# Compact Nanoparticle Size Distribution Measurement System for Unmanned Aerial Systems (UAS)

Final Technical Progress Report for the Period Feb-2016-May 2017

July 2017

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## 1. *Abstract*

Brechtel Manufacturing Incorporated (BMI) is developing a compact, nanoparticle sizer optimized for use on Unmanned Aerial Vehicles (UAVs) and other applications where space, weight, power and cost are significant barriers to deployment. The instrument will allow observations of size-resolved aerosol number concentration ($0.005<D_p<0.3$ μm, $D_p$ is particle diameter). The new development helps address the need for reduced uncertainties in atmospheric radiative transfer and weather prediction model sensitivities to ambient aerosol properties by promoting the capability to perform aerosol measurements more often, in more locations, and at reduced cost. Applications of the new technology include vertical atmospheric profiling with UAVs, balloons and other mobile platforms to constrain weather forecast models, long-term air quality measurements, aerosol health effects studies, and routine monitoring of ambient aerosol properties in urban air sheds.

## 2. *Technical Description of the Technology*

The miniature-Scanning Electrical Mobility Sizer (mSEMS) measures the aerosol size distribution over the 0.005 to 0.3 micrometer diameter range using an electrical mobility spectrometer to size electrically charged particles. A differential mobility analyzer (DMA) is used to size-select particles which are then sampled into a Mixing Condensation Particle Counter to be counted. Alternatively, a Micro-Electromechanical System (MEMS) electrometer may also be deployed downstream of the DMA in order to measure the concentration of particles based on the deposited electrical current. The electrometer has the advantage of using no working fluid but suffers from relatively high noise due to the extremely low currrents (sub-femtoamps) that must be detected at the low concentrations downstream of the DMA. Control hardware and software are required to control air flow rates within the system, high voltages on the DMA and to acquire counts from the MCPC.

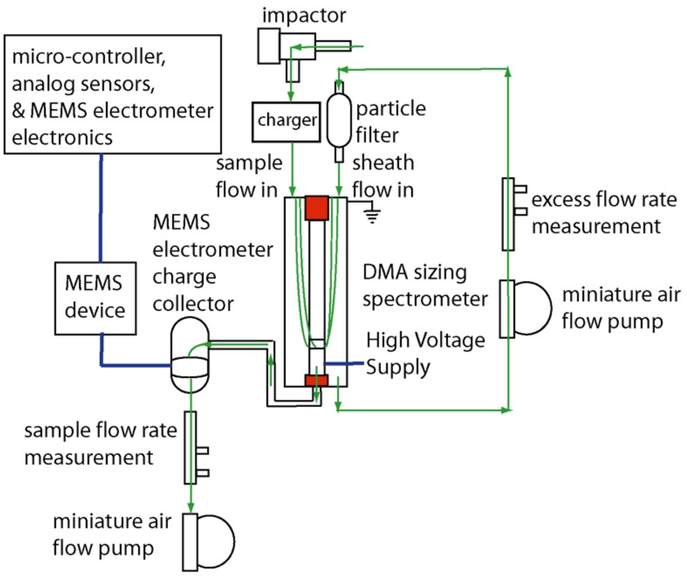

**Figure 1 Schematic of mSEMS system showing electrometer in place of MCPC as detector. Green arrows designate air flows.**

## *3. Phase I Progress*

The primary objectives of the Phase I research were to:

1. Complete the electrical mobility sizer miniaturization and fabricate and test a prototype,
2. Complete and test the aerosol charger prototype, and
3. Miniaturize and reduce the background noise level of an existing MEMS electrometer design.

A design for the mini-differential mobility analyzer (DMA), (Fig. 2) was completed during the Phase I. Due to time and funding limitations, one prototype unit was fabricated and tested of a slightly larger design. The final, miniaturized DMA is roughly 2.5” diameter by 8” long, weighing 2.1 lbs when fabricated from aluminum.

Testing results of the new DMA design have been extremely promising, with sizing of reference PSL particles within a few percent of the reference size and measured DMA transfer function widths equaling that predicted by theory. Shown in figure 3 below are results of sizing and transfer function width validation studies with the new DMA scanning downstream of a reference DMA and aerosol generation system maintained at our facility for testing commercial SEMS units. Figure 4 demonstrates excellent linearity of the sizing response of the new DMA design when challenged with NIST traceable PSL reference particles of known size.

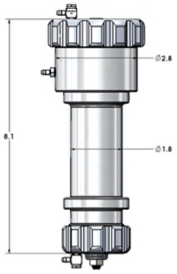

**Figure 2 Nanosizer DMA**

A. Corless completed significant work on the mSEMS firmware as well as components of the user interface (automatic plumbing delay calculation, diffusion loss correction, etc.) that will increase the ease of use of the software and increase data quality. Work continues exploring how 3D printing the DMA components might reduce cost and weight.

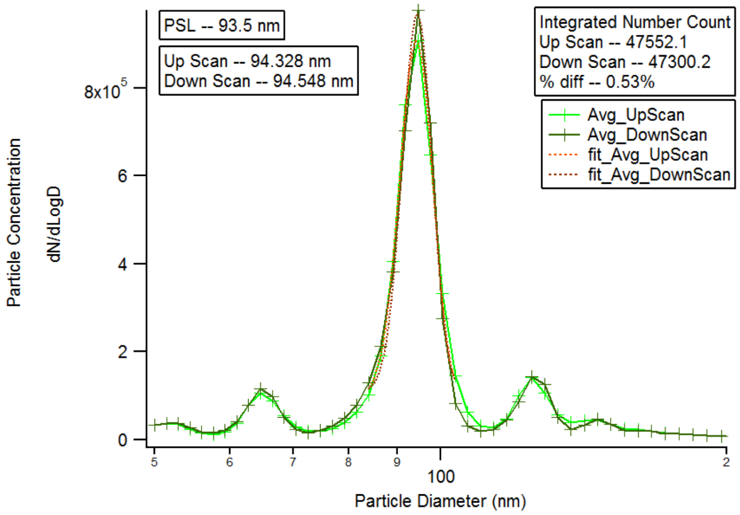

**Figure 3 Sample PSL sizing results.**

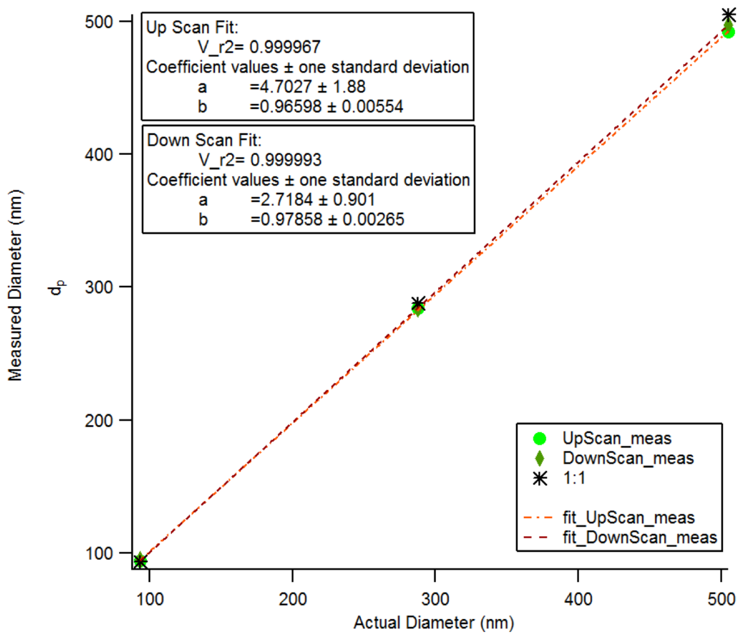

**Figure 4 DMA measured vs actual PSL diameters.**

All electrical mobility sizing-based instruments require an aerosol charger on the input sample flow to guarantee that the aerosol are brought to a known charge state as a function of size before they enter the DMA. Without a known charge distribution, the inversion of raw DMA data cannot successfully reproduce the true ambient size distribution. Many chargers use radioactive materials to produce ions that promote well-behaved charging conditions. However, radioactive materials are generally prohibited from aircraft and would be problematic to deploy on a UAS. Soft X-ray chargers on the market eliminate the need for radioactive sources but produce electrons with sufficient energy that sampled particles can become chemically modified. Furthermore, the lamp in these chargers require replacement costing several thousand dollars once every year of use. Significant effort was spent by Dr. Lopez-Yglesias prototyping and testing a new aerosol charger that will eliminate the need for radioactive materials and also greatly reduce the maintenance costs associated with lamp replacements in soft x-ray chargers. Results from tests on the new charger as well as results from a traditional Polonium-21 neutralizer are shown in figure 5 below. The results plotted show the number fraction of singly charged particles as a function of particle size for both chargers (‘UV’ vs ‘Po’). Studies were conducted with silver (‘Ag’) and ammonium sulfate (‘salt’) particles. The red curve represents theoretical calculations based on work by Wiedensohler, which is often used in DMA data inversion codes. Results in Fig. 5 indicate agreement within a factor of 2 between theory and Polonium charger results (grey and black curves) The data show that the singly-charged fractions from the new charger for salt particles (purple curve) agree reasonably well with theory for particles between 30 and 100 nm, with a decrease in the charged fraction for larger particles attributable to the larger fractions of multiply charged particles for the new design. The decrease in charged fraction shown by the pink curve for the new design is an artifact of the particular test setup where bipolar ions were generated in the new charger instead of unipolar ions as in the real design. Tests still need to be performed to confirm that the design is stable under different temperature, sample flow gas composition, relative humidity and pressure conditions. The patent-pending design will be easy to use, miniaturizable and have significantly lower cost than current solutions. An invention disclosure has been submitted to DOE associated with the new aerosol charger.

The electrometer control circuitry was redesigned during Phase I. Our current goal is to reach <0.2fA noise, which is equivalent to a particle concentration of roughly 80/cc at 1lpm flow. This minimum particle concentration is still too high for routine operation behind a DMA under low-to-moderate concentration conditions. Operation of the electrometer as the mSEMS detector would be a significant improvement over the MCPC as a liquid would no longer be required. However, the typically high electrical noise in aircraft environments could make use of the electrometer difficult. For this reason, we continue to pursue both the MCPC and electrometer as alternative particle counting devices. New circuit designs for the MEMS electrometer were explored that are predicted to reduce the current noise level of the device below 1femtoamp. Further work to miniaturize the electrometer has not yet been completed.

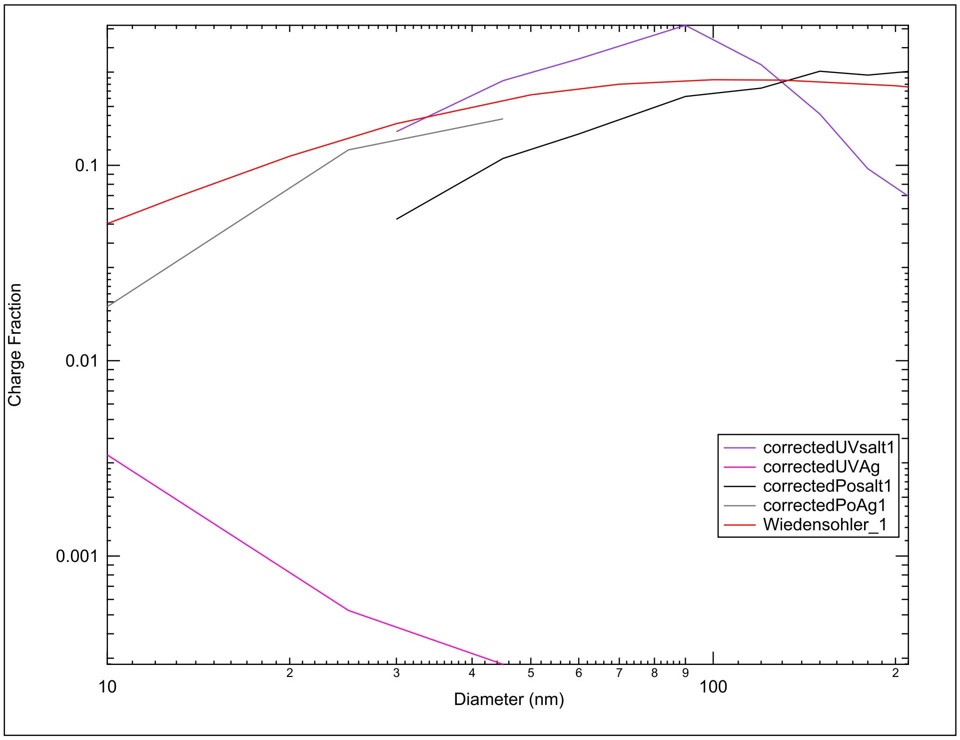

**Figure 5 Preliminary results from UV aerosol charger compared to a Polonium (Po) based unit and theory.**

Hot box testing was completed on the Mixing CPC to evaluate the performance at 40 deg C operating temperature for several weeks. Five independent units were operated in particular to verify proper operation of the liquid butanol handling system. All units passed the tests.

The mSEMS will integrate into a UAV-deployable suite as well as operate as a stand-alone instrument. This requires that the control system design be flexible enough to facilitate both integration and separation of the various modules. Work to create and test software subroutines for the mSEMS and UAV-MCPC modules continued up to the end of the project. The software controls and communicates with the modules to integrate them with the system control hardware and software. A. Corless continued work on system integration software that would provide a unified graphical user interface (GUI) for the suite of instruments. The GUI allows the output from multiple instruments to be viewed simultaneously and automatically adjusts to the configuration of instruments connected to the GUI computer. The software was successfully tested with the MCPC, mSEMS, STAP and gust probe modules.

### *4. Development Challenges & Solutions*

A no cost extension was granted to extend the project to May 31, 2017. The arrival of Louie Rezonable as senior mechanical designer accelerated progress on the project, especially the DMA design. The departure of Dr. Xerxes Lopez-Yglesias was mitigated by his return on a part-time basis, but his absence reduced progress on the charger during 2016.

### *5. Cumulative Expenses and Labor Hours*

The following table outlines the detailed breakdown of expenses by personnel, fringe benefits, materials, sub-contract, indirect expenses and fee for the entire project period.

**Cumulative Expenses**

| | |
|---|---:|
| **Senior Key Personnel (FJB)** | **23,127.43** |
| **Senior Key Personnel (FPB)** | **397.72** |
| **Engineers - Professionals** | **62,214.90** |
| **Interns, Technical Staff, Admins** | **1,738.89** |
| **Fringe Benefits** | **23,172.12** |
| **Equipment** | **-** |
| **Material, Supplies & Meals** | **449.68** |
| **Sub-Contractor:** | **23,377.50** |
| **Indirect Costs** | **75,808.30** |
| **Fee - 7%** | **14,720.06** |
| **Project Total to 5/31/2017** | **225,006.60** |

The following table outlines the hours spent by person on the project over the entire project period.

**Cumulative Labor Hrs**

| Category | Employee | Hours |
|---|---|---:|
| Senior Key | FJB | 371.05 |
| Senior Key | FPB | 12 |
| Engineer | AC | 799 |
| Engineer | CP | 322 |
| Engineer | LR | 169 |
| Technician | CT | 2 |
| Technician | PJT | 1 |
| Technician | TJ | 5 |
| Admin | GTP | 27.75 |
| Total Hours to 5/31/2017 | | 1,708.80 |