Triple Interval Phase Doppler Interferometry: Improved Dense Sprays Measurements and Enhanced Phase Discrimination

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Abstract In this work the authors have added an additional sensor to the traditional Phase Doppler Interferometry (PDI) configuration yielding three independent measures of phase shift between detectors. This seemingly minor enhancement has a profound impact on the limitations of the PDI technique in two important areas: the minimum laser beam diameters and the ability of the technique to discriminate liquid droplets from solid particles.

Phase Doppler measurements can be impacted by reflection/refraction errors in which a droplet’s measured diameter is substantially different from its actual size. This is most critical when small droplets are measured as very large but the converse is possible as well. Consideration for this error source places a major constraint on the minimum laser beam diameter at the measurement volume. The addition of a third independent measure of phase shift effectively eliminates reflection/refraction errors allowing PDI measurements with smaller laser beams than would ordinarily be recommended. The authors demonstrate this ability by measuring the same location of a spray with decreasing laser beam waists. Since the droplet number density limit of the Phase Doppler technique scales inverse to the square of the laser beam diameter, such an optical configuration would substantially enhance the instrument’s performance in dense sprays applications.

For applications such as icing cloud measurements, the ability to discriminate and size only liquid droplets in a mixed-phase environment is an important capability of the PDI technique. The relationship between the phase shifts of Phase Doppler signals can be used to differentiate liquid droplets or other spherical particles from irregularly-shaped solids. The authors demonstrate that the addition of a third independent measure of phase shift reduces the number of false positives (solids measuring as droplets) by a large factor – from 11.7% to 0.33% in one example.

1. Introduction

Phase Doppler interferometry (PDI) is a robust and mature technique for measuring droplet size and velocities in sprays (Bachalo 1980, Bachalo and Houser 1984). One aspect of PDI is the ability to identify and discriminate signals generated by droplets vs. those created by non-spherical particles. In an effort to improve the phase discrimination of liquid water droplets from ice crystals in icing flows the authors have proposed and demonstrated the “triple interval” extension to the standard PDI. By adding a fourth detector to standard three detector PDI configuration the authors have greatly enhanced the technique’s ability to reject signals associated with non-spherical particles and of random noise sources in general. It is the rejection of random noise sources that extends the operation of general PDI to smaller focused laser beam diameters than would ordinarily be recommended.

Far-Field Scattering

In order to understand how triple-interval phase Doppler Interferometry improves on the standard technique it is important to understand the far-field scattering of the laser beams by a droplet during measurement. For practical purposes, the scattering phenomenon may be treated as two superposed Mie scattering fields. As the two fields are created by coherent sources they add in a vector rather than scalar sense resulting in constructive and destructive interference. Figures 1 and 2 visualize the interference patterns at the face of the receiver lens for two different droplet diameters from the same optical configuration (Bohren and Huffman 1983 and Laven 2010).

Due to droplet velocity and/or an induced frequency shift between the beams, the visualized pattern is not static. It rotates nearly about (0,0) from the A detector towards the C detector (clockwise in Figures 1 and 2). Each detector A, B and C collects light over a sub-region of the receiver lens. The integrated signals for each sector are plotted relative to one another through two cycles.
The “pinwheel arms” of the scattering pattern for the 50 μm drop are spaced half as far apart as for the 25 μm droplet. This scaling is the fundamental relationship between diameter and phase shift for the phase Doppler technique. As the diameter increases the spacing between the far-field bands decreases with a concurrent increase in the absolute phase shift between detectors. To first order, the phase shift between two detectors is linearly proportional to the diameter of the droplet and to the angular spacing between detectors.

Figure 1. Intensity of the interference field generated by a 25 μm droplet illuminated by two coherent 532 nm laser beams generating a fringe spacing, δ, of 4.44 μm. The gray circle represents the outline of an f/5 receiver lens. The angle Θ is measured from the centerline between the laser beams and normal to the plane containing the beams. The angle Φ is the elevation out of that same plane. Below the interference field are the intensities integrated over each region plotted through two cycles as the “pinwheel arms” move past the detectors. That signal A leads signal B leads signal C is easily discerned from these plots.

Figure 2. The interference field generated by a 50 μm drop. All other optical parameters are the same as for Figure 1. The scaling of color to intensity between these two plots is not preserved. It may appear that there is a small phase shift between A (blue) and C (green). However, signal A leads signal B which leads signal C. The phase shift between A and B is nearly half a cycle. Therefore, the shift from A to C must be greater than that. In fact, the total phase shift from A to C is more than one cycle in this example.
Phase Validation

Fundamentally, droplet size can be calculated from the phase shift between two detectors. Why then do commercial PDI have more? By adding an additional independent phase shift interval it is possible to extend the size range of the instrument without a loss of resolution while simultaneously enabling a data integrity check referred to as phase validation.

Consider the scenario described by Figure 2. The absolute phase shift between detectors A and C is 415°. However is generally impossible to distinguish a 415° phase shift from 55° making it impossible to distinguish a 50 μm drop from a 6.6 μm drop by a single phase shift alone. Utilizing only two detectors would limit the maximum possible phase shift to 360° and therefore the size to 43 μm for this optical configuration. Anything larger would be mis-measured as a much smaller droplet.

Addition of another independent phase shift allows operation over a much larger measurement range. This independent measurement can be accomplished in one of two ways. A third detector can be added in line with the first two (such as the ‘B’ detector in Figures 1 and 2). This is referred to as three detector “standard” phase Doppler interferometry (simply referred to as “standard PDI” going forward). One may also combine planar phase Doppler which places two detectors in the plane of the transmitter beams with the original two detectors to create a “dual-mode” phase Doppler interferometer. Such an instrument requires either two receiver lenses aligned to the same point in space or, more commonly, a second laser beam pair rotated 90° relative to the first. Even though a dual-mode instrument adds two detectors it adds only one independent measure of phase shift. The absolute value of phase of one detector per laser beam pair is arbitrary. The authors restrict further discussion to standard phase Doppler configurations with the acknowledgement that much of the following work would apply to the dual-mode case as well.

As has already been stated, to first-order approximation the phase shift between detectors is proportional to the diameter of the droplet and to the angular spacing between detectors. Therefore, for three detectors (two independent phase shifts and one arbitrary absolute phase) the following statement should hold true:

\[
\Phi_{AC,Total} / \Phi_{AB,Total} = S_{AC} / S_{AB}
\]  

(1)

Where \(S_{ij}\) is the spacing between the \(i\) and \(j\) detectors and \(\Phi_{ij}\) is the phase shift between those same detectors possibly exceeding 360° (such as \(\Phi_{AC} = 415°\) for the example in Figure 2).

Measurements are always in the range of \(\Phi = [0, 360)°\) but Equation 1 may be used to determine how many cycles the original phase shift experienced. Consider again the example described in Figure 2. For this case \(\Phi_{AB,measured} = 160°\) and \(\Phi_{AC,measured} = 55°.\) It quickly becomes apparent that in order to satisfy Equation 1 \(\Phi_{AB,Total}\) must equal 415° and not 55°. A 6.6 μm droplet would have a measurement pair of (21, 55) which can easily be distinguished from the (160, 415) pair for a 50 μm drop. By adding an additional phase measurement there is no longer any ambiguity between the two diameters.

In addition to extending the size range of the instrument it is possible to use the relationships between the two phase measurements as a validation criterion intended to reject noise and otherwise faulty measurements. Figure 3 schematically represents how this is accomplished. For every droplet a pair of independent phase shifts between detectors is measured. Since phase shift is proportional to droplet diameter, very small drops will have a phase shift pair very near the origin. As diameter increases the expected phase shift pair will follow the blue line up and to the right (the blue arrow denotes increasing diameter). When any phase shift exceeds N•360°, the calibration line will “wrap around” to 0° and continue increasing (a 361° phase shift being indistinguishable from 1°). The first two such wrap-around jumps are illustrated with a dotted blue line in the figure. Theoretically, measurements should fall on the solid blue line. However, real signals contain noise and the scattering response is not perfectly linear. Therefore, an acceptance band around the calibration line is used to validate signals from noise (the light blue area around the line). Depending on conditions, the acceptable displacement may range from 5 to 20°. This would correspond to approximately 0.5-2% of the full scale measurement range. Phase validation of dual-mode PDI operates in a similar fashion with one important distinction. Dual-mode PDI responds to the droplet surface radius of curvature in two dimensions (Damaschke 1998). Therefore the sphericity of the droplet will convolve with measurement error sources to potentially reject droplets that would have otherwise been sized as very nearly their equivalent diameter.
Phase Discrimination

The phase Doppler technique is capable of sizing spheroidal particles so long as they have a different index of refraction than their surroundings. This may include air bubbles in water, water drops in air, glass beads in water, or even molten metal droplets (entirely in reflection). PDI is not, however, capable of sizing irregular particles or crystals. For certain measurement conditions, the ability of the instrument to reject signals originating from irregular solids is of paramount importance. For instance, in icing conditions for aviation certification only the droplet distribution is of interest (e.g. 14 CFR 25 App. C). Though solid ice crystals may trigger the instrument’s sampling system, processing of the signals should ideally eliminate any trace of these particles in the data. In fact, it was the desire to better discriminate ice from liquid droplets that funded the development of this work.

Figure 4 plots the raw phase response for droplets in air, powdered salt crystals, and a mixed-phase environment of liquid water and solid ice crystals. Droplets generate signals very nearly along the theoretical line shown in Figure 3 whereas non-spherical particles generate uncorrelated phase shift measurements that essentially fill the $\Phi_{AC}$ vs. $\Phi_{AB}$ domain. For the mixed-phase case, phase validation accepts only those signals within the valid band. This eliminates a large fraction of the ice signals but not all. Since phase shift pairs of crystals can have any random orientation some fraction of signals will always fall within the phase acceptance band. The goal is to have valid measurements of liquid droplets far outnumber any crystals that may be improperly validated.

The length of the calibration line in Figure 3 is $1.07 \cdot \Phi_{AC,max}$. The fraction of the domain that falls within the phase validation region can then be approximated as:

$$V_{p,2D} = 2.14 \cdot \Phi_{AC,max} \cdot R / 360^2$$

where $R$ is the allowable distance from the calibration line. For $\Phi_{AC,max} = 1,000^\circ$ the fraction may vary from 8.3% to 33% given $R = [5^\circ, 20^\circ]$. This corresponds directly to the fraction of non-spherical particles that will fail rejection through phase validation. Though these particles may be rejected by other validation criteria such as intensity validation (Bachalo 1991) only phase validation is addressed in this work.
Reflection and Mixed-Mode Scattering

To first order approximation; standard, forward-scatter phase Doppler works by responding to the rays of light that have passed through the droplet once before exiting the drop (p1 rays) and being detected by the receiver. PDI can also be used to respond to single internally-reflected (p2) rays in the case of back scatter configurations, or even to externally-reflected rays (p0) in the case of measuring metal balls or droplets. The key is that one scattering mode should dominate all others.

If PDI droplet scattering were actually Mie scattering, the refracted signal in forward scatter would always be dominant. The angle between the transmitter centerline and the receiver is partially chosen for this reason. However, true Mie scattering requires uniform illumination and laser beams ideally have a Gaussian intensity profile. As such the incident intensity of a p0 (reflected/diffracted) ray may be sufficiently higher than that of a p1 (refracted) ray that the far field interference pattern is dominated by the reflected photons. Figure 5 visualizes the far-field p0 interference pattern along with the signals collected on the three detectors (Laven 2010). The pattern may look similar to that of Figures 1 and 2 but it is important to realize that this pattern moves in the opposite direction – up in this case.

Phase validation can be used to reduce or eliminate the impact of improperly sized droplets due to pure reflection errors. Reflected signals will be on- or near the red lines in Figure 6 which lie entirely outside of the blue valid regions.

Problems arise when neither the refraction nor reflection signal is dominant. For mixed scattering the resultant far-field is primarily the superposition of four fields – refraction and reflection from each beam. The resultant interference pattern is highly complex. Figure 7 illustrates the issue. Scattering by pure refraction (Debye Series p=1) is in blue, pure diffraction/reflection (Debye Series p=0) in red, and three different ratios where the two are very nearly of equal mean intensity (green). The result is that mixed-component scattering can generate almost any phase shift pair in the $\Phi_{AC}$ vs. $\Phi_{AB}$ domain. This is similar to the instrument response to non-spherical particles. While phase validation can essentially eliminate reflection-dominant sizing errors, mixed-mode scattering signals can appear anywhere in the domain. It is this concern that limits the minimum size of the focused laser beam diameter (the width of the Gaussian profile) with respect to the droplet distribution. Scattering from larger beams is more nearly uniform for a larger number of drops in a distribution.
Figure 5. Reflection-dominated interference pattern for the same optical configuration as in Figures 1 and 2. The reflection pattern moves in the opposite direction of the Mie pattern – in this case from bottom to top. Since the spacing between the pinwheel arms is quite large relative to the detector spacing, the absolute phase shift from A to B should be quite small. However, since the B signal leads the A signal in this case, the instrument will incorrectly identify the phase shift as large. Note that the color scale of this plot is different than in Figures 1 and 2.

Figure 6. Phase validation and reflection. The blue phase validation bands from Figure 3 are plotted along with the instrument response to reflected signals in red. Phase shifts for reflected signals are negative and therefore start at (0,0) for minimum diameter and decrease down and to the left. Since all phase shifts are recorded on [0, 360) the net result is that reflection first appears in the top right and extends down into the plot as diameter increases (the red arrow). As with refraction signals, absolute phase shifts beyond 360° wrap around about either axis.
Figure 7. Response of PDI to mixed-component scattering. Each dot represents the calculated scattering for a number of evenly-spaced droplets diameters through the measurement range. Scattering by pure refraction (Debye Series p=1) are blue. Scattering by pure refraction/reflection (Debye Series p=0) are red. The green dots plot the results of three different mixed-mode scattering conditions for which the mean p=0 and p=1 fields were nearly equal.

Innovation: Triple Interval Phase Doppler

In this work the authors have added a fourth detector to the standard PDI configuration as shown in Figure 8. In order to compare the performance of the instrument with and without the added channel the geometry of the original three detector sectors was left unchanged.

Figure 8. Figure 1 repeated to include the sector of the lens used for the ‘D’ detector. The phase shift from A to D should be between that from A to B and from A to C for valid signals. The order of the detector labels is not alphabetical to maintain consistency with the nomenclature of standard PDI.

The authors refer to this configuration as triple interval as there are now three independent phase shifts between detectors (the absolute phase of one of the four channels is again arbitrary). With an extra phase shift measurement there are now a pair of validation equations:
\begin{align*}
\Phi_{AC,\text{Total}} / \Phi_{AB,\text{Total}} &= S_{AC} / S_{AB} \\
\Phi_{AD,\text{Total}} / \Phi_{AB,\text{Total}} &= S_{AD} / S_{AB}
\end{align*}

(3)

(4)

Of course, Equation 3 is simply a restatement of Equation 1. Together these equations represent a parametric line in three dimensional space through the origin. As with standard phase Doppler phase validation, a measurement in phase space within a given distance from the calibration line is considered acceptable. However, for triple interval PDI such a region is a tube in three dimensions rather than a rectangle in two dimensional domain. Figure 9 illustrates the validation sub-volume in phase space.

![Figure 9](image)

**Figure 9.** Phase validation in a three-dimensional measurement space. The theoretical calibration is a line through this space starting at the origin that once again “wraps around” as phase shifts exceed 360° on any axis. The first two such wrap-around jumps are indicated with a dotted blue line. The valid region is no longer a two-dimensional subset as in Figure 3 but rather a tube centered on the calibration line. The faces where the tube intersects the walls of the measurement space are color coded to more easily follow the calibration line as it goes through the various cycles. Faces where the valid tube region enter the space are colored green and exit faces are colored dark blue. Were this imaged viewed along the \(\Phi_{AD}\) axis the image would collapse to that in Figure 3.

As with Equation 2 it is possible to approximate the fraction of the measurement domain within the phase validation region. Given that the length of the calibration line is \(1.29\Phi_{AC,\text{max}}\) then the valid fraction is:

\[ V_{p,3D} = 1.29 \pi \Phi_{AC,\text{max}} \cdot R^2 / 360^3 \]  

(5)

For the same 5-20° range for \(R\) this results in a valid fraction of 0.2 to 3.4%. By combining Equations 2 and 5 the relative improvement for rejecting random signals may be evaluated:

\[ V_{p,2D} / V_{p,3D} = 190 / R \]

(6)

For a given \(\Phi_{AC,\text{max}}\) and a range of \(R\) from 5 to 20°, triple interval PDI will accept 9.5 to 38 times fewer random signals such as non-spherical particles than standard PDI.
Reflections and mixed-phase scattering are still of concern for triple interval PDI. Figures 10 and 11 add the expected locations of reflection/diffraction-dominated signals to the valid volume plot from Figure 9. Figure 11 changes the viewpoint parallel to the calibration curve to highlight the separation between refraction- and reflection-dominated signals.

**Figure 10.** Phase validation and reflection in a three-dimensional measurement space. Reflection-dominated signals (red lines) are added to Figure 9. Since reflection phase shifts are negative in all three dimensions, the line for these drops grows from the origin in the opposite direction of refracted signals as diameter increases. The starting point for reflected signals is marked with a large red dot.

**Figure 11.** The calibration and reflection curves in three-dimensional space are all parallel line segments. If one were to view Figure 10 parallel to these lines the calibration and reflection curves would collapse to points. The valid regions about each calibration point would appear as circles. The blue circles are the projections of those validation regions while the red dots denote the expected locations of reflected signals. Once again, the origin of reflected signals is marked with a large red dot. Note that reflection-dominated signals fall well outside of valid measurement regions.
Demonstration of Triple Interval Phase Doppler: Phase Discrimination

The first demonstration of the triple interval PDI technique is improved rejection of non-spherical particles by phase validation. The powdered salt data from Figure 4 was actually acquired with a four detector receiver. As such, the data has three independent phase shift measurements per particle. Figure 12 plots the measured phase shift data from these particles in a volumetric space.

![Figure 12. Measured triple interval phase Doppler data for salt crystals. Non-spherical particles create random phase shifts between detectors resulting in data that fills the three-dimensional domain.](image)

Phase validation can be performed on these data in both two and three dimensions. As none of these signals is from a valid droplet the goal is to reject 100% of the signals. Table 1 summarizes the performance of each technique for a $\Phi_{AC,max} = 1,170^\circ$ and for two validation criteria of $R = 5^\circ$ (red) and $R = 20^\circ$ (black).

<table>
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<th>Standard PDI Phase Validation</th>
<th>Triple Interval PDI Phase Validation</th>
<th>Rejection Increase Factor</th>
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<tr>
<td>False Positives</td>
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<td>348</td>
<td>9.5</td>
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<tr>
<td>(of 7000 total)</td>
<td>816</td>
<td>23</td>
<td>35.5</td>
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<tr>
<td>Measured Rejection</td>
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<tr>
<td>Rate</td>
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<td>99.7%</td>
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</tr>
<tr>
<td>Theoretical Rejection Rate</td>
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<td>96%</td>
<td>99.7%</td>
</tr>
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**Table 1.** Rejection of salt crystals by means of phase validation. Results in black are for a validation criterion of $R = 20^\circ$. Those in red are for $R = 5^\circ$. Theoretical values are based on Equations 2 and 5. As none of these signals was generated by a droplet, the target validation would be zero counts and the target rejection rate is 100%.

As expected the number of false positives (salt crystals not rejected) is reduced by using triple interval PDI phase validation rather than standard PDI. The measured rejection increase factor ranging from 9.5 to 35
times very nearly equals that predicted by Equation 6 (9.5 to 38). The original goal of enhancing rejection of signals due to non-spherical particles is certainly met.

**Demonstration of Triple Interval Phase Doppler: Sprays Data**

As the focused beam diameter is reduced smaller than the droplets in a spray, the fraction of mixed-mode scattering and reflection-dominated signals is expected to increase (Strakey 2000). In order to demonstrate this expectation and to demonstrate the advantages of triple interval PDI the authors built a transmitter capable of delivering beams of varying sizes to the measurement point at the same crossing angle without requiring realignment. Though a series of beam diameters were tested, for clarity’s sake only the results of the smallest and largest are presented here. The focused laser beam waist diameters \(1/e^2\) for these two cases were \(2\omega_0 = 204 \mu m\) and \(2\omega_0 = 51 \mu m\) respectively.

A reduction in beam diameter by a factor of 8 results in an increase in laser intensity of 64. To balance intensity with receiver sensitivity one would normally adjust the photomultiplier tube gain (commonly referred to as the PMT voltage though the gain scales as voltage to the seventh power). However, as with any amplifier, changing the gain would change the amount of noise added to the signal. Instead the authors chose to reduce the laser power to maintain constant instrument sensitivity. All other optical, electrical, and software settings remain unchanged.

Figure 13 plots the diameter and cumulative volume distributions for the demonstration spray. The largest droplets in the spray are approximately 200 \(\mu m\) in diameter – substantially larger than the smallest focused beam diameter.

![Figure 13. Diameter histogram (blue) and cumulative volume distribution (green) for the test spray.](image)

The spray has a Sauter Mean Diameter \(D_{32}\) of 73 \(\mu m\) and a Median Volume Diameter \(D_{v,0.50}\) of 87 \(\mu m\). It was measured with laser beam waists \(1/e^2\) ranging from \(2\omega_0 = 204 \mu m\) to \(2\omega_0 = 51 \mu m\). Measurements were made at the same location in the spray by not adjusting the receiver during the measurements.

Figure 14 presents the standard raw phase data for this spray for the two different beam diameters. The left plot is the data generated with the larger (204 \(\mu m\)) laser beams while the right plots is for the smaller (51 \(\mu m\)) beams. Note in the right plot the larger collection of points between the main clouds. This enhancement is caused by reflection-dominated signals (parallel to the main clouds) and to mixed-mode scattering (randomly distributed).
Figure 14. Measured phase Doppler data acquired at two different focused laser beam diameters. The left data set was acquired with 204 μm diameter laser beams while the right was acquired with 51 μm beams. The data are plotted with a larger marker than in Figure 4. This emphasizes those measurements outside of the main band of valid measurements. Within those bands the points tend to overlap and create a solid black region. Both data sets are composed of 7,000 measurements.

Figures 15 and 16 include the extra phase information from detector ‘D’ by extending the plots from a square into a cube. Figure 16 is viewed along the calibration lines similar to Figure 11.

Figure 15. Measured triple interval phase Doppler data. This is the same data as in Figure 14 plotted to include Φ_AD in an extra dimension. Valid points are still near the calibration line. However, that line now traverses a cube rather than a square. If viewed along the Φ_AD axis these plots will collapse to those in Figure 14.

Figure 16 highlights the increase in reflection-dominated signals as the laser beam diameter is decreased. The right (smaller beam) plot contains clusters of measurements (red) along the predicted locations of reflection measurements in this view. While it is impossible to identify a measurement that is clearly the result of mixed-mode scattering the expectation is that an increase in reflection-dominated measurements should accompany an increase in mixed-mode measurements.
Figure 16. Raw triple interval phase Doppler data viewed along the calibration line. These plots are the same data as from Figure 15. The point of view has been rotated to look along the calibration lines. The theoretical calibration and reflection curves would collapse to a series of points in this view. Markers colored blue are within 10° of a calibration line. Markers colored red are near a reflection line. Black markers are those measurements that are outside of the allowable valid range from the calibration line but cannot be identified with certainty as reflection. These may be noisy valid signals or mixed-mode scattering signals. Either way, they are rejected for the purposes of building a diameter distribution. Note the larger number of red markers in the right plot (smaller laser beam) highlighting the enhanced reflection of this measurement.

Figure 17 is the plot from Figure 14 with the color coding from Figure 16. In this orientation the reflections in the right plot are clear to see. The diagonal cluster of red marks between the main groups of blue marks is one group of reflection-dominated signals. Black and red marks are to be rejected as invalid. However, there are black and red marks on top of- and in line with the blue marks. The measurements would not have been rejected in the absence of $\Phi_{AD}$ data.

Figure 17. Raw phase Doppler data after triple interval validation. The blue, red, and black markers are the same as from Figure 16 simply plotted without $\Phi_{AD}$. Droplets validated by triple interval analysis are a subset of those that would have been validated using traditional phase validation. However in the above plots (especially in the right plot corresponding to smaller laser beam diameters) it is possible to see black and red markers on top of the blue markers. These are measurements that do not satisfy the desired validation criteria but could not have been rejected by normal phase validation.
Extension to Dense Sprays

The authors believe that the triple interval phase Doppler technique will increase the maximum practical number density limit for PDI. Dense sprays PDI data are noisy due to multiple scattering near the measurement volume. Enhanced rejections of random noise is clearly demonstrated in this work. Additionally, reducing the acceptable working beam diameter will reduce the probability of having multiple droplets in the measurement region at a time (coincidence rejections). Since the measurement volume scales as the focused beam diameter squared, an improvement in allowable beam diameter of a factor of three would enable an order of magnitude higher number density. Concurrent with a decrease in laser beam diameter is an expected increase in the number of mixed-mode or reflection-dominant signals. This work has demonstrated that triple interval PDI is able to substantially improve on standard PDI in rejecting such signals.

Conclusions

The authors have demonstrated an improvement to the standard phase Doppler technique that improves liquid/solid phase discrimination, rejection of random noise, and rejection mixed-mode and reflection dominant signals. The improved validation allows the operation of PDI with smaller focused laser beams than would ordinarily be recommended. As such, this technique holds promise for improving measurements both in multi-phase flows and in dense sprays applications.

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References


