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 a revised manuscript will address these issues in an effort towards improving the 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.**

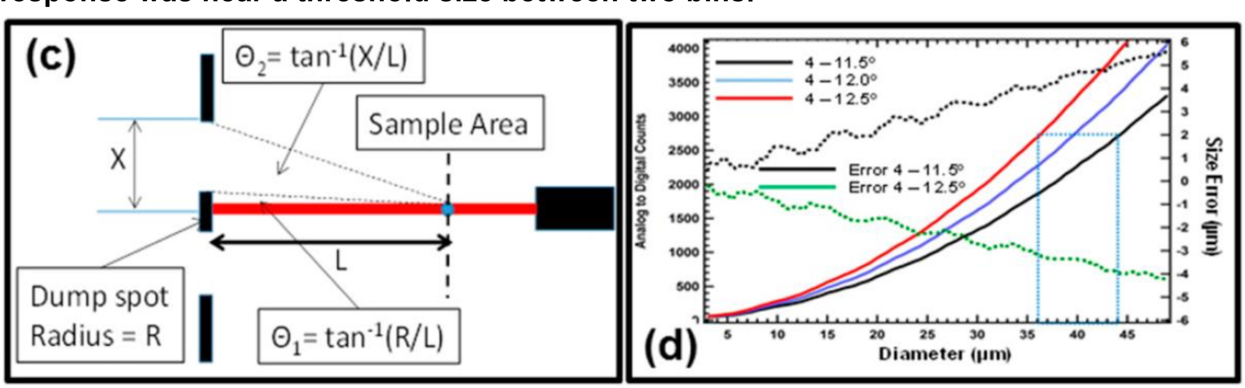
The revised version of the text will be more explicit about how this study differs from this earlier work.

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 < 10um) and for large particles (d > ~40 um). However, these Mie resonances also depend on the collection angles as illustrated in Figure 2 of the original manuscript (We had a poor choice of color for the two Mie response curves in Fig 2...this makes it hard to distinguish between the response for two different set of collection angles; this will be remedied in a 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 at the bottom of page 8 and top of page 9.

The figure from our Chapter 9, shown below, illustrates clearly the issue. With only a 0.5_0 change in the outer collection angle, there can be differences as much as ±4 um, 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, ±0.75mm 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 direction. The only test (of the seven performed) that showed any longitudinal dependence on sizing was for 17 um droplet, 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 um droplets, mean differences were within 1 um 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$_{o}$, in 0.5$_{0}$ 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 will be 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 will be corrected.

Page 4, line 5, "...in an ~12° arc, remove photons in the innermost 5 ~4°, and..". This is poorly worded and confusing. The CDP collects forward scattered light over a solid angle from 4-12$_0$, 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.