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Atmospheric Measurement Techniques Discussions

Interactive comment on "Water droplet calibration of a cloud droplet probe and in-flight performance in liquid, ice and mixed-phase clouds during ARCPAC" *by* S. Lance et al.

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———————— General Comments ————————

"The paper is very compelling in tying together various aspects which were previously mostly addressed in separate papers: (1) Sizing bias and its removal by use of a water droplet generator; (2) effects of coincidences; (3) modeling of the instrument's response; (4) explanation of real-world data and biases using the model results. Figures 9 and 10 are very impressive. They show that their model of the instrument's response reproduces both the sizing and the counting bias for measurements in liquid

and mixed-phase clouds. A by-product of the paper is that the authors can explain all biases without resorting to particle shattering (at least for this particular probe and for the cases shown). The paper is well-structured, figures illustrate the content of the manuscript nicely, and the paper is relatively short (sometimes a little more detail would be helpful, see below)."

Thank you very much.

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"There appears to be one inconsistency in the paper. If the CDP size bins were shifted by 2 microns to account for intensity heterogeneity within the laser beam, shouldn't that remove the bias that is related to under-sizing? Why then does an additional negative bias occur at low concentrations in Figure 9a? If the shift was already applied, the error for D should be zero for C=0. This problem occurs throughout the paper (details below in specific comments). I believe though that it could be addressed by minor revisions. "

You are correct. The uncorrected CDP response results in oversizing, and we have overcorrected for this sizing bias. The overcorrection results from assuming that the maximum sizing response occurs at the center of the DoF (the position at which the drop sizing calibration was performed using various sized water droplets, whereby the 2um shift was obtained). This assumption was not necessary, since we had already obtained measurements to the contrary (Figure 4 of the paper). Although the qualifier pulse amplitude is greatest at the center of the DoF, the scattered light signal recorded by the sizer is greatest at the edge of the DoF (Figure S1). Now, we normalize the distortion matrix used in the simulations by the average voltage rather than the maximum voltage, for consistency with the drop sizing calibrations, and the sizing error (as well as the CDP-LWC bias) approaches zero for C = 0 in the simulations.

The CDP-LWC bias obtained from the ambient measurements, however, remains the same as before, with a negative intercept at approx. - 35% relative to the King-LWC. We suspect now that the negative CDP-LWC bias observed at low droplet concentrations results from a positive bias (∼36%) in the King-LWC measurements in mixed-phase conditions. We did not correct for the ice bias on the King-LWC measurements, because we do not know of a correction procedure during sustained sampling in mixed-phase conditions that does not require a good deal of manual manipulation, which we felt was subjective, especially given the possibility of measurement hysteresis. However, we estimate that the presence of ice can shift the King-LWC baseline by as much as 0.08 g mˆ-3, since LWC can remain elevated at this level for several minutes after exiting a cloud (Figure S2). When the King-LWC is in the range of 0.1-0.2 g mˆ-3, which is common for the mixed-phase clouds sampled, this results in as much as 40-80% error. Further evidence in support of this theory is the linear fit to the liquid-only observations, which has an intercept much closer to zero (Figure 5 of the paper).

"I also believe that the title understates the achievements of this work which consists precisely in the consistency of calibration, instrument response modeling, and field data. As to my knowledge, this was never achieved before, and the title and/or abstract could be a little more self-confident in that respect."

The title accurately describes the work that was done. If we could think of a better title we would use it...

——————— Specific Comments ———————

"Most comments concern the aforementioned inconsistency. First of all, the manuscript could use a little more detail about the instrument. For example, you should state upfront that we are dealing with a mono-mode Gaussian laser here (we only learn that quite late in the text). A subsection with a general description of CDP might help. Sections 2.2-2.4 don't quite cover it. Explain how the sizing is done (pulse height analyzer or AD converter?), give more details about the slit used by CDP as opposed to the FSSP annulus, state upfront that this instrument internally accumulates drop size distributions and does not store data for each individual drop. (This is in fact an issue,

I believe. Nowadays, with DA systems like NI cRIO around, it shouldn't be a problem to store individual droplets.) Furthermore, explain what the laser intensity looks like within SAQ. If it's a Gaussian laser - shouldn't it vary a lot? Or is the SAQ limited to such a small fraction of a relatively broad Gaussian that there are only a few percent variability? From looking at Figure 7, one cannot tell."

We now add a paragraph with the requested information to introduce the basic operation of the CDP. Thank you for this suggestion.

"Looking again at Figure 7: Your SAQ contour (small area) encompasses normalized sizer amplitudes ranging from about 0.85...0.95 (if my eyes are properly calibrated). Unfortunately, the SAQ is *not* centered around the maximum intensity of the laser beam within the lateral and longitudinal extent. The red areas (amplitude=1) are a few pixels left. If you aligned the droplet stream such that it maximizes the signal on the oscillator, you were about 0.2 cm away from the center of SAQ. If you had centered your droplet stream in the center of the SAQ instead, you would have had smaller signal amplitudes. Can you discuss the consequences of the mismatch between center of SAQ and maximum intensity of the laser beam on the calibration? Perhaps that's the explanation for the mis-sizing right there."

The sizer signal measured within SAE (Figure 7) does not directly indicate the laser beam intensity, since the amount of light collected by the sizer for a given droplet size is also influenced by the optical DoF and the scattered-light collection angles. The basic shape of the sizer signal within SAE is mainly a result of the DoF of the optics (the same lens systems that constrains SAQ). You will notice that the qualifier signal within SAQ and the sizer signal within SAE have the same basic shape, on different spatial scales (compare plots on the right in Figure S1 and Figure 7 of the paper). Again, this means that the detector signal is not simply reflecting the laser intensity profile. While the qualifier mask limits the location over which scattered light is collected, the finite physical size of the sizing detector does the same thing on a larger scale.

So, when you write that "...SAQ is *not* centered around the maximum intensity of the laser beam within the lateral and longitudinal extent", actually it is the qualifier mask and the center of the sizing detector that are not aligned exactly. Looking at Figure 7 of the paper, it is not entirely obvious how the two detectors are aligned relative to the center of the laser beam.

During the sizing calibration (Figure 2 of the paper), water droplets were aligned near the center of the qualifier DoF. Thus, we were mistaken when we wrote that the sizer response was maximum for these calibrations. In fact, these calibrations agree well with the average sizer response within SAQ. We now retract the statements made on Page 3149, Line 25 and Page 3150, Line 4. Thus, the reason postulated (Page 3150, Line 4) for a greater than expected scattering signal for the water droplet calibrations is not valid (i.e. the red symbols really should correspond to the blue curve, according to our optical model of the instrument). This means that the 2um shift is actually appropriate for correcting the droplet volume mean diameter for the ambient observations.

We now offer a new hypothesis for the discrepancy between the modeled and calibrated instrument response for water droplets. We speculate that the optical model is insufficient for this particular instrument due to optical misalignment (beyond the symmetrical $\pm$0.5 degree shift modeled). If the qualified sample area is out of alignment with the center of the laser beam, this would result in a different range of collection angles for qualified droplets than the 4-12 degree specification. Incomplete blocking of the primary forward scattering lobe can result in a dampening of the Mie resonance structure (if the misalignment is nonsymmetrical) and also an increase in scattered intensity (Figure S3). The result of this type of misalignment was determined by integrating the Mie solution over different collection geometries. A lateral displacement of $\sim$1 mm for the qualified sample area relative to the center of the laser beam, results in a change in collection geometry for qualified droplets as depicted in Figure S4. We now add a paragraph in the paper describing the simulated effect of this type of non-

symmetrical optical misalignment and also an appendix describing the technical details of these simulations

Figure S3 Caption: The calibrated response of the CDP to PSL and glass beads, and the calculated response for PSL, glass beads and water droplets assuming that all forward scattered light 4-12 degrees is collected by the sizing detector. The light blue dots show the modeled CDP response for water droplets given a 1 mm misalignment in the y-dimension (laterally across the laser, and perpendicular to the droplet trajectories). The dark blue dots similarly show the modeled CDP response for water droplets given a slightly greater misalignment. The fit to the water droplet calibrations is shown for comparison. The CDP response to PSL and glass beads, given these misalignments, are also shown, and often agree well with the PSL and glass bead calibrations.

Figure S4 Caption: Calculated scattered light intensities for 10 um (left) and 40 um (right) droplets, respectively, as projected on a flat plane at 4 cm distance from the droplet (the approximate location of the dump spot, which nominally collects light 0-4 degrees off-axis, Fig. S1). Image intensity represents the logarithm of scattered irradiance normalized by the incident laser intensity, for an unpolarized light source with lambda = 658 nm. The solid white circles represent 4-12 degree symmetric collection angles. The dotted white circles represent the CDP light-collection geometry accounting for a lateral misalignment of 1 mm in y (top) and 1mm in both x and y (bottom) for qualified droplets relative to the intended optical alignment.

"I don't like the "brute-force" shift of the instrument response by 2um. As you state yourself, the undersizing occurs because droplets don't just pass through the maximum intensity section of the laser beam but also through regions latitudinally and longitudinally away from the center. The fact that Nagel et al. (2007) did a calibration only for the maximum intensity of the laser beam shouldn't keep you back from calibrating the probe all across SAQ. You already did that in Figure 3 and 4 (i.e., you measured 22 and 12 micron droplets at various locations). Why didn't you use these all-SAQ measure- ments to perform a calibration that takes the intensity distribution into account? Strictly speaking, you should hardly ever measure the "greatest CDP sizing response" (p3134,l6) in real-world measurements since droplets cross the laser beam everywhere and the signal will always be below the possible maximum."

We now include in Figure 2 of the paper the sizer signal averaged over all positions within SAQ (Figure S5), obtained from the calibrations reported in Figure S1 (for 12 and 22 um droplets, respectively). The average response agrees well with the response reported for droplets at the center of the DoF. Again, this contradicts the statements above that we are now retracting from the paper.

Figure S5 Caption: Figure 2 from the paper with additional water droplet calibrations added. The average sizer pulse amplitudes (as well as the standard deviation, minimum and maximum) are shown for calibrations with 12 um and 22um water droplets, respectively, over all positions within SAQ. Also shown are water droplet calibrations of various sizes near the center of the DoF on another day (about 6 months after the calibration that was originally reported in the paper). These added data illustrate that calibrations at the center of the DoF are representative of the average instrument response.

"I would encourage you to make the following additional plot after Figure 4: Within SAQ, plot a histogram of D_V/D_true. Make sure you identify the pixel where you originally did the calibration. At this pixel, D_V/D_true should be equal to 1. However, following Figure 7, I am not even sure that the maximum intensity lies within SAQ!"

We provide a histogram of D_v/dtrue values within SAQ for the reviewer (Figure S6). However, we find that a histogram of sizer pulse amplitudes within SAQ is more instructive, because this is actually what was used in the simulations to constrain the instrument response for droplets randomly transiting across SAQ (Figure S7). Since

Dv is a binned value, with resolution on the order of 10-20% of the droplet size, the histogram of D_v/dtrue has multiple local maxima, whereas the histogram of pulse amplitudes has a more Guassian shape (although truncated at larger pulse amplitudes due to misalignment between the qualifier mask and the center of the sizing detector).

"Page 3150 (line 23-26) is slightly confusing. You say that undersizing of 74% and oversizing of 25% may occur within SAQ, but in the same sentence you say that the "most likely" bias is -1.2% (-8.6% on average). The "most likely" vs. "average" vs. "maximum" (-74%...+25%) would be far better illustrated by adding the aforementioned additional figure. Also, how does that relate to the bias shown in Figures 2 and 3? Is Figure 4 based on the CDP response that was shifted by 2 microns? The fact that the "maximum" bias is +25% suggests that indeed it was already shifted - why else should you get a *larger* size across the sampling volume if you already positioned you calibration droplets at the intensity maximum!"

Actually, we said that oversizing by as much as 12% (not 25%) was possible. Since we are discussing the CDP sizing response using the binned size distributions, oversizing on the order of 10% is possible due to the coarse resolution of the bins. However it is not likely.

We agree that the textual description is confusing, and the best way to relay this information is with a histogram. You are correct that the 2um shift had already been applied for the D_v/dtrue results, and we say this explicitly now in the paper.

Again, however, we believe that showing a histogram of sizer pulse amplitudes (Figure S7), rather than a histogram of D_v/dtrue, more clearly communicates the instrument response. We add to this histogram the response for equivalently sized droplets transiting through the center of the DoF (using the power fit to the water droplet calibrations from Figure 2 of the paper). By doing this, one can directly compare the response at the center of the DoF (from which the 2um offset was obtained) to the average response within SAQ.

"Around the discussion of Figure 5, 9, 10, 11 you sometimes don't make a distinction between the two different biases you describe: sizing and concentration. We do not necessarily need coincidences to get undersizing (otherwise, why would we get an LWC bias at C=0?). Although coincidences do contribute to part of the sizing and LWC bias, especially at large concentrations, don't forget to mention SAQ heterogeneities as well, especially in the summary/conclusion where this distinction is completely blurred. It is also not mentioned in the abstract (line 9) - biases are not just due to coincidences!"

This is a good point. We try to make this distinction clear in the discussion and in the abstract.

——————— Minor / technical comments ———————

"p3136, l13-15: run-on sentence p3139, l25: replace "precise" with "precisely" p3141, l10: insert "the" between "with" and "long""

The preceding three comments have been addressed in the paper revision.

"p3142, 2.4.1: Doesn't a Gaussian laser do just the same (dampen the Mie oscillations?). After all, we have an intensity distribution within SAQ - that's all we we to smooth out the Mie structure! You could use this section to describe the laser a little better (e.g. percent variability within SAQ)"

Because the beam profile is much larger than the droplet size, and the sample area falls within the Rayleigh range of the laser beam, the laser intensity and phase do not vary significantly over the scale of the droplet (~50 um). The width of the beam is ~2mm (in y) and ~1mm (in x) and the beam divergence is small (~0.2 degrees). Thus, for droplets positioned at one location within SAQ, we expect that the scattered

intensity will follow Mie Theory.

"p3149, l30: "for reasons that are not known" - I don't understand this statement. First of all, the response of CDP in Figure 2 is *not* completely linear, secondly, it does correspond to the theoretical CDP response curve. I assume the CDP pulse analyzers are binned non-linearly, to counteract the _DËĘ2 signal amplitude."

When we wrote that the "response of the CDP to varying water droplet sizes is surprisingly monotonic. . .", we did not mean that the response is linear. Monotonic simply means that there is only one 'x' value for every 'y' value (i.e. only one droplet size for every pulse amplitude). Mie resonances fundamentally constrain the sizing resolution of the instrument. Therefore, the absence of Mie resonances is worth discussing (although we could not offer an explanation for it at the time of publication).

The results reported in Figure 2 were obtained using an oscilloscope connected to the CDP photodetectors. The resolution of the oscilloscope (mV/div) was adjusted during the calibration as the droplet size varied, so that smaller pulses could be adequately sampled.

We assert that there is a distinct difference between the water droplet calibrations and the theoretical CDP response curve for water droplets, which can be clearly seen for droplet sizes smaller than ~20 um. We believe that calibration uncertainties in the droplet sizing and measured pulse amplitudes cannot explain this discrepancy. We now posit that nonsymmetrical misalignment of the photodetector collection geometry relative to the center of the laser beam is causing the observed shift in the water droplet response and dampening of Mie resonance structure.

"p3151, 4.2: How do you deal with ice crystals in CDP measurements: Mie code? T-Matrix?"

The CDP (Cloud Droplet Probe) was designed to measure liquid water droplets, not ice crystals or frozen drops. A hidden assumption in this paper is that the CDP measured only liquid droplets during ambient sampling (even in mixed-phase clouds). We make this assumption because the King-LWC and CDP-LWC measurements track each other in ways that we can understand. We also believe that the conditions encountered allow for this assumption, since there is a natural size separation between liquid droplets and ice crystals due to the rapid growth of ice crystals at near saturated conditions (allowing liquid water droplets to co-exist). We assume that the spurious ice crystal that transits the CDP laser beam does not have a significant effect on the reported droplet concentrations or the CDP-LWC (even if the forward scatter signal is within the range of the CDP detectors) simply due to the much lower number concentration of ice crystals than cloud droplets. Shattering of large ice crystals is a much greater concern, since the concentration of small artificially produced ice crystals can be comparable or greater than natural concentrations of cloud droplets. However, this concern is nullified by the fact that the King-LWC and CDP-LWC measurements track each other well (whether or not large ice crystals are present), and because we can almost always explain biases arising between these two measurements without resorting to shattering artifacts

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"Section 5: This is a great idea. You might want to reference Coelho's thesis, or at least Brenguier et al. (1998). Also: the Brenguier paper lists more possibilities that can occur with coincidences, you only list the (most relevant) cases."

We do reference Brenguier et al (1998) in this paper! We now add the citation here as well.

"p3156, l5: This section (description how you simulate the response) comes too late, it should be introduced earlier."

Agreed. We have now reorganized the paper with this section moved to the Methods section.

Interactive comment on Atmos. Meas. Tech. Discuss., 3, 3133, 2010.

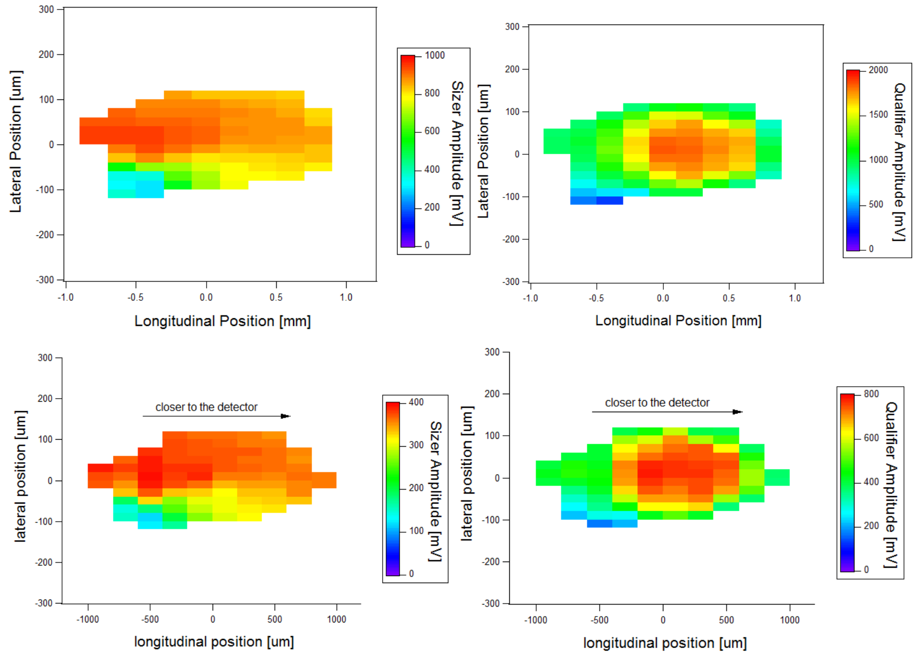

Fig. 1. (S1) Calibrated sizer (left) and qualifier (right) signals as a function of position within SAQ for 22 um (top) and 12 um (bottom) droplets.

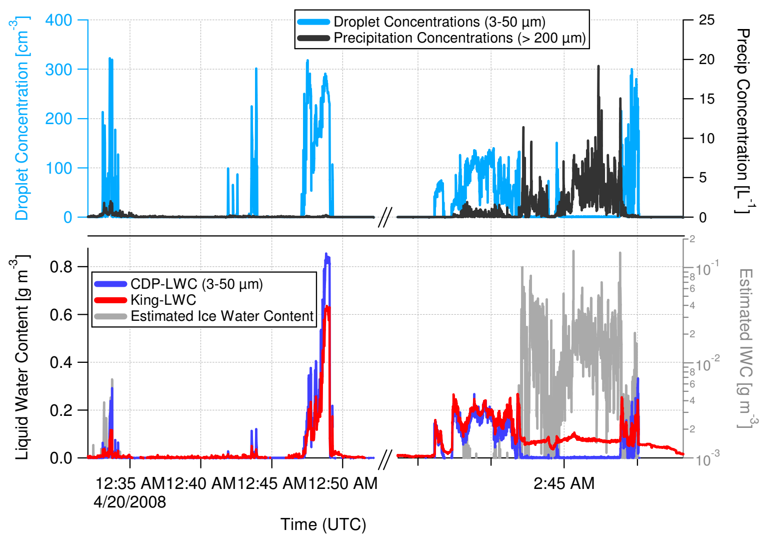

Fig. 2. (S2) Cloud microphysical observations on the 4/19-4/20/2008 flight during ARCPAC.

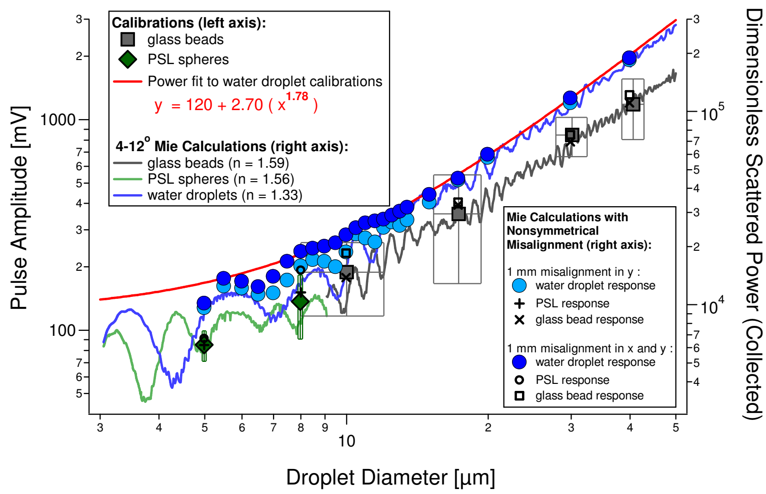

Fig. 3. (S3) Simulated CDP response assuming various degrees of misalignment (see text for full caption)

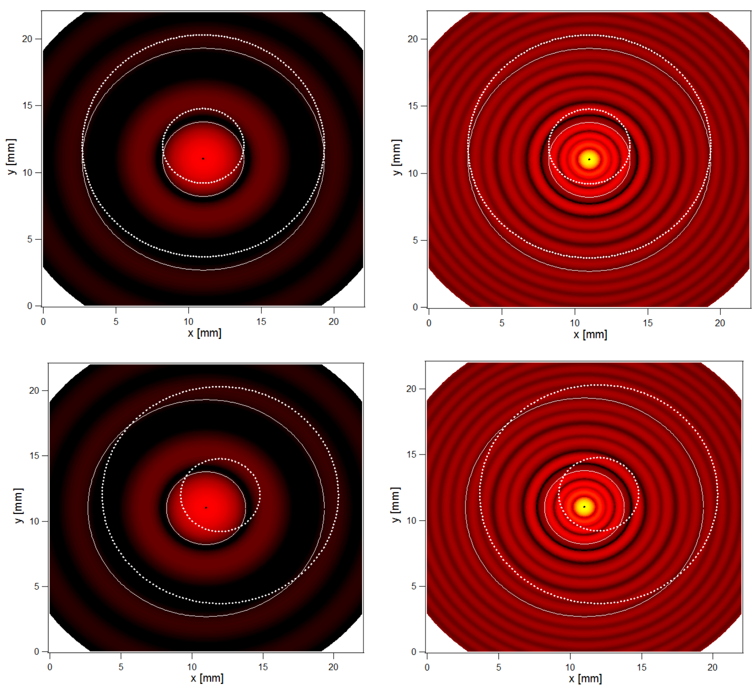

Fig. 4. (S4) Simulated scattered light intensities for 10 um (left) and 40 um (right) droplets (see text for full caption)

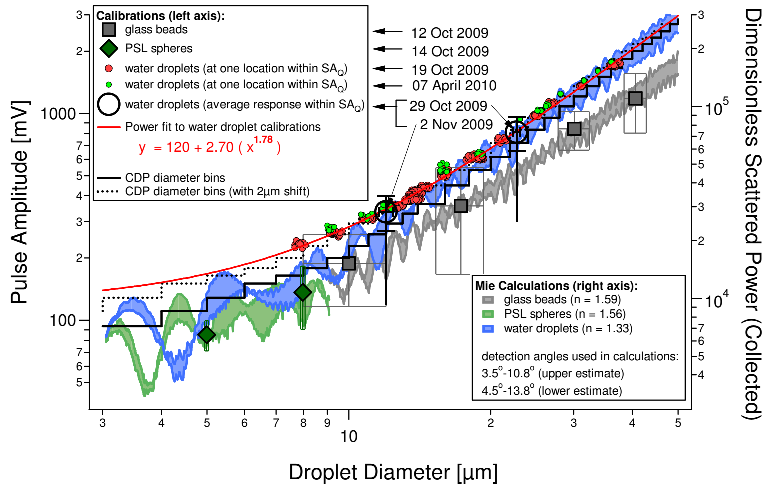

Fig. 5. (S5) Update of Figure 2 (see text for full caption)

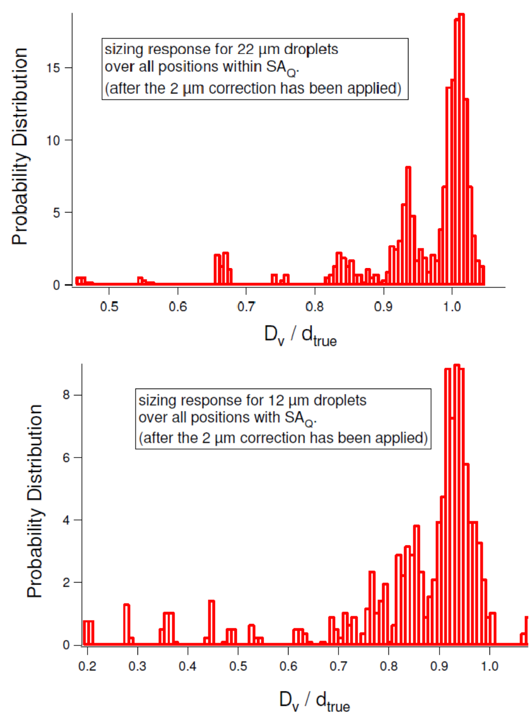

Fig. 6. (S6) Histograms of the volume mean diameter normalized to dtrue, for 22 um (left) and 12 um (right) water droplets distributed throughout SAQ

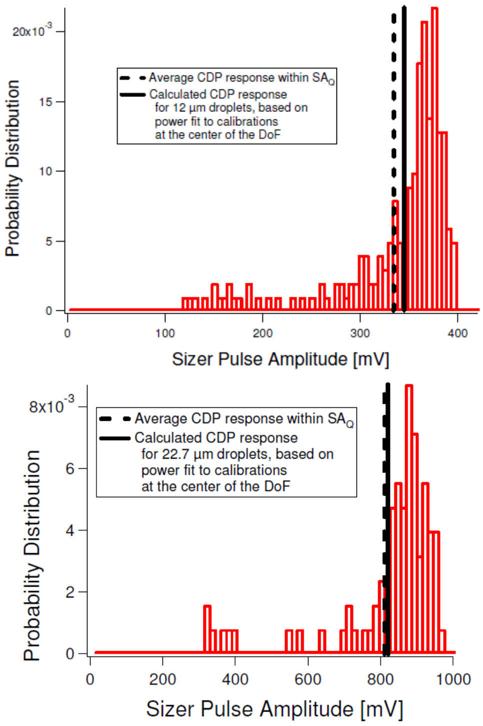

Fig. 7. (S7) Histograms of sizer pulse amplitudes for 22 um (left) and 12 um (right) water droplets distributed throughout SAQ.