of the error spikes and the time required for the performance to settle back to the desired operating point will be dependent on the quality of the sensors and components in the system, the location of the sensors in the system, and the quality of the control algorithms designed by the manufacturers.

Some modern spray equipment can operate at extremely high field speeds. At 20 mph, a vehicle will cover about 30 feet every second. If the rate controller takes even 5 seconds to respond to a change (which is not uncommon), that would mean an area the width of the boom and 150 feet long would receive the wrong application rate. With a 90-foot boom, that is more than three tenths of an acre.



**Figure 3.** Example of spray rate controller performance showing the time required for the flow and pressure to return to the desired operating point when boom sections are turned off or on.  
 Source: American Society of Agricultural and Biological Engineers

#### 4. Speed Variations Across Boom During Turns

The rate control systems currently available on application equipment rely exclusively on the forward speed of the machine measured either by a radar sensor, transmission speed sensor, or GNSS data. They attempt to output the same flow rate at every nozzle across the boom, which is appropriate if the vehicle

is going straight. If the vehicle is turning, the nozzles toward the outside end of the boom are moving much faster than those on the inside of the turn. The turning effect gets more pronounced as the booms get longer and as the steering angles get tighter. This means that the outer limits of the boom will not be applying the desired amount of material per acre.

The graph in Figure 4 illustrates the anticipated error across the boom at 1 degree, 3 degrees, and 5 degrees steer angles, which is the angle of the front steering wheels relative to the vehicle chassis. It is based on the “bicycle” model for vehicle movement and it assumes no boom whip, no wheel slip, boom located over rear axle of a front steered machine, and 150-inch wheelbase, which is typical for larger high-clearance sprayers.

Even very small turning angles will create significant application errors. The dotted lines in Figure 4 indicate 10 percent error, which is often held as an acceptable threshold for application accuracy. The steering limits for different common boom sizes that will keep errors below 10 percent are listed in Table 1. For the larger 120-foot booms,

**Table 1.** Tightest allowable turn to keep application errors at boom tip below 10 percent.

Boom Width (ft.)	Steering Angle (degree on 150-in. wheel base)	Turn Radius (ft.)
60	2.4	300
90	1.6	450
120	1.2	600
160	0.9	800

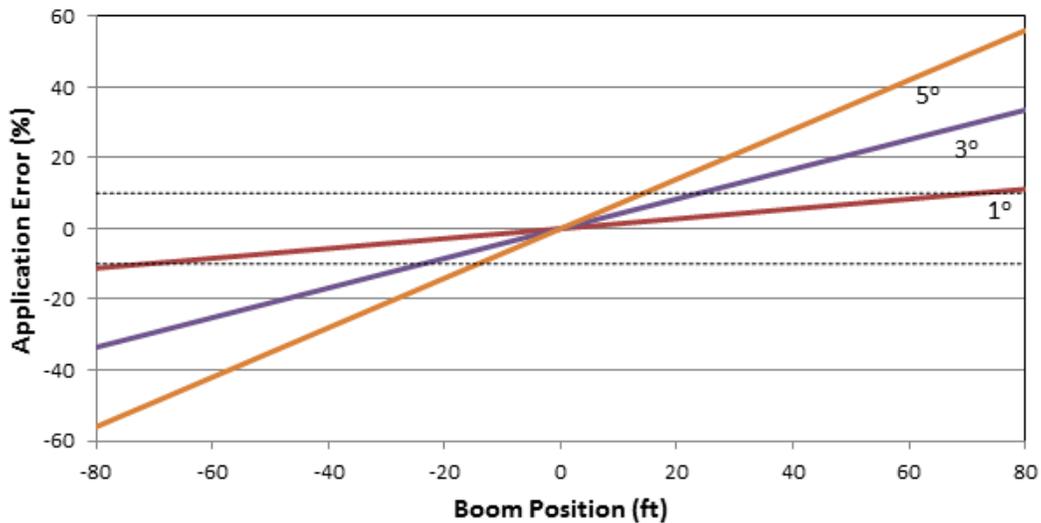
the wheels cannot be steered more than about 1 degree to keep errors below 10%. In field practice, turning maneuvers are often coupled with speed changes. Since speed changes also perpetuate application inaccuracy, these theoretical turning errors represent the minimum that will probably be observed in the field while turning.

#### 5. Boom Height

Nozzles are carefully designed to produce a given angle of spray with a controlled flow profile across the spray pattern. That flow profile is designed to require a certain amount of overlap by adjacent nozzles to produce a uniform application pattern across the boom.

**GNSS: Global Navigation Satellite System**

GPS has become a staple in agriculture, but many people do not realize that GPS is only one of many Global Navigation Satellite Systems maintained by different countries around the world. Many of the higher-end receivers used in agriculture today are dual system receivers that receive both GPS and GLONASS signals. GLONASS is a Russian satellite system very similar to the U.S. GPS. Thus the more generic GNSS term was derived to describe all of these satellite systems.



**Figure 4.** Application errors at different positions along a boom for various steering angles on a typical high clearance sprayer.

To keep adjacent spray patterns from colliding, which would create pattern distortions and large random droplets, most nozzle manufacturers incorporate a slight (5-15 degree) twist in the nozzle relative to the boom.

Nozzle overlap is defined as a percentage. Zero percent overlap means that the nozzle patterns touch at the surface but do not overlap; 100 percent overlap would occur when the edge of the pattern of one nozzle hits the surface directly below the adjacent nozzle. A 100 percent overlap means that 100 percent of the ground surface will receive some spray from 2 different nozzles.

Nozzle pattern overlap is directly affected by the boom height. Nozzle manufacturers typically specify a boom height for a given spacing of each nozzle. The extreme example in Figure 5 shows that in areas where the boom is too

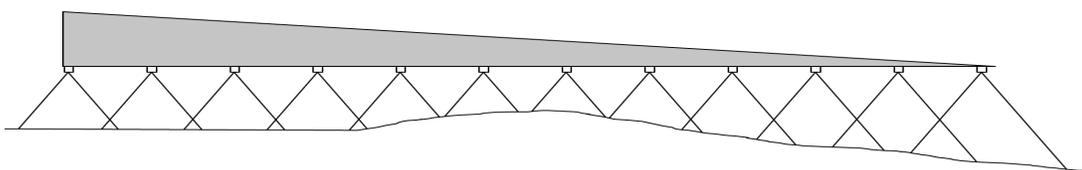
close to the ground, there will actually be skipped streaks across the field. If the boom is too high, the nozzles will overlap too much and there could be streaks with over- and under-application. Depending on the nature and rate of the chemical being applied, this streaking could cause problems such as chemical burn of the crop or inadequate control of pests. It is imperative that the boom always be held at the proper height for accurate application.

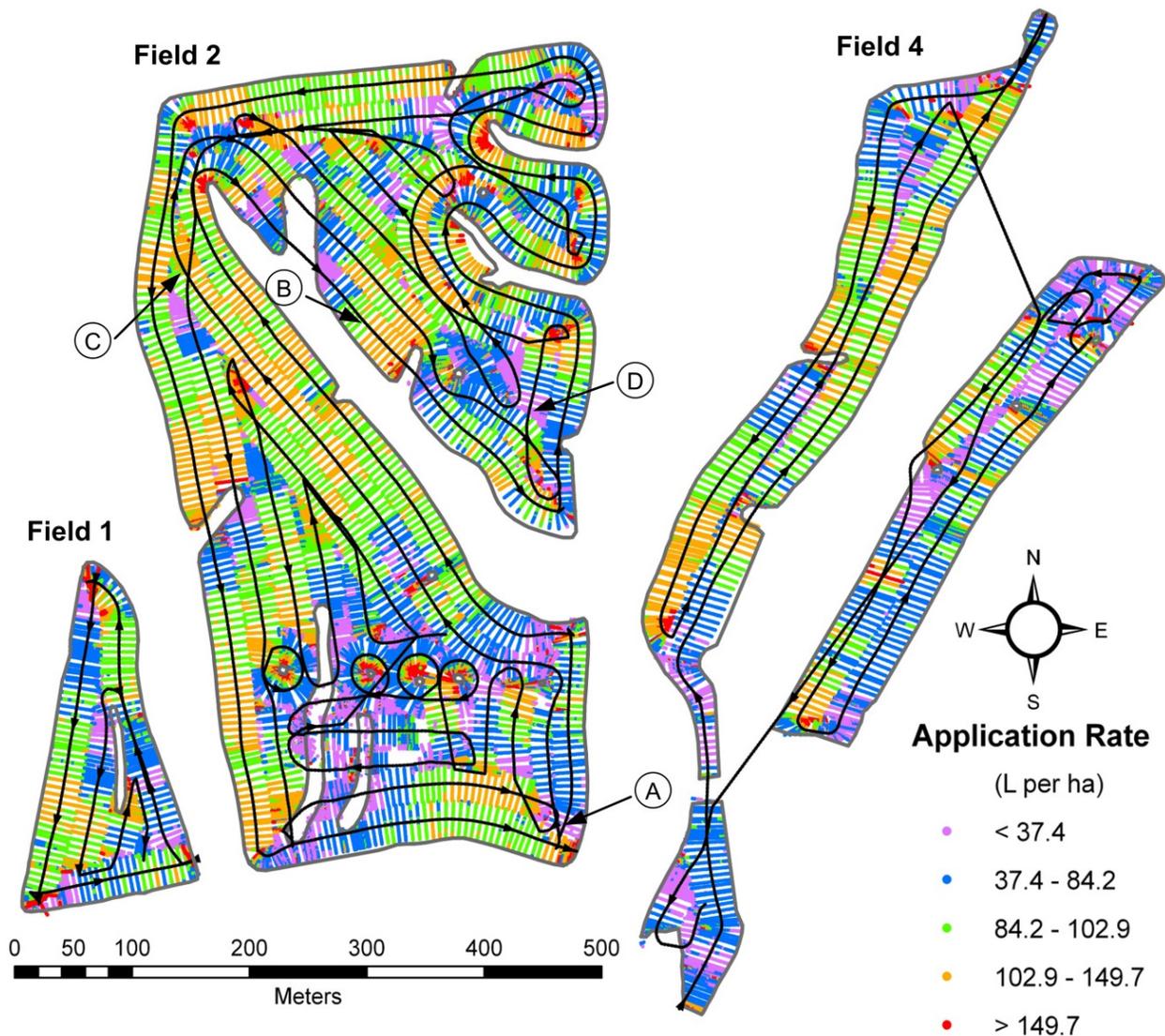
### Effects of Application Errors

With all of the potential error sources, just how good of a job is the typical operator doing at applying inputs? It is somewhat difficult to get a handle on the effects of all of these errors together. The “as-applied” data that are recorded by many modern sprayer controllers indicate what the machine *thought* it

was putting out at a given place and time. As-applied data rarely include actual pressure variations at the nozzle, turning rates, boom height, and other sources of error. Researchers in the article “A Case Study Concerning the Effects of Controller Response and Turning Movements on Application Rate Uniformity with a Self-propelled Sprayer” used extra pressure sensors mounted across the boom with some advanced analyses of vehicle turning motion to estimate application accuracy. An example of their results (Figure 6) reveals that significant portions of the fields were not being treated as desired. The green areas in Figure 6 received application rates within 10 percent of the desired rate—the rest of the field did not. Alarmingly, the machine evaluated in that study was utilizing many of the advanced technologies that will be discussed below.

**Figure 5.** Illustration of the effects of boom height on spray pattern coverage. Nozzles to the left are at the proper height, nozzles in the middle are too close to the target, and nozzles to the right are too high.





**Figure 6.** Spray coverage map generated by recording pressures across the sprayer boom.  
Source: American Society of Agricultural and Biological Engineers

## Technology Solutions

Given all these potential sources for application errors, manufacturers have developed an array of technologies for sprayers to help operators achieve more accurate application in the field. Some of these technologies are improvements to the basic equipment and structure of the machine and many are additions that can be installed either as options on new equipment or as aftermarket solutions.

### Automatic Section Control

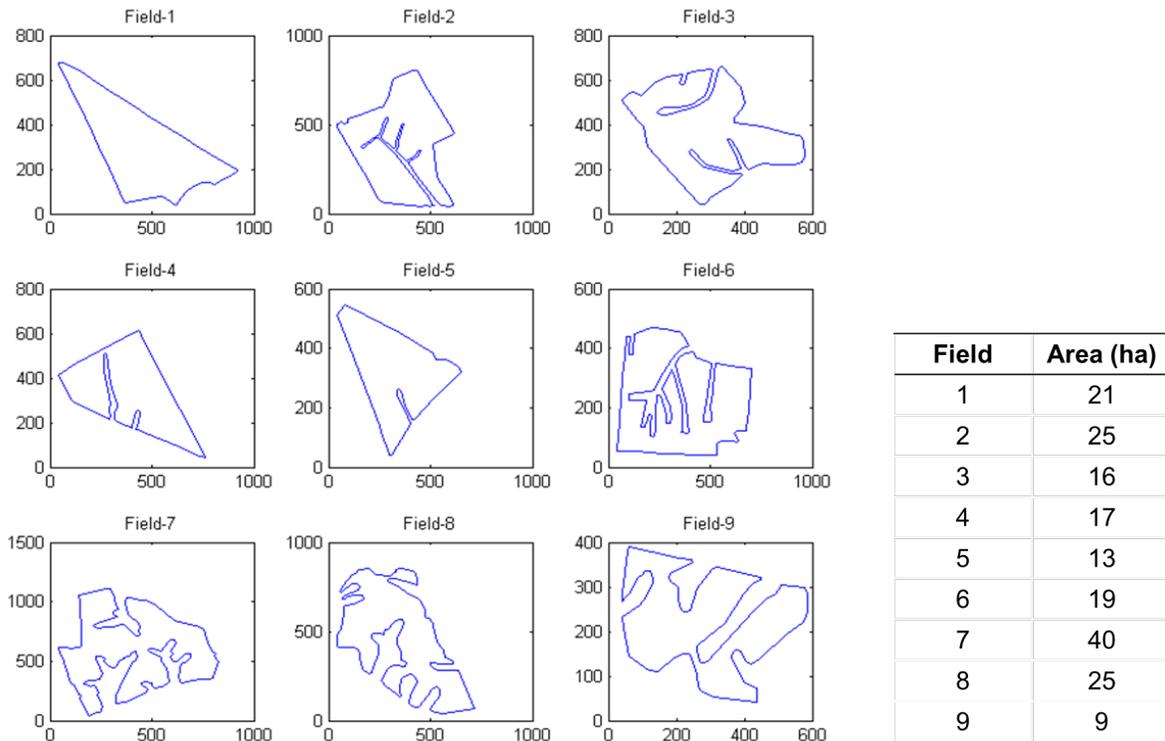
Automatic section control (ASC) systems are a newer technology designed to reduce off-target application. These GNSS-based systems will sense when sections of the boom pass over an area

that should not be treated and automatically turn them off. All of the systems continually record the areas that have been covered by the machine to prevent double coverage on those areas. Some systems also allow the user to preload a field boundary into the control system to prevent any application outside the boundary. There are a variety of systems available with different resolutions of control varying from a few boom sections down to individual nozzles.

Adoption of ASC is nearly a “no-brainer” decision simply because of reduction in the amount of inputs used. Most adopters are able to pay for ASC systems in 1-2 seasons with input savings alone and not even considering the potential consequences of double

covering parts of a field or destroying grassed waterways and other riparian features outside the boundary. There are numerous research studies and farmer testimonials attributing input savings of anywhere from 5 percent to as much as 20 percent to 25 percent. A crude rule of thumb that works well for much of Kentucky agriculture is a 7 percent savings. The variation in savings is based on field characteristics (size and shape) as well as machine size and configuration.

One study in the article “A Case Study Concerning the Effects of Controller Response and Turning Movements on Application Rate Uniformity with a Self-propelled Sprayer” compared two seasons of operation on several fields by one particular farmer with an 80-foot



**Figure 7.** Nine example fields used to demonstrate the effects of controlled section width on off-target application.

boom. During the first season the machine was divided into five sections with manual in-cab control of the 5 sections available. During the second season, the boom was divided into seven sections and controlled with an ASC system. The off-target application was reduced from 12.4 percent to 6.2 percent over a variety of field sizes and shapes when using the seven-section automatic control. Note that this error was inclusive of all off-target errors including those caused by guidance errors.

In short, ASC far out-performed manual control, but part of the difference was due to operator performance. The operator in this study admitted that he did not attempt to control the individual sections in areas where increased steering and speed control efforts were required. Ironically, these areas are often the very areas where section control is most needed, so ASC is an obvious advantage.

Another study further evaluated resolution of control by developing a software package called FieldCAT (Field Coverage Analysis Tool) that calculated

the theoretical off-target application for any field shape and machine configuration. Nine different example fields (Figure 7) were analyzed to determine how much off-target application would occur with different boom control resolutions on an 80-foot boom.

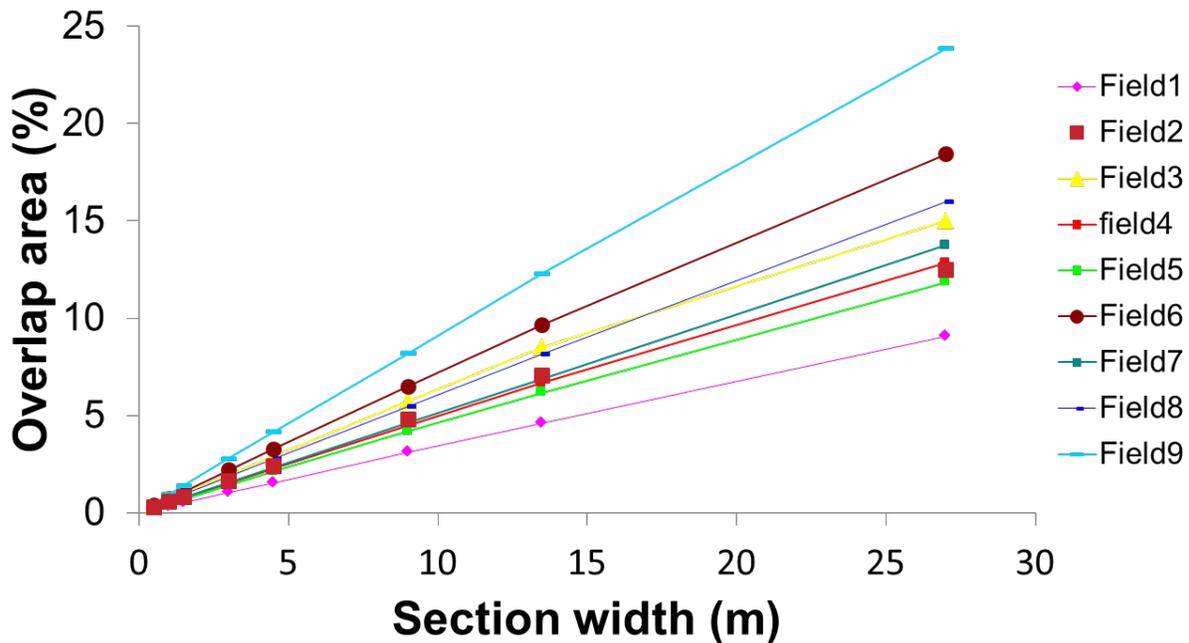
The results of the analysis (Figure 8) are very helpful in deciding how many sections should be controlled to reach the desired application accuracy. The rightmost set of data points in Figure 8 are a prediction of the off-target application errors from whole boom (no ASC) control in the nine different fields. In this worst case, off-target errors ranged from just under 10 percent to almost 25 percent. The next set of data points to the left represents two sections of the boom controlled, the next is three sections controlled, etc. This study revealed that it does not take a very fine control resolution (about six sections) before off-target application caused by section width is reduced to less than 1 percent of the total field area. Remember that this is a theoretical analysis that does not take into account other factors such as GNSS accuracy, system latencies, and system

control response that are also causing errors. With six to eight sections controlled, the errors will begin to be dominated by these other factors, and the “low hanging fruit” in terms of performance gains is not through increasing section control resolution.

## Flow Control Response

Another major cause of application inaccuracy lies in the performance of the flow control system on the sprayer. These issues are sometimes accentuated with ASC systems. As mentioned earlier, when individual sections or nozzles on a boom are turned on or off, pressure variations are often propagated back through the plumbing system. If the flow control system cannot respond quickly to these spikes to maintain proper flow rates through the rest of the boom, application errors will result.

Manufacturers use a number of different techniques to control pressure and flow in sprayers. The simplest systems still used on small sprayers consist of a fixed displacement pump and a relief valve. The pump, usually attached to a



**Figure 8.** Effects of the number of sections controlled on off-target application area. The right-most set of points is whole boom control, the next set to the left is two-sections controlled (half boom), the next is three sections controlled, etc. *Source: American Society of Agricultural and Biological Engineers*

tractor PTO, generates more flow than needed by the nozzles. The mechanical relief valve is set to the desired pressure, and any excess flow not needed by the boom is diverted back to the tank. A relief valve system relies on the machine always moving at a fixed forward speed to make accurate applications. Because of inefficiencies in the relief valves, these low-cost systems are often susceptible to large and consistent pressure changes with boom flow rate changes.

Most modern larger sprayers use some form of electronic feedback compensation. System operating parameters are measured with pressure and/or flow sensors. Those parameters are compared to the desired operating point, and the control system will adjust performance by changing pump speed and/or flow control valve settings. Electronically-controlled systems generally are much better at maintaining flow rate, and they also have the ability to adjust flow rate based on the actual measured forward speed of the machine.

One main challenge facing designers of these systems is the fact that the control sensors are often located well

upstream from the nozzles. To keep system costs reasonable, manufacturers commonly use a single flow meter located upstream of the manifold(s) and valves that divide and control the flow to each boom section. In technical terminology, this introduces a phase lag into the system, which essentially means that there is a slight time delay between when something happens at the boom (nozzle or section shut off, for example) and when the control sensors will actually begin to sense the effects of that event. This delay can be further complicated by things like hose compliance (stretching), fluid inertial properties, and sensor response rates. The control system is always in a catch-up mode, which makes it challenging to keep the system on the desired operating point.

The technology exists to put pressure and flow meters on each nozzle to measure actual nozzle performance. The cost of all the additional electronics, the complexity of data management and control, and the additional maintenance requirements have, to this point, rendered this level of control impractical on production equipment. Manufacturers

are continually working on solutions that will improve controllability at the nozzle level.

The ability to compensate for the forward speed of the machine is a real advantage of modern control systems, but there is a downside. With most nozzles, droplet size is directly tied to pressure, and so is flow rate. That means that when the control system compensates for, say, an increase in machine speed by increasing flow rate, the pressure at the nozzle will also increase. The increased pressure will decrease the droplet size in the spray pattern, which could introduce a spray drift problem. Because of this tie, most modern sprayer control systems will signal a warning to the operator if the machine speed is above or below reasonable limits of operation.

### Nozzle Options

A number of technologies are aimed at controlling droplet size independent of flow. One option is to develop new nozzle hardware that will be less susceptible to droplet size variations. At least one manufacturer produces a variable orifice nozzle that mechanically adjusts

the opening in the nozzle based on the amount of material flowing through the nozzle to maintain droplet size. Other nozzle solutions use various active or passive methods to introduce air into the flow exiting the nozzle to better control droplet size.

### PWM Nozzle Control

Another solution that exists for nozzle control is to use Pulse Width Modulation (PWM). PWM is a technique for controlling flow rate through valves that involves rapidly pulsing a valve on and off. The amount of time the valve is on or open vs. the amount of time it is closed determines the flow rate. The width of the “on” part of the pulse is the basis for the term pulse width. PWM is often measured in duty cycle, which is the percentage of the total time that the valve is on. As illustrated in Figure 9, a 75 percent duty cycle means that the valve is open 75 percent of the time, and the flow rate will be approximately 75 percent of the maximum flow. A 25 percent duty cycle would be a narrower pulse resulting in about a quarter of the maximum flow rate. The maximum flow rate is achieved with the valve on all of the time, which is a 100 percent duty cycle.

The frequency of the pulses will determine how the valve will respond. With individual nozzle control, most manufacturers use a pulsing frequency of 5-10 Hz, which means there will be 5-10 on commands in each second. At this frequency, a human can see and hear the action of the nozzle because it is physically pulsing on and off.

Do not confuse nozzle PWM control with the main product PWM control. Many of the modern flow control systems will also use PWM strategies to control the main product flow control valve or the hydraulic flow control valve that controls pump speed. These systems will often pulse at a higher frequency (100-200 Hz). At these higher pulsing frequencies, the valves will not have time to close between pulses so they will essentially “float” or stay partially open much like a manual hydraulic valve can be held partially open to control flow. A higher duty cycle will cause the valve to open further while lower duty cycles will keep it more closed. The result is a continuous

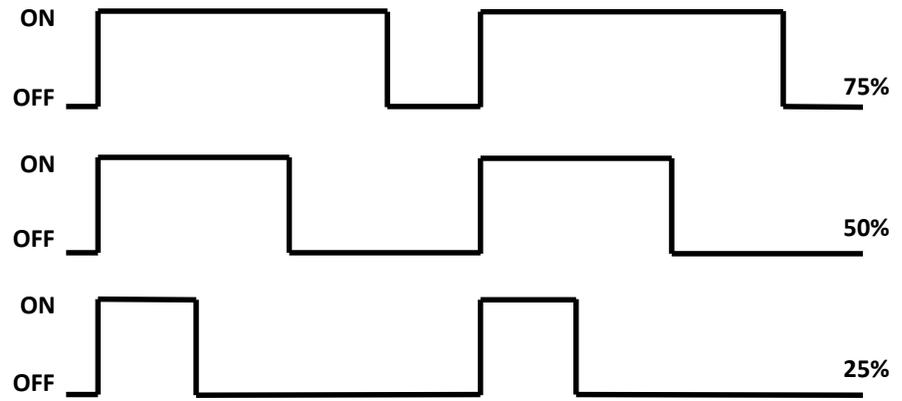


Figure 9. Illustration of PWM control at three different duty cycles.

or smooth flow of material at a controlled flow rate. This smooth flow control is often referred to as proportional flow control.

Proportional control of individual spray nozzles would give the undesirable effect of varying spray patterns and droplet sizes with flow rate. That is why nozzles are pulsed at the lower frequencies. The idea is that any time the nozzle is on, the pressure drop across the nozzle will always be the same and the spray pattern characteristics will be consistent. The amount of material applied is controlled by only leaving the nozzle on for a limited percentage of time. The result is a pulsing flow but with a consistent droplet size over a wider flow variations.

One concern with pulsing flow is the spatial effect. As the machine is moving across the field, pulsing flow will cause a “checkerboarding” effect of skipped areas and areas receiving a higher than desired application rate. Manufacturers of PWM nozzle control systems recommend using wide angle nozzles with patterns that are designed to overlap well into adjacent nozzle coverage. Then they will alternate pulsing adjacent nozzles. Not only does this help to minimize the checkerboarding effect, it also manages the electrical current demand by the nozzles, which can be significant.

The selection of nozzles and operating conditions (pressure and flow) can have an effect on the efficacy achieved with PWM nozzles. If nozzles are too big, operation will be consistently at lower duty cycles, which will enhance the checkerboarding effects. Even though the

systems can theoretically provide compensation for wide variations in vehicle speeds, the best application accuracy will be achieved at consistent operation near optimum control points.

### Turn Compensation

Several manufacturers are on the verge of release of systems that will provide flow rate variation across the boom to compensate for the effects of turning. The initial offerings will provide the compensation through individual PWM nozzle control. They will utilize a distributed control scheme to determine actuation signals for each nozzle. These systems are extremely sophisticated in terms of computational capabilities and data transfer, and they will potentially generate a tremendous amount of information that could be useful for record keeping and/or performance assessment.

### Boom Height Control

Controlling the height of the boom can be very challenging as machines get wider and as operating speeds increase. Small movements of the vehicle chassis from undulations in the field surface can create large movements at the boom tips. Therefore, all larger spray machines incorporate some kind of boom suspension system to keep the boom level while the machine rocks from side to side. This suspension alone might be sufficient in level fields, but as the machine encounters obstructions such as field slopes and terraces, more control is required to keep the entire boom at a given height above the target surface.

Hydraulic controls are provided on all machines that give the operator the ability to, at minimum, raise and lower the right and left boom sections independently. Several commercial options are offered as optional equipment or as aftermarket systems that will tie into this hydraulic system to automatically adjust the boom height. Most systems utilize a number of ultrasonic sensors placed across the boom. These sensors measure the distance to the target surface by analyzing the properties of reflected ultrasonic waves. The systems will then automatically adjust the boom height toward target values hopefully providing a better coverage pattern and preventing damage to the boom components from accidental contact with the target or ground surface. Some systems will even actively control the roll of the boom relative to the machine chassis. Obviously if there is undulating terrain under that boom as illustrated in Figure 5, it is impossible with a rigid boom to keep all nozzles at the desired height. Systems that utilize multiple sensors across the boom will combine the readings to determine the best operating position for the boom.

The operator has some control over the performance of the systems through changing the response time or aggressiveness of the height control. A system that is too aggressive will exhibit more oscillations especially when encountering sharp obstructions. Systems without enough aggressiveness will respond very slowly and may go for extended distances at improper heights. While automatic boom height control systems generally work very well, there are some instances where the sensors will not give perfect results. Occasionally a tall weed passing under the boom will cause an erroneous

jump in boom height. Sometimes the waving surface of some crops such as small grains will cause errors in height measurements. Operators still must remain alert and monitor the status of the boom.

## Conclusions

A number of technologies are available to help operators do a more accurate job of applying chemicals to a field. Adoption of these technologies will depend on the size and type of machine used as well as the typical characteristics of the fields such as size, shape, and terrain. Regardless of the technology, though, there are a number of fundamental things that operators should always be doing to improve accuracy.

- 1. Calibrate.** Remember to calibrate often. Nozzle tips and pumps will wear, sensor performance will drift, and hoses will shrink and expand. Periodic recalibration will insure that the electronics really understand what is going on in the hardware system.
- 2. Drive straight,** or at least as straight as possible. As discussed earlier, even small steering corrections can cause large speed variations at the tips of sprayer booms. While some field shapes require operators to drive curved paths, think critically about how tight the curves really are and avoid errors.
- 3. Drive smooth,** which means limit abrupt speed changes. Start slowing down early and gradually before headlands and ditches. Avoid rapid accelerations. Remember that the faster the machine is moving when error-causing changes are occurring, the further across the field those errors will be propagated.

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