**Overview**

Characterization of clouds and the ability to accurately model a range of microphysical processes, including droplet activation, growth, and precipitation formation, is crucial to improving our ability to predict everything from localized precipitation to global cloud albedo. A more thorough understanding of these processes is required despite many years of focused work and rapid advances in computer modeling and in-situ probe capacities. Continued improvement of cloud, weather, and climate models requires a detailed understanding of how processes influence deviations from adiabatically-predicted environmental parameter values (Boucher 1995). Investigations are complicated by many factors including the fact that relevant processes are modified by complex feedback mechanisms and occur on temporal and spatial scales which span orders of magnitude. Further challenges are presented by the incomplete characterization of probe limitations.

The use of cloud droplet size distributions (DSDs) are nearly ubiquitous in cloud microphysical studies because they provide key insight regarding droplet formation, precipitation initiation, and feedbacks through dynamic processes (Lamb and Verlinde 2011). Furthermore, several distribution statistics (for example kurtosis, skewedness, and measures of bi-modality) are characteristic to specific cloud properties and processes. Distributions composed of small diameter droplets (less than 100 μm diameter) are especially useful for studies focusing on droplet activation and initial precipitation formation processes. Clouds composed of newly-activated droplets show narrow monodisperse DSDs of small diameter because vapor diffusion growth rate is inversely proportional to droplet diameter. Growth to precipitation-sized particles by vapor diffusion alone would require timescales far longer than are observed, implying the importance of primary precipitation processes. One such process, droplet collection and coalescence, shifts the narrow newly-activated droplet distributions to a more disperse bi-modal shape (Lamb and Verlinde 2011). Distribution widening can create positive coalescence feedbacks (due to droplet terminal velocity being proportionally related to diameter) which accelerates droplet growth rates.

Extra-tropical clouds are rarely composed solely of liquid water. Therefore, ice processes further complicate DSD evolutions and precipitation formation studies. The Bergeron process, which is driven by the fact that saturation vapor pressure over ice is less than that over over supercooled liquid water, can quickly (with regards to convective cloud lifetime) accelerate ice particle growth. Ice particles are also subject to interactions with other particles including growth through droplet collection and freezing, growth through ice particle collection, and splintering caused by impacts with other ice particles. Impact splintering can lead to positive ice formation feedbacks by increasing the number of available freezing nuclei.

Macro-scale dynamic processes including entrainment, mixing, and particle recycling can further complicate DSD evolutions (Tölle, 2014). For example, the mixing of entrained sub-saturated air can influence DSD evolution in a number of ways depending (primary) upon the relationship of timescales required to “mix in” entrained air and the characteristic time required to evaporate a droplet population in that entrained air. At one end of the spectrum, DSDs subject to mixing timescales much greater than evaporative timescales will exhibit deceased particle counts but show little change in distribution shape. In contrast, if a distribution’s characteristic evaporative timescale is greater than the entrained air’s mixing timescale droplet distribution will be shifted towards a small mean diameter with little change in droplet counts (Tölle, 2014).

**The Cloud Droplet Probe and Nevzorov Hotwire Instrument**

The Droplet Measurement Technology, Inc. Cloud Droplet Probe (CDP) is a cloud particle counting and sizing instrument commonly used to provide measurements of cloud droplet size spectra (DSD) from aircraft. It operates on principles similar to the predating Particle Measuring Systems, Inc. Forward Scattering Spectrometer Probe (FSSP) but incorporates improvements including a reduction in particle shattering and decreased electronic response times (Needs Reference). The CDP uses the intensity of light scattered by hydrometeors to retrieve size distributions of sub-precipitation sized cloud droplets (up to 50 μm diameter). Particles are placed in one of 30 size bins (of 1 μm resolution for particles up to 14 μm diameter or 2 μm resolution for particles with diameters of 14 – 50 μm) according to a photodiode array’s pulse amplitude. Several other key parameters including liquid water content (LWC), effective particle diameter, and particle concentration are calculable using CDP DSDs (Droplet Measurement Tech. 2014). The probe also includes a particle-by-particle (PBP) feature which returns detector pulse amplitudes and inter-arrival times (time since last detected particle) for the first 256 particles within a sample interval. Table 1 outlines the CDP’s retrievable parameters.

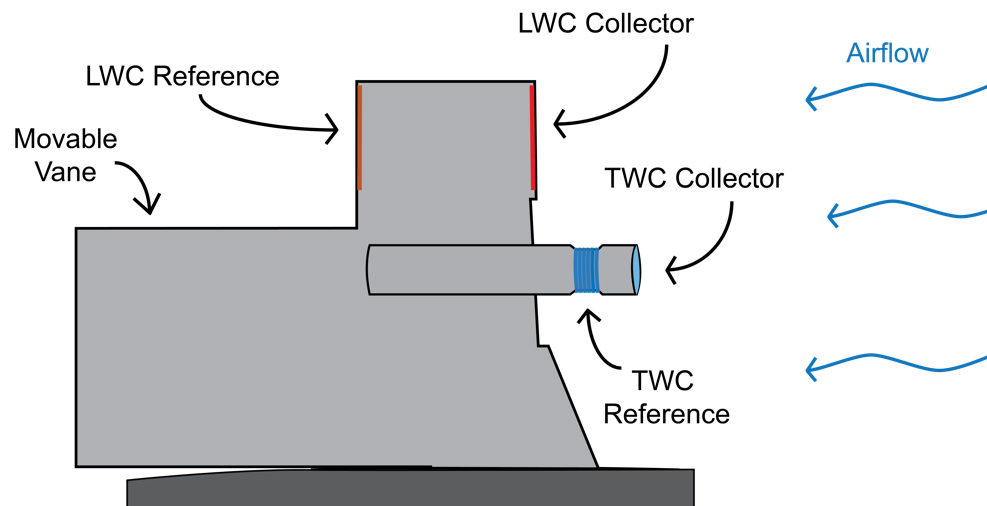
**Table 1. CDP Retrievable Parameters**

|  |  |
| --- | --- |
| **Parameter** | **Source** |
| Particle Diameter | Scattered light intensity |
| Particle Number Concentration | Scattering event counts, sample volume dimensions, aircraft airspeed |
| Liquid Water Content | Derived from DSD※ |
| Effective Diameter | Derived from DSD※ |
| Median Volume Diameter | Derived from DSD※ |
| Particle-By-Particle Diameter† | Scattered light intensity |
| Particle-By-Particle Arrival Time† | Clock cycles since last scattering event |

※*Derived DSD computed using derived particle diameter and particle counts.* †*Particle-by-Particle data available for first 256 particles of each sample interval.* (Droplet Measurement Technologies, Inc., 2014)

The Nevzorov is among the latest generation of hotwire probes which is capable of retrieving both bulk liquid and total water content (LWC, TWC). The Nevzorov has several advantages over other hotwire designs including phase discrimination capability, a freely rotating vane to decrease aircraft orientation bias, and paired collector/reference sensor architecture. Paired sensors simplify convective heat loss calculations (power consumption by sources other than particle evaporation), significantly reduce baseline noise, and increase retrieval confidence in low water content environments (Korolev 1998).

Water contents are calculated using the power consumption of two constant-temperature elements; one in the form of a coil intended to collect only liquid particles (LWC collector sensor) and the other shaped as an inverted cone which is designed to capture and sense particles of both phases (TWC collector sensor). Both the LWC and TWC collector sensors are paired with a similarly-sized reference sensor which is positioned so cloud particle impacts are unlikely (therefor reference sensor power consumption is assumed to be caused by convective heat losses only). Figure 1. shows the Nevzorov’s general layout including collector and reference sensor locations.



***Fig 1.*** *Schematic of the Nevzorov device illustrating sensor pairing. The vane (vertical light grey structure) is freely rotating to ensure collector sensor faces remain orthogonal to the airflow.*

Hotwire-sensed liquid water content (LWC) values hold utility for both model and observationally based studies. Water content is a key parameter in bulk cloud models which, perhaps most importantly, provides a constraint on precipitable water values. Hotwire-sensed LWC is also useful for airborne probe limitation studies because bulk water content values are analogous to the integrated third moment of a droplet distribution. Both the Nevzorov and CDP are capable of calculating LWC (the Nevzorov through bulk measurements and the CDP through DSD-derived values) which provides opportunity for probe uncertainty assessment and performance constraint. Furthermore, Nevzorov and CDP LWC have been shown to be in good agreement in a variety of operating conditions. In-situ analysis preformed by Sulskis (2016) investigated CDP and Nevzorov LWC agreement across various mean particle diameters ranging 5 to 30 μm and particle concentrations ranging 10 to 1500 cm-3. CDP and Nevzorov LWC were within 13% agreement across all diameter and concentration ranges with the exception of particle diameters of 5 to 10 μm (where Nevzorov values were 21% greater).

**Significance**

The CDP is subject to error introduced by two overarching sources. Firstly, inhomogeneity in laser beam intensity, optical component imperfections, and component misalignment can lead to particle sizing error (this error source will hereafter be referred to as “mis-sizing error”). Lance et al. (2010) found mis-sizing error can realistically skew particle diameter values by 2 μm. The second major error source, known as “coincidence error”, occurs because CDP sample volume (laser beam regions which are sensitive to particles) are many times more extensive than theorized. It is therefore likely that multiple particles can be simultaneously within a sample volume. These coincidence events are a concentration-dependent occurrence which contribute to both errors in particle counting and sizing. Relative contributions to mis-counting and mis-sizing are difficult to characterize because coincidence can lead to several different outcomes; particles can be undercounted, undercounted and oversized, or rejected altogether (Lance et. al., 2010). Manufacturer specifications state the CDP is capable of retrieving concentrations of up to 2,000 particles cm-3 but studies have shown that coincidence effects can contribute to 27% undercounting and 30% oversizing bias at concentrations as low as 500 particles cm-3 (Droplet Measurement Technologies, Inc., 2014, Lance et. al., 2012).

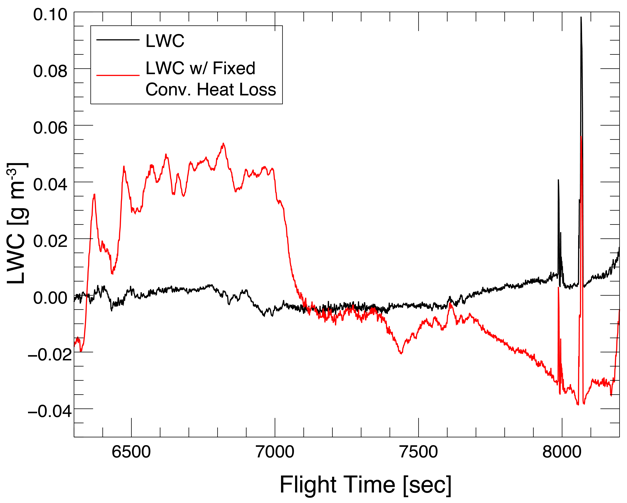
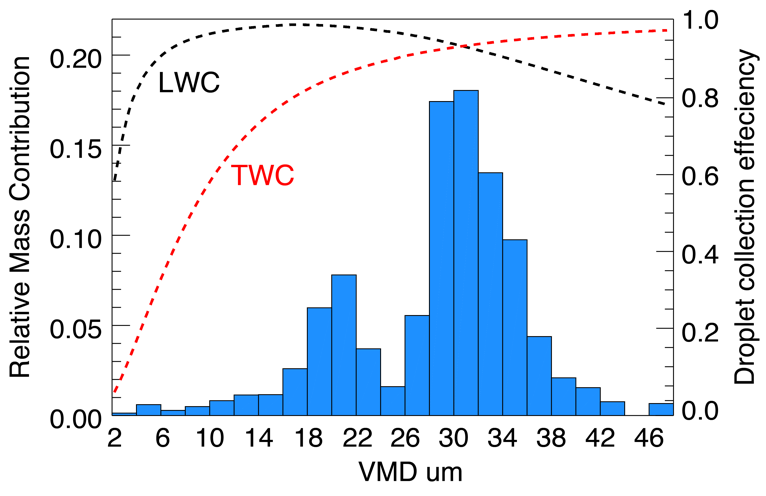
Traditional forward scattering spectrometer calibration techniques aren’t suitable for addressing the impact of sizing error because they lack the required precision in particle placement and concentration. Furthermore, they use glass microbeads or polystyrene spheres as calibration media; both of which introduce complexities due to their differences in refractive indices (with respect to water) and imprecise particle shape and size. A handful of institutions and instrument manufactures have developed water droplet calibration devices (or droplet generators) to improve calibration and better characterize instrument response. These devices are designed to create pure water droplets of repeatable size, velocity, concentration, and placement; attributes which would allow for calibration and uncertainty investigations less affected by refractive index problems and spatial uncertainty.

Nevzorov measurements can be compromised by various error sources including sensor saturation in high water content environments, non-unity particle collection efficiency, and convective heat losses. It has been found that LWC sensor saturation is significant for particle median volume diameter (MVD) greater than 50 μm (Strapp et al. 2003) or LWC greater than 1.3 g m-3 (Sulskis 2016). It should be noted that Sulskis’ findings were mainly employed as a threshold value; ranges of actual affected water content measurements vary based on operating conditions. Sensor saturation error is considered to be of secondary concern because upcoming University of Wyoming King Air (UWKA) missions will feature updated Nevzorov electronic designs which should minimize power supply bottlenecks.

Airspeed, pressure, and temperature dependent convective heat losses can also introduce LWC/TWC error that most often manifests as baseline drift. Ignoring convective heat loss dependencies can introduce mean LWC/TWC error on the order of 100% and seriously compromise measurements made in low water content environments. Figure 2a. shows an example of convective heat loss-related baseline drift caused by ignoring the aforementioned dependencies.

A 1998 study by Korolev et al. investigated LWC sensor collection efficiencies for droplets with volume weighted mean diameters (VMD) of 2 – 25 μm. subsequent work by Schwarzenboeck et al. (2009) expanded LWC efficiency estimates to include droplets of up to 300 μm VMD. The two studies indicate collection efficiency effects are significant for droplet VMD less than 5 μm (due to aerodynamic effects) or greater than 25 μm (due to incomplete evaporation).

Korolev et al.’s 1998 study also examined TWC droplet collection efficiencies for 2 – 25 μm VMD particles and estimated that efficiencies are significantly less than unity for very small particles (~ 3 – 15 μm VMD) but approach values of .9 by 25 μm VDM. Estimates of TWC collection efficiencies for droplets as large as 236 μm MVD were later examined in work by Strapp et al. (2003) in which wind tunnel tests supported that TWC efficiencies remain near unity for large droplets. It should be noted that in-situ based studies of TWC efficiencies for droplets of greater than 25 μm VMD are sparse. Further in-situ analysis is pertinent because estimates of TWC collection efficiency are key for phase discrimination and water content calculations in mixed-phase clouds. Figure 2a. shows a distribution of relative water mass contributed by droplets of various VMD in a typical CDP DSD (from the 2013 COPE-MED campaign). Overlaid collection efficiency estimates show that collection efficiency effects can contribute to significant Nevzorov LWC error for droplet sizes typically encountered during UWKA missions. Effects can be especially apparent for TWC sensor measurements made in droplet distributions with a VMD of around 20 μm or both LWC and TWC sensor measurements made in distributions with a VMD of around 32 μm.

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***Fig 2.*** *(****a****) An example of the nature of baseline LWC drift (shown by the red line) that would be introduced by assuming fixed convective heat losses (therefore neglecting convective heat loss airspeed, pressure, and temperature dependence). (****b****) Shows the relative mass contributions of droplets binned by VMD for CDP droplet distributions collected during COPE-MED where Mass Contribution ≣ Frequency \* Bin Geographic Mean3. Dashed curves are estimates of droplet collection efficiencies for the LWC and TWC sensors (Korolev et al. 1998, Strapp et al. 2003, Schwarzenboeck et al. 2009).*

**Objectives**

A two-tiered methodology, including both laboratory-based experiments and in-situ analysis, will enhance the Atmospheric Science department’s observational study abilities through improved error characterization and performance constraint for the CDP and Nevzorov devices. Proposed objectives fall into three general categories.

Firstly, a droplet generating calibration device will expand the department’s ability to calibrate and characterize error sources for several optical cloud probes. Efforts are to be focused on preliminary system development, operating procedure development, and algorithm coding. The system will initially be capable of calibrating the CDP but future work will expand compatibility to include the FSSP and SPEC inc. 2D-S. Major objectives include

1. Hardware installation
2. Development of control software
3. Development of best operating practices
4. Conducting preliminary tests to confirm system performance
5. Collecting CDP calibration data including
   1. Position-dependent droplet sizing accuracy
   2. Sample volume dimensions

Objective 5 entails recording detailed measurements of CDP sample volume characteristics including position-dependent mis-sizing error and measurements of sample volume bounds. CDP particle-by-particle data will provide detector pulse amplitudes for individual counting events; a parameter with much finer resolution than derived droplet diameters.

Secondly, newly developed algorithms will perform Nevzorov LWC and TWC calculations which consider well-defined error sources. Nevzorov algorithm focused objectives include

1. Development of software to calculate Nevzorov LWC and TWC from UWKA data
   1. Algorithms will consider error sources including
      1. Estimates of droplet collection efficiencies from work by Korolev et al. (1998), Strapp et al. (2003), and Schwarzenboeck et al. (2009)
      2. Corrections for convective heat losses
2. Testing of algorithm performance using COPE-MED LWC/TWC calculations provided by Alexei Korolev

Thirdly, error assessment for the CDP and Nevzorov will be performed using in-situ data collected during the PACMICE campaign. Investigations will utilize the two instrument’s mutual LWC retrieval ability (a bulk measurement for the Nevzorov and DSD integration for the CDP) to characterize and constrain instrument performance. In-situ studies are to accomplish the following objectives

1. CDP – characterize error sources including
   1. Mis-sizing error using
      1. Droplet generator calibration results
      2. CDP/Nevzorov LWC comparison
   2. Coincidence related error using
      1. Mis-sizing error investigations (previous objective)
      2. CDP/Nevzorov LWC comparison
      3. DSDs derived from PBP data
      4. Characterization of coincidence error’s concentration dependence
2. Constrain CDP operational ranges
3. Nevzorov – characterize error sources including
   1. TWC collection efficiencies for 25 – 50 VMD μm droplets
   2. Aircraft orientation effects

CDP mis-sizing specific investigations (objective 8a) are to be constrained to relatively low droplet concentrations in order to exclude the more severe error introduced by coincidence events. A threshold of relevant concentration ranges will be determined by considering CDP/Nevzorov LWC comparisons and findings from previous studies by Lance et al. (2010, 2012).

Characterization of CDP-derived LWC error caused by coincidence events (most importantly the effect’s concentration dependence) will be performed by considering CDP/Nevzorov LWC comparisons at higher droplet concentration ranges. Coincidence event’s relative contribution to mis-sizing and mis-counting error may be further investigated using DSDs derived from particle-by-particle sizing detector responses and their deviations from idealized distributions.

CDP LWC and refined CDP error characterization will in turn be used to explore droplet collection efficiencies for the Nevzorov TWC sensor. Work regarding TWC collection efficiency estimates for 25 – 50 μm VDM liquid particles is currently sparse. Further investigation is pertinent in order to more truthfully measure water content and discriminate between water phases in mixed phase environments.

**Development of a Water Droplet Generating Calibration System for Cloud Particle Probes**

Designs for the water droplet generating calibration device are based on work by Nagel et. al. (2007), which was later expanded on by Lance et. al. (2010), in which a piezoelectric print head (typically used for circuit printing or biomedical applications) dispenses pure water droplets inside a tube containing a sheath airflow (MicroFab inc.). The print head device includes a fluid cavity surrounded by a piezoelectric membrane which forces fluid through a precision glass nozzle. The piezoelectric element is driven by a programmable controller which supplies voltage pulses in order to create droplets at the nozzle’s exit. Droplets are accelerated by the flow, focused through the tube’s tapered exit region, and passed through an instrument sample volume. High speed cameras and imaging software independently verify droplet size, velocity, and trajectory while computer controlled microstages alter the point of sample volume injection. Generator setups can produce a range of droplet sizes, velocities, and concentrations by altering the position where droplet enter the sheath flow, interchanging print head size, and modifying print head driver pulses. Droplet generating calibration devices are especially adept at investigating an instrument’s spatially-dependent sizing precision and measuring sample volume dimensions.

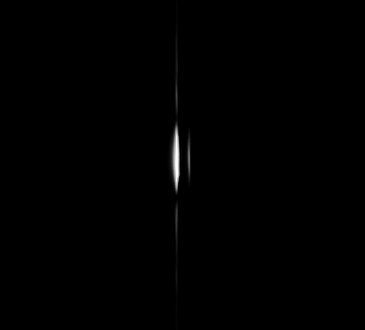
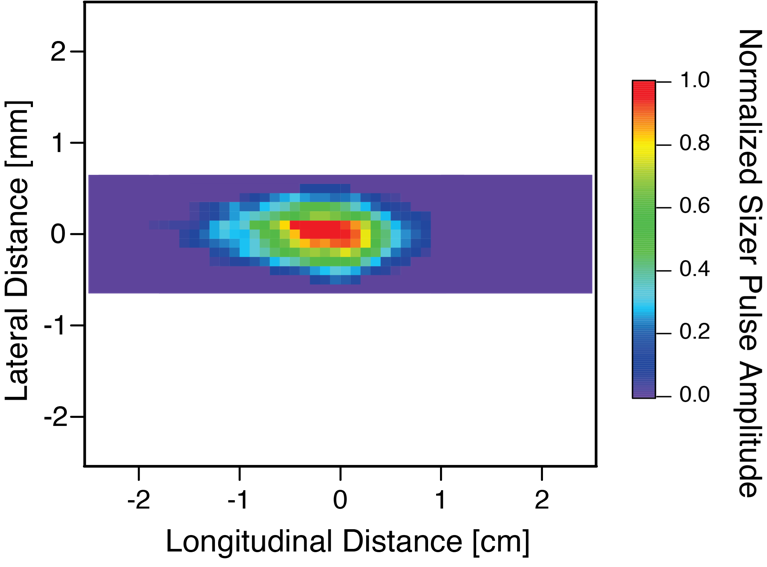
Calibration system development is currently underway with a majority of components already installed and tested. Figure 3. shows a schematic of the major system components. The droplet generator assembly (in grey) includes a glass flow tube (semi-transparent structure at the bottom) and print head (available in diameters of 5 μm increments spanning 20 – 80 μm) positioned within the sheath flow. The print head device is fixed to the end of a movable rod. Raising or lowering the rod alters droplet in-flow residence time providing adjustment of droplet velocity and diameter (through evaporation).



***Fig 3.*** *Schematic of the droplet generator system layout. Note: brown lines are links to/from the PC, red lines are cables from controllers, purple denote pressurized air lines, and blue show water lines.*

Separate compressed air sources provide both reservoir water level regulation and sheath flow to the droplet generator assembly. A microfluidic pressure regulator placed between the first air source and reservoir provides both the precise adjustments required during print head operation and pass through of higher pressures used to purge water lines of air bubbles and contaminants. Control of sheath flow rate and minimization of flow tube/ambient pressure differential is accomplished using a critical orifice and choked flow principles.

Independent droplet diameter and velocity estimates are calculated using the glare technique, as initially described by Korolev et al. (1991). A high speed metrology camera images droplet glares (bright regions located at a droplet’s left and right sides) as droplets are illuminated in the CDP’s sample volume. Droplet diameters are estimated using glare pixel separation, pixel/distance relationships determined using glass microbeads, and camera geometry. Droplet velocity can be deduced by further considering a glare’s Y-axis pixel counts and camera exposure times. Figure 4a. shows an image of glares created by a 40 μm droplet.



***f***

***Fig 4.******(a)*** *40 μm droplet glares captured with 125 us exposure. (****b****) An example CDP beam map from work by Lance et al. (2012) which shows position-dependent sizing detector response.*

Reliable print head operation has proven to be problematic. The devices are intended to be operated in a cleanroom environment; a condition which cannot feasibly be met in our lab. Therefore, clogging caused by both airborne particles and contaminants picked up by disconnected tubing is an ever-present issue. The addition of in-line filters on both the air and water supply lines (red cylinders in Figure 3.) has decreased downtime due to blockages by a significant amount. But the need to clear print head clogs is still a common occurrence and procedures which utilize an ultrasonic cleaner, mild solvents, and a vacuum source for back flushing have been proven to be consistently affective. Achieving consistent passage and ejection of droplets from the flow tube has also been arduous. Successful ejection is dependent on a precise combination of sheath flow rate, print head location, water reservoir pressure, and jetting parameter values. Static interactions between droplets and the flow tube also prevent successful droplet passage; an issue which has been remedied by placing an air ionizing device between the air source and droplet generator sheath flow inlet.

The microstage system remains as the last unintegrated component. A proposed system by Thorlabs, Inc. will allow droplet placement in the X/Y axes at sub-micron repeatability. Calibrations will be conducted by continuously operating the droplet generator while the microstages reposition the CDP to cause droplets to traverse the sample volume in a serpentine pattern (where droplets are placed at set increments across the distance of the sample volume’s Y-axis, move one increment in the X-axis, and traverse the Y-axis in the opposite direction). Both the microstage positioning and CDP data acquisition software incorporate LABVIEW which will allow the integration of microstage positioning and CDP sizing response data. CDP sizing and positioning data will be compiled to create a detailed parameterization of sizing performance or “beam map” (see Figure 4b.).

**Nevzorov Data Processing**

Nevzorov data processing routines have been developed (objective 6) and tested using well-established COPE-MED calculations (objective 7) provided by Alexi Korolev, an expert directly involved in Nevzorov development. Calculated and Korolev’s independent LWC have been shown to be in good agreement despite using unique calculation methods. Algorithms include corrections for convective heat losses and parameterizations of collection efficiency.

Several algorithm processes require identification of clear air (out of cloud) points which is accomplished using raw LWC collector sensor voltage and the following methodology:

1. A baseline LWC collector sensor voltage is defined by
   1. Dividing sensor voltage into 30 second increments
   2. Locating each increment’s minimum voltage
   3. Applying a low pass filter to selected minimum voltages
2. Normalized voltage is then calculated as VLWC Col – Vbaseline
3. A threshold is set as the 25th percentile of normalized voltage
4. A point is then flagged as clear air if its normalized voltage is less than the threshold value

Figure 5a. provides a graphic representation of the filtering process. It should be noted that the process by no means flags every clear air point but it does provide a sample sufficient for subsequent calculations and performance testing.

Nevzorov LWC and TWC are calculated using the following formulae as defined in the Nevzorov operating manual (SkyPhysTech).

Sensor power consumption due to hydrometeor evaporation is calculated as

(1)

where Vcol and Vref are collector and reference sensor voltage and sensor current is denoted as Icol and Iref. k is a convective heat loss coefficient (elaborated below).

Liquid water content is calculated as

(2)

e is particle collection efficiency (assumed to be 1 for these calculations), U represents true airspeed, S is collector sensor surface area, and L\* is the expended heat for liquid water which is defined as

(3)

where Tambient is environmental temperature, Cliq is the liquid water specific heat capacity, and Lv liq is the latent heat of vaporization at Tsensor.

The convective heat loss coefficient (k) is defined as a ratio of collector and reference sensor powers when data are measured in clear air environments.

(4)

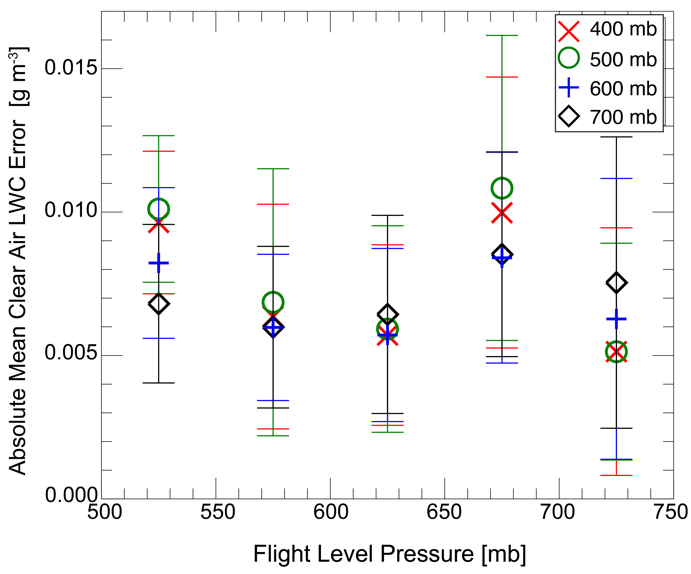
k is dependent upon pressure, temperature, and airspeed. Neglecting this dependence introduces mean LWC error on the order of 100% (assuming Korolev’s COPE-MED calculations as truth). Correcting for k requires Nevzorov calibration maneuvers composed of clear air legs flown at various pressure levels and airspeeds. A March 2016 flight provided calibration data with the following attributes.

1. 4 legs flown at separate pressures
   1. 700 mb
   2. 600 mb
   3. 500 mb
   4. 400 mb
2. Each pressure level contained sections of 5 discrete indicated airspeeds spanning approximately 80 – 115 m s-1
3. Calibration legs required
   1. Clear air
   2. Level flight
   3. Consistent airspeed

Parameterizations of k/airspeed relationships were calculated on a per-pressure level basis (one parameterization for each of the legs in bullet point 1) in order to investigate which calibration level was most suitable for future UWKA campaigns. Each of the pressure level legs were manually analyzed and five 60 second sections with discrete airspeeds were selected. Care was taken to exclude sections with significant pitch, roll, yaw, sideslip, or acceleration. An indicated airspeed vs. k exponential fit was applied to the resulting datasets filtered from each of the flight level legs. The resulting relationships provided airspeed-dependent k estimates for Pliq calculations (equation 1). It should be noted that indicated, instead of true, airspeeds were employed because indicated airspeed includes an intrinsic “compensation” for pressure and temperature deviations.

Performance of each of the four airspeed/k parameterizations (where each parameterization was calculated from either 400, 500, 600, or 700 mb pressure level data) was tested using points sourced from subsequent UWKA flights. Flight data were filtered to select test points of clear air flight using the process outlined at the beginning of this section. The mean absolute LWC error of test points (where LWC error is equal to LWC for clear air points) was used as a performance metric. The four parameterizations performed quite similarly but the 700 mb k parameterization showed the least absolute clear air error with consistent performance across a majority of test point pressure levels. Therefore, calculations only use the 700 mb k parameterization. Figure 5b. shows each parameterization’s performance binned by the pressure level that test data were collected.

baselineSelEx.ps.ai



***Fig 5. (a)*** *Shows a representation of the clear air selection process. Baseline values (red solid line) are minimum voltages from each 30 second period smoothed by a low pass filter. The threshold (red dashed line) is selected as the 25th percentile of normalized (*VLWC Col – Vbaseline) voltage and points with normalized voltage less than the threshold are flagged as clear air (blue dots).***(b)*** *Illustrates each k parameterization’s performance. Baseline error is considered to be LWC for points flagged as clear air. The 700 mb parameterization showed consistent performance for most test data pressure levels (curiously, excluding the 700 - 750 mb interval).*

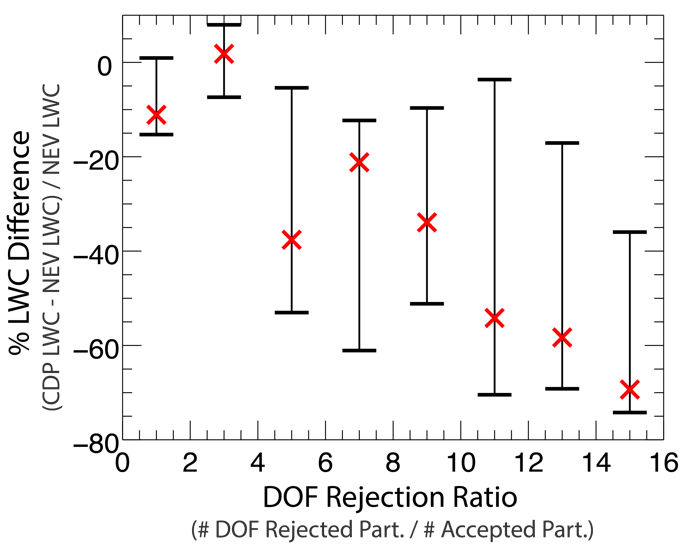
LWC calculated using airspeed-corrected k values is still subject to mean error on the order of 0.03 g m-3 due to residual k pressure and temperature dependence. Correction for pressure and temperature related error is performed by linearly fitting pressure vs. Pliq values for clear air data and then forcing the slope of the linear regression to zero. The aforementioned process typically reduces LWC error caused by k pressure/temperature dependence by an order of magnitude.

Several other potential source of LWC error including aircraft angle of attack, yaw, sideslip, roll, presence of turbulence, and differing sources of airspeed, pressure, and temperature measurements have been found to be negligible (objective 10b). No trends in aircraft orientation vs. LWC baseline error were detected and sources of various environmental data are so similar that resulting differences in LWC are trivial. The Nevzorov processing scripts use the following parameter sources; static pressure: Rosemount 1501 digital sensor A, static temperature: reverse flow temperature sensor, indicated and true airspeed: pilot boom pitot.

**In-situ Instrument Error Analysis and Operating Condition Constraint**

In-situ error analysis and constraint of probe operating conditions will be performed for the CDP and Nevzorov (objectives 8 – 10) by using droplet generator calibration results, consideration of Nevzorov uncertainty due to convective heat losses and droplet collection efficiencies, and comparisons between Nevzorov and derived CDP LWC.

In-situ investigations will address three main objectives. Firstly, Nevzorov/CDP LWC comparisons and droplet generator results will be used to probe the nature of CDP droplet mis-sizing error (objective 8a). Mis-sizing specific investigations will be confined to low droplet concentrations because coincidence events, a concentration dependent phenomenon, introduce much more significant error (when compared to error contributed by mis-sizing alone). Relevant concentration ranges will be selected using the previously mentioned error characterizations, work by Lance et al. (2010, 2012), and a handful of diagnostic CDP variables. For example, counts of depth of field rejected particles (particles that pass through the CDP’s laser but are deemed to be outside the sample volume) can provide a diagnosis of coincidence. Figure 6a. demonstrates the relationship between the relative number of DOF rejected particles and differences in Nevzorov/CDP LWC. In general, Nevzorov/CDP LWC percent difference and the spread of percent LWC difference increases in magnitude as more DOF rejected particles are counted.

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***Fig 6. (a)*** *Shows the relationship between the ratio of DOF rejected particle counts to accepted particle counts vs. Nevzorov/CDP LWC percent difference. Red markers are median percent LWC difference and error bars mark the 1st and 3rd quartile of percent difference.*

Secondly, the nature of coincidence error and its impact on CDP derived values will be investigated (objective 8b) and used to define viable CDP operational ranges (objective 9). Methods will mainly employ Nevzorov/CDP LWC comparisons and refined parameterization of mis-sizing error for higher droplet concentrations. Lance et al. (2010) estimated that coincidence events could realistically introduce 30% oversizing and 27% undercounting error for concentrations as low as 500 cm-3. Such error would significantly compromise CDP derived LWC. The UWKA CDP features a detector sensor pinhole mask which is designed to substantially decrease the occurrence of coincidence events but further investigation is still pertinent. Especially considering the complex nature and significant error caused by such events.

Thirdly, the previously mentioned mis-sizing and coincidence error investigations will be used to better characterize Nevzorov TWC droplet collection efficiencies (objective 10). Nevzorov collection efficiencies have been explored by several studies including work by Korolev et al. (1998), Strapp et al. (2003), and Schwarzenboeck et al. (2009), but further investigation is none-the-less relevant. Collection efficiencies are one of the most significant sources of LWC/TWC uncertainty and a more complete understanding is required to accurately retrieve water contents, especially in mixed phase clouds.

**Timeline**

* + End of 2016 spring semester
    - Nevzorov uncertainty characterization completed for known sources
    - Nevzorov algorithm performance tested using COPE-MED data
  + End of summer 2016
    - Major droplet generator components installed
    - Required operational software developed
    - Best operational practices defined
    - Proof-of-concept CDP calibration data collected
  + End 2016 fall semester
    - Complete CDP calibration data collected
    - Initial CDP/Nevzorov uncertainty investigations using in-situ data underway
  + End of winter break 2016
    - CDP/Nevzorov uncertainty investigations nearing completion (using full fall/winter dataset)
    - Initial thesis writing stages underway
  + Mid 2017 spring semester
    - In-situ error investigations complete
    - Initial thesis draft complete
  + End of 2017 spring semester
    - Thesis completed and successfully defended

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