**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 another vapor diffusion effect, the Bergeron process, further complicates precipitation formation studies. Preferential vapor diffusion to ice particles is driven by the fact that saturation vapor pressure over ice is less than saturation pressure over supercooled liquid water. The Bergeron process can quickly (with regards to convective cloud lifetime) narrow and shift DSDs to greater mean diameters.

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).

**Significance**

The Droplet Measurement Technology, Inc. Cloud Droplet Probe (CDP) is a cloud particle counting and sizing probe commonly used to provide measurements of cloud droplet size spectra (DSD) from aircraft. It operates on principles similar to the predating Forward Scattering Spectrometer Probe (FSSP) developed by Particle Measuring Systems, Inc. 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 sub-precipitation sized cloud droplet (up to 50 μm diameter) size distributions. 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 droplet 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 Retrieved Parameters**

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

It is known that the CDP is subject to error introduced by two overarching sources. Firstly, inhomogeneity in laser beam intensity, optical 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 typically skew particle diameter values by 2 μm. The second major error source, known as “coincidence error”, arises from the fact that CDP sample volumes (laser beam regions sensitive to particles) are often many times more extensive than theorized, suggesting it is likely that multiple particles can reside within a sample volume simultaneously. 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 DSD truthfulness can be significantly impacted at concentrations as low as 500 particles cm-3 (Lance et. al., 2012).

Traditional forward scattering spectrometer (including the CDP and FSSP) 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 liquid 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. Designs are generally 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 sheath airflow tube (MicroFab inc.). 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 precision microstages alter the point of sample area 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 extended sample volume dimensions (areas beyond the bounds of idealized sample volumes where particles can contribute to counting and sizing error).

Hotwire probes are another common class of cloud physics instrument which retrieve bulk water content based on a heated element’s hydrometeor evaporation induced power consumption. 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 the amount of water available to form precipitation. Hotwire sensed LWC is also useful for airborne probe limitation studies when considering that bulk water content values are analogous to the third moment of a droplet distribution. A constraint can therefore be placed on additional probes’ (in this case the CDP’s) calculated LWC providing bounds to effective operating conditions.

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 similar hotwire designs including phase discrimination capability, a freely rotating vane to decrease bias caused by changes in aircraft orientation, and paired collector/reference coil architecture. The latter simplifies calculations, significantly reduces baseline noise, and increases retrieval confidence in low water content environments (Korolev 1998). A few well-characterized error sources including water content underestimation (or roll off) in high water content situations (due to sensor saturation), non-unity particle collection efficiency, and baseline drift due to power consumption by sources other than particle evaporation (dry air heat losses) can compromise Nevzorov measurements. Fortunately, many of these major error sources have been characterized and can be compensated for using straight-forward methods. Baseline drift compensation is performed using parameterizations of dry air heat loss airspeed and pressure dependence. Collection efficiency estimates have previously been established by Korolev et al. (1998) and further developed by Schwarzenboeck et al. (2009). Likewise, operating bounds imposed by sensor saturation has been explored in work by Strapp et al. (2003) and Sulskis (2016).

Analysis by Sulskis (2016) has shown Nevzorov LWC values to be in very good agreement with CDP LWC (when compared to CDP and additional hotwire probes’ agreement). The Nevzorov and CDP’s mutual LWC retrieval ability (the Nevzorov through a basic bulk measurement and the CDP through droplet size spectra integration) provides opportunity for probe uncertainty assessment and performance constraint. Of particular interest is the nature of DSD retrieval error contributed by droplet mis-sizing and mis-counting. More recent work by Lance et. al. (2012) demonstrated that a modification of the CDP’s sizing detector mask significantly reduces droplet sizing and counting uncertainty but further investigation is pertinent for more completely defining limitations. It is also expected that mis-sizing and mis-counting uncertainty is, to a certain extent, probe specific. UWKA CDP uncertainty investigation will provide tailored knowledge for in-situ studies and future UWKA missions.

**Background**

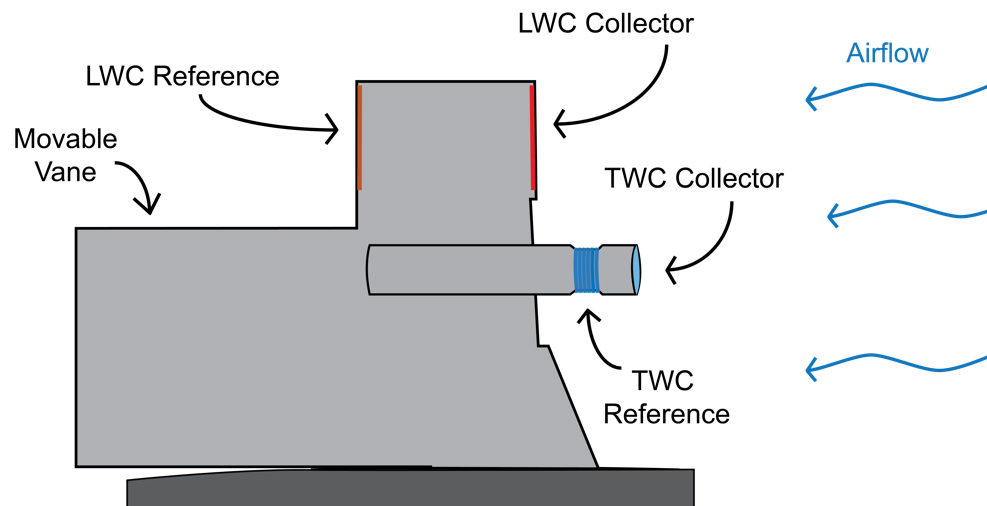
Lance et. al. (2012) have shown the CDP is subject to sizing response error and coincidence effects contributing to as great as 27% undercounting and 30% oversizing bias at concentrations as few as 500 droplets cm-3. A detector pinhole mask modification substantially reduced the occurrence of coincidence events but the effect remains significant, especially for larger particle concentrations or populations composed of small diameter droplet (~ 20 μm or less) (Lance et al. 2012).

In-situ inter-probe 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 within 5 to 10 μm (where Nevzorov values were 21% greater).

Several major Nevzorov uncertainty sources have been previously characterized. Work by Korolev et al. (1998) outlined methods for correcting airspeed and pressure related baseline water content drift. The same study examined LWC and TWC sensor collection efficiencies for liquid particles with volume weighted mean diameters (VMD) of 3 – 25 μm and subsequent work by Schwarzenboeck et al. (2009) expanded LWC sensor liquid collection efficiency estimates to include particles of up to 300 μm VMD. The two studies indicate collection efficiency effects introduce significant bias for liquid particle VMD less than 5 μm (due to aerodynamic effects) or greater than 25 μm (due to incomplete particle evaporation). Korolev et al.’s 1998 study estimated that TWC liquid collection efficiencies for 3 – 25 μm VDM particles are significantly less than unity for very small VMD particles (~ 3 – 15 μm) but asymptotes to efficiencies of .9 by 25 μm VDM. It is assumed TWC collection efficiencies remain greater than .9 for liquid particles larger than 25 μm VDM. Sensor saturation also introduces significant error in water content measurements. It has been found that LWC sensor saturation is apparent for particle median volume diameter (MVD) greater than 50 μm (Strapp et al. 2003) or LWC equal to or 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. Water content error introduced by sensor saturation is considered to be of secondary concern because upcoming UWKA missions will feature updated Nevzorov electronics designs which should minimize power supply bottlenecks.

**Nevzorov Data Processing**

The Nevzorov retrieves bulk water content by recording 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 designed to sense particles of both phases (TWC collector sensor). Values are derived using sensor power consumption due to hydrometeor evaporation and energy balance principles. Both the LWC and TWC collector sensors are paired with a similarly-sized reference sensor which is positioned such that cloud particle impacts are unlikely (and reference sensor power consumption is therefore assumed to be caused by only convective heat losses). The collector/reference sensor architecture simplifies calibration and baseline drift compensation caused by “dry air” convective heat loss’s pressure/airspeed dependence. Figure 1. provides a Nevzorov schematic showing the location of the LWC and TWC collector and reference sensors and the freely-translatable vane structure.



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

Nevzorov data processing routines have been developed and tested against well-established COPE-MED calculations 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 employing unique calculation methods. Algorithms include corrections for baseline drift due to airspeed and pressure deviations and parameterizations of collection efficiency related uncertainty. Derived Nevzorov values are calculated using the following formulae as defined in the Nevzorov operating manual (SkyPhysTech).

Nevzorov liquid water content is defined as

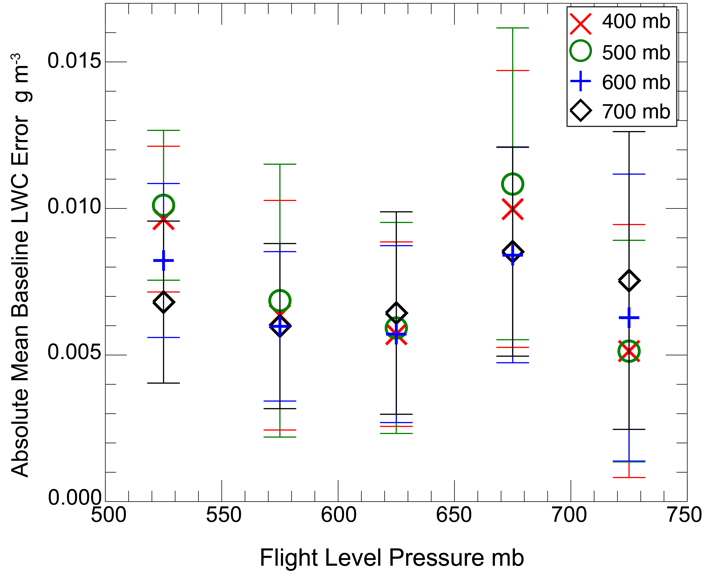
where Vcol and Vref are collector and reference sensor voltage, sensor current is denoted as Icol and Iref, k is the convective heat loss coefficient (further explanation provided below), e is particle collection efficiency (assumed to be 1 for calculations), U represents true airspeed, S is collector sensor surface area, and L\* is the expended heat for liquid water.

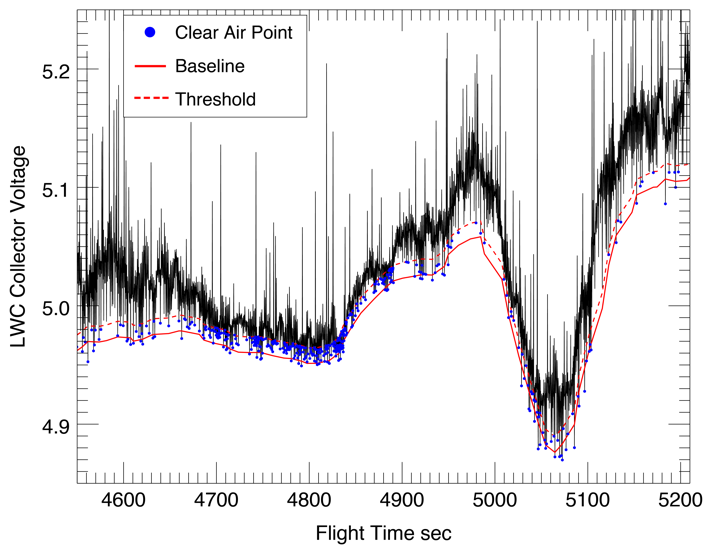
Heat expended due to hydrometeor evaporation is calculated as

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

Neglecting energy consumption due to factors other than particle evaporation, or convective heat loss, and its dependence on airspeed and pressure introduces mean LWC error on the order of 180% (assuming Korolev’s COPE-MED calculations as truth). The convective heat loss coefficient (valid only for clear air points) is defined as the ratio of collector/reference sensor power consumption

March 2016 test flights provided data for k airspeed and pressure calibrations. Four flight legs flown at 700, 600, 500, and 400 mb levels each contained multiple one minute sections of various true airspeeds ranging from 80 to 115 m s-1. A power law function fitted to each calibration leg’s indicated airspeed/k relationship provided dry air heat loss estimates across the King Air’s operational airspeed range. k values were fitted against indicated, instead of true, airspeed because indicated airspeed minimizes k uncertainty due to pressure drift. The effectiveness of each k parameterization (calculated from each of the 700, 600, 500, and 400 mb calibration legs) was examined using additional clear air points collected at flight levels spanning 400 – 700 mb and true airspeeds covering 80 – 125 m s-1. The four k parameterizations performed quite similarly but the 700 mb k calibration showed the least mean absolute LWC error for clear air points (where error is equal to LWC for clear air points) regardless of the flight level pressure. Therefore, calculations only use the 700 mb k parameterization.



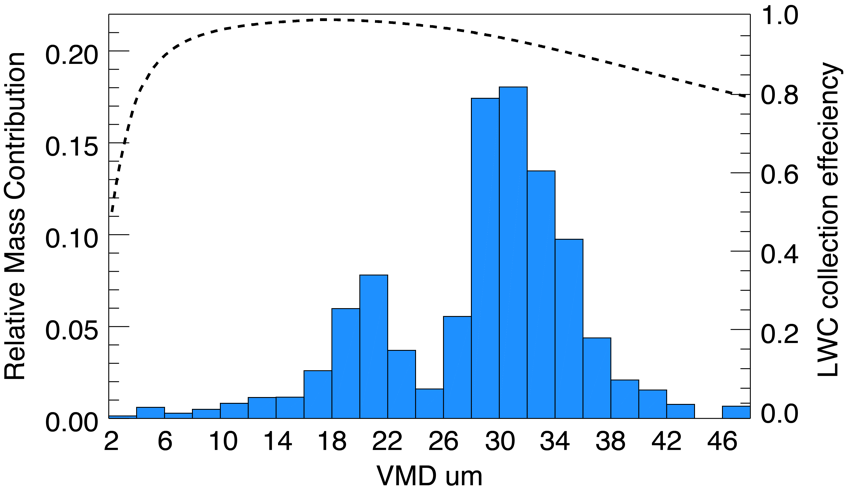


***Fig 2. (a)*** *Illustrates each k parameterization’s (400, 500, 600, 700 mb denoted in legend) performance. Baseline error is considered to be LWC for points flagged as clear air (details about clear air points in following paragraph).* ***(b)*** *Shows a representation of the clear air selection process. Baseline values (red solid line) are discrete 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).

Evaluation of k calibration performance and correction for pressure fluctuation-related baseline drift requires identification of clear air (out of cloud) points which is accomplished using raw LWC collector sensor voltage. First, a “baseline” is calculated by selecting the minimum voltage for each 30 second period and then smoothing the resulting signal with a boxcar average function. A clear air threshold is then defined as the 25th percentile of normalized voltages (where “normalized” is VLWC Col – Vbaseline). Points with normalized voltages less than the threshold value are considered clear air (see Figure 2b. for a schematic representation). It should be noted that the outlined filtering process by no means flags every clear air point but provides a sample sufficient for baseline drift compensation and k calibration testing.

Post airspeed-corrected LWC is still subject to mean error on the order of 0.03 g m-3 due to flight level pressure fluctuations, despite k/indicated airspeed parameterizations including an intrinsic pressure compensation. Correction for pressure-related baseline drift is performed by linearly fitting environmental pressure vs. Pliq values for clear air data (where clear air points are filtered as outlined in the previous paragraph) and then forcing the slope of the linear clear air regression to zero. The aforementioned process reduces pressure fluctuation induced baseline drift by at least an order of magnitude.

LWC error is also introduced by non-unity particle collection efficiencies due to small droplet (VMD less than 6 μm) aerodynamic effects or splattering and incomplete evaporative complications for VMD greater than 35 μm. Figure 3. shows a typical relative droplet mass distribution with Nevzorov LWC collection efficiency estimates as modeled by Korolev et. al. (1998) and later elaborated on by Schwarzenboeck et. al. (2009). Very little water mass is contributed by droplets in the range biased by aerodynamic effects but a significant portion of mass lies in the region where splattering and saturation effects are non-trivial.

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***Fig 3.*** *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.*

Several other potential LWC error sources 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. No trends in aircraft orientation vs. LWC baseline error were detected and sources of various environmental data are so similar that resulting differences in calculated 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.

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

Development of an optical cloud probe calibration system which uses pure water droplets as calibration media is currently underway with a majority of components already installed and tested. Figure 4. shows a schematic of the major system components. The droplet generator assembly (in grey) includes a glass flow tube and print head device (available in diameters of 5 μm increments spanning 20 – 80 μm) which produces droplets inside the flow tube’s sheath flow. Droplets are focused and accelerated in the flow tube’s tapered exit region and passed through a probe’s sample volume. 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).

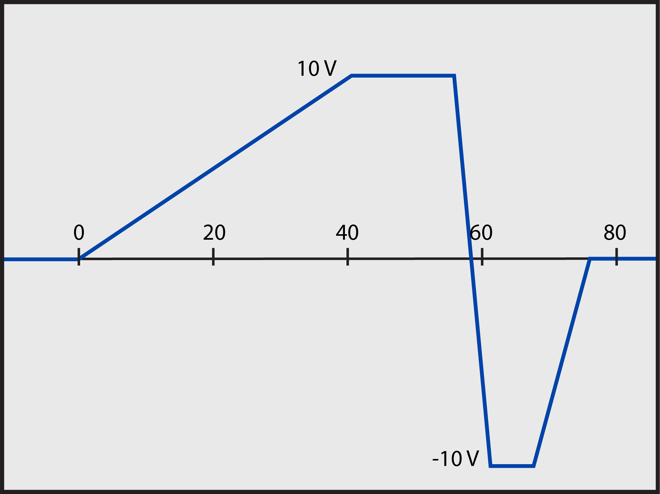


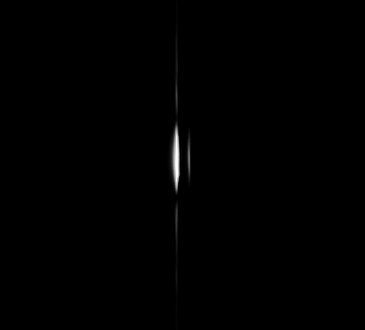
***Fig 4.*** *Schematic of the droplet generator system layout. Note: brown lines are links to/from the PC, red lines are cables from controllers, purple denote pressurized air lines, and blue show water lines.*

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.

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 pulses of positive voltage for water intake and a following negative pulse in order to force droplet creation at the nozzle’s exit. Figure 5a. shows an example waveform for producing 40 μm droplets.

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 they are illuminated in the CDP’s sample volume. Droplet diameters are estimated using glare latitudinal pixel separation, pixel/distance relationships determined using glass microbeads, and camera geometry. Droplet velocity can be deduced by further considering the pixel counts of glare “streaks” in the longitudinal dimension and camera exposure times. Figure 5b. shows an image of glares created by a 40 μm droplet.





***Fig 5.******(a)*** *Print head ejection waveform for 40 μm droplets (x-axis in us). Water is pulled into the main cavity during the positive pulse spanning 0 to 60 us and subsequently ejected during the more rapid negative pulse. This example waveform is programmed to create stable drops at 250 hz.* ***(b)*** *40 μm droplet glares captured with 125 us exposure.*

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 4.) has decreased downtime due to blockages by a significant amount. But the need to clear print head clogs is nevertheless 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 generator assembly flow tube (semi-transparent structure which encloses the print head in Figure 4.) 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.

**Objectives**

The proposed work will improve King Air in-situ droplet distribution and LWC retrieval capabilities through algorithm development, laboratory equipment setup and testing, and UWKA data analysis. A two-tiered methodology, including both laboratory-based experiments and in-situ analysis, will enhance departmental observational study abilities through improved calibration capabilities for optical cloud probes and error characterization for both the CDP and Nevzorov devices (through the two instruments’ mutual retrieval of LWC). CDP specific investigation will parameterize the nature of sizing error due to non-ideal detector response and derived LWC error caused by coincidence events. Nevzorov-focused efforts will further investigate TWC sensor collection efficiencies for liquid particles.

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.

Once operational, the calibration system will collect detailed measurements of CDP sample volume characteristics including position-dependent sizing accuracy and sample volume dimensions. CDP particle-by-particle data will provide individual counting events’ raw sizing detector pulse amplitudes; a valuable parameter given the non-linear relationship of pulse amplitude to derived particle diameter. Modifications to bin thresholds may be proposed pending the nature and severity of particle mis-sizing.

A combination of droplet generator calibration results and comparisons of CDP-derived LWC to Nevzorov-sensed LWC values (to be collected during Fall/Winter 2016 UWKA missions) will be employed to explore the nature of mis-sizing error. Mis-sizing specific investigations are expected to be constrained to data obtained in relatively low droplet concentrations in order to exclude the more severe error introduced through coincidence events. A threshold of relevant concentration ranges will be determined by considering CDP calibration results, refined Nevzorov uncertainty parameterization, and findings from previous studies by Lance et al. (2010, 2012).

Characterization of coincidence error (most importantly the effect’s particle concentration dependence) will be performed considering CDP/Nevzorov LWC comparisons at higher particle concentration ranges. Results are expected to most importantly provide CDP operational range constraints based on particle 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 derived LWC and refined CDP error characterization will in turn be used to explore liquid particle 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 liquid and ice contributions to measured water contents in mixed phase environments.

**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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