Development of a Phase-Doppler Technique for Mass Balance and Spray Characterisation of Orchard Air-Blast Sprayers within New Zealand Horticultural Cropping Systems

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Rory Lucas Roten

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The knowledge of the sprays emitted from orchard air-blast sprayers has historically been assessed using an array of samplers to capture airborne particles such as various strings/ribbons, paper material, and/or patternation structures. While these methods provide flux data, no other information is obtained which is pertinent to understand the potential movement of droplets. Qualitative droplet information can be acquired *in situ* which can be related to the deposition, coverage, and off-target losses. However, the quantitative analysis for agricultural sprays has predominately been conducted in a laboratory setting with the use of laser devices which are comprised of multiple pieces; ergo the necessity for controlled environments for the alignment of these pieces is essential. In this research, a new self-contained phase Doppler (pD) was tested to assess the droplet size spectrum, velocity, and flux in uncontrolled outdoor field conditions with the overall hypothesis that the pD will be a superior means of data collection in that the data will be more robust with fewer sources of error, highly repeatable, fast, and inexpensive.

To test this hypothesis, a step-wise research plan was developed to determine 1) if pD could accurately measure flux by traversing through a similar spray plume to an orchard sprayer while still in the controlled setting of a laboratory; 2) compare and validate pD derived flux data to that of passive strings collectors in a wind tunnel in areas of heightened flux and droplet/air velocities; 3) compare these samplers in outdoor environments with no crop presence; and 4) determine if pD could be used in place of other collectors in a horticultural setting.

Results demonstrated an average error of the computed flux versus measured flow rate was -3.3% using a disc core (D1/DC33) hollow cone nozzle at spray pressures of 3.1, 4.1, and 5.2 bar pressure (45, 60, and 75 psi) and at five heights (10, 20, 30, 40, and 50 cm). In the wind tunnel with varying wind speeds (1.4, 4.2, 8.3, 12.5, and 16.7 m/s) and spray exposures times (5, 10, 15, 30, and 60 s), the pD accurately measured the spray flux while the string samplers overload with saturation. From here, the pD was taken outdoors and displayed that the sampling volume of the pD was too small to acquire enough samples for sufficient flux data; therefore this research ceased. However, in all of these studies, regardless of the sampling frequency and inadequate flux output, important data was still acquired related to the droplet size distribution and droplet velocity. This is thought to be a major point of difference whereas pD may not yet be able to be the sole tool, but an important support tool for other instruments that can only measure flux. Lastly, the ability to quantitatively understand the droplet size differentiations at various heights and distances in relation to a crop can provide profound feedback to the application of plant protection chemistries, their fate, and their efficacy.

Keywords: Sampler, phase Doppler, coverage, deposition, flux, velocity, droplet size distribution, patternation, horticulture, orchard, air-blast sprayer, pesticide, plant protection, fate, efficacy.

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*Work related acknowledgements can be found in individual chapters.

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Chapter 1

Introduction

1.1 Background

The science of the airborne movement of agrichemicals (i.e. drift) has developed greatly over the past 30 years. Models and supporting algorithms have been developed by governments, universities, and industries to establish a methodology for the prediction of pesticide drift and on-target placement (i.e. deposition). However, these models have focused on drift from aerial and ground boom application only, and little has been successfully developed in the prediction of drift from orchard air-blast sprayers and the mass balance thereof.

Orchard air-blast, also referred to as air-assist, sprayers have historically been the predominate means of chemical application for New Zealand horticultural crops such as kiwifruit, grapes, and various tree orchard systems. These types of application devices are advantageous to these farmers due to the sprayer's ability to get the small droplets in hard-to-reach locations such as under-leaf surface, within fruiting zones, upper tree canopy, and three-dimensional coverage to dormant kiwi vines. Furthermore, for applications of insecticides and fungicides where cover is imperative, the air assistance opens the canopy and provides momentum for the sub-100 µm droplets which provide better coverage but lose inertia or evaporate before reaching the intended target.

Unfortunately, the sprays from these rigs are difficult to predict which is of great concern when sensitive species, protected land, and waterways are involved. In current modelling algorithms, sprays only project downwards under the nozzle's hydraulic force. Orchard sprayers have the potential to spray >180° upward and outward with air velocities exceeding 40 m/s. When these characteristics are combined with independent variables such as canopy characteristics (i.e. height, width, and leaf area index) driver speed, and meteorological conditions within the cropping system (i.e. relative humidity, temperature, wind speed and direction), predictive tools become even less applicable.

The validation of these models is done in-field or within the controlled environment of a wind-tunnel using various methodologies such as the use of nylon strings to assess flux, and laser technology to examine the drop size distribution of a particular nozzle at a given wind speed. However, these methods are labour-intensive and time-consuming due to the shear nature of the work and the fact that these variables cannot be assessed simultaneously in real-time.

Current laser technologies used in spray droplet analysis include laser diffraction (Malvern and Oxford), imaging PMS (Particle Measurement System), and PDPA (Phase Doppler Particle Analyzer). However, each of these tools contains a set use and set of limitations. For example, the laser diffraction instruments cannot be easily used in the field as they are bulky and rely on precise alignment prohibiting its removal from a controlled environment; also, these instruments only provide particle size. Phase Doppler (pD) provides the ability to assess not only particle size, but flux and velocity as well. However, these instruments have historically been for laboratory use only as they too are quite reliant on alignment.

Recently, another laser has begun to surface using pD technology in a robust, field measurement device called the Demeter Probe (and later the TurnKey) which has evolved from Artium's Flight-PDI used cloud characterisation. Unlike diffraction and imaging systems, pD provides the ability to collect the droplet size distribution, flux, and velocity simultaneously. Furthermore, it is these features that are believed to strengthen the current flux measurement methods as the user can start and stop a given measurement as needed to ensure that the spray plume has developed.

The current string method for flux sampling has been used extensively for over thirty years by groups such as the Spray Drift Task Force, Agriculture and Agri-Food Canada (AAFC), CropLife Canada, and Lincoln Agritech's Chemical Applications, Research and Training (CART) group. However, this method, especially in a wind tunnel, does not give the ability to begin sample collection after the completion of spray plume formation, causing potentially erroneous data; the pD provides the ability to start sampling at any time. These data can then affect the modelling algorithms that they are input to. Furthermore, multiple string types are used in-field to capture driftable particles, and though this method does not assess the particle size differentiation in the vertical profile, it has been a common tool for measuring mass balance.

Therefore, it is the rationale of this research to gain better insight to the mass balance of applied agrichemicals within one or more of these unique, horticultural canopies. It is the hypothesis of this proposal that the pD will advance the current methods for data collection in the laboratory and field environments. Additionally, a comprehensive understanding of orchard air-blast sprayers will be gained which will supply current drift modelling software including spray plume mapping, nozzle to nozzle interaction, and air-assisted droplet size differentiation against gravitational forces.

1.2 Research objective and hyphotheses

To date, the quantification and accountancy of sprayed agrichemicals is unable to recover 100% of sprayed agrichemical (Jensen and Olesen, 2014). A better understanding of this quantification (i.e. mass balance) is essential for current and future modelling efforts. Therefore, the objectives of this research are as follows:

Laboratory/ Wind-tunnel

- Administer a detailed investigation of string drift collectors, their collection efficiency and shortfalls
- Administer a thorough investigation of pD technology including detailed cross comparison of current sampling methods and differentiating features

In-field

- Detailed examination of air-assist sprayer(s) using pD to assess droplet distribution, velocity, and flux
- Thorough examination of pD technology for the quantification of droplet displacement within canopy in comparison to on-target deposition

Overall objective

To tie together the aforementioned objectives to develop an enhanced methodology for mass balance and pD data capture in horticultural settings such as kiwifruit, vineyards, and orchards to discern a more accurate means of pesticide quantification.

Hypotheses

1. The pD will give equivalent flux and deposition data as string collectors until a point at which string samplers might become saturated
2. That the pD can be used to infer the collection efficiency of string samplers
3. The pD will provide useful and immediate feedback regarding flux, droplet size distribution and velocity in field environments
4. Data from the pD will be able to provide useful information regarding the patternation and potential application quality of spray from a horticultural sprayer

1.3 Facilities

1.3.1 University of Queensland Wind Tunnel

The University of Queensland Wind Tunnel in Gatton, Australia (Figure 1.1) provided the necessary controlled environment to compare the pD to classical string samplers. The tunnel generates the majority of its wind via its rear fan (Figure 1.2) and goes through a series of straighteners to create a laminar airflow before passing through one of the working sections with appropriate necking/converter (Figure 1.3). The working sections range from a large, 1,750 by 1,750 mm section for low air speed to a small, 400 by 400 mm section which is used for aerial applications. (Table 1.1). Extraction fans are also employed to maintain airflow as well as to filter droplets before exiting the building. All collected liquid is retained in a number of tanks.

Figure 1.1 External view of the University of Queensland Wind Tunnel facility and is extraction fans.

Figure 1.2. Main, rear fan for University of Queensland Wind Tunnel.

Figure 1.3 Illustration of Wind Tunnel working section.

Table 1.1 Airspeed capabilities of the Gatton Wind Tunnel.

Section	m/s	kmh	mph	Knots
400 by 400	75	270	168	146
600 by 600	50	180	112	97
1000 by 1000	18	65	40	35
2000 by 2000	5	18	11	10

1.3.2 Lincoln University/Agritech

A schematic of the test facility is shown in Figure 1.4. All of the equipment can be operated off a standard 12 VDC power supply, with an automobile battery being used to supply electrical power to both the water pump and the traverse motor. The 2.5 m long traverse frame was made of weather-resistant materials (aluminium and stainless steel), providing a 1.6 m sampling length. The traverse was designed to pull the pD with tray operated by an anti-slip toothed belt which was connected to an axle which was powered by a 12V ATV winch (680 kg/1,500 lbm, Ridge Ryder, Lawnton, Queensland, Australia). The winch was geared down to a 1.43:1 ratio with pullies so that slower speeds were possible with this motor. This setup provided a speed range of 0.0079 to 0.0376 m/s with the use of a DC speed controller. The traverse was attached to a base so that it could move over a collection table thereby enabling the operator to move the probe to the desired location. The water spray system included a 12V pump (7 L/min, 8.27 bar max (120 psi), Smoothflo model DDP-552, Aquatec Water Systems, Inc, Irvine, CA, USA). In order for the height to be adjusted the selected nozzle can be attached to a crossbeam which could be moved incrementally, upwards of 1 m above the PDI.

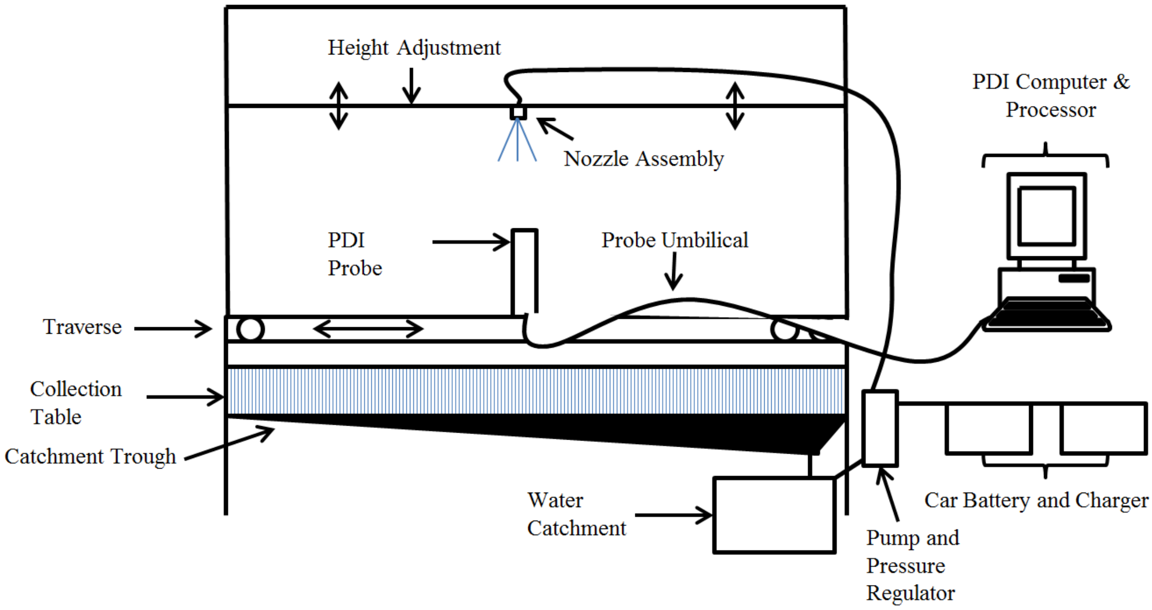

Figure 1.4 Schematic of spray table.

1.4 Thesis Structure

Great effort was made to reduce redundancies, however as these chapters were drafted for individual publications, limited repetition should be expected. Further, depending on the context and where the manuscript was submitted, English spellings may vary as well as the abbreviation for phase Doppler (pD, PDI).

The thesis consists of 6 chapters.

Chapter 1	Provides relevant background information from the original proposal, original research objectives, facility descriptions, and thesis structure.
Chapter 2	Brief literature review regarding development of orchard sprayers, mass balance assessment, and phase Doppler evolution.
Chapter 3	Manuscript for validation of using phase Doppler to assess mass of conical spray plumes which are commonplace in orchard spraying.
Chapter 4	Examination of phase Doppler ability to capture data in areas of high air/droplet velocities and heightened exposure time.
Chapter 5	Field validation of phase Doppler against two string types in close proximity to an orchard sprayer.
Chapter 6	Concluding remarks regarding the use of phase Doppler in-field, as well as potential future uses.
Appendix A	Published manuscript from Chapter 3.
Appendix B	Published manuscript from Chapter 4.
Appendix C	Alternate version of Figure 4.2.

Appendix D	Published manuscript from Chapter 5.
Appendix E	A referred conference proceeding generated from the thesis.

Chapter 2 Literature review

2.1.1 Air-blast sprayers

The application of pesticides commenced in the 1860's and the equipment thereof has advanced accordingly (Brann 1956). The use of air-assistance was born circa 1886 with the use of bellows to atomize and project a given solution (Large 1965). However other pumping mechanism became quickly available with the advent of steam, and later, gasoline driven pumps. In 1925 the Rex Liqui Duster made an appearance in tree crops, however due to low volume rates and poor coverage, the popular high-pressure, high-volume hydraulic spray devices became the standard (Brann 1956). Then in the early 1940's, the essential upgrade from an airplane propeller to an axial flow fan was made, giving birth to what we now call the axial fan air-blast sprayer (Daugherty 1949).

Fox et al. (2008) explained that three main components affect the performance of these sprayers: design factors (i.e. droplet distribution from the given nozzles and the orientation thereof), spray conditions (i.e. driver's speed and meteorology) and plant variables (i.e. height, spacing, growth stage, etc.). These are also the same factors which contribute to the likelihood of pesticide drift. Further, the beauty of air assistance is the ability to give small droplets the increased acceleration that they need to get to the target; this ability also puts the most drift-prone droplets in a drift-prone atmosphere (Cross et al. 2002).

There exists a great conundrum in picking the ideal nozzle/pressure relationship for every cropping system. For orchard sprayers, this conundrum is even more complex as each location is different by entirely different plant species, or simply a differing variety within species (Cross et al. 2002). For example, in the last 50 years there has been a push for shorter orchard species which yield more fruit and are easier to spray (Fox et al. 2008). Yet due to the nature of orchard rotations, one sprayer may be used in dissimilar orchards. If these factors are not taken into account, the risk of drift and the efficacy of the spray solution will be compromised (Walklate et al. 1996).

Due to these sprayer variables, it is difficult to model the interaction between sprayer airstreams, droplets, and canopy in terms of the overall fate of the chemicals being applied. Attempts have been made to model drift using Lagrangian models (Teske & Thistle 2003), Gaussian models (Raupach et al. 2001), or a combination of both (Da Silva et al. 2006). Da Silva et al. (2006) introduced the Lagrangian equation for droplet trajectory but made two major assumptions: droplets and airflow have no interaction and that droplets of spray cloud all have approximately the same diameter and equivalent mass of liquid per droplet. However, they do recognize that their model does not account for the transport of the droplet from the sprayer to the canopy. There has since been ongoing development within the Lagrangian model, AgDISP where new procedures have been added to improve droplet fate predictions (Bilanin et al. 1989; Forster et al. 2012; Schou et al. 2012). Connell et al. (2012) discusses the need to better understand the physical properties of droplets emitted from a sprayer so that these models can be used more precisely, regardless of location.

However, the aforementioned models have solely worked with aerial and ground-boom application. Horticultural sprays are much more difficult to model due to extreme differences in particle distribution parameters. The works of Endalew et al. (2010) illustrate that computational fluid dynamics (CFD) modelling approach for orchard air-blast sprayers is plausible. However, their work focused solely on the airflow from types of three sprayers: the Hardi Condor V, the BAB Bamps, Duoprop, and the BAB Bamps, Airjet Quatt. These works will play a vital role in the development and framework of this thesis as the Condor V, single axial- fan sprayer (or similar to) is the focus of the proposed studies and give great insight to airflow/tree relations. Further, the research of Endalew et al. (2010), supported by Delele et al. (2005), exhibit that plane jet theory is not supported due to non-uniform jet velocities and presence of a vertical profile.

2.1.2 Samplers and methodolgies

To date, no standard method has been established for mass balance of agrichemicals an no further standardisation has occurred since Salyani's analysis in 2007 (Salyani et al. 2007). Table 2.1 illustrates the variety of samplers, tracers, and methods used for agrichemical spray quantification and characterisation for more than 30 years; however, these methods have evolved from practices dating back to the 1950's (Whitney & Roth 1985). The collector type poses great risk due to differing collection efficiency and their droplets sizes effects. For instance, Egner and Campbell (1960) reported that sub-100 µm droplets were the most affected by the diameter of a collector, showing that the smallest 2.5 mm treatment received 74% efficiency. This droplet class is essential to drift research as well as mass balance and will play a substantial role in the proposed research.

Key differences presented here are 1) the use of a new fluorescent dye for field work (1, 3, 6, 8-Pyrene tetra sulfonic acid tetra sodium salt (PTSA)) which was introduced to the market in 2013 as an inexpensive and stable compound suitable for spray drift analysis (Hoffman et al. 2014); 2) the proximity of the sprayer to the samplers range from 1 to 5 m is not a common area of interest; and 3) the air velocities to which the samplers are exposed here are unprecedented.

The samplers tested in this thesis where chosen as they are largely accepted in field and wind tunnel studies, and their collection efficiencies (CE) have been thoroughly discussed (Hewitt 2010). Debate does exist to the CE of cotton string materials as these have an undefined diameter which is an essential variable in the calculations of the theoretical CE (May & Clifford 1967; Fritz et al. 2011; Bonds & Leggett 2015). However, it has also been observed that the CE is near, or greater than 100% with cotton strings as they have the ability to absorb as well as possess omnidirectional strings which are a capable of retaining fine droplets (Figure 2.1) (Cooper et al. 1996).

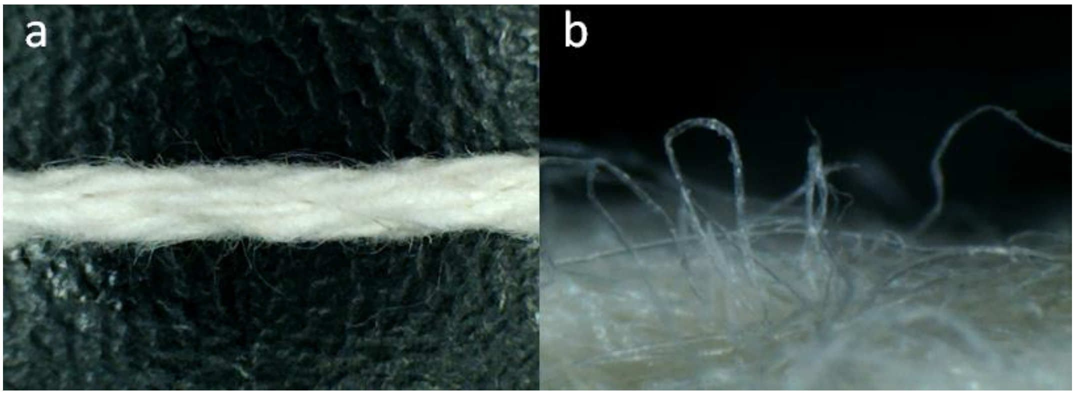

Figure 2.1 a) 20x view of the cotton string illustrating physical differences in diameter as well as the fibrous nature of the textile and b) a 400x view of the outstretched fibres, approximately 15 µm thick.

Table 2.1 Examples of collectors, dyes and methodologies for agricultural spray assessment.

	Samplers		Tracer	Tunnel Speed	Sampling Distance (m)
	Wind Tunnel	Field			
Arvidsson et al. (2011)	Static (pipe cleaners, 2 kinds of balls) and a dynamic	dynamic and pipe cleaners	Uvitex LV	1.3-3.1	5
Hewitt (2010)		Rotorods®, hair curlers, 0.8 mm cotton string, 2 mm Teflon string	Eosine OJ, Tinopal CBS-X, Uvitex OB		0, 30 and 150
Fox et al. (2004)	Various nylon screens, 1 mm cotton string, and 2 mm polyester string		Acid yellow 7	2 to 6	
Salyani et al. (2007)		25.4 mm cotton tape	Pyranine		5+
Balsari et al. (2005)		200x220 cellulose	Tartrazine		~3
Zhu et al. (1996)	Various steel plate		Tinopal CBS-X	0.5 to 8.0	
Bui et al. (1998)	High-volume air samplers, disk impactor and bubblers, rotating rods, foam plugs, and 2 mm cotton string		Malathion		30 m
Cooper et al. (1996)	Rotating rods with Magnesium oxide plates and yarn (size unknown)		Uvitex OB	0.25 to1.5	

2.1.3 Mass balance

One of the greatest downfalls of mass balance is quantifiable amount of mass collected in a field trial is very rarely near 100%; Jensen and Olesen (2014) reported on 66 mass balance studies and as much as 61% of spray goes unaccounted. Salyani et al. (2007) observed deposition of five different sprayer types and found no significant difference in spray deposition (74 to 82%). However, calculated drift data did not take in all parameters and merely calculated these as a proportion of wasted material (i.e. proportion lost to the ground and the unaccounted) as the difference of the mass balance of deposited solution. This is of dire consequence as this assumption of drift is not accurate and can be due to other issues such as collector efficiency, photo-degradation of florescent dye, human error, etc. (Salyani et al. 2006; Hoffman et al. 2014). This could indicate an under-prediction of deposited solution. As discussed by Fox et al. (2008), leaves are not stationary objects but can articulate in many fashions, thus making deposition readings difficult to grasp and be subjective. Moreover, in instances where collection efficiencies were high, high inputs and costs were also involved as can be seen by Holland et al. (1997) where a reported 96% recovery was observed. However, this study used pesticide, high cost laboratory analysis, invasive harvesting of biological matter, and had no reported replication.

With orchard sprayers, it is difficult to capture drop data near to the sprayer with string-type collectors. Due to air velocity, string diameter and material, several things may happen during droplet/string encroachment including sampler saturation and droplet shearing, either of which will provide less than satisfactory results. Further, even when acceptable flux data is obtained, string data simply does not supply information such as droplet velocity and size, thus the story of flux is not fully told. Using pD technology, one can simultaneously analyse the droplets' movement in a forward and backward fashion whereas with a string, when the droplet deposits, it is there to stay. This is potentially a key piece of the mass balance puzzle as over-depositing may be occurring on the strings which does not account for the mass falling back to earth.

2.1.4 Phase Doppler

Phase Doppler has been used in many arenas such as cloud research (Chuang et al. 2008), agricultural sprays (Sidahmed et al. 1999; Nuyttens et al. 2007b; Nuyttens et al. 2009), and soil physics (Bah et al. 2009), to name a few. The use of phase Doppler (pD) is by no means a new development as it began to make its appearance in the late 1960's when it was referred to as laser Doppler velocimeter. Circa 1983, "phase Doppler" began to surface with the works of Bachalo and Houser with their work at NASA Lewis (Bachalo & Houser 1984; Dan Hirleman 1996). Soon after, Bachalo patented a specialized detector redundancy which was used widely within Aerometric and now Artium Technologies where the tested PD systems haled (Bachalo 1985; Dan Hirleman 1996).

In short, phase Doppler works by way of a single laser being split in half and the two halves travel through an optical array where they are emitted from the transmitter. Once emitted, the two beams cross, resulting in a distinct and constant signal (fringe spacing); this signal is detected from the receiver (Figure 2.2). Changing the angle of the beams changes the size of the probe volume, which affects the overall spectrum that can be tested. For example, the Demeter has two pre-set angles that the operator can choose from, depending on the expected droplet spectrum (Table 2.2); the wider 50.8 mm beam spacing has a more obtuse angle of intersection causing a smaller fringe spacing and focused beam diameter (3.2 µm and 156 µm, respectively). Conversely, the more acute the angle of intersection, the larger the sampling volume, resulting in a larger droplet range.

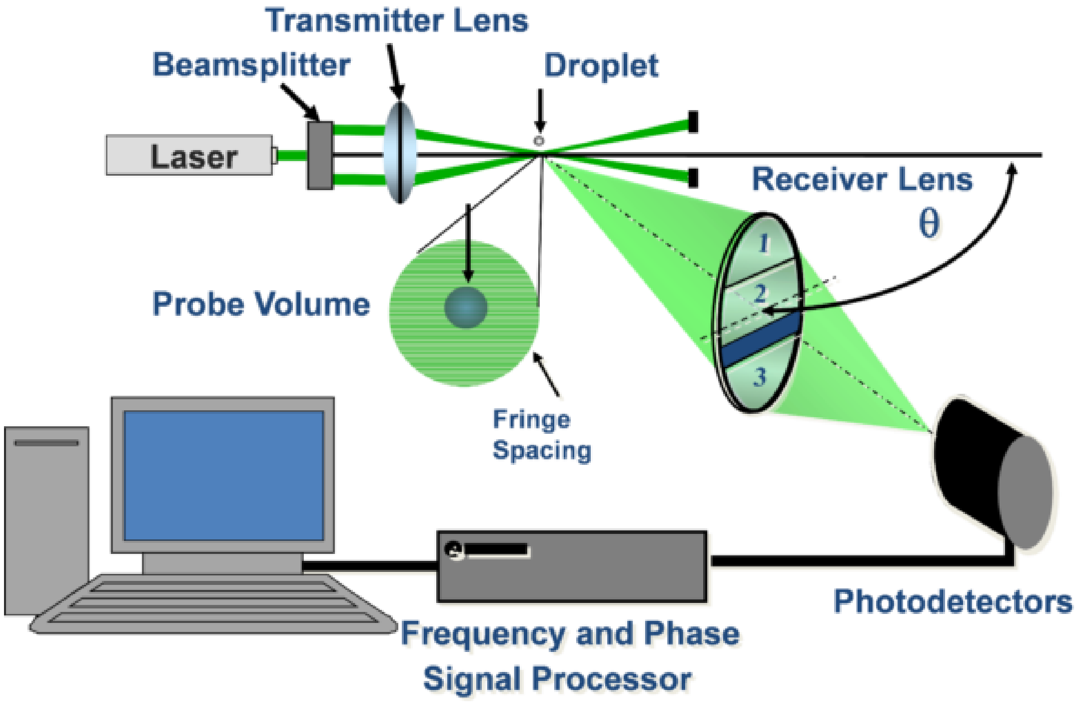

Figure 2.2 Phase Doppler theory. Photograph credit: Artium Technologies Inc.

Though phase Doppler technology has been used in many industries, nearly all applications have been in controlled areas (i.e. laboratories or other controlled, indoor environments) because the alignment of the detector relative to the beams' intersection is critical as well as the parameters like the focal length. In the evolution of the technology, a cloud probe which was designed to be mounted to the exterior of an aircraft which required the implement to be completely enclosed with fixed angles. Eventually, taking the enclosed system evolved into the Demeter probe (Figure 2.3) with the intent to measure agricultural spray drift and, finally, the TurnKey (TK) probe (Figure 2.4). Both of which are used in this research and, to date, the Demeter presented here is the only one in existence, providing a large opportunity for redefining our current understanding of droplet relations from agricultural sprayers.

Table 2.2 Specifications of Demeter probe by beam separation (Anon. 2013).

	Beam Separation	Transmitter Focal Length	Receiver Focal Length	Fringe Spacing	Focused Beam Diameter	Velocity Range	Droplet Diameter Range
	mm	mm	mm	μm	μm	m/s	μm
Demeter	50.8	300	150	3.2	156	-200 to 200	0.5 to 90
	8.4	300	150	19.0	1594	-300 to 350	3.0 to 550
TurnKey	1.56	100	50	34.1	80	-125.3 to 125.3	5 to 694

Figure 2.3 Demeter PDI. Photograph credit: Artium Technologies Inc.

Figure 2.4 Turnkey (TK) PDI. Photograph credit: Artium Technologies Inc.

Chapter 3

Volumetric Validation of Mass Balance Using a Computational Phase Doppler Approach for Disc Core Nozzles

This chapter was published in Crop Protection 79:1-7 (Appendix A)

3.1 Abstract

The mass balance of orchard air-blast sprayers has historically been assessed using an array of samplers to capture airborne particles. However, these methods only provide an idea of flux with no other information which is pertinent to understand the movement of droplets and their potential to drift. While droplet analysis for agricultural sprayers has always been conducted in a laboratory setting with the use of laser devices, a new phase Doppler approach is being explored to assess droplet spectra, velocity, and flux in outdoor field conditions. Therefore it is the objective of this study to develop a methodology and the potential limitations for using a phase Doppler system while in a laboratory setting. Due to the expected variability of field conditions as well as the turbulence of orchard sprayers, a computational approach was sought to assess flux from a single scan of a conical spray plume's diameter. Using a constant scanning speed of 0.0079 m/s, a disc core (D1/DC33) hollow cone nozzle was examined at 3.1, 4.1, and 5.2 bar pressure (45, 60, and 75 psi) at five different heights (10, 20, 30, 40, and 50 cm). Computational flux was then compared to the actual flow rate, finding a 3.3% average error. Further, comparisons were also assessed including pattern/symmetry, droplet spectra, velocity, and the overall number of samples. The proposed methodology indicates potential for the use of phase Doppler technology for *in situ* measurements of spray equipment using a conical-type spray nozzle, such as that of the orchard air-blast sprayer.

3.2 Introduction

The axial-fan orchard air-blast sprayer is the most common device for agrochemical application for tree, bush and vine crops. The air produced from the fan propels the liquid droplets into the canopy, assisting in the necessary canopy penetration and deposition. However, though these sprayers have been widely adopted over the last century with relatively few changes, our cropping systems have changed substantially. This consequently carries a greater risk to place drift-prone droplets into the air for potential transport downwind. When assessing these sprays in the field, it is typical to use collection samplers such as cotton ribbons, high-volume air samplers, impingers, monofilament fishing line, nylon cords, Petri dishes, plastic fallout sheets, polyurethane foam, mylar sheets, and rotating rods (Bui et al. 1998; Salyani et al. 2006). With each collector type, potential risk of inaccuracy is heightened due to differing collection efficiency. For instance, Egner and Campbell (1960) reported that sub-100 µm droplets were the most affected by the diameter of a collector, showing that the smallest 2.5 mm treatment received 74% efficiency. This droplet class is essential to drift research and is also important to the mass balance. Furthermore, accurate droplet information is essential when examining and predicting the performance of agricultural nozzles. For example, small droplets provide better coverage but quickly lose their inertia, sometimes causing an undesired result (i.e. drift, evaporation, and/or deposition on off-target locations). Larger droplets are often used to counteract these phenomena, however these droplets may also provide less coverage and are also likely to have unintentional deposition by run off, shattering, and/or bouncing off the leaf surface (Dullenkopf et al. 1998; Forster et al. 2005; Schou et al. 2011).

Droplet data are also useful for modelling spray drift and deposition by understanding the droplets’ size distribution and their interaction with meteorological conditions (i.e. temperature, humidity, wind speed and direction, etc.). To acquire these spray plume characteristics, one or more of these common methods are typically used: laser diffraction, Particle Measuring Systems (PMS), and phase Doppler interferometry (PDI), also referred to as phase Doppler particle analyser (PDPA) or phase Doppler analyser (PDA). These methods are largely accepted within spray industries, though each technology provides different distributions, especially in dense, poly-disperse sprays such as in agricultural applications (Parkin 1993). However, while these laser technologies provide droplet distributions, only the PDI directly provides velocity and flux measurements which are important to determine the mass balance of a nozzle. As discussed by Goguen et al. (1997), by understanding the fluxes of a plume, a better knowledge of the mass balance will be obtained.

Historically, the mass of a spray plume in laboratory settings has been assessed by traversing a nozzle over a stationary PDI system. The nozzle stops at discrete locations thereby accurately mapping the plume with a differentiation of droplet sizes, velocity, and flux at each coordinate. These laboratory PDI systems are comprised of two pieces of equipment which (with few exceptions) must stay stationary to keep transmitter and receiver in alignment. In 2008, the F/PDI (Artium Flight-PDI, Artium Technologies, Inc, Sunnyvale, California, USA) for *in situ* cloud droplet analysis was introduced which combined the transmitter and receiver into one enclosed system, allowing the technology to be taken out of the laboratory and separating itself from laser diffraction (Chuang et al. 2008). In 2011, Artium, with collaborative effort of Lincoln Agritech, Ltd. (Lincoln, New Zealand), developed the Demeter probe which was developed to assess sprays from agricultural sprayers (Hewitt et al. 2013). The Demeter probe is used in this study.

Past research has varied substantially in the setup and analysis of agricultural sprays with phase Doppler technology (Table 3.1). Each author, depending upon their specific objectives, phase Doppler system, and laboratory capabilities had a specific method for obtaining their data. It is important to note that there is no standard for sampling procedure or system specifications. For instance, the droplet and velocity range is directly related to the fringe spacing and sampling volume which is determined by a number of hardware decisions including the light scatter angle, the optical focal length, various optical lenses, and the chosen beam separation (Bachalo & Houser 1984; Tuck et al. 1997), however these setting are not always stated in the literature. In previous laboratory work (summarized in Table 3.1) the light scattering angle and focal length range between 30 to 70° and 310 to 1,000 mm, respectfully. With these settings, the maximum droplet diameter achievable varied between 451 and 1,000 µm.

Most authors only use the PDI to make measurements near the nozzle to find the drop size distribution, either for the purpose of initializing a simulation or to relate the drop size distribution to the measured drift in the field. However, with a sufficiently long traversing system, the PDI can also provide the mass distribution, much as a patternator would, while also providing drop size information along the width of the spray, which is important for efficacy.

However, no methods have been established to assess agricultural sprays *in situ* using PDI technology and it is hoped that this work will be the building blocks for more comprehensive mass balance research for in-field analysis. Also, with the ability to move the PDI from its historically static position, previous practices may no longer be applicable. Therefore, it is the objective of this study to establish and validate a preliminary methodology for assessing spray characteristics, such as pattern, distribution, velocity, and flux, in a relatively controlled environment to determine what is feasible for in-field analysis my means of traversing the PDI probe non-stop through a conical spray plume that is typical of such orchard sprayers.

Table 3.1 Examples of past research and variations of methodologies between phase Doppler systems.

Citation	Phase Doppler System	Size Maximum (µm)	Distance from nozzle (cm)	Counts (#)	Liquid Pressure (bar)	Traverse/Static	Traversing speed (m/s)	Voltage
Chapple et al. (1993)	Aerometrics PDPA	800	30	*	2.76	T	0.0025	325
Chapple et al. (1995)	Aerometrics PDPA	700	20-30	<200 - 30,000>	2.07-2.76	T/S	0.0025	325
Dullenkopf et al. (1998)	Aerometrics PDPA	*	10	≥10,000	5.00	S	N/A	*
	DANTEC DualPDA	*	10	≥10,000	5.00	S	N/A	*
	Qiu and Sommerfeld PDA	*	10	≥10,000	5.00	S	N/A	*
	Aerometrics PDPA	*	10	≥10,000	0.50	S	N/A	*
	DANTEC DualPDA	*	10	≥10,000	0.50	S	N/A	*
	Qiu and Sommerfeld PDA	*	10	≥10,000	0.50	S	N/A	*
Miller et al. (2008)	*	*	35	*	3-4.5	T	0.020	*
	*	*	35	*	2.00	T	0.020	*
	*	*	35	*	2.50	T	0.020	*
Nuyttens et al. (2007a)[1]	Aerometrics PDPA	1000	50	≥10,000	2-4.5	T	0.025	*
	Aerometrics PDPA	1000	50	≥10,000	2-4.5	T	0.017	*
	Aerometrics PDPA	1000	50	≥10,000	2-4.5	T	0.030	*
Nuyttens et al. (2009)[1]	Aerometrics PDPA	1000	50	≥10,000	2-4	T	0.025	*
	Aerometrics PDPA	1000	50	≥10,000	3.00	T	0.025	*
	Aerometrics PDPA	1000	50	≥10,000	3.00	T	0.025	*
Sidahmed et al. (1999)	Aerometrics PDPA	875	4	10,000	2.07	S	N/A	*
	Aerometrics PDPA	875	4	10,000	2.07	S	N/A	*
Tratnig and Brenn (2010)	Dantec	451	8	20,000	7.5-152	S	N/A	*
Tuck et al. (1997)	Dantec	900	35	24,000	3.00	T	0.001	*
Wolf et al. (1995)	Aerometrics PDPA	1020	45	10,000	2.00	T/S	0.020	350

Farooq et al. (2001)	Aerometrics PDPA	552	5-30	20,000	2.75	S	N/A	310
Womac et al. (1999)	Aerometrics PDPA	*	50	10,000	2-4.5	S	N/A	*

[1] PDPA specifications were cross-referenced in Nuyttens et al. (2006)

3.3 Materials and Methods

3.3.1 Spray analysis setup

A schematic of the test facility is shown in Figure 3.1. One of the objectives of the current study is to demonstrate that the PDI could be used for field measurements of sprays for drift research, and so the experimental laboratory facility was designed with this in mind. All of the equipment can be operated off a standard 12 VDC power supply, with an automobile battery being used to supply electrical power to both the water pump and the traverse motor. The PDI itself can also be powered by a 12 VDC power supply, though mains AC power was used for these experiments.

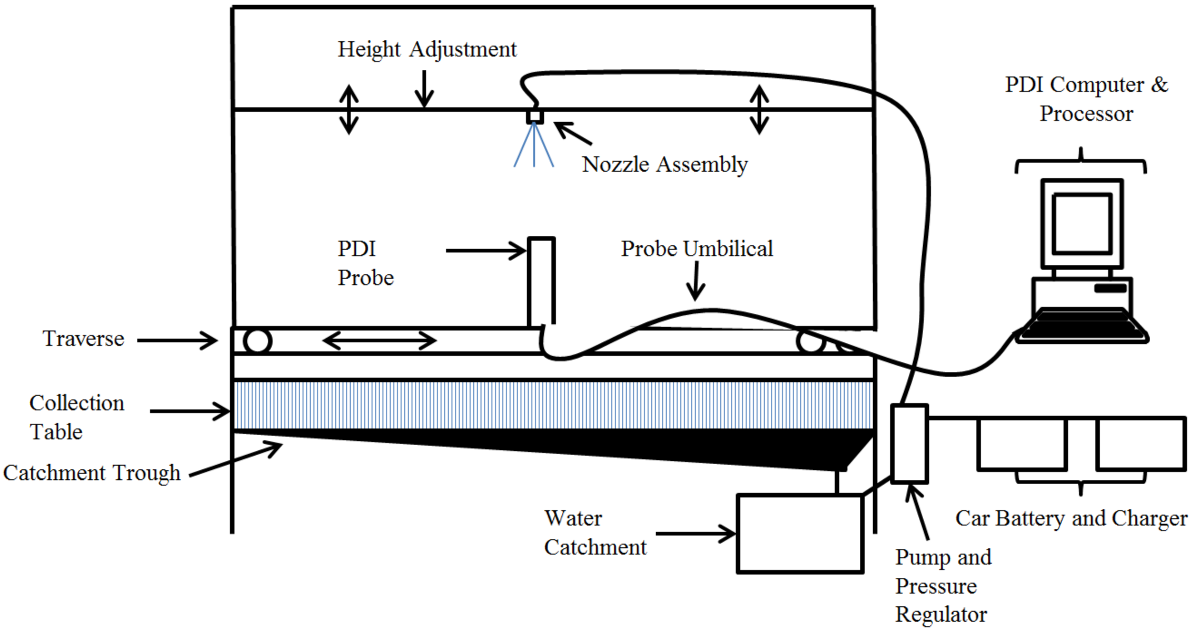

Figure 3.1 Schematic of test rig.

The 2.5 m long traverse frame was made of weather-resistant materials (aluminium and stainless steel), providing a 1.6 m sampling length. The PDI sat upon a tray pulled by an anti-slip toothed belt which was connected to an axle which was powered by a 12V ATV winch (680 kg/1,500 lb, Ridge Ryder, Lawnton, Queensland, Australia) which was geared down to a 1.43:1 ratio with pullies so that slower speeds were possible with this motor. This setup provided a speed range of 0.0079 to 0.0376 m/s with the use of a DC speed controller. The traverse was attached to a base so that it could move over a collection table thereby enabling the operator to move the probe to the desired location.

The water spray system included a 12V pump (7 L/min, 8.27 bar max (120 psi), Smoothflo model DDP-552, Aquatec Water Systems, Inc, Irvine, CA, USA) connected to a single nozzle body with a disc core nozzle and check valve type strainer with size 50 mesh to assist the rate in which the plume is formed and to promote accuracy (nozzle type D1/DC33, strainer model 4193A-PP, Teejet Spraying Systems, Wheaton, Illinois, USA). In order for the height to be adjusted the nozzle was attached to a crossbeam which could be moved incrementally, upwards of 1 m above the PDI.

3.3.2 Phase Doppler interferometer

The Demeter probe uses a green, diode pumped solid state laser at 532 nm wavelength. Because the Demeter is an enclosed system with no lens options and a constant focal length of 150 mm, the only adjustment is the beam separation of either 8.4 or 50.8 mm which corresponds to the 3.2 and 19.0 µm fringe spacing (respectively) and the differentiation of droplet size ranges and velocities. Depending on the chosen beam separation, it is capable of measuring droplets between 0.5 and 550 µm, as shown in Table 3.2, to an accuracy of ±0.5 µm, with velocity ranging between -200 and 500 m/s with ±0.1% accuracy, and volume flux at ±0.1% accuracy. The maximum size of 550 microns limits the PDI to sprays of ASAE Medium ($D_{V0.9}$ = 495 µm) and finer classification in order to capture most of the spray mass. The wider beam setting with a maximum size of 90 µm was designed to measure in-field drift, not to measure the whole spray cloud near the nozzle, and so is not used in this study. The chosen beam separation for this study was the narrow, 8.4 mm setting and was selected with the expectation that all mass would be well above the 19 µm minimum capacity of the probe volume. The accompanying computer system is comprised of Fourier transform based Advanced Signal Analyser (ASA) with Automated Instrument Management System (AIMS) software (version 4.6) (Artium Technologies Inc., 2013). The voltage was chosen based on spray plume density at differing distances, ranging between 335 and 400 V. This is slightly higher than the voltages used in other measurements of agricultural sprays with phase-Doppler equipment reported in the literature; 310 to 350 V have been reported in the past (Chapple et al. 1993; Chapple et al. 1995; Wolf et al. 1995; Farooq et al. 2001), however few authors report voltage(s) used (Table 3.1).

Table 3.2 Specifications of Demeter probe by beam separation (Anon. 2013).

Beam Separation	Transmitter Focal Length	Receiver Focal Length	Fringe Spacing	Focused Beam Diameter	Velocity Range	Droplet Diameter Range
mm	mm	mm	µm	µm	m/s	µm
50.8	300	150	3.2	156	-200 to 200	0.5 to 90
8.4	300	150	19.0	1594	-300 to 350	3.0 to 550

3.3.3 Treatments and Analysis

PDI measurements were made at distances 10, 20, 30, 40, and 50 cm below the nozzle exit. Further, at each height spray pressure was set at 3.1, 4.1, and 5.2 bar (45, 60, and 75 psi) with four replications per treatment. The PDI sampling volume (where the lasers cross) was aligned to measure the vertical velocity. The traversing mechanism was set at its slowest speed of 0.0079 m/s, moving the PDI across the spray plume horizontally. AIMS data were exported into a spreadsheet (Excel) where data could be organized and volume flow calculations made, and graphs were constructed using SigmaPlot (v. 11.0).

To calculate the total volume (or mass) flowrate at each height in each run, the spray flux measured by the PDI had to be integrated across the spray plume. The AIMS software can take the individual measurements of drop size and velocity, and using the cross-sectional area of the laser probe volume, provide vertical volume flux values calculated over a specified interval of time. For these studies, a calculation window of 1.0 s was used. At the traversing speed of 0.0079 m/s, this corresponds to a spatial distance of 0.0079 m = 0.79 cm. That is to say, flux values were averaged over a 0.79 cm distance. This selection provided a reasonable compromise between fine spatial resolution and having a large enough number of drop counts sampled for good statistics for each flux value. These individual flux values at different spatial locations were then integrated numerically to find the total mass flow rate of spray. Circular symmetry was assumed, with the traversing path intersecting the spray centreline. At each measurement location, r, the cross section of the spray is a ring-shaped section of width Δr, whose area is given in Equation 1. Here the ring thickness Δr is equal to the distance between data points of 0.79 cm. The AIMS software provides flux values in units of cm^3 of water volume per cm^2 of probe area per second. When the volume flux ($cm^3/cm^2/s$) is multiplied by the cross sectional area of each ring segment (cm^2) and summed over the entire cross-section of the spray, the total volume flow rate in units of mL/s is obtained, as in

Equation 2. From this calculation, the mass can compared to the physical collection. Finally, the physical capture was acquired using a graduated cylinder and stopwatch; this data was used to calculate the flow rate in L/min.

Equation 1: $$Area = \pi[\left(r + \frac{\Delta r}{2}\right)^2 - \left(r - \frac{\Delta r}{2}\right)^2]$$

Equation 2: $$\text{flowrate} = \sum(Area \times flux)\, cm^2 \times \left(\frac{cm^3}{(cm^2(s))}\right) = \frac{cm^3}{s} = \frac{mL}{\text{s}}$$

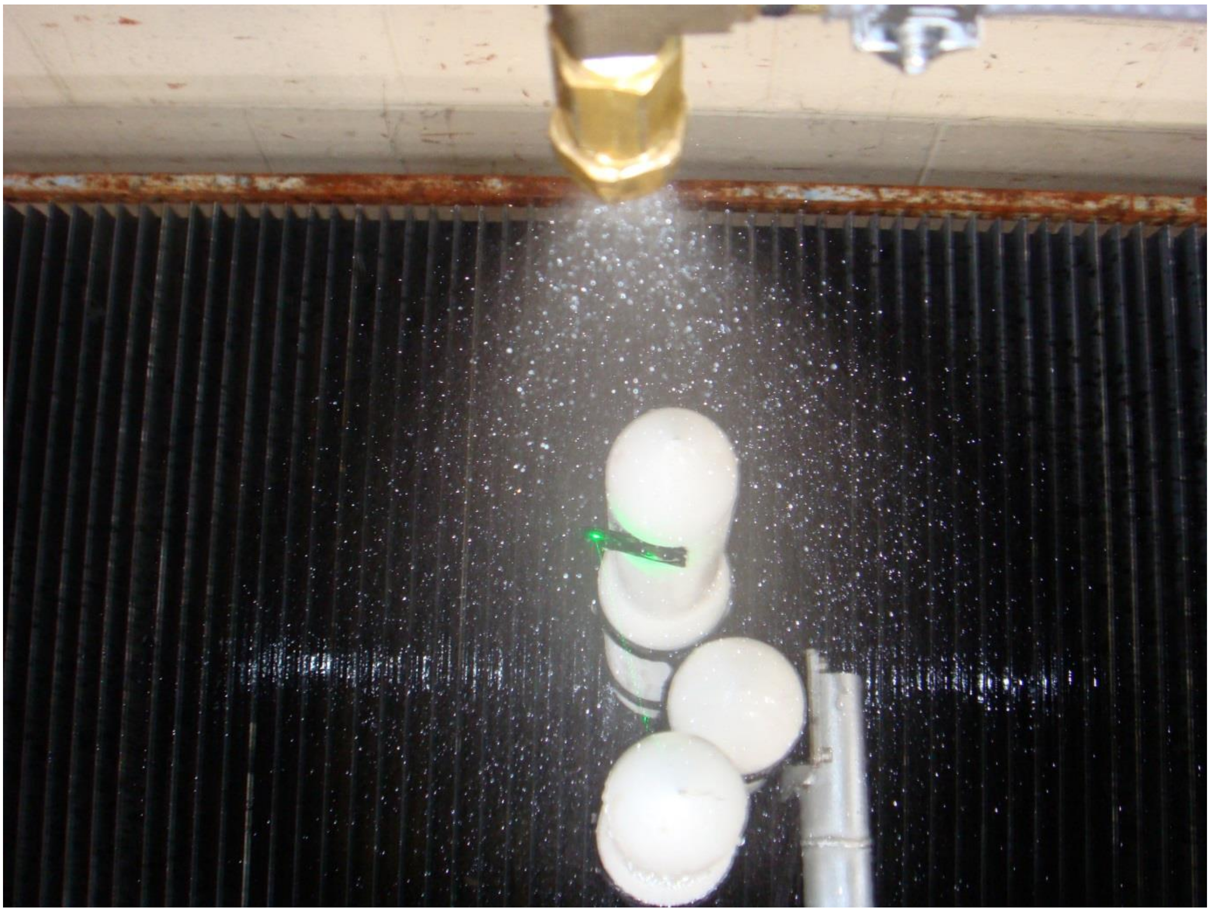

Figure 3.2 Orientation of Demeter probe traversing the plume in its vertical sampling setting.

3.4 Results and Dicussion

3.4.1 Spray characterisation

Inconsistent PDI data was obtained for all 10 cm treatments which were determined to be a result of non-spherical droplets still undergoing atomization. Therefore, these treatments were eliminated from the original treatment list. It important to note, however, that the closeness of measurement is a factor of sprayer/nozzle technology and will change accordingly: sprayers that produce low droplet spectra at high pressures hasten the atomisation process which will alter the near-source sampling procedure. For example, Tratnig and Brenn (2010) found that 8 cm was a suitable distance for a similar nozzle (Delvan type SDX) at pressures ranging between 7.5 and 152.0 bar; this distance was also thought to be the more applicable distance for such research because it was the nearest point that ensured spherical droplets still undergoing atomization to avoid evaporation and coalescence. These high pressures (compared to 3-5 bar in the current study) will result in more rapid atomization of the liquid sheet into drops closer to the nozzle. It should also be noted that the PDI will give drop size data at close distances, but the flux will be incomplete due to validation requirements.

The shape of the spray plume at the five sampling heights is illustrated in Figure 3.3. As can be expected, the closer the PDI is to the nozzle, the narrower the plume and vice versa. This shows a potential for assessing spray patterns as well as flux: at the 20 cm samplings, a concave apex can be observed which is indicative of the hollow cone nozzle used; as the sampling distance increases, the breakdown of the plume is apparent and by 50 cm exhibits a uniform distribution across the axes' entirety. This side-by-side comparison also displays the possibility to assess the initial differences of flux between pressures as well as the nozzles' symmetry. Disc core nozzles, which work from a binary disc, swirl the spray solution before exiting the secondary orifice; this can also be seen with the lack of symmetry at the apexes of the 20 cm measurements and is most evident at the 3.1 bar (45 psi) treatment as the 40 and 50 cm distance is slightly skewed right of centre which could also be partially due to the physical turbulence of the solution from the 90° elbow which preceded the nozzle. The velocity and droplet distribution comparisons (Figure 3.4) illustrate the spray pattern in detail, exhibiting the decay of droplet speed over time, the central targeted spray area, and providing insight to the most drift-prone mass which, in this situation is approximately 10% (Figure 3.4).

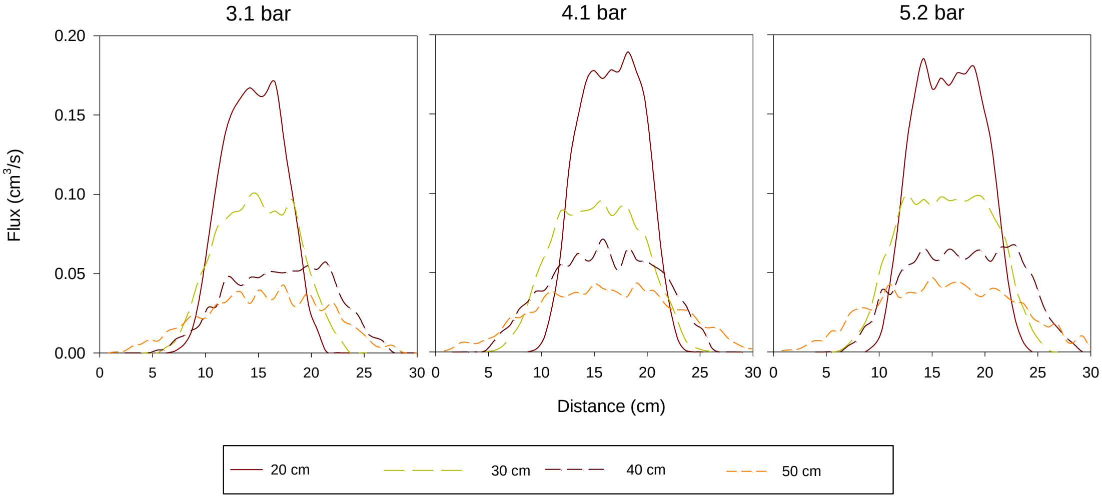

Figure 3.3 Average flux over time per pressure and height (n=4).

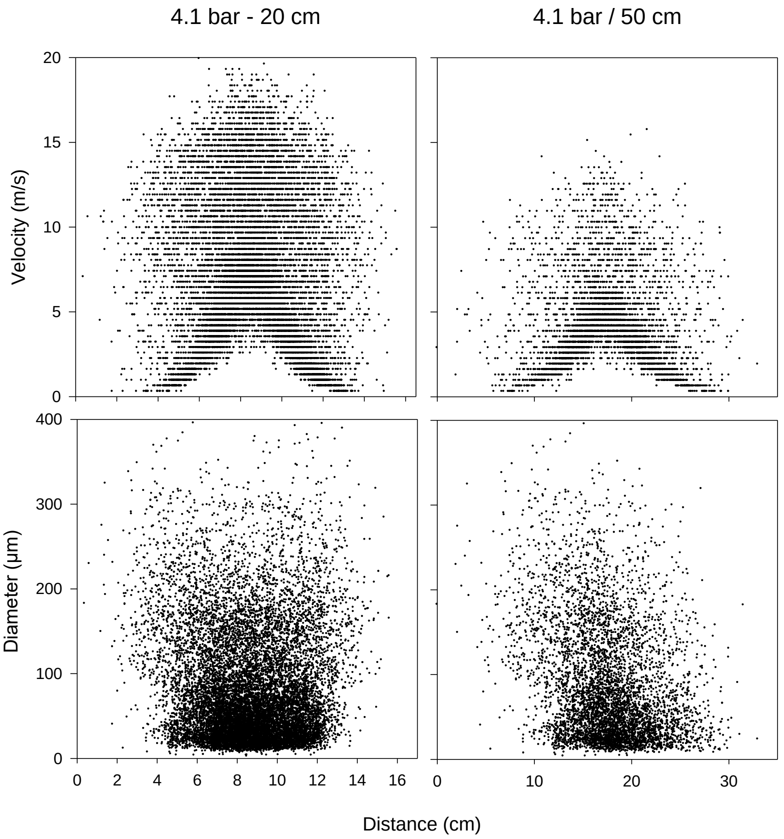

Figure 3.4 Velocity (top) and size distributions (bottom) for the 4.1 bar (60 psi) treatment at 20 (left) and 50 cm (right) above the sampling volume.

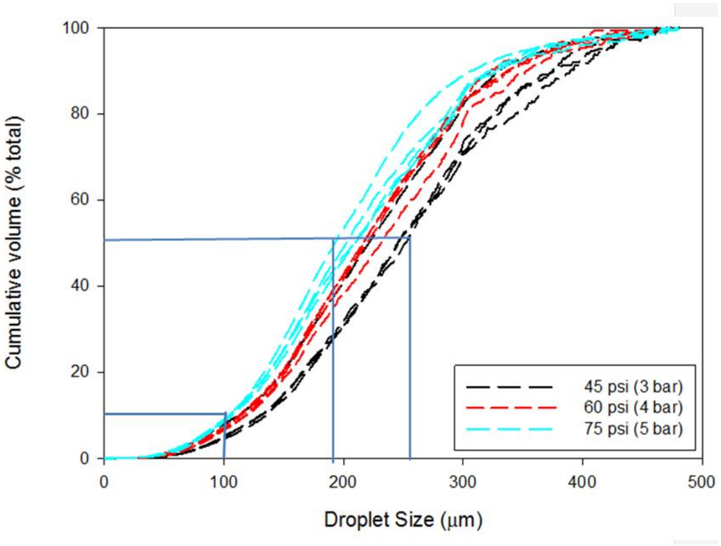

Figure 3.5 Percent cumulative volume for all treatment heights, grouped by pressure, exhibiting a 13% difference of volume median diameter ranging between 195 and 253 µm as well as ≤ 9.2% of the cumulative volume being ≤ 100 µm which is indicative of the most drift-prone droplets.

The cumulative volume (Figure 3.5) across all heights and pressures followed a similar trend. Volume median diameter ($D_{V0.5}$) differed 13% ranging from 195 to 253 µm which also indicates the most opposite treatments of the 5.2 bar (75 psi) at 20 cm to 3.1 bar (45 psi) at 50 cm (Table 3). Tuck et al. (1997) discuss the differences in droplet distributions as sampling height changes in their research as compared with others; with another laser system which works using imaging processes, the particle measuring system (PMS). The PMS showed that $D_{V0.5}$ has a potential to stay the same or decrease with decreasing sampling heights (Lake & Dix 1985; Young 1990). The data from the present study (Table 3.3) also indicates that there exists a relationship of $D_{V0.5}$ and sampling height for all three pressures. However this is possibly due to a biasing of the sampling as the smaller droplets, with faster losses of inertia, will not get sampled with larger droplets. But it is important to take into consideration that the volume profile is mostly decided by the large droplet classes and the small droplets play a less significant role. Lastly, droplets ≤ 100 µm are considered to be the most prone to drift. The tested parameters exhibited 5.0 to 9.2% cumulative volume beneath the 100 µm threshold which increased with increasing pressure (Table 3.3).

Table 3.3 Average percent volume ≤100 µm, $DV_{0.5}$, and velocities for all heights and pressures (n=4).

	20 cm			30 cm			40 cm			50 cm		
Bar	%V ≤100 µm	$D_{V0.5}$	Velocity	≤100 µm	$D_{V0.5}$	Velocity	≤100 µm	$D_{V0.5}$	Velocity	≤100 µm	$D_{V0.5}$	Velocity
3.1	8.0	221	6.17	6.6	246	5.27	5.3	247	4.35	5.0	253	3.75
4.1	7.3	218	7.06	6.8	221	5.89	6.6	233	4.99	7.2	218	4.24
5.2	9.1	195	7.76	9.2	202	6.48	8.6	210	5.46	9.0	209	4.71

3.4.2 Mass flux validation

Application volume for the 3.1, 4.1, and 5.2 bar treatments (45, 60, and 75 psi respectively) were 590, 670, and 770 mL/min, respectively, following the expected trend of flow increasing with the square root of pressure. The calculated mass flux error ranged between -16.9 and 4.7% with a trend to under-predict mass, especially as the nozzle distance to the PDI increased (Table 3.4). Dullenkopf et al. (1998) also observed an under-prediction with their similar phase Doppler system (a first generation Aerometrics PDPA), capturing ≤ 50% of the sprayed mass from a swirl-type atomizer at 5 bar. Their research also examined two additional PDI systems (a DANTEC, DualPDA and a Qui & Sommerfield PDA) which were more accurate with this arrangement, however all three phase Doppler systems underestimated mass when the atomizer was changed from a simplex pressure-swirl to an air-blast at 0.5 bar water pressure and 3 bar air pressure. The authors attribute this deficit to the inability to assess the dense sprays at their 10 cm sampling distance. However, it is possible that their sampling height was too low thereby being affected by non-spherical droplets at a low pressure as was seen in the 10 cm treatment in the present study.

Table 3.4 Treatment list and results (averaged across replications; n=4) including voltages per sampling locations.

Height[1] cm	Pressure bar	Voltage	Output[2] mL/min	Calculated[3] mL/min	Error %
20	3.1	400	590	568	-3.7
30	3.1	370	590	566	-4.1
40	3.1	340	590	534	-7.9
50	3.1	335	590	491	-16.9
20	4.1	390	670	695	2.2
30	4.1	365	670	651	-4.2
40	4.1	350	670	666	2.1
50	4.1	340	670	654	-2.4
20	5.2	395	770	806	4.7
30	5.2	375	770	791	2.8
40	5.2	350	770	746	-3.1
50	5.2	335	770	708	-9.3
				Average	-3.3

[1] Sampling distance between nozzle tip and sampling volume.

[2] Nozzle output physically captured.

[3] Computational nozzle output from PDI.

3.4.3 Limitations

Limitations for PDIs vary between systems, however the number of droplets required to pass through the probe volume is a consistent concern and is important for accuracy and validation**.** Many authors have discussed the minimum droplet count as a limiting factor and it is evident among the literature that 10,000 to 20,000 droplet counts is acceptable for sound statistical analysis (Parkin 1993; Nuyttens et al. 2007b; Tratnig & Brenn 2010); Dullenkopf et al. (1998) sampled 10,000 counts with the exception of the edges where flux is naturally low. This is an important difference when sampling the plume with a single traverse/pass versus taking static measurements which made it possible to assess the flux in a like manner for the plume’s entirety while still gaining acceptable counts and errors. However, this is not always possible, particularly when operating in the proposed in-field environments where conditions readily change. More feasible to control, traverse speed was deemed more important for the present study whereas time will be the limiting factor that will always be at a conflict against meteorological turbulence. Nuyttens et al. (2007b) also aimed for ≥ 10,000 droplets per scan, but traversed the whole plume during each scan at traversing speeds between 0.0166 and 0.0300 m/s. However, their work was solely for velocity and size distribution analysis which do not need the elevated frequency. In the present study, where flux and time were the focus, with a constant speed of 0.0079 m/s (2.1 to 3.8 times slower than the aforementioned research), accepted frequency of ≥ 10,000 counts were achievable for the majority of treatments within 9% error regardless of counts, ranging from 5,884 to 38,034 (Table 3.5); with the exception of the lowest count observed at the lowest pressure and furthest distance with a 17% error and 4,413 average counts. However, this is expected because higher pressures supply more volume as well as further atomization with heightened sampling frequency.

Table 3.5 Average samples/counts per pressure and height combination (n=4).

Bar	20 cm	30 cm	40 cm	50 cm
3.1	17,592	9,139	5,884	4,413
4.1	26,491	15,194	10,541	7,970
5.2	38,034	25,792	15,434	10,390

Yet another limitation is the technology’s intrusiveness due to the unavoidable hardware design. Early model PDI systems were not intrusive as the detector and receiver are far from the sampling volume. Probes such as the F/PDI and the Demeter have uprights which may interfere with the droplets’ trajectories as well as the droplets influence on the uprights and protective windows. It was observed in this study that window saturation interfered with accurate flux measurements and shrouds were carefully fashioned over the windows so that the spray would not deposit on these surfaces as well as deter the spray away from the sampling volume which would provide erroneous data from the bouncing and shattering droplets. Furthermore, as discussed by Chuang et al. (2008), “Optical contamination” may lead to uncertainties in droplet data, it is important to note the differences of each application whereas the F/PDI was engineered to be situated on an airplane for cloud measurements where aircraft speeds range from 50 to 100 m/s minimizing such saturation/contamination. Lastly, data acquisition for PDI technologies rely on frequency of counted droplets, and minor laser obscuration should not impact data if there is enough frequency. However, in the atmospheric condition of a laboratory where no such air velocities are present, a simple droplet deposited onto the optics can deter the laser away from the receiver thereby missing data points through a traversing sample or reduce the lasers' intensity (affecting the fringe spacing of the merging beams). Dullenkopf et al. (1998) also observed hardware malfunction and missing data points with the Qui and Sommerfeld PDA, attributing to a 5% error. It is hoped that the air velocities from air assisted orchards sprayers (upwards of 30 m/s), as well as the heightened frequency, will also play a role in optical cleansing and reliable data acquisition. Lastly, the Demeter's narrow sampling range (Table 1) which is limited to spectra below the 550 µm threshold which is common for such droplet work and unique for each phase Doppler system. For instance, the Dantec PDA of Tratnig and Brenn (2010) had a maximum drop size of 451 µm while the Dantec system of Tuck et al. (1997) had a maximum of 875 µm, and the Aerometrics PDPA of Sidahmed et al. (1999) was able to measure up to 700 µm. This, of course, was a moot issue for that of the F/PDI where cloud droplets range from 5 to 50 µm (Chuang et al. 2008). Unfortunately, this is very limiting for agricultural sprayers whereas future research with the Demeter probe will be limited to nozzle classifications of extra fine, very fine, fine, and possibly medium (depending on pressure) with maximum droplet spectra of ≤ 550 µm (Anon. 2009).

3.5 Conclusions

The use of a field grade phase Doppler was investigated to computationally assess the mass flux of a spray plume with a hollow-cone nozzle. Preliminary results indicate that in-field analysis of mass for an orchard air-blast sprayer is plausible. Depending on atmospheric turbulence, it is anticipated that the high air velocities and pressures of these sprayers should provide adequate sampling counts beyond 50 cm as the current research has observed <10% error up to 50 cm from the spray source for pressures ≥ 4.1 bar (60 psi). Future research is needed to assess the differences of measured mass against other sampling techniques. A comprehensive review by Jensen and Olesen (2014) reported total recovery within multiple tree crops (apple, mandarin, orange, and peach) ranging between 30.8% and 98.4%. Of course, these trials were completely different in terms of their sampling procedure and treatments which all differed in application volumes whereas the most mass was recovered where application volume was 500 L/ha (Balsari et al. 2002) compared to 4,000 L/ha (Cunningham & Harden 1998). Further, a great deal of research has not quantified the amount of airborne drift, but assumed that if it were not recovered in the near-source, it was then drifted material. Therefore it will be the goal of future research to assess these differences in the near-spray source to determine if the proposed phase Doppler technique can fill these gaps. Most phase-Doppler studies of agricultural sprays simply measure the drop size and calculated $D_{V0.5}$, but we have shown the PDI can also measure the mass flux distribution across a nozzle and capture the total mass of spray.

3.6 Acknowledgments

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Chapter 4

Wind Tunnel Flux Comparisons using a Phase Doppler Interferometer

This chapter was published in The Journal of Crop Protection Research 57(3):281-287 (Appendix B)

4.1 Abstract

It is essential to know the movement of droplets in time and space (i.e. flux) when measuring and/or predicting spray drift in agricultural application. A study was performed to assess the flux measurements of a phase Doppler system against a standard monofilament system in a wind tunnel. The primary objectives of the study were to compare flux from a new phase Doppler system against 1.7 mm cotton and 2.0 mm nylon strings at varying wind speeds (1.4, 4.2, 8.3, 12.5, and 16.7 m/s) and spray exposures times (5, 10, 15, 30, and 60 s) with an overarching hypothesis that the active, phase Doppler is able to accurately measure the flux regardless of exposure and spray mass whereas the static string samplers are limited to a maximum retention. The phase Doppler did measure linearly as expected, however strings did not reach a point in which they loss mass; conversely, they appeared to overload with saturation. These findings are believed to be among many variables which influence the variability of previous mass balance studies.

4.2 Introduction

As pesticides are applied, the sprayed liquid solution is typically forced through the small orifice of a nozzle which begins the process of atomization, resulting in the formation of an aerosol spray. Spray characteristics change depending on the physical characteristics of the given nozzles (e.g. presence or absence of a venturi, designs, size and shape of exit and any pre-orifices), the characteristics of the sprayed (especially the viscosity and surface tension), and the spray pressure. Once released through a nozzle, a spray will be affected by meteorological conditions such as relative humidity, temperature, wind speed and wind direction, the external forces such as the operator’s driving speed and physical field conditions (e.g. the terrain angle and roughness). Finally, the selected operating pressure will dictate how much force is applied to the spray as it passes through the nozzle, which is the first point of contact that will influence atomization and the production of fine droplets: the higher the pressure and the smaller the orifice, the finer the overall droplet spectrum will be for hydraulic nozzles (Nuyttens et al. 2007a).

To assess how particular nozzles will influence a spray under different pressures and liquid physical properties, wind tunnels or spray chambers are typically used. The wind tunnel provides a relatively controlled environment, whereas in-field assessment presents dynamic conditions of meteorology, hardware/sprayer configuration, surface terrain, and driving speed. In wind tunnels, laser based technologies such as laser diffraction (e.g. those manufactured by Malvern and Sympatec), imaging and forward scattering probes (e.g. Particle Measurement System), and phase Doppler systems (e.g. Artium, Dantec and TSI PDA/PDPA/PDI instruments) have predominantly been used to measure the key spray characteristics of droplet size, velocity and flux. However, the choice of spray measurement system affects the type of data acquired. For example, only phase Doppler and pulsed imaging technologies are able to instantaneously measure velocity and flux. Laser diffraction devices typically only provide droplet size distributions, while PMS and other imaging technologies have been successfully tested to measure flux and velocity but require further calculations of flux (Goguen et al. 1997). Further, flux in a wind tunnel can be assessed using various collection systems such as monofilament line and strings to act as static collectors; the cumulative loading of these strings with a tracer sprayed at a known concentration can be converted into a flux measurement which is common (Fritz et al. 2011). However, as with many physical and intrusive samplers, considerable handling is required to harvest and store the sampler and extract the tracer which was accumulated.

In theory, a phase Doppler system should be able to provide reliable, in-situ flux measurements and eliminate some of the handling and human error issues associated with intrusive and passive sampling. The phase Doppler system presented here is the Demeter PDI (Artium Technologies, Inc., Sunnyvale, California, USA), which was recently discussed in detail (Roten et al. 2016b) as part of series of studies using the Demeter PDI for in-field droplet assessment and mass quantification. In short, this particular PDI is different than most other laser measuring devices used in agricultural spray assessment in that it is an enclosed, portable unit which allows the PDI to be used out of laboratory environments and potentially used in the diverse environments in which pesticides are applied. The primary objective of this study was to compare flux data from two string materials to the flux data obtained from the Demeter PDI using exposure time and wind speed as treatments. It was hypothesized that the flux data from all three collectors will agree until a certain time and/or threshold wind speed when string collectors will begin to lose collected material through runoff following saturation and/or shattering; the PDI, as an active non-intrusive collector will reliably collect data regardless of exposure time or aerosol load. Secondary objectives were to assess the differences between adsorption and absorption of the two string types with the hypothesis that fibrous string material will collect more spray mass when high cumulative loading is expected due to the fibrous string's ability to absorb whereas the dense, non-permeable, smooth nylon string can only adsorb until it becomes saturated and loses mass due to droplets falling off.

4.3 Materials and Methods

4.3.1 Wind tunnel arrangement

This experiment was conducted at the University of Queensland Wind Tunnel Facility (Gatton, Australia). A 1 x 1 m working section was selected to achieve wind speeds between 1 and 60 km/h. Wind tunnel set up (Figure 4.1) consisted of the spray nozzle oriented in a downward fashion with the spray tip offset 45° and 80 cm from the wind tunnel floor; nozzle orientation was selected to make the most use of the spray cloud by keeping the spray within the airflow and not on the wind tunnel walls. Cotton (1.7 mm piping cord, Birch Haberdashery, Heidelberg, Victoria, Australia) and nylon (2 mm, Stihl, Weingärten, Germany) strings were alternatively mounted at 39 or 41 cm high, 1 m downwind of the nozzle. The PDI was positioned directly behind the strings at a sampling height of 40 cm which, due to the probe design, placed the sampling volume 10 cm behind the strings. Because time constraints and environmental conditions are constantly in conflict, all samplers per run were tested simultaneously. To generate the spray, a XR80-015 nozzle (Teejet Spraying Systems, Wheaton, Illinois, USA) was operated at 350 kPa for a flow rate of 600 ml/min; this nozzle was selected to provide a finely sized spray for maximum sampling frequency for the phase Doppler.

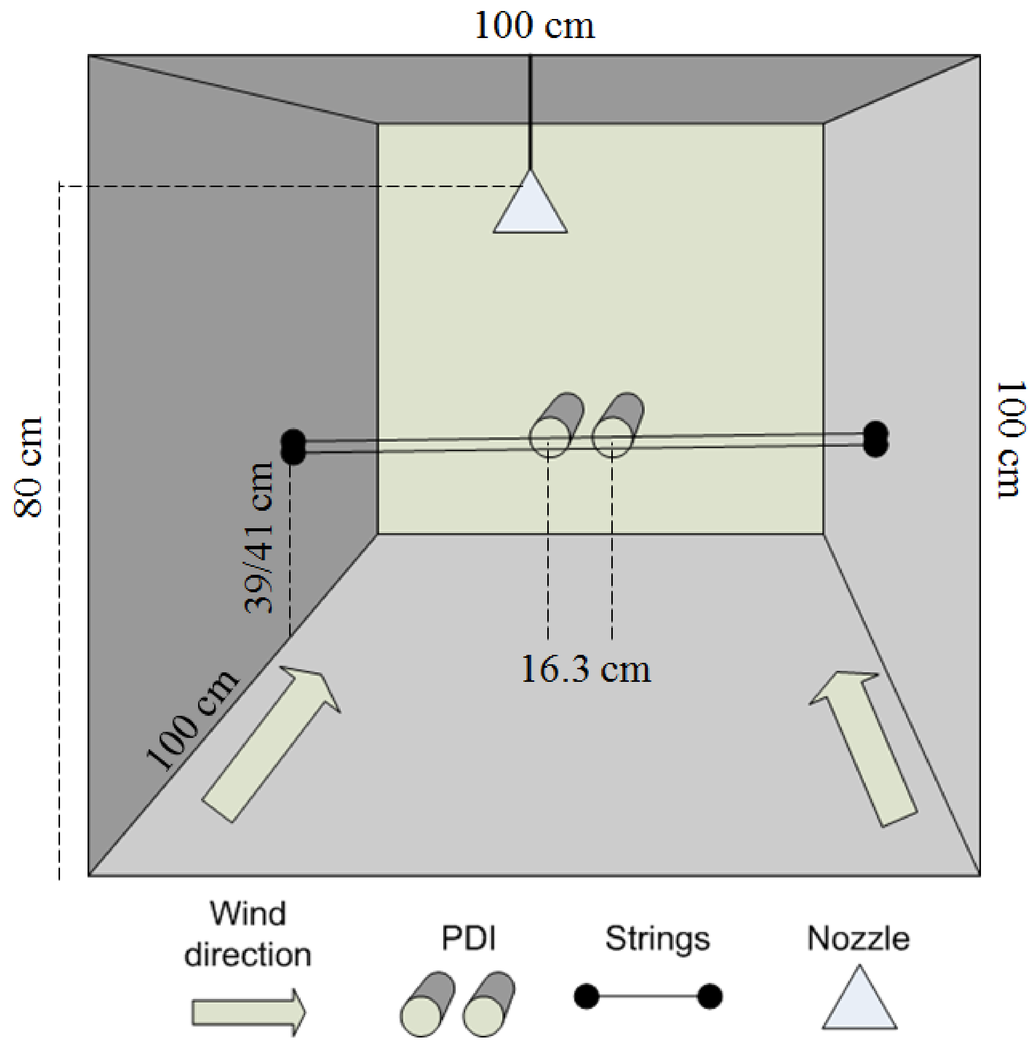

Figure 4.1 Schematic of tunnel set up.

4.3.2 Sampling procedure

The treatment matrix included wind speeds of approximately 1.4, 4.2, 8.3, 12.5, and 16.7 m/s (5, 15, 30, 45, and 60 km/h, respectively) and spray exposure times of 5, 10, 15, 30, and 60 s. Wind speeds were assessed at the point of sampling using a hand held anemometer (Kestrel 4500, KestrelMeters, 2241 Cole Street, Birmingham, MI, USA). Precise wind speeds were not relevant as all treatments occurred simultaneously.

In order to measure spray flux with passive string collectors, a spray solution which contained water and 1% v/v Pyranine 10G fluorescent dye (Keystone Aniline Corporation, Kansas USA) was added. After the given treatment was complete, samples were immediately harvested which consisted of the middle 16.3 cm (the distance between the two PDI uprights) and placed into individual re-sealable bags which were stored in the dark in a freezer until processing. The phase Doppler voltage was set at 250 V for all measurements which was validated beforehand to provide most reliable data based upon the density and volume of the spray.

All samplers were replicated six times in total: three consecutive replications per day for two days. Consecutive replications were essential in the repeatability of the study to support uniformity in all other variables, especially the wind speed in the wind tunnel working section.

4.3.3 Flux, collection effeciency and droplet assessment

PDI volume flux (V”) is calculated with Artium’s AIMS software using Equation 1 (Anon., 2013). To convert the PDI’s Volume Flux data to a comparable unit to string deposition, the V” was multiplied by the total time (t_{ttl}) (Equation 2) to obtain volume deposition per unit area, V_{dep}.

Equation 1: $V" = \frac{V_{tot}}{t_{tot}A_p} = \left(\frac{\pi}{6}\right)\frac{N_{tot}D_{30}^3}{t_{tot}A_p} * 1000\,\frac{\mu L}{cm^3}$

Equation 2: $V_{dep} = V" * \; t_{tot}$

$V"$ = volume flux (µL/cm^2/s)

t_{tot} = total time (s)

A_p = probe area (cm^2)

V_{tot} = total liquid volume (µL)

N_{tot} = total number of drops

D_{30} = volume mean diameter (µm)

Quantitative dose data for string treatments was acquired by soaking individual samples for 15 minutes with 58 or 166 ml of deionized water, the latter for samples which needed dilution due to fluorimeter saturation. After soaking, a 3 ml subsample was read and fluorescence recorded in µg/l units using a spectrofluorophotometer (Shimadzu RF-5301PC, Shimadzu Scientific Instruments, Hyoto, Japan) with an excitation and emission wavelength of 403 and 511 nm, respectively. Throughout the fluorometry process, a pyranine standard of 1,000 µg/l concentration was tested to ensure calibration was maintained. All samples were matched with their representative tank concentration and the data were normalized accordingly. String data were then normalized against their collection efficiency using equations 3 to 9 using the appropriate string diameter (either 1.7 or 2 mm) across all wind speeds and droplet distributions relative to droplet percent volume acquired from the PDI at the time of sampling. These theoretical equations, verified by the work of Fritz and Hoffmann (2008), were used to calculate the theoretical collection efficiencies for the two string types. The derivation of original equations is reported in the works of Hinds (1982), Mercer (1973), and May and Clifford (1967).

The string deposition data were then calculated to a unit of flux (µl/cm^2) using Equation 3 and converted to µL by multiplying by 1,000.

Equation 3: $$S_{dep} = \frac{\frac{D_m}{D_{con}}}{A_s}$$

D_m = Measured dye mass deposited on string per volume sampling solution (µg/cm^3)

D_{conc} = Dye concentration in tank mix sprayer (µg/cm^3)

A_s = String area (cm^2)

4.3.4 Methods for Absorption vs. Adsorption trial

Two small studies to assess the physical differences of the two string collectors were performed. The first test was conducted in the wind tunnel where three cotton and three nylon strings were affixed alternatively, 2 cm apart in the center of the tunnel working section. The tunnel was set at 4.2 m/s wind speed and stings were exposed to the same water+Pyranine spray for 90 s, a time in which saturation and loss of mass was apparent. Unlike the primary objective, strings for this purpose were left in the wind tunnel until dry (~20 minutes). The center 16.3 cm sections were harvested, bagged and stored as previously mentioned. The second test placed three, 16.3 cm cotton and nylon string sections directly in a container of the water + Pyranine solution. The strings were left to soak for 5 minutes. At harvest, strings were individually removed from the solution with forceps and carefully bagged so that any droplets adhering to them remained. Both studies were repeated in time.

4.3.5 Analysis

Deposition data were separated by wind speed and exposure time and means separated using Tukey's HSD (honest significance difference) with a 95% confidence level using R (version 3.2.0, R foundation for Statistical Computing, Vienna, Austria).

4.4 Results and discussion

4.4.1 PDI vs. Strings

To date, there are no data that examine flux or deposition at the heightened wind speeds presented here. Most research has either focused on relative speeds for ground boom or aerial application whereas the current study is examining wind speeds relative to a location near the source of an orchard airblast sprayer (i.e. 1 to 5 m). For this, there were few statistical differences between wind speed at the given exposure time, per sampler (Table 4.1); therefore data were pooled by wind speed per sampler at each time interval for Figure 4.2, which is solely for illustration to express the overall trends of the samplers. From this, the initial hypothesis that the PDI will not become saturated and express a linear trend is confirmed. Interestingly, a point of saturation, plateau or decline was not observed with either string type as hypothesized. Instead, an increased linear accumulation with the nylon was observed beyond 30 s exposure time. Cotton strings performed with linearity although provided heightened deposition beyond 5 s.

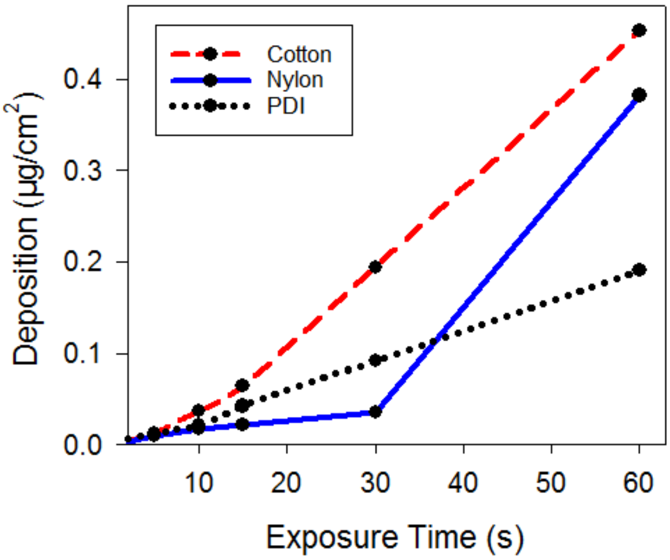

Figure 4.2 Deposition data (μg/cm^2) with wind speed pooled per exposure time (n=6 for strings, 2 to 6 for PDI).

As discussed by Jensen and Olesen (2014), a larger portion of spray is lost with orchard sprayers as opposed to ground boom application. Their review illustrates the scope of the issue whereas losses in vineyards were between 10.8% and 25.7% and fruit tree spray losses were between 20% and 40%. In the current study, both string types statistically compared reasonably well with the PDI deposition data up to 8.3 m/s (Table 4.1). There was a degree of uncertainty associated with using strings in areas of high spray volume: cotton and nylon samples exhibited maximum errors of 25% and 33% (respectively) while the maximum PDI error was only 1%; this error can also be observed in Appendix C. This would entail that in areas of high concentration/spray volume, (i.e. in close proximity of orchard airblast sprayer) that measurements using strings samplers could be one of the many factors of unaccounted spray in past mass balance studies.

Table 4.1 Deposition (µg/cm^2) among different sampler types. Means within column followed by the same letter are not statistically different based upon Tukey's HSD ($P \leq 0.05$); n=6 for strings, 2 to 6 for PDI.

Exposure time (s)	Sampler	Wind Tunnel Speeds (m/s)									
		1.4		4.2		8.3		12.5		16.7	
5	Cotton	9.35E-03	A	1.61E-02	A	1.17E-02	A	3.24E-03	A	2.22E-02	A
	Nylon	5.53E-03	B	1.74E-02	A	1.37E-02	A	1.93E-03	B	1.11E-02	A
	PDI	n/a		1.24E-02	A	1.60E-02	A	1.36E-02	C	1.87E-02	A
10	Cotton	2.83E-03	A	5.54E-02	A	4.02E-02	A	9.65E-03	A	4.87E-02	A
	Nylon	8.98E-04	A	3.69E-02	A	2.95E-02	A	3.48E-03	B	5.15E-03	B
	PDI	n/a		2.19E-02	A	2.81E-02	A	2.26E-02	C	2.61E-02	AB
15	Cotton	1.88E-02	A	1.12E-01	A	8.03E-02	A	2.01E-02	A	8.89E-02	A
	Nylon	3.71E-03	A	4.81E-02	A	4.43E-02	A	6.17E-03	B	3.50E-03	B
	PDI	n/a		3.38E-02	A	4.10E-02	A	3.59E-02	C	5.35E-02	AB
30	Cotton	1.83E-02	A	4.06E-01	A	2.60E-01	A	5.67E-02	A	2.28E-01	A
	Nylon	2.63E-03	A	7.95E-02	B	7.91E-02	A	1.10E-02	B	6.09E-03	B
	PDI	n/a		7.67E-02	AB	9.05E-02	A	8.47E-02	C	1.15E-01	AB
60	Cotton	1.49E-01	A	7.65E-01	A	7.47E-01	A	1.51E-01	A	4.54E-01	A
	Nylon	7.20E-02	A	1.27E+00	A	3.92E-01	A	1.07E-01	B	6.68E-02	A
	PDI	n/a		1.54E-01	A	1.79E-01	A	2.02E-01	C	2.26E-01	A

4.4.2 Sampler Functionality

The theoretical string collection efficiencies ranged from 98% to 99% regardless of string type and wind speed. For cotton string measures, it has been discussed that precise diameters are impractical to discern due to the ambiguous nature of the textile (Fritz & Hoffmann 2008); this is clearly observed in Figure 4.3 (a). Diameter is an important parameter when calculating flux. The best estimate of 1.7 mm was assigned for the cotton string diameter; however when assessing the collection efficiencies using the same database criteria for diameters of 1.6 and 1.8 mm, efficiencies only differ by ± 0.08%. The works of Cooper et al. (1996) explain that fibrous materials, such as yarn, possess the benefit of almost 100% collection efficiency in circumstances where wind speed is >1.5 m/s and droplets are ≥15 µm, which agrees with the current data. It is believed that these fibrous materials are better suited to collecting smaller droplets due to the fine, outstretched strands (Figure 4.3 (b)).

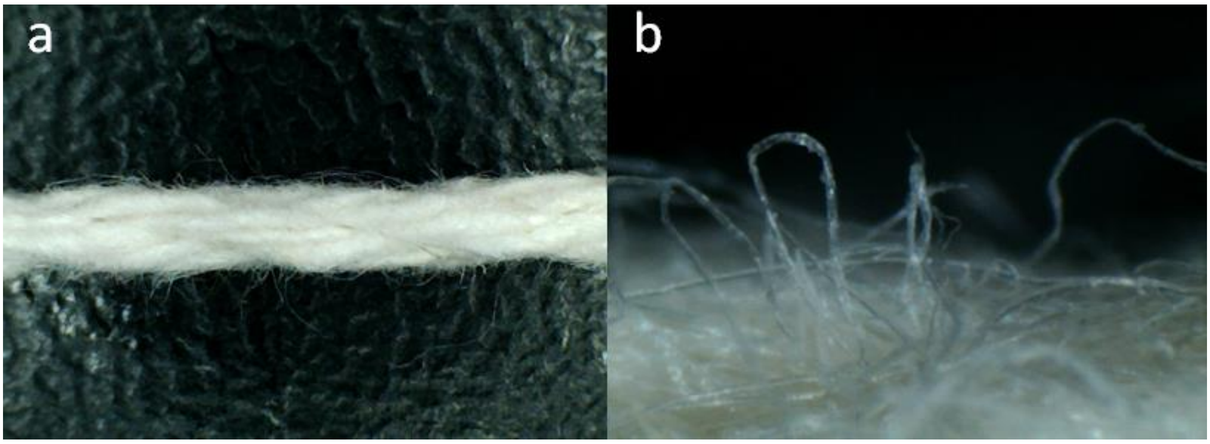

Figure 4.3 a) 20x view of the cotton string illustrating physical differences in diameter as well as the fibrous nature of the textile and b) a 400x view of the outstretched fibers, approximately 15 µm thick.

Regardless, due to this ambiguity in width, cotton samplers are not believed to provide quantitative spray deposition data as a true sampling area cannot be discerned (Bonds & Leggett 2015). As was observed in the present study with the cotton sampler, consistent tension was difficult to maintain and higher wind velocities had a visible tendency to stretch the sampler; the more these are stretched, the narrower the diameter and less permeable they become resulting in less absorption. This is illustrated in the secondary objective whereas the cotton strings that were left immersed in their neutral position, absorbed 1,970 µg/l ± 113 whereas when these strings were stretched in the wind tunnel, they only absorbed 566 µg/l ± 23. The nylon strings, which can only adsorb, retained 238 µg/l ± 30 when left immersed whereas 1003 µg/l ± 174 retained in the tunnel. This increased adsorption can be seen in Figure 4.4.

Figure 4.4 Illustration of saturation and droplet accumulation on nylon (upper) and cotton (lower) strings.

The PDI processor validation that provides information regarding the quality of the Doppler signals, ranged between 76% and 90%, which is partially due to the low frequency of droplets passing through the sampling volume (Table 4.2). Up to 14% of the droplets counted were dismissed by the PDI software due to a lack of droplet "sinusoidal coherency" (Anon. 2013). The sampling frequency has been observed to be a common limitation. Previous research has demonstrated that 10,000 to 20,000 counts are necessary for high validations (Dullenkopf et al. 1998; Nuyttens et al. 2007a;

Tratnig & Brenn 2010). The frequency in the present study for the 1.4 m/s treatment only provided a range of 9 to 34 counts which indeed caused inaccurate flux data; therefore these data were not included in the flux/deposition comparisons. However, all other treatments provided a range of 36 to 901 counts still provide a reasonable flux. Further, previous efforts to compare the Demeter PDI against string measurements illustrated no statistical difference at wind velocities of 1.4 to 4.2 m/s with sampling frequency of 50 to 4,000 counts (Roten et al. 2015b). Therefore it is apparent that this relationship between sampling frequency and validation rates is dependent upon the hardware and software used.

Table 4.2 Sampling frequency (counts/number of droplets) and signal validation rates of the PDI per treatment (n=2 to 6).

Wind Speed (m/s)	Exposure Time									
	5		10		15		30		60	
	Counts (#)	Val. (%)	Counts (#)	Val. (%)	Counts (#)	Val. (%)	Counts (#)	Val. (%)	Counts (#)	Val. (%)
4.2	70	85	125	88	209	85	518	83	890	82
8.3	58	93	94	91	158	90	330	90	750	89
12.5	43	90	100	90	134	87	285	89	606	90
16.7	36	76	84	87	167	88	481	89	901	90

4.4.3 Droplet size and velocity

Though there is an apparent, linear relationship to the number of samples as the exposure time increases, there is no obvious relation between counts per exposure time by wind speed; in fact, the lowest wind speed observed a higher sampling frequency than all treatments except the 60 s at 16.7 m/s treatment (Table 4.2). This observation could be due the difference droplet size spectrum being carried by the air. An explanation for this is the shift of droplet spectrum relative to the surrounding air speed (Table 4.3). Fritz and Hoffmann (2008), using laser diffraction, also observed that as the wind tunnel speed increased, the droplet size data tended to coarsen or increase in average size as larger droplets do not accelerate as rapidly as their smaller counterparts. At the lower wind speeds, the smaller droplet spectrum consumes a larger part of the cumulative volume that will be carried;

therefore more samples were available to pass the probe volume at the lower speed. Further, the smaller the droplet spectrum, the closer it appears to relates to the surrounding wind speed (Table 4.3). This could be a valuable tool when assessing the PDI in-field where air velocities can be difficult to accurately obtain, such as with an orchard airblast sprayer.

Table 4.3 Measured wind velocity, mean droplet velocity, and size statistics data by wind speed (n=2 to 6).

Wind Speed (m/s)	Droplet V (m/s)	Droplet size (µm)		
		$D_{V0.1}$	$D_{V0.5}$	$D_{V0.9}$
1.4	1.4	na	na	na
4.2	4.1	125.5 ± 4.3	139.1 ± 0.7	198.8 ± 13.5
8.3	8.5	148.6 ± 1.3	165.4 ± 0.6	197.7 ± 13.1
12.5	11.3	155.3 ± 4.5	170.8 ± 0.8	194.7 ± 4.0
16.7	15.2	165.3 ± 0.4	187.0 ± 1.0	209.37 ± 3.7

4.5 Conclusions

The PDI proved to measure flux, velocity, and droplet size in a wind tunnel across wide spray exposure sampling times (≥10 s) and high wind speeds (≥16.7 m/s). These measurements confirmed the first hypothesis, that the PDI would exhibit a linear trend as exposure time increased. The secondary hypothesis was only partially correct: smooth nylon and fibrous cotton strings were predicted to saturate and/or lose mass at a point in time and wind speed as they are static, passive collectors; however, fewer statistical differences were observed than expected. A recurring limitation in this research is the sampling frequencies of the PDI in these spray conditions. However, when cross examined against strings, it is apparent that the severe errors associated with the strings were of greater consequence than the errors observed with the PDI. Therefore, the PDI could be a valuable tool in future mass balance assessment, particularly in areas of high spray mass such as with orchard sprayers.

4.6 Acknowledgements

The authors would like to thank the University of Queensland staff that assisted in the experiment including Jason (Connor) Ferguson, Christopher O’Donnell, and Gary Dorr as well as allowing us to use their facility.

Chapter 5

Phase Doppler Quantification of Horticultural Spray Compared to Traditional Sampling Materials

This chapter was published in New Zealand Plant Protection 70:142-151 (Appendix D)

5.1 Abstract

The quantification of spray mass has historically been accomplished by means of fluorescent dyes and various string and ground samplers to capture the dye-laden spray. However, these methods are typically not used in the close proximity to orchard sprayers and are prone to many sources of error. It was the objective of this study to assess an in-field phase Doppler (pD) interferometer's ability to quantify spray mass against two common string samplers. Measurements were taken at 0.5 m increments to 4.5 m vertically and 1.0 m increments to 5.0 m downwind from the spray. Converted flux measures from the strings were compared to that of the pD. The current pD technology was found not to be capable of collecting equivalent flux data to the strings. However, the pD equipment provided useful data on droplet velocity and size.

Keywords spray mass, phase Doppler interferometer; flux; droplet size; velocity.

5.2 Introduction

In 2015, New Zealand horticultural export crops were worth ca $4.3 b/annum, the majority of which is made from fresh fruits and processed fruit goods: apples, kiwifruit, wine, avocados and fruit juices (Anon. 2015). Export market phytosanitary requirements and the New Zealand maritime climate together require the use of agrichemical spray programmes. Agrichemical inputs to horticultural crops make up approximately 40% of the total NZ agrichemical use (Manktelow et al. 2005). This is due to increased pressure of newly introduced pests and diseases. Subsequently, the intensification of agrichemical spray programmes and agrichemical spraying will continue to be an essential part of successful horticultural production for the foreseeable future.

The assessment of pesticide spray deposition in orchards and vineyards is complex because many factors can influence deposits. Firstly, horticultural canopies can range from ca. 1.3 to >10.0 m in height and ca. 0.3 to >5.0 m deep (using grapevines and avocados as examples of extremes). However, similar spray delivery technologies are used across the range of horticultural crops. It is important to have an understanding of the target canopy, the sprayer droplet sizes, air output characteristics and how they interact together with the weather conditions at the time of application. Although agrichemicals ultimately target pest or disease organisms, the primary target of spray application is the crop canopy where the default application aim is to maximise spray retention on the target as uniformly as practical. Secondly, understanding the potential movement of these pesticide-laden droplets *outside* of the crop is important to minimise the risk of drift and off-target contamination.

Historically, many types and styles of samplers have been used to measure spray deposits and coverage (Bui et al. 1998). However, many of these devices provide qualitative rather than quantitative data, and rely on subjective measurements and experience for interpretation of the results. Coverage has been observed by means of water sensitive papers (WSPs), spray additives such as Kaolin clay (e.g. Surround®) or Kromekote® paper with coloured dye; however coverage does not quantitatively inform the applicator of deposition of the active ingredient (Roten et al. 2015a). This is especially true in orchard environments when the carrier volume can saturate the canopy as well as the samplers. Further, droplet size assessment in-field can also be subjective with little regard to the actual spectrum of droplets, and again, difficult to obtain with large carrier volumes. Various sampler riggings have been used for drift measurements and some have included efforts towards understanding the pattern of the spray vertically, none of which provide quick, quantitative and repeatable measurements (Balsari et al. 2005; Salyani et al. 2007; Khot et al. 2012b).

To date, no published research has occurred to test pD technology in outdoor, agricultural environments or in close proximity to an orchard sprayer. This, and the limitations of common sampling methods, provided the motivation for a series of studies. Work began in laboratory and wind tunnel environments to test phase Doppler against historical string samplers. Findings included an average error of -3.3% quantification of mass when traversing the pD through a conical spray plume (Roten et al. 2016b); no statistical differences when assessing pD versus nylon with relatively low flux between 1.34 and 4.47 m/s (Roten et al. 2016b). The pD performed very well in high flux conditions with wind speeds up to 16.67 m/s and exposure times up to 60 s; where string samplers were prone to saturation and loss of mass, the pD performed with ca 1% error (Roten et al. 2016a). For the purposes of measuring flux in areas of heightened air velocities and spray mass, as is the circumstance near an orchard sprayer, these precursory studies concluded that pD technology had developed to the point where it was ready to be taken to the field and tested. Therefore, the objectives of the present study were to (1) validate mass collection of pD against two common string types, and (2) assess spray plume characteristics such as drop size distribution and droplet velocity which static collectors cannot obtain.

5.3 Materials and Methods

To produce the spray, a Taral three-point linkage style axial fan orchard sprayer (Taral, Instanbul, Turkey) was set to deliver an application volume of 9.5 l/min from the left side of the sprayer using four ceramic disc nozzles. Nozzle orientation was recorded and kept consistent for the duration of the study. In a best attempt for consistency, weather was closely observed using a wind vane and hand held anemometer (Kestrel 4500, KestrelMeters, 2241 Cole Street, Birmingham, MI, USA), predominately for wind direction which varied from a Nor’easterly to WNW which was suitable for the experimental setup (Table 5.1).

Table 5.1 Weather data for experimental days from the Lincoln University Broadfield weather station, accessed from Cliflo.

Sampler	Date	Wind Direction (°)	Wind Speed (m/s)	Temperature (°C)	Humidity (%)
Strings	22 Oct 2016	41.1 ± 12.6	6.2 ± 1.1	13.1 ± 1.6	63.3 ± 6.8
Strings	6 Dec 2016	298.8 ± 15.5	4.25 ± 1.1	24.8 ± 1.8	52.2 ± 8.4
pD	16 Feb 2017	47.1 ± 13.6	7.2 ± 1.4	20.2 ± 1.1	72.0 ± 6.9

5.3.1 Strings

A total of five replicates were taken for the string measurements: two full replications on 22 October and three replications on 6 December 2016 for strings. The chosen strings for testing were a 2.0 mm nylon string (Stihl, Weingärten, Germany) and a 1.7 mm natural cotton string (Birch Haberdashery, Heidelberg, Victoria, Australia). Strings were pre-cut to a length of 4.7 m with a targeted sampling length of 4.5 m, using the excess material to securely attach the strings to the sampling frames. Strings were vertically suspended on 1.5 m by 6.0 m array using scaffolding frames erected at 1, 2, 3, 4 and 5 m downwind of the spray in a staggered positioning (Figure 5.1). From the top of each frame, a pulley system using a 70 mm by 1,000 mm pvc pipe to which the strings were attached was used to raise the strings to an approximate height of 4.5 m. In spray drift research, it is commonplace to have quasi-replicates during the same treatment, therefore 6 strings were attached to each sampling rig 100 mm apart (3 cotton and 3 nylon). To stretch and secure the strings at ground level, the strings were attached to an additional 1,000 mm pipe which was tied to the bottom of the scaffolding frame. After the given spray event, 15 minutes were allowed to elapse to ensure the strings were dry, then they were carefully rolled onto the bottom pipe and stored in clean plastics bags. All bagged samples were placed in a freezer within 30 minutes to avoid any potential degradation. This system allowed for quick turnaround of treatments as well as eliminated many concerns for contamination. For string assessment, ca. 2 g/litre of the fluorescent tracer PTSA (1,3,6,8-pyrenetetrasulfonic acid tetrasodium salt) was mixed for dye recovery and quantification. For the moving spray treatments for the strings, a driving speed of 2.3 km/h was selected to provide sufficient deposition on the string samplers.

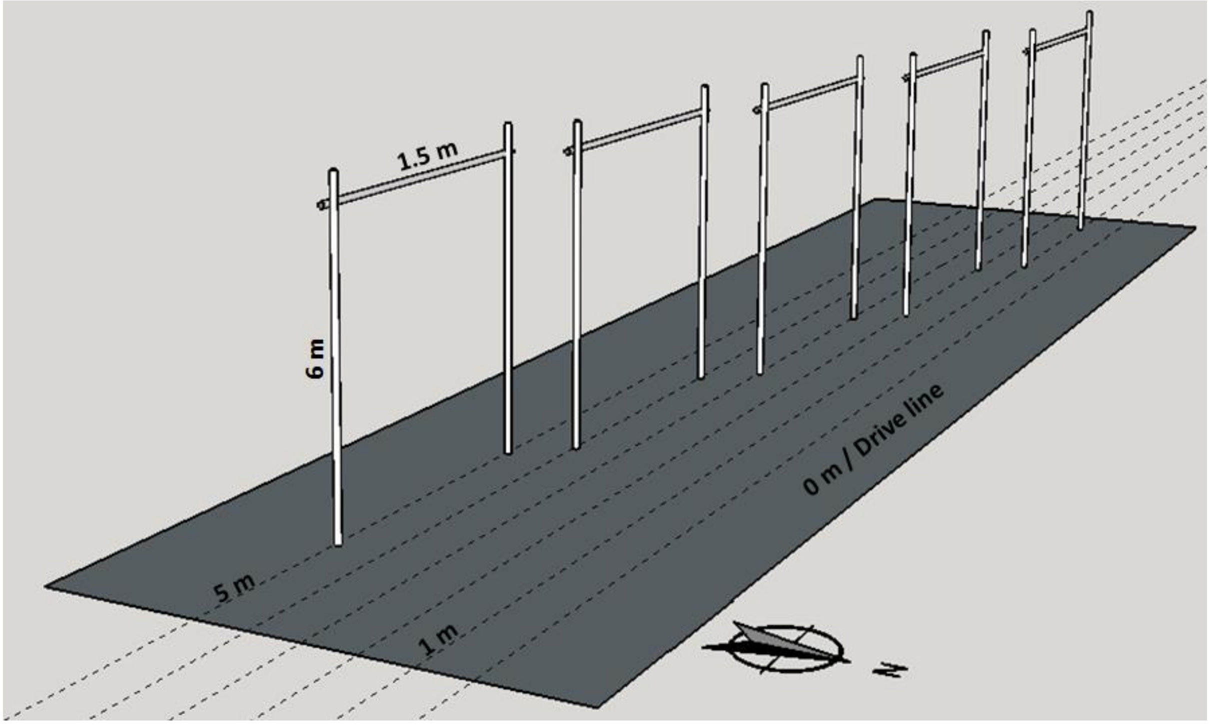

Figure 5.1 Illustration of sampling structures for string treatments.

5.3.2 Phase Doppler

The pD system tested was the TK1-600 (Artium Technologies, Sunnyvale, CA, USA) which is an enclosed system, requiring no positioning or alignment of laser beams, and allows for droplets ranging from 5 to 694 µm in size to be measured in-field. However, due to the small sampling area of the pD (ca 1 mm^2), pD sampling required a longer time than string samples to obtain sufficient data for a valid measurement. Therefore, it was not feasible to have simultaneous pD data acquisitions with the strings nor was it possible to acquire data with a moving tractor. Therefore, pD treatments occurred on a separate day (16 February 2017) and data was acquired with the tractor/sprayer in a static position spraying only water at the same sampling increments as the strings. A minimum of two replications were taken.

5.3.3 Analysis

For laboratory processing, designated strings were removed from the freezer and each string individually uncoiled. Because of slight differences in string length, each string was harvested from the bottom/ground level as a 0.0 m point was known. From here, 0.5 m sections were cut, individually stored in pre-labelled bags, and either returned to the freezer or underwent immediate processing. Dye extraction was accomplished by adding 24 ml of 90:10 water:isopropyl alcohol to the same bags in which the sample was stored, agitated/shaken for a few seconds to be sure that samples were submerged in the extraction fluid, and allowed to rest for a minimum of 15 minutes. When time elapsed, a 3 ml subsample was taken and dye quantification was accomplished using a fluorometer to provide a linear RFU (relative fluorescence unit) value with a 350 nm excitation wavelength PTSA module (Turner Trilogy®, Turner Designs, Sunnyvale, CA, USA). A standard curve was then used to convert the RFU data to g/litre. For this, a stock solution of 2 g/litre PTSA was made using the 90:10 water:isopropyl alcohol mix and processed using increasing sample concentrations until quenching was observed; linearity was observed up to 1.6 M RFUs (r^2=0.992; $y=2.65*10^8x$) and samples above this value were diluted and reprocessed accordingly. Tank samples which were taken at each string run were also processed to obtain the true PTSA concentration of the tank; associated data per tank concentration were then normalised to a uniform concentration of 1.74 g/litre.

Prior to analysis, the pD data had to be conditioned before final processing. The current experiment experienced gapping in the flux data due to introduced turbulence from the sprayer as well as shifting wind caused a fluctuation in spray and missing the pD, as well as to the agglomeration of spray deposits on the pD housing into large drops that obscured the laser beam. These large drops were periodically cleaned by wind shear or their own weight causing them to fall off. These gaps were removed by applying a correction algorithm to the data series whereby the computed flux was multiplied by the quotient of true data over total data: true data being points where data was recorded versus the total data which included non-existing data (data recorded in between true data points). Dullenkopf et al. (1998) also found for similar pD technology that up to 5% of the total measured time was gapped, even for the simpler case of laboratory patternation; field data was gapped up to 85%.

Finally, string deposition data were converted to a unit of flux (ml/s/cm^2) using the string recovery data to express time with a known dye output of 0.276 g/s; here, flux is defined geometrically as the volume of liquid spray passing through the sampling area divided by that area, per unit time**.** These flux data, as well as velocity and droplet size distributions, were then separated by distance and height, and means separated using Tukey's HSD (honest significance difference) with a 95% confidence level using R (version 3.2.0, R foundation for Statistical Computing, Vienna, Austria).

5.4 Results and Discussion

No statistical differences were observed between all string flux replicates (P=0.30 to 0.99), therefore all replicates were kept for analysis. As an overall trend, cotton deposition was greater than nylon (not significant), and both nylon and cotton collected significantly more flux than the pD (data not shown). Absorbent string samplers (cotton, woollen and synthetic yarn) have been used in various mass balance and drift experiments because they are believed to have collection efficiencies of nearly 100% which is attributed to their omnidirectional fine hairs (Cooper et al. 1996). This, and their capacity to absorb, does provide some benefit over the nylon string samplers, but nothing notable in the present conditions.

The unfortunate outcome of the pD is thought to be due to the sampling frequency for accurate flux measures has been low which has reoccurring limitation in this series of research. Ideally 10,000 to 20,000 counts (individual droplets passing through the probe volume) are needed; however the data here seldom achieved >2,000 counts. The pD was also unable to obtain any data beyond a height of 2.5 m or a distance >4.0 m. Strings, however, indicated that spray was going over the collection structures as a baseline/zero was not observed beyond 2 m (Figure 5.2). Losing mass over sampler riggings is a common limitation; the works of Khot et al. (2012b), which was used for the design of this experiment, also sampled to a height of 4.5 m. They found losses of up to 15% using a portable, vertical patternator at an approximate distance of 2.0 m however had large gaps between sampling panes. Using the normalised dye output of 0.276 g/s, it is suspected that the spray plume has fully developed by 2.0 m downwind and the assumption was made that the exposure time would remain consistent. Using these data, the best estimate of mass lost over the sampling frames ranged between 1% and 40%, from 1 to 5 m respectively (Table 5.2). It is important to note that the spray plume was still being actively projected at these sampling distances and droplet fallout would not likely be a large cause of loss at mass.

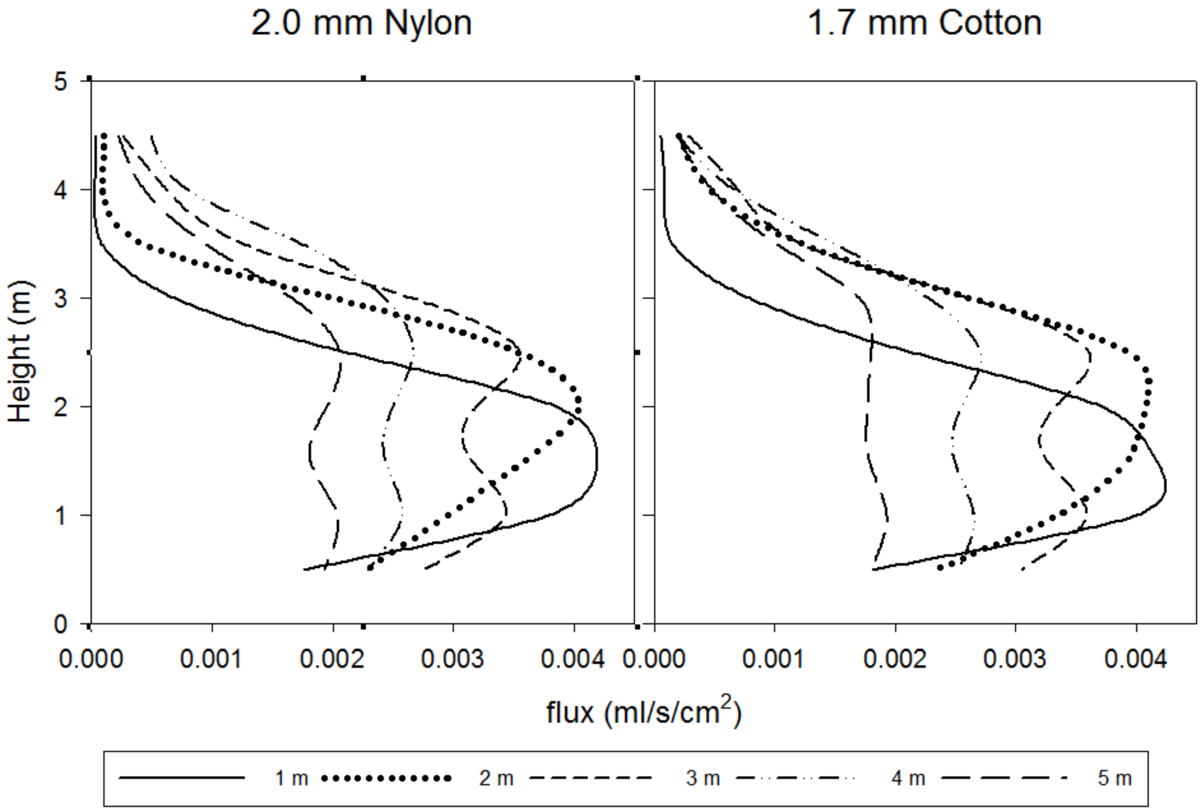

Figure 5.2 Flux profiles for the 2.0 mm nylon string (left) and 1.7 mm cotton string (right) at 1, 2, 3, 4 and 5 m spray distances (n=15).

Table 5.2 Deposition (g/sample) and standard deviation data for pooled string data as well as estimated spray exposure time and percent recovered (n=15).

	Distance (m)									
Height (m)	1		2		3		4		5	
	Deposition	±SD	Deposition	±SD	Deposition	±SD	Deposition	±SD	Deposition	±SD
0.0 to 0.5	0.027	0.011	0.039	0.020	0.049	0.027	0.039	0.022	0.032	0.016
0.5 to 1.0	0.062	0.012	0.055	0.025	0.058	0.026	0.042	0.022	0.034	0.019
1.0 to 1.5	0.068	0.014	0.063	0.019	0.053	0.014	0.040	0.019	0.030	0.015
1.5 to 2.0	0.063	0.012	0.069	0.015	0.054	0.007	0.041	0.017	0.031	0.017
2.0 to 2.5	0.039	0.027	0.063	0.016	0.060	0.010	0.044	0.014	0.032	0.016
2.5 to 3.0	0.016	0.020	0.043	0.031	0.044	0.012	0.038	0.019	0.028	0.013
3.0 to 3.5	0.003	0.003	0.018	0.024	0.020	0.017	0.026	0.018	0.017	0.010
3.5 to 4.0	0.001	0.001	0.007	0.010	0.010	0.012	0.012	0.014	0.008	0.005
4.0 to 4.5	0.001	0.001	0.003	0.004	0.004	0.005	0.006	0.012	0.004	0.003
Total (g)	0.28		0.36		0.35		0.29		0.22	
Time (s)	1.0		1.3		1.3		1.3		1.3	
Recovered	100%		100%		97%		79%		60%	

Lastly, the pattern assessment of the spray plume(s), or patternation, of agricultural for aerial, ground and orchard sprayers has been a work in progress since the late 1950’s (Whitney & Roth 1985). Whitney and Roth (1985) devised a way to do this using a string system and a relatively automated fluorimeter to assess the pattern, and more recent studies such as Balsari et al. (2005) and Salyani et al. (2007) use engineered approaches to suspend samplers (strings or cellulose filter cloth) to assess the movement of liquid mass through orchard vegetation. All examples provide useful information regarding the spray pattern and the engineered approach completely wrap around the canopy to capture mass that may otherwise go over the sampling structure (such as was the case here). While it was originally hoped that the pD would be able to provide instantaneous feedback regarding the movement of mass and subsequent pattern, the data here suggest that current pD technology is not yet ready for in-field use, especially in areas of less dense spray plumes as would be the case on the far side of a canopy to a sprayer.

5.4.1 Droplet size and velocity

Though reliable flux measures were not possible, cumulative droplet profiles (irrespective of sampling frequency) from 1 to 4 m still provided useful information that strings alone cannot provide. As can be seen from Table 5.3, a number of interesting things occurred: as the spray moved upward, the total droplet spectrum became finer at all distances from the sprayer. However, as the distance from the sprayer increased the droplet spectrum gets coarser. Smaller droplets lose their momentum more quickly than the coarser therefore shifting the overall spectrum in these first 4 m to a coarser spread. However, as the gravitational pull on the coarser droplets is greater, eventually these larger droplets will fall out and leave only those in the sub-150 µm size. This class of droplets comprise 50% of the cumulative volume of nearly all measurements with this particular spray and also constitute those droplets with the greatest risk of drift.

Table 5.3 Droplet size distribution data. Like letter in the same column are statistically similar (P=0.05; n=5).

	Distance (m)							
Height (m)	1		2		3		4	
				$D_{V0.1}$				
0.5	78.6	A	75.3	A	93.1	A	92.1	A
1.0	62.9	A	72.9	A	74.2	B	81.9	AB
1.5	65.5	A	71.3	A	71.5	B	76.8	AB
2.0	53.4	A	68.5	A	70.9	B	71.3	AB
2.5			58.5	B	67.0	B	62.6	B
				$D_{V0.5}$				
0.5	146.4	A	158.2	A	175.7	A	175.6	A
1.0	122.3	A	151.8	A	160.0	AB	161.0	A
1.5	142.2	A	150.3	A	156.7	AB	163.9	A
2.0	113.0	A	149.5	AB	150.7	B	157.0	A
2.5			134.8	B	148.4	B	143.7	A
				$D_{V0.9}$				
0.5	196.4	A	240.1	AB	252.9	A	263.2	A
1.0	189.3	A	233.4	AB	230.3	A	246.8	AB
1.5	195.9	A	243.4	B	247.7	A	248.5	AB
2.0	178.6	A	225.7	AB	225.4	A	249.5	AB
2.5			212.4	A	246.1	A	212.0	B

As discussed by García-Ramos et al. (2012), the air velocities generated from axial fan airblast sprayers can cause discrepancies in spray deposition. Their work assessed a double fanned spray system in an effort to compensate for differences in deposition caused by air pattern differences within a spray plume. This is not a common sprayer in NZ orchards, however the air affects from any orchard sprayer is not well documented, and this work clearly exhibits the lifting and dumping phenomena of the air currents (Figure 5.3). The majority of orchard sprayers are tow-behind varieties with an anti-clockwise rotation causing the air to be lifted on the right side of the sprayer and dumped on the left, causing droplet interaction and discrepancies in the vertical profile (Manktelow & May 2011; García-Ramos et al. 2012). For example, Khot et al. (2012a) observed 49% higher flux profiles 3.0 to 4.5 m on the right side of the sprayer (with nozzles and air flow at 100% open); conversely, 26% greater flux was captured from 1.0 to 2.5 m on the left side. The sprayer in the present study is geared differently and the fan, consequently, rotates in a clockwise fashion. Table 5.4 illustrates these differences by measuring the velocities of the droplets through the pD: the droplet/air velocities are quite low (3.2 to 3.9 m/s) at 0.5 m off the ground but exhibit a pattern of heightened speeds as the sampler height climbs for all measured distances. At the 1.0 m distance, a clear pattern can also be seen where the sprayer, being round, was the closest to the PD; by 3.0 m this difference plateaued. Lastly, statistical differences are seen within distances with 47% to 72% differences from 0.5 to 2.5 m.

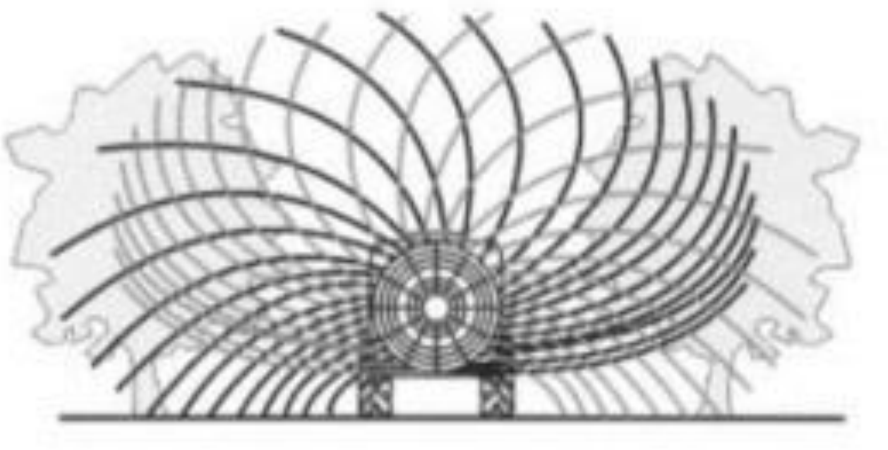

Figure 5.3 Illustration of air current patterns from (García-Ramos et al. 2012). Black lines signifying the air effects of conventional, single fan orchard sprayers.

Table 5.4 Mean phase Doppler velocity data per height and distance. Like letter in the same column are statistically similar (P=0.05; n=5).

Height (m)	Distance (m)							
	1		2		3		4	
	Velocity (m/s)							
0.5	3.7	A	3.9	A	3.2	A	3.5	A
1.0	15.5	B	7.2	B	4.5	B	4.1	B
1.5	12.1	C	7.2	B	5.9	C	5.0	BC
2.0	13.1	C	7.7	B	6.3	D	5.2	BC
2.5			8.0	B	7.4	D	6.7	C

The differences observed in droplet size and velocity is important to understand when assessing the fate of plant protection chemicals. When calibrating these sprayers, nozzle selection, configuration and orientation are critical factors to achieve adequate coverage and mitigate spray drift (Manktelow & May 2011). With fundamental spray data, it is well known that while smaller droplet spectrums provide better coverage, air assistance is required these to carry the droplets upwards, as well as to penetrate the canopy (Tuck et al. 1997; Fox et al. 2008). However, these two parameters are also two of the largest culprits of spray drift. Conversely, larger droplets hold their momentum for longer and represent very little risk for drift as can be seen since the advent of the air induction nozzle. However, though large droplets do well to promote coverage to easy to reach locations and to minimise drift, they have a greater risk to bounce, shatter and fall off-target (Spillman 1984; Schou et al. 2012).

Finally, when taking into account these retention issues for assessment of sprayed mass, the compilation of strings with pD can be quite useful. Forster et al. (2014) explains well of the need for artificial collectors that will capture and retain spray mass is crucial, but also the need to know the spray volume and droplet size. These factors are also important to discern collection efficiencies (Fox et al. 2008). Cross et al. (2003) acknowledges decades of debate regarding the optimum amount of air (volume and velocity) and found that lower air volumes still provided adequate deposition while also substantially reducing risk of drift; however, they also note that in windy conditions, as with NZ, that this would not likely be suitable. Therefore, though it is clear that pD technology is not yet ready to replace strings samplers, it could certainly be a useful tool in the future to better understand our sprayed droplets as well as predicting their fate.

5.5 Acknowlegements

The authors would like to extend our gratitude to the Lincoln University Field Service Centre and the Biological Husbandry Unit (BHU) for their assistance with equipment and field site. Also thanks to Travis Cook and Kevin Wang for their laboratory contributions.

Chapter 6

Conclusions

6.1 General discussion

Originally, the pD was hoped to be used in spray drift research, making measurements far downwind of the sprayer. It was quickly realised that measuring non-dense spray plumes did not provide robust data. This resulted in the shift in the planned research to occur in close proximity of the sprayer. Further, early ground boom exercises also observed to be unsuitable data acquisition, shifting the research to horticulture applications where spray volumes were substantially larger. From these early decisions, it became increasingly clear that the pD is not yet at a state of development to measure these sprays if the intent to gain knowledge of flux; however, it is imperative to note that through this research, important droplet size and velocity data were acquired which is a definitive difference between any other field sampler, to date.

6.2 Findings

It was the intent of this research to assess the use of a new pD technology for its ability to capture flux data in close proximity of an orchard airblast sprayer. Overall, the pD performed as expected in controlled, indoor environments where spray mass was kept constant. Unfortunately, when introduced to outdoor environments, flux measurements were not possible. Key findings of the present research are:

1. Laboratory: Mass flux was an average error of -3.3% quantification of mass when traversing the pD through a conical spray plume.

2. Wind Tunnel: No statistical differences when assessing pD versus nylon with relatively low flux between 1.34 and 4.47 m/s (Appendix E).

3. Wind tunnel: The pD performed very well in high flux conditions with wind speeds up to 16.67 m/s and exposure times up to 60 s; where string samplers were prone to saturation and loss of mass, the pD performed with ca 1% error.
4. Field: The pD was not capable of acquiring sufficient data for flux measurements in close proximity of an orchard airblast sprayer; droplet size and velocity data were still acquired.

The last finding, and fail hypothesis, stopped further field investigations. This was due to a number of limitations, namely the inability of capturing enough data for accurate flux measurements. However this is not to say that the pD's inability to capture data was the fault of the pD, but that the environment to which it was introduced was not conducive. Throughout the field experiment, it was observed that driving the sprayer past the pD did not collect sufficient data and that the turbulence from the static sprayer made it impossible to keep the spray plume on the pD. To overcome these issues would be an engineering challenge as the probe would likely need to be attached to the moving sprayer, which falls outside the scope of this thesis. Lastly, one unexpected result was the validation for the use of cotton and nylon strings to be used in close proximity of an orchard sprayer.

This research therefore concludes that current generation of pD technology is not suitable for field use of spray flux assessment. To make this technology feasible it will require:

1. Lower cost, which may be achievable with ongoing advances in diode lasers
2. Larger sampling volume, which would require more powerful lasers with wider beam, or use of multiple lasers
3. Solution to window-wetting problems
4. Wireless transmission to a laptop, without the need for bulky computer, so that the pD would be truly field-portable

6.3 Academic Outputs

This thesis research has already led to 1 journal publication (an addition manuscript in review), and 4 peer-reviewed conference presentations (Suprofruit, NZPP, ILASS, ASABE), plus 5 other presentations (Lincoln University Postgraduate Conference and extension presentations). Further publications can be seen in Table 6.1.

Table 6.1 Publications during PhD career.

Year	Journal	Title	Author	Co-Author
2013	New Zealand Plant Protection	Evaluation of Spray Deposition in Potatoes using Various Spray Delivery Systems	x	
2014	Journal of Plant Protection Research	Developing a Comprehensive Drift Reduction Technology Risk Assessment Scheme		x
2014	New Zealand Plant Protection	Drift Reducing potential of low drift nozzles with the use of spray-hoods. New Zealand Plant Protection	x	
2015	New Zealand Plant Protection	Comparison of pesticide dosage on leaf surface versus coverage onto a simulated leaf collector	x	
2016	Crop Protection	Volumetric validation of mass balance using a computational phase Doppler approach for disc core nozzles	x	
2017	American Society of Agricultural and Biological Engineers	Discharge coefficients of flat fan nozzles		x
2017	Computers and Electronics in Ag.	Urine Patch detection using LiDAR for the Betterment of Nitrogen Application to Pastures. Computers and Engineering in Agriculture	x	
2017	New Zealand Plant Protection	Phase Doppler Quantification of Horticultural Spray Compared to Traditional Sampling Materials	x	
2017	Journal of Plant Protection Research	Wind Tunnel Flux Comparisons using a Phase Doppler Interferometer	x	

Appendix A – Published manuscript

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Appendix B – Published Manuscript

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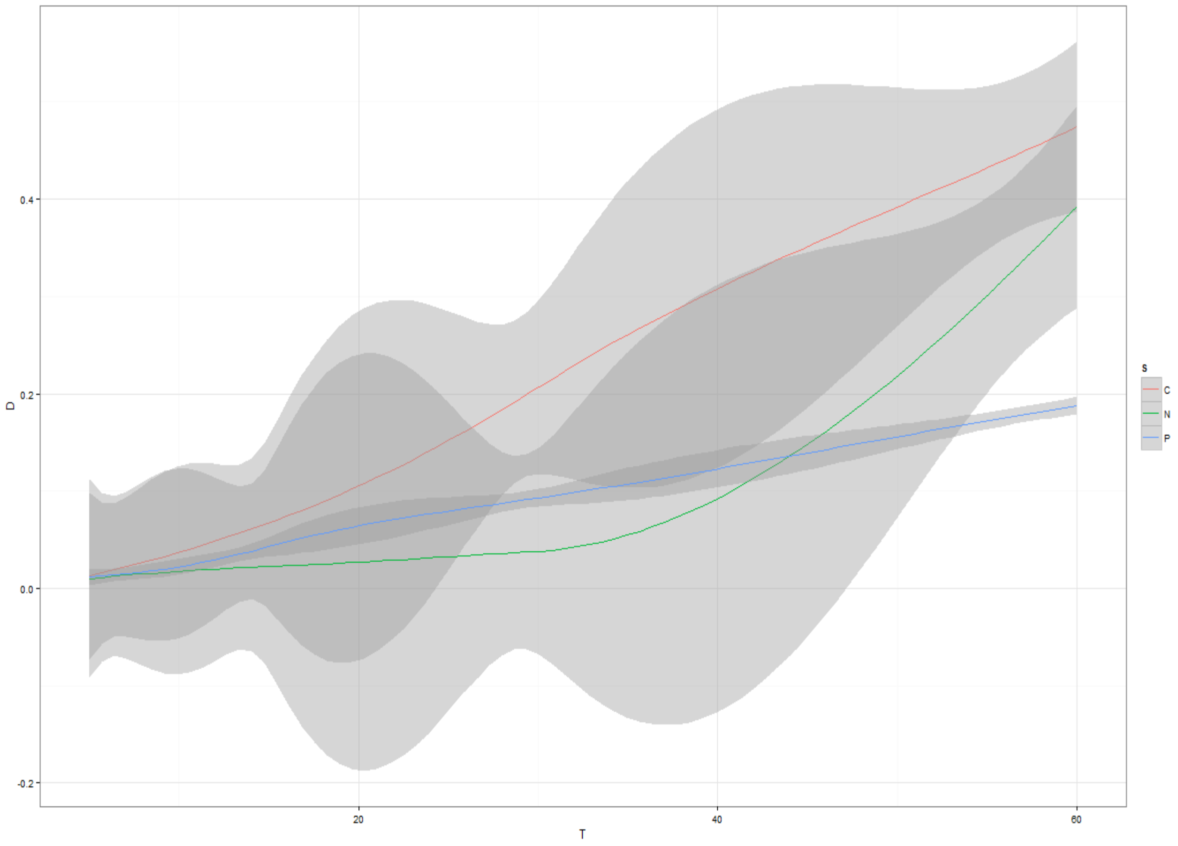
Appendix C – Alternate version of Figure 4.2



Appendix D – Published Manuscript

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http://journal.nzpps.org/index.php/nzpp/article/view/40/23.

Appendix E– Referred conference proceeding

(2015, 15-18 July). Preliminary investigation of Phase Doppler derived flux measurements in a wind tunnel for the sampling of orchard spray drift. Paper presented at the Suprofruit, Lake Constance,

Germany.

Preliminary Investigation of Phase Doppler Derived Flux Measurements in a Wind Tunnel for the Sampling of Orchard Spray Drift

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Introduction

Air-assisted spray equipment used for horticultural cropping systems depend on high air velocities to project the spray as well as to open the canopy for greater droplet penetration and deposition. However, these sprayer-types are also at a heightened risk for spray drift as they possess the potential to place drift prone droplets in the atmosphere where they can be carried to off-target locations. Unfortunately, quantifying these droplets can be difficult and expensive using samplers such as high-volume air samplers, rotating rods and strings. However, while these measuring techniques may give some idea of flux, no particle information can be gained which is imperative to predicting the mass which may be the most prone to drift. In wind-tunnels and field studies, polyester and nylon strings have proven to be an efficient collecting surface. Therefore, it was the objective of this study to assess the potential for the use of a novel, field grade phase Doppler interferometer (PDI) as a replacement for strings as a sampler for driftable mass for orchard type sprayers.

Materials and Methods

This study was conducted at the University of Queensland, Wind Tunnel Facility (Gatton, Australia) 19 and 20 March 2014. Tunnel wind conditions were set to deliver 1.34, 2.24, or 4.47 m s^{-1} (3, 5, or 10 mph, respectively) laminar air flow. Examined nozzles consisted of the XR110-02 and XR110-04 flat fans which were pressurized at 3 bar (43.5 psi). The spray solution for string sampling procedure included a 0.4 gm/L pyranine solution and spray timer set at 10s; water only was used for PDI measurements and sampling time was extended to 40s to allow for more samples and statistical validity. String flux measurements were assessed using the 1,600 mm x 2 mm nylon strings whereas strings were stretched taunt and parallel to the tunnel floor, 2m away from the spray nozzle at 0.1, 0.2, 0.3, 0.4, and 0.5 m high. Once individual treatments were complete, the strings were given ≥5 minutes in the running wind tunnel to dry before harvesting. Samples were then directly analysed or placed in the freezer for later analysis. Analysis consisted of adding 60 mL directly to the bag in which the coiled string was stored. The bag was then pinched closed and solution distributed to extract florescent material from the string. Once this was sufficiently accomplished, a subsample was added to a test tube/cuvette and fluorescence read. These readings were compared to a base curve from a subsample taken from the spray tank before the commencement of the experiment. Once these data points were made and calculated into the percent applied, the deposition was then calculated using the diameter and length of the string, and the time exposed. PDI flux measurements were acquired at three static points measured from the tunnel wall (centre/800 mm, 528 mm and 264 mm) and at the aforementioned heights. The three flux points were then averaged and doubled to encompass the whole width of the tunnel. These data were then divided by their specific sampling time to determine a deposition reading. Finally, an analysis of variance was conducted to determine similarities between the two sampling techniques as the conducted ($P \geq 0.05$).

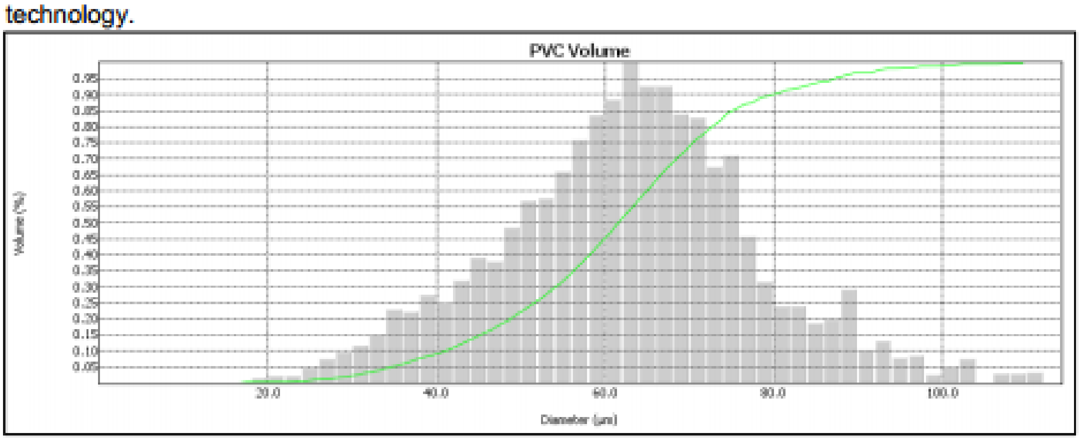
Results

P-values (Table 1) indicate no statistical differences between the strings' deposition data and the converted flux data of the PDI for the two nozzles, three wind speeds and five heights. One disadvantage to the use of the PDI in the wind-tunnel is that the number of droplet/sample counts that is typically required is impractical; the sheer volume of solution that is needed to receive an "adequate" reading inundates the tunnel, ergo flooding the facility. Past researches have suggested sampling between 2,000 and 10,000 counts might be sufficient. Counts from the present study varied largely (0 to 4,000), however no differences were observed and it was quickly determined that it was essential that time be the constant factor in this instance. It is also important to note that while there may be a discrepancy in the number of samples that this is preliminary work for orchard spray research where air velocity and sprayer volume will immediately increase the number of counts. For field sampling it is predicted that PDI technology will not face the same issues as strings and will perform better as the PDI will not become saturated or have particle effects such as droplet shatter and bounce from the string surface. Lastly, other pertinent information is accrued via the PDI technique such as droplet size distribution (Fig 1) and velocity, for example.

Table 1. Statistical summary of PDI versus string flux data for two nozzles.

Wind Speed m/s	Height cm	P-value XR110-02	XR110-04
1.34	10	0.735	0.678
1.34	20	0.487	0.566
1.34	30	0.484	0.675
1.34	40	0.802	0.260
1.34	50	na	na
2.24	10	0.361	0.788
2.24	20	0.175	0.134
2.24	30	0.823	0.308
2.24	40	0.646	0.237
2.24	50	0.076	0.694
4.47	10	0.364	0.878
4.47	20	0.580	0.538
4.47	30	0.565	0.900
4.47	40	0.976	0.723
4.47	50	0.779	0.725

Figure 1. Example of droplet spray distribution of driftable mass using phase Doppler technology.



References

Anon. 2009. Spray Nozzle Classification by Droplet Spectra. American Society of Agricultural and Biological Engineering: 1.

Anon. 2013. Demeter PDI User Manual. In ed., Artium Technologies, Inc.

Anon. 2015. FreshFacts. In ed., New Zealand Horticulture. http://www.freshfacts.co.nz/ (accessed on 1 April 2014).

Arvidsson T, Bergström L, Kreuger J 2011. Comparison of collectors of airborne spray drift. Experiments in a wind tunnel and field measurements. Pest Management Science 67: 725-733.

Bachalo WD 1985. Apparatus and Method for Determining the Size and Velocity of Partilces, Droplets, Bubbles or the like using Laser Light Scattering. In ed. Pp.

Bachalo WD, Houser MJ 1984. Phase/Doppler Spray Analyzer For Simultaneous Measurements Of Drop Size And Velocity Distributions. Optical Engineering 23: 235-583.

Bah AR, Kravchuk O, Kirchhof G 2009. Fitting Performance of Particle-size Distribution Models on Data Derived by Conventional and Laser Diffraction Techniques All rights reserved. No part of this periodical may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, recording, or any information storage and retrieval system, without permission in writing from the publisher. Permission for printing and for reprinting the material contained herein has been obtained by the publisher. Soil Sci. Soc. Am. J. 73: 1101-1107.

Balsari P, Marucco P, Oggero G 2002. Spray Applications in Italian Apple Orchards: Target Coverage, Ground Losses and Drift. In ed. Pp.

Balsari P, Marucco P, Tamagnone M 2005. Technical Note: A System to Assess the mass balance of spray applied to tree crops. Transactions of the ASAE 48: 1689-1694.

Bilanin AJ, Teske ME, Barry JW, Ekblad RB 1989. AGDISP: The Aircraft Spray Dispersion Model, Code Development and Experimental Validation. 32(1): 327-334.

Bonds JA, Leggett M 2015. A Literature Review of Downwind Drift from Airblast Sprayers: Development of Standard Methodologies and a Drift Database. Transactions of the ASABE 58: 1471-1477.

Brann JL 1956. Apparatus for Application of Insecticides. Annual Review of Entomology 1: 241-260.

Bui QD, Womac AR, Howard KD, Mulrooney JE, Amin MK 1998. Evaluation of samplers for spray drift. Transactions of the ASAE 41(1): 37-41.

Chapple AC, Downer RA, Hall FR 1993. Effects of spray adjuvants on swath patterns and droplet spectra for a flat-fan hydraulic nozzle. Crop Protection 12: 579-590.

Chapple AC, Taylor RAJ, Hall FR 1995. The Transformation of Spatially Determined Drop Sizes to their Temporal Equivalents for Agricultural Sprays. Journal of Agricultural Engineering Research 60: 49-56.

Chuang PY, Saw EW, Small JD, Shaw RA, Sipperley CM, Payne GA, Bachalo WD 2008. Airborne Phase Doppler Interferometry for Cloud Microphysical Measurements. Aerosol Science and Technology 42: 685-703.

Connell RJ, Schou WC, Nuyttens D, Wolf TM, Praat JP 2012. Comparison of the mechanistic AGDISP ground boom spray model with experimental data. New Zealand Plant Protection 65: 93-99.

Cooper JF, Smith DN, Dobson HM 1996. An evaluation of two field samplers for monitoring spray drift. Crop Protection 15: 249-257.

Cross J, Walklate P, Murray R, Richardson G 2003. Spray deposits and losses in different sized apple trees from an axial fan orchard sprayer: 3. Effects of air volumetric flow rate. Crop Protection 22: 381-394.

Cunningham GP, Harden J 1998. Reducing spray volumes applied to mature citrus trees. Crop Protection 17: 289-292.

Da Silva A, Sinfort C, Tinet C, Pierrat D, Huberson S 2006. A Lagrangian model for spray behaviour within vine canopies. Journal of Aerosol Science 37: 658-674.

Dan Hirleman E 1996. History of Development of the Phase-Doppler Particle-Sizing Velocimeter. Particle & Particle Systems Characterization 13: 59-67.

Daugherty GW 1949. Spraying and dusting machines. U.S Patent 2,476,960. In U.S. ed. Pp.

Delele MA, De Moor A, Sonck B, Ramon H, Nicolaï BM, Verboven P 2005. Modelling and Validation of the Air Flow generated by a Cross Flow Air Sprayer as affected by Travel Speed and Fan Speed. Biosystems Engineering 92: 165-174.

Dullenkopf K, Willmann M, Wittig S, Schöne F, Stieglmeier M, Tropea C, Mundo C 1998. Comparative Mass Flux Measurements in Sprays using a Patternator and the Phase-Doppler Technique. Particle & Particle Systems Characterization 15: 81-89.

Egner DO, Campbell D 1960. Aerosol impaction on small diameter collectors. In Army US ed. U.S. Army Chemical Warfare Laboratiories. Pp. 24.

Endalew AM, Debaer C, Rutten N, Vercammen J, Delele MA, Ramon H, Nicolaï BM, Verboven P 2010. A new integrated CFD modelling approach towards air-assisted orchard spraying—Part II: Validation for different sprayer types. Computers and Electronics in Agriculture 71: 137-147.

Farooq M, Balachandar R, Wolf T 2001. Assessment of an Agricultural Spray in a Non-Uniform Cross-Flow. Transactions of the ASAE. 44(6): 1455-1460.

Forster WA, Kimberley MO, Zabkiewicz JA 2005. A Universal Spray Droplet Adhesion Model. Transactions of the ASAE. 48(4):1321-1330.

Forster WA, Mercer GN, Schou WC 2012. Spray droplet impaction models and their use within AGDISP software to predict retention. New Zealand Plant Protection 65: 85-92.

Forster WA, Gaskin RE, Strand TM, Manktelow DWL, van Leeuwen RM 2014. Effect of target wettability on spray droplet adhesion, retention, spreading and coverage: artificial collectors versus plant surfaces. New Zealand Plant Protection 67: 284-291.

Fox RD, Derksen RC, Zhu H, Downer RA, Brazee RD 2004. Airborne spray collection efficiency of nylon screen.

Fox RD, Derksen RC, Zhu H, Brazee RD, Svensson SA 2008. A History of Air-Blast Sprayer Development and Future Prospects. Applied Engineering in Agriculture 20(2):147-152.

Fritz BK, Hoffmann WC 2008. Development of a System for Determining Collection Efficiency of Spray Samplers. Applied Engineering in Agriculture 24(3):285-293.

Fritz BK, Hoffmann WC, Bonds JAS, Farooq M 2011. Volumetric Collection Efficiency and Droplet Sizing Accuracy of Rotary Impactors. Transactions of the ASABE 54(1):57-63.

García-Ramos FJ, Vidal M, Boné A, Malón H, Aguirre J 2012. Analysis of the Air Flow Generated by an Air-Assisted Sprayer Equipped with Two Axial Fans Using a 3D Sonic Anemometer. Sensors (Basel, Switzerland) 12: 7598-7613.

Goguen RJ, Saunders BAJ, Picot JJC 1997. Flux-Based Measurements with the Malvern Spectrometer. Transactions of the ASAE 40(5):1233-1236.

Hewitt AJ 2010. Tracer and collector systems for field deposition research. Aspects of applied biology: 283-289.

Hewitt AJ, Roten RL, Giles DK, Bachalo W, Connell R 2013. A new phase Doppler interferometer system for evaluation of pesticide sprays in the field. In ed. ILASS Americas, 25th annual conference of liquied atomization and spray systems. Pittsburgh, PA. Pp.

Hinds WC 1982. Aerosol technology: properties, behavior, and measurement of airborne particles. New York, Wiley-Interscience, 1982. 442 p. 1.

Hoffman WC, Frintz BK, Ledebuhr MA 2014. Evaluation of 1, 3, 6, 8-Pyrene tetra sulfonic acid tetra sodium salt (PTSA) as an agricultural spray tracer dye. Applied Engineering in Agriculture 30: 25-28.

Holland P, Maber J, May W, Malcolm C 1997. Drift from orchard spraying. Proceedings of the New Zealand plant protection conference: 112-118.

Jensen PK, Olesen MH 2014. Spray mass balance in pesticide application: A review. Crop Protection 61: 23-31.

Khot LR, Ehsani R, Albrigo G, Landers AJ, Larbi PA 2012a. Technical Note: Spray Pattern Investigation of an Axial-Fan Airblast Precision Sprayer Using a Modified Vertical Patternator. Applied Engineering in Agriculture 28(5):647-654.

Khot LR, Ehsani R, Albrigo G, Larbi PA, Landers A, Campoy J, Wellington C 2012b. Air-assisted sprayer adapted for precision horticulture: Spray patterns and deposition assessments in small-sized citrus canopies. Biosystems Engineering 113: 76-85.

Lake JR, Dix AJ 1985. Measurement of droplet size with a PMS optical array probe using an X-Y nozzle transporter. Crop Protection 4: 464-472.

Large EC 1965. The advance of the fungi. American Potato Journal 42: 205-205.

Manktelow DW, May B 2011. Spray Nozzle Guide. http://www.kvh.org.nz/vdb/document/896 (accessed on 4 April 2017).

Manktelow DW, Stevens P, Walker J, Gurnsey S, Park N, Zabkiwicz J, Teulon D, Rahman A 2005. Trends in pesticide use in New Zealand: 2004. In ed. Pp.

May KR, Clifford R 1967. The Impaction of Aerosol Particles on Cylinders, Spheres, Ribbons and Discs. Annals of Occupational Hygiene 10: 83-95.

Mercer TT 1973. Aerosol technology in hazard evaluation, by Thomas T. Mercer: Monograph series on industrial hygiene. Academic Press, New York. pp.

Miller PC, Tuck CR, Murphy S, da Costa Ferreira M 2008. Measurements of the droplet velocities in sprays produced by different designs of agricultural spray nozzle. European Conference on Liquid Atomization and Spray Systems, Como Lake, Italy: 8-10.

Nuyttens D, Baetens K, De Schampheleire M, Sonck B 2006. PDPA Laser-Based Characterization of Agricultural Spray Nozzles. CIGR E-Journal Volume 8.

Nuyttens D, Baetens K, De Schampheleire M, Sonck B 2007a. Effect of nozzle type, size and pressure on spray droplet characteristics. Biosystems Engineering 97: 333-345.

Nuyttens D, Schampheleire MD, Baetens K, Sonck B 2007b. The Influence of Operator-Controlled Variables on Spray Drift from Field Crop Sprayers. Applied Engineering in Agriculture 50(4):1129-1140.

Nuyttens D, Schampheleire MD, Verboven P, Brusselman E, Dekeyser D 2009. Droplet Size and Velocity Characteristics of Agricultural Sprays Transaction of the ASABE 52(5):1471-1480.

Parkin CS 1993. Methods for measuring spray droplet sizes. In: ed. Application Technology for Crop Protection. Pp. 57-84.

Raupach MR, Briggs PR, Ahmad N, Edge VE 2001. Endosulfan transport: II. Modeling airborne dispersal and deposition by spray and vapor. J Environ Qual 30: 729-740.

Roten RL, Post SL, Hewitt AJ 2016a. Phase Doppler Flux Comparisons. In ed. 2016 ASABE Annual International Meeting. 162461508. St. Joseph, Mich., ASABE. Pp. 1.

Roten RL, Connell RJ, Hewitt AJ, Woodward SJR 2015a. Comparison of spray dose measured on leaf surfaces with spray coverage estimated from Kromekote® paper. New Zealand Plant Protection 68: 38-43.

Roten RL, Ferguson JC, Connell RJ, Gary JD, Hewitt AJ 2015b. Preliminary investigation of Phase Doppler derived flux measurements in a wind tunnel for the sampling of orchard spray drift. Suprofruit.

Roten RL, Post SL, Werner A, Hewitt AJ, Safa M 2016b. Volumetric validation of mass balance using a computational phase Doppler approach for disc core nozzles. Crop Protection 79: 128-134.

Salyani M, Sweeb RD, Farooq M 2006. Spray Capture Efficiencies of Ribbon and String Targets Used in Orchard Applications. In ed. Pp.

Salyani M, Farooq M, Sweeb RD 2007. Spray Deposition and Mass Balance in Citrus Orchard Applications. Transaction of the ASABE 50(3):1963-1969.

Schou WC, Forster WA, Mercer GN, Teske ME, Thistle HW 2011. Building Canopy Retention into AGDISP: Preliminary models and results. In ed. 2011 Louisville, Kentucky, August 7-10, 2011. Pp.

Schou WC, Forster WA, Mercer GN, Teske ME, Thistle HW 2012. Building Canopy Retention into AGDISP: Preliminary Models and Results. Transaction of the ASABE 55(5):2059-2066.

Sidahmed MM, Brown RB, Darvishvand M 1999. Drop-Size/Velocity Correlations at Formation of Sprays from Fan Nozzles. Transactions of the ASAE 42(2):1557-1564.

Spillman JJ 1984. Spray impaction, retention and adhesion: An introduction to basic characteristics. Pesticide Science 15: 97-106.

Teske ME, Thistle HW 2003. Release height and far-field limits of lagrangian aerial spray models. Transactions of the ASAE 46(4):977-983.

Tratnig A, Brenn G 2010. Drop size spectra in sprays from pressure-swirl atomizers. International Journal of Multiphase Flow 36: 349-363.

Tuck CR, Ellis MCB, Miller PCH 1997. Techniques for measurement of droplet size and velocity distributions in agricultural sprays. Crop Protection 16: 619-628.

Walklate PJ, Weiner KL, Parkin CS 1996. Analysis of and Experimental Measurements made on a Moving Air-Assisted Sprayer with Two-Dimensional Air-Jets Penetrating a Uniform Crop Canopy. Journal of Agricultural Engineering Research 63: 365-377.

Whitney RW, Roth LO 1985. String Collectors for Spray Pattern Analysis. Transactions of the ASAE 28.

Wolf T, Stumborg M, Caldwell B, Grover R 1995. A chamber for scanning spray from agricultural nozzles using an Aerometrics phase/doppler particle analyzer. Canadian Agricultural Engineering 37: 305-310.

Womac AR, Maynard I, R. A., Kirk IW 1999. Measurement Variation in Reference Sprays for Nozzle Classification. Transaction of the ASAE 42(3):609-616.

Young BW 1990. Droplet dynamics in hydraulic nozzle spray clouds. Pesticide Formulations and Application Systems, 10th Volume, ASTM STP 1078: 142-155.

Zhu H, Reichard DL, Fox RD, Brazee RD, Ozkan HE 1996. Collection Efficiency of Spray Droplets on Vertical Targets. Transaction of the ASAE 39(2)415-422.