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System Development for String Analysis During Operation S.A.F.E Clinics

Yin-Lin "Jack" Chiu

Research Associate Coordinator, BAE Department, LSU AgCenter, Baton Rouge, LA

ychiu@agcenter.lsu.edu

Roberto N. Barbosa, Ph.D.

Associate Professor, BAE Department, LSU AgCenter, Baton Rouge, LA

rbarbosa@agcenter.lsu.edu

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Abstract. *Operation S.A.F.E workshops, commonly known as "fly-ins" help agricultural pilots "fine tune" their aircraft for aerial application work. During the fly-in several ancillary measurements are recorded; aircraft speed, aircraft spray release height, air temperature and relative humidity, wind speed and direction. These measurements are recorded by personnel operating the flight line with manually operated sensors. Some of the difficulties arise when the lack of personnel and or experience level hinders the ancillary measurement, or when equipment becomes difficult to repair and/or replace. To address some of the issues, two automated systems were developed. An automated ancillary measurement system to observe and record the above mentioned measurements and a new automated string analysis system for processing liquid spray deposition patterns on 1 mm diameter cotton string. This paper discusses the development of the automated ancillary measurement system and new string analysis system and the results of our testing.*

Keywords. Sensor automation, aerial application, spray deposition analysis.

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Introduction

Improvements in aerial spraying practices and application technology are needed for on-target deposition and enhanced efficacy of agricultural chemical products for plant and pest control Operation S.A.F.E. (Self-regulated Application and Flight Efficiency) analysis clinics sponsored by the National Agricultural Aviation Association (NAAA), aims to help agricultural pilots to make adjustments to their aircraft to ensure proper calibration and equipment maintenance. During an operation SAFE workshop, also known as “fly-in”, pilots navigate their aircraft and release a mixture of tap water and Rhodamine WT dye from their sprayer system over a 45 meter (150 feet) long, 1 mm diameter cotton string that is placed perpendicular to their direction of flight. The cotton string is then analyzed with a modified fluorometer to produce an average deposition graph (Whitney and Roth 1985). The graph is used to correct common depositional problems found in agricultural aircrafts, such as “prop wash” (spray over deposition to the left side of the aircraft, creating a hole in the middle), or overcompensation for prop wash (spray over deposition to the right side of the aircraft). Deposition graphs also help pilots understand how wide their application swath is and what is the best combination of swath width and flying method (back-and-forth versus racetrack). During a fly-in several ancillary measurements are taken to aid in the analysis of the correspondent deposition graph. Water-sensitive cards (WSC) are used to estimate droplet size and drift potential; weather variables such as air temperature and relative humidity, wind direction and speed, aircraft speed, and spray release height are also measured. Weather variables are usually read from a portable weather station, aircraft speed is measured using a portable handheld doppler radar, and spray release height is measured with a scope and graduated scale using similar triangles technique (STT) as shown on Figure 1 (WRK 2009).

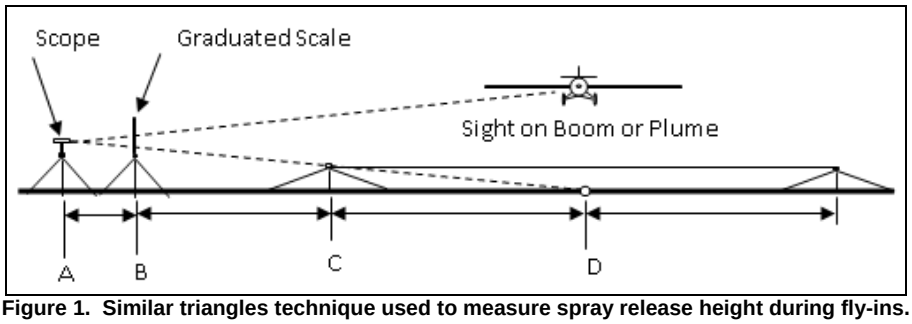

Figure 1. Similar triangles technique used to measure spray release height during fly-ins.

Challenges facing Operation S.A.F.E. fly-ins are: (i) the lack of trained personnel to help the analyst collect all required measurements, and (ii) the age of some equipment components used in the analysis of the deposition string. It is estimated that a minimum of six people plus the aircraft pilot are required to perform a single clinic. This personnel commitment is very difficult to achieve. Traditionally, both Extension Service and the State Department of Agriculture and Forestry are responsible for providing manpower to run a calibration clinic. When the necessary manpower is not available, the clinic is compromised. Frequently, due to lack personnel, ancillary measurements are not taken and the true “big picture” of the analysis will have missing information. Conversely, adequate personnel are available but their lack of

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experience may lead to improper data collection. Common mistakes such as failure to operate the portable hand-held radar gun (HHR) in time for the speed measurement or measuring wind speed and direction while personnel block the sensor(s) do occur frequently during a fly-in. Measuring spray release height can difficult, especially if the person does not have prior experience using the STT; sometimes producing large errors and questionable results.

The WRK String Analysis\Graphics System (herein referred as WRK System) is currently in use to analyze the spray deposition. It is composed of a WRK String Analysis Door (WRK of Oklahoma, Stillwater, OK), a third-party modification, attached to a bench-top filter fluorometer (Model 110, 111 or 112) built by Turner Associate (discontinued) refer to Figure 2. The modified door attachment contains a motor drive system that moves the cotton sample string through a guide that uses mirrors to distribute the excitation light source throughout the string as it is moved through system and focuses the fluorescence from the rhodamine tracer dye to the detector. Replacement units and parts are difficult to obtain and time consuming to repair; consequently fly-ins could be cancelled in the event of equipment malfunction.

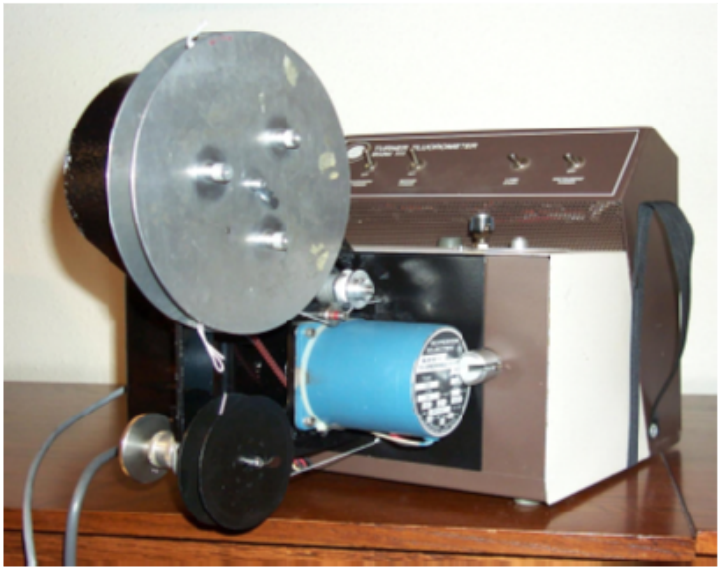

Figure 2. WRK String Analysis Door and Model 111 Turner Fluorometer

There are two objectives to this research project. The first objective is to develop an integrated system, to aide in a fly-in, by automating ancillary measurement data acquisition of aircraft speed and spray release height; air temperature and humidity; wind direction and wind speed. The data would then be made available in real-time and archived for post analysis if needed. The second objective is to develop a new string analysis system (herein referred as NSA System) which will use a fluorescence detection sensor, constructed of commercially readily-available components and output distance/location and excitation intensity to an text file for analysis using Microsoft® Excel.

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Materials and Methods

System Components and Design

The automated ancillary measurement system (AAMS) was designed to acquire aircraft speed and spray release height; air temperature and humidity; wind direction and wind speed. The AAMS consists of two strategically placed sensor platforms and a portable terminal used for viewing summary data and controlling the two sensor platforms; all of which wirelessly communicate with each other.

The AAMS platform 1 is responsible for acquiring aircraft ancillary measurements uses the Stalker® Speed Sensor Stationary unit (Applied Concepts Inc. - Plano, TX, USA) to determine the maximum aircraft speed. The sensor uses RADAR, *Radio Detection and Ranging*, and the Doppler Effect to determine a targets speed. This unit is similar to the ones used by law enforcement for determining vehicle traffic speed. To automate the determination of aircraft spray release height the system uses the LaserAce® ILM-150HR (Measurement Devices LTD, York, England). This is a compact class 1 eye safe, rugged, multipurpose laser distance meter with a reflector-less range up to 150 m (500 ft). It determines distance through an algorithm based on the difference in time between the transmission and return signal of a “known” laser pulse. Similar models are currently installed and used on some agricultural aircraft to monitor altitude. These two sensors are connected to an adjustable mounting system and a “black-box” unit that houses a 12 V-DC power-supply and supporting circuitry with customized firmware that captures, archives aircraft speed and spray release height measurements, and wirelessly connects the weather station and portable terminal.

The AAMS platform 2, the automated weather station, is constructed of high-end research grade components that have been modified and purchased from Campbell® Scientific, Inc. (CSI, Logan, UT). Air temperature and humidity is determined by the HMP45C probe (with CSI, 41003-5 mounting hardware), wind speed and direction is determined by the 034B Wind Set sensor. The sensors are connected a CR3000 Micrologger®, which monitors and archives the weather information, and several customized components that complete the wireless connectivity between the AAMS platform 1 and portable terminal. The system is powered by an integrated 12 V-DC power supply (CSI, model PS100, Logan, UT). The above mentioned components are mounted in a 16 x 18 x 10 in enclosure which is attached to a stainless-steel instrumentation tripod (CSI, model ENC16/18 and CM115, Logan, UT).

The third component of the AAMS is a portable terminal, which can be any device that is able to connect to a Wi-Fi ™ network and is able to run a web browser that that supports JavaScript (i.e. smartphones, laptops, tablet computing devices, etc.). It should be noted that an internet connection is not used or required for the AAMS system. The portable terminal frequently used for testing was the Apple Inc. iPad® (Apple Inc., Cupertino, CA). The AAMS platform 1 contained a Wi-Fi™ router which easily connects the AAMS platform 2 and portable terminal wirelessly. The portable terminal can send control signals to the AAMS platform 1 to start/start/reset data acquisition and retrieve the real-time summary data after a data acquisition

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event occurs. The AAMS platform 2 generates a separate graphical based web page of the acquired data that the portable terminal can retrieve.

Separate from the AAMS, a new string analysis system (NSA System) was designed reuse the cotton string sample storage reels, address the difficulties of repairing the WRK System and automate the sample string analysis. The NSA System consists of two gear motors, pulley guides, red-green-blue color sensor, rotary encoder and rhodamine water tracing dye sensor (illustrated in Figure 3).

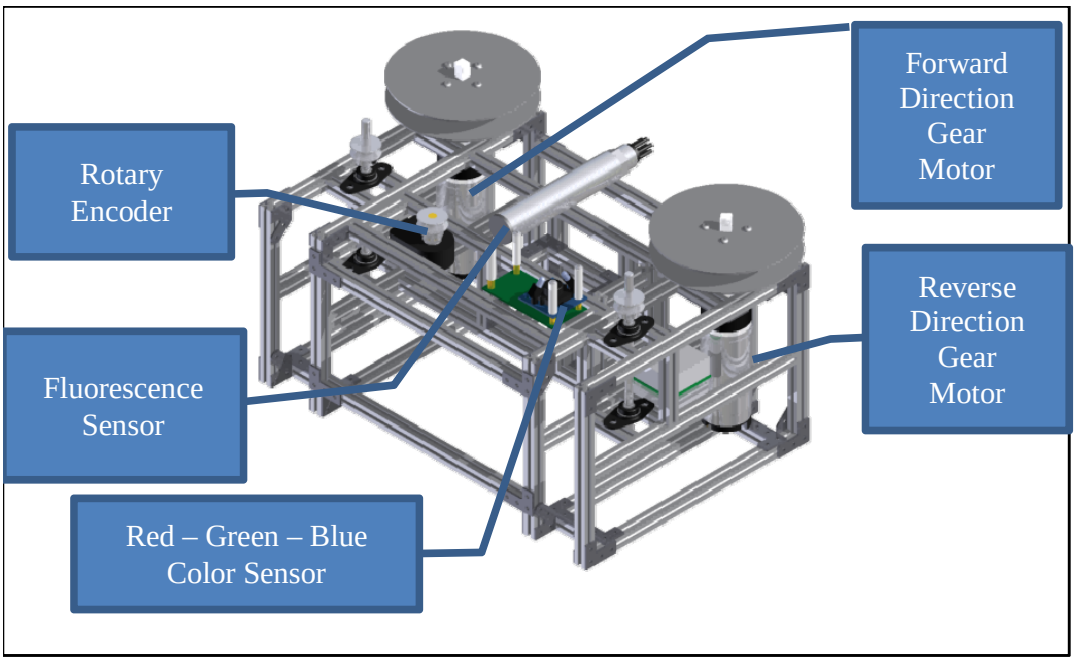

Figure 3. New String Analysis System platform.

The NSA System was built with modularity of each component in mind, which reduces the difficulty of component replacement if the need arises. An adapter was installed onto the shaft of each gear motor which allows the usage of the existing sample storage reals used by the WRK System. After placing the sample reel on one motor and "priming" the other reel with several inches of sample string, the gear motor pulls the sample string from the sample storage reel across a red-green-blue color sensor, fluorescence sensor and rotary encoder sensor. The red-green-blue color sensor continuously scans the reflected color of the sample string to detect the color indicators marked on the string during the sample collection phase of the fly-in (red and green marks that indicate the right and left sides of the aircraft, respectively) which also represents the start and stop of a trial. The fluorescence sensor outputs the intensity based on the amount of detectable rhodamine water tracer dye accumulated on the section of the sample string. A rotary encoder indicates the amount of sample string has been processed through the system. The rotary encoder values also represent the location in millimeters. The linear distance/location and fluorescence intensity information are archived onto a removable storage device as a text file.

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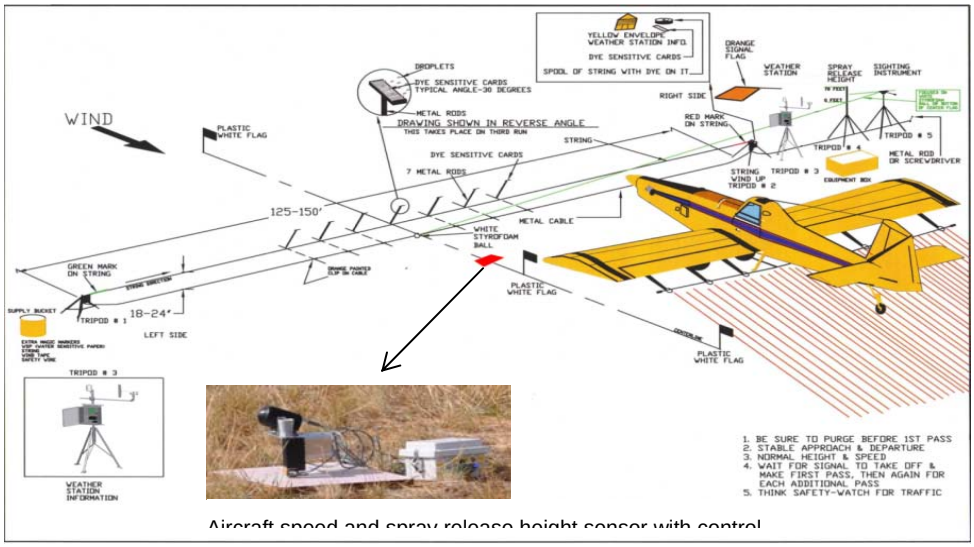
Field Test

The AAMS was evaluated during a Louisiana Agricultural Aviation Association sponsored fly-in located in Jennings, LA on October 4th, 2011. Dr. Roberto N. Barbosa, Biological and Agricultural Engineering Department, Louisiana State University was the analyst supervising the fly-in. Personnel from Louisiana State University – Agricultural Center, Department of Agriculture and members of the LAAA were available throughout the day to help collect data and operate customary ancillary measurement equipment.

During the fly-in, one person was assigned to observe and record weather data from a portable weather station while others collected aircraft speed using a Bushnell® HHR and spray release height using STT. The AAMS platform 1 with portable terminal was installed in the field to collect aircraft speed and spray release height (refer to Figure 4).



Aircraft speed and spray release height sensor with control

Figure 4. Ag Aviation Wet Material Collection Layout with AAMS platform 1.

The NSA System was evaluated by conducting aerial spray applications at Kent's Flying Service Airport located in Moreauville, LA on October 14th, 2011. The samples were collected then transported to Louisiana State University and processed by the WRK and NSA Systems. Kent's Flying Service provided a pilot with an AT-401 (Air Tractor, Inc. Olney, TX) outfitted with a 64 position spray boom. In order to test the abilities of the NSA System to detect deposition patterns of spray released from aerial application, an experiment was setup with the aircraft spraying two different concentrations of a mixture rhodamine water tracer dye and tap water and two different nozzle patterns. The two concentrations of fluorescent red dye tracer (Cole-Parmer: SI00298-26) used were 2.7 and 5.4 grams per liter (which will be referenced as 1X and 2X, respectively). Two nozzle configurations were used for each concentration. The normal operation nozzle setup referred as standard nozzle setup and 10 nozzles on the right-hand side of the spray boom disabled will be referenced as modified nozzle setup (refer Figure 5).

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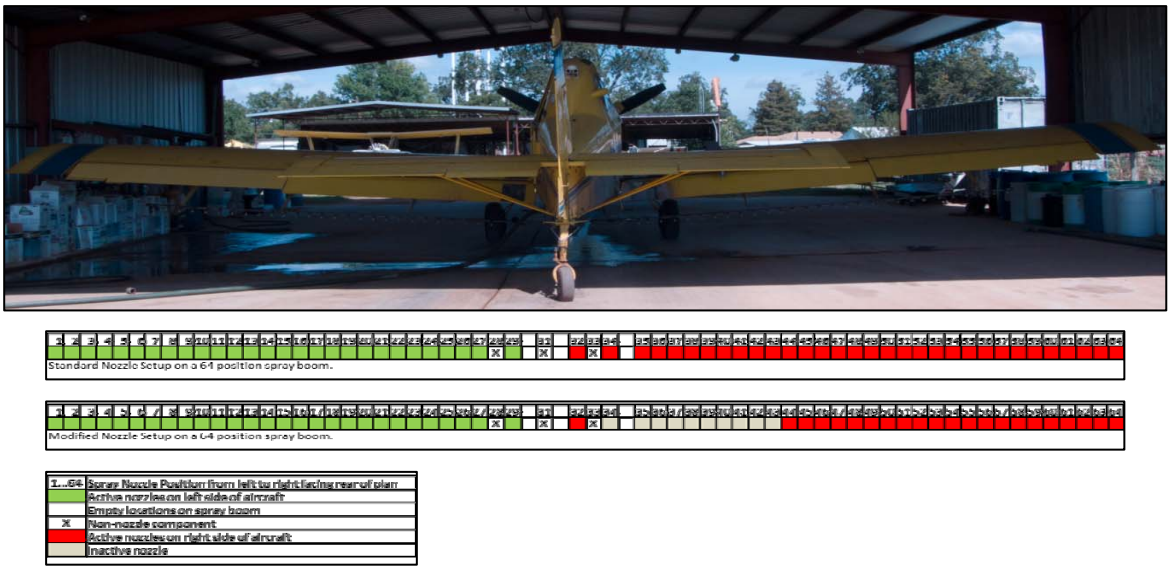

Figure 5. Aircraft with standard and modified nozzle setup configuration diagram.

A 45 meter (150 feet) long, 1 mm diameter cotton string was setup perpendicular to their direction of flight across a field along with 29 water sensitive cards located every 1.52 m (starting from 1.52 m and ending at the 44 m). Four trials with 2 replicates were performed (refer to table 1) for a total of 8 spray pattern passes. Each aerial application string sample pass was stored onto individual reels and then placed in a standard 8 ¾ by 11 ½ brown kraft clasp envelop along with the 29 water sensitive cards. The individual string samples were processed using the WRK System and analysis software, and then re-round onto the sample storage reels. The results were saved as a text file. The individual reels were then placed into the NSA System where the distance/location and fluorescence intensity values were recorded to text file. The water sensitive cards were scanned and processed using DropletScan v2.4 and the percent coverage of each card was recorded.

Table 1. Aircraft aerial spray and concentration tables for each spray pattern pass.

Aircraft Pass	Nozzle Pattern	Concentration
1	Standard	1X
2	Standard	1X
3	Modified	1X
4	Modified	1X
5	Standard	2X
6	Standard	2X
7	Modified	2X
8	Modified	2X

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The pilot was instructed to operate under normal aerial application conditions, approximate speed of 65 ms^{-1} (145 MPH) and 3.7 – 4.6 m (12-15 feet) spray release height. The air temperature and humidity, wind direction and speed were recorded and new water sensitive card sets were placed after each aircraft spray pass.

Results

Automated Ancillary Measurement System

During the October 4th, 2011 fly-in only the AAMS platform 1 with portable terminal (automated aircraft speed and spray release height system) was tested. Each time the aircraft flew through the automated sensor's "field of view" (illustrated in Figure 6), the sensor information was archived to onboard storage and a summary data set was transmitted to the portable terminal for real-time viewing.

Figure 6. Aircraft exiting "field of view" of automated speed sensor (represented by the triangle shape between speed sensor and aircraft) and flying towards automated height sensor and string (represented by red vertical line).

A summary of six aircraft flight passes which includes the speed information acquired by the manual HHR, an instantaneous value, and maximum value from the automated speed sensor are listed in Table 2.

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Table 2. Speed values acquired using manual Bushnell® HHR and maximum speed values recorded by automated Stalker speed sensor for 6 aircraft flight passes.

Aircraft # - Pass	HHR (ms^{-1})	Automated Speed Sensor (ms^{-1})
Aircraft 1 – A	63	63
Aircraft 1 – B	60	63
Aircraft 2 – B	56	57
Aircraft 2 – C	58	58
Aircraft 3 – A	61	62
Aircraft 3 – C	62	62

Height data for the aircraft release height was also recorded each time a pass was made. A manual reading using the similar triangles method and an automated height sensor were used. The instantaneous recorded value determined by the SST method and the minimum height value recorded by the automated height sensor are summarized in Table 3.

Table 3. Aircraft release height data recorded using manual SST and minimum recorded value recorded by the automated height sensor for 6 aircraft flight passes.

Aircraft # - Pass	STT (m)	Automated Height Sensor (m)
Aircraft 1 – B	7.6	7.7
Aircraft 1 – C	6.1	6.1
Aircraft 2 – A	4.6	6.4
Aircraft 2 – C	4.3	4.3
Aircraft 3 – A	7.6	7.3
Aircraft 3 – B	5.5	4.6

New String Analysis System

It was difficult to define a metric in order to properly determine the effectiveness of the NSA System as compared to the WRK System and WSC. In the end, the relative deposition, a unit-less value derived by computing the average deposition collected for each spatial location divided by the overall average deposition of the entire sample collector(s) (forty-five meters of1 mm diameter cotton string for the NSA and WRK Systems and the water sensitive cards for the WSC method), was used to compare the three systems. The spatial locations mentioned are the sections of cotton string and water sensitive cards placed every 1.52 m to 44 m (starting

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from the left hand side/green mark of the string). The NSA and WRK Systems use the raw text data files to extract the average deposition for each spatial location and overall average deposition. The WSC method used DropletScan v2.4 to process the percent coverage of each of the 29 cards. Then relative deposition for each spatial location was calculated by dividing the percent coverage of each card by the average percent coverage of all 29 cards. The relative deposition was processed and computed using the raw data from the NSA and WRK Systems and WSC method for each of the eight aircraft aerial application passes. The results were compiled and graphed for each respective pass for a total of eight graphs. The relative deposition derived from the NSA System is represented by a solid green line, the WRK System is represented as a dashed red line and finally WSC method is represented as blue diamonds. The string location represents the spray deposition of the aircraft as if it were flying into the paper with 0 – 22.8 m representing the left side of the pilot and aircraft, 22.8 m representing the center of the aircraft and 22.8 – 45.7 mm representing the right side of the pilot and aircraft. The results are grouped by each trial and respective replicates: trials 1 and 2 with 1X concentration and standard nozzle setup in Figure 7a and b; trials 3 and 4 with 1X concentration and modified nozzle setup in Figure 8a and b; trials 5 and 6 with 2X concentration and standard nozzle setup in Figure 9a and b; and trials 7 and 8 with 2X concentration and modified nozzle setup in Figure 10a and b.

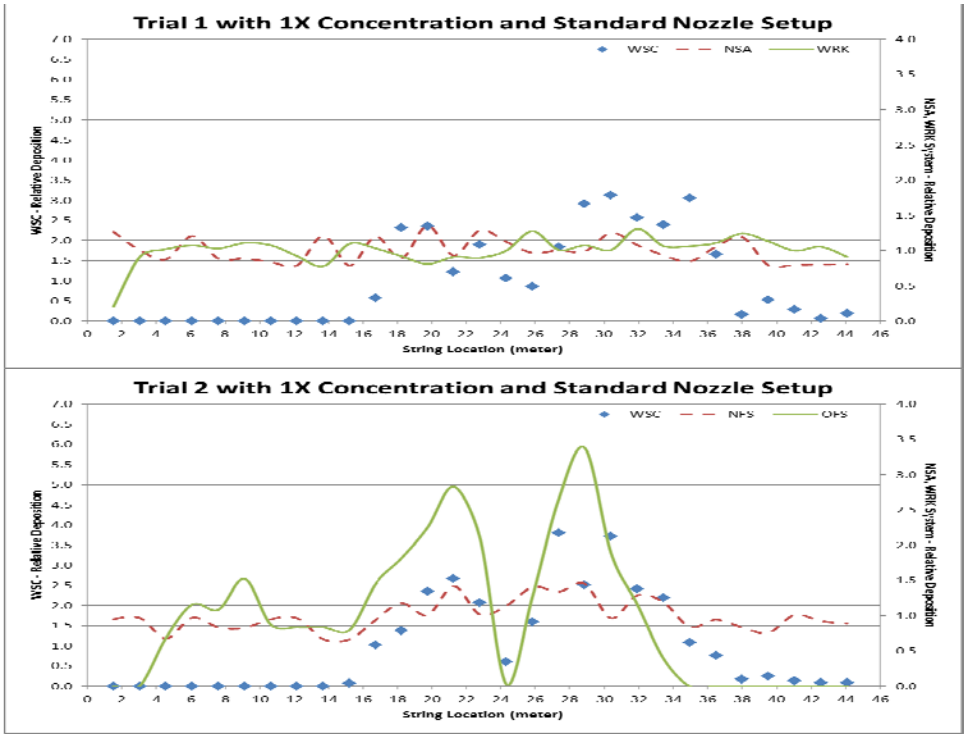

Figure 7a and 7b. Relative Deposition Comparison of NSA, WRK System and WSC method at 1X Concentration and Standard Nozzle Setup.

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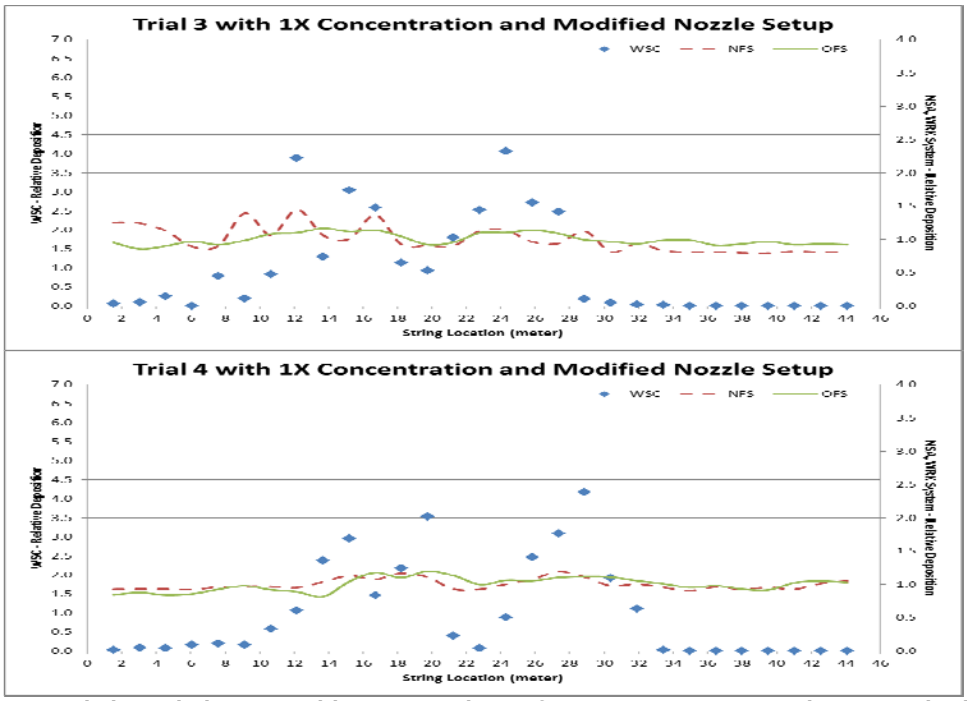

Figure 8a and 8b. Relative Deposition Comparison of NSA, WRK System and WSC method at 1X Concentration and Modified Nozzle Setup.

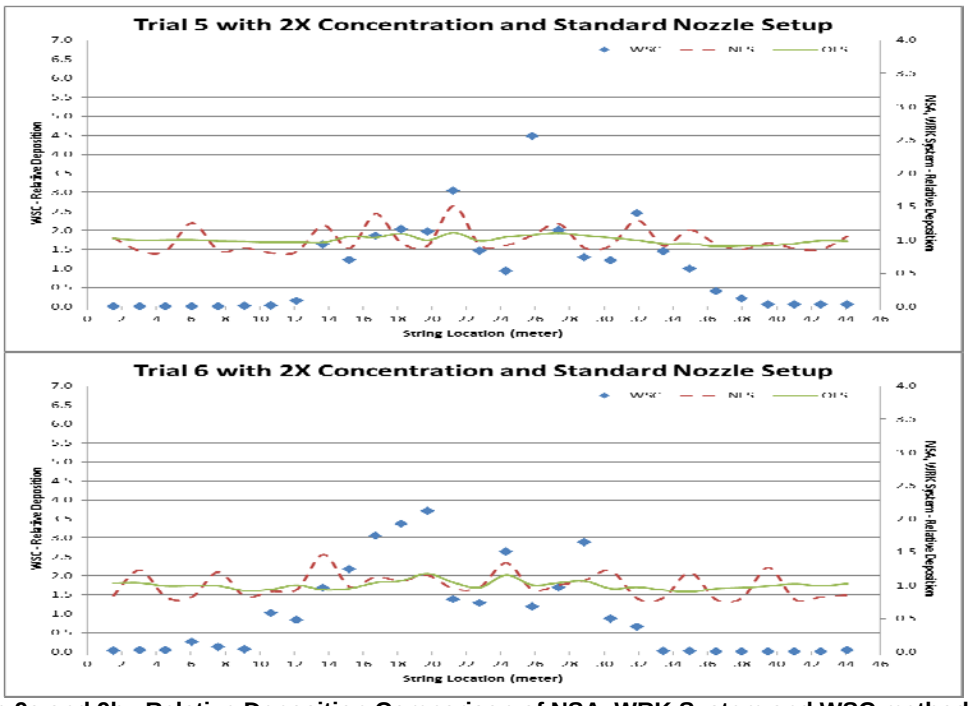

Figure 9a and 9b. Relative Deposition Comparison of NSA, WRK System and WSC method at 2X Concentration and Standard Nozzle Setup.

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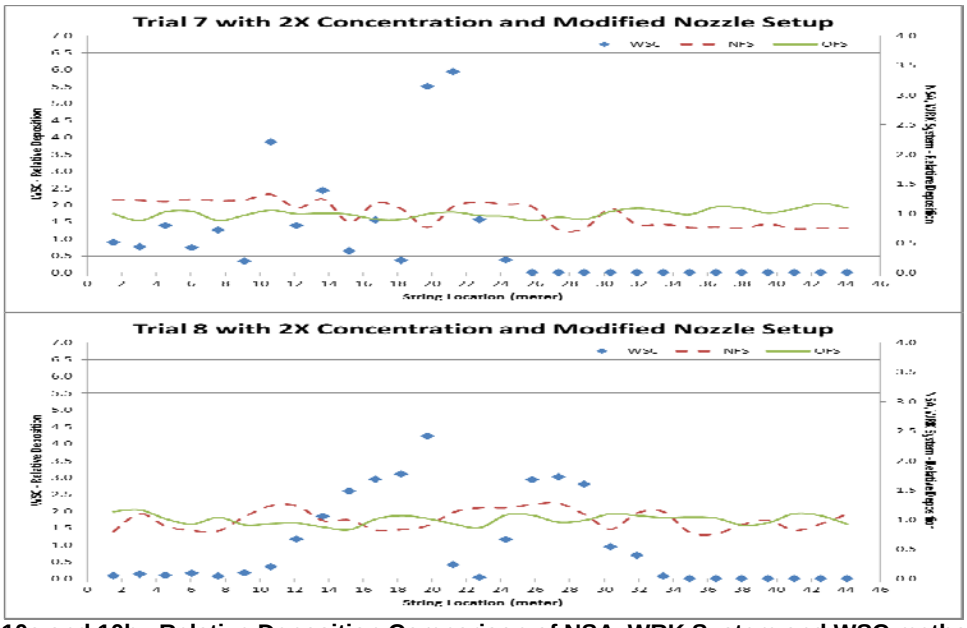

Figure 10a and 10b. Relative Deposition Comparison of NSA, WRK System and WSC method at 2X Concentration and Modified Nozzle Setup.

Discussion

AAMS Automated Speed Sensor

The automated aircraft speed and release height system was able to record continuous data as well as provide summary data to a wireless terminal after the aircraft entered the "field of view" of the height sensor. The automated aircraft speed sensor was able to obtain a continuous lock on the fastest target within the sensor's "field of view", in this case the incoming aircraft. The automated system was able to obtain a target lock within 1 mile while the manual HHR was only able to obtain a lock within 1000 feet. The automated sensor was able to record 22 samples per second of speed data of the aircraft during its approach, while the HHR could only obtain 1 sample reading within the same time frame. The automated speed sensor was able to obtain the speed of the aircraft repeatedly from the same distance and location between the aircraft and sensor; the same cannot be said from HHR due to the dependency of human interaction and reaction times.

AAMS Automated Height Measurement

The automated aircraft release height sensor was also able to continuously record height information the instant the system detected the aircraft was within the "field of view" of the sensor. Depending on the aircraft's speed and reflectance response between the aircraft components and the height sensor's receiver, only 70 to 100 samples produce usable data. As the aircraft passes over the automated height sensor, the signal from the sensor transmits and receives a "known" pulse to determine the distance between the sensor and different components of the aircraft. The signal returned could represent various aircraft components

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such as portions of the propeller, bottom of the aircraft fuselage, spray pump, spray nozzle boom, and then the remaining portions of the aircraft body. A different signal response would be generated, if the center aircraft is offset from the automated height sensor, the signal return could represent reflectance from portions of the bottom of the fuselage, landing gear wheel, wing, a zero response, then horizontal stabilizer. The signals from both scenarios, a perfect centered or offset flight, have distinctive patterns that would provide hints to the operator of the flight. In a centered flight approach, the return signal has a complete and continuous dataset of 70 to 100 points with a range of data of only 1.52 m (5 feet) between the maximum and minimum height data. If the aircraft were flying offset, then portions of the landing gear and wing data would be observed. The 70 to 100 point data set would have several samples resulting in 0 m which represents an unsuccessful return of the signal from the height sensor. For example, the sensor would detect the front of the wing as the aircraft passes, and return a signal of the bottom of the wing, then open sky between the sections of the wing and horizontal stabilizer and then continue to return values from the horizontal stabilizer until the aircraft passes. At this point in the project, the preliminary method to interpret the data is to use the minimum value of the usable dataset for each trial to determine the aircraft release height which is assumed to be the spray boom component of the aircraft. The automated sensor is able to repeatedly produce 70 to 100 height information samples each time the aircraft passes over the automated height sensor. The manual STT is able to acquire 1 sample and is heavily dependent on the experience level and reaction times of the human operator.

NSA System

The new string system was compared to the WRK System and WSC method (29 cards placed at 1.52 meter intervals and analyzed with DropletScan v2.4). The water sensitive cards are 2-dimensional collection samplers that are placed at a 30° angle from the ground in order to increase the chances of the droplets imprinting onto the card and minimize streaking during impact. It should also be noted that, smaller fine droplets less than 50 microns (Hoffmann and Hewitt 2005) may not be detected due to inability to be absorbed and react to the water sensitive card. Both the NSA and WRK Systems use a 1 mm diameter cotton string as the collection sampler which is a 3-dimensional cylindrical object that is able to absorb droplets that have adhered to the cotton fibers of the string. The relative depositions between the NSA and WRK systems show similar overall trends, however a one-to-one match between the relative deposition and location between the two systems was not evident. The lack of an exact one-to-one correlation could be due to several factors. The first relates to the physical interaction between the cotton string and the mechanical components of both fluorometer systems. Each string was processed through the WRK System and then the NSA System. There is a possibility that mechanical related destruction and/or removal of string fibers as it was processed through the WRK System may have occurred, and therefor would fluorescence intensity would decrease when processed in the NSA System. A second possibility for the lack of a direct match could be related to the method in which distance/location of string is determined. The WRK System performs a calibration routine once, when the system is first turned on, and then the distance determined by a set calibrated factor of string length per minute. The new fluorometer system uses a rotary encoder which measures 39.8 mm of string per revolution. Due to the two different measurement methods to determine length/location of the string, a discrepancy of the measurement for a particular location may occur. An offset

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correction factor could be applied to the dataset of either system if it is required. A third possibility of the discrepancy could be due to sampling method. The surface area of the water sensitive card(s) was calculated; then the length of string to sample was calculated to produce an equivalent surface equal to the water sensitive card. From each of the NSA and WRK System data sets, the calculated length of string for each sample location (1.52 – 44 m) was averaged. The NSA System averaged approximately three times as many data points as compared to the WRK System. The fourth possibility of the discrepancy is related to the fluorescence sensor system itself. The NSA System uses a different fluorescence sensor and focusing mirror that may not be adequately distributing the excitation source and reflecting the fluorescence signal back to the sensor.

Comparing both fluorescence based systems to the water sensitive cards yield similar trends near the respective data's centers (which reflects center of aircraft and spray boom) but discrepancies at the extremes could be seen. An offset in physical location may contribute to a one-to-one match of relative deposition and location, but this could also be related to possible weather related drift when comparing the string sampler to the water sensitive cards. As mentioned earlier, the efficiencies of the two systems may also explain the differences in measurements at the extremes. The string collector may be collecting the finer droplets whereas the water sensitive cards do not absorb and imprint them. In contrast, the string system may miss larger droplets while the water sensitive cards are able to collect and factor the larger droplets into the final results.

With only the relative deposition reported in the graphs, it does not show the effect of the 1X and 2X concentration. After analyzing the raw data from both the NSA and WRK Systems, it was difficult to determine if there was a significant change based on the concentration of the red dye tracer tap water mixture. The WRK System required adjusting the sensitivity settings in order to obtain a valid intensity reading for each of the string samples. After the adjustment it was difficult to correlate the recorded intensity levels to concentrations. The NSA System's fluorescence sensor reported very little change in the range of values from the samples with either 1X or 2X concentrations in order to make a correlation. The water sensitive cards were not designed to measure different concentration, only liquid droplet size and percent coverage.

Summary and Conclusions

Automated Ancillary Measurement System

The AAMS was able to be deployed in the field and required little in-field maintenance during the entire fly-in operations, the only exception was when the string collector had to be adjusted due to shift in wind direction. The system was placed on the centerline and 4.6 m in front of the string collector. Each time the aircraft performed a pass, the system was able to produce a continuous record of the aircraft's speed and spray release height during each successful approach. In addition, the system would send generate a wireless trigger signal and provide summary data for each pass that could be viewed on the portable wireless terminal. An automated weather station based off of Campbell® Scientific, Inc. equipment and several third-

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party wireless components was constructed; it was tested separately from the automated aircraft speed and release height measurement system. This unit was assembled as a proof concept model, a future design would allow for a lower cost weather station that provides the same capabilities and an integrated application for use with different types of wireless terminals such as tablet's, laptops, smartphones, etc. However the main goal will be to allow a user to view the summary data of the aircraft speed and spray release height, weather station information and control them from a similar interface illustrated in Figure 11.

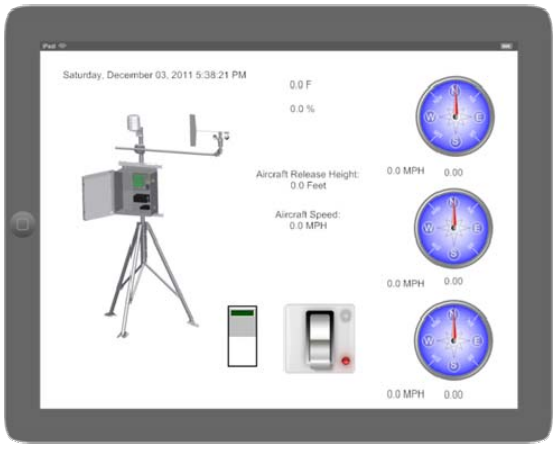

Figure 11. Concept illustration of wireless terminal interface and automated sensor system.

New String Analysis System

The new string analysis machine is a system that is able to reuse the existing string collection storage reels and analyze fluorescence from the string samples. Several custom circuits and microcontrollers with custom firmware allow for automated control of string movement, string distance/location, and start/stop marker detection. Two gear motors with control circuitry that provides an auto-adjustment in speed to aide in controlling the tension in the string during the analysis. With the addition of the second gear motor, it allows the system to run in forward and reverse directions, therefore the string does not have removed or manually rewound if a test has to be processed again. The rotary encoder installed in the new string analysis system allows for a consistent and repeatable measure of string distance. The red-green-blue color sensor, adds the benefit of an automated start and stop for each sample. All components are made to operate, or built with power circuits to allow it to operate from a 12 V-DC power source such as a sealed lead acid battery or alternating current to direct current power supply. Finally, the NSA System was built with modularity in mind, if the need to replace specific component arises, one could be easily remove and replace the component without disturbing other components. This system should be considered to be in its infancy. To make this a complete system, future work will be required to improve the motorized control system and more research with regards to the fluorescence sensor and optics is required as well as development of software to process the data and provide more meaningful interpretations of spray deposition patterns.

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