

Manuscript Review

Laboratory and In-flight Evaluation of a Cloud Droplet Probe (CDP) Spencer Faber, Jeffrey R. French, Robert Jackson

Overview

This study of the Cloud Droplet Probe (CDP) is a follow-up to an earlier study by Lance et al. (2010) who established the technique that is used in the present study. Using a droplet generator on a micro-positioner, the authors repeat the measurements published in the earlier Lance et al. paper. As far as I can determine, the only difference in the two studies is that the current study uses a computer controlled positioner, the number of droplet sizes used is larger, covering almost the entire range of the CDP, and a different CDP serial number was used. There do not appear to be any results that contradict those in the earlier study, nor are there any new results that would suggest the need for any serious correction procedures. Hence, I would label this a confirmatory study.

We would like to thank Darrel for his thoughtful comments. Below we provide responses to general and specific comments and detail how the revised manuscript addresses these issues and improves the final manuscript.

Major comments

Uncertainty in collection angles

As I state in the overview, it doesn't appear that the current study differs in any significant way from that of Lance et al. If I err in this conclusion, then I suggest that the authors be more clear in the abstract, introduction and summary with respect to how this study distinguishes itself from Lance et al. I am a firm believer in confirmatory experiments even though they are rarely published. Even though it appears to me that the results support those of Lance et al., the broader size range used in this study justify its publication.

It is clear from your comments and those made by other reviewers that more needs to be said about how this study differs from Lance et al.'s 2010 work. In the big picture, the

use of computerized vs. manual positioning stages is a minor detail that seems to catch more attention than is warranted.

There are a few important ways the droplet generator tests conducted for this work differs from Lance et al.'s 2010 experiments.

- Our experiments tested CDP responses in locations covering the sample area for all seven droplet sizes whereas Lance et al. 2010 performed full “beam maps” for 12 and 22 μm droplets and then tested response at only the center of the sample area using a range of additional droplet sizes. Conducting beam maps for the entire range of droplet sizes provides more information about how droplet size influences the spatially-dependent nature of counting/sizing uncertainty. It also allows for a more complete investigation of how droplet diameter influences sample area dimensions.*
- Our experiments used finer spatial resolutions (sample locations every 30 x 20 μm for 9 μm droplets and 10 x 10 μm for all larger droplet sizes) than those conducted by Lance et al 2010 (200 x 20 μm spacing across a majority of the sample area with 50 x 10 μm spacing at the edges of the sample area). Finer resolutions were used to provide a more detailed picture of how CDP performance varies spatially and to provide more precise measurements of sample area dimensions.*
- This work was performed on a CDP that includes the pinhole mask modification. Lance et al 2012 did perform droplet generator tests on a modified CDP to measure ‘qualified’ and ‘extended’ sample area dimensions but limited detail was provided about the tests, as the paper focused on coincidence error. It seemed worthwhile to conduct detailed droplet generator experiments on a modified CDP to examine how the pinhole mask modification might affect the spatial nature of counting/sizing performance.*

The revised version of the text will be more explicit about how this study differs from this earlier work.

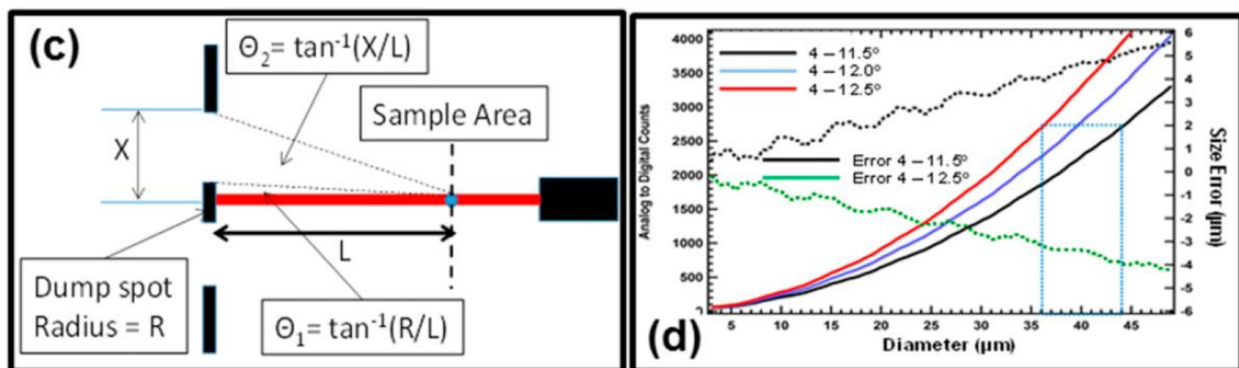
There are several points that are either missing or understated in this paper. Although the authors allude to our Chapter 9 in the AMS monograph, I don't think that they fully evolve the discussion of how important the collection angles are in introducing variations in the derived sizes from the scattering signal. The sizing accuracy for single particle light scattering spectrometers has been estimated as 20% and the concentration accuracy as 16% (Baumgardner, 1983; Dye and Baumgardner, 1984) and every publication since these have used these numbers, including the most recent book on aircraft measurements and our Chapter 9 in the monograph.

There are really two issues that cannot be separated. One, as you correctly point out, is the collection angles. The other is amplitude of the Mie resonances as illustrated in

figure 9.2 in Chapter 9 of the Monograph. The latter depends of course on particle size such that expected errors in drop sizing can be largest (~20%) for small particles ($d < 10\mu\text{m}$) and for large particles ($d > \sim 40\mu\text{m}$). However, these Mie resonances also depend on the collection angles as illustrated in Figure 2 of the original manuscript (Figure 3 in the revised manuscript). In the revised manuscript we further explore the impacts of both of these issues and how they relate to each other over a reasonable range of collection angles. This will be discussed in both the introduction and in the context of our measurements, expanding upon the current discussion in Section 4.2 on page 9 and in Section 6.

The figure from our Chapter 9, shown below, illustrates clearly the issue. With only a 0.5° change in the outer collection angle, there can be differences as much as $\pm 4\mu\text{m}$, depending on the size range and whether the actual collection angle is larger or smaller than the nominal. The length of the sample area, i.e. the DOF, is about 1.5 mm. Given that the particle distance from the dump spot determines the collection angle, $\pm 0.75\text{mm}$ changes the amount of scattered light collected and contributes to this uncertainty, particularly for the larger droplets, consistent with the observations.

This is an interesting point and one we hadn't really thought of in the context of our measurements. Because of the size of the DOF leading to a change in the collections angles along it, we should expect expect a gradient in sizing. However, our measurements do not show any appreciable change in sizing along the beam direction. The only test (of the seven performed) that showed any longitudinal dependence on sizing was for 17 μm droplets, and based on the individual counts (illustrated by the vertical bar in figure 2) across all of the drops for this test, the gradient in instrument response was very small and likely only shows up on the beam maps (Figure 3) because the probe response was near a threshold size between two bins.



I am frankly quite surprised that the average differences are so small between the actual versus the measured. These differences are well within the expected uncertainty.

Quite honestly, so were we. For all of the tests except the 9 μm droplets, mean differences were within 1 μm and errors based on these averages were on the order of 1-2% in most cases!

When we consider the difference between median diameter from the CDP compared to true droplet size, the comparison looks less good, but still well within the 20% expected uncertainty, and mostly within 10%. We do believe this difference (between whether using mean or using median {or modal}) should be considered carefully by investigators when considering calibration for a particular probe. A similar recommendation is suggested in Dye and Baumgardner (1984), but in a different context--they considered issues associated with 'clumping' of calibration beads. For the CDP this needs to be considered because of the skewing of the distribution that results from a severe undersizing of a very small percentage of droplets, at the far end of the DOF.

It should be possible to reanalyze the results after recalculating the Mie curves for the correct collection angles and setting new size thresholds to the 30 channels. How to do this? Very straight forward. Just run Mie calculations over a range of angles from perhaps 2 – 15°, in 0.5° steps and fit the results to the droplet measurements, using the particle by particle values that are given in digital counts without pre-binning. The collection angles that produce the best fit are the ones optimum for this particular CDP. If this unit doesn't have the PbP, the digital scattering values can be interpolated from the channels where the counts fall. With this optimization I predict excellent agreement over all sizes.

We began to investigate something very similar to what you describe here and actually reached a conclusion that it was anything but straightforward. In Figure 2, we provide Mie Response curves for two sets of collection angles (4-12 and 5-13). We overlay on these curves results from the PBP output for each of the tests. In this example, it is not clear to us which set of curves best represents the data.

Part of the difficulty comes down to determining the proper scaling between the Mie Calculations and the A/D counts output by the probe. The actual value of this scaling factor is not known, such that each individual curve is scaled to fit within the A/D range of the probe. IF we knew the actual scaling factor, which must be a function of the gain and the relationship between incident light intensity and probe voltage output, the true scale factor could be determined. Discussions with engineers at DMT indicated they used a methodology similar to what we describe above.

Laser intensity map

Completely overlooked in this study is the impact of the laser intensity on the sizing and sample area accuracy. This was overlooked in Lance et al. other than a brief mention at the very beginning acknowledging that laser beam intensity gradients can contribute to sizing uncertainty; however, the laser intensity was never mapped in their study.

Given that the intensity distribution is Gaussian across and along the beam, there will be a gradient within the sample area, although the design is meant to minimize missizing by centering the sample area in the flattest intensity region. That being said, without an intensity map that shows how the laser intensity varied within the sample area, it is pure speculation to hypothesize the edge effects on misalignment when some can be explained just be changes in collection angles within the area and others may be do to inhomogeneous laser intensity. This is an issue that can't be dismissed without some serious discussion.

We agree and appreciate you bringing this point to us. Because we don't measure the laser intensity, we cannot comment directly on its impact but it does indeed provide a plausible explanation for our results showing lateral-dependent sizing. Within the revised manuscript we provide more thorough discussion following the (modified) first paragraph in the Section 6 (renamed Summary and Discussion).

This expanded discussion explores all three potential contributors to missizing: laser inhomogeneities, optical misalignment, and Mie resonances & scattering angles. The 'flavors' of missizing reported in the manuscript (general over/under sizing for a particular droplet diameter vs lateral dependence) may likely come from different sources due to nature of the physical manifestations of these three potential contributors. This is also discussed in the revised manuscript along with specific recommendations for future studies.

Summary

I think that it should be clearly stated that the sizing and sample area uncertainties fall well within those that have been published over the past 25 years. I also think that the issue of broadening is overstated without and actual estimate of the degree of broadening. Otherwise, it is misleading and possibly even insignificant.

In the revised manuscript we clearly state that the uncertainties fall within the expected range reported in earlier studies.

We also use the PBP measurements to quantify the broadening based on the width of the 'true' droplet sizes and the width of the measured droplets for each test. These data will be included in one of the tables (likely table 2) or added as an additional table in the manuscript.

Minor comments

Page 1, Line 25: Nominal size range for CDP is 2-50 um.

The nominal size range of the CDP is corrected in the revision.

Page 2, Line 28. Dead-time has not been an issue in the FSSPs since the late 1980's when DMT introduced the SPP-100 replacement electronics for the FSSP.

The introduction will include discussion about how the SPP-100 electronics negate dead time losses in FSSP measurements.

Page 3, Line 3. "indexes" should be "indices".

This will be corrected in the revised version.

Page 4, Line 3, "568" should be "658"

Thank you for catching that mistake. It is corrected in the revision.

Page 4, line 5, "...in an $\sim 12^\circ$ arc, remove photons in the innermost $5 \sim 4^\circ$, and..". This is poorly worded and confusing. The CDP collects forward scattered light over a solid angle from $4-12^\circ$, determined by the distance of the center of focus from the dump spot, the diameter of the dump spot and the aperture in the arm of the CDP.

The wording has been corrected.

Page 4, Line 10. "The qualifier's rectangular mask is designed to reduce the collection angles of the detector so that responses are maximized when droplets pass through the qualified sample area.". This is not correct. The mask is designed to accept for sizing only those droplets that pass through the optimum simple area.

The wording has been corrected.

Interactive comment on “Laboratory and In-flight Evaluation of a Cloud Droplet Probe (CDP)” by Spencer Faber et al.

Anonymous Referee #2

Received and published: 26 February 2018

This is a thorough and concise manuscript which I recommend for publication after a couple of changes have been considered. Laboratory and airborne field characterizations of a commercial cloud droplet sizing spectrometer (CDP, Cloud Droplet Probe) are reported. As such it fits well into the scope of Atmos. Meas. Tech.

I have three general and a number of specific comments/suggestions:

We appreciate the feedback from the anonymous reviewer. Below, inline, we provide responses to the reviewer's general and specific comments.

General comments

Some discussion about the general applicability of the presented test results of a specific instrument of the CDP type to other instruments of the same type than tested here is required. To which extend the reported sizing deviations are systematic problems of the CDP, and to what extend they hold for the specific probe used here only?

We strongly agree with the sentiment that ‘to what extent our findings, for this specific probe, are more generally applicable to other CDPs’ is an important question’. In the original manuscript, we briefly mention at the end of paragraph 1 in the summary that the lateral dependence of sizing was also measured in two other CDPs tested on our system. It turns out, that those measurements also indicate a 1-2 μm oversizing through much of the sampled region for drops larger than about 25 μm . We will add the results of these measurements to the summary in the revised manuscript. However, to some extent, these measurements are anecdotal only. But they do show at least some consistency across different CDP instruments.

We also note in the original summary that a similar lateral dependence on sizing was reported by Lance et al (2010); although (and not discussed in our original manuscript) their limited resolution and test sizes did not reveal how this dependence changed with droplet size. The position dependent-sizing described by Lance et al (2010) shown in their figure 6a & 6d differed from our results. In particular, where it occurred within the sample volume--in all of our tests, the mis-sizing of droplets was rather symmetric with a lateral dependence across the sample volume (laser beam), and a small region near the detector where droplets were severely undersized. It may be that the specific probe described by Lance et al was not well-aligned (as suggested in their paper), and for later generations of the CDP, the optical alignment is better positioned/characterized by the manufacturer. Regardless, the missizing, in response to sample location, appears to have much better symmetry with the sample volume than reported by Lance. This discussion is added to the summary section of the revised manuscript (now revised as Section 6: Summary and Discussion)

It should be made clearer which progress has been achieved over the results reported previously (in particular with respect to Lance et al., 2010, 2012). Is there more than the incorporation of computerized position stages, instead of manual positioners as used by Lance et al. (2010)?

We discuss some of this above in our response to general comment #1. In terms of the droplet generator system, yes, only the addition of computerized stages has progressed over the system originally designed and described by Lance et al (2010). However, this manuscript is meant to focus not on the droplet generating system, but rather how using

that system enables further evaluation of CDP performance. To that end, the UW droplet generator provides a more thorough set of the experiments covering a broader range of droplets with higher spatial resolution across the sample volume. Lance et al.'s 2010 work tested CDP response at a grid of location throughout the sample area using only 12 and 22 μm droplets. This study includes similar experiments for seven droplet sizes, conducted at a much finer spatial resolution.

The revised manuscript elucidates how these additions provide a greater understanding of instrument response across its entire sample volume over the range of particles it was designed to measure. Much of this addition is in the summary and discussion in the revised manuscript. We also lay the groundwork for this in the introduction (Section 1) and discussion of the UW droplet generating system (Section 3).

It should be discussed that the two major parts of the paper (laboratory and field observations) actually don't have much to do with each other. In the lab the sizing was tested, in the field LWC data were evaluated. Also, droplet sizing spectrometers are not made to derive higher order moments of the size distribution, deriving LWC from this type of measurements is originally not intended by these droplet sizers. The immanent sizing uncertainties amplify (cube) in LWC. For LWC measurements different operating principles are much more appropriate, such as the well tested hotwire probes (e.g., the Nevzorov probe). Therefore, it is kind of unfair to compare the extremely error prone LWC data from the droplet sizing spectrometer to the much more straight-forward hotwire bulk probe LWC measurements. Why should you use a droplet spectrometer for LWC measurements if a bulk hotwire instrument is cheaper and much more accurate? I don't say that it makes no sense to compare both LWC measurements, in an ideal world both LWC measurements would agree. However, in the real world I am not surprised at all, that there is a huge discrepancy between the two approaches as illustrated in Figure 6 of the paper. I suggest to include a short discussion on this subject into the manuscript.

In terms of cloud property measurements, closure studies are very important. One way we accomplish this is by comparing different types of measurements--for example, those that respond to different aspects of the particle size distribution such as the 2nd moment (effective radius), 3rd moment (mass), or 6th moment (Rayleigh reflectivity). The point of all of this is that under the appropriate conditions, these closure tests should agree to within the uncertainty of the individual measurements after allowing for error propagation. The fact that we do not find complete agreement between the bulk LWC and the CDP-derived measurements is not a surprise (as you state). But rather, that the disagreement between the two is greater than what is able to be quantified by our best estimate of uncertainty in both measurements is disconcerting. This tells us that our error quantification for one (or both) of the measurements is incorrect. In the revised manuscript we add discussion in this regard. For the case presented here, one must accept uncertainty in LWC greater than that which is suggested based strictly on the Hotwire (or CDP) uncertainty estimates alone resulting from this closure argument. In the revised manuscript, we add discussion to this regard in section 5.

Specific suggestions

Title: The wording in the title is inaccurate in the sense that not the CDP probe itself, but its measurement uncertainties in terms of droplet sizing and LWC are evaluated. Maybe the title could be changed to something like "Laboratory and In-flight Evaluation of Uncertainties of Droplet Size and Liquid Water Content Measurements of a Commercial Cloud Droplet Probe". BTW: I always try to avoid acronyms in the title.

We have changed the title in the revised manuscript to: "Laboratory and in-flight evaluation measurement uncertainties from a commercial Cloud Droplet Probe (CDP)"

We acknowledge that the measurements are being evaluated and we spell-out the name of the probe. However, we suggest maintaining CDP within a parenthetical because it is well-established in the airborne cloud physics community (such as FSSP).

Abstract: Please quantify the seven droplets sizes generated in the lab; otherwise it is unclear what you mean with “For the smallest diameters” (lines 5-6 of abstract) and with “For all larger diameters” (line 7).

In the revised abstract we are explicit about the drop sizes tested. The revised abstract also provides quantification of the specific tests fkor different droplet sizes.

1. Introduction

I always try to avoid mentioning specific companies (PMS, DMT) in scientific papers, we should not advertise. That should be replaced by appropriate references to reviewed papers.

Agreed. While this is difficult in such a small field and (because of that) we often have probes with similar acronyms (for instance the DMT CDP and the SPEC F-CDP which are two different probes)...we have revised the manuscript to remove manufacturer’s name wherever possible.

I am glad you appreciate the major contribution of Lorenz and call it the “Mie-Lorenz theory” instead of mentioning Mie only. However, to be consequent you should call it “Lorenz-Mie theory”, Lorenz was first! And please stay consistent, later in your text you forget Lorenz and use “Mie-theory” only.

Instances of “Mie” have been standardized to “Lorenz-Mie” throughout the document.

I suggest to include the following additional reference when discussing the FAST-FSSP and instrumental broadening of size distribution: Schmidt, S., K. Lehmann, and M. Wendisch, 2004: Minimizing instrumental broadening of the drop size distribution with the M-Fast-FSSP. J. Atmos. Ocean. Tech., 21, 1855–1867.

This reference is now included in the discussion of OPC sizing uncertainty sources.

Page 3, first paragraph: You imply that Lorenz-Mie theory only holds for small droplets, which is not true. It is just not appropriate to apply Lorenz-Mie theory for larger particles; it is much more efficient to use geometric optics for larger particles. But in principle Lorenz-Mie theory is not restricted to small droplets, please would you make respective changes to the text.

Of course, you are correct...all scattering follows Lorenz-Mie theory. In the revised manuscript we state: “Due to the relationship between particle diameters and wavelength of incident radiation used in most OPCs, full Lorenz-Mie theory calculations must be considered to accurately relate particle size to scattered intensity.”

2. CDP Operating Principle

A schematic drawing of the CDP would greatly help readers not familiar with this type of instrument to follow your explanation of the principal of operation of the CDP. Alternatively, you may drastically reduce the description of the operational principal and refer to respective literature.

I mostly avoid to refer to gray-literature manuals provided by companies in scientific texts. If unavoidable, just give the web site address.

The revised manuscript includes reference to schematics of the optical design that were provided in Lance et al. (2010) and Baumgardner et al. (2017).

We agree with your comments regarding 'gray literature'. In the revised version of the manuscript, we removed references to the manufacturer's instrument manual. We do note, however, that some of the discussion can be confusing, especially if the paper is read several years from now; because probes such as these are constantly being 'improved' by the manufacturer. For instance, the probe used in our test has different characteristics than the one used by Lance et al. (2010) and the modified one used by Lance et al. (2012).

The differences between FSSP and CDP should be emphasized, progress achieved by CDP in addition to the revised electronics should be highlighted.

The revised manuscript includes additional discussion throughout section 1 and 2 about key differences between the CDP and the FSSP. Here we include revised electronics, the exclusion of the laser shroud, the unimodal (vs multimodal) laser and the differences in qualifier mask design.

Last line in paragraph 20 on page 4: Please quantify "high droplet concentration".

Standard coincidence depends upon flight speed (faster speed, greater probability for two particles being in the sample volume at same time). But at most research aircraft flight speeds (~80-120 m s⁻¹), standard coincidence is anticipated at less than 5% for concentrations on the order of 500 cm⁻³ based on a qualified sample volume of 0.3 mm² (Lance et al. 2010). This revised manuscript has been revised accordingly.

3. University of Wyoming Droplet Generating System

You need to make clear why you partly repeat work done already by Lance et al. (2010). A schematic illustration of the droplet generator setup might be helpful.

As noted above (and elucidated in the revised manuscript), the focus of this work is not to expand on the droplet generator setup (from Lance et al. 2010) but rather to expand on the measurements they provide. The revised manuscript describes how the UW setup allows a greater range of testing, across the full dynamic range of droplet sizes measured by the CDP and the full volume sampled.

A schematic illustration (now figure 1) has been added along with additional description of factors controlling the droplet sizes and placement.

Droplet speed measurements are discussed, at this point the reader asks why this is important. Later it becomes obvious that this is needed to compare with droplet velocities occurring in real aircraft measurements. Just make sure the reader understands here that these measurements have some meaning for the later text.

In the revised manuscript, we add text to describe to the reader that velocity measurements are needed to ensure that droplets are traveling at speeds within the operational airspeed of the CDP and to compare droplet velocity with typical aircraft airspeeds.

Maybe you briefly discuss about droplet evaporation during generation and transport to the sampling volume of the CDP.

How about mechanical distortions of the droplet generation setup and its impact on droplet generation, is there a problem with small-scale wind turbulence?

We, in part, control droplet size through evaporation. Increased residence time within the sheath flow increases evaporation and allows us to tune our experiment to a specific drop size (i.e. increasing residence time in the sheath flow reduces droplet diameter...therefore we can increase/decrease diameter by ejecting the droplets later/earlier in the flow field). The range of residence time in the sheath flow is provided in the revised manuscript.

Turbulence in the vicinity of the flow tube exit is an important consideration and is the main factor limiting droplet velocity. It turns out that turbulence at the point of droplet generation does not appear to be important (based on high speed photography of droplet generation events). However, the acceleration of those droplets (once generated) may induce distortions in the droplets as they are ejected from the accelerated flow into the CDP sample volume. Because we measure (independently) the size of droplets as they pass through the sample volume of the CDP (through the glare technique) we assume any impact of distortion is accounted for; however departures from spheroidal shape may result in slight mis-sizing...this is acknowledged in the revised manuscript; although the data collected does not allow for quantification.

4. Results of Droplet Generator Tests on the CDP

Second paragraph in 4.1: Quantify “Smaller droplets”, “shorter test periods”, and “less stable”.

In the revised manuscript we better describe the constraints of the experimental setup. In particular, for the smallest droplet produced (9 um) we needed to complete the test runs in roughly 25% of the time required for larger droplets. This was because we found that after a certain length of time, the size of the droplets (and/or the position of the droplets) was no longer predictable. Because of the shorter test periods, the resolution of the measurements was reduced and the number of droplets at each location was also reduced. The same was true for the 17 um resolution test, although the test was conducted over roughly 75% of the time required for larger droplets; so that the statistics are significantly improved. All other tests (for drops 24 um and larger) were completed at the same temporal and spatial resolution.

Figure 1: Maybe you add a similar figure just including droplets passing through the center of depth of field. The axis labels are way too tiny. Coloring is not optimal in my point of view.

The font size of axis labels for Figure 1 will be increased for better readability. The semi-transparent bars in Figure 1 are blue and a neutral grey so that overlapping regions don't appear as a third color. Changing the grey bars to a more obvious color could complicate interpretation of the figure.

Center of DOF measurements can be quite misleading. While this may (or may not) represent how the manufacturer calibrates the CDP, it does not represent what the probe itself measures in a cloud. In fact, we assert that the range of droplet mis-sizing quantified in Figures 1 and 3 is key to understanding how best to calibrate the probe. As we

discuss in the summary, determining whether to calibrate based on particle modal diameter or mean diameter has impacts across the droplet spectrum. Because the degree of mis-sizing depends on the droplet location within the sample volume, we believe that plotting the droplet size within a specific location (such as the center of DOF) is misleading and can result in wrong conclusions. For this, we maintain, that describing the response of the probe throughout the entire sample volume using a (nearly) monodisperse distribution is the best way to represent measurement sizing accuracy.

I don't see any reason why the pure counting efficiency is not exactly 100 %, please comment on that.

In general, we agree. Of course, on the very edges (within one 10 X 10 um sample bin) a droplet might fall on the edge resulting in reduced counts...but the more curious points in our study result from the over counting in the small region near the detector. Our results suggest something is occurring that is not well accounted for in the model of how the probe responds. We have no suggestion as to what might cause this result. While the overall effect (impact on total number counted) is small, it is curious that it occurs in the region located between the 'expected' normal sample volume and the 'region outside of the expected sample volume, where particles are severely under-sized'. The revised manuscript discusses this in sections 4 and 6, but at this time we don't offer any concrete explanations.

We find it curious that Lance et al (2010) found significantly larger mis-counting at different locations for their two tests (Figs 6b & 6e). Their results appear much more difficult to reconcile than our findings. This is discussed in the revised manuscript.

5. Comparison of . . . (please use capital letters for the section title, as you did before)

Some words in the section title are not capitalized in order to follow AMT guidelines: 'titles and headings should follow sentence-style capitalization standards (only first words and proper nouns are capitalized)'. Section titles with unnecessary capitalization are corrected in the revised manuscript.

As discussed above already, you are entering a new world here. Anyway, these data cannot be compared to your lab studies. Just discuss this, I don't want you to delete this section.

Agreed. We add a few sentences at the beginning of Section 5 outlining why are are conducting the comparison and how we are using results reported in the previous section to complete the closure study. We also add text at the end of Section 5 providing additional insight into the interpretation of these results.

Sometimes you duplicate/repeat figure captions in the text.

The revised manuscript removes these duplications.

The discussion of the differences in Figure 6 is kind of speculative. This is unavoidable, at least partly. A reader could ask why you mostly use data collected in complicated super-cooled conditions with quite some chance to encounter mixed-phase clouds. The matter is already complicated enough in pure liquid water clouds.

We agree, the discussion of Figure 7 (in the revised manuscript) is quite speculative. The main takeaway from this section is that further work utilizing data collected under a broader range of conditions and additional lab

experiments is needed to get a better understanding of exactly what is leading to the greater than expected difference between LWC estimates provided by the two instruments.

A majority of data used in this analysis were taken in super-cooled conditions because there were very few cloud penetrations with temperatures greater than 0 C encountered during SNOWIE and PACMICE. Comparing measurements from the two instruments in conditions that could contain liquid and ice particles is not ideal but IWC estimates from the Nevzorov were used to exclude periods that contained a significant number of ice particles. There are surely some mixed phase penetrations still included in the analysis but we believe ice particles minimally affected results because the Nevzorov LWC sensor has been shown to only be sensitive to 12% IWC (as demonstrated by Korolev et al., 1998), with IWC typically being small compared to LWC in mixed phase conditions. Also, Lance et al (2010) and Khanal (2013) have shown that the CDP is not greatly affected by natural or shattered ice particles.

The discussion on the droplet speed influence is not satisfying. No way to at least roughly test something in this regard?

Ideally, additional droplet generator tests using greater velocities would have been conducted to test how droplet speed influences the results. The current design of the UW droplet generator is not capable of that. We recommend that future tests should aim to increase droplet velocity to test instrument response at near-aircraft flight speeds.

Laboratory and in-flight evaluation of measurement uncertainties from a commercial Cloud Droplet Probe (CDP)

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Abstract. Laboratory and in-flight evaluations of uncertainties of measurements from a Cloud Droplet Probe (CDP) are presented. A description of a water droplet-generating device, similar to those used in previous studies, is provided along with validation of droplet sizing and positioning. Seven experiments with droplet diameters of 9, 17, 24, 29, 34, 38, and 46 μm tested sizing and counting performance across a 10 μm resolution grid throughout the sample area of a CDP. Results indicate errors in sizing that depend on both droplet diameter and position within the sample area through which a droplet transited. The CDP undersized 9 μm droplets by 1 – 4 μm . Droplets with diameters of 17 and 24 μm were sized to within 2 μm , which is the nominal CDP bin width for droplets of that size. The majority of droplets larger than 17 μm were oversized by 2 – 4 μm , while a small percentage were severely undersized, by as much as 30 μm . This combination led to an artificial broadening and skewing of the spectra such that mean diameters from a near mono-disperse distribution compared well (within a few percent) while the median diameters were oversized by 5 – 15%. This has implications on how users should calibrate their probes. Errors in higher order moments were generally less than 10%. Comparisons of liquid water content (LWC) calculated from the CDP and that measured from a Nevzorov hotwire probe were conducted for 17,917 1 Hz in-cloud points. Although some differences were noted based on volume-weighted mean diameter and total droplet concentration, the CDP-estimated LWC exceeded that measured by the Nevzorov by approximately 20%, more than twice the expected difference based on results of the laboratory tests and considerations of Nevzorov collection efficiency.

1 Introduction

In-situ cloud studies often utilize measurements from forward scattering optical particle counters (OPCs) to provide size and concentration information about cloud hydrometeors up to a few 10's of microns in diameter. The Forward Scattering Spectrometer Probe (FSSP; Dye and Baumgardner, 1984) and the Cloud Droplet Probe (CDP; Lance et al., 2010) are forward scattering OPCs used to measure hydrometeors of 2 – 50 μm in diameter. These instruments measure the intensity of light scattered from particles transiting an open-path laser and relate that to particle size utilizing Lorenz-Mie theory and assumptions about the particles (typically that they are liquid and spherical). The instruments output measurements as cumulative binned counts of droplet diameter. Some instruments including certain versions of the CDP, Fast CDP (FCDP)

Microsoft Office User 4/30/2018 11:01 AM
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Jeff French 5/21/2018 3:57 PM
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Microsoft Office User 4/14/2018 2:37 PM
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and FAST-FSSP (Brenguier et al., 1998) are also capable of providing the sizes and interarrival times of individual particles. Cloud particle sizes and counts are used to construct size distributions and calculate higher distribution moments.

Several sources may contribute to OPC sizing and counting errors that in turn propagate through to higher moments (Dye and Baumgardner, 1984; Baumgardner et al., 1985; Cooper, 1988; Baumgardner and Spowart, 1990; Brenguier et al., 1998; Schmidt et al., 2004; Wendisch and Brenguier, 2013; McFarquhar et al., 2017). Sizing error can also result in artificial broadening of hydrometeor size distributions which can mistakenly be attributed to distribution-modifying cloud processes (Baumgardner et al., 1990). The non-linear relationship between droplet diameter and the intensity of light scattered by a droplet limits the resolution of size bins (Pinnick et al., 1981). The CDP has a default bin width of 2 μm for diameters larger than 14 μm , which can result in as great as 15% uncertainty in diameter (Nagel et al., 2007). Lorenz-Mie resonance, which is more pronounced for the CDP's unimodal laser, also introduces sizing uncertainty for droplet diameters smaller than 14 μm (Knollenberg, 1976; Nagel et al., 2007).

Laser intensity and droplet scattering angles vary based on droplet transit location (Dye and Baumgardner, 1985; Brenguier et al., 1998). Therefore, droplets are only counted and sized if they pass through the qualified sample area; an elliptical region within the depth of field (DOF) where laser intensity and droplet scattering angles are relatively homogenous. Nonetheless, laser intensity and scattering angles are somewhat variable within the qualified sample area, resulting in counting and sizing error that is dependent on droplet transit location (Brenguier et al., 1998; Wendisch et al., 1996). For the geometry of the CDP, one may expect a variation of 2° in collection angles along the DOF, introducing uncertainty as large as 20% in sizing along the beam (Baumgardner et al., 2017). Uncertainty in collection angles can also be a result of variations in optical component placement for individual probes (Dye and Baumgardner, 1984). The cross-sectional area of the depth of field (DOF) is included in calculations of sample volume, such that errors in the length of the DOF will propagate as a scaling bias in concentration (Wendisch et al., 1996).

Coincidence error is a concentration-dependent phenomenon that occurs when multiple droplets are simultaneously within the sensitive area of an OPC's laser. Coincidence can affect sizing and counting accuracy but errors can be difficult to characterize because they depend on many factors including particle concentration, particle size, the location that particles transit the laser, and instrument optical design (Baumgardner et al., 1985; Cooper, 1988; Brenguier, 1988).

Historically, FSSP electronic limitations required an 'electronic delay sequence' for a period after particle detection. Particles passing through the sample area during the delay sequence were not detected resulting in undercounting, or 'dead time losses', which required algorithmic corrections to FSSP-measured concentration (Baumgardner et al., 1985; Brenguier et al., 1998; Baumgardner and Spowart, 1990; Brenguier et al., 1998). Improved electronics introduced in the 1990s negated

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dead time losses in FSSP measurements. Likewise, dead time losses do not impact newer OPCs such as the FAST-FSSP, CDP, and FCDP.

Forward scattering OPC measurements require that several assumptions be made about cloud particles. OPC techniques assume that measured particles are primarily composed of water and therefore have refractive indices equal to that of pure water (Pinnick et al., 1981). Due to the relationship between particle diameters and wavelength of incident radiation used in most OPCs, full Lorenz-Mie theory calculations must be considered to accurately relate particle size to scattered intensity. Particle shape affects scattering behaviour, so it is assumed that liquid hydrometeors are spherical (Nagel et al., 2007). Several researchers have used the FSSP to study ice hydrometeors but such measurements are subject to uncertainty imposed by the variability in ice particle shape (Gardiner and Hallett, 1985; Field et al., 2003).

In mixed and ice phase cloud, ice particles are prone to shattering on contact with OPC structures. If passed through the sample area, ice fragments can be erroneously identified as natural particles leading to errors in counting and sizing and an artificial bimodality in hydrometeor distributions (Gardiner and Hallett, 1985; Korolev and Isaac, 2005). FSSP measurements can be greatly affected by shattering artifacts because the probe's laser is housed in a cylindrical shroud (Heymsfield, 2007; McFarquhar et al., 2007). The CDP features an open-path laser that is passed between two arms that are often outfitted with anti shattering tips. As a result, particle shattering introduces negligible uncertainty in CDP measurements, as demonstrated in work by Lance et al. (2010) and Khanal (2013).

The FSSP and CDP are often calibrated by passing glass microbeads or polystyrene spheres through the sample area. These methods have crude control of calibration media placement and concentration such that they are only capable of testing OPC sizing response. Because these methods have limited control of particle concentration, coincidence can compromise calibrations (Wendisch et al., 1996). Furthermore, the refractive indices for glass and polystyrene differ from that of water requiring a correction be applied to calibration measurements (Nagel et al., 2007). Wendisch et al. (1996), Korolev et al. (1991), Nagel et al. (2007), and Lance et al. (2010, 2012) developed droplet generating calibration systems that can produce and precisely place a mono-disperse stream of droplets of a known size/frequency at discrete locations within an instrument's sample area. These systems can test locationally-dependent sizing/counting accuracy at specific locations throughout an instrument's sample area and in turn provide measurements of sample area dimensions.

This work uses a water droplet generating system to assess CDP counting and sizing performance and to provide measurements of sample area dimensions. Seven droplet generator experiments with droplets of 9 – 46 µm in diameter provide data for detailed evaluations of CDP performance at locations throughout the sampling area of the probe. This work is similar to the earlier work reported by Lance et al. (2010), but utilizes a wider range of droplet sizes over the entire qualified sample area and a much higher resolution of measurements across that area. This in turn provides a more

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comprehensive estimate of uncertainties associated with droplet sizing throughout the sample area for the entire range of droplet sizes measured by the CDP. Estimates of how errors in sizing and counting affect higher order moments are provided. Comparisons of in-situ CDP-derived liquid water content (LWC) and bulk LWC measurements from a hotwire device provide an additional means of evaluating probe performance.

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2 CDP operating principles

The CDP features two forward-protruding arms. One houses a 658 nm unimodal laser diode intended to provide a more uniform distribution of laser intensity compared to the multimodal laser used in the FSSP. The other arm contains a series of collecting optics and photodetectors. As the CDP is flown through cloud, some droplets transit the laser beam projected between the arms of the probe and scatter energy. The collecting optics are designed to capture forward-scattered light over a solid angle of 4-12°. Collected photons are focused onto a beam splitter that divides the scattered light before passing it to a sizer photodetector that is covered by an 800 µm diameter pinhole mask and a qualifier photodetector that is masked by a rectangular slit. Lance et al. (2010) and Baumgardner et al. (2017) provide optical schematics that demonstrate the operating principles of the CDP. Responses from the two photodetectors are converted to digital counts ranging from 1 – 4095 counts. Sizer responses are used to estimate droplet diameter through Lorenz-Mie theory. A droplet is considered to be within the qualified sample area (or a “qualified droplet”) if the signal from the qualifier is greater than one-half of the signal from the sizer. The CDP uses a rectangular qualifier mask, instead of the circular design found in legacy FSSPs, to more precisely constrain the sample area to regions of relatively homogenous laser intensity (Lance et al., 2010). The CDP employs a dynamic sizer signal threshold in order to minimize false counting events resulting from impinging solar radiation or other sources of noise. This is accomplished by considering all sizer responses within a 10 Hz period that result in less than 512 digital counts. A noise band is defined as the region that contains at least 75% of responses with less than 512 counts. Sizing/counting events are rejected if sizer response is less than the determined noise band.

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Standard coincidence occurs when multiple droplets are simultaneously within the qualified sample area of a CDP. OPCs are designed to count/measure a single particle at a time so standard coincidence results in undercounting and can also lead to oversizing due to the additional light scattered by coincident hydrometeors (Baumgardner et al., 1985; Cooper, 1988). Because the qualified sample area of the CDP laser is relatively small (on the order of 0.3 mm²), the probability of standard coincidence has been estimated to be less than 5% for a droplet concentration of 500 cm⁻³ (Lance et al., 2010).

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Originally, the sizer detector was unmasked, meaning that it was sensitive to light scattered by droplets transiting through a region surrounding the qualified sample area, called the extended sample area. Droplets passing through the extended sample area cause insignificant qualifier detector responses so they are not counted or sized. A specialized form of coincidence,

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called extended coincidence, occurs when droplets are simultaneously within the qualified and extended sample areas (Lance et al., 2010 and 2012). Coincident droplets within the extended sample area scatter additional light that can in turn result in oversizing of qualified droplets. Extended coincidence can also lead to undercounting if sizer response exceeds a threshold value. Lance et al. (2010) used a droplet generating calibration system to measure the qualified and extended sample areas (SA_Q and SA_E) using droplets with 12 and 22 μm diameters. The researchers found that SA_E can be much larger than SA_Q (20.1 mm² vs. 0.3 mm²) resulting in errors from extended coincidence up to 60% oversizing and 50% undercounting in concentrations as low as 400 cm⁻³ (Lance et al., 2010). Results from Lance et al.'s 2010 study motivated the addition of an 800 μm diameter sizer pinhole mask that decreases the size of the extended sample area to ~2.7 mm², thus reducing the occurrence of extended coincidence (Lance et al., 2012). It was concluded that extended coincidence introduces negligible uncertainty in droplet concentrations less than 650 cm⁻³ for CDPs featuring the sizer mask modification.

Lance et al.'s (2010) droplet generator work also tested CDP sizing and counting accuracy throughout the qualified sample area (at a spatial resolution of 200 x 20 μm) using 12 and 22 μm droplets. Ten additional tests investigated sizing accuracy at the centre of the qualified sample area using droplet diameters of 8 – 35 μm. It was shown that droplets are systematically oversized by 2 μm at the centre of the qualified sample area and that sizing accuracy for 12 and 22 μm droplets is dependent upon where droplets transit the qualified sample area. Droplets were undersized by as much as 74% in certain sample locations and oversized by as much as 12% in others (Lance et al., 2010). It was found that on average, 12 and 22 μm droplets were counted to within 95% accuracy. Counting error is more severe at the edges of the qualified sample area as a result of photodetector signal noise (Lance et al., 2010).

3 University of Wyoming droplet generating system

The University of Wyoming (UW) Atmospheric Science Department developed a droplet generating calibration system very similar to the system built by Lance et al. (2010, 2012) which is based on work by Korolev et al. (1991), Wendisch et al. (1996), and Nagel et al. (2007). A detailed explanation of the design and operation of a droplet generating system can be found in Lance et al. (2010). Figure 1 shows a cross section view of the UW droplet generator flow tube assembly. A piezoelectric print head (shown in red) is fixed to the end of the print head positioning rod (green) so that it can produce a consistent stream of droplets within the glass flow tube. Dry air enters the assembly through the sheath flow inlet (purple inlet at the top-left) and passes through the honeycomb flow straightener (blue) before entering the flow tube. The sheath flow and suspended droplets travel downward and exit through the tapered region at the end of the flow tube. Here the sheath flow is accelerated, which by extension, accelerates and focuses the suspended droplets into a precise stream. The accelerated droplet stream then passes through the CDP's sample area at discrete locations. The CDP is mounted atop a pair of two-axis

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computer-controlled positioning stages that are used to control the point of droplet injection and provide the coordinates of injection locations.

Droplet size is coarsely adjusted by utilizing print heads with different orifice sizes. Altering droplet residence time within the sheath flow, and thus the degree of evaporation, allows for more precise droplet size adjustments. The print head positioning rod and, by extension, the vertical position of the print head is raised or lowered within the flow tube to vary the droplet residence time and provide fine adjustments to droplet sizes at the point of ejection. During experiments the print head is typically placed 65 – 120 mm above the flow tube exit.

A high speed metrology camera outfitted with a 10X microscope objective provides an independent measurement of droplet diameter using the glare technique as described by Korolev et al. (1991), Wendisch et al. (1996), Nagel et al. (2007), and Lance et al. (2010). As droplets pass through the laser of the CDP, the left and right sides of the droplet are illuminated as a result of reflection and refraction. The metrology camera images these illuminated regions (glares) which appear as two parallel lines when using an exposure time of 1/1000 sec. Estimates of droplet diameter are obtained by considering the pixel separation of glares, a pixel to distance conversion, and a formula that accounts for the angle of the camera objective relative to the laser (Wendisch et al., 1996; Korolev et al., 1991). Using this technique, the UW system is capable of determining individual droplet diameters to within $\pm 0.355 \mu\text{m}$.

Estimates of droplet velocity are necessary to compare droplet ejection speeds to aircraft airspeeds encountered during research missions and ensure that ejection velocities are within the operational limits of the CDP. The metrology camera is used to estimate droplet velocity by capturing images with exposures on the order of 1/150,000 – 1/300,000 second, which produces glare images with well-defined start and end points. Droplet velocity is estimated by considering glare length, a pixel to distance conversion, and exposure time. The longitudinal position of glares can also be used to evaluate droplet placement precision.

A number of validation tests were performed to ensure that the UW droplet generator can produce droplets of consistent diameter for the amount of time required to conduct a test (~4 hours), precisely place droplets at discrete locations within the sample area, and eject droplets at suitable velocities. Seven droplet generator tests that produced droplet diameters of 9 – 46 μm are used to evaluate accuracy and consistency in droplet diameter. During the course of each test, glare images were captured once every second and a random sample of 80 images were analysed to provide distributions of true droplet diameter (D_{true}). Table 1 shows that standard deviation of D_{true} is less than 0.7 μm for all seven tests. It also shows that all but one test produce 95th – 5th percentile range of D_{true} less than the 2 μm bin width of the CDP (for droplets larger than 14 μm).

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Two tests were conducted that used the deviation of glare position to validate droplet placement precision. To confirm that placement precision is similar along orthogonal axes, glare images of 32 μm droplets were captured for 1 hour with the metrology camera placed at 124.9° incident to the CDP laser and an additional hour at 214.9° incident. Glare position for a random sample of 50 images from each camera angle show that droplet deviation is similar along orthogonal axes. The absolute deviation of glares is 5.7 μm along both axes and standard deviations are 1.5 and 1.7 μm for the 124.9° and 214.9° camera angles respectively. A separate experiment tested long term placement precision by analysing 80 random glare images captured over the course of a four-hour test. Droplet position for the sample has an absolute range of 11.4 μm and a 95th – 5th percentile range of 9.3 μm . Approximately 8% of droplets were placed beyond 10 μm .

10 Droplet ejection velocity is validated by capturing images using exposure times of 1/150,000 – 1/300,000 sec. It was found that when droplets were created and accelerated in a 13 l min⁻¹ sheath flow, 40 μm diameter droplets cross the CDP laser at ~32 m s⁻¹. This velocity is only about 30% of typical University of Wyoming King Air research airspeeds but is greater than the minimum operational airspeed of the CDP (10 m s⁻¹). Droplet exit velocity is limited by turbulence in the vicinity of the flow tube exit, which results in significant deviations of droplet position when sheath flow rate exceeds 13 l min⁻¹.

15 4 Results of droplet generator tests on the CDP

4.1 Experimental design

To quantify uncertainty in CDP measurements of droplet counting and sizing, seven tests using nominal droplet diameters of 9, 17, 24, 29, 34, 38, and 46 μm provided measurements over most of the size range detectable by the CDP. For each test, droplets were injected at fixed locations through the qualified sample area of the CDP. Droplets were injected at a frequency of 200 Hz for 9 μm droplets and 250 Hz for all other sizes. Following a dwell time at a given location, the position of the droplet injector relative to the CDP sample area was moved a small distance. The tests proceeded in this fashion, injecting droplets throughout the entire qualified sample area of the CDP. The start and end times at each location were recorded. Post-test, 5 Hz data from the CDP were synchronized to match droplet location and CDP measurements.

25 The time required to complete a full test was in some cases as long as 5 hours (see Table 1). Stability of the droplet generator system over this time depends, in part, on the size of droplets being produced. For tests producing droplets with diameters less than about, the droplet generator system tended to be less stable, reducing the total time that it could produce drops of a similar size. Thus, for the two tests with droplet diameters less than 20 μm , shorter test periods were required. For the five tests using droplets 24 μm and larger, the dwell time at each sample location was 2 seconds. This resulted in 500 droplets passing through the CDP sample area at each location. For these same tests, a 10 μm by 10 μm grid of sample locations covered the entire test area, corresponding to 2700 discrete sample locations across the approximately 0.27 mm² qualified sample area of the CDP. For the test using 17 μm droplets, the dwell time at each location was reduced by a factor of 2 and

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the grid resolution remained the same. The system was least stable when producing 9 μm droplets and required test times of less than 2 hours to ensure consistent droplet sizes and placement throughout the experiment. For this test, dwell time was further reduced such that 200 drops were placed at each location and the resolution of the grid was reduced to 30 μm by 20 μm , resulting in roughly 450 discrete locations across the qualified CDP sample area.

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4.2 CDP sizing

CDP measurements for all droplets detected during a given test were used to produce a distribution of droplet diameters for that test. Droplet distributions were computed using number counts from each of the CDP's 30 pre-determined size bins. Bin widths are 1 μm for diameters less than 14 μm , and 2 μm for diameters greater than 14 μm . For each bin, we considered the geometric mean diameter, hereafter referred to as D_{CDP} . Also, for each test, 80 randomly selected droplet glares were analysed to determine a distribution of actual droplet diameters, D_{true} . These droplets, when binned according to CDP size bins, resulted in a distribution of droplets, D_{true}^* .

Figure 2 shows distributions of normalized frequency for D_{CDP} and D_{true}^* for each of the seven tests. In general, the mode diameter of the distribution based on sizing from the CDP (D_{CDP}) was within one to two size bins (1 to 4 μm) of the D_{true}^* mode. For the test using 9 μm droplets, more than 50% of the droplets detected by the CDP were placed in the 7.5 μm bin and another 30% were placed in the 8.5 μm bin. Nearly 90% of the randomly selected droplets were determined to have actual diameters between 8 and 10 μm , suggesting that the CDP undersized droplets in this range by about 1 to 2 μm . Table 2 shows that the absolute difference between mean D_{CDP} and mean D_{true}^* was 1.3 μm .

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Tests using 17 and 24 μm diameter droplets resulted in a better match between D_{CDP} and D_{true}^* . For each test, the medians and modes of D_{CDP} and D_{true}^* were in the same bin and more than 95% of the droplets were contained in the same two bins. However, the breadth of the distribution measured by the CDP was slightly larger than the actual distribution for the 17 μm test. And, for the 24 μm test, the distribution measured by the CDP was skewed to smaller sizes. For both tests, absolute differences between the means of the distributions were less than 1 μm (Table 2).

For the 29, 34, 38, and 46 μm diameter tests, a steady trend of oversizing with increasing droplet diameter is apparent when comparing the normalized histograms of D_{CDP} and D_{true}^* (Fig. 2). In all cases, the mode diameter from CDP measurements was one bin larger than the true diameter mode. For the largest droplet test, 46 μm , 55% of the droplet diameters from the CDP fell in the 48 to 50 μm bin and another 10% fell in each of the 44 to 46 and 46 to 48 μm bins. More than 95% of the actual diameters were split roughly equally between the 44 to 46 and 46 to 48 μm bins.

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Skewing of the CDP-measured distribution to smaller sizes occurred for all tests using droplets 24 μm and larger. Further, the breadth of the CDP-measured distribution increased with increasing droplet diameter. This is perhaps more apparent

from the data in the last column in Table 2. Here we compare the difference between the 95th and 5th percentile range for D_{true}^* and D_{CDP} . The difference increased significantly for larger diameter tests. Interestingly, even though the difference in both the mode and median diameters of the CDP-measured distributions (compared to D_{true}^*) were larger for these larger diameters, the absolute difference between the means of the distributions were quite small, roughly 0.1 to 0.2 μm . This is because, with the measured distributions skewed to smaller diameters, comparisons of mean diameters appeared to compare more favourably.

By matching the measured response of the CDP to the expected Lorenz-Mie scattering curve, it is possible to investigate whether the errors in sizing observed from the droplet generator tests may be accounted for by limitations due to Lorenz-Mie resonances or by uncertainty in scattering angle collection. The CDP's nominal collection angles are 4° to 12°. However, collection angle uncertainty can be introduced by variations in the mounting of optical components and the fact that collection angles vary based on droplet transit location. Baumgardner et al. (2017) showed that a 500 μm variation in the longitudinal transit location of a droplet could alter the outer collection angle by as much as 2°. However, as will be shown later in this section, locationally-dependent sizing errors occur across the beam rather than longitudinally along the beam. One may still find differences in scattering angles across the beam, but due to the much narrower width of the DOF and the geometry of the optics, impacts on scattering angles should be significantly less, and they should be symmetric about the center of the beam, at least for perfectly aligned optics. Figure 3 shows that the Lorenz-Mie response curve matches reasonably well with the CDP threshold counts that are used to sort droplets into discrete size bins. Two ranges of scattering angles are considered and both show similar behaviour. In fact, regardless of which range of angles are considered, the error in sizing is expected to be, on average, nearly the same. Errors in drop sizing for individual drops, however, will vary depending on collection angles.

The shaded region in Fig. 3 illustrates the range of threshold counts that the CDP uses to determine the size bin for an individual drop. Regions where the Lorenz-Mie curve(s) lie within the shaded regions are locations where a drop will be sized 'correctly'. If the Lorenz-Mie curve is above the shaded region, the drop will be oversized; below the shaded region it will be undersized. The amplitude of the Lorenz-Mie resonances and the locations of the peaks and valleys depend on droplet diameter and vary with collection angles. Generally, the amplitude of the Lorenz-Mie resonances increases with increasing drop size, however, so does the 'steepness' of the curve. Therefore larger droplets, 40 to 50 μm in diameter, should not be undersized or oversized by more than about 2 μm . However, smaller droplets less than about 20 μm in diameter may easily be mis-sized by more than 2 μm , accounting for as much as $\pm 20\%$ error in sizing (Baumgardner et al., 2017).

Results from the droplet generator tests overlaid on Fig. 3 provide additional insight into CDP response. The mean and 5th to 95th percentile range of D_{true} illustrates that the droplets being produced nearly all fell within one size bin of the CDP for any

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given test. The corresponding [Lorenz-Mie](#) resonance curves over those same size ranges generally fluctuate over a range of A/D counts that correspond to threshold values of up to 2 to 3 size bins. This can be seen by examining the [Lorenz-Mie](#) response ($4^\circ - 12^\circ$) for the test producing $29\ \mu\text{m}$ drops. Over the range of droplet sizes produced, some locations of the [Lorenz-Mie](#) curve fall just below the threshold box (for $28\text{-}30\ \mu\text{m}$ bin), while others fall slightly above and still other fall inside the box.

The skewing of CDP-measured distributions to smaller sizes is also apparent by examining the CDP response compared to the threshold curves. For each test, the mean value of A/D counts (Fig. 3) lies either within or very near the appropriate threshold box for that droplet diameter. However, the median value of A/D counts exceeds the threshold box for that droplet diameter for all tests using droplet diameters $29\ \mu\text{m}$ and greater. This suggests that the calibration of the CDP is based upon mean diameter of drops rather than the median or mode diameter. While this may be appropriate, because of the unnatural skewing to smaller sizes, it does have implications on calculations of higher order moments. The severe undersizing of a small sample of drops for these same tests cannot be explained based on [Lorenz-Mie](#) resonance or collection angle considerations.

Figure 4 illustrates sizing from the CDP across the entire qualified sample area. For each sample location, the mean of D_{CDP} is compared to the mean of D_{true}^* . A positive difference (warm colours) indicates oversizing by the CDP, negative values (cool colours) indicate undersizing. For the $9\ \mu\text{m}$ diameter tests, undersizing of droplets by 1 to $2\ \mu\text{m}$ was found throughout most of the CDP sample area. Droplets passing through the centre of the beam and laterally towards the top experienced somewhat less undersizing than in other regions. No regions indicated oversizing of droplets. For the $17\ \mu\text{m}$ tests, droplets throughout much of the sample area were sized correctly. In only a small region, laterally towards the top of the beam and towards the detector, were droplets oversized, on average by about $1\ \mu\text{m}$.

The five remaining droplet tests, $24\ \mu\text{m}$ and larger, all revealed a similar behaviour. In all cases, there was a lateral dependence on sizing from the top to the bottom of the beam along the entire length of the qualified sample area. The magnitude of the sizing difference laterally across the beam increased with increasing droplet size. For the $24\ \mu\text{m}$ test, the sizing difference was only about $2\ \mu\text{m}$ across the beam, but for the $46\ \mu\text{m}$ test, the sizing difference was nearly $6\ \mu\text{m}$ across the beam. Also, for each of these five tests, a region near the detector showed significant undersizing of droplets that also increased in magnitude with increasing droplet size. For the $46\ \mu\text{m}$ test, droplets were undersized by as much as $30\ \mu\text{m}$. This region accounts for the skewing to smaller sizes of the distributions discussed earlier in this section.

Columns three and four in Table 2 provide information about how sizing differences for each test impact higher moments of the droplet size distribution. For the $9\ \mu\text{m}$ test, the volume-weighted mean diameter (VMD) measured by the CDP was $1.1\ \mu\text{m}$ small compared to that computed from the D_{true}^* distribution, resulting in a 36.7% underestimate in LWC. For the 17 and

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24 μm tests, the absolute difference between the actual and measured VMD was less than 0.25 μm and resulted in a roughly 8% overestimate and 2% underestimate in LWC for these droplets, respectively. For tests using droplets larger than 24 μm , the CDP oversized VMD from 1 to 1.5 μm , resulting in overestimates of LWC of 2.4 – 11%. Readers should note that errors in sizing by a given amount will have a much more significant impact on LWC for smaller droplets. However, for real measurements in cloud, it is often the larger droplets that carry the majority of the liquid mass. Therefore, these middle and larger sizes from 20 μm and greater are expected to have the greatest impact on LWC estimates from the CDP.

4.3 Counting accuracy and qualified sample area measurements

Counting accuracy is evaluated by comparing CDP-recorded counts to the actual number of droplets based on print head ejection frequency and dwell time at each sample location. For all tests, droplets are counted to within 98% accuracy in ~95% of the sample locations. Experiments indicate that all sizes of droplets are undercounted around the perimeter of the qualified sample area. This behaviour is likely a result of small deviations in droplet placement. Figure 5 shows locationally-dependent counting accuracy for 46 μm droplets where purple areas correspond to locations where the CDP recorded 10 - 50% of actual counts, blue show locations where 50 – 90% of actual counts were recorded, and green denotes where at least 90% actual counts were recorded. Only 46 μm droplets were over counted, specifically in two isolated regions where droplets were over counted by as much as 100%. The regions are located just left of the area where 46 μm droplets were significantly undersized (see Fig. 4g and discussion earlier). Over counting in these regions contributes to less than 1% overall count error because they occupy less than 1% of total SA_Q .

Figure 6 shows SA_Q calculated by summing the individual areas of sample locations that received a certain percentage of actual counts. SA_Q is calculated three times for each test by constraining which sample locations are considered to those that received at least 10, 50, and 90% actual counts ($SA_{Q_{10\%}}$, $SA_{Q_{50\%}}$, $SA_{Q_{90\%}}$). Evaluating SA_Q using this count threshold method provides uncertainty ranges of SA_Q and accounts for the fact that ~8% of droplets were placed beyond sample area bounds.

The mean value of $SA_{Q_{50\%}}$ considering all tests is 0.269 mm^2 ; compared to a value of 0.30 mm^2 provided by the manufacturer. $SA_{Q_{50\%}}$ varies 0.03 mm^2 across the range of droplet diameters tested. It is smallest for 9 and 17 μm droplets, reaches a maximum of 0.28 mm^2 for 24 μm droplets, and then decreases to 0.27 mm^2 for 46 μm droplets. The range of $SA_{Q_{10\%}}$ to $SA_{Q_{90\%}}$ is smallest for the largest droplets, most likely because detector noise is less of a consideration for larger droplets that scatter relatively more light and hence provide a greater detector response. The test using 9 μm droplets shows the greatest difference between $SA_{Q_{10\%}}$ and $SA_{Q_{90\%}}$, but it should be noted that SA_Q variability is likely exaggerated by the coarse spatial resolution used for that experiment.

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For calculations of number concentration and higher moments, SA_Q can be provided by either using a fixed value equal to the mean for all droplet sizes (solid red line in Fig. 6) or by using a variable value based on a second degree polynomial fit (blue curve in Fig. 6). To explore the impact of employing a fixed vs. variable SA_Q , three Poissonian droplet distributions with means of 10, 25, and 35 μm are prescribed. The concentration of each distribution equals 100 cm^{-3} when calculated with a fixed $SA_{Q,50\%}$ of 0.27 mm^2 . Table 3 illustrates how using a fixed vs. variable SA_Q affects concentration and LWC. It shows that choice of SA_Q type most affects concentration and LWC for the distribution with a 10 μm mean diameter. Using a variable SA_Q results in 6% greater concentration and ~4% greater LWC. For distributions with greater mean diameters, the choice of using a fixed or variable SA_Q results in less than 3% difference in concentration and LWC.

It seems best to calculate higher moments using a fixed SA_Q of 0.27 mm^2 , given that the choice of SA_Q type has relatively little impact on concentration or LWC. Furthermore, the second-degree polynomial fit used to model variable SA_Q does not completely capture variations in SA_Q for droplets with diameters between 20 to 30 μm and requires extrapolation of SA_Q for droplets with mean diameter less than 9 μm or greater than 46 μm .

5 Comparisons of liquid water content from the CDP and Nevzorov probes

For cloud property studies, closure experiments provide an important means to evaluate uncertainties in one or more cloud microphysical measurements. Here, in-situ data collected by aircraft are used to further investigate uncertainty in CDP measurements by comparing LWC derived from CDP measurements to bulk LWC measured by a Nevzorov hotwire probe. Comparisons of in-situ LWC measurements provide an independent evaluation of CDP performance and an indication of how error in real-world CDP measurements compares to laboratory droplet generator results. In our comparisons, we account for known uncertainties in the hotwire measurements and the uncertainties reported in previous sections of this manuscript for the CDP.

5.1 The University of Wyoming King Air

The University of Wyoming King Air (UWKA) is a Beechcraft Super King Air modified to carry a variety of atmospheric in-situ and remote sensors capable of collecting information about atmospheric thermodynamics, dynamics, and cloud particle properties (Wang et al., 2012). In the following, we utilize measurements from two field campaigns conducted in late 2016 and early 2017. The Precipitation and Cloud Measurements for Instrument Characterization and Evaluation (PACMICE) campaign began in August 2016 and lasted until May 2017, with flights over eastern Wyoming and western Nebraska, USA. It focused on collecting cloud and precipitation measurements in precipitating stratiform and convective systems primarily in the shoulder seasons. The Seeded and Natural Orographic Wintertime clouds – the Idaho Experiment (SNOWIE) occurred during January – March 2017, and focused on wintertime orographic clouds in southwestern Idaho, USA (French et al., 2018). The majority of clouds sampled in both PACMICE and SNOWIE were mixed phase.

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5.2 Constant temperature hotwire probes

The UWKA carries both a LWC-100 and a deep-cone Nevzorov constant temperature hotwire probe. Both provide estimates of bulk cloud water content utilizing changes in current supplied to heated elements that are exposed to impacts of cloud particles (King et al., 1978; Baumgardner et al., 2017). Element temperature is maintained near 100 C such that impinging particles will vaporize transferring energy from the element through the effects of sensible and latent heating. Control circuitry maintains element temperature by altering the power supplied using element resistance as a proxy for temperature. Measurements of water content are obtained by relating the power required to maintain element temperature as particles are vaporized to the sensible and latent heat capacities of water, and element surface area (King et al., 1978; Korolev et al., 1998).

Convective losses due to moist airflow over the sensor also transfer energy from collector elements and can be quite large at aircraft flight speeds (King et al., 1978; McFarquhar et al., 2017). The Nevzorov probe features reference elements that are positioned on the devices' trailing edge such that they are aerodynamically shielded from particle impact (Korolev et al., 1998; Strapp et al., 2003). Energy losses from the reference elements are then assumed to arise solely due to convective considerations and thus the total power delivered to the reference elements can be used to estimate the convective heat losses from the sensing (collector) elements. The relationship between collector and reference element convective losses depends on airspeed and density (Korolev et al., 1998, Abel et al., 2014). Data collected during clear air calibration manoeuvres are used to compute the ratio of collector to reference power and determine how the ratio varies with airspeed and density. The manoeuvres are typically flown at several flight levels over a range of airspeeds. Any inaccuracy in the estimate of convective heat losses in the collector sensor based on power delivered to the reference sensor results in baseline drift of the Nevzorov-derived LWC (LWC_{NEV}) measurement (Abel et al., 2014). For the data used herein, the effectiveness of the Nevzorov data processing method was evaluated using ~60,000 out-of-cloud points. LWC_{NEV} residual (i.e. departure from zero when not in-cloud) was used to determine uncertainty in baseline LWC. LWC_{NEV} baseline uncertainty is estimated to be no greater than 0.05 g m^{-3} (the 95th – 5th percentile range of residual LWC) and minimum detectable LWC_{NEV} is $+0.02 \text{ g m}^{-3}$ (95th percentile residual LWC).

The Nevzorov is capable of measuring both LWC and total condensed water content (TWC) using two collector elements with different geometrical designs (Korolev et al., 1998). Estimates of ice water content (IWC) can then be obtained by differencing the two measurements. The LWC element is in the shape of a thin rod designed to only evaporate liquid particles. Ice particles shatter on impact with the sensor and are swept away before significant melting or evaporation can occur (Korolev et al., 1998). The TWC collector has a 'deep inverted cone' shape designed to capture both liquid and ice particles (Korolev et al., 2013). Korolev et al. (1998) showed that in mixed phase conditions, interactions between the LWC collector and ice particles can result in LWC overestimation on the order of 12% IWC.

In some conditions, collection efficiency may be significantly less than unity resulting in underestimation of LWC_{NEV} . Because airflow diverges in the vicinity of the LWC collector, LWC_{NEV} may be underestimated by as much as 30% in droplet populations with VMD less than 8 μm since particles with insignificant mass are unable to cross the divergent streamlines and impact collector elements (Korolev et al., 1998). Collection efficiency also departs from unity for droplets with VMD greater than 30 μm because larger droplets tend to splatter on impact leading to incomplete evaporation (Schwarzenboeck et al., 2009).

5.3 Dataset overview

Data were used from 29 research flights from both PACMICE and SNOWIE. Measurements from both probes were filtered to 1 Hz. Here we select only those data points in which both LWC_{NEV} and LWC_{CDP} exceeded a threshold value of 0.05 g m^{-3} . To minimize uncertainty due to presence of ice hydrometeors in CDP and Nevzorov LWC measurements, the IWC from the Nevzorov was used to select periods of liquid phase only penetrations from PACMICE and SNOWIE missions. However, IWC estimates from the Nevzorov may be affected by as-of-yet uncharacterized sources of uncertainty such that one cannot conclude the dataset used here is completely devoid of mixed-phase penetrations. Nonetheless, uncertainty in LWC resulting from the presence of ice is expected to minimally impact results. LWC_{NEV} is subject to overestimation of less than 12% IWC, which is often small compared to LWC in mixed phase cloud (Korolev et al., 1998). It has been also been demonstrated that the CDP is minimally affected by ice shattering artifacts (Lance et al., 2010, Khanal 2013).

The resultant data subset used in the comparison contains 17,917 1 Hz in-cloud points. Droplet concentrations encountered during SNOWIE were uncharacteristically low for continental clouds. Mean droplet concentration for the dataset is 113.6 cm^{-3} with 50% of data points having concentration less than 50 cm^{-3} . Consequently, droplets were relatively large; with an average VMD of 22.2 μm and 1st and 3rd quartiles of 16.7 and 27.7 μm . Nearly all measurements were taken in supercooled conditions, the environmental temperature range for the 5th and 95th percentile is -18.7 and -1.3 $^{\circ}\text{C}$.

5.4 In-situ results

For each 1 Hz data point, measured spectra from the CDP were used to compute the total droplet concentration and the VMD of the spectra. The data were first subdivided based on droplet concentration and then further divided based on VMD. For all VMDs larger than 10 μm , LWC_{CDP} exceeded LWC_{NEV} by as much as 40% (Fig. 7a-d). For VMDs less than 10 μm , LWC_{CDP} was less than LWC_{NEV} by 5 – 10% for those cases in which total droplet concentrations were less than about 400 cm^{-3} . The general trend, for all droplet concentrations, suggests increasing LWC_{CDP} (compared to LWC_{NEV}) for increasing VMD. However, the mean difference in LWC, across all VMDs, does not indicate any specific trend when considering different ranges of total droplet concentration.

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Estimates of percent LWC difference expected based on results from droplet generator tests and Nevzorov collection efficiency estimates predict that LWC_{CDP} should be at most 11% greater than LWC_{NEV} (green shaded regions in Fig. 7).

However, when all of the data in this study are considered, the mean percent difference is 19.6%. Two striking features of the data show that the percent difference for large VMD, greater than about 25 – 30 μm , is considerably larger than expected.

5 And, for droplet concentrations greater than 400 cm^{-3} , the percent difference is significantly larger than expected for all VMDs. The larger than predicted difference between LWC_{CDP} and LWC_{NEV} is unlikely to be a result of coincidence error. The UWKA CDP features a sizer pinhole mask modification such that it is expected to be relatively unaffected by coincidence in concentrations less than 600 cm^{-3} (Lance et al., 2012). Figure 7d shows that mean percent LWC difference for data with concentration of 400 – 1600 cm^{-3} is not significantly different than mean values for much smaller total droplet concentrations. On the other hand, for this concentration range, percent LWC difference is significantly larger for smaller VMDs when compared to similar VMDs for lesser droplet concentrations, suggesting that those CDP measurements may indeed be impacted by coincidence for these higher concentrations. Regardless, these data account for less than 4% of all points and suggest coincidence is unlikely to account for differences across all ranges of concentration.

15 The droplet generator tests used a near constant droplet velocity that was ~30% of typical UWKA airspeeds. They provide no information about how CDP sizing/counting accuracy and SA_Q may vary with airspeed. Some of the discrepancy between estimated and actual percent LWC difference could be a result of a change in CDP performance at typical aircraft flight speeds which could result from limitations in photodetector response (Dye and Baumgardner, 1984). However, in order for airspeed-dependent errors in sizing and/or SA_Q to account for the discrepancies shown, increased flight speeds would need to result in an increase in sizing (and hence photodetector output for the sizer signal) and/or an increase in SA_Q , both of which are unlikely outcomes; one might expect the opposite behaviour. On the other hand, overcounting could increase with increasing particle velocity if photodetector response limitations result in more significant signal noise. But it seems unlikely that such considerations could cause overcounting on the order of 5 - 20% given that only 46 μm droplets were overcounted (by less than 1%) during droplet generator tests.

25 It is possible that the discrepancy between estimated and actual percent LWC difference could be a result of a change in counting/sizing behaviour for droplets passing through the qualified sample area region where droplets are severely undersized (blue areas in the rightmost 10% of the beam maps shown in Fig. 4). Sizer responses are characteristically within the noise band range (less than 512 digital counts) for droplets transiting these regions; thus, severely undersized droplets could be rejected during 'real-world' operation. If LWC_{CDP} error estimates (as described in section 3.2) are recalculated excluding these regions where droplets are severely undersized, the resultant oversizing throughout the rest of the sensitive sample area could result in as much as 17% overestimation of LWC_{CDP} (effectively shifting upward the hatched green areas in Fig. 7, for large VMD).

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Error in Nevzorov measurements could also contribute to the discrepancy between LWC_{CDP} and LWC_{NEV} . Instrument icing was a common issue during SNOWIE. The 0.05 g m^{-3} threshold applied to LWC_{CDP} and LWC_{NEV} was used to exclude measurements taken when one (or both) of the instruments was (were) completely unresponsive. In the case of ice accumulation on the Nevzorov sensing element, build-up of rime ice near (or over) the LWC element often results in significant baseline drift along with an accompanying reduction in sensitivity to liquid water (due to changes in airflow and shielding of the sensing element). Such situations would result in an underestimation of LWC by the Nevzorov and could explain some of the differences shown in Fig. 7. However, examination of baselines prior to and after exiting clouds suggests this is not a large problem for the cases examined. Regardless, nearly all measurements were obtained in supercooled conditions so the data used in this study were not able to be further subdivided to investigate differences in regions where temperature greater than $0 \text{ }^{\circ}\text{C}$ would exclude possibility of icing. Future studies should include cloudy regions at temperatures greater than $0 \text{ }^{\circ}\text{C}$ to mitigate possible contamination cause by ice particles and/or rime ice build-up near the sensing elements.

6 Summary and discussion

A droplet generating calibration system was used to test the sizing and counting performance and provide measurements of the qualified sample area of the UWKA CDP using seven discrete droplet diameters ranging from $9 - 46 \text{ }\mu\text{m}$. Experiments reveal that droplet sizing accuracy varies depending on where droplets transit the sample area and the size of the droplets. Errors in droplet sizing tend to be less than 10% when comparing modes of the droplet distributions and even less when comparing the mean diameter of the droplet distribution; significantly less than the typically quoted 10 - 20% sizing accuracy normally attributed to single-particle scattering probes (Baumgardner et al., 2017).

This study extends the results from previous studies reported by Lance et al. (2010, 2012) by challenging a CDP throughout its sample area using seven droplet diameters ranging from $9 - 46 \text{ }\mu\text{m}$. One of the findings of this study that was unable to be captured by the earlier studies is that locationally-dependent errors in sizing vary by droplet diameter and that gradients in sizing error increase with increasing droplet diameter. This study also uses a finer grid spacing to test CDP response than did the Lance et al. studies, providing more precise measurements of sample area dimensions. Finally, the CDP tested in this study contained the pinhole modification reported on by Lance et al. (2012). However, the 2012 study did not report on sizing response, rather only on counting accuracy and coincidence effects.

Errors in sizing for the majority of droplets across the size ranges tested can be accounted for by the amplitude of Lorenz-Mie resonances on the response curve. The Lorenz-Mie resonances often result in a slight broadening of the distribution by 1 - 2 bins. How much broadening occurs depends on droplet size and the actual range of collection angles for the probe. This finding confirms results of earlier studies (Rosenberg et al., 2012; Baumgardner et al., 2017). Droplets with nominal

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diameter of 9 μm are undersized by 1 μm or less for roughly 33% of the droplets sampled and are undersized by 1 – 4 μm for the remaining 66% of droplets. Errors in droplet sizing for 9 μm droplets do not depend strongly on where droplets transited the sample area. The errors in sizing for these smallest droplets are likely related to the amplitude of Lorenz-Mie resonances compared to the relatively shallow slope of the Lorenz-Mie function.

Droplets with diameters of 17 and 24 μm are sized to within 2 μm of the true droplet diameter for nearly all droplets sampled (>90%), but there appears to be a small lateral dependence within the sample area on errors in sizing, such that droplets passing through the top half of the sample area are sized larger than those transiting through the bottom half. Tests for droplets with diameters 29, 34, 38, and 46 μm reveal more significant oversizing, by as much as 2 – 4 μm , with an even stronger lateral dependence on sizing error that is relatively symmetric within the qualified sample area. A 0.5° uncertainty in outer collection angle could account for the observed degree of oversizing. It is possible that the actual collection angles for the CDP tested deviate from the nominal 4 – 12° collection range provided by the manufacturer (Dye and Baumgardner, 1984; Baumgardner et al., 2017). However, results shown in Fig. 3 indicate that the CDP response for the seven droplet sizes tested fits well with expected scaled response of the Lorenz-Mie curve considering both 4 – 12° and 5 – 13° collection angles. If one considers 4 – 12.5°, for example, or 4 – 11.5°, the data appear to fit just as well, given the amplitude of the Lorenz-Mie resonances.

Droplet generator experiments performed by Lance et al. (2010) using 12 and 22 μm droplets also reveal a gradient in sizing accuracy. The sizing accuracy gradients discovered in their study are less symmetric, with the most severe undersizing occurring in an area in the lower-left 10% of the qualified sample area. In this region, 12 and 22 μm droplets were undersized by as much as 10 μm (Lance et al., 2010). The researchers attributed this behaviour to a misalignment of the qualifier detector mask. However, in their study as well as in this study, errors in sizing could also be simply due to variations in laser intensity across the beam. Laser intensity was not measured in this study so we are unable to attribute errors due to this specifically. Follow-on tests using the UW droplet generator on two other CDPs (owned by an outside research group) suggest similar lateral dependencies on sizing accuracy. These data are not presented in this study, but they do suggest a potential for some type of systematic behaviour across different probes.

Tests performed for this work also reveal that for droplets 24 μm and larger, nearly all droplets passing through 10% of the qualified sample area (that portion closest to the detector) are undersized, by as much as 30 μm , depending on the droplet diameter. The locationally-dependent nature of sizing accuracy results in artificial spectral broadening of droplet size distributions, which is most pronounced for droplets with diameters 34 μm and larger. Although droplets are oversized by 2 – 4 μm in most locations within the qualified sample area, the resulting errors in higher order moments such as mean diameter, VMD, and LWC, are mostly offset by undersizing of droplets throughout the rest of the sample area. This has implications for how sizing should be calibrated for the CDP. For example, matching distribution modes when performing

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calibrations will result in an underestimation for higher order moments because distributions are artificially skewed. Conversely, calibrations that match mean droplet diameter will result in an over estimation of the diameter of the droplet distribution mode in real clouds.

5 Droplets were counted to within 98% accuracy over roughly 95% of sample locations. Under counting only occurred around the perimeter of the sample area and was likely a result of small deviations in droplet placement. Only the largest droplets tested, 46 μm , indicated any significant over counting. This occurred in two regions bordering the area where these same droplets were significantly undersized. However, these regions account for less than 1% of the total qualified sample area so they introduce less than 1% overall count error. These findings differ from Lance et al.'s (2010) results that show as great as 20% over counting of 12 and 24 μm droplets at several sample locations near the perimeter of the qualified sample area as well as significant over counting of 12 μm droplets in a region located $\sim 300 \mu\text{m}$ from the left side of the qualified sample area.

15 All sizes of droplets are undercounted around the perimeter of the qualified sample area and this must be considered when defining SA_Q for higher moment calculations. $SA_{Q,50\%}$ varies only 0.03 mm^2 depending on droplet diameter and thus the use of a mean of $SA_{Q,50\%}$ for all droplet sizes (0.27 mm^2) is warranted. SA_Q for the CDP used in this work and the CDPs examined by Lance et al. (2010, 2012) agree to within 10%.

20 Comparisons of in-situ LWC measurements from the CDP and a Nevzorov hotwire probe provide another means of evaluating CDP performance. In-situ comparisons show that, on average, LWC_{CDP} is greater by about 20% whereas droplet generator results and Nevzorov collection efficiency considerations predict that LWC_{CDP} should be no more than 12% larger. Droplet generator tests used a droplet velocity that is $\sim 30\%$ of typical UWKA airspeeds. The discrepancy between the expected and actual LWC_{CDP} and LWC_{NEV} difference may be a result of CDP performance at higher droplet transiting speeds, however the current design of the UW droplet generator system does not provide enough stability in droplet placement to run tests at higher flow rates. Future testing should aim to increase droplet velocities by a factor of three. It also cannot be ruled out that the discrepancy may be partially due to rime ice build-up on the Nevzorov element. Further studies should include a concerted effort to incorporate in situ measurements in cloud at temperatures greater than $0 \text{ }^\circ\text{C}$. Our results indicate, for the data reported here, one must accept uncertainty in LWC greater than that which is suggested based strictly on hotwire uncertainties reported in the literature and CDP uncertainties suggested by laboratory experiments reported in this study.

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Author contributions

SF completed the bulk of this work and wrote the manuscript. This manuscript was based on SF's Master's Thesis from University of Wyoming. The work was supervised by JF. Significant edits to the original manuscript were completed by JF. RJ constructed the early version of the droplet generator and worked closely on initial testing.

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Tables

5 Table 1. Droplet generator test characteristics including the number of droplets injected at each sample location, longitudinal and latitudinal resolution, test duration, mean droplet diameter from glares (mean D_{true}), and the 95th to 5th percentile range of D_{true} . D_{true} statistics are from 80 randomly-selected glare images.

Test	Droplets per sample location	Long. Res. [μm]	Lat. Res. [μm]	Duration [hour:min]	Mean D_{true} [μm]	D_{true} 95 th – 5 th percentile range [μm]
9 μm	200	30	20	01:43	9.0 \pm 0.5	1.6
17 μm	250	10	10	03:14	17.3 \pm 0.5	1.6
24 μm	500	10	10	04:37	24.4 \pm 0.4	0.8
29 μm	500	10	10	04:15	28.8 \pm 0.7	2.3
34 μm	500	10	10	03:57	33.6 \pm 0.4	0.8
38 μm	500	10	10	03:35	38.5 \pm 0.4	0.8
46 μm	500	10	10	04:44	46.0 \pm 0.4	0.8

5 Table 2. Comparisons of the difference in several distribution parameters when calculated using CDP-recorded droplet diameter (D_{CDP}) vs. diameter from glares rounded to the geometric mean of CDP size bins (D_{true}^*). A positive difference (or positive percent difference) indicates that calculations using D_{CDP} result in a larger value than D_{true}^* . Percent LWC difference is calculated by comparing the integrated 3rd moment of normalized D_{CDP} distributions vs. normalized D_{true}^* distributions.

Test	Mean D_{CDP} minus Mean D_{true}^* [μm]	Difference in VMD [μm]	% LWC difference [μm]	Difference in 95 th – 5 th percentile range [μm]
9 μm	-1.3	-1.1	-36.7	0.0
17 μm	0.4	0.2	8.2	2.0
24 μm	-0.3	-0.1	-2.0	2.0
29 μm	0.8	1.3	11.1	4.0
34 μm	-0.1	1.0	2.4	12.0
38 μm	0.2	1.2	5.1	10.0
46 μm	-0.1	1.5	4.5	16.0

5 **Table 3. Concentration and liquid water content (LWC) for prescribed droplet distributions calculated with fixed and variable qualified sample area thresholded at 50% actual counts ($SA_{Q\ 50\%}$). Fixed $SA_{Q\ 50\%}$ concentration is not shown because it equals 100 cm^{-3} for all distributions. Uncertainty is equal to 1/2 the range of each parameter when calculated with $SA_{Q\ 10\%}$ and $SA_{Q\ 90\%}$.**

Distribution Mean [μm]	Variable $SA_{50\%}$ Conc. [cm^{-3}]	Variable $SA_{50\%}$ LWC [g m^{-3}]	Fixed $SA_{50\%}$ LWC [g m^{-3}]	% Diff Variable $SA_{50\%}$ LWC vs. Fixed $SA_{50\%}$ LWC
10	106 ± 3	0.082 ± 0.002	0.079 ± 0.001	4.21
25	99 ± 2	0.925 ± 0.013	0.943 ± 0.016	-1.84
35	98 ± 1	2.294 ± 0.027	2.338 ± 0.039	-1.87

Figures

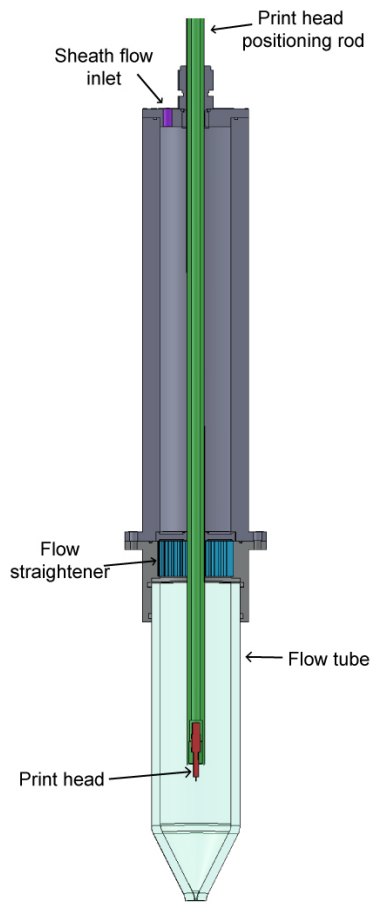
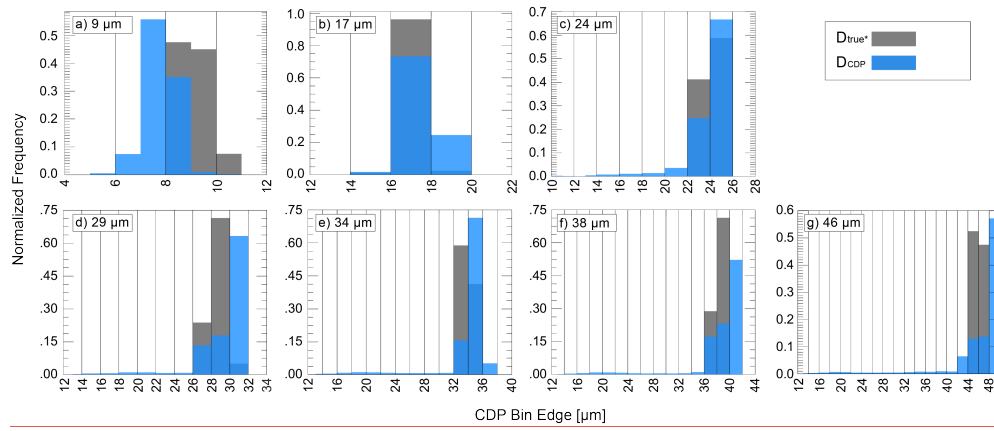


Fig. 1. Cutaway schematic of the flow tube assembly for the UW droplet generator system with pertinent components labelled.

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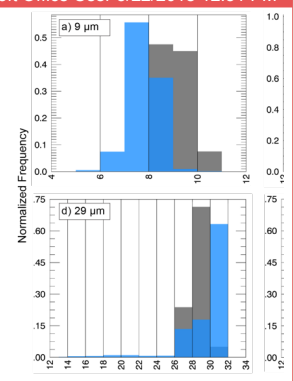
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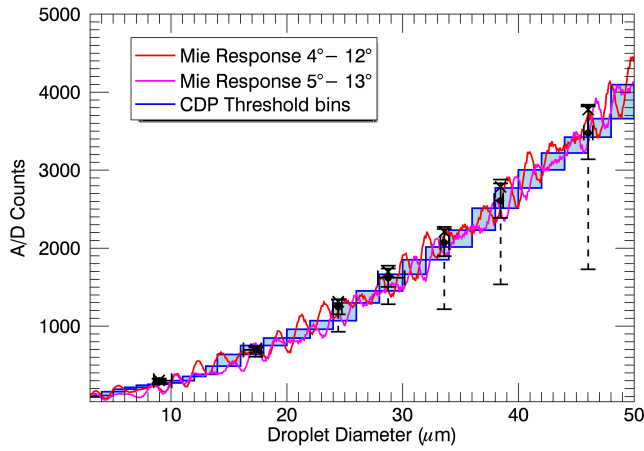


5 **Fig. 2.** Normalized distributions of droplet diameter from 80 random glares rounded to the geometric mean of CDP size bins (D_{true}^*) in grey and CDP-recorded diameter (D_{CDP}) from all responses during each test in blue. Nominal droplet size used for each test is indicated in upper left corner.

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5 | Fig. 3. Lorenz-Mie response scaled to CDP A/D counts computed for 4°-12° collection angles (red) and 5°-13° collection angles overlaid on the CDP A/D threshold (shaded blue) that is used to bin individual drops. Black dots show mean droplet diameter (D_{true}) for the 7 droplet generator tests. The horizontal bar with end caps represents the 5th to 95th percentile range of D_{true} for each test. The solid (dashed) vertical bar with end caps shows the range of the 25th to 75th (5th to 95th) percentile CDP-measured A/D counts for each test. The vertical location of the black dots (X's) show the mean (median) A/D counts for each test.

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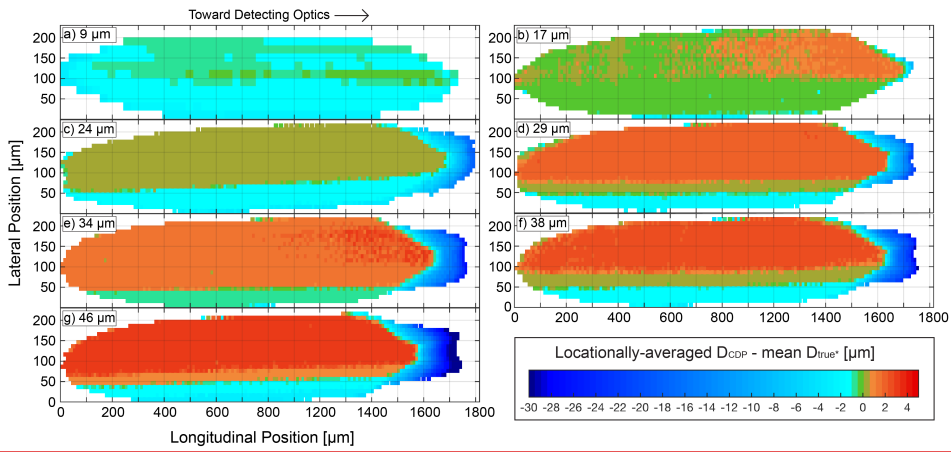
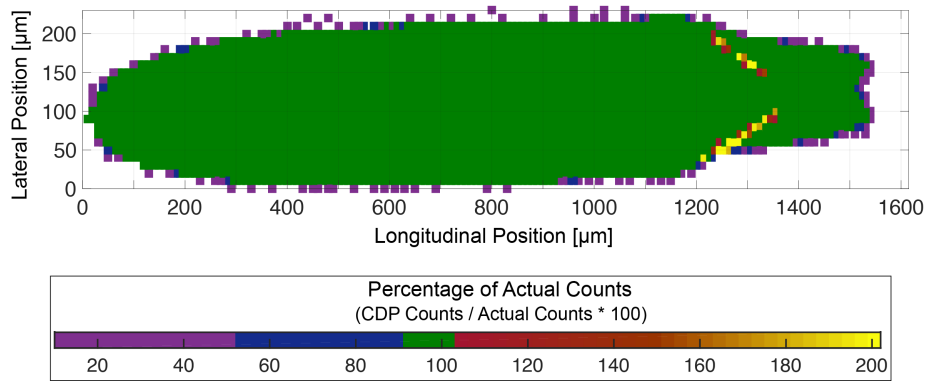


Fig. 4. Beam maps of spatially-dependent sizing accuracy. Colours represent the difference between CDP diameter (D_{CDP}) averaged at each sample location and mean glare diameter rounded to the geometric mean of CDP size bins (D_{true*}) from the 80 randomly-selected glares. Droplet diameter used for each map is listed in the upper-left corner. The right side of each map is nearest the detecting optics of the CDP.

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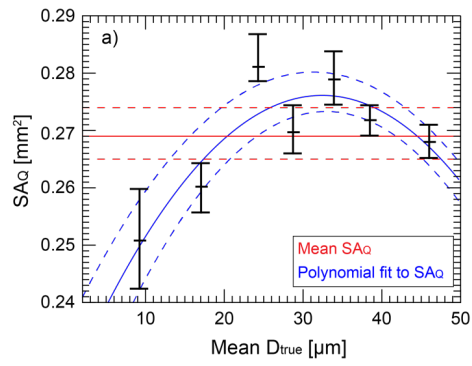
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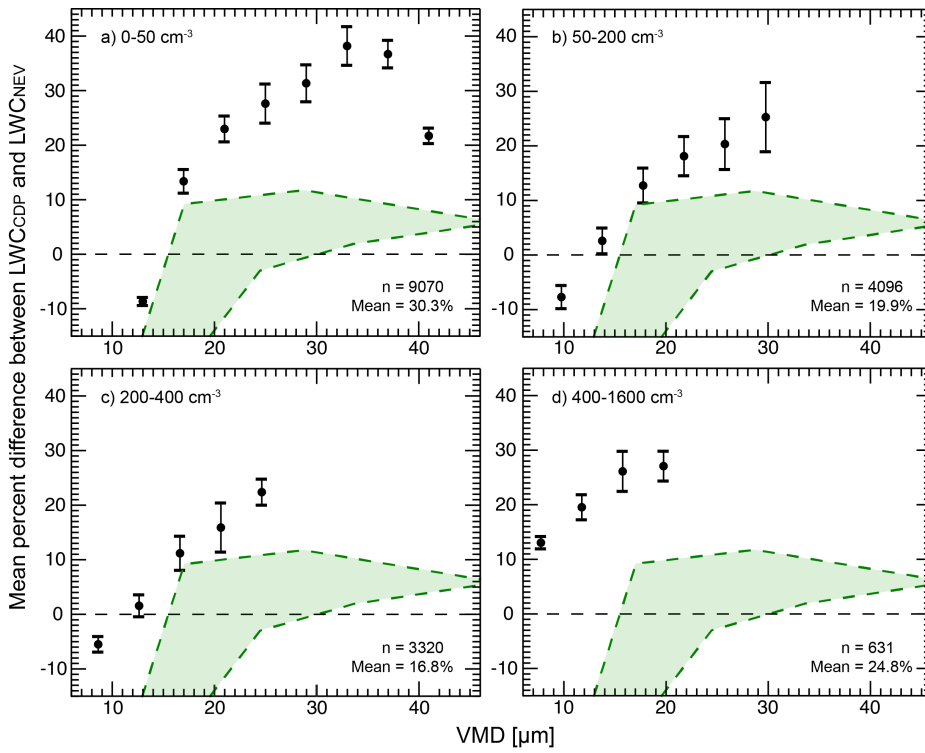
5 | Fig. 5. Percentage of CDP-recorded counts vs. actual counts (from print head ejection frequency). Purple areas show where at least 10% of actual counts were reported, blue shows where at least 50% were reported, and green shows where at least 90% were reported. Warm colours show areas that received more than 100% of actual counts.

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5 | Fig. 6. Measurements of qualified sample area (SA_Q). Horizontal bars represent SA_Q calculated using 10, 50, and 90% true count thresholds. Red lines show mean SA_Q for all droplet generator test and blue show a second degree polynomial fit to SA_Q .

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5 | Fig. 7. Mean percent difference between CDP LWC (LWC_{CDP}) and Nevzorov LWC (LWC_{NEV}) binned by volume-weighted mean diameter (VMD) for four concentration ranges (shown in upper left corner). Mean percent difference is calculated using a linear regression with the intercept forced through the origin. Error bars show root mean square error. Green dashed areas are estimates of percent difference based on droplet generator tests and Nevzorov collection efficiency considerations. The mean percent LWC difference for all data included in each concentration range and the number of data considered (n) are shown in each plot.

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