Phase Doppler Interferometry Measurements In Icing Clouds Beyond the Traditional 50:1 Dynamic Size Range Limit

C. M. Sipperley*, G. A. Payne, and W. D. Bachalo
Artium Technologies, Inc.
Sunnyvale, CA 94086, USA

Abstract
Numerous applications include sprays or multiphase flows composed of droplets with a size range beyond the measurement capability of any single instrument. This is especially true of clouds which are of great interest to meteorologists and the icing research community. Icing researchers are actively engaged in attempts to characterize, simulate, and ultimately overcome an aircraft icing condition known as SLD – Supercooled Large Drops.

In SLD conditions large drops – hundreds of microns in diameter – may be responsible for significant ice accumulation, but may or may not represent a large mass fraction of the cloud. In order to simulate such conditions, icing wind tunnel operators must be able to measure the droplets in simulated clouds across a large diameter range – from a few microns to over a millimeter. The state-of-the-art is to use several instruments of multiple operating principles across many size ranges. The tunnel calibration is then generated from a blending of results. Although each instrument used may be able to make good measurements in atmospheric clouds, wind tunnel icing conditions are generally run at water mass loadings many times higher than would be encountered in nature. The resultant number density of drops is too high for several of the instruments used in the tunnel calibration process.

The Phase Doppler Interferometer (PDI) is capable of making measurements at droplet number densities that far exceed those encountered in even the densest wind tunnel spray. Additionally, the PDI technique is capable of measuring droplets over the entire droplet diameter range. Unfortunately, no single PDI optical setup can be used to measure this entire size range. Furthermore, the number density of the largest drops may be very low necessitating the use of extremely large beams – a requirement inconsistent with the desire to measure very small droplets at high number densities.

The solution is to operate two separate PDI instruments simultaneously in proximity to one another. Each instrument can be optimized for different, overlapping size ranges. By combining the measurements from both single instruments, a global spray distribution for the entire size range may be generated. The challenge is to accurately measure the volume flux distribution across the measurement range of each PDI instrument. If done correctly, these functions match in the overlap of the measurement ranges.

The authors demonstrate data collected in wind tunnel icing clouds with a dual-range PDI. The instrument itself is fully deiced and aerodynamically shaped and can be mounted inside of a wind tunnel or on the exterior of an aircraft. It is capable of making diameter measurements from 1 μm to 2000 μm – a ratio forty times larger than a standard, single-range PDI.

*Corresponding author: csipperley@artium.com
Introduction

Characterization of the droplets that constitute atmospheric and man-made clouds is important to meteorology and to aircraft safety. Direct measurements of cloud droplets improve the understanding of the physical processes responsible for cloud growth and precipitation. This knowledge is not only important for short-term weather forecasting but may prove invaluable to understanding how the albedo of the Earth’s clouds impacts long-term climate change. Aircraft safety can be improved through cloud characterization by advancing the understanding of icing conditions which may threaten these aircraft. In addition to understanding icing clouds, deice technologies can be engineered in ground- and flight-based cloud simulations. These research facilities also require the ability to characterize the icing clouds generated to ensure consistent conditions for aircraft component icing certification.

In any given mission, or even in a single cloud, researchers may encounter drop size distributions ranging from nucleation in the 1 μm diameter range to rain drops greater than 1 mm. In order to measure the drop size distributions over such a large range, the drop velocity distributions, and the liquid water content (LWC) over many orders of magnitude, cloud researchers have traditionally deployed large suites of instruments – each designed to measure a subset of the information desired – on their flight vehicles. The data from these instruments must then be merged to create a single representation of any given cloud. Adding to the complexity of the task is the realization that a given mission profile may allow for only a single pass through any given cloud.

Icing researchers have similar measurement needs to meteorologists when it comes to cloud measurements. However, they must be able to translate these measurements into meaningful ground- or flight-based simulations that allow for controlled study of ice accretion on flight hardware or development of deice technologies. This poses an additional challenge for the instrumentation as most simulations are operated at many times the LWC of atmospheric clouds. Given that the drop distribution of the simulation is intended to be similar to that encountered in-flight, the only way to achieve the increased LWC is to have a higher droplet number density than actual clouds – and generally beyond the capabilities of several of the flight-based instrument suite.

Of active interest to icing researchers and key to new Federal Aviation Administration (FAA) regulations [1] is the need to measure and the ability of flight hardware to manage supercooled large droplets (SLD). These are icing conditions in which the largest drops may be many hundreds of microns in diameter wherein the temperature of the liquid has dropped well below the freezing point of water. With the addition of a nucleation source, such drops can freeze much faster than a droplet above the freezing point. This has dire consequences for deice equipment not designed to handle SLD. Such conditions have been blamed for the loss of American Eagle flight 4184 on October 31, 1994 resulting in the loss of 68 lives. SLD conditions may also be partially responsible for the crash of Air France flight 447 on June 1, 2009 killing 228.

In the case of American Eagle flight 4184 the National Transportation Safety Board found that SLD conditions created a “ridge of ice” beyond the wing’s deice boot [2] resulting in a violent loss of control including two full rolls before the plane slammed into the ground at nearly 700 km/h. In the case of Air France 447 it is believed that the icing (possibly SLD) conditions overwhelmed the deice capabilities of all three of the plane’s heated Pitot tubes. As of this writing the investigation into the accident is still ongoing. However, in response to this crash the Federal Aviation Administration has issued an Airworthiness Directive that all Airbus A330 and A340 aircraft with pitot probes of the same manufacture as the downed aircraft immediately replace those with a Goodrich Pitot tube that had better demonstrated the robustness to “withstand high-altitude ice crystals” [3].

Unfortunately, the entire range of SLD conditions that may be encountered is difficult, if not impossible, to characterize with the current suite of cloud measurement devices. In fact, it is possible that many of the facilities worldwide that provide aircraft icing certifications may not be able to generate and measure the entire range of sprays as dictated by the enhanced FAA regulations on SLD.

There is a need for new instrumentation capable of operation under extreme icing conditions capable of measuring the drop size/velocity and the LWC across a wide range of size distributions and number densities – including SLD. Phase Doppler interferometry (PDI, also referred to as PDPA or PDA) is capable of measuring these parameters across the entire range of cloud droplet distributions at number densities far exceeding those found in any wind tunnel simulation. Such instruments have been used at several ground-based and flight platforms since the early 1990’s. However, these have generally been traditional PDI instruments limited to a 50:1 dynamic size range. In this work the authors describe a fully deiced instrument combining two PDI instruments and the methodology to rigorously combine the data from each to generate a single diameter distribution and measure of LWC. Such an approach is not only of interest to meteorologists and icing researchers. Any research investigating sprays with a diameter range of greater than 50:1 can benefit from the methodology presented – the ability to rigorously combine the results
of multiple PDI data sets generated by multiple optical configurations spanning multiple size ranges.

State of the Art

Standard instruments of the cloud characterization community have been a pair of instruments designed by Particle Measuring Systems (PMS) in the 1970’s. This includes the Forward Scattering Spectrometer Probe (FSSP) to measure small drops (either 2 to 47 µm or 0.5 to 20 µm depending on configuration) and the Optical Array Probe for larger drops. Designed to operate as a pair, the results from the two instruments are blended to produce a diameter distribution beyond the range of either single instrument.

The FSSP is an intensity-based instrument that relies on the scattering of light proportional to the square of the diameter for small particles in the near-forward direction. Like most intensity-based instruments, it requires frequent recalibration due to changes in laser intensity and/or profile, detector drift, window contamination, etc. At the low droplet number densities expected in clouds, this instrument appears to perform satisfactorily compared to more modern laser-based diagnostics. At number densities greater than approximately 300 drops/cc the FSSP will overestimate the median volume diameter (MVD or D_{0.50}) of the portion of the spray distribution within its measurement range [4, 5]. This number density limit is easily exceeded in ground simulations of clouds.

The OAP uses a shadow-imaging technique to measure droplet diameter. Originally offered with a scanned linear array detector, there are now versions with 2D imaging arrays as well. Unfortunately, investigation of this instrument has revealed variability in the size of the measured diameter as a function of the location of the droplet as it crosses the measurement region in addition to variable depth of field as a function of drop size [4, 6, 7]. Additionally, due to the increased depth of field at larger ranges, large drops splashing off the nacelles of the probe can bias the measurement. Finally, the OAP also has a number density limit as well. Because the OAP is insensitive to drops below 12 µm diameter it is generally capable of making measurements in normal clouds. Cloud drops greater than 12 µm are generally relatively sparse. However, in wind tunnel simulations it’s quite easy to overwhelm the number density limit of the OAP especially under SLD conditions.

Neither the FSSP nor OAP have sufficient heating to keep the instrument windows free of fog and the bodies deiced under high LWC SLD conditions. They also fail to make reliable measurements at the droplet number densities such conditions would produce. As such, tunnel operators generally operate only a subset of their spray nozzles during their tunnel calibration with these instruments and reserve the full LWC condition for component testing and certification.

In most cloud characterization studies, separate instruments are used to measure the liquid water content (LWC) than are used to measure the diameter distribution. In general LWC is measured with the use of a hotwire probe similar to the Johnson-Williams (JW) probe released in 1955 or the constant-temperature King probe invented by PMS in the 1970’s. Both devices rely on the energy required to vaporize the droplets incident on the wire. Recent investigation of these devices reveals that their collection efficiency falls off for droplets smaller than about 10 µm and for droplets larger than 30 to 50 µm [6]. The smallest drops have sufficiently low momentum to follow the streamlines around the wire. For the larger drops it is believed that liquid water stripped from the surface of the wire or drops scattering on the wire before the droplet is fully vaporized may contribute to the lower-than-expected LWC measurements.

Gas phase velocity measurements for flight and ground simulations are typically acquired with Pitot probes. Unfortunately this is yet another instrument that often is incapable of making measurements at the LWC of ground-based SLD simulations. In this case the water may overwhelm the heating capacity of the probes or the vaporization of water may influence the air speed measurements. In either case, the Pitot probes may be run with only a subset of the spray nozzles enabled or in the absence of spray entirely.

Notably absent from the list of instruments above is the Malvern or other ensemble-scattering instruments. The lack of strong gradients, near-uniform velocity distribution of the drops, and the large sample volume of such an instrument would seem to make this an attractive candidate for inclusion in the cloud characterization suite. Even the droplet number densities of the highest LWC SLD conditions should not pose a substantial obstacle to the method. However, since ensemble-scattering instruments are sensitive to droplets along their entire beam path, contamination of the windows will yield biased results. Though there are a handful of these instruments at ground-based test facilities they are prone to window fogging or ice accumulation that make them difficult to use in any reliable manner. There are no available instruments based on this methodology that are compact and de-iced which would make them suitable for operation inside of large ground-based cloud simulations or for flight applications.

Traditional Phase Doppler Interferometry

Phase Doppler interferometry (PDI) is a well-characterized measurement technique [8]. It is a “point” measurement technique that builds droplet statistics and
distributions by measuring the diameter and velocity of individual droplets and generates an ensemble of many measurements.

**DIAMETER MEASUREMENT RANGE**

A laboratory-based PDI may have multiple possible optical configurations. By changing the front lens of the transmitter, receiver, or both it is possible to change the measurement range of the instrument. The same laboratory PDI can be configured to measure drops as small as 0.1 μm to drops as large as 2,800 μm with a simple configuration change that takes minutes. This range spans well beyond the entire size range of interest for cloud and icing measurements.

However, a droplet in the measurement range of the optical setup is not necessarily within the current dynamic range of the instrument. The detectors inside PDI receivers are photomultiplier tubes (PMTs). Along with the intensity of the focused transmitter beams in the measurement volume, the PMT gain (voltage) dictates the smallest drop that will be detectable for a given optical configuration. Increasing the voltage will decrease the smallest drop measurable so-long as it’s within the measurement range of the configuration.

In general, the light intensity scattered in the angles commonly used by PDI scales as the square of the droplet diameter. Increasing PMT voltage may decrease the smallest drop measurable, but it also makes all the larger drops generate more signal as well. Given that PMTs have a finite dynamic range there is a maximum drop size for which the signal strength exceeds the detectors’ linear response (a condition known as saturation). Traditionally this limit has been expressed as a multiple of the smallest drop’s diameter such that the PDI technique is generally considered as having a 50:1 dynamic range in size. Though this may not seem like a particularly large size range it does represent a 125,000:1 dynamic range in the mass or volume of the drops.

**NUMBER DENSITY**

Phase Doppler interferometers can be adapted to make measurements in a range of number density conditions. In dilute flows the laser beam waist can be made as large as desired so long as the laser intensity remains sufficiently high to measure the drops of interest. Large laser beams and a large aperture within the receiver can produce a measurement volume with a characteristic dimension of many millimeters. For dense sprays the probe region can be minimized to avoid coincidence rejections. The laser beams can be more tightly focused and the aperture inside the receiver can be made smaller. For fuel injector applications where the MVD of the spray may be somewhere between 20 and 70 μm the number density limit is in the range of 10^4 drops/cc. In nucleation studies where the MVD may be 3-5 μm the number density limit may be as high as 10^6 drops/cc. Depending on the optical configuration, the PDI number density limit is well beyond that required to measure the most demanding ground-based cloud simulation.

**PROBE VOLUME CORRECTION**

Inherent to all phase Doppler interferometers is the condition that the instrument has an effective sampling volume that increases with droplet diameter. This generally works out to the researcher’s advantage in that most sprays contain substantially more small drops than large. In order to collect a sufficient number of the largest drops for statistical certainty, the total sample size is smaller with this diameter-specific bias than it would be if the instrument responded uniformly to drops of all sizes. However, the raw data has a bias toward larger drops which must be corrected to obtain the proper diameter distribution.

Fortunately, this bias is invertible. The process by which this is done is referred to as probe volume correction (PVC). Essentially, one must determine the cross sectional area normal to a droplet trajectory for which the instrument is capable of detecting a drop of a given size. The major component in this approach is the realization that the effective laser beam diameter is a monotonically-increasing function of the droplet diameter. Rather than go into the details of how the PVC process is executed there is a summary in Chuang et al. [9].

Applying probe volume correction to the raw PDI data allows the researcher to convert droplet counts and arrival rates into device-independent variables such as total flux (liquid volume per time per area), number density (number of droplets per volume), and LWC (mass of water per volume of air).

**FLUX DISTRIBUTION**

The total flux, Φ, is the total volume of liquid per unit area per unit time contained in drops of all sizes that crosses though a unit area at a given location in space. The flux distribution, φ(D) is the diameter-specific distribution of the total flux such that:

\[ \int_0^\infty \phi(D) dD = \Phi \]  

(1)

For finite data sets φ(D) and Φ can be approximated from the data as:

\[ \Phi = \frac{1}{\pi} \sum_{i=1}^{N} \frac{\pi D_i^3}{6} A_i \]  

(2)
where \( N \) is the number of drops in an ensemble, \( T \) is the sampling time, and \( A_i \) is the effective instrument cross sectional area for droplet diameter \( D_i \) as calculated from the PVC process. The discrete version of the flux distribution is a histogram of the flux based on diameter:

\[
\phi(D_j) = \frac{1}{T \Delta D} N_j \frac{\pi D_j^2}{6} A_j
\]  
(3)

where \( j \) is the histogram bin index and \( N_j \) is the number of drops in the ensemble such that \( D_j < D \leq D_j + \Delta D \).

The importance of the flux distribution is that if a PDI instrument is performing well, the flux distribution will be correct for all diameters within the dynamic range of the instrument regardless of whether this range spans a substantial fraction of the distribution of the flow being measured. Restated, any PDI data is “valid” data if we consider it a subranged measurement conditioned on the dynamic size range of the instrument.

An illustrated example will help clarify this point. Consider a spray with a diameter distribution from 1 to 100 \( \mu \)m. Now imagine measuring this spray with two separate, poorly-optimized PDI configurations. The first configuration is optimized to measuring small drops with highly focused beams and a PMT gain set such that the dynamic range of the instrument is 1 to 50 \( \mu \)m. The second configuration is optimized for large drops with large, weakly-focused beams, large fringe spacing, large receiver aperture and \( f/# \), and a PMT voltage set such that the instrument’s dynamic range is 20 to 1,000 \( \mu \)m. We assume ideal instruments that produce perfect measurements within the dynamic ranges.

Neither instrument will do a good job of characterizing the spray in its entirety. Figure 1 plots the diameter distribution of the mock spray along with the distributions that would be measured by each ideal instrument (25,000 random samples from the original diameter distribution in the appropriate ranges). Table 1 summarizes several of the mean diameter statistics that might be used to characterize a spray. Neither measured distribution well represents the overall spray and the mean statistics support this observation.

Table 1. Reduced statistics of the example spray distributions of Figure 1.

<table>
<thead>
<tr>
<th></th>
<th>Spray</th>
<th>Small PDI</th>
<th>Large PDI</th>
</tr>
</thead>
<tbody>
<tr>
<td>( D_{10} )</td>
<td>16.7</td>
<td>14.7</td>
<td>35.4</td>
</tr>
<tr>
<td>( D_{32} ) (( \mu )m)</td>
<td>41.9</td>
<td>30.1</td>
<td>46.8</td>
</tr>
<tr>
<td>( D_{0.50} ) (mm)</td>
<td>51.7</td>
<td>35.9</td>
<td>52.3</td>
</tr>
<tr>
<td>Fraction of Total Flux Measured</td>
<td>-</td>
<td>0.473</td>
<td>0.945</td>
</tr>
</tbody>
</table>

Figure 1 and Table 1 demonstrate a somewhat obvious fact. Measuring a spray with a poorly-optimized instrument will result in poor measurement of global statistics. However, there is still value in such measurements. Figure 2 plots the flux distribution of each instrument along with that of the original spray while Table 2 summarizes some of the diameter-specific statistics. Since these are finite data sets the convergence is not perfect but the trend is apparent.

![Figure 1. An example spray as measured by two poorly-optimized but otherwise ideal PDI instruments. Diameter distributions of the original spray (black), the small-range optimized PDI data (blue), and the large-range optimized PDI data (red).](image)

![Figure 2. Flux distributions of the original spray (black), the small-range PDI data (blue), and the large-range PDI data (red).](image)

Table 2. Diameter-specific statistics of the example spray distributions of Figure 1.

<table>
<thead>
<tr>
<th></th>
<th>Spray</th>
<th>Small PDI</th>
<th>Large PDI</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \phi(40) ) (( \mu )m(^3)/cm(^2)/s/( \mu )m)</td>
<td>337</td>
<td>347</td>
<td>328</td>
</tr>
<tr>
<td>( A_D = 40 \mu )m (cm(^2))</td>
<td>-</td>
<td>0.0065</td>
<td>0.52</td>
</tr>
<tr>
<td>( R_D = 40 \pm 0.5 \mu )m (s(^{-1}))</td>
<td>-</td>
<td>6.7\times10(^{-4})</td>
<td>5\times10(^{-3})</td>
</tr>
</tbody>
</table>
Table 2. Flux distribution and related parameters around \( D = 40 \, \mu \text{m} \) for the example spray and as would be measured by two separate, ideal PDI configurations.

Even though neither ideal PDI configuration can characterize the entire spray, both would accurately capture the flux distribution within their size dynamic range to within finite sampling limits. As shown in Table 2 there is a large ratio in the relative areas that each instrument would be using to measure \( \sim 40 \, \mu \text{m} \) drops. Such a larger area would result in more possible trajectories for these drops to be measured by the large-range PDI. Consequently the arrival rate of these \( \sim 40 \, \mu \text{m} \) drops is substantially higher for this larger setup. However, since the calculation of the flux distribution ratios the number of arrivals by the cross sectional area, both instruments would measure essentially the same value at this diameter range.

Of course, no instrument or measurement is perfect. Real signals and finite ensembles necessarily limit how close to the true spray distribution the measurements can approach.

Multiple Range PDI

In the previous section the operational bounds of the PDI technique were discussed. Even limited by the 50:1 dynamic size range limitation there is a PDI configuration to measure almost any droplet-laden flow. But what happens when no single optical configuration is capable of measuring all of the drops of interest or a PDI is of a fixed-alignment variety that lacks the flexibility to easily change the static measurement range? Such concerns may exist, for example, when measuring sprays produced by in-cylinder fuel injectors. Perhaps the vast majority of the fuel is finely atomized. However, rare large drops may contribute significantly to wall wetting. In paint and agricultural sprays the concern may be extremely small drops that create overspray or drift. Cloud researchers encounter this condition on a regular basis when, as mentioned above, any single mission may include the requirement to measure drops not much larger than the nucleation stage all the way to raindrops.

In a laboratory environment it may be possible to measure the same spray system with two (or more) configurations optimized for different size ranges. For flight measurements this is not an option. In these cases the solution is to fly two completely separate PDI instruments each optimized for a different size range with a substantial overlap between instruments.

Regardless of whether one instrument is used in multiple configurations or if two instruments are used, the result is that the researcher is presented with multiple completely separate data sets which must be merged in a rigorous manner. The key is the realization from the previous section that the flux distribution from any high-quality PDI data is accurate regardless of whether the instrument’s dynamic range was well-matched to the diameter distribution of the flow.

In the diameter subregions outside the overlap sections(s) there is only one measure of the flux distribution. Obviously the combined flux distribution will be identically equal to this value. Within the overlap region one must decide how to merge from one measure of the flux distribution to the other. Experimentation by the authors has shown little impact as to how this process is done. In this work the merging is accomplished with a simple linear weighting of one data set to the other. The cut-in and cut-out thresholds were chosen just inside of the extent of the overlap region.

The example spray and idealized PDI instruments from Figures 1 and 2 can illustrate this process. The dynamic range of the small-size PDI ends at 50 \( \mu \text{m} \) while the dynamic range of the large-size PDI starts at 20 \( \mu \text{m} \). Therefore the overlap region for these data is 20 to 50 \( \mu \text{m} \). Appropriate limits for the merging are 22 \( \mu \text{m} \) and 45 \( \mu \text{m} \) – a 10% step into the overlap region from each direction. Each data set is scaled by a function that scales from zero to unity in the overlap region (in the appropriate direction) and is unity elsewhere. Figure 3 plots the scaled flux distributions for each range along with the merged distribution. Above the flux distributions is the scaling function applied to each data set.

![Figure 3. Demonstration of the merging process for the example spray of Figures 1 and 2. The full-range flux distribution is equal to that of the small-range PDI (blue) below the cut-in value of 22 \( \mu \text{m} \). Above the cut-out value of 45 \( \mu \text{m} \) the flux distribution is equal to that of the large-range PDI (red). In the merge region (black) the flux distribution is equal to the sum of the scaled flux distributions from the two ranges. In this region of the plot the dotted blue and red curves plot the scaled flux distributions. The weighting functions are above the plot on a scale of zero to unity. The](https://example.com/figure3.png)
original flux distributions before scaling are plotted in Figure 2.

The combined diameter distribution is equal to the combined flux distribution divided by the cube of the droplet diameter normalized to unity. From this it’s possible to calculate the Sauter mean diameter, the MVD, or any other reduced diameter statistic. With the integral of the flux distribution (the total flux) and the mean velocity it’s possible to calculate the LWC of the combined set as well. From this it’s possible to calculate the Sauter mean diameter, the MVD, or any other reduced diameter statistic. With the integral of the flux distribution (the total flux) and the mean velocity it’s possible to calculate the LWC of the combined set as well. Any statistic that can be calculated from a traditional PDI data set can be computed from a combined data set so long as the proper PVC area corrections are made and the two sets are merged on a flux-weighted basis. Table 3 illustrates the power of this method. By combining data from two poorly-optimized instruments it is possible to rapidly converge on reduced statistics accurately representing the entire spray with reasonably-sized data sets.

<table>
<thead>
<tr>
<th>Spray</th>
<th>Small PDI</th>
<th>Large PDI</th>
</tr>
</thead>
<tbody>
<tr>
<td>D_{10}</td>
<td>16.7</td>
<td>14.7</td>
</tr>
<tr>
<td>D_{32} (µm)</td>
<td>41.9</td>
<td>30.1</td>
</tr>
<tr>
<td>D_{0.50} (mm)</td>
<td>51.7</td>
<td>35.9</td>
</tr>
<tr>
<td>Fraction of Total Flux Measured</td>
<td>-</td>
<td>0.473</td>
</tr>
</tbody>
</table>

**Table 3.** Reduced statistics of the example spray distributions of Figure 1. Results for the individual ranges are repeated from Table 1. Values from the combined distribution are added for comparison. With only 25,000 samples per range the combined statistics have almost perfectly converged on the theoretical values.

In the case of perfect instruments, there would be no need for a merge region at all. The maximum diameter of the small size range could simply coincide with the minimum diameter of the large. Such a configuration would not be robust with real data. There is always some finite error associated with any diameter measurement. As a percentage of the measurement, this error is always greatest for the smallest drops in a measurement. Therefore the greatest uncertainty in the flux distribution will be at the small end of any PDI data set. Additionally, since there are only a finite number of drops for any given diameter bin (N_i in Equation 3) there will be considerable noise in the flux distribution unless an excessively large sample size is used. A substantial overlap region helps reduce the impact of both these issues.

This need for a substantial overlap region also reduces the flexibility of changing the PMT voltages to better match the spray’s diameter distribution. In the case of using multiple data sets to span a distribution it’s more important that there be a sufficient overlap between the ranges than having either instrument measure the spray optimally. The diameter at which PMT saturation occurs on the smaller range must be sufficiently larger than the minimum diameter on the larger range to have a robust measurement. The overall distribution will take care of spanning the entire diameter of the spray – neither individual dynamic range is solely responsible for this.

**PDI Flight Probe, Dual Range**

As earlier noted, flight applications do not allow the possibility of repeating measurements with different PDI configurations. In order to measure the entire diameter range of all clouds it is necessary to fly two separate PDI instruments. To reduce the complexity of having two separate devices to mount, the PDI Flight Probe, Dual Range (PDI FPDR) packages two complete sets of PDI optics into one package. The measurement regions are separated by 25 mm in the flight direction to reduce any errors associated with asymmetries in the simulated clouds. With a combined diameter range of 1 to 2,000 µm the instrument is capable of measuring the entire range necessary for meteorological and icing research including SLD conditions. Of course, since the instrument is designed for icing characterization it has electric heaters for deicing.

![Figure 4. Photograph of a PDI FPDR during testing at the Icing Research Tunnel at NASA Glenn Research Center. Note the ice buildup on the unheated tripod legs. As a scale reference, the dis-](image-url)
tance from the top of the wing surface to the bottom of the mounting flange is 23 cm.

The goal of the PDI FPDR is to eliminate the need for as many instruments as possible from the current suite of cloud characterization devices and to minimize measurement uncertainties. The diameter range is greater than that of the FSSP/OAP combination without severe number density limitations. Velocity is, of course, part of any PDI measurement. In wind tunnel testing it is easy to seed the tunnel with a cloud of fine droplets that can be used as flow tracers. With the spray bars enabled during a simulation or when flying through clouds there are always enough drops to get good velocity measurements. The only case where researchers must still rely on Pitot tubes is when flying through clear air between clouds. LWC measurements are possible from the combined flux measurement but in the presence of mixed-phase water (ice crystals and liquid water droplets) the PDI FPDR will only measure the liquid drops. Heated icing blades or other instrumentation will still be required to measure the irregularly-shaped ice particles. A companion article in this publication compares the performance of the PDI FPDR to other icing/cloud instruments [10].

Merged PDI Data

Figure 5 (in the Appendix) plots data collected with the PDI FPDR under icing conditions (T = -15 °C, \( V_{air} = 75 \text{ m/s} \)). The dynamic ranges of the two instruments are such that the maximum droplet diameter of the small range is about 75 \( \mu m \) and the minimum diameter of the large range is 45 \( \mu m \). Notice the convergence of the large (green) and small (blue) flux distributions from 55 \( \mu m \) to about 100 \( \mu m \). Even though the small size range may begin to saturate at 75 \( \mu m \) not all drops larger than this necessarily do. Therefore it’s possible to see reasonable agreement in flux distribution beyond the dynamic range. At 100 \( \mu m \) the static range of the small PDI is met.

The facility used for this particular test also has a traditional PDI outside of the wind tunnel walls. This instrument has a dynamic range of 5 to 250 \( \mu m \). For the cloud condition plotted in Figure 5, the facility’s PDI measured a \( D_{50} \) of 26.6 \( \mu m \) and an MVD of 35.3 \( \mu m \). The PDI FPDR measured a \( D_{50} \) of 27.3 \( \mu m \) and an SMD of 32.2 \( \mu m \). While one might hope for better agreement on the MVDs, the results are reasonable.

Figure 6 (in the Appendix) plots a data set where the PVC failed. In this case there is no point at which the small-range flux distribution matches the large range. If the cross sectional areas are not properly accounted for the merging of PDI data sets will not produce a physically realistic solution.

Future Work

The largest potential area of improvement in merging PDI data sets is improvement in probe volume correction methods. Currently, PVC algorithms work best when the flow is aligned with the velocity component measured with the diameter. For trajectories not aligned with the velocity these algorithms tend to overestimate the flux [11]. Fortunately, the flows measured in both atmospheric and simulated clouds are exceptionally one-dimensional. Extension to general-purposed spray characterization will require a more robust ability to correct for diameter bias for all possible drop trajectories.

Summary

A methodology for rigorously combining data from multiple PDI instrument configurations into a single diameter distribution has been presented. The key requirement of this method is accurate probe volume correction of all original PDI data. The combined distribution, possibly spanning a larger diameter range than the dynamic range of any given configuration, is generated through a flux-weight blending of data in their diameter overlap regions.

Results from a new instrument, the PDI FPDR, leveraging this methodology have also been presented. The FPDR was designed specifically to meet the needs of the cloud characterization researchers in the meteorology and icing research communities. Both groups are in need of modern instrumentation capable of measuring droplet diameters, velocities, and liquid water content while operating in severe icing environments and at the relatively high droplet number densities of simulated clouds. The FPDR meets these needs and may allow a reduction in the number of different diagnostics required to fully characterize the target clouds.

Acknowledgements

The authors are grateful to the US Navy, ONR, US Army, and NASA Glenn Research Center funding under Phase I and Phase II SBIR grants used in developing this instrument. Funding and support were also received from NASA Glenn Research IRT and the U.S. Air Force McKinley Laboratory.

References

1. FAA’s Aviation Rulemaking Advisory Committee (ARAC) and the National Transportation Safety Board (NTSB), http://edocket.access.gpo.gov/2010/2010-15726.htm.


Appendix: Plots

Figure 5. Flux distributions of merged PDI data. The green and red vertical lines are the limits of the overlap region between the two PDI data sets. The merged flux distribution (red) is equal to the small-range flux distribution (blue) in a diameter range below the overlap region and to the large-range flux distribution (green) for diameters larger than the overlap region. Within the overlap region the merged flux distribution is generated by a linear weighting of the two data sets. However, because the two original flux distributions are so close to one another for most of the overlap region there is not much apparent impact of the weighting.

Figure 6. Flux distributions of merged PDI data. In this data set we see poor agreement between the flux distributions of the small (blue) and large (green) range sets in the overlap region. Therefore the merged flux distribution (red) must make transition from one data set to the other across the merge region while never matching either well. The merging methodology can always make a combined distribution. However, that does not ensure that the final result is accurate or consistent with the original data sets.