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A Fast Evaluation of PDA Experimental Parameters Using Mie Scattering to Enhance the Measurement Accuracy of Droplet Size Distributions

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Abstract

The Phase Doppler technique, PDA, and its implementation in research instrumentation generally relies on the geometric optics formulation for light scattering to estimate drop sizes from the measured phase differences between Doppler signals from two or more detectors. Although this limits experimental PDA scattering geometries, to those where only one component of the geometric scatter is dominant, the calculations are relatively simple. Although Mie scattering algorithms have been developed to describe the true physics they have the disadvantage of being computationally intensive. The authors have previously developed a Mie scattering program and included a full Monte Carlo variation for particle sizes, trajectories and velocities. Whereas it proved a sound basis to judge the performance of an existing PDA system it would not have been efficient to use it to investigate other potential scattering geometries. The analytical approach described here is very efficient computationally and is intended to investigate the potential of many scattering geometries. All particle trajectories pass through the center of the measurement volume and the transient Doppler signal burst characteristics and amplitudes are output. Any signal processing technique can be applied to these signals but here the time shift technique has been used to measure the particle size and velocity to provide plots of the measurement probability for a given particle size range. It has been found effective even for particles with trajectories near parallel to the fringes. Once a PDA geometric configuration is found to be acceptable, that configuration along with the appropriate characteristics including Mie scattering coefficients are available for the Monte Carlo simulation to then determine a far more detailed and accurate assessment of the capabilities of the selected configuration.

Introduction

Fully documented Mie scattering codes were developed by Wiscombe (1980) that offered improved algorithms with the aim of maximum computational efficiency and robustness compared with those derived by Dave (1968) for large spheres of order 100 microns or more. To make these general codes applicable to fringe-type laser velocimetry (LV) and PDA respectively, then light scattering has to be considered for the interaction of a particle traversing two crossed laser beams.

Meyers and Walsh (1974) produced an analytic simulation of the photomultiplier signals from an LV system designed to provide insight into the probability of making measurements in a transonic wind tunnel. The code later included the Mie characteristics of the polarized light scattered by tracer particles from each of the crossed laser beams and their interference with each other at the PMT photocathode surface, Adrian and Early (1975). Furthermore, Mayo (1975) showed that photo-multiplier signals generated by an LV system are actually triply stochastic Poisson processes and that they could be accurately simulated using a Monte Carlo approach, and processed with frequency domain techniques, Meyers and Clemmons (1987).

Meyers *et al* (2012) published details of a complete redesign of the optics, electronics, data acquisition, and real time signal processing upgrades of the dedicated LV system in the NASA – Langley 14-by 22-Foot Subsonic Tunnel. The objective was twofold: move as many optical components including the laser out of the harsh environment in the plenum surrounding the test section, and replace the dedicated signal processing electronics with systems that could be supported in the future. The LV Monte Carlo simulation program was extensively used to predict and validate the results from detailed investigations. The investigations of the upgraded system were to determine its capabilities, and measurement accuracy. The upgraded system was tested in the laboratory and in a 1x1 meter wind tunnel at coaxial back scatter distances of 3 to 8 meters to match final specifications. The document includes details of each upgraded component, their operation and measurement accuracy, along with a detailed description of the simulation program to establish its simulation accuracy.

Negus and Drain (1982) developed a Mie scattering code for a particle passing through the fringe pattern produced by the crossing of two laser beams. This study was intended to determine the feasibility of a droplet sizing technique based on a laser Doppler system, LV. They evaluated the integrated signal intensity and visibility for different polarization cases and, specifically, for various shaped collection apertures. These were positioned both on and off, the optical axis and in the forward and back scatter directions. However, the bulk of the work discussed in these papers used IBM or Cray main frames for the computations.

Modern desktop computers are readily capable of performing Mie scattering calculations but for the phase Doppler technique, PDA, with complex scattering geometries and multiple detectors, then Mie scattering computations can again be time consuming. For a particle passing through the laser beam crossover then the multiple detectors produce signal bursts that have a time shift in their envelopes and a phase shift in the modulated signal. Details of the time shift technique can be found in, Albrecht *et al* (2002), chapter 9.

The particle size can be related to the phase shift assuming geometrical optics. This method is very attractive for a computational analysis of possible PDA geometries. Sellens (1989) presents a simple derivation for PDA measurements for arbitrary geometries. Dave (1969) compared the Mie scattering results with geometric calculations for large water spheres and showed that anomalies did exist.

The authors began the investigation of the characteristics of a phase Doppler system in 2015. The trigger that started the investigation was the general assumption of the use of the geometric reflection/refraction physics instead of Mie scattering. The question was whether Mie scattering would yield measurement properties that may not be found with the geometric approach. Since the phase Doppler technique is basically a fringe-type LV system with one or two extra PMTs, could the LV Monte Carlo simulation already created be modified to predict the characteristics of scattered light from droplets representative of sprays generated by liquid atomization?

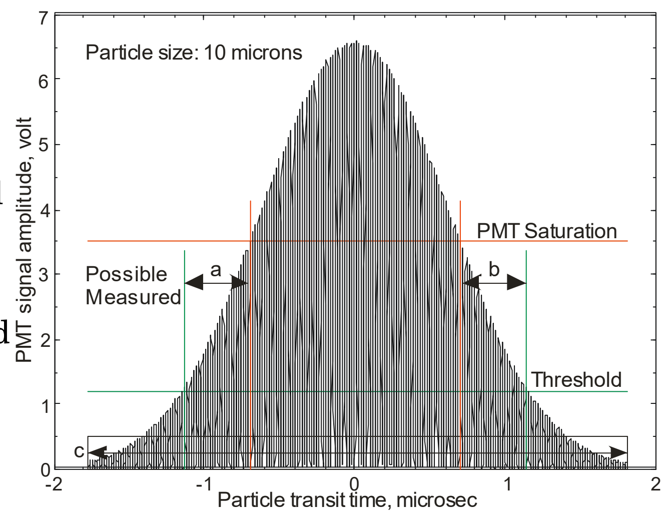
The first task was to determine what needed to be changed, eliminated, or added to the simulation program that would convert the LV simulation to a PDA simulation. This included a review of the signal processing techniques currently in use to determine their accuracy as regards burst signal frequency and their delays. These techniques were added to the simulation along with an approach that used modified techniques developed for LV processing (2012 Meyers *et al*). Since in the simulation the actual particle size is known, a direct comparison of measurement versus actual can be made particle by particle. Testing of various settings of particle velocity, flow angle, and particle size using mono-disperse particles showed that the errors varied greatly among the current techniques, and the most accurate, by approximately an order of magnitude, was the modified LV technique. The key was not to use the Bragg shifted signal itself, but the burst envelope to determine the signal arrival delay between the PMTs (2016 Meyers and Wigley). Further work showed that the PDA was very accurate in determining the size of a single particle. However, looking at the Mie scattering profile, it also became obvious that the size of the measurement volume would have drastic differences among signal bursts that would have PMT voltage levels sufficient to trigger the data acquisition system or to high yielding saturated or clipped signal bursts. Thus, the measurement probability distribution is particle size dependent because of Mie scattering, and could not be assumed to be constant. This error source now became the prime target.

The investigation was limited to a single PDA configuration. With the ability of the Monte Carlo simulation it was possible to isolate the physical characteristics that would determine the extent of particle size and velocity measurement errors. Additionally, particles of a size range from 1 to 25 microns were selected since according to Mie scattering results, the range had the largest range of accepted particles from very low signal burst amplitudes (1-5 microns) to PMT saturation levels (20-25 microns). These uniformly selected particles were launched at random locations identified by their vertical and horizontal flow angles. Four probability areas were determined: (a) particles that missed the measurement volume, (b) particles with insufficient signal strength to trigger the data acquisition system (c) particles that produced scattered light that saturated the PMT, and (d) particles that yielded a measurement. The minimum signal or threshold level has been taken as 1.2 volts, for best accuracy, or 0.5 volts to assess the effects of optical noise on the measurements. All PMTs have a transimpedance amplifier and the maximum output level has been chosen as 3.5 volts. Amplifiers may well be designed to limit the gain but here the concern is with signal saturation within the PMT and hence its lifetime. With this comparison capability, virtually all characteristics, except a change in the PDA geometric configuration, were varied to determine their effects on measurement accuracy (particle size and velocity) and measurement probability distribution. This investigation led to the ability to adjust the acquired measurement probability distribution that would negate the Mie scattering influence, e.g., a uniform probability distribution of particle size launched would yield a uniform measured probability distributions Meyers and Wigley (2018).

The current investigations have concentrated on an increase of the simulation capability to determine the results and effects from extreme characteristics of PDA configurations and particle trajectory. In order to assist in determining the PDA configuration characteristic studies, only the analytic portion of the Monte Carlo simulation was used. The basis of a new analytic program is that it is designed to quickly and efficiently determine the characteristics of signal burst amplitudes and quality. It is able to calculate the Mie scattering coefficients, and produce signal burst plots, and plots of measurement probability distribution estimates. Granted, determining signal burst amplitude is not a sufficient condition to establish the characteristics of a given PDA system configuration or its ability to measure particle velocity and size accurately, but it is a necessary condition. Once a PDA geometric configuration is found to be acceptable, that configuration along with the appropriate characteristics including Mie scattering coefficients are available for the Monte Carlo simulation to then determine a far more detailed and accurate assessment of the capabilities of the selected configuration.

The Analytic Approach

The objective of the analytic program is to provide a time efficient method to investigate the characteristics of signal bursts at their maximum amplitude obtainable with any selected PDA configuration. If a particle size distribution is selected, the program will select a single particle at the smallest particle size of the selected range and launch it along the X-axis with flow angles set to zero. That trajectory would send the particle through the exact center of the measurement volume producing a signal burst at the maximum amplitude possible for that particle size. Trigger level and saturation limits are shown in the plot of the signal burst generated, Figure 1. The measurement volume along the X-axis has a laser power that follows a Gaussian spatial distribution as shown by the signal burst profile. If Figure 1 was rotated clockwise 90 degrees, its shape would match the laser power profile that the particle would face approaching along the horizontal X-axis from the left. Since there is a viewing slit to limit the Y-axis view, the change in laser power along the viewed Y-axis would not change significantly. Thus the measurement probability determination becomes a linear relationship. A particle passing between areas a and b would have saturated PMT signals, and thus be rejected. Particles passing exclusively outside the lines crossing the threshold level would not trigger the electronics, and thus be considered as missed. Particles that pass through areas a or b would trigger the electronics and would be measured, even if the trajectory caused the particle to travel through the low power areas. Since the length of a and b are the only portions that would yield measurements, their length becomes the measurement probability when normalized by the length of c, the viewed portion along the Z-axis of the signal burst, as shown in Figure 1. This approach is the measurement probability method used in the analytic



Measurement Probability = 100*(a+b)/c
= 24.2 percent

Figure 1.- Simulated signal burst for a 10 micron particle

program. The particle size is then incremented by 0.1 micron, and the process is repeated, and continues until the maximum particle size characteristics are determined.

The simulation uses two coordinate systems, one to define the location of the optical receiver, and the second to define the trajectory of the particles. The optical receiver has its origin at the opposite side of the measurement volume than the transmitting optics along the Y-axis, Figure 2.

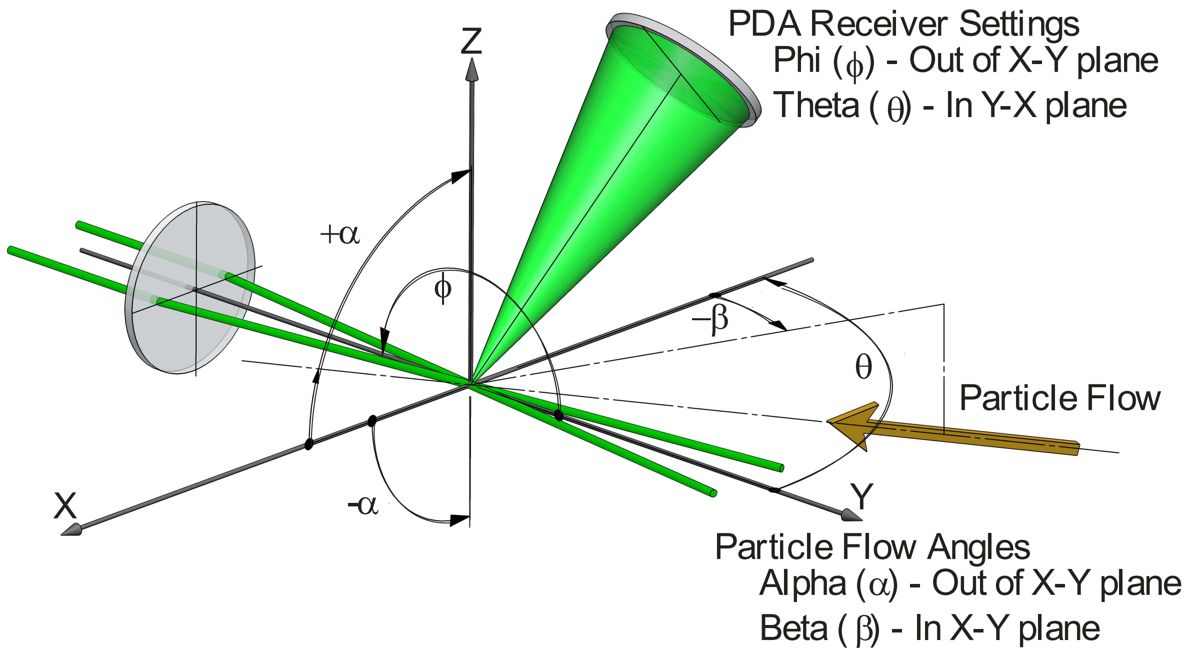


Figure 2.- Graphic view of the two coordinate systems

The scattering angle Phi is the receiver location arced out of the X-Y plane from 10 degrees to 170 degrees. The scattering angle Theta is the receiver location arched from the origin on the Y-axis counter clockwise to the X-axis. Since Mie scattering is rotationally symmetric about the Y-axis, these two angles would allow the determination of the measurable characteristics for all possible scattering angles.

The particle trajectory has its origin along the input side of the X-axis. The launch angle Alpha defines trajectories in the vertical direction with a positive flow angle indicating a particle trajectory going upward. The launch angle Beta defines the trajectory angle within the X-Y plane. For example, if Alpha was set to 42.4 degrees, the analytic program would ignore the angle since the simulation is fixed at an Alpha = Beta = 0.0. However, the Monte Carlo program would pivot the launch point about the measurement volume so that the mean flow angle, assume 40 degrees Alpha in this example, would send the particle through the center of the measurement volume. In this case, the trajectory offset of 2.4 degrees from the mean Alpha would set the trajectory away from the center. Additionally, the random selection of the launch point could also move the trajectory away from the center even if there was no offset.

The analytic program includes the same Mie code as the Monte Carlo simulation that assures that the polarization of scattered light from each input laser beam is adjusted according to the receiver's location, and the interference between the two scattered light beams at the photocathode surface is determined and applied (1975 Adrian and Earley). Also any in-balance of laser power between the two input laser beams is included to determine accurate visibility functions for the signal bursts. The code that determines the collected scattered light energy from each aperture of the receiving lens mask used to measure the delays in the arrival of the signal bursts, is identical to the code in the Monte Carlo code. The prime differences between the two programs is the conversion of collected scattered light energy to photons in the Monte Carlo code to establish the signal burst whereas the Analytic code uses the energy level, and the elimination of all random variables in the analytic code.

Applying the Analytic Code

In order to apply the code in this example, a system configuration needs to be described. The specifications of the system used for all testing for system efficiency using the analytic code, and velocity and particle size measurements testing by the Monte Carlo code are presented in Table 1. This configuration is modeled after a system used by Wigley *et al* (1998) except the system is rotated about the

Transmitter		**Receiver**	
Laser wavelength:	0.5145 m	Focal distance:	0.31 m
Laser power:	0.4 W	Phi:	10 – 170 deg
Bragg frequency:	40 MHz	Beta:	0
Cross beam angle:	6.36 deg	Receiving lens diameter:	0.078 m
Optical loss:	0	Viewing slit width:	100 microns
Polarization:	0 and 90 deg	Viewing mask:	Dantec A
Laser beam diameter:	0.005 m	Optical loss:	0
Focal distance:	0.45 m	Velocity measured:	U-component
Electronics		Particle Characteristics	
PMT quantum efficiency:	0.21	Index of refraction:	1.47 -0*i*
PMT gain:	0.05 M	Particle size range:	1–20 microns
PMT saturation:	3.5 V	Particle launch distribution:	Uniform
Low Pass Filter:	200 MHz	Maximum number launched:	20,000
High Pass Filter:	20 MHz	Mean particle velocity:	50 m/s
A/D Triger:	1.2 V	Standard deviation:	0 m/s
Digitizing sample rate:	1.0 GHz	Alpha mean:	varies
		Alpha standard deviation:	5 deg
		Beta mean: 0 deg	0 deg
		Beta standard deviation:	0 deg

Table 1.- Test PDA configuration specifications

measurement volume by 90 degrees to place the crossed laser beams in the horizontal plane, Figure 2. The viewing mask attached to the collecting lens of the receiver is the Dantec A mask, Meyers and Wigley (2018).

For dense evaporating sprays, as in high pressure fuel injections systems, then a 70 degree scattering angle is considered a prerequisite as it minimizes the length of the measurement volume, to only 40 percent greater than the slit width installed in the receiver. Furthermore, according to the geometric reflection/refraction model, the reflected light components are eliminated and the dropsize estimates are quite insensitive to refraction index changes of the droplets (Pitcher, Wigley and Saffman 1990). This work used both geometric optical and Mie scattering codes, the later based on algorithms detailed by Wiscombe (1980).

Assuming that the PDA system is specified together with a receiver mask designed for a particle range from 1 to 20 microns, then what is the most efficient configuration that would produce the largest measurable particle size range with the highest measurement probability distribution? First, a series of course configurations were input to the analytic simulation to determine where these optimum conditions might occur. The investigation began with the first configuration set with the scattering angle Phi equal to 10 degrees and Theta equal to 0 degrees – i.e. a forward scatter configuration. The angle Phi would then be incremented by 10 degrees in a series of steps that ended at 170 degrees – i.e.. a back scatter configuration. Phi is then reset back to 10 degrees with Theta now set to 10 degrees and the process repeated. This sequence continues until the point where Phi is 170 degrees and Theta is 90 degrees. This complete exercise coarsely develops a complete grid of Mie scattering conditions. The program calculates the Mie scattering coefficients for every 0.1 micron increment in the selected particle size range. The larger the particle the more complicated the Mie scattering functions, e.g., the calculations for a range from 1 to 4.6 microns takes a minute, from 18.7 to 19.7 microns also takes a minute. The calculations from 1 to 20 microns take 12.5 minutes. These timings are for a desktop computer with an i7 CPU running at 3.8 GHz. The three sets of coefficients (one set for each mask window) for the entire range are stored on the computer disk as a text file for later use in either the analytic or Monte Carlo programs. When the run command is given in the analytic program, it takes less than 2 seconds to retrieve the coefficients, calculate the Mie scattering over a 1080x1080 grid on the scattered light collecting lens, integrate the amount of scattered light for each window, and have the results presented as a plot on the computer screen for all 191 particle sizes in the 1 to 20 micron range. The efficiency of this process is given by, in this case, the results for the optimal configurations presented in Figure 3 for three forward scatter angles, and Figure 4 for three back scatter angles.

The optical configuration shown in Figure 3b can be eliminated since these results were the worse of the four options. The results shown in Figures 3c and 3d are nearly equal, including the major loss of probability between 16 and 19 microns due to low light scattered intensities.

The optical configuration data in Figure 3 indicates that Phi = 60 degrees provides greater measurement probability with Figure 3a not having the loss of probability between 16 and 19 microns. Thus, the configuration in Figure 3a should be tested using the Monte Carlo simulation along with the commonly used configuration in Figure 3c. However, the results in Figure 3a also show that the probability trace is much smoother with the Phi = 50 degree setting. Even though the overall probability is less than the 60 degree setting, the smoothness of the 50 degree setting may have an advantage. Thus, the 50 degree setting will also be tested using the Monte Carlo simulation.

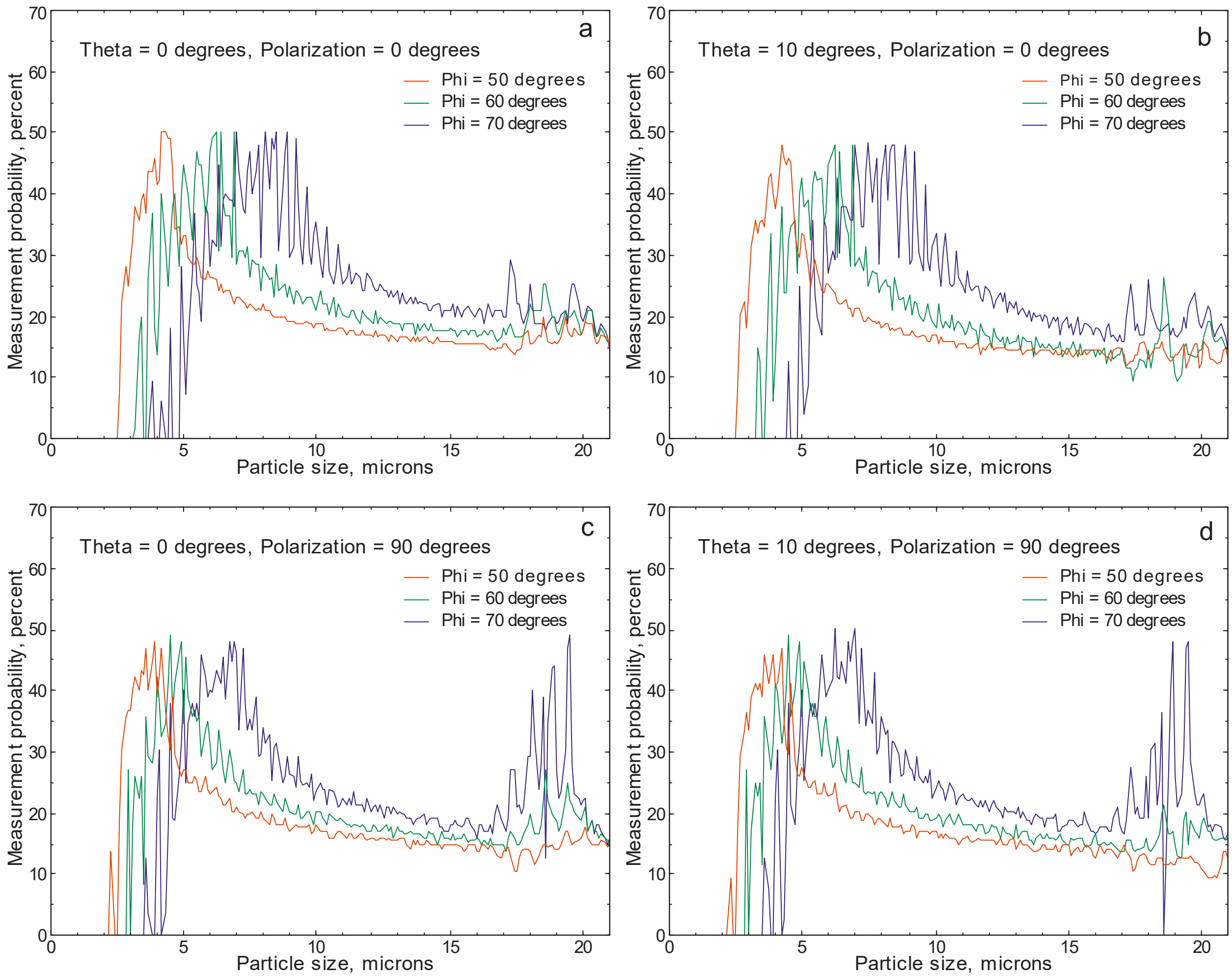


Figure 3.- Measurement probability distributions obtained from the analytical program for forward scatter

Moving to the investigation of back scatter light, Figure 4, the first thing noticed is that the probability distribution above 16 microns is not acceptable for Phi = 150 and 170. Eliminating those results then the greatest probability is presented for Phi = 160 degrees in Figure 4a with particles between 3 and 12 microns, but after 12 microns it falls until 16.5 microns when it rises again albeit with a great deal of oscillation in probability. The most stable is Figure 4d which becomes the greatest average probability above 14 microns. Thus the configuration shown in Figure 4d would be tested by the Monte Carlo simulation.

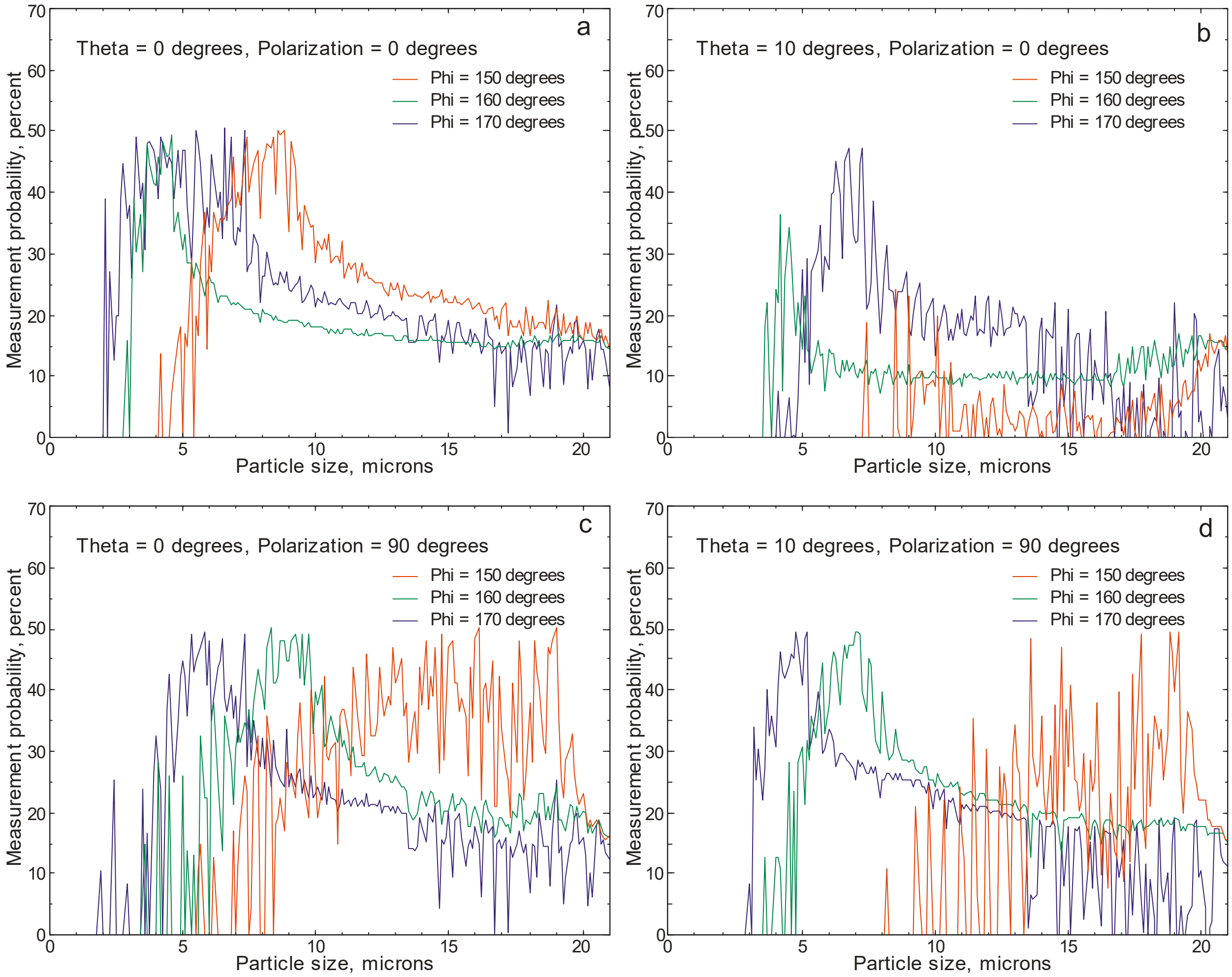


Figure 4.- Measurement probability distributions obtained from the analytical program for back scatter

These results show that in order to obtain the greatest measurement probability, the configuration could be totally different between forward and back scatter. Also, a single configuration may not be the best over the entire desired particle size range. However, the above tests may not provide the final configuration that has the measurement probability because of the many assumptions being made with the analogical approach. To continue further, the configurations selected in Figures 3 and 4 are re-tested using the Monte Carlo simulation which should yield a better accuracy in the choice of configuration. However, the analytic program quickly eliminated configurations that would not be candidates. The above example was based on no physical limitations that may be present in a real test case, but by limiting the selection of Phi and Theta, the most efficient configuration within the limitations can still be determined.

The Monte Carlo Investigation

The primary goal regarding the Monte Carlo PDA simulation was to increase the capabilities of the simulation beyond that reported by Meyers and Wigley (2018). The PDA system used in that report launched particles from a vertical frame with dimensions of twice the width of the optical slit in the receiver, used to limit the measurement volume size along the Y-axis, and twice the diameter of the measurement volume in the Z-axis. The launch frame was always centered on the X-axis. This approach caused approximately 35 percent of the particles to miss the measurement volume due to the random particle launch location and with large flow angles arbitrarily limited to be below 50 degrees.

The objective was to increase the particle size measurements for larger flow angles, while reducing the number of particles that would miss the measurement volume and thereby increase computational efficiency. The first improvement was to shorten the distance of the launch frame from the measurement volume. Instead of launching the particles at twice the radius from the measurement volume centerline, the distance was decreased to 1.5 times the radius. This helped, but the increase in flow angles was still limited.

Since a single launch frame had worked well previously, two additional launch frames were added and located above and below the measurement volume at 1.5 times the radius from the measurement volume. Furthermore, each frame was moved so that the input mean flow angles, Alpha and Beta, would cause the launch frame to slide, within the plane, such that the mean flow angle launched through the center of the launch frame would align its trajectory with the center of the measurement volume. Figure 5 shows the measurement volume cross section together with the three launch frames. The mean flow angle selected here was 45 degrees, with a 5 degree standard deviation. Since 45 degrees is the limit for both the vertical and the bottom frame the particle launch locations align with the center of both frames. While this alignment locates the center of the flow, there are four parameters that determine the actual launch location and the particle trajectory. Since the particles should be launched anywhere within a frame, two uniform random number generators determine the launch location within the frame for a given particle. Likewise, the flow angles, Alpha and Beta coupled with their standard deviations have a particle trajectory determined by two Gaussian random number generators. In this two dimensional figure, the 40 degree example has been randomly selected to launch from a location higher in the vertical frame than the center. The same is true with the 50 degree example where instead of shifting vertically by the random location, it is shifted horizontally in the bottom frame to keep the launch area within a frame for the random, in this case Alpha, flow angle that is greater than 45 degrees. The same process is applied to the Beta flow angle.

In an attempt to determine if this method would allow the launch simulation of large Alpha angles, the Monte Carlo program was tested with particle mean flow angles of 0 degrees, ±45 degrees, and ±90 degrees, each with a standard deviation of 5 degrees. The histograms of measured velocity are presented in Figure 6. The symmetry of the histograms about their mean flow angle indicates that the shifting process described above accurately models the Gaussian shape of the U-component

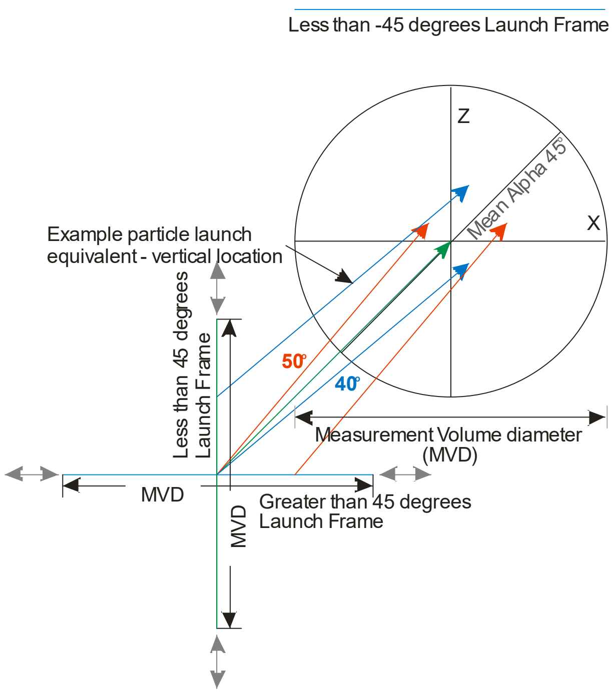


Figure 5.- Particle launch location configuration in the Monte Carlo program example: Mean flow angle: 45 degrees, Standard deviation: 5 degrees

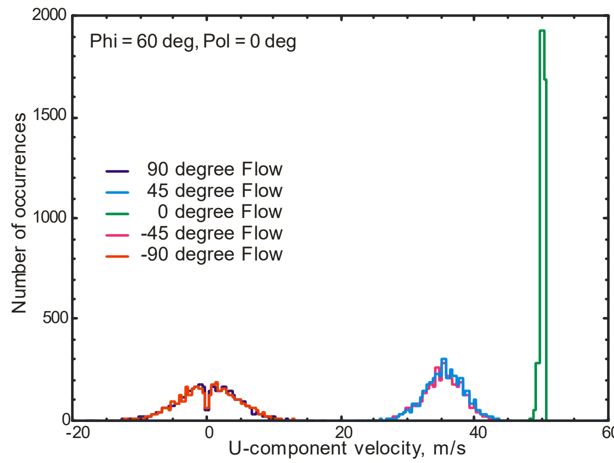


Figure 6.- Measured particle velocity distributions for the test Alpha flow angles: Particle velocity: 50 m/s, Alpha standard deviation: 5 degrees

velocity. That includes the ±45 degree cases where half of the measurements were made shifting vertically (flow angle magnitude 45 degrees or less), and the other half shifting horizontally (flow angle magnitude greater than 45 degrees). Notice that there is a notch in the histogram at both 90 and -90 degrees; the Doppler frequency is equal to zero, so, neither the velocity nor the particle size can be measured. However, acceptable measurements were obtained at 0.5 degrees on either side of 90 degrees.

The next step is to determine how the three most efficient forward scatter configurations identified by the analytic program compare within the Monte Carlo simulation. Additionally, how do the measurement probability distributions compare among the five Alpha test mean flow angles.

Monte Carlo Investigation Results

The objective of this part of the study is to determine if the variation in flow trajectory has an effect on particle size measurement accuracy and/or the measurement probability distribution. The results from the three forward scatter candidates, Phi = 50, 60 and 70 degrees are compared to determine which is the most efficient configuration.

Beginning with the configuration, Phi = 50 degrees with the laser polarization set to be orthogonal to the fringes, the overlay of the measurement probability distributions for all five Alpha trajectories are shown in Figure 7. The effect of the random properties in the Monte Carlo approach in simulating the actual physics in the PDA is clearly illustrated by the random probability oscillations found in Figure 7. They are caused by the small number of measurements obtained, approximately 18 percent of the 20,000 particles launched. However, the overlaid results indicate that the measurement probability distributions are very similar. Also, particle size measurement accuracy was little different except at ±90 degrees where measurements from particles with trajectories between 89 and 91 degrees were

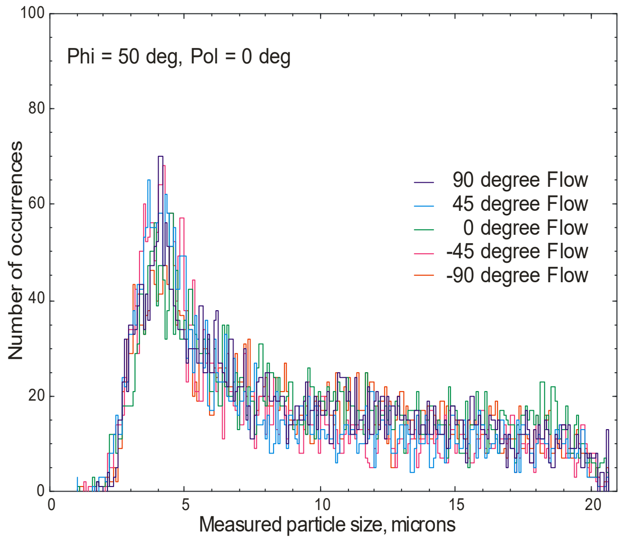


Figure 7.- Overlay of the measured probability distributions Phi: 50 degrees, Polarization: Orthogonal to fringes

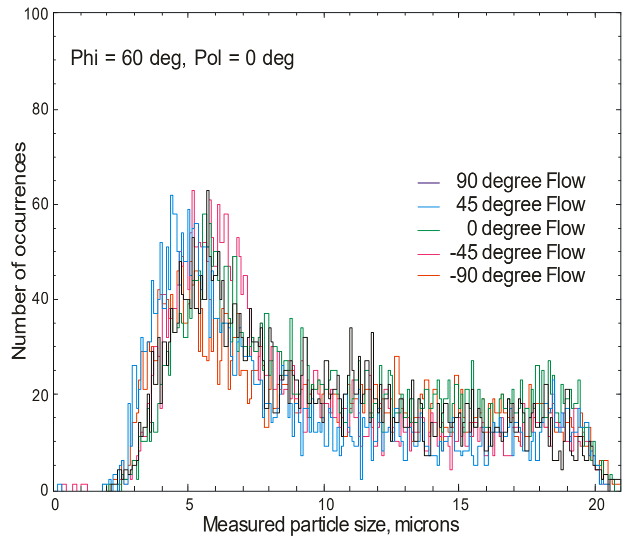


Figure 8.- Overlay of the measured probability distributions Phi: 60 degrees, Polarization: Orthogonal to fringes

compromised by inaccurate velocity measurements. This was due to the small velocity uncertainties becoming significant whenever the U-component velocity became less than two percent of the actual particle velocity. Similar characteristics were found with Phi set to 60 degrees, Figure 8, but with a higher probability.

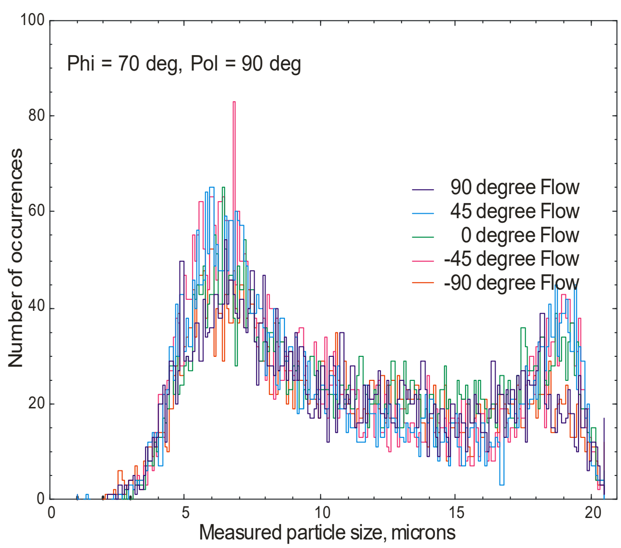


Figure 9.- Overlay of the measured probability distributions Phi: 70 degrees, Polarization: Parallel with fringes

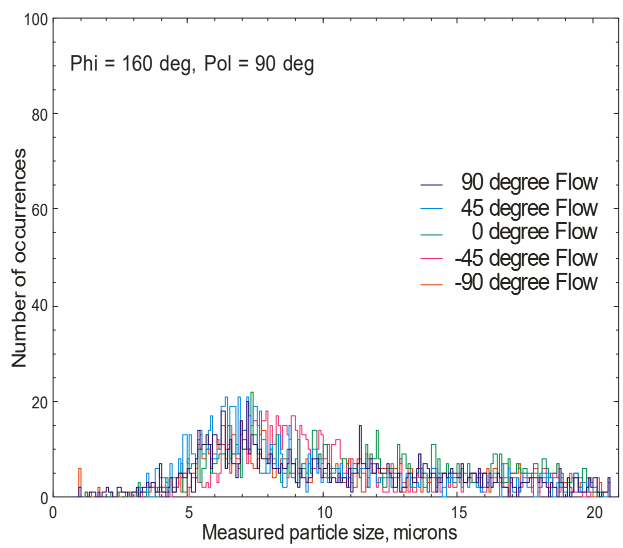


Figure 10.- Overlay of the measured probability distributions Phi: 160 degrees, Polarization: Parallel with fringes

The results obtained from the Phi = 70 degrees with a polarization set parallel to the fringes are shown in Figure 9. Although the measurement probability distribution is different, the random characteristics found in Figures 7 and 8 remain. The measurement probability distribution was found to be quite different in the back scatter configuration, Phi = 160 degrees, especially with the decrease in particles measured, Figure 10. The loss of 26 percent, yielding only 4.7 percent of the launched particles, is attributed to the slit used in the PDA receiver optics to limit the length of the measurement volume. At the low viewing angle, only a small section of the viewed measurement volume contained the full diameter, thus clipping a large percentage of the signal bursts. These clipped signal bursts would yield inaccurate results in the burst time delay approach to signal processing and are thus rejected.

Overlaying the measurement probability distributions from all three configurations for two flow trajectories typically found in spray measurements, 0 and 45 degrees, are shown in Figures 11 and 12 respectively. The probability distributions could be affected by flow angle. These differences cannot be attributed to the random effects that provide the deviations found in Figures 7-10. Since the distributions for the Phi = 60 degree configuration appears to be more stable with the greatest probability, how stable is it? A B-spline fit (40 knot) was applied to all five particle

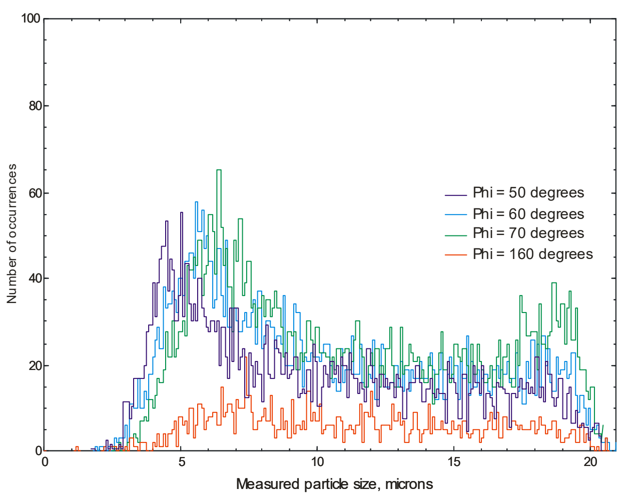


Figure 11.- Overlay of the measured probability distributions Alpha: 0 degrees

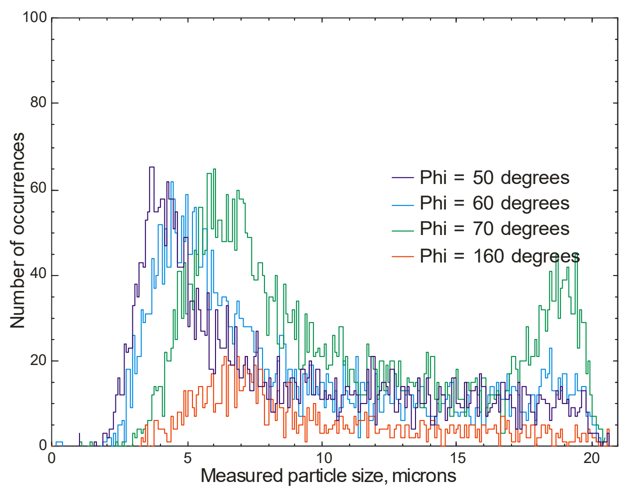


Figure 12.- Overlay of the measured probability distributions Alpha: 45 degrees

trajectories to determine how similar they were, Figure 13. That figure shows that they are not too similar after all. Is it because of the relatively small number of measurements obtained, or was it due to the variation in the flow angles? Assuming that it might be the statistics, the particle size measurements obtained for the five flow angles were combined into a single probability distribution with a B-spline fit also applied for the four configuration results, Figure 14. The correction method developed by Meyers and Wigley (2018) was applied to the Phi = 60 degree configuration and that distribution is also presented in Figure 14. The resulting probability distributions closely match the overlaid distributions shown in Figures 7-10 with far less statistical noise due to the increased number of measurements available. The corrected distribution also matches the uniform distribution of the launched particles. Thus the deviations found in Figure 13 were caused by lack of statistical significance, and not flow angle.

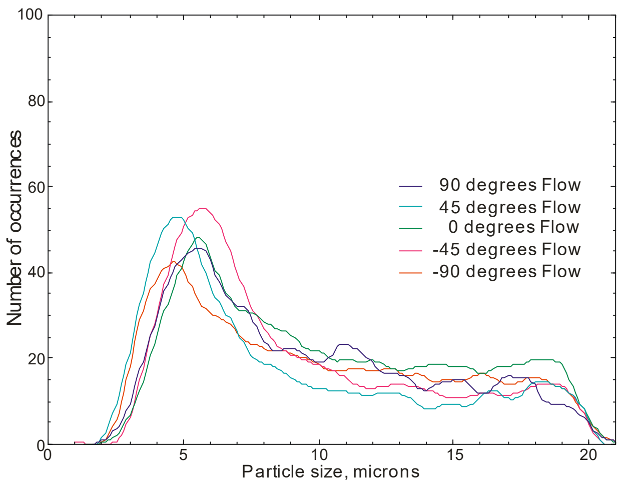


Figure 13.- B-spline fit of the measurement probability distributions for all five flow angles obtained from the Phi = 60 degree configuration

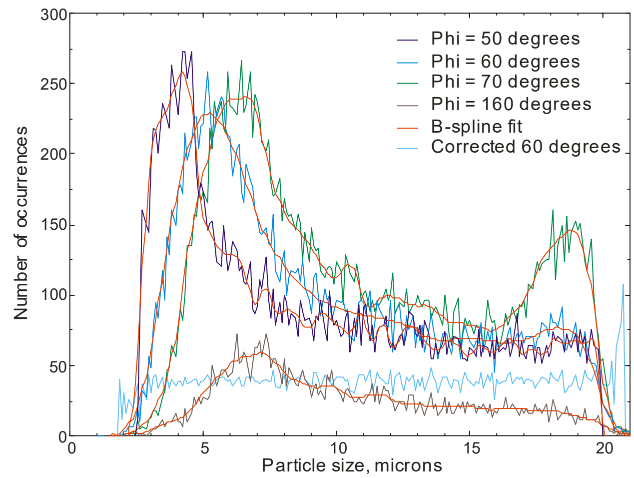


Figure 14.- Measurement probability distributions for all measurements obtained for each of the four configurations studied

Concluding Remarks

The application of the Mie scattering program described by Meyers and Wigley (2018) included a full Monte Carlo variation for particle sizes, trajectories and velocities to evaluate the potential of a phase Doppler system to estimate and correct particle size distributions accurately. It proved to be a sound basis to judge the performance of the specific PDA system. However, the calculations of the Mie characteristics combined with the variables of the Monte Carlo approach would have made it highly time consuming to use for the investigation of other scattering geometries. The analytic program obtains its estimate of measurement probability by launching one particle for each given size through the exact center of the measurement volume to produce signal bursts with the maximum amplitude possible for that particle size. That amplitude is then used as the peak of the Gaussian distribution of laser power along the diameter of the measurement volume to determine locations of trigger voltage and PMT saturation. The area between those two limits allows the calculation of an estimated measurement probability for that particle size.

The analytical approach described here is very efficient computationally and has been used to investigate all 170 configurations with two different light polarizations in the coarse selection of all possible configurations. This led to the selection of three forward and three back scatter PDA configurations that were then studied further with the Monte Carlo program.

When potential scattering geometries have been selected, the Monte Carlo program would then be run for an in depth investigation. Since the system specification file and the Mie coefficient files are the same as for the analytical program then the next major variable to investigate is the particle trajectory. A significant improvement to the Monte Carlo program was made by expanding from one particle launch frame to

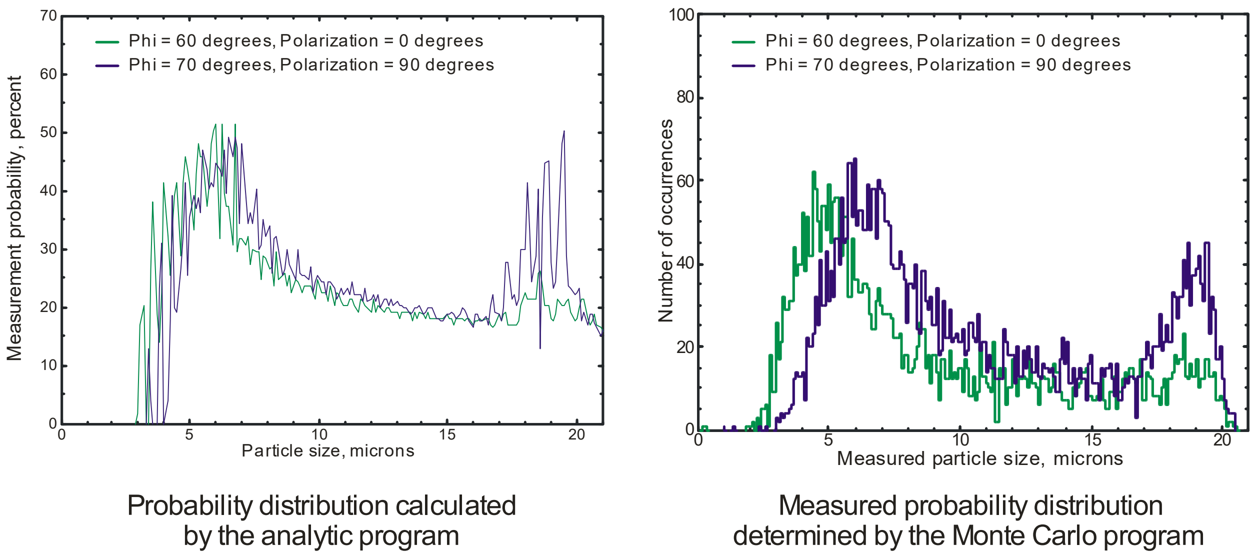


Figure 15.- A direct comparison of the Analytic and Monte Carlo results for the two likely candidates to be used as the selected configuration

three. This allowed the measurement of flows in Alpha and Beta directions to be greater than ±90 degrees, e.g., figure 6 shows measured velocities at ±101 degrees. Loss of measurements at Alpha = ±90 degrees, i.e., for particles with trajectories parallel to the fringe pattern, verifies the measured results.

The overlay of the measurement probability distributions for each of the four optical scattering geometries for five flow angles shows that the PDA's particle size measurements are, within statistical bounds, not sensitive to flow angle. However, in order to obtain accurate measurements, a large number of measurements, at least 20,000 must be made since, for these configurations, only 18 percent met the criteria for a successful measurement. The statistical jitter was reduced by the addition of all of the measurement results from the five flow angles for a given configuration, e.g., Figure 14, shows a more significant measurement accuracy, and a smoother estimate for the B-spline fit. The B-spline fit can then be inverted to become the correction for the measurement probability (Meyers and Wigley 2018), also shown in Figure 14 to yield a uniform distribution, i.e. the same type of size distribution for the launched particles.

The results from the analytic program are very similar to the Monte Carlo results, certainly enough to determine the more efficient PDA configurations. The use of the analytic program provides more information for the user regarding the choice of configuration that would be best for their given application. However, configurations either side the selected configuration should also be analysed with the Monte Carlo program. For example, the prediction by the analytic program for the 50 degree scattering angle is shown to have far less Mie scattering jitter on the measurement probability distributions, Figure 3a. While considering the results from the Monte Carlo program, Figures 11, 12, and 14, they show that the 60 degree scattering angle exhibits lower jitter in all cases. The jitter is in part due to the statistics and part due to Mie scattering. The analytic program only deals with Mie scattering, whereas the Monte Carlo program deals with both. The programs provide the information, the researcher makes the decision. That decision would be finalized by the results from the Monte Carlo program, based on the selections provided by the Analytic program, Figure 15.

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14. ABSTRACT

The Phase Doppler technique (PDA) and its implementation generally relies on a geometric optics formulation for light scattering to estimate drop sizes from the measured phase differences between Doppler signals from two or more detectors. Although this limits experimental PDA scattering geometries to those where only one component of the geometric scatter is dominant, the calculations are relatively simple. This TM describes a fast method to evaluate PDA experimental parameters analytically using Mie scattering that provides a performance estimate of all possible configurations. The best configurations are fully tested using a Monte Carlo simulation to obtain a more accurate capability estimate for each one.

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PDA; Particle size; Mie scattering; Monte carlos

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