**Overview**

Characterizing cloud processes and their large scale influence is central to accurately modeling physical processes spanning ranges from localized precipitation to global albedo affects. A more thorough understanding of these processes is required despite many years of focused work and rapid advances in computing 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 fine temporal and spatial scales, complex feedbacks, and incomplete instrument limitation characterization.

The use of cloud droplet size distributions (DSDs) are nearly ubiquitous in microphysical studies because they provide key insight regarding drop formation, precipitation, and dynamic processes (Lamb and Verlinde 2011). Furthermore, distribution traits are characteristic to specific cloud properties and 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 cloud lifetime) narrow and shift DSDs to greater mean diameters. Macro-scale dynamic processes, including entrainment and mixing, further complicate DSD evolutions. Several factors, most importantly mixing/evaporation timescale relationships, substantially alter the evolution of drop spectra (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 predecessor Forward Scattering Spectrometer Probe (FSSP) developed by Particle Measuring Systems, Inc. but incorporates improvements not limited to a reduction in particle shattering and decreased electronic response times (Needs Reference). The CDP retrieves sub-precipitation sized cloud droplets (up to 50 um diameter) size distributions. Several other key parameters including liquid water content (LWC), effective particle diameter, and droplet concentrations are readily calculable using CDP DSDs (Droplet Measurement Tech. 2014). Manufacturer specifications state the CDP is capable of retrieving concentrations of up to 2,000 particles cm-3 but studies have shown sample volume dimension uncertainty, inhomogeneous sizing response, and coincidence error (error caused by multiple droplets simultaneously passing through an instrument’s sample volume) significantly impacts useful CDP operational ranges. Sample volumes have been found to be many times more extensive than theorized, suggesting that coincidence events are quite likely. Coincidence events’ respective contributions to droplet sizing and counting error are difficult to determine because coincidence can lead to several different outcomes; droplets can be undercounted, undercounted and oversized, or rejected altogether (Lance et. al., 2010). Lance et. al. (2012) have shown that DSD truthfulness can be significantly impacted at concentrations as low as 500 particles cm-3.

Traditional CDP calibration techniques aren’t suitable for addressing the impact of sizing and counting errors because they lack the required particle placement and concentration precision. 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. Ideally, these devices would be capable of creating pure liquid water droplets of repeatable size, velocity, concentration, and placement; attributes which 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), and 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. 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. They retrieve bulk liquid water content (LWC) based on a heated element’s power consumption caused by hydrometeor evaporation. Hotwire-sensed LWC values hold utility for both modelling and observationally-based studies. Water content is a key parameter in bulk cloud models providing (perhaps most importantly) a constraint on the amount of water available to form precipitation.

The Nevzorov is among the latest generation of hotwire probes and 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 vein 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 bias sources including LWC underestimation (or roll off) in high water content situations (due to sensor saturation), non-unity particle collection efficiency, and power consumption due to 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.

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. Furthermore, it is expected 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.

5-10 -> Nev LWC is 21% greater

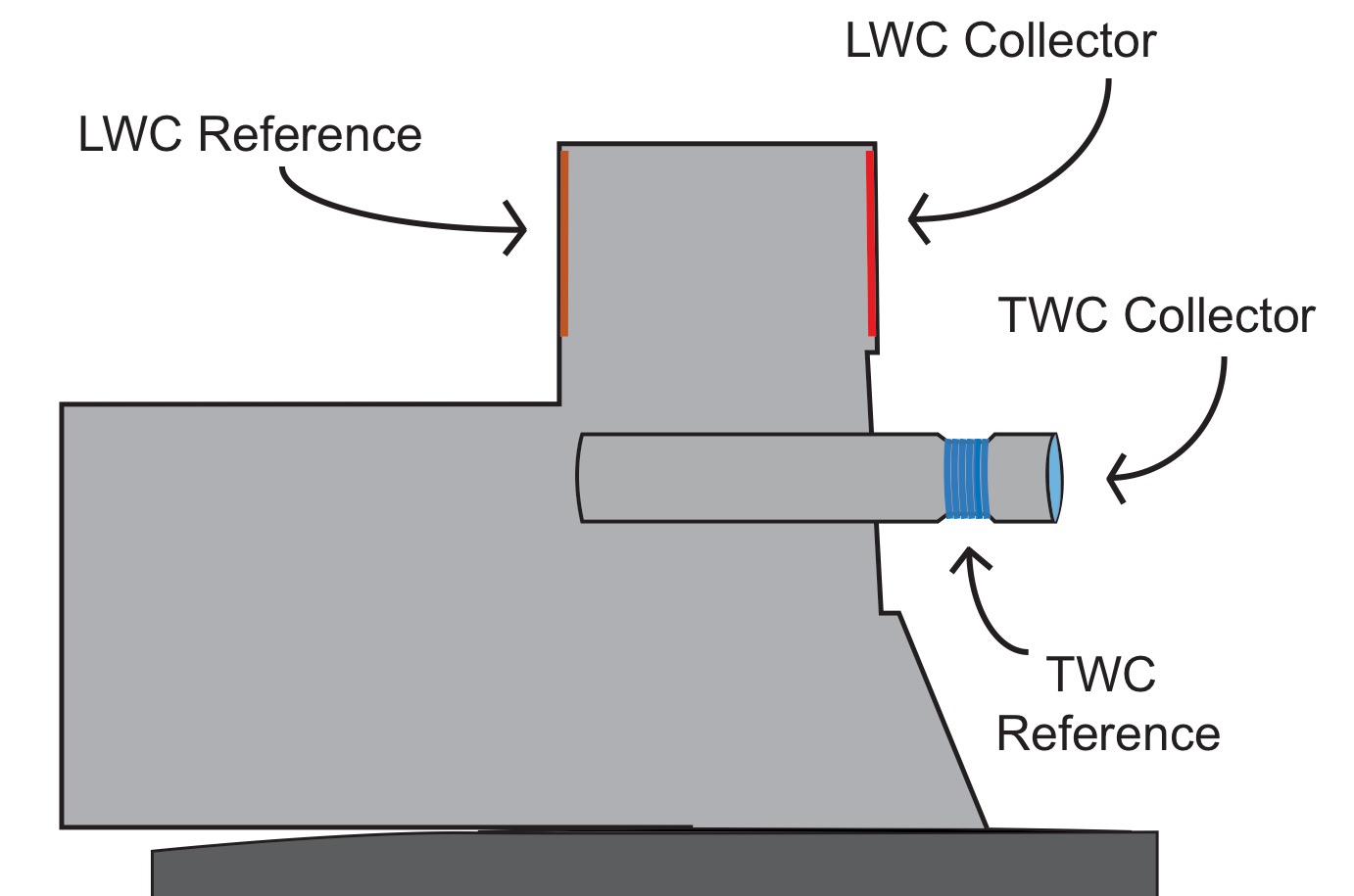
**Background**

Lance et. al. (2012) have shown the CDP is subject to sizing response inhomogeneity 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 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 um and particle concentrations ranging 10 to 1500 cm-3. CDP and Nevzorov LWC were within 13% of each other across all diameter and concentration ranges with the exception of particle diameters within 5 to 10 um (where Nevzorov values were 21% greater). Many Nevzorov uncertainty sources have been previously characterized including baseline drift caused by airspeed and altitude deviations which can skew LWC measurements as much as 2.0\*10-3 g m-3 / 10 m s-1 and 5.0\*10-3 g m-3 / km respectively (Korolev 1998). Collection efficiency effects introduce significant bias for particle volume weighted mean diameters (VMD) less than 5 μm (due to aerodynamic effects) or greater than 25 μm (incomplete particle evaporation) (Korolev 1998, Schwarzenboeck 2009). Sensor saturation roll off is apparent for particle median volume diameter (MVD) greater than 50 μm (Strapp 2003) or LWC equal to or greater than 1.3 g m-3 (Sulskis 2016).

**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. The collector/reference sensor architecture simplifies calibration and baseline drift compensation caused by “dry air” convective heat losses. Figure XXX provides a schematic Nevzorov layout including LWC and TWC sensor placement.



***Fig XXX.*** *Schematic of Nevzorov device illustrating sensor pairing. The vein (vertical light grey structure) is freely translatable to ensure 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

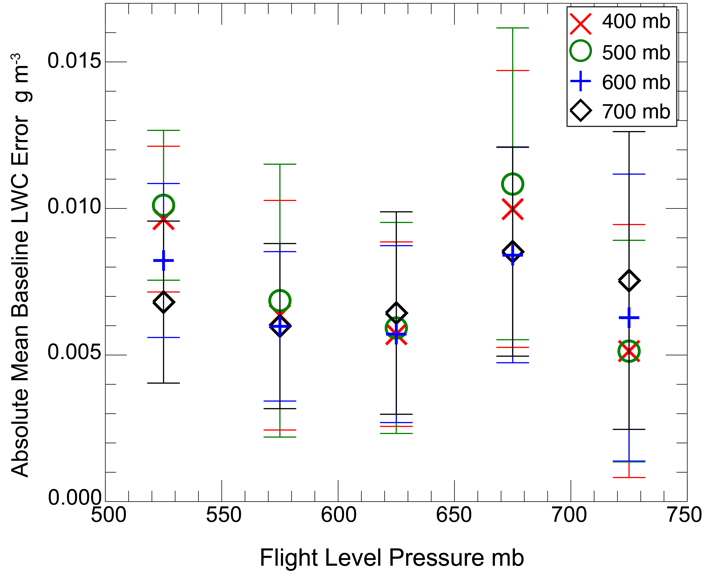
where Vcol and Vref are collector and reference sensor voltage, sensor current is denoted as Icol and Iref, k is the convective heat loss coefficient (further explanation provided below), e is particle collection efficiency (assumed to be 1 for calculations), U represents true airspeed, S is collector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

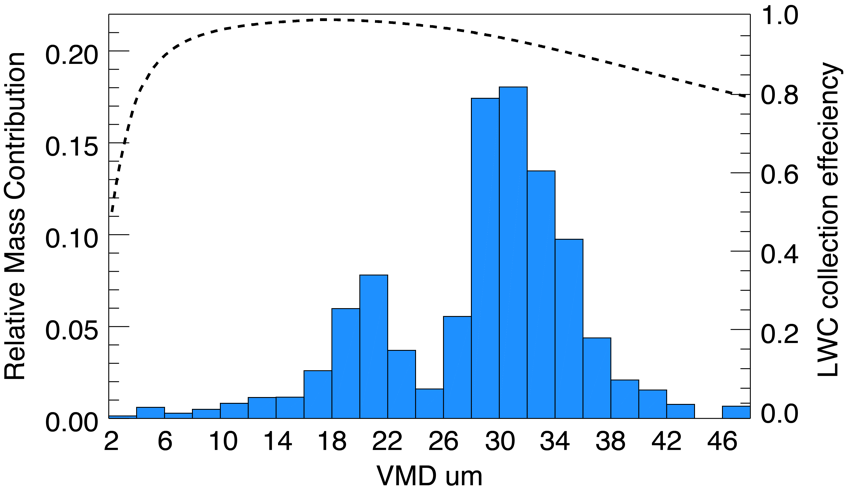


***Fig XXX.*** *(a) Illustrates each k parameterization’s (400, 500, 600, 700 mb denoted in legend) performance. Baseline error is considered to be LWC for points flagged as clear air (details about clear air points in following paragraph).*

k calibration and correction for pressure fluctuation-related error requires identification of clear air (out of cloud) points which is accomplished using raw LWC collector sensor voltage. In order to isolate clear air pointssignal is normalized in 30 second increments and a clear air voltage threshold is then set as the 75th percentile of normalized voltages. A point is considered clear air if it and the following 5 points’ voltages are less than the threshold value. Requiring the threshold criteria be met by consecutive points ensures isolated signal events are not erroneously flagged as clear air.

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 fluctuation 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 um) aerodynamic effects or splattering and incomplete evaporative complications for VMD greater than 35 um. Figure 1a. 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.

****

***Fig 1.*** *(a) 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 airspeed: pilot boom pitot.

**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 implemented. Fig 2a. 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 um increments spanning 20 – 80 um) 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).

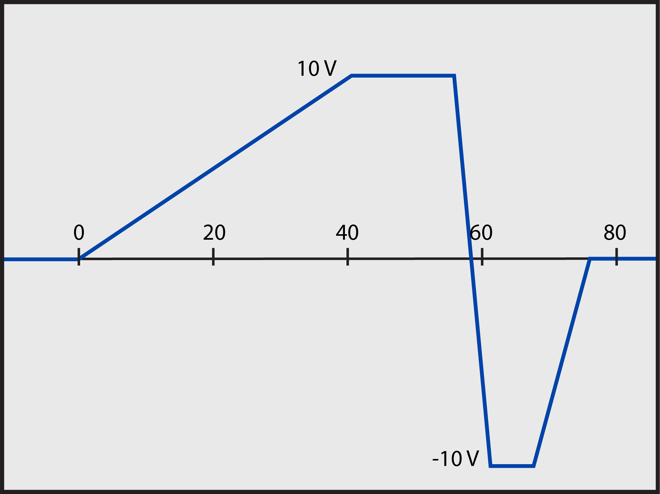


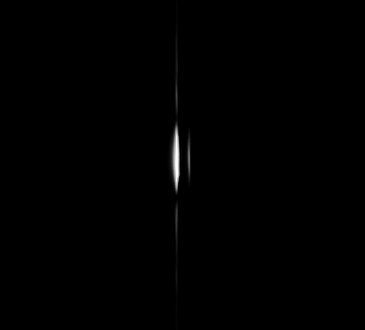
***Fig 2.*** *Schematic of the droplet generator system layout. Note: brown lines are links to/from the PC, red lines are cables from controllers, purple denote pressurized air lines, and blue show water lines.*

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 4a. shows an example waveform for producing 30 um 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 longitudinal 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 latitudinal dimension and camera exposure times. Fig 4b. shows an image of glares created by a 30 um droplet.





***Fig 4.*** *(a) Print head ejection waveform for 40 um 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 rapid negative pulse. This example waveform is programmed to create stable drops at 250 hz. (b) 30 um 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 2.) 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 2.) 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 detailed error characterization for both the CDP and Nevzorov devices (through the two instruments’ mutual retrieval of LWC). CDP specific investigation will probe sizing error due to non-ideal detector response and LWC error caused by coincidence events. Efforts focused on Nevzorov error sources will characterize LWC uncertainty introduced by sensor saturation (insufficient electronic response time).

A droplet generating calibration device will expand departmental optical probe calibration and characterization capabilities. Efforts are to be focused on preliminary system development, operating procedure development, documentation of procedures, and algorithm coding. The system will initially be compatible with 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. Calibration data will be used to develop a Monte-Carlo simulation (similar to work by Jackson et. al., 2014, Lance et. al., 2010, and Perrin et. al., 1998) which will model concentration-dependent sizing and counting error due to both inhomogeneity in sample volume response and coincidence error. Perhaps most importantly, the model will provide an estimate of droplet concentration ranges where CDP DSDs are reasonably truthful.

Fall 2016 King Air flights will collect cloud penetration data for both the Nevzorov and CDP. A handful of CDP parameters, including trends in droplet concentrations vs. rejected particle counts and average particle transit times (Lance et. al. 2012), will be used to diagnostically test results from the afore-mentioned simulations. Estimates of CDP LWC error will be defined using both parameterization of CDP operational bounds and comparison with Nevzorov LWC measurements. Inter-probe LWC comparison is especially useful due to a couple reasons; major sources of Nevzorov LWC uncertainty have been previously explored and the two probe’s unique operating principles make it less likely that respective LWC measurements will be biased in a similar manner. Refined CDP error characterization will in turn allow further investigation regarding Nevzorov error sources, namely, operational limits imposed by sensor saturation effects and the collection efficiency of a modified “deep cone” total water content sensor. Ice collection efficiencies for the modified design have been explored in work by Korolev, Strapp, and Isaac (2013) but liquid collection efficiencies remain relatively unexplored.

**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
    - Droplet generator procedures documented
    - Complete CDP calibration data collected
    - Initial CDP/Nevzorov uncertainty investigations 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

**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.

DMT, 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/.

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.