Aircraft Icing Research: Challenges in Cloud Simulation and Characterization

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Abstract
Recently, FAA requirements for aircraft icing certification have been updated to include characterization of supercooled large drops (SLD). Cloud measurements and icing wind tunnel simulations of existing Federal Aviation Regulations, Appendix C, Part 25 and these new conditions (Appendix O) require advances in instrumentation capable of measuring droplet size and liquid water content (LWC) under a much wider range of conditions. Cloud microphysics investigations and measurements have revealed that some clouds containing large drops can have droplet size distributions that are bi-modal. Such conditions present an additional challenge to the instrumentation. Existing instrumentation based on concepts developed in the 1970’s are known to have difficulties measuring spray drops in the SLD range. Currently, up to five or six different instruments utilizing different measurement principles are needed to characterize icing clouds and icing cloud simulations in icing wind tunnels. The phase Doppler interferometer flight probe, dual range (PDI FPDR) has been developed to address these new and challenging spray measurement conditions. This instrument is capable of simultaneously measuring droplets in the size range of 1 µm to 2000 µm or larger and LWC over a full range of cloud and cloud simulation conditions. To ensure reliable operation under the harshest icing conditions, the probe incorporates deicing and temperature controls. Since the instrument is considered to be relatively new to the meteorological and icing research community, extensive tests and evaluations of the instrument were conducted to demonstrate its measurement capabilities. An extensive program of instrument comparisons between the well-established PMS FSSP and OAP instruments was conducted. Results of these comparisons are reviewed and discussed. Significant measurement differences were found under higher droplet number density spray conditions and these differences are discussed and reconciled. Comparisons of LWC measurements are also provided and compared to the well-established hot wire devices and icing blade data.

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Introduction:

Aircraft icing remains a potential threat to flight safety and continues to be the subject of intense research, testing, and certification to ensure that aircraft can operate safely under a wide range of atmospheric conditions. Ice buildup on aircraft components occurs when aircraft encounter supercooled droplets in the atmosphere which then freeze upon or after impact with the aircraft surfaces producing ice accretion that can seriously affect the drag, lift, and control of the aircraft. Ice accumulates not only on the wings and control surfaces but also on exposed engine components and instrumentation. For example, Air France flight 447 from Rio de Janeiro to Paris was lost over the Atlantic near the Equator due to consequences of what is believed to be icing on the pitot-static systems needed for monitoring air speed. Satellite images and observed weather conditions indicated that the aircraft may have encountered rime icing and possibly clear or glaze icing conditions. Turbojet, turboprop, and turbofan engine induction systems are also affected by ice accretion on internal engine vanes and compressor blades when encountering mixed phase conditions (supercooled liquid drops and ice crystals). Ice particles are known to melt within the engine and then freeze onto the compressor blades inside of the engine affecting compressor performance producing compressor surges and stalls, flameouts, which can lead to engine damage.

Recently, the FAA [1] has proposed a significant expansion in its icing certification standards to include the condition known as supercooled large droplets (SLD). SLD refers to the drizzle-sized droplets in the approximate size range (median volume diameter, MVD) of 100 to 500 μm in diameter (Federal Aviation Regulations, Part 25, Appendix O). Droplets in this size range can remain as liquid at temperatures well below freezing (to -40°C) and are especially dangerous since they can collect and freeze almost anywhere on aircraft surfaces. Coupled with smaller drops, they can create a rough surface or structure which spoil aircraft lift and control performance. A key event leading to these expanded regulations was the tragic 1994 ATR 72 icing related accident in Roselawn, Indiana. Investigations of the accident concluded that liquid water runback of SLD produced a subsequent ice formation aft of the deicing boots near the leading edge.

Simulations and characterization of mixed phase and SLD icing conditions remain a challenge for existing icing wind tunnels and instrumentation. Available wind tunnels were designed for general operation with large spray droplets. Challenges that must be confronted include production of a large drop size range with a relatively uniform droplet size and concentration distribution within the test section. Flow through the contraction and gravitational force can be expected to produce segregation of droplet trajectories based on their inertial characteristics and air flow speed. Furthermore, large droplets require much greater time to reach supercooled conditions than smaller drops. Thus, the relative residence times of the droplets may need to be controlled which is very difficult in icing wind tunnels. Existing instruments based on light scattering can be frustrated by the mixture of spherical liquid droplets and ice crystals. For example, commonly used PMS FSSP instruments [2,3] based on forward scattered light intensity measurements are known to produce significant error under mixed phase conditions [3,4].

More recently, the phase Doppler interferometry technique developed into a configuration for aircraft-based and wind tunnel studies has been applied to measurements of droplet size distributions under mixed phase and SLD conditions. With a dual range capable of covering droplet sizes from 1 to 2000 μm or larger has proven to be more resistant to errors in reporting liquid particle measurements and in rejecting ice crystals. Instruments for measuring liquid water content (LWC) consisting of hot wire and heated collection devices also experience difficulties when attempting to measure a wide range of drop sizes included under SLD conditions. Uncertainties in droplet collection efficiency and shattering are problems identified as sources of measurement error.

A goal of this work is to address measurement requirements for icing research under the new FAA certification requirements including characterizations of median droplet diameter (MVD) and liquid water content (LWC) for icing simulations including SLD. Based on the impending FAA regulations, instrument requirements, capabilities and limitations will be discussed. As a starting point, measurement comparisons of droplet mean size (Median Volume Diameter, MVD), LWC, and number density will be provided and compared to other established methods in size ranges where these methods should be reliable. Differences are analyzed and discussed and some observations made as to the reasons for significant differences in the results.
Experimental Investigation

National and international icing facilities including wind tunnels, open free jet systems, and other facilities are used along with a wide range of instrumentation for characterizing icing cloud simulations required in aircraft component certifications. Cloud measurements including icing clouds are also being made by a number of institutions using aircraft-based instruments. These wind tunnel simulation data are acquired with different types of instruments leaving open the possibility of different certification results. Measurements are often carried out by groups with varying degrees of sophistication and understanding of the instrumentation and metrology capabilities. Often, measurements in similar cloud conditions produce significantly different results. Questions remain as to what measurements, if any, are reliable and what are the measurement uncertainties associated with these cloud characterizations. Measurement challenges and uncertainties increase when measuring in mixed phase cloud conditions consisting of droplet and ice crystal spectra typified by a relatively broad range of droplet sizes and number densities. Added to the complexity is the recent requirement of characterizing supercooled large drops (SLD). Existing instruments used to characterize clouds over the past decades encounter difficulties when attempting to measure under these conditions. Furthermore, different types of instruments using different physical principles are required for measuring in mixed phase conditions and SLD. These conditions further add to the questions regarding measurement uncertainty and reliability.

Instrumentation:

Forward Scattering Spectrometer Probe (FSSP)

The FSSP instrument was developed by Particle Measuring Systems (PMS) in the early 1970s and has served the meteorology community. Originally, the instrument was designed for measuring atmospheric particulate consisting of both solid and liquid particles over a size range of approximately 0.5 to 50 µm. It is a single particle counting method [2,4,5,6,7] based on the measurement of light scatter intensity by particles passing through a focused laser beam and detected in the near forward direction. The measurement principle is based on the fact that particles scatter light in proportion to their diameter squared \( I_{sc} = kL(r)d^2 \). Innovative means were incorporated into this instrument to limit the detection to only particles passing through the central nearly uniform intensity peak of the focused laser beam. The masking system also limits the depth of field to form the measurement volume. Nonetheless, forward scatter light detection inevitably produces a relatively large sample volume with dimensions of approximately 200 µm in diameter and 2000 µm in length. This limits the number densities of the clouds in which this instrument can be used reliably. Although it is not described in the literature, the size of the sample volume must inevitably be a function of the droplet size being measured. Larger drops will be detected over a larger sample volume than the smallest drops. As the cloud droplet number density increases, probability of coincidence (more than one particle in the sample volume at a time) increases which leads to measurement uncertainty. In addition, as the droplet number density increases droplets within the laser beam path but outside the probe volume will scatter light to the detector and will appear in the background of droplets that pass the validation logic. Presumably, the particle upper size measurements are limited by the need to measure only those particles passing the nearly uniform peak intensity region of the laser beam. The beam would need to be proportionately larger to measure large drops which would then exacerbate coincidence problems and measurement errors.

The FSSP design incorporates the use of a tube to straighten the flow and limit the length of the exposed beam path for the reasons described. Under some conditions droplet shattering on the rim of this tube can be significant producing errors in the measurements. This problem may be expected when measuring SLD since drops in this condition are relatively large and can produce a cascade of smaller drops when they impact the rim of the tube. The probe was designed for atmospheric testing from aircraft and due to power limitations, it has inadequate heating capacity to keep it ice free under the higher LWC loading conditions in icing wind tunnels. Accumulation of water on the receiving optics has also been reported as a problem. Similar to other instruments utilizing light scattering intensity, the method needs relatively frequent calibration due to detector drift, changes in laser beam intensity, and optical contamination.
PMS Optical Array Probe

Optical array probes (OAP) were developed by Particle Measuring Systems, Inc. (PMS) in the early 1970s and have been used extensively for cloud droplet and ice particle spectra measurements. The OAP instrument utilizes a linear detector array to capture the images as they sweep past at a predetermined speed. Shadows of the particles are measured by the detector array to obtain their size and some information on shape. Although the instrument incorporates strategies to identify and limit the depth of field for the particles passing through the exposed laser beam, these methods have been shown to be somewhat unreliable [8,9]. OAP instruments have been subject to numerous investigations [8,9] with attention focused on various sources of measurement error related to the underlying measurement principles used. A key finding of this work was the dependence of the particle size measurement on the particle distance from the object plane which was found not to be monotonic and is dependent on the particle size. Similar depth of field effects on the image size are generally present in shadow imaging techniques [10].

A detailed investigation by Korolev et al. [8] evaluated the effects of depth of field on the droplet size measurements. Streams of monodisperse water droplets were traversed along the beam axis to obtain quantitative information on the measurement error as a function of distance from the focal plane of the instrument. The authors observed that as the droplet trajectories moved out of the expected depth of field of the instrument, the rate at which the droplets are measured did not diminish sharply as expected. Data rate gradually fell off as the droplets were traversed outside of the acceptable depth of field of the instrument. The authors found that the detection distance of the droplets as they were moved away from the focal plane depended strongly on the drop size. The authors observed that these depth of field effects resulted in size measurement error for the smaller particles of as much as 85% (measured as larger than actual size). They also noted that for droplets larger than 125 µm in diameter, the depth of field was constant and limited by the separation distance between the probe windows. This affects the measurements of SLD where the droplets will be much larger than 125 micrometers. Although the depth of field will not affect the measurement of larger droplets, collisions and shattering of droplets from the probe arms will undoubtedly result in recording smaller droplets, adding to the measurement uncertainty.

PDI Flight Probe, Dual Range (FPDR)

Phase Doppler interferometry (PDI, also known as PDPA, PDA) is now a well-known and well-established spray flow measurement method [11]. This instrument has been demonstrated to have numerous advantages over light scattering intensity-based instruments. Measurements are based on the wavelength of light and hence, are not significantly affected by intervening droplets in the laser beam or in the light scattering intensity path to the receiver. After factory calibration, additional calibration is unnecessary. Since laser wavelengths remain constant and the optical configuration does not change, field calibrations are unnecessary. Signals produced by the instrument have a unique sinusoidal characteristic which allows easy and reliable detection of the signals even in low signal-to-noise ratio environments using digital means and the full complex Fourier transform. A feature sometimes overlooked is the fact that the sample volume may be reduced or increased over a relatively large range to accommodate the prevailing number density. The method has undergone more than two decades of development and evolution as well as extensive evaluations on a wide range of measurement tasks. It is now a mature technology with the measurement capability fully validated and sources of error identified and reconciled. Surprisingly, in the meteorological and aircraft icing cloud research community, the method is not well-known nor understood and is not yet widely used.

An early version of the phase Doppler icing probe was developed under NASA funding and tested in the NASA Icing Research Tunnel (IRT), Figure 1. [12,13] as well as on the NASA Twin Otter aircraft. Similar versions of the probes have been used by Boeing Airplane Company to obtain measurements in icing clouds from their 737 and 777 aircraft. The Phase Doppler icing probes are also used in the CIRA icing facility in Italy. These tests have revealed advantages of the PDI method as compared to the other light scatter detection instruments. In icing wind tunnels and in some clouds, mixed phase conditions can prevail (liquid water droplets and ice crystals). The PDI expects spherical particles and has several signal validation tests to reject particles that are not spherical (crystals or solid particles with morphologies significantly different
than spherical). This capability is important in isolating the measurements to only supercooled liquid droplets. In wind tunnel testing, ice crystals shed from wind tunnel walls, spray bars, screens and other surfaces that may be present after extended periods of operation. The phase Doppler method has been demonstrated capable of rejecting more than >99% of these particles.

After a hiatus in the development and application of the phase Doppler method for meteorological and icing cloud characterization, advanced phase Doppler instruments have been developed for cloud studies under U.S. Navy Office of Naval Research, NASA Glenn Research Center, US Air Force, McKinley Climatic Laboratory, and U.S. Army funding. These efforts resulted in an advanced instrument capable of making measurements over a size range of 0.5 to 2000 µm in the most challenging icing conditions.

**LWC Methods**

Currently, hotwire probes and icing blades [9,14,15] are commonly used to estimate liquid water content (LWC) in clouds. The first device known as the Johnson-Williams (JW) was developed in 1955. In the 1980s, PMS produced constant temperature hotwire devices referred to as the "King" probe. The devices are analogous to well-known hotwire anemometers which are used for aerodynamic mass flow (µm) measurements and use both constant current and constant temperature methods. The device responds to the cooling of the wire due to evaporation of cloud droplets that have impacted and collected on the wire. It is argued that constant temperature devices have a response that is more predictable based on first principles and thus, is theoretically independent of calibration [14]. The wire diameters for these devices are in the range of approximately 0.5 to 2 mm. Investigations have revealed that at typical aircraft speeds of 100 m/s and pressures of 70 KPa, collection efficiencies rapidly fall below 90% for droplets smaller than about 9 to 12 µm in diameter for the JW and King probes [9]. Other investigations of the collection efficiency have determined that the response of the hotwire devices also drops off with increasing drop size. For example, it was hypothesized that for droplets above 30 µm, the JW probes experienced partial aerodynamic removal of captured water mass before full evaporation. Thus, researchers have found that there is not only a rapid loss of collection efficiency with the decreasing droplet diameter below about 10 µm but there is also a loss of captured water for droplets larger than 30 µm. In general, LWC measurements with the cylindrical hotwire sensors showed a roll off in the LWC response with increasing spray MVD. This is believed to be due to entrainment or shedding of captured water before the water was fully evaporated from the wire.

Extensive research by Strapp, et al. [9] was conducted covering a MVD size range from approximately 13 to 236 µm to address issues of liquid water content measurement reliability, especially when extending the measurements to SLD conditions. This study concluded that measurements of large droplets in the SLD range are difficult both for MVD and LWC. In that study, they also concluded that up to three different droplet sizing instruments with overlapping size ranges may be necessary to cover the size range for SLD characterizations. They also concluded that estimations of MVD were very sensitive to the choice of instruments which, in turn, casts doubt on measurements of large MVD. Hence, biases probably exist between different icing wind tunnels and aircraft measurements.

**Measurement Procedure**

Extensive testing has been conducted to evaluate performance of the most common instruments used for icing cloud characterization. Since the newly developed dual range phase Doppler interferometer probe identified as PDI FPDR is relatively new to the icing and meteorology research community, these tests were in part, an effort to demonstrate the capabilities of the instrument. Although the existing wind tunnel data cannot be concluded to be completely reliable or accurate, wind tunnel spray characterizations have evolved over extensive and numerous tests with carefully calibrated instrumentation [16]. This is especially true for data obtained in the NASA Icing Research Tunnel (IRT) and in the icing facility at CIRA (Centro Italiano Ricerche Aerospaziali, Italy). The IRT facility was calibrated using primarily older PMS FSSP and OAP instruments. Liquid water content was measured using both hotwire devices and icing blades (see Strapp et.al. [9]). In some cases, cloud data were obtained using a PDPA instrument developed in the early 1990s.

As a historical reference, figure 1 shows a direct comparison of spray MVD measurements conducted in the NASA IRT and described by Rudoff, et al., [12,13].
In the IRT, there are 8 spray bars in the inlet section each with 10 to 15 spray nozzles making up approximately 100 nozzles. Testing was conducted using two sets of spray nozzles in the facility. Because of number density limitations of the FSSP, measurements with that instrument are performed with one half of the spray nozzles shut off. The tests showed a systematic shift with the PDPA measuring smaller drops by as much as 50% in the small end of the MVD size range considered. For larger MVD values, the percent difference between the IRT calibration results (FSSP and OAP merged data) decreased. For spray conditions with the largest MVD values, the difference increased again. The PDPA had an upper size limit of approximately 150 µm and hence, was not detecting all of the larger droplets in the distribution. Questions remained as to why the PDPA consistently reported MVD values at the lower size range where the instrument should have reported reliable measurements. Data analyses offered in the following sections may help explain these earlier results.

In subsequent tests, direct comparisons between various instruments were conducted. A complete set of data from the new PDI instrument were recorded including MVD, flow velocity, droplet number density, volume flux, and liquid water content. Since the PDI instrument incorporates two size measurement ranges, drop sizes from 1 to 2000 µm, are measured simultaneously. Comparisons were made to updated PMS FSSP and OAP instruments and to the hotwire devices used for measuring liquid water content. Spray conditions were varied over a range of liquid water flow rates and atomization air pressures. Consequently, droplet number densities varied widely for these conditions. Acquired data were carefully analyzed and evaluated in an effort to reconcile and understand why there were significant differences in the measurements under a certain range of spray conditions.

Results and Discussion

Measurements reported here were acquired under typical icing conditions with air temperatures in the range from -5° to -30° C. Flow speeds ranged from 10 m/s to 100 m/s. As seen in figure 2, ice accumulated on the instruments that were not properly heated which necessitated routinely shutting down the facility and deicing the probes. The first version of the PDI flight probe instrument shown here had sufficient heating to maintain ice free operation under most icing spray conditions. However, at speeds of above 80 m/s and high LWC, the probe had some trouble maintaining the internal temperature within the operating range of the laser. The design and heating capability has been changed in the most recent design so it can operate under the most severe icing conditions.

Comparison of PDI Results

Initially, the new PDI probe was compared with standard Artium PDI systems to ensure that the system was working properly and producing results that were consistent with our highly developed laboratory scale instruments. In one key facility, we have accumulated extensive data over the past 15 years using a PDI system that was installed external to the wind tunnel and produced measurements through the tunnel windows. This instrument has produced consistent year-over-year results as shown in figure 3. Variations in the MVD measurements are within a few micrometers. The PDI flight probe was installed inside this wind tunnel and direct comparisons measurements were made between the flight probe and instrument that was external to the tunnel. Figure 4 provides an example of the results obtained under these tests. In general, the results agreed to within a difference of +/- 3%. Hence, between like instrument technologies, the agreement was within the expected uncertainty range.

Comparison of PDI and PMS FSSP and OAP Results

An extensive series of tests with direct comparisons between the PMS FSSP and OAP, considered to be the standard within the icing community, and the dual range PDI instrument were conducted to evaluate the new PDI instrument. Unfortunately, these tests revealed some very large differences between the measurements of as much as 80%. In general, the FSSP data under the prevailing spray conditions were systematically much larger than the MVD measured by the PDI probe. An example of the results is shown in figure 5, wherein the spray conditions were changed over a range of water flow rates and atomization pressures. In an effort to reconcile these differences, a number of tests were conducted including moving the probes to the same relative positions and repeating the measurements to eliminate any differences that may have been produced by spray nonuniformity. A review of the measurement characteristics of the FSSP instrument and reports
relating to this general method suggested that high droplet number densities and coincidence (more than one droplet passing the sample volume at one time) could potentially be the source of the differences. Therefore, the number density measured by the PDI was plotted versus the range of water flow rates applied to the nozzles, figure 6. The number densities range from 500 to 3000/cc. In the literature (e.g. Strapp, et al. [9]), number densities above 300/cc or 400/cc have been recognized as the conditions for the beginning of measurement uncertainty for the FSSP probe. However, in these reports, it is suggested that the droplet coincidence at the higher number densities would affect the counting efficiency but do not mention an effect on the MVD measurements. In the present investigation, the droplet number densities measured by the PDI instrument were well beyond the limits of reliable operation for the FSSP. Note that as the number density fell with reduced water flow rate to the nozzles, the difference in the MVD measurements between the PDI and the FSSP decreased, figure 7. The measured values are within a few percent at the low end of the number density distribution.

Differences in the MVD measurements between the PDI and FSSP instruments are plotted in figure 8 for a range of atomization conditions. Measurements with lower number density were produced using lower atomization pressure and lower water flow rate so that the MVD values were larger (~20µm) for these low number density conditions. Note that the differences at high number densities are as large as 45%. At low number densities, the differences are negative since the PDI is measuring larger MVD values than the FSSP. For the low number density conditions, the MVD's are larger and the FSSP has an upper size measurement limit of 47 µm. Hence, the largest drops in the distribution are not being measured and therefore, the FSSP is under-sizing the spray distribution. To emphasize this point, figure 9 shows measurements at low number densities for the FSSP and combined FSSP and OAP compared to the PDI. The PDI combined data (small and large range) reported smaller MVD in the PDI small size range alone. This unexpected behavior, albeit only a difference of 2 µm, is due to a fault in the merging of the results which is currently under investigation and further development. This problem occurs when the drop size distribution is such that the small and large measurement ranges do not have adequate overlap. In this case, the complete size distribution can be measured by the small size range part of the instrument.

FSSP measurement results should not be unexpected or surprising since they were predicted by Hovenac [17] in 1991. He conducted an analytical and experimental study to evaluate the effects of droplet number density on measurements reported by the FSSP. His results determined that for droplet number densities greater than approximately 300/cc, the instrument would under-predict the reported number density, over-predict MVD, and under-predict liquid water content. Figure 10 shows the predicted results of Hovenac for nearly symmetric and for highly skewed droplet size distributions. Also plotted in this figure are the differences between FSSP and PDI data obtained during these investigations for a wide range of spray number densities. Since the size distributions were moderately skewed, the results fall within the bounds of the predicted measurement error.

Liquid water content

Liquid water content (LWC) data were acquired with the PDI and PMS instruments as well as with various hot wire devices identified here as J-W #1 and J-W #2. The hot wire devices are considered to be a standard for LWC measurements although as described above, they do have their sources of measurement uncertainty [9,18]. No additional description of these methods will be provided here. Over the series of tests, direct comparisons of the optical data were made with the results from these devices. Figure 11 shows a typical result under a range of atomizer water flow rates and a single atomizing air pressure (500 kPa). The comparison between the PDI and hot wire devices are in good agreement except at the highest water flow rate. These tests were taken by cycling from the highest water flow rate to the minimum and then back to the same maximum value. Closer observation of these results showed that the beginning LWC measurements were higher than the ending LWC measurement at the same water flow rate condition. This behavior repeated very closely for each of the three runs shown here so the behavior was systematic. Further investigation will be required to determine why this was happening. The measured droplet number density also showed this behavior whereas the other parameters affecting LWC (flow velocity, D30, and probe area) did not change significantly. As expected and predicted by Hovenac, the LWC measured by the PMS combined instruments
(FSSP and OAP) showed significantly lower LWC values. For these spray drop size conditions, the FSSP data dominate since most of the droplets were within the range of the FSSP. Also as expected and predicted, the LWC measurements converged and agreed very well at the lower water flow rate (lower number density) conditions. At the lowest water flow rate, the FSSP was expected to produce reliable measurements.

**Summary**

Extensive tests were conducted on the newly developed PDI FPDR icing research instrument. In a programmatic effort to evaluate the measurement capabilities of the instrument, direct comparisons of PDI data were made with data obtained by the established PMS FSSP and OAP instruments. Comparisons were also made of the LWC measurements obtained with the well-established hot wire devices. In general, there were significant differences in the MVD values measured by the PDI and FSSP instruments. Analysis of the results indicated that the number densities for these tests were well above the upper limits suggested for the FSSP. At lower number densities, the instruments produced MVD measurements that were in excellent agreement. These results were also consistent with measurements obtained in the NASA IRT wherein the PDI and wind tunnel calibration data agreed to within a few percent for the smaller MVD values (within the measurement range of the FSSP). LWC measurements between the PDI and the hot wire devices were in good agreement except at the highest water flow rate values. Differences in the higher LWC conditions need to be reconciled in future tests. Consistent with predictions, the LWC measured by the FSSP instrument was significantly lower at higher droplet number densities.

One can conclude that these instruments work well under the measurement conditions for which there were originally intended. The FSSP was designed for cloud studies wherein droplet concentrations are relatively low (<500/cc). Unfortunately, wind tunnel certification tests have been conducted using the FSSP and OAP in spray conditions for which they were not designed. These tests require reevaluation to determine whether these data are within acceptable uncertainty limits.

The newly developed dual range PDI FPDR instrument has been demonstrated to be capable of measuring droplet size distributions over the full size range of interest including SLD. Droplet number densities prevalent in wind tunnel icing cloud simulations are well within the limits of this instrument. In addition, the PDI instrument can measure the flow velocity, spray droplet number density, and liquid water content under the full range of icing conditions.

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![Figure 1](image_url). Example of data acquired in the NASA IRT with the original PDPA flight probe showing the systematic smaller MVD measured by the phase Doppler instrument [12]. The IRT data were obtained using an FSSP.
Figure 2. Phase Doppler Interferometer FPDR with extended size range of 1 to 2000 μm installed in the McKinley Climatic Laboratory, Eglin AFB. Also shown are the older PMS FSSP and OAP instruments.

Figure 3. PDI Icing tunnel spray measurements over a number of years showing the repeatability of the results.
Figure 4. Comparisons of the PDI FPDR and PDI External Instrument

Figure 5. Typical results from direct comparisons of the PDI (lower points) and FSSP (upper points) during icing spray tests taken over several different runs at the same atomization conditions. Flow rates shown were distributed uniformly over approximately 100 spray nozzles.
Figure 6. Number density plotted as a function of water flow rate for four different repeated measurements at similar atomization conditions. Arrows indicate the sequence of measurements as they were acquired for each of the four tests.

Figure 7. MVD plotted versus measured droplet number density over a range of conditions with the minimum following within the acceptable range for the FSSP.
Figure 8. A plot of the difference between the FSSP and the PDI MVD measurements for a range of spray conditions with number densities as high as 4000/cc.

Figure 9. Measurements of the MVD produced by the PDI small range (PDI s), PDI combined small range and large range (PDI Comb), FSSP, and combined FSSP and OAP (PMS Comb) for low number density conditions.
Figure 10. Error in MVD measurements as predicted by Hovenac, 1991 in the difference between the FSSP and PDI MVD measurements.

Figure 11. Series of LWC measurements obtained by the PDI, PMS FSSP and OAP compared to the hot wire devices (J-W).