# THE EFFECT OF OPTICAL CONFIGURATION SELECTION ON PHASE DOPPLER ANEMOMETER FIRE SUPPRESANT NOZZLE CHARACTERIZATIONS†

John M. Davis
UC-FEST, Department of Aerospace Engineering, University of Cincinnati
Cincinnati, Ohio 45221-0070, USA

Peter J. Disimile
USAF 46 Test Wing, Aerospace Survivability and Safety Flight
2700 D Street, Bldg 1661
Wright-Patterson AFB, Ohio 45433-7605, USA
peter.disimile@wpafb.af.mil
937-255-6823 ext. 212

## ABSTRACT

Phase Doppler Anemometry is widely used to characterize spray nozzles, and is currently being used to aid in the validation of suppressant transport modeling. For these purposes, absolute diameter and velocity of the suppressant droplets must be measured. During the characterization of a two-phase suppressant nozzle it was found that the droplet diameters measured by PDA are very sensitive to the specific optical configuration utilized. This can cause major setbacks since most PDA systems are used as turnkey, and the optical configurations are chosen for physical reasons, other than the diameter dynamic range of the PDA system. The current work presents an investigation into the effects of using a less than optimum optical configuration for PDA measurements. A standard three dimensional fiber optic PDA system was configured with several transmitting/receiving lens and receiving aperture combinations and used to acquire velocity and drop diameter data downstream of an air/water fire suppressant spray nozzle. Experimental results show that velocity measurements are relatively unaffected by the optical configuration while the diameter measurements can have a considerable bias depending on the optical configuration selected. The optimum optical configuration can be very difficult to choose without apriori knowledge of the diameter range to be measured. Therefore, a straightforward experimental method to determine the optical configuration that provides the least bias for an unknown droplet diameter range is presented.

---

† This research is part of the Department of Defense's Next Generation Fire Suppression Technology Program, funded by the DoD Strategic Environmental Research and Development Program

## INTRODUCTION

Phase Doppler Anemometry (PDA) is a widely used diagnostic technique capable of non-intrusive diameter measurement of both drops and particles in multi-phase flows. In general Phase Doppler Anemometry does not require calibration since the measurements are based off of light scattering theories. As a result, PDA diameter measurements were reported as absolute measurements and were not reported with any error. However, the recent demand for error analysis reporting for all measurements has sparked an interest into several effects that could cause a bias in the diameter measurements recorded using PDA.

The most researched phenomenon that can cause a bias in diameter measurements is known as the trajectory ambiguity effect (TAE), or measurement volume effect (MVE). Many researchers have attempted remedies for TAE or even used TAE to their advantage.[1-3] This paper will not further address TAE since absolute measurements were are not required. Naqwi[4] provides a more relevant study investigating different receiving aperture shapes and sizes. However, this study does not include the combination of the optical lens selection with the receiving aperture. Another study[5] presented a three step procedure for determining the important parameters of a PDA system but was never tested experimentally and requires apriori knowledge of the diameter range to be measured. Therefore the need exists for a relatively easy to use method in which a proper selection of PDA optical lens / receiving aperture configuration can be chosen for an unknown drop diameter range.

This paper is a continuation of an ongoing effort focused on the effect on PDA measurements due to varying optical parameters. A previous work by Davis and Disimile[6] presented the first published results of this ongoing work. The current paper clears up the confusion of the difference in the mean velocities measured at the two off centerline positions presented in the previous paper[6] and presents a more complete analysis by investigating the Sauter mean diameter and the diameter concentration differences between each configuration. In addition, this paper better describes how the noted differences between optical configurations can effect a suppressant spray nozzle characterization.

## EXPERIMENTAL SETUP

A standard three-dimensional Phase Doppler Anemometry system was used to measure the velocity and drop diameter distribution downstream of a two phase air/water spray nozzle. Preliminary measurements were acquired at three separate spatial locations across the center of the spray for each optical configuration examined. At each location 20,000 samples were acquired and velocity and diameter statistics computed. Two separate lens configurations were used. The first lens configuration consisted of 1000mm lenses on both the transmitting and receiving optics. The second configuration consisted of a 402.5mm lens installed on the U, and V component transmitting probe and a 310mm lens installed on the receiving optic/W component transmitter. Velocity and drop size measurements were taken at each position, each using three different apertures or masks (namely Mask A, B, and C) for each lens configuration. All three masks are shown in Figure 1. Mask A had the largest aperture thus providing a smaller depth of field while Mask C has the smallest aperture, which provided a larger depth of field. Mask B's aperture fell between that of Masks A and C.

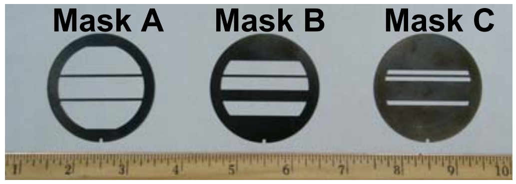


**Figure 1: Aperture Masks**

Data was collected at three radial positions across the center of the jet. The zero position represents the center position of the jet while the other two positions were located ±25.4 mm (1.0”) off the centerline. All measurements were located at 27.9 cm (11”) downstream of the nozzle exit. Each aperture mask was used with each lens configuration to take measurements at all three positions in the jet. This resulted in six lens/mask configurations measuring at three locations combining for a test matrix of 18 total test points. The actual test matrix used can be seen in the previous work of Davis and Disimile.[7]

Table 1 shows how changing the aperture masks and/or lens configuration affects the maximum diameter size that the PDA system could measure. These maximums were generated using the software provided by the PDA system manufacturer. The column to the far right indicates the percent change from the previous configuration (directly above it). From this table it can be seen that the receiving optic’s aperture mask, as well as the focal length of the lenses will change the diameter range that the system can effectively measure.

**Table 1: Maximum Configuration Diameter**

| Transmitting Lens | Receiving Lens | Mask | Max Diam. (μm) | Max Diam % Change |
|---|---|---|---|---|
| 310 mm | 402.5 mm | A | 193 | 0 |
| 310 mm | 402.5 mm | B | 313 | 62 |
| 310 mm | 402.5 mm | C | 751 | 140 |
| 1000 mm | 1000 mm | A | 827 | 10 |
| 1000 mm | 1000 mm | B | 1340 | 62 |
| 1000 mm | 1000 mm | C | 3213 | 140 |

## RESULTS

The experimental results are displayed here in the form of tables and charts. For all of the data presented, it was thought that the zero position represents the center of the spray. The other two positions are ± 25.4 mm relative to this position and extend radially outward along the centerline of the jet. It will be shown later that what was thought to be the zero position for this experiment was not actually in the center of the jet. The term ‘Long Lenses’ refers to the measurements using the 1000mm lenses, and the term ‘Short Lenses’ refers to the cases when the 310mm and 402.5mm lenses were used.

### *Velocity Measurement Effects*

Since the measured drop velocity is only a function of the Doppler frequency and fringe spacing, the lens/mask configuration should not pose a direct effect on the velocities measured. However, since each data sample was validated on the signal for all three velocity components and the diameter, an improper lens/mask configuration could have a slight indirect effect on the measured velocities. This is due to the concentration difference and a bias toward larger or smaller drops (smaller drops tend to move faster than larger ones). Figure 2 presents the mean streamwise velocities for each configuration for each of the three positions within the jet. At the -25.4 mm and 0.0 mm positions the velocity data is grouped within ± 7%, while the velocity data at the +25.4 mm position has a much larger spread.

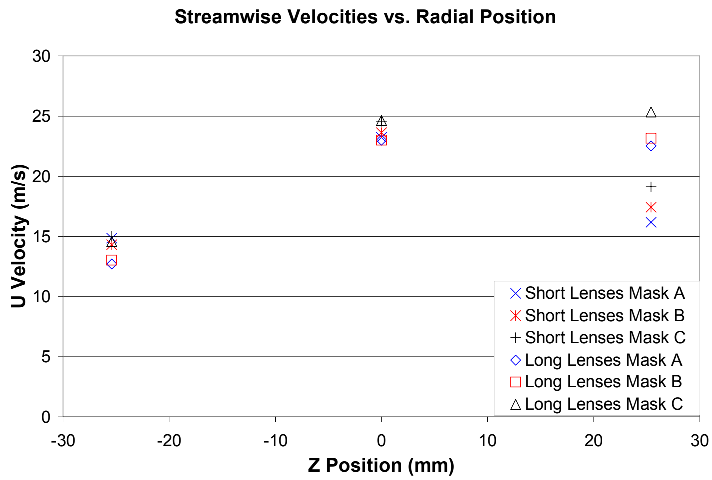


**Figure 2: Mean Streamwise Velocities for Each Configuration**

It should also be noted that the velocities measured at the +25.4 mm position are much higher than those measured at the -25.4 mm position. Assuming that these two positions are the same distance from the jet's centerline, the velocities measured should be relatively equal. Two main factors are most likely the cause of the discrepancy between the +25.4 mm and -25.4 mm positions and the scatter in the data at +25.4 mm. The first cause is signal attenuation due to the dense spray pattern. At the +25.4 mm position the transmitted and received signal must pass completely through the center of the jet thus attenuating the received signal. The second cause can be contributed to a mis-positioning of the measurement volume. The zero position which was initially thought to be on the jet's centerline, was determined to be off center, thus the velocities at the radial positions would not match. The second cause will be investigated later when a complete nozzle characterization has been completed.

*Diameter Measurement Effects*

PDA systems measure drop diameter by actually measuring the Doppler signal reflected, or refracted from the drop using two or more separate photo detectors. The diameter measurement is then formulated using the phase shift between the measured Doppler signals as well as knowing the distance and angle between the photo detectors. Unlike velocity measurements, the lens/mask configuration changes parameters in the diameter size relations such that the diameter dynamic range of the PDA system is increased or decreased. In turn, the diameter measurements rely heavily on the user's choice of the lens/mask configuration.

An important indicator that aids the PDA system user to verify if the physical parameters of the system meet the range of measurements actually collected is the histogram. The histogram shows the frequency distribution of the collected drop population. However, the user should not rely on this tool alone.

If a relatively large amount of data was collected at the maximum diameter set by the physical constraints of the system, then the physical properties of the system (lens/mask configuration) were not optimally configured. Figure 3 shows an example of a histogram in which the lens/mask configuration was improper. The vertical red line in Figure 3 (and Figs. 4 and 5) represents the arithmetic mean diameter. The measurement shown in Figure 2 was taken in the -25.4 position in the jet with the short lenses/Mask A configuration. Referring back to Table 2 the maximum diameter that can be measured for this configuration is 193 µm. The extreme of the abscissa of Figure 3 is set to this maximum diameter. In determining if the diameter histogram is acceptable, one should observe the number of samples collected at the maximum cut-off diameter. It can be easily determined that the configuration used for Figure 3 was not optimal since a large amount of data was measured at the maximum cut-off diameter. This suggests that the drop diameter range is beyond the dynamic range of this configuration.

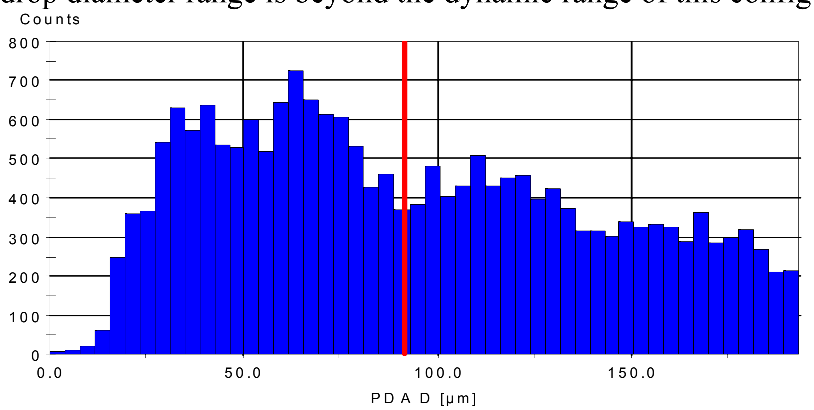


**Figure 3: Diameter Histogram, Short Lenses/Mask A, -25.4mm Pos.**

Figure 4 shows the histogram of the measured diameters acquired at the +25.4 mm position of the jet, when an optimized optical configuration (i.e., long lenses/mask A) was used. Again the extreme of the abscissa in Figure 4 is set to this maximum diameter for the given configuration found in Table 2. It can be seen that the frequency of measurements tapers off toward the maximum diameter and not a single measurement was acquired at this maximum. This could possibly indicate a proper lens/mask configuration.

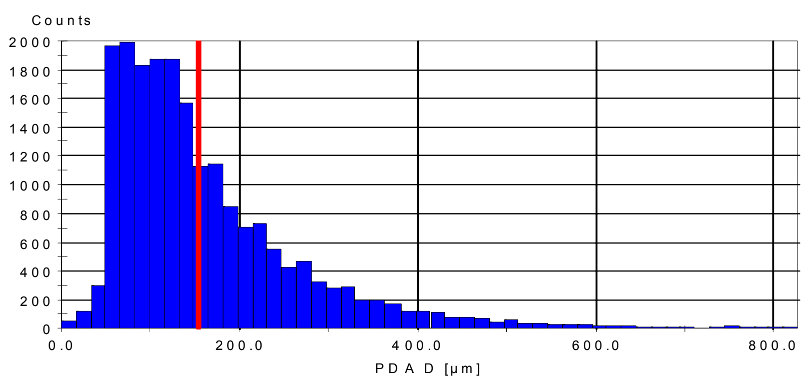


**Figure 4: Diameter Histogram, Long Lenses/Mask A, -25.4mm Pos.**

However, it cannot be readily determined that a low drop count recorded at the maximum cut-off diameter indicates an optimum configuration. The reasoning for this can be seen in Figure 5 where the extreme of the abscissa was not set to the maximum cut-off diameter but rather the maximum diameter that was actually encountered during experimentation. Figure 5 clearly indicates that no diameters were measured past approximately 830 µm. However, for the given configuration (long lenses/Mask C) the maximum diameter that could have been measured was 3213 µm. Therefore solely using this reasoning of no data cut-off due to configuration limitations, the lens/mask configuration can be determined to be appropriate. It will be later shown that the configuration used to obtain Figure 5 was not the proper configuration for the given measurement condition, and the diameter measurements were biased toward the larger diameters. Therefore, a more reliable method to help select the proper lens/mask configuration is needed for each application.

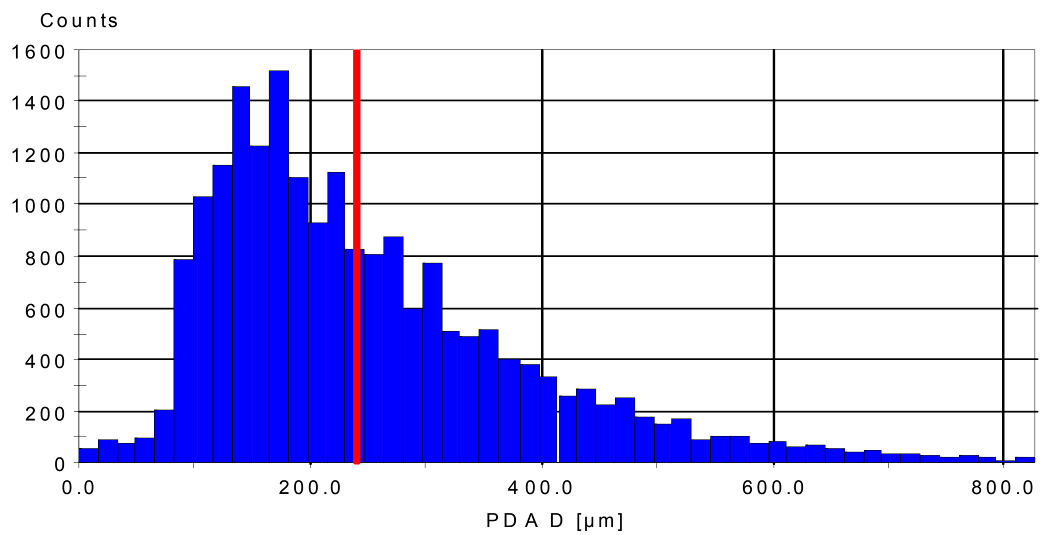


**Figure 5: Diameter Histogram, Long Lenses/Mask C, -25.4mm Pos.**

Measured Sauter mean diameters for all six lens/mask configurations at all three positions in the spray are shown in Figure 6. From an examination of position 0.0 mm it can be noted that the long lenses with both aperture Masks A and B are both measuring Sauter diameters relatively close to one another (279 microns ± 3%). Through examination of the Sauter mean diameters measured with the long lenses and aperture Masks A and B at the edges of the spray the following measurements are observed. At the lower edge of the spray (-25.4 mm) Sauter mean drop diameters were determined to be 330 microns ± 1%. Likewise at the positive edge the diameter was 295.5 microns ± 6%.

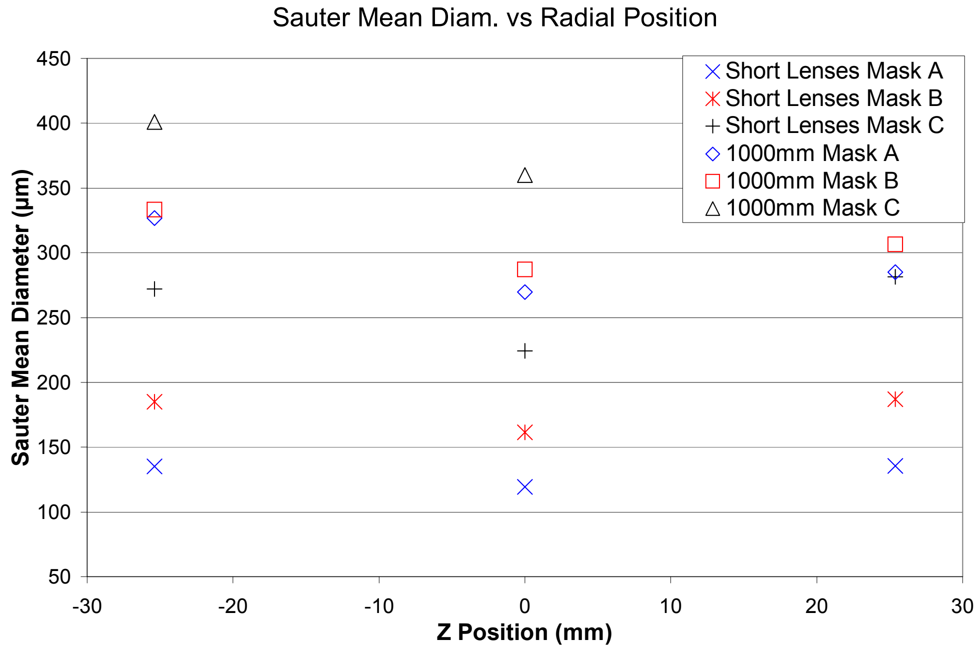


**Figure 6: Sauter Mean Diameters for Each Configuration**

As expected larger drops reside at the edges of the spray and have a corresponding lower velocity, while drops toward the center of the spray are smaller in size and have a higher velocity. At all three positions the Sauter mean diameter increases as the diameter dynamic range of the system is increased. The Sauter mean diameters measured with the remaining four optical configurations were not as closely matched as the long lenses / Masks A and B. The overall spread from the short lens/Mask A to the long lens/Mask C configurations was 66% or on the order of approximately 250 microns. This gives further insight into which optical configuration is optimal for the given measurement condition.

A similar plot displaying the diameter concentration or number density (in #/cm$^3$) is shown in Figure 7. Here the short lens/Mask C and the long lens/Masks A and B configurations were all measuring relatively close to the same diameter concentrations, while the remaining optical configurations showed much different values. In general, the diameter concentration decreases with increasing diameter dynamic range of the system. At all three positions it can also be noted that for any given set of lenses Mask C recorded much lower diameter concentrations than with Masks A or B. This is intuitive since examination of Figure 1 shows that Mask C blocks considerably more light than Masks A or B. Also it can be seen that at the +25.4 mm position the diameter concentration is lower than expected by comparison to the other two positions. This is again thought to be due to signal attenuation caused by the dense spray pattern.

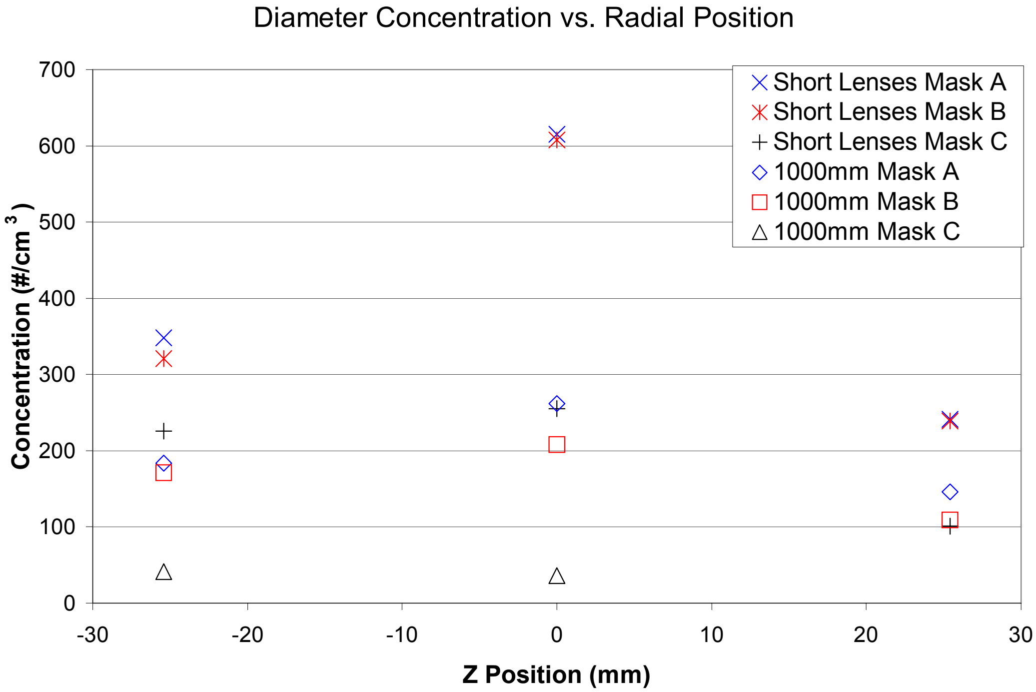


**Figure 7: Diameter Concentrations for Each Configuration**

*Lens/Mask Configuration Selection*

Figure 8 presents a final method of highlighting the best lens/mask configuration for the current PDA application. This method takes into account the bias that the configurations have on measuring either larger or smaller drops, and the arithmetic mean diameter increase. The configuration bias is determined by inspecting the diameter histograms and determining the number of diameters measured below and above 100 μm. This 100 μm limit was chosen in order to best determine the loss of sensitivity for smaller drops. Since the velocity remained relatively unaffected by the lens/mask configuration the velocity is neglected in this method.

Figure 8 displays the percentage change for the mean diameter, number of samples lost below 100 μm, and the number of samples gained above 100 μm between mask/lens configurations, for two separate positions in the jet. The mask/lens configurations were put into order by the maximum diameter of the dynamic range for each configuration (Table 2), least to greatest. Thus, for this case: 1- Mask A, Short Lenses; 2-Mask B, Short Lenses; 3-Mask C, Short Lenses; 4-Mask A, Long Lenses; 5-Mask B, Long Lenses; and 6-Mask C, Long Lenses. The chart abscissa (x-axis) describes between which two configurations the percentages were acquired. The first x position (x = 1 index) indicates the change from configuration 1 (described above) to configuration 2. The second x position indicates the change from configuration 2 to configuration 3 and so on.

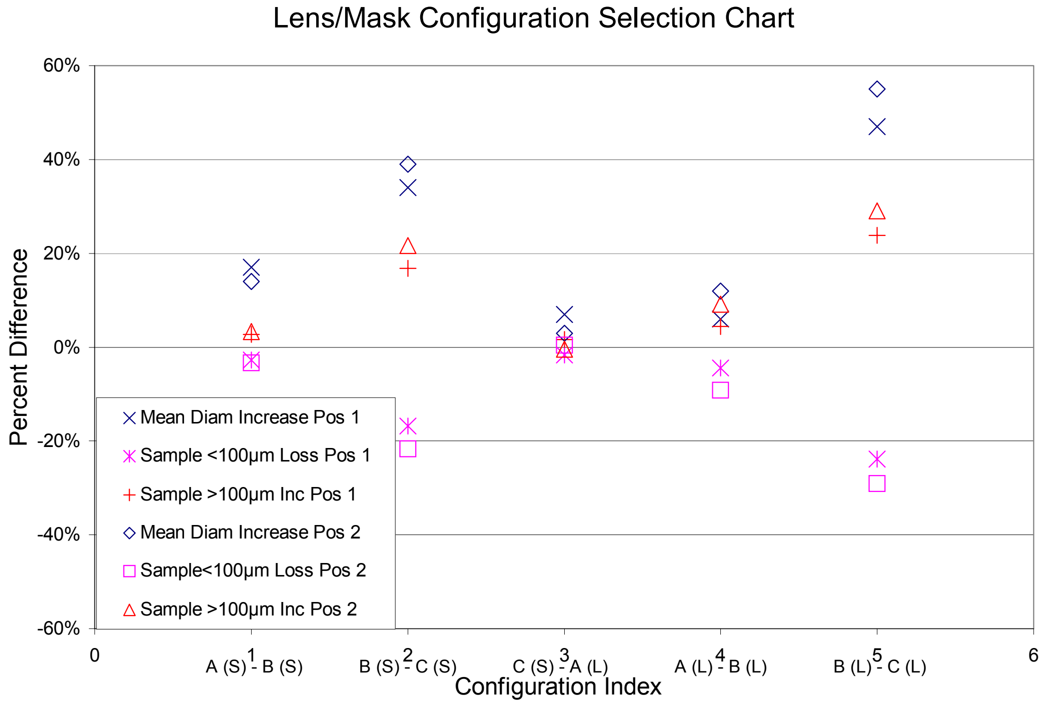


**Figure 8: Configuration Selection Chart**

From Figure 8 it can be observed that the least percentage change in all three plotted values for both positions is at the x = 3 index, corresponding to the change between Mask C/short lenses, and Mask A/long lenses. Therefore, Mask A with the long lenses was selected for the test conditions examined. The reason for selecting the long lens/Mask A configuration was chosen over the short lens/Mask C configuration was two fold. First, the difference between the measurements produced by the short lens/Mask B and the short lens/Mask C configurations (x = 2 index) were much larger than the difference between the long lens/Mask A and long lens/Mask B configurations (x = 4 index). The second reason is not shown in Figure 8 but involves examining the data rate of the incoming measurements. The data rate of the measurements can be of high importance especially when monitoring transient events. The long lens/Mask A provided a faster data rate than the short lens / Mask C configuration which further supports our selection of an optimal optical configuration.

*Suppressant Nozzle Characterization*

After the optimal optical configuration was chosen using the method described above, a full spray characterization was completed for the two-phase (air/water) nozzle. The suppressant spray nozzle used in the present study was a dual-fluid, solid cone nozzle patented by the Navy as a Liquid Atomizing Nozzle, under the patent number of 5,520,331. Based on preliminary PDA measurements it was decided to reverse the gas liquid entrance locations as opposed to the specifications listed in the patent. The full characterization includes measuring drop diameter and three dimensional velocities at several downstream distances. The downstream distances measured included 8”, 10”, 12”, and 14”.

Figure 9 shows the measured spray pattern in the u-v plane and the corresponding arithmetic mean diameters at each location. This plot provides a representation of not only the velocity and diameter profile across the jet but also how the jet develops downstream. The arrows represent the u-v velocity vectors at the given location while the circles are representative of the droplet diameters.

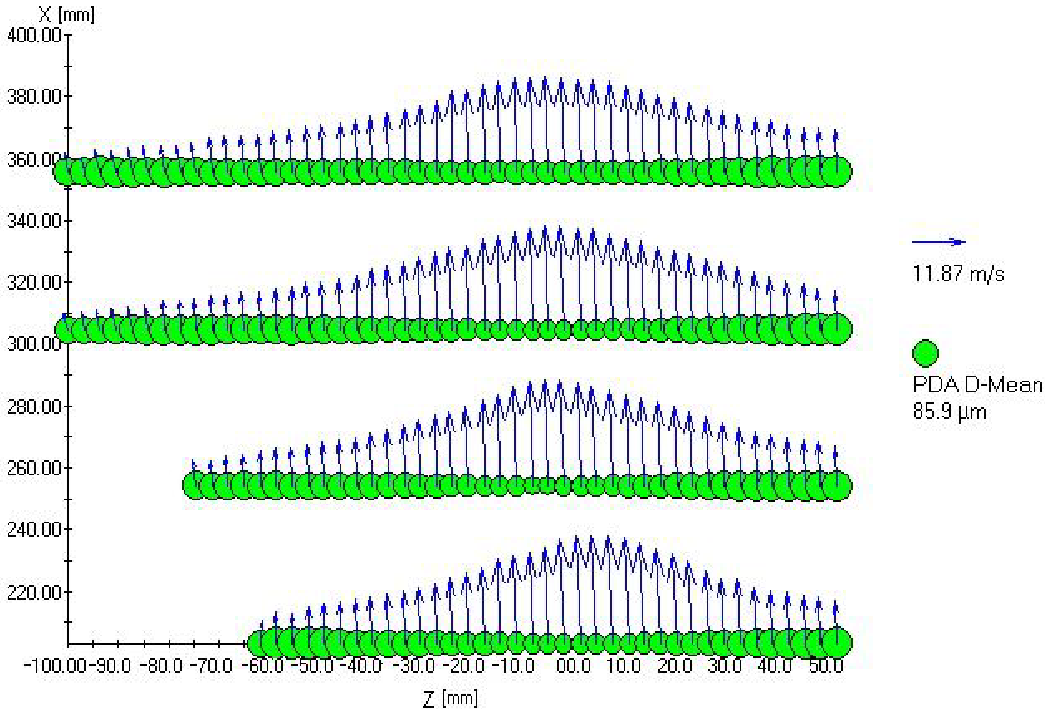


**Figure 9: Nozzle Characterization**

The higher the velocity the longer the arrow or velocity vector, in turn, large circles represent large diameters. It can be seen that at any downstream location the droplet velocity is highest in center position of the jet where the droplet diameter reaches a minimum. From the center outward, the droplet velocity follows a Gaussian distribution decreasing outward. It follows that when a decrease in the droplet velocity is evident the droplet had a larger diameter. This type of characterization can be of great importance in droplet transport models and shows how useful the PDA technique can be in spray research.

Figure 10 shows the streamwise velocity profile 11" downstream of the nozzle exit. This data was measured with the optimum optical configuration selected above (long lenses/mask A). The measurements taken for the examination of the optical configuration shown in Figure 2 were overlaid on this nozzle profile to confirm the location of these measurements. In doing this it was observed that the three points measured above, matched the profile within 7% if the position of the three points was corrected by –9.5 mm. The data was also compared in the same manner for the arithmetic and Sauter mean diameters and diameter concentration with all comparisons suggesting that all three positions were -9.5 mm off the location they were originally we thought to be. Therefore, it can be confirmed that the measurements presented for the investigation into the optical configuration were actually –9.5 mm off their stated values. This explains why the velocity and diameter data at the +25.4 mm position did not match that measured at the –25.4 mm position. So it can now be said that the data that what was thought to be the +25.4 mm position was higher in velocity due to a mis-positioning of the measurement volume in the jet. Now only the spread in the velocity between configurations at this position (shown in Figure 2) is accredited to the signal attenuation of the dense spray pattern.

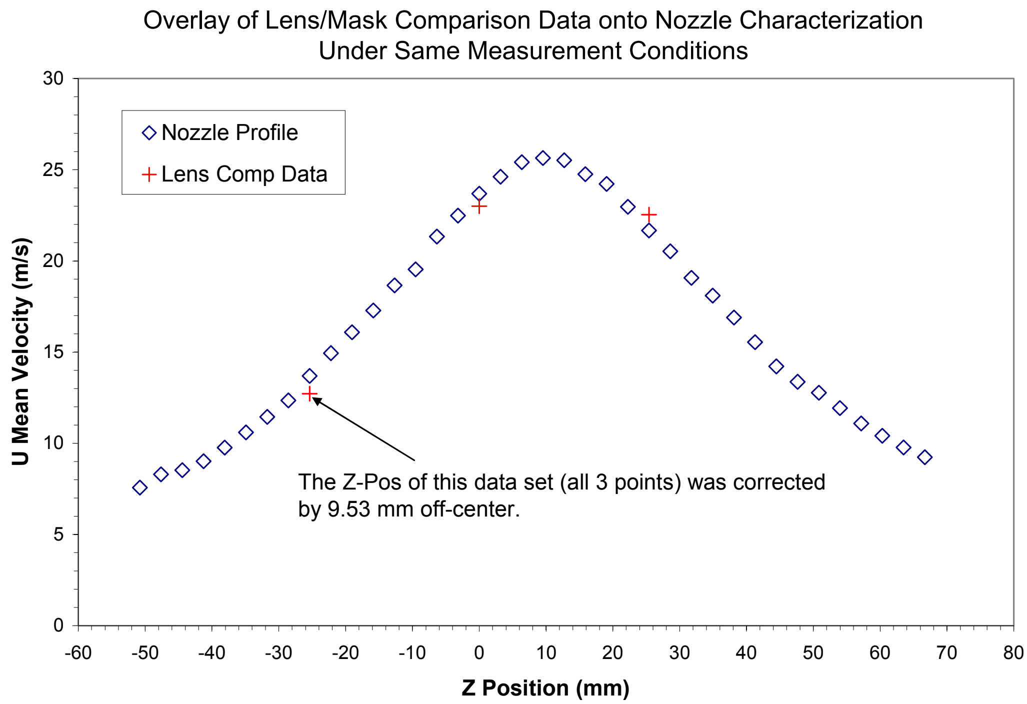


**Figure 10: Lens/Mask Comp. Data Overlay**

## ERROR ANALYSIS

Several parameters can cause error in both the measurement of drop velocity and size using a PDA system. The biggest source of error using laser scattering measurement techniques comes from the Gaussian intensity distribution of laser light beams. These Gaussian effects, sometimes referred to as measurement volume effects can cause a considerable bias in the diameter measurements for any drop over 1/3 the size of the measurement volume.[7] Therefore one might ask if the difference reported in the diameter measurements is due to the Gaussian effect. The biggest concern would then be directed at the how the size of the measurement volume changed for each lens/mask configuration. The Gaussian effects can only be ignored in this paper if the measurement volume size remained relatively constant over the range of lens/mask configurations and only comparisons between diameter measurements are reported rather than absolute drop diameters.

Since the mask is attached to the receiving optics only, the measurement volume size does not depend on the aperture mask used. Therefore during the present experiments the measurement volume size only changed between lens configurations. For all configurations using the smaller lenses the measurement volume's size was reported to be 150 microns in diameter. This changed to 260 microns for configurations using the long lenses. In turn, the Gaussian effects could be biasing any drop over 50 microns with the smaller lenses and 86 microns for the longer lenses. Despite this difference, the fact that the diameter measurements between the short lenses with Mask C and the long lenses with Mask A were in close agreement gave us confidence that the Gaussian effects can be ignored if the diameter measurements are taken as relative measurements and not absolute.

The repeatability checks indicated a maximum error of ± 2% for all quantities measured. The repeatability measurement shows that nozzle fluctuations, user error setting experimental parameters, among other equipment and user errors are all relatively low.

Another error causing concern is the laser power output and the photo detector amplification settings. To evaluate the impact of laser power a large range of laser powers were used during the drop velocity and size measurements. It was shown that the velocity measurements can differ up to 5% and the arithmetic mean diameter by up to 12% if a less than optimal laser power was used. However, these percentages were taken from the extremes of the laser power range and in actuality as long as a laser power was chosen to be within 50 mW of the power required for accurate measurement this percentage decreases to less than 2%. Since the diameter measurements leveled off to a nominal value as the high voltage was increased, it is believed that this power level was indeed appropriate. This was also confirmed by monitoring the received Doppler signals using an oscilloscope.

In addition to the possible errors described above, a nominal error of 4% for diameter measurements and 2% for velocity measurements was suggested by the PDA system manufacturer. This is the error associated with the measurement system itself and should not be taken as the sole source of error.

As it can be seen further study is needed to enable the reporting of absolute diameter measurements. Although to date some research has been conducted to explain Gaussian effects, experimental investigations quantifying these effects using standard PDA systems has yet to be reported.

## SUMMARY

Phase Doppler Anemometry can appear to provide very good diameter data during a first inspection. However, upon further investigation it has been shown that the acquired data may have a considerable bias based on the specific geometric configuration. From the present tests it was determined that the Sauter mean drop diameters could be as much as 66% higher than that actually produced by the spray jet. This is of high importance for the input of diameter measurements into droplet transport models which heavily depend on accurate diameter measurements. This paper shows that the researcher could be easily mislead into using an improper optical configuration for PDA measurements thus unknowingly biasing all diameter results. The bias in this data would then be passed on to the model in which it is used thus creating unknown inaccuracies in the model. Therefore, a relatively simple method is presented to help determine the optical lens/receiving aperture mask configuration giving the least bias when the diameter range of the drops to be measured is unknown.

## ACKNOWLEDGEMENTS

The authors would like to thank Mr. Nathaniel McElroy with General Dynamics for technical support on this project.

## REFERENCES

1. Qui, H., and Chin, T. H., "Method of Phase-Doppler Anemometry Free from the Measurement-Volume Effect," Applied Optics, Vol. 38, No. 13, 1999, pp. 2737 – 2742.

2. Gouesbet, G., and Grehan, G., "Gaussian Beam Errors in Phase-Doppler Anemometry and Their Elimination," Developments in Laser Techniques and Applications to Fluid Mechanics, Proceedings of the Seventh International Symposium, edited by R. J. Adrian, D. F. G. Durao, F. Durst, M. V. Heitor, M. Maeda, and J. Whitelaw, Springer-Verlag. New York, 1996, pp. 243 - 259.

3. Sankar, S. V., and Bachalo W. D., "Response Characteristics of the Phase Doppler Particle Analyzer for Sizing Spherical Particles Larger than the Light Wavelength," Applied Optics, Vol. 30, No. 12, 1991, pp.1487 – 1496.

4. Naqwi, A. A., "Optimization of the Shape of Receiving Aperture in a Phase Doppler System," Developments in Laser Techniques and Applications to Fluid Mechanics, Proceedings of the Seventh International Symposium, edited by R. J. Adrian, D. F. G. Durao, F. Durst, M. V. Heitor, M. Maeda, and J. Whitelaw, Springer-Verlag. New York, 1997.

5. Naqwi, A., and Menon, R., "A Rigorous Procedure for Design and Response Determination of Phase Doppler Systems," Developments in Laser Techniques and Applications to Fluid Mechanics, Proceedings of the Seventh International Symposium, edited by R. J. Adrian, D. F. G. Durao, F. Durst, M. V. Heitor, M. Maeda, and J. Whitelaw, Springer-Verlag. New York, 1996, pp. 340 – 353.

6. Davis, J. M., and Disimile, P. J., "The Effect of Lens/Aperture Selection on Phase Doppler Anemometer Measurements," 42nd AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, 2004, AIAA Paper No. 2004-604.

7. Dantec Dynamics, "Laser Doppler Anemometry: Introduction to Principles and Applications," Dantec Dynamics, Publication 9040U5717, Dantec Dynamics A/S, Denmark.