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Comparison of Drop Size Distributions From Two Droplet Sizing Systems

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SUMMARY

A comparison between the Phase Doppler Particle Analyzer and the combined measurements from Particle Measuring Systems' Forward Scattering Spectrometer Probe and the Optical Array Probe was conducted in an icing wind tunnel using NASA Icing Research Tunnel spray nozzles to produce the supercooled water droplet cloud. Clouds having a range of volume median diameters from 10 to greater than 50 microns were used for the instrument comparisons. A volume median diameter was calculated from combining the droplet distributions of the Optical Array Probe and the Forward Scattering Spectrometer Probe. A comparison of the combined volume median diameters and the Phase Doppler Particle Analyzer volume median diameters showed agreement from 10 microns up to 30 microns. Typical drop size distributions from the Phase Doppler Particle Analyzer, the Forward Scattering Spectrometer Probe, and Optical Array Probe are presented for several median volume diameters. A comparison of the distributions illustrates regions of the distributions where there is good agreement and other regions where there are discrepancies between the Phase Doppler Particle Analyzer and the Particle Measuring Systems' droplet sizing instruments.

INTRODUCTION

The accretion of ice on aircraft components is very sensitive to the supercooled cloud droplet size distribution which, in icing research, is typically characterized by the volume median diameter (MVD). Therefore, it is important that instrumentation can accurately and reliably measure the droplet distribution. In the last two decades, laser based systems have been developed to provide a fast efficient means of obtaining the droplet distributions. In icing research, the Forward Scattering Spectrometer Probe (FSSP) and Optical Array Probe (OAP), manufactured by Particle Measuring Systems, Inc. (PMS), are most commonly used.

Although the PMS probes are commonly used in flight and in large ground icing test facilities, their large size prevents them from being used in some smaller test facilities. Also, for clouds with MVDs greater than 20 microns both the FSSP and OAP are required to adequately characterize the cloud. This requires using a facility large enough to operate both probes simultaneously or repeating the test cloud with each probe individually. Because of these restrictions, NASA Lewis Research Center is sponsoring the development of a new instrument for icing cloud measurements based on the Phase Doppler Particle

Analyzer (PDPA) manufactured by Aerometrics, Inc.[1] This development program strives to incorporate the large adjustable size range of the current PDPA into a rugged compact probe.

To improve the understanding of the PDPA and PMS probes, a comparison test was conducted over a typical range of icing cloud conditions. The results of this test also will provide useful data for the development of a new droplet sizing instrument for supercooled cloud characterization.

APPARATUS AND PROCEDURE

The comparison test was conducted in the BFGoodrich Icing Wind Tunnel in Uniontown, Ohio. The tunnel has a test section which is 22 inches wide x 44 inches high x 5 feet long. The tunnel can supply air temperatures down to -20°F and velocities up to 200 mph.[2] The test section had a door on each side of the tunnel with heated windows measuring 12 x 30 inches which provided optical access for the PDPA.

Droplet Sizing Instruments

The instruments used in the comparison were a Particle Measuring Systems Forward Scattering Spectrometer Probe Model FSSP-100 and Optical Array Probe Model OAP-200X, and an Aerometrics, Inc., Phase Doppler Particle Analyzer. The FSSP had a size range of 0.5 to 47 microns and the OAP had a size range of 15 to 310 microns. Each instrument had 15 equally sized bins. Because of the limited maximum droplet diameter measurable by the FSSP, the FSSP and OAP distributions were combined into one distribution for comparison with the PDPA. The PDPA had a size range which could be adjusted within limits defined by the optical configuration. The size range had 50 equally sized bins with a fixed ratio between the largest and smallest size bins of 35:1. The PDPA size range was set during testing to best measure the droplet size distribution of each icing cloud.

Forward Scattering Spectrometer Probe (FSSP). The optical configuration of the FSSP is shown in figure 1. The FSSP established the size of a water droplet by measuring the intensity of light scattered into the collecting optics by a droplet traversing the focused region of the laser beam. The peak intensity of the scattered light increases with increasing droplet size. Droplets are sized one at a time and placed in one of 15 size bins. The FSSP had four size ranges. The largest range, 2 to 47 microns, was used for the comparison. For additional information on the operation of the FSSP refer to reference 3.

Optical Array Probe (OAP). The optical configuration of the OAP is shown in figure 2. A laser beam is projected across the open space between two probe arms, magnified by a set of lenses, and projected onto a 24 element linear photodiode array. Droplets crossing the laser beam shadow one or more of the photodiode elements. The droplet size is determined by the number of photodiode elements shadowed, the element spacing, and the magnification factor of the droplet image. The Model OAP-200X has 15 size channels, the photodiode elements are spaced on 200 micron centers, and the magnification is 10X which defines a size range of 15 to 310 microns with nominal 20 micron bin width. Refer to reference 4 for additional information on the OAP.

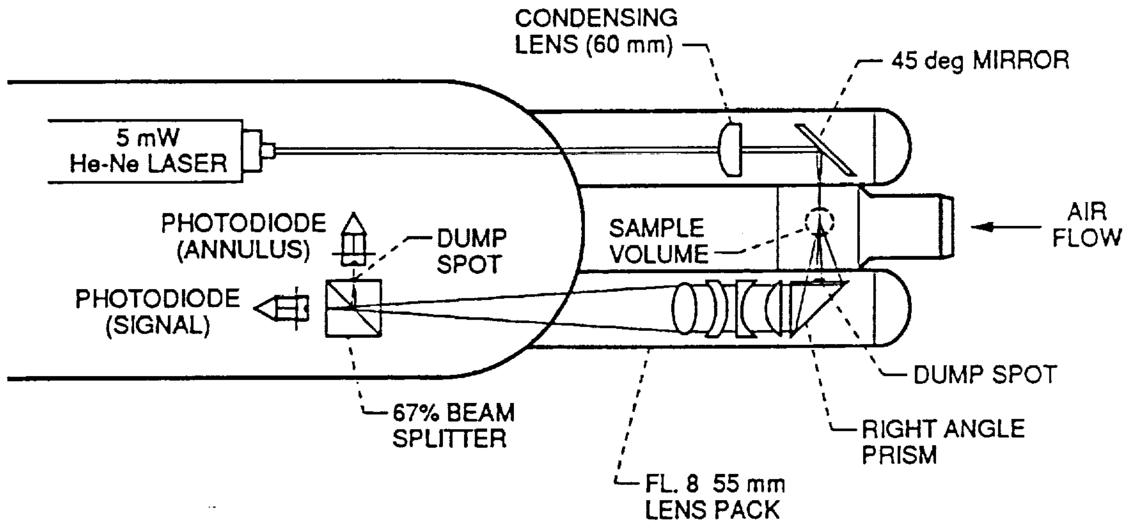


Figure 1. Forward Scattering Spectrometer Probe optical configuration.

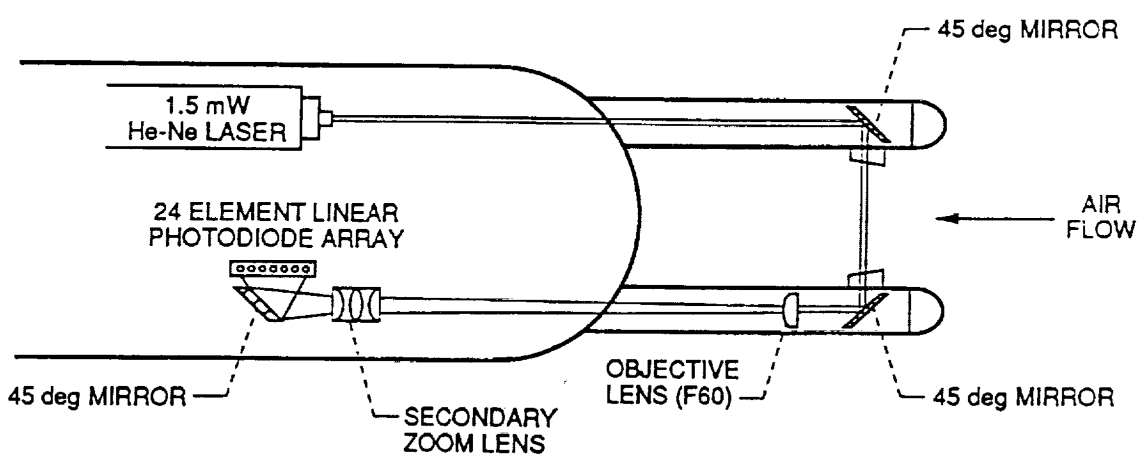


Figure 2. Optical Array Probe optical configuration.

Phase Doppler Particle Analyzer (PDPA). The Phase Doppler Particle Analyzer[5,6] developed by Aerometrics, Inc. uses scattered light from droplets to make simultaneous droplet size and velocity measurements. The PDPA uses an optical system which is essentially the same as that of a typical Laser Doppler Velocimeter shown in figure 3. Droplets crossing the intersection of the two laser beams scatter light, producing a far field interference fringe pattern. The spacing of these fringes is inversely proportional to the droplet size. To obtain a measurement of this fringe spacing, the PDPA receiver uses three detectors, located at selected spacings. The three detectors produce three Doppler burst signals which have a phase shift between them, figure 4. The phase shift is related to the droplet size using a linear relation illustrated in figure 5. The phase shift between detectors 1 and 3 is sufficient to measure the droplet size. However, to increase the droplet size range while maintaining resolution of the measured phase shift, a third detector (detector 2) is used to identify phase shifts, between detectors 1 and 3, which are greater than 360 degrees. This also provides a second independent measurement of the droplet size which is used in the signal validation logic.

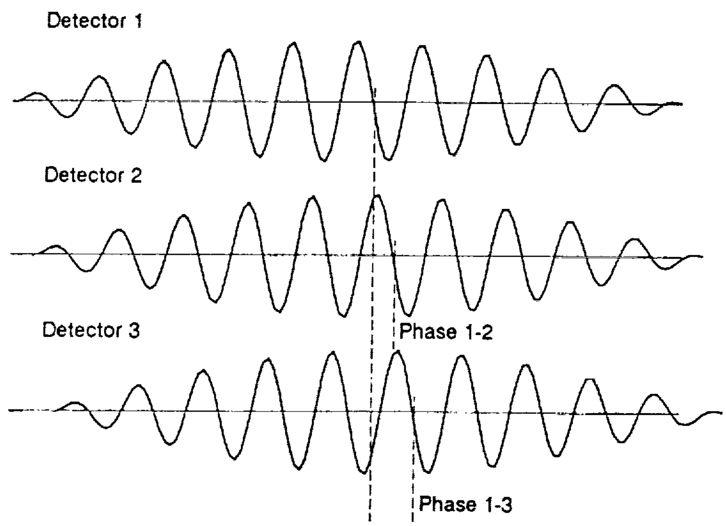


Figure 3. PDPA filtered Doppler burst signals from three signal detectors with the phase shift between signals illustrated.

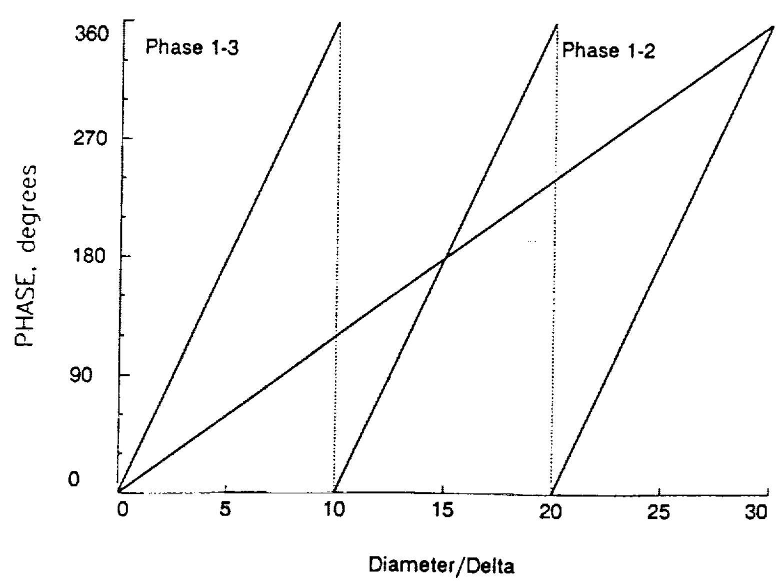


Figure 4. PDPA instrument response curves.

Combined FSSP and OAP Distribution. Because the FSSP is limited to a maximum droplet size of 47 microns, it is necessary to combine the FSSP and OAP distribution to produce a complete characterization of the droplet size distribution which will be refered to as a PMS distribution. This PMS distribution is used to calculate a MVD for comparison to the MVD calculated from the PDPA droplet size distribution.

The PMS distribution was generated by excluding the first two size bins of the OAP and combining the size bins from each instrument which has been normalized by their respective sample volumes. The sample volume is the product of the sample area, measurement time, and air velocity. The first two size bins of the OAP were omitted because of the errors which occur in these bins.[7] The counts in these bins are typically lower than the counts in the equivalent FSSP bins. The resultant PMS distribution has a size range from 2 to 310 microns with a small gap from 47 to 54 microns.

Setup and Measurement Procedure

The FSSP was mounted on a strut attached to the ceiling of the test section and positioned on the center line of the tunnel with the front of the flow straightening tube centered between the pair of heated windows. The PDPA transmitter and receiver were mounted on a pair of support columns attached to a common metal plate laying on the floor under the test section. The metal plate locked the transmitter and receiver together providing a stable alignment and permitted the alignment of the PDPA sample area with the FSSP by moving both components as a system.

Figure 5 illustrates the relative position of the PDPA sample area, the PMS sample areas, and the PMS instrument canister. The PDPA was mounted such that its sample area was positioned on the center line of the FSSP and one centimeter in front of the flow straightening tube. This placed the PDPA sample area 12 cm upstream of the FSSP sample area. The front dome of the FSSP canister was 26 cm downstream of the PDPA sample area. The OAP was mounted such that the distance from the instrument canister to the PDPA sample area and the distance between the OAP and PDPA sample area was the same as with the FSSP.

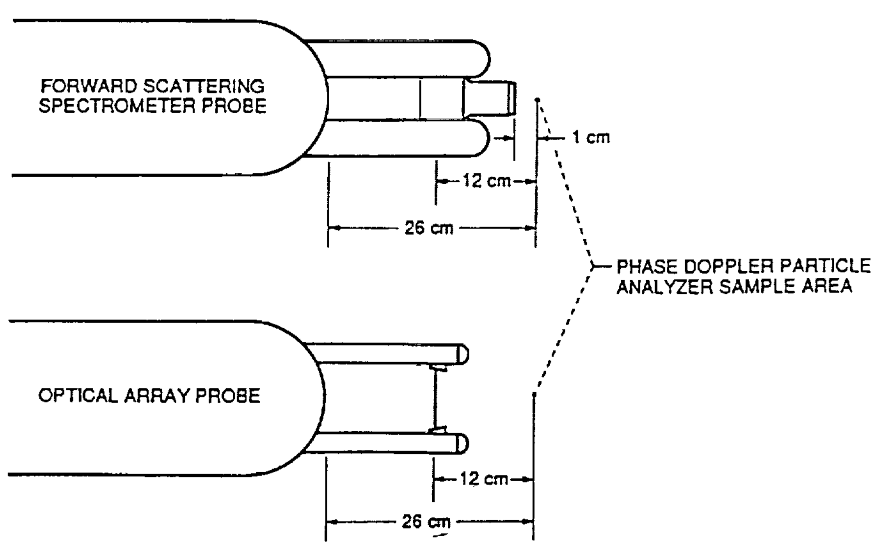


Figure 5. Illustration of the relative position of the PDPA sample area to the FSSP and OAP.

For each set of nozzles, measurements were taken in two steps. FSSP and PDPA measurements were taken for all nozzle test points. Then, the OAP was installed and all test points were repeated. Instrument measurements were started simultaneously after the spray nozzle pressures were set and stable. The sample time of the PMS and PDPA were not matched because the instrument's droplet sampling rates differ substantially. The PMS instruments sampled the cloud for a fixed time period. The FSSP sampled for 10 seconds and the OAP sampled for 40 seconds. The OAP's sample time was longer to compensate for the lower number densities of the large droplets in the tail of the distributions. The PDPA was set up to sample until it had processed 20,000 valid counts. The PDPA sample times varied from 9 to 60 seconds. In order to evaluate the repeatability of the cloud, the PDPA droplet size range was held constant for both the FSSP and OAP measurements.

RESULTS AND DISCUSSION

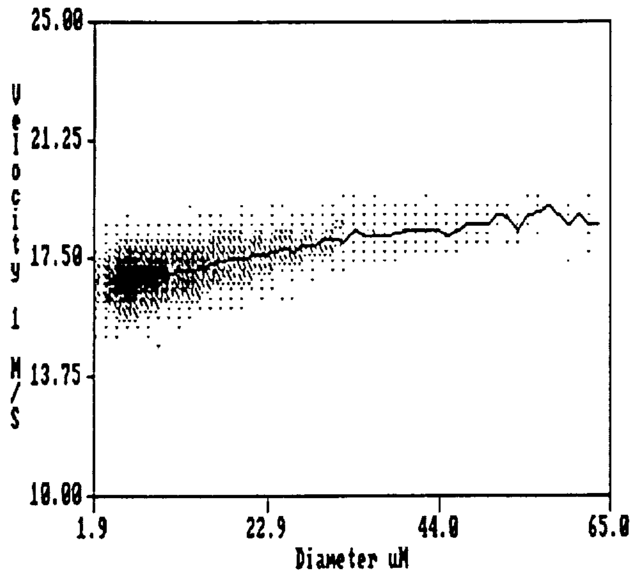
FSSP Velocity Averaging Circuitry

A previous comparison between the PDPA and FSSP was conducted at the Arnold Engineering Development Center in the R1D icing test facility. This comparison indicated large differences between the FSSP and PDPA.[8] The PDPA consistently measured a larger number of droplets in a range from 20 to 47 microns than the FSSP and in many instances the PDPA measured a significant number of droplets in this range when the FSSP measured none. Throughout the comparison the PDPA's MVDs were 50 to 100 percent higher than the MVDs from the FSSP.

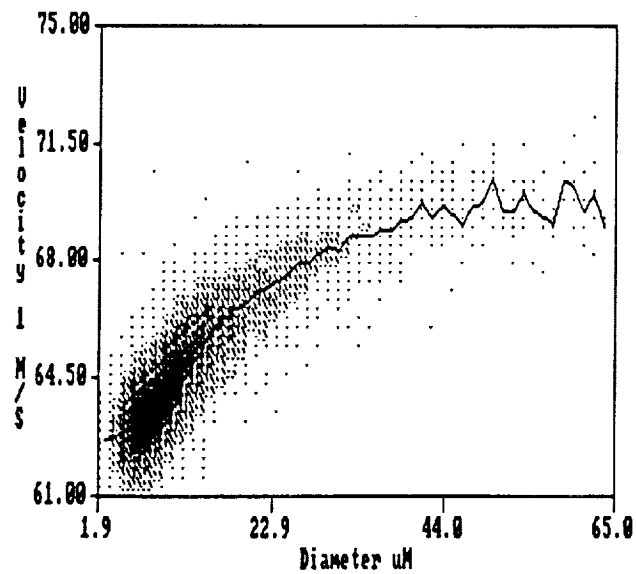
A possible explanation for the differences between the FSSP and PDPA distributions is that the large droplets had higher velocities than the small droplets. The higher velocities produce shorter transit times and therefore the droplets would be rejected by the velocity averaging circuitry. To evaluate this theory, a test was conducted to study the effect of the velocity averaging circuitry on the FSSP's droplet distribution and to measure the droplet size-velocity correlation entering the FSSP's flow straightening tube.

The velocity averaging circuitry was designed to prevent droplet undersizing due to droplets traversing the edge of the laser beam where the light intensity is lower than at the center of the beam. To reject the droplets traversing the edge of the laser beam, the velocity averaging circuitry maintains a running average of the transit times of all droplets which were within the depth of field and were within the droplet size range. Each droplet transit time is compared to this average. All droplets with transit times less than the average are rejected and all droplets with transit times greater than the average are accepted. The droplet transit time is a function of the droplet size, velocity, and the particular chord through the beam. To minimize the droplet size (signal amplitude) effect on the transit time, the transit time is measured at the 50 percent of peak voltage point of each signal. If all droplets are assumed to have the same velocity, then the droplet transit time would only be a function of the chord through the laser beam. Droplets traversing the center of the beam would produce the longest transit times. The PDPA provided a means of evaluating the assumption that all droplets have the same velocity.

The PDPA was used to measure the size and velocity of the droplets 1 cm upstream of the FSSP's flow straightening tube for nominal tunnel velocities of 25 m/s and 75 m/s as shown in figure 6. The scatter plot shows all points where there is one or more counts at a particular size and velocity. The solid line through the points represents the average velocity of each size bin. At 25 m/s the size-velocity correlation demonstrates a small increase in average velocity with increasing droplet size. The average velocity increased from 16.5 m/s to 18.5 m/s. Figure 6(b) shows the size-velocity correlation at 75 m/s. The average velocity increases from 63 m/s for the smallest droplets to 70 m/s for droplets above 40 microns. The change in droplet velocity for both examples is about 10 percent. Because there are significantly more small droplets than large drops, the average velocity is dominated by the velocities of the small droplets. The average transit times should behave in a similar manner, being dominated by the small droplets. The large droplets should have shorter transit times, due to their higher velocities, causing them to be rejected.

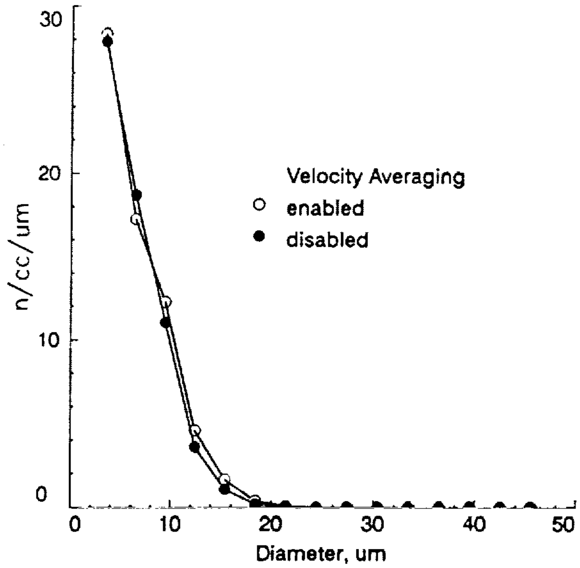


(a) 25 m/s

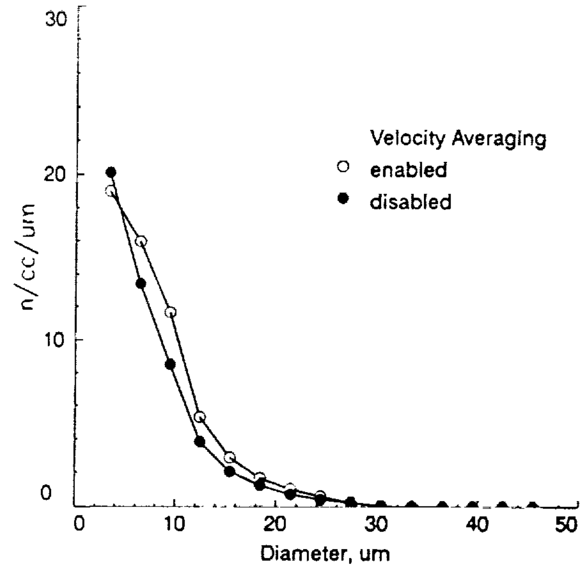


(b) 75 m/s

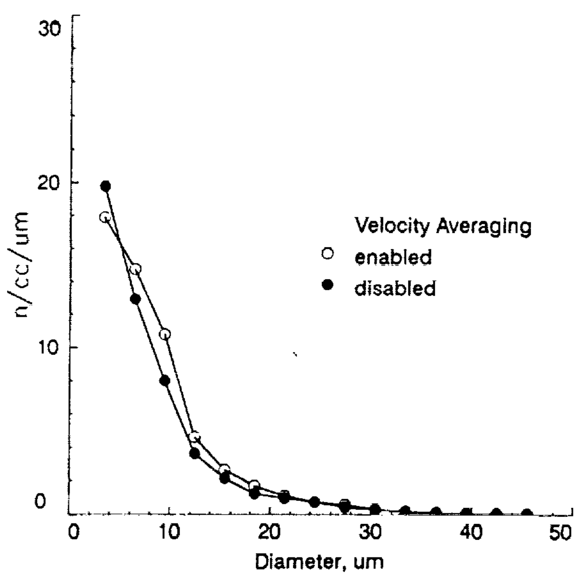
Figure 6. Droplet size-velocity correlation entering the FSSP's flow straightening tube.



(a) 11 micron MVD.



(b) 18 micron MVD.



(c) 30 micron MVD.

Figure 7. FSSP droplet distributions with the velocity average circuit enable and disabled.

Figures 7(a) to (c) presents FSSP droplet distributions measured with the velocity averaging circuit enabled and disabled for three MVDs; (a) 11 microns, (b) 18 microns, and (c) 32 microns. The nominal tunnel air velocity for all three cases was 60 m/s. For the 11 micron MVD cloud the velocity averaging circuit had very minimal effect on the distribution shape. At 18 and 30 micron MVDs (figures 7(b) and (c)) disabling the velocity averaging circuit causes the distributions to shift to the left and has a small effect on the shape. Undersized droplets could cause this shift. With the circuit disabled, the counts of the first size bin are about 10 percent higher and the counts of the rest of the bins are about

10 percent lower. Although the trends shown in figures 7(b) and (c) are well defined, the differences between the droplet distributions with the circuit enabled and disabled are minor. Although disabling the velocity averaging circuit increases the number of droplets sized per unit time indicating that the circuit was functioning, it never produced significant differences in the distribution shape, total number density, or the MVD.

These comparisons imply that the average transit time for all droplet sizes is approximately the same because the velocity averaging circuit does not produce a large difference between the two distributions. The droplet size-velocity correlation, which shoud have caused large droplets to have shorter transit times, may not be strong enough to cause the circuit to preferentially reject the large droplets. Possibly, large droplets have longer transit times due to their larger size that offsets the shorter transit times we expected because of their higher velocities.

Comparison of Drop Size Distributions

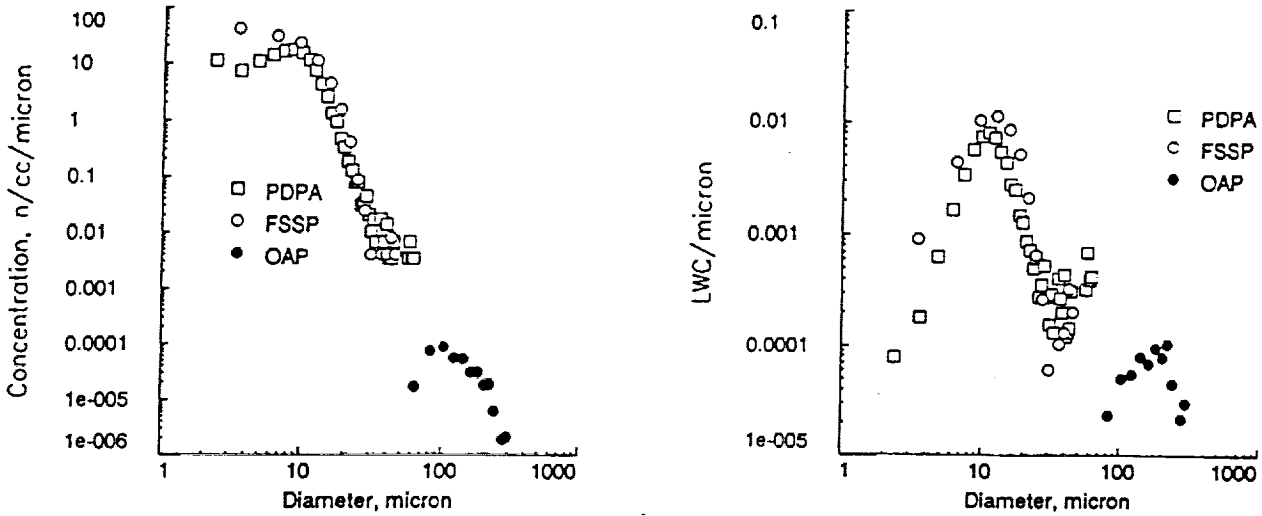
Figures 8 - 11 present typical drop size distributions from the FSSP, OAP, and PDPA. Tables 1 - 4 list the MVD, total number density, and total liquid water content (LWC) for these four distributions. The first two size bins of the OAP distributions have been omitted. For each figure only one PDPA distribution is presented to improve the figure clarity.

Figure 8(a) shows that for a 13 micron MVD there is a large difference between the FSSP and PDPA number density distribution below 10 microns. The first three bins of the FSSP have significantly higher counts than the equivalent bins for the PDPA. The FSSP and PDPA distributions have good agreement above 10 microns.

The difference between the PDPA and FSSP at small drop sizes may be caused by frozen droplets. In the NASA Icing Research Tunnel, droplet freeze-out was found to be significant at high air pressures and low water flow rates.[9] The FSSP would undersize a frozen droplet because of the reduction in scattered light intensity. However, the PDPA would probably reject these droplets because surface defects, internal air bubbles, and internal crystalline structures would cause large differences between the two independent phase measurements. Although the difference in number density for small drop sizes is large, the effect on the MVD is only one micron because the volume contribution of the small droplets to the total volume is small. Figure 8(b) shows that only the first FSSP bin has significantly higher LWC than the equivalent PDPA LWC. Above 6.5 microns the agreement between the two distributions improves. For this case, the FSSP and PDPA agree within one micron as shown in table 1.

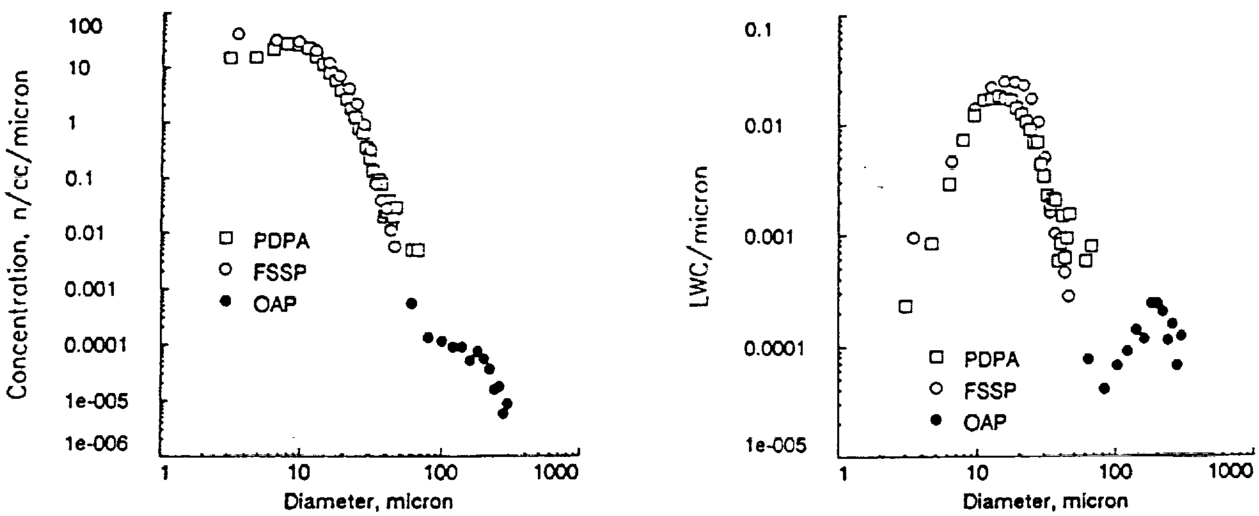
The scattering of data points evident at the end of the number density versus droplet size distribution is due to low counts in the last few size bins of the distribution. The two horizontal groupings of data at the end of the PDPA number density distribution represent one and two counts per bin. This scattering of data is also evident in the FSSP distribution.

The magnitude of the OAP distribution is higher than expected. Typically the OAP would have no counts for this condition.[9] These counts are believed to be caused by frost shedding from the walls of the tunnel and small water leaks from the tunnel spray bars. These non-spray particles prevailed despite repeated attempts to eliminate them.



(a) Number Density (b) Liquid water content

Figure 8. Distributions for a 13 micron cloud from the FSSP, OAP, and PDPA



(a) Number Density (b) Liquid water content

Figure 9. Distributions for a 18 micron cloud from the FSSP, OAP, and PDPA

Table 1. Numerical Data for Distributions in figure 8.

INSTRUMENT	MVD um	NUMBER DENSITY n/cc	LWC gm/m3
FSSP	12.7	338	0.135
OAP	181.4	0.0121	0.0127
PDPA with FSSP	12.2	151	0.0752
PDPA with OAP*	11.7	174	0.0852
PMS	13.3	338	0.148

Nozzle Condition: Pair=80 psig DeltaP=40 psi
* Distribution not shown to improve figure clarity.

Table 2. Numerical Data for Distributions in figure 9.

INSTRUMENT	MVD um	NUMBER DENSITY n/cc	LWC gm/m3
FSSP	18.1	457	0.44
OAP	182.2	1.04	0.0391
PDPA with FSSP	16.9	345	0.317
PDPA with OAP*	16.9	296	0.299
PMS	18.8	457	0.474

Nozzle Condition: Pair=80 psig DeltaP=200 psi
* Distribution not shown to improve figure clarity.

Figure 9 presents a slightly larger MVD of 18 microns. This figure is similar to figure 8 containing the same difference between the PDPA and FSSP below 10 microns and agreement from 10 to 47 microns. Although the OAP distribution in this figure is slightly more ordered, the count levels are still higher than expected. The counts for the OAP distribution, after omitting the first two size bins, are 517 raw counts and 1088 corrected counts for a 40 second sample.

Figure 10 represents the typical distributions for a cloud with a 30 micron MVD. This figure presents several changes from figures 8 and 9. For this condition counts in the OAP increased. The raw counts are 5929 and the corrected counts are 21,243 after omitting the first two size bins. The improved statistics result in a smooth distribution over the OAP's droplet size range out to 300 microns.

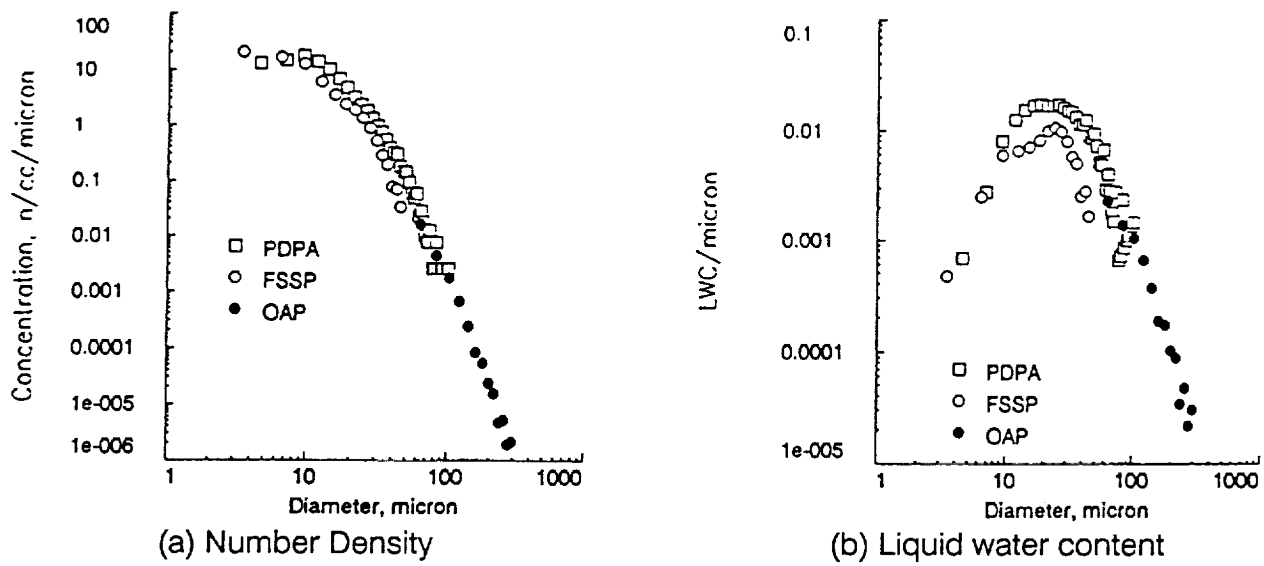


Figure 10. Distributions for a 30 micron cloud from the FSSP, OAP, and PDPA

Figure 10(b) shows that the agreement between the PDPA and FSSP has deteriorated. The FSSP LWC distribution is significantly lower than the PDPA distribution and has become distorted. The LWC distribution has an uncustomary concave curve from 9.5 microns to a peak at 24.5 microns.

In figure 10 the PDPA's size distribution ends at 116.4 microns whereas the OAP's size distribution continues out to 300 microns. Table 5 lists the PDPA counts per bin for the distribution presented in figure 10. The counts per bin drops below 10 above 65 microns and the counts are less than 2 above 82 microns. From 82 microns to 122 microns there are only 8 total counts. The PDPA size range for this measurement appears to be satisfactory with the distribution ending well before 122 microns. However based on the OAP distribution which continues out to 300 microns, the PDPA measurement is not adequately characterizing the distribution.

The PDPA distribution is not limited by the measurement range, but is limited by poor statistics in the large drop size bins, even though the total sample size was 38,059 corrected counts. As shown in table 5, counts per bin at the end of the PDPA's distribution are zeros and ones. The OAP's ability to characterize the distribution is superior to the PDPA's because, considering the relative sample areas, bin widths, and sampling times, the

PDPA would record one count and the OAP 7000 counts. The OAP's number density distribution was used to calculate the counts the PDPA would register if the PDPA measured the same distribution as the OAP for bins 26 through 50 (listed in table 5 as calculated counts). Above 82 microns the calculated counts are below 2 counts and are fractions of a count above 95 microns which is consistent with the PDPA measurement. A valid MVD requires that there is good statistics in all of the size bins that affect the calculated MVD, especially size bins at the end of the distribution.

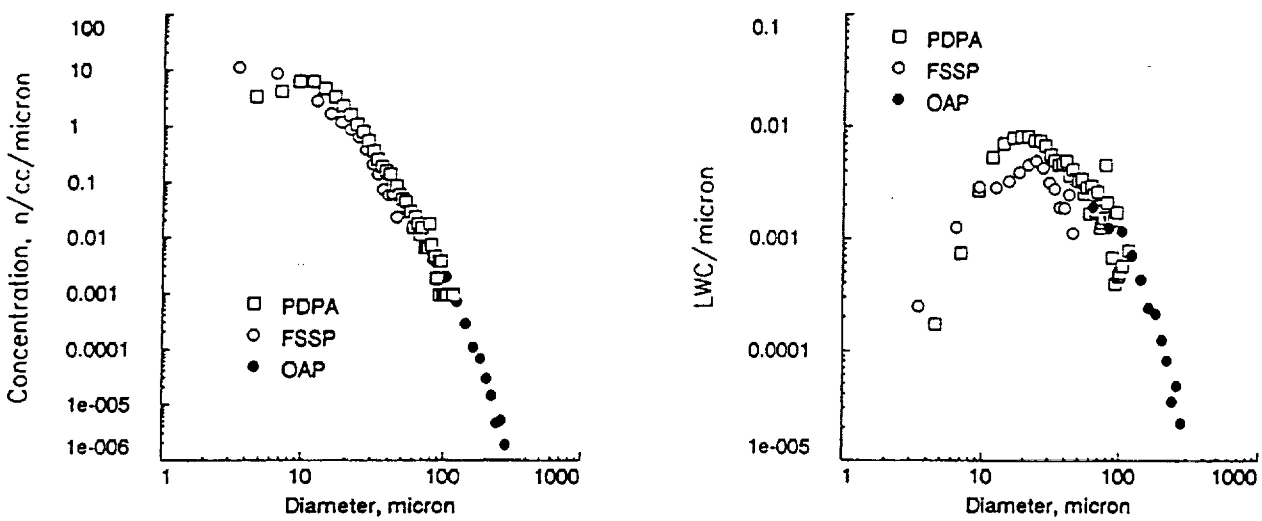
The PDPA's configuration could have been changed for the OAP tests to more closely match the OAP's measurement range, but was kept constant so that the cloud repeatability could be determined. The PDPA size range would have been approximately 8.5 to 300 microns. Also, the sample area and measurement time would have to be increased to address the low number density of the large droplets. This range may have been sufficient to accurately determine the MVDs above 30 microns. If not, the two PDPA measurements would need to be combined in a similar manner as the PMS measurements.

Table 5. PDPA corrected counts per bin for a 30 micron cloud. Calculated counts based on converting the OAP number density distribution to equivalent PDPA counts.

Bin	Diameter micron	PDPA Counts		Bin	Diameter micron	PDPA Counts	Calculated Counts
1	4.6	6187		26	64.1	11	6.17
2	7.0	6055		27	66.5	5	5.46
3	9.4	6927		28	68.9	3	4.86
4	11.8	5553		29	71.2	5	4.21
5	14.1	4003		30	73.6	3	3.65
6	16.5	2765		31	76.0	3	3.12
7	18.9	1999		32	78.4	3	2.62
8	21.3	1233		33	80.7	4	2.12
9	23.7	914		34	83.1	1	1.75
10	26.0	639		35	85.5	0	1.41
11	28.4	480		36	87.9	0	1.27
12	30.8	321		37	90.3	2	1.13
13	33.2	235		38	92.6	1	1.02
14	35.5	183		39	95.0	0	0.94
15	37.9	117		40	97.4	1	0.86
16	40.3	94		41	99.8	1	0.78
17	42.7	87		42	102.2	0	0.71
18	45.1	69		43	104.5	1	0.64
19	47.4	31		44	106.9	0	0.59
20	49.8	25		45	109.3	0	0.53
21	52.2	23		46	111.7	0	0.48
22	54.6	20		47	114.1	0	0.42
23	57.0	25		48	116.4	1	0.38
24	59.3	18		49	118.8	0	0.33
25	61.7	11		50	121.2	0	0.28

The PDPA's measurement range was defined during testing to best measure the droplet distribution. Typically an initial range is used to sample the cloud. The suitability of this measurement range is evaluated based on 1) the largest few bins have zero counts, 2) the ratio of the maximum drop size of the range to the MVD is greater than 4, and 3) the shape of the number density and volume distributions indicates that the distribution is ending before the limits of the range. During testing, based on these criteria, it appeared that the PDPA's measurement range was properly defined. However, only through comparison with the OAP distribution did the deficiency in the PDPA's measurement range become apparent. In the PDPA, as well as other instruments, criteria are needed to determine whether the measurement range is sufficient to produce a valid MVD.

Figure 11 presents typical distributions for a 47 micron MVD icing cloud. This figure shows trends similar to the trends shown in figure 10. The PDPA and OAP appear to be measuring different droplet size ranges of the same distribution. The FSSP's distribution is lower than the PDPA's distribution and has the same distortion as shown in figure 10.



(a) Number Density

(b) Liquid water content

Figure 11. Distributions for a 47 micron cloud from the FSSP, OAP, and PDPA

Table 3. Numerical Data for Distributions in figure 10.

INSTRUMENT	MVD um	NUMBER DENSITY n/cc	LWC gm/m3
FSSP	23.8	207	0.259
OAP	62.6	7.19	0.18
PDPA with FSSP	29.1	241	0.654
PDPA with OAP*	30.6	233	0.704
PMS	30.5	207.4	0.388

Nozzle Condition: Pair = 60 psig DeltaP = 247 psi
* Distribution not shown to improve figure clarity.

Table 4. Numerical Data for Distributions in figure 11.

INSTRUMENT	MVD um	NUMBER DENSITY n/cc	LWC gm/m3
FSSP	24.1	103	0.124
OAP	72.7	4.44	0.151
PDPA with FSSP	33.6	86.2	0.337
PDPA with OAP*	32.6	119	0.404
PMS	47	103.3	0.248

Nozzle Condition: Pair = 20 psig DeltaP = 20 psi
* Distribution not shown to improve figure clarity.

The combination of the failure of the PDPA to measure the large drop sizes and the reduction of the FSSP's volume distribution, shown in figures 10(b) and 11(b), causes the

The combination of the failure of the PDPA to measure the large drop sizes and the reduction of the FSSP's volume distribution, shown in figures 10(b) and 11(b), causes the large differences between the PMS and PDPA MVDs above 30 microns. For these conditions the PMS MVDs are oversized and the PDPA MVDs are undersized.

Figure 12 presents MVD comparison data between the PDPA and PMS (combined droplet size distribution from the FSSP and OAP) instruments for three nozzle sets tested. From 10 to 30 microns most of the data is clustered in a band about the line of perfect agreement. Above 30 microns, the agreement quickly deteriorates. The average of the two PDPA measurements for each PMS measurement is represented by the symbol and the ends of the horizontal line through the symbols represents the two PDPA MVDs. Although most of the PDPA data indicated good cloud repeatability, a series of IRT Mod1 nozzle data from 20 to 40 microns suffers from poor cloud repeatability as indicated by the long horizontal lines through the symbols. This data exhibits differences of 4 to 10 microns between the two PDPA MVDs. The validity of the PMS MVDs for this series of data is doubtful because the poor repeatability indicates that the OAP and FSSP were measuring two different clouds. The fact that the cloud did not repeat may be the reason that this series of data are displaced from the 1:1 line and the rest of the comparison data. Above 30 microns, the data imply that the PDPA measurements have approached a maximum as the PMS continues to increase.

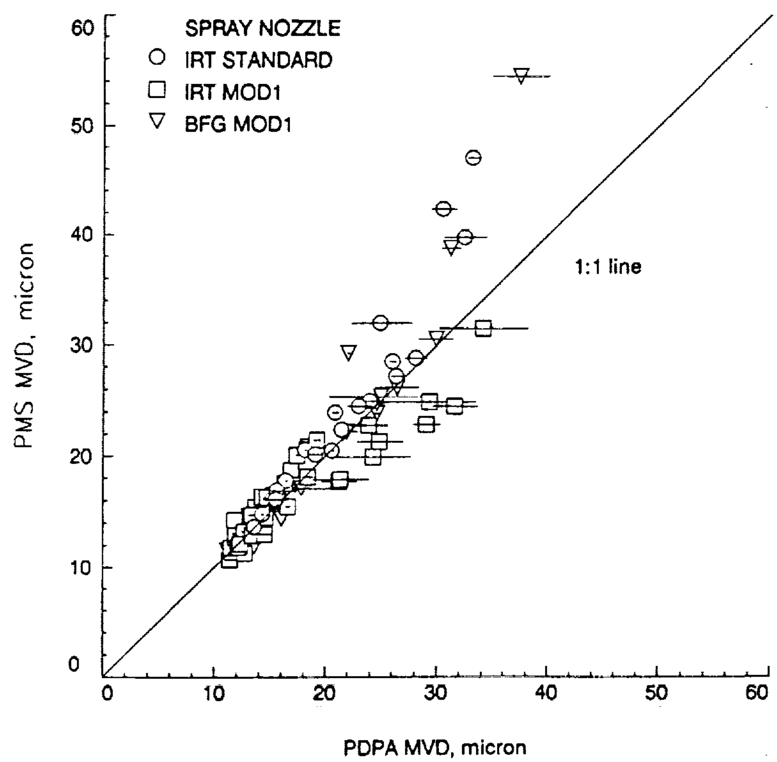


Figure 12. Comparison of the MVDs from the PDPA and the PMS combined distribution. Limits of the horizontal bars represents the two PDPA MVDs and the symbol represents the average of the two MVDs.

CONCLUSIONS

The comparison of the Phase Doppler Particle Analyzer, the Forward Scattering Spectrometer Probe, and Optical Array Probe over a large range of drop sizes has been presented. Comparison of number density and liquid water content distributions has demonstrated good overall agreement and has identified several specific areas where they differ.

A comparison of the droplet size measurements from the Phase Doppler Particle Analyzer and the combined Particle Measuring Systems (Forward Scattering Spectrometer Probe and Optical Array Probe) shows good agreement for median volume diameters between 10 and 30 microns.

For most icing cloud conditions, the drop size distribution of the Phase Doppler Particle Analyzer and Forward Scattering Spectrometer Probe below 10 microns differ significantly. This difference has a small effect on median volume diameters between 10 and 15 microns and no effect on median volume diameters above 15 microns.

For icing cloud conditions with median volume diameters above 30 microns, the Particle Measuring Systems median volume diameters are oversized because the magnitude of the volume distribution from the Forward Scattering Spectrometer Probe decreases relative to the Optical Array Probe. The Phase Doppler Particle Analyzer undersizes MVDs above 30 microns because for the configuration used, it failed to detect the large drop size end of the distribution because of inadequate sampling statistics. These effects combine to cause large differences between the median volume diameters above 30 microns measured by these two droplet measurement systems.

RECOMMENDATIONS

This test revealed specific areas where the PDPA and the PMS instruments disagree. Further comparison should be conducted to investigate these areas. A comparison between the PDPA and FSSP should be conducted with an ambient temperature droplet cloud to determine if droplet freeze-out causes the difference between these two instruments below 10 microns. For cloud conditions above 30 micron MVDs, a comparison between the PDPA and OAP should be conducted with the PDPA configured so that the upper limit of the PDPA's size range matches the OAP's and the counts at the end of the distribution are statistically significant. This test should be repeated using different types of spray nozzles to determine the effect of distribution shape on the comparison of these instruments.

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16. Abstract

A comparison between the Phase Doppler Particle Analyzer and the combined measurements from Particle Measuring Systems' Forward Scattering Spectrometer Probe and the Optical Array Probe was conducted in an icing wind tunnel using NASA Icing Research Tunnel spray nozzles to produce the supercooled water droplet cloud. Clouds having a range of volume median diameters from 10 to greater than 50 microns were used for the instrument comparisons. A volume median diameter was calculated from combining the droplet distributions of the Optical Array Probe and the Forward Scattering Spectrometer Probe. A comparison of the combined volume median diameters and the Phase Doppler Particle Analyzer volume median diameters showed agreement from 10 microns up to 30 microns. Typical drop size distributions from the Phase Doppler Particle Analyzer, the Forward Scattering Spectrometer Probe, and Optical Array Probe are presented for several median volume diameters. A comparison of the distributions illustrates regions of the distributions where there is good agreement and other regions where there are discrepancies between the Phase Doppler Particle Analyzer and the Particle Measuring Systems' droplet sizing instruments.

17. Key Words (Suggested by Author(s))

Droplet sizing instruments; Particle sizing instruments; Instrument comparisons; Droplet size distributions; PDPA; FSSP; OAP

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