1. **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 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) is 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 DSDs of small mean diameter because the rate of mass growth through condensation is inversely proportional to the square of droplet diameter. Growth to precipitation-sized particles by condensation alone would require timescales far longer than are observed, implying the importance of additional processes. One such process, droplet collection and coalescence, widens narrow small droplet distributions to a more disperse bi-modal shape (Lamb and Verlinde 2011). Distribution widening can in turn lead to positive coalescence feedbacks (due to droplet terminal velocity being proportionally related to diameter) which further accelerates droplet growth rates.

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. Furthermore, ice particles are subject to interactions with other particles including growth through droplet collection and freezing, aggregational growth, 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.

Dynamic processes including entrainment, mixing, and particle recycling can also affect 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).

**2. ——Something about aircraft measurements———**

**2.1 The Cloud Droplet Probe Forward Scattering Spectrometer**

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 cloud droplets of 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**

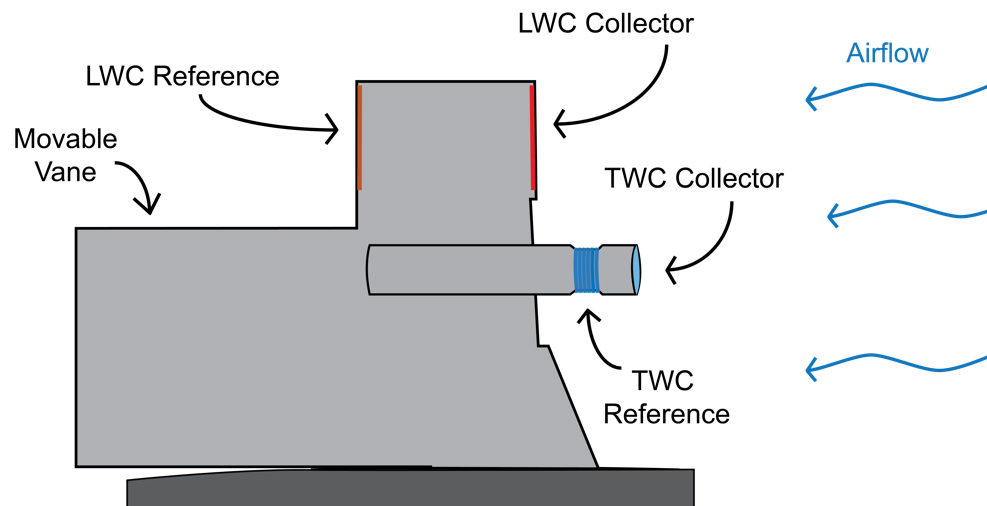
|  |  |
| --- | --- |
| **Parameter** | **Source** |
| Particle Diameter | Scattered light intensity |
| Particle Number Concentration | Scattering event counts, sample volume dimensions, aircraft airspeed |
| Liquid Water Content | Derived from DSD※ |
| Effective Diameter | Derived from DSD※ |
| Median 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)

**2.2 The Nevzorov Hotwire Probe**

The Nevzorov is among the latest generation of hotwire probes capable of retrieving both bulk liquid water content and combined liquid and ice 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 similarly-sized reference sensors 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.



***Figure 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).

**3. Significance**

**3.1 Error Sources Affecting CDP Measurements**

The CDP is subject to both significant particle mis-sizing and mis-counting error. Mis-sizing uncertainty can be caused by a variety of effects that fall into two overarching categories; sizing response error and coincidence error. Errors in sizing response are primarily caused by inhomogeneity in laser beam intensity and optical component mis-alignment which alters the intensity of collected light. Lance et al. (2010) found sizing response error can realistically skew particle diameter values by 2 μm. Coincidence errors occur when multiple particles are within an instrument’s beam simultaneously. The additional light scattered by coincident particles is collected by the sizing detector causing particles to likely be oversized. Coincidence error can also lead to significant particle counting errors because, at most, a counting event is triggered for only one of multiple coincident particles (every coincident particle can be rejected additional scattered light raises digital sizing counts above threshold values). Coincidence error is more difficult to parameterize than “pure” sizing response error because a variety of factors (including the ambient particle concentrations and coincident particle’s position and size) can lead to several different outcomes. Manufacturer specifications state the CDP is capable of truthfully retrieving DSDs for 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). The UWKA CDP features a sizing detector pinhole mask intended to decrease the occurrence of coincidence events. Lance et al. (2012) demonstrated that pinhole masks do significantly decrease the impact of coincidence events but an instrument-specific investigation is nonetheless pertinent.

To be clear, sizing response error is a “single particle” phenomenon which most likely contributes to relatively predictable particle sizing error. In contrast, coincidence error is a concentration dependent event which can lead to both errors in particle counting and/or sizing. Coincidence error is much less predictable because it can lead to several different outcomes depending on several factors.

Investigating the nature of sizing response error requires detailed measurements of sample volume dimensions and the truthfulness of sizing response at discrete positions within the sample volume. Traditional forward scattering spectrometer calibration techniques aren’t suitable for such investigations 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.

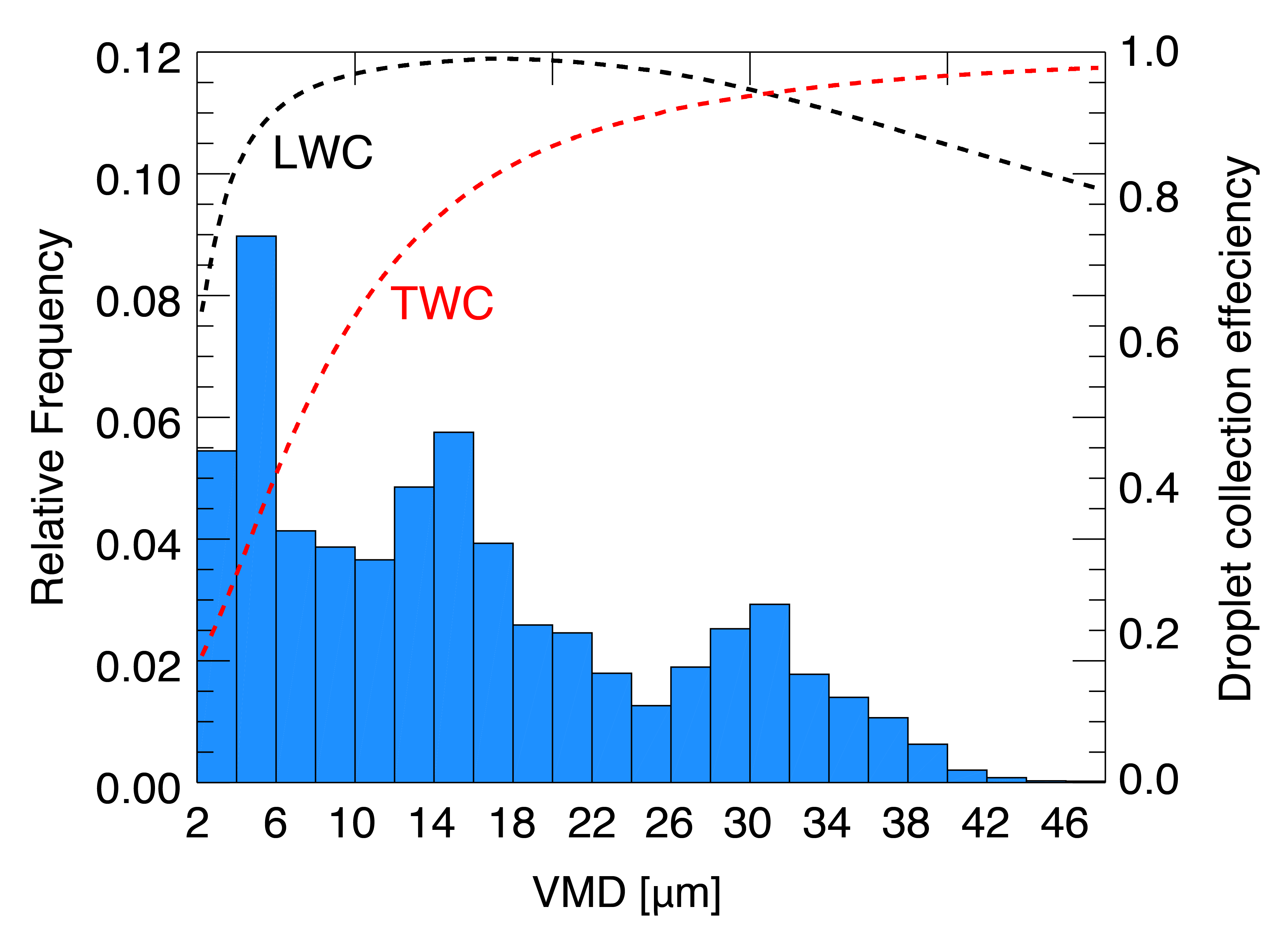
**3.2 Error Sources Affecting Nevzorov Measurements**

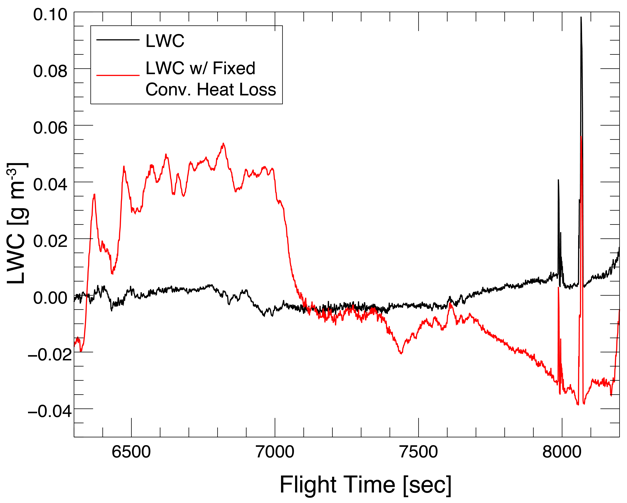
Bulk measures of LWC and TWC from the Nevzorov can be compromised by various error sources including sensor saturation in high water content environments, non-unity particle collection efficiency, and convective heat losses. It has been found that LWC sensor saturation is significant for particle median 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 the latest design of the University of Wyoming King Air (UWKA) Nevzorov probe features updated circuitry which should minimize power supply bottlenecks.

Convective heat losses (or sensor power consumption due to factors other than particle evaporation) are an airspeed and density dependent phenomena that can seriously compromise Nevzorov measurements. Calculations often use a mean convective heat loss value and therefore neglect the effect of small-scale airspeed and density fluctuations. Such approximations can introduce pronounced LWC baseline drift and error on the order of 100% (when compared to our calculations). Figure 2a shows a comparison of LWC calculated with our methods (black line) and LWC calculated using a mean convective heat loss value (red line). The red line illustrates the typical character of baseline drift introduced by using simplifying approximations.

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 small particles (~ 3 – 15 μm VMD) but approach values of .9 by 25 μm VDM. Figure 2a shows a CDP droplet distribution for cumulative measurements collected during several COPE-MED flights. Overlaid collection efficiency estimates (provided by Korolev et al. 1998, Strapp et al. 2003, Schwarzenboeck et al. 2009) show that collection efficiency effects are especially apparent for both LWC/TWC sensor measurements taken in distributions with VMD of 12 μm or less. 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 Strap et al. used extrapolated TWC efficiency estimates for 25 - 50 μm VMD droplets (due to equipment limitations). It is reasonable to assume that efficiencies in that range follow a well-behaved parameterization but 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 2.*** *(****a****) An example of the nature of baseline LWC drift (shown by the red line) that would be introduced by assuming a mean convective heat loss coefficient (therefore neglecting convective heat loss airspeed, pressure, and temperature dependence). (****b****) CDP droplet size distribution binned by VMD for measurements collected during COPE-MED. 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).*

**4. 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 Precipitation and Cloud Measurements for Instrument Characterization and Evaluation (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. Mis-counting error using
      1. Mis-sizing error estimates from objective 8a
      2. CDP/Nevzorov LWC agreement and its concentration dependence
2. Nevzorov – characterize error sources including
   1. TWC collection efficiencies for 25 – 50 VMD μm droplets
      1. Results of objectives 8a and 8b
      2. Comparisons of LWC/TWC sensor liquid water contents
   2. Aircraft orientation effects
      1. Relationships of aircraft orientation and out of cloud LWC error

CDP mis-sizing specific investigations (objective 8a) are to be initially constrained to relatively low droplet concentrations in order to exclude 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 mis-counting error will be performed by first considering the results of mis-sizing error investigations (objective 8a) and comparisons of CDP/Nevzorov LWC at various concentration ranges. It is expected that a positive correlation between particle concentration and CDP/Nevzorov LWC bias will be evident in the presence mis-counting due to coincidence error.

CDP/Nevzorov LWC comparison and refined CDP error characterization will in turn be used to explore droplet collection efficiencies for the Nevzorov TWC sensor (objective 9a). The nature of aircraft orientation’s affect on Nevzorov LWC error will be evaluated using relationships of aircraft orientation (including pitch, roll, yaw, and sideslip angle) and out of cloud LWC error.

**5. 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.

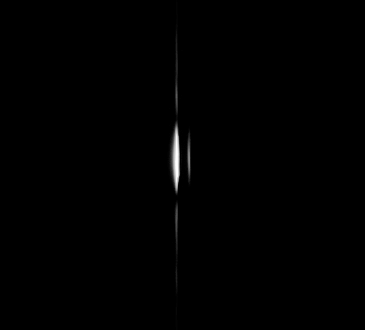
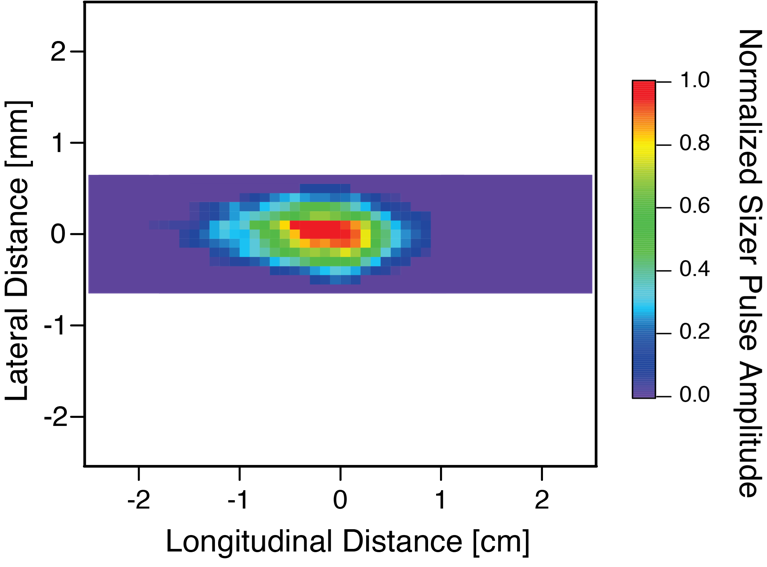
Calibration system development is currently underway with a majority of components already installed and tested. Figure 3 shows a schematic of the major system components. The droplet generator assembly (in grey) includes a glass flow tube (semi-transparent structure at the bottom) and print head (available 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).



***Figure 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***

***Figure 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 often 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 a “beam map” (see Figure 4b).

**6. 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. Our calculated LWC and Korolev’s independent values 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 the following methodology:

1. The ratio of LWC collector sensor voltage to LWC reference sensor voltage (Vratio = Vlwc,col / Vlwc,ref) is calculated
2. A baseline Vratio (or Vratio,base) is defined by
   1. Dividing Vratio into 30 second increments
   2. Locating each increment’s minimum Vratio value
   3. Applying a low pass filter to the selected minimum Vratio values
3. A normalized voltage ratio is calculated by taking the difference of voltage ratios and baseline voltage ratios (Vnorm = Vratio – Vratio,base)
4. A threshold is then set as the 25th percentile of Vnorm
5. A preliminary subset of clear air points is selected where Vnorm is less than the threshold value
6. The final clear air point subset is defined after excluding the largest 5% of Vnorm values

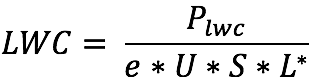
Step 6 removes the small number of in-cloud points that are erroneously flagged as clear air. Figure 5a provides a graphic representation of the clear air filtering process. It should be noted that the process by no means flags every clear air point but it does provide a sample sufficient for subsequent calculations.

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)

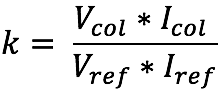
e is particle collection efficiency (assumed to be 1 for these calculations), U represents true airspeed, S is collector sensor surface area, and L\* is the heat expended for the vaporization of liquid water which is defined as



(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.



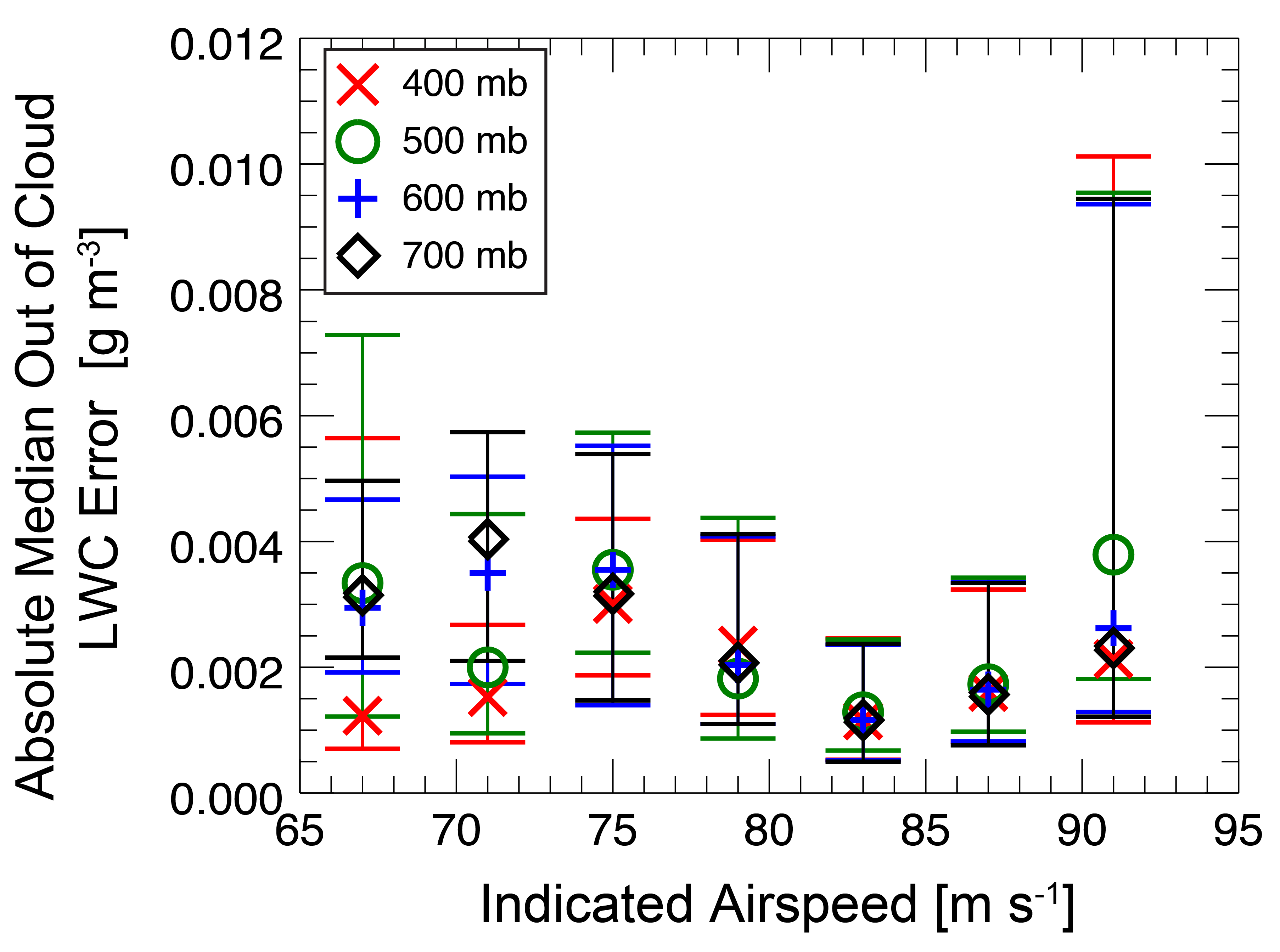
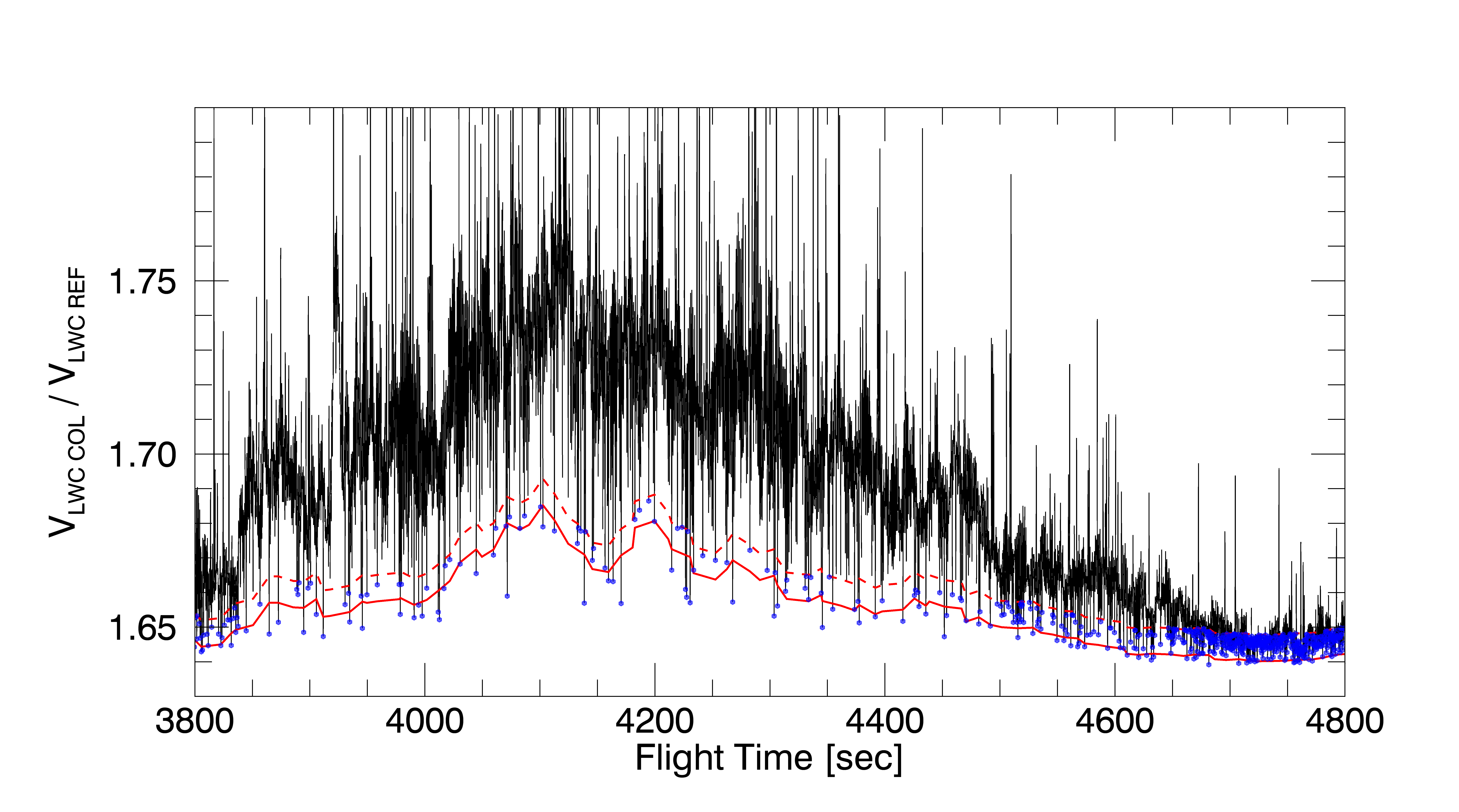
(4)

k is dependent upon airspeed and atmospheric density. Neglecting these dependencies by using a mean k value introduces mean LWC error on the order of 100% (assuming Korolev’s COPE-MED calculations as truth). Our calculation methods use a dynamic k value based on parameterizations of airspeed and density dependence which increases LWC confidence in low water content environments and negates the need for manual baseline corrections. Parameterizations require Nevzorov calibration maneuvers composed of out of cloud 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 within each discrete airspeed section

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 differences in density.

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 out of cloud test points using CDP concentration values. Points are considered out of cloud if CDP particle concentrations = 0 g m-3 for a consecutive 2 second period. The median absolute out of cloud LWC error (where LWC error is equal to LWC for out of cloud points) was used as a performance metric. The four parameterizations performed quite similarly but the 400 mb k parameterization showed the least absolute out of cloud LWC error with consistent performance across a majority of test point indicated airspeeds. Therefore, calculations only use the 400 mb k parameterization. Figure 5b shows each parameterization’s performance binned by test point indicated airspeed.



***Figure 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 (*Vnorm) voltage and points with normalized voltage less than the threshold are flagged as clear air (blue dots).***(b)*** *Illustrates each k parameterization’s performance. Out of cloud LWC error is considered to be LWC for out of cloud points. The 400 mb parameterization consistently showed the best performance across all mean indicated airspeed ranges (perhaps excluding the interval with 79 m s-1 mean indicated airspeed).*

One final step corrects for mean out of cloud LWC error on the order of 0.03 g m-3 which is due to residual k density (or pressure and temperature) dependence. Correction for residual effects are 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 out of cloud LWC error caused by k density dependence by an order of magnitude.

LWC agreement between our calculated values and Korolev’s was examined using data collected during several COPE-MED flights. Mean LWC bias (LWC - LWCKorolev) for the ~130000 examined points equals -0.0017 g m-3. Figure 6a shows median percent LWC differences binned by Korolev’s LWC.

***Figure 6. (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 (*Vnorm) voltage and points with normalized voltage less than the threshold are flagged as clear air (blue dots).

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 9b). 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.

**7. 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.

***Figure 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.

**8. 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

**9. References**

Boucher, O., and U. Lohmann, 1995: The sulfate-CCN-cloud albedo effect. *Tellus B*, **47**, 281–300, doi:10.1034/j.1600-0889.47.issue3.1.x. http://www.tellusb.net/index.php/tellusb/article/view/16048.

Droplet Measurement Technologies, Inc., 2014: Cloud Droplet Probe (CDP-2). http://www.dropletmeasurement.com/products/airborne/CDP-2.

Jackson, R. C., G. M. Mcfarquhar, J. Stith, M. Beals, R. A. Shaw, J. Jensen, J. Fugal, and A. Korolev, 2014: An assessment of the impact of antishattering tips and artifact removal techniques on cloud ice size distributions measured by the 2D cloud probe. *J. Atmos. Ocean. Technol.*, **31**, 2567–2590, doi:10.1175/JTECH-D-13-00239.1.

Korolev, A., J. W. Strapp, G. A. Isaac, and E. Emery, 2013: Improved airborne hot-wire measurements of ice water content in clouds. *J. Atmos. Ocean. Technol.*, **30**, 2121–2131, doi:10.1175/JTECH-D-13-00007.1.

Korolev, A. V., J. W. Strapp, G. A. Isaac, and A. N. Nevzorov, 1998: The Nevzorov airborne hot-wire LWC-TWC probe: Principle of operation and performance characteristics. *J. Atmos. Ocean. Technol.*, **15**, 1495–1510, doi:10.1175/1520-0426(1998)015<1495:Tnahwl>2.0.Co;2.

Korolev, A. V., S. V. Kuznetsov, Y. E. Makarov, and V. S. Novikov, 1991: Evaluation of measurements of particle size and sample area from optical array probes. *J. Atmos. Ocean. Technol.*, **8**, 514–522, doi:10.1175/1520-0426(1991)008<0514:EOMOPS>2.0.CO;2.

Lamb and Verlinde, 2011: Physics and Chemistry of Clouds. Cambridge University Press, 584 pp.

Lance, S., 2012: Coincidence errors in a cloud droplet probe (CDP) and a cloud and aerosol spectrometer (CAS), and the improved performance of a modified CDP. *J. Atmos. Ocean. Technol.*, **29**, 1532–1541, doi:10.1175/JTECH-D-11-00208.1.

Lance, S., C. A. Brock, D. Rogers, and J. A. Gordon, 2010: Water droplet calibration of the Cloud Droplet Probe (CDP) and in-flight performance in liquid, ice and mixed-phase clouds during ARCPAC. Atmos. Meas. Tech., 3, 1683–1706, doi:10.5194/amt-3-1683-2010. http://www.atmos-meas-tech.net/3/1683/2010/.

MicroFab Inc.: Applications Overview. Accessed 9 August 2016. [Avalable online at http://www.microfab.com/overview-sp-1927588172]

Nagel, D., Maixner, U., Strapp, W., and Wasey, M.: Advance- ments in Techniques for Calibration and Characterization of In Situ Optical Particle Measuring Probes, and Applications to the FSSP-100 Probe, J. Atmos. Oceanic Technol., 24, 745–760, doi:10.1175/JTECH2006.1, 2007.

Perrin, T., J. L. Brenguier, and T. Bourrianne, 1998: Modeling coincidence effects in the Fast-FSSP with a Monte Carlo model. *Preprints, Conf. on Cloud Physics, Amer. Meteor. Soc., Everett, WA*, 112–115.

Schwarzenboeck, A., G. Mioche, A. Armetta, A. Herber, and J.-F. Gayet, 2009: Response of the Nevzorov hot wire probe in clouds dominated by droplet conditions in the drizzle size range. *Atmos. Meas. Tech.*, **2**, 779–788, doi:10.5194/amt-2-779-2009. http://www.atmos-meas-tech.net/2/779/2009/.

Sky PhysTech Incorporated: Operating Manual, Nevzorov hot wire LWC / TWC Probe.

Strapp, J. W., and Coauthors, 2003: Wind tunnel measurements of the response of hot-wire liquid water content instruments to large droplets. *J. Atmos. Ocean. Technol.*, **20**, 791–806, doi:10.1175/1520-0426(2003)020<0791:WTMOTR>2.0.CO;2.

Sulkis, J.: A Comparison and Survey of the Measured Cloud Liquid Water Content and an Analysis of the Bimodal Droplet Spectra Observed During the Summer 2014 Convective Precipitation Experiment – Microphysics and Entrainment Dependencies (COPE-MED) Field Campaign. University of Wyoming

Tölle, M. H., and S. K. Krueger, 2014: Effects of entrainment and mixing on droplet size distributions in warm cumulus clouds. J. Adv. Model. Earth Syst., 6, 281–299, doi:10.1002/2012MS000209.