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Scanning Mobility Particle Spectrometer Instrument Handbook

C Kuang

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ARM CLIMATE RESEARCH FACILITY

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Office of Science, Office of Biological and Environmental Research

Acronyms and Abbreviations

#/cc	particle number per cubic centimeter
°C	degrees Celsius
ARM	Atmospheric Radiation Measurement
cc/min	cubic centimeters per minute
CPC	condensation particle counter
DMA	differential mobility analyzer
$dN/dlogD_p$	size distribution function
hh:mm:ss	hours:minutes:seconds
lpm	liters per minute
n	particle counts
nm	nanometer
sccm	standard cubic centimeters per minute
SMPS	scanning mobility particle spectrometer
TSI	manufacturer name
UTC	coordinated universal time
yyyy-mm-dd	year-month-day

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1.0 Instrument Title

Model 3936 Scanning Mobility Particle Spectrometer (pictured in Appendix A; more resources available on manufacturer's manual)

2.0 Mentor Contact Information

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4.0 Instrument Description

The Model 3936 Scanning Mobility Particle Spectrometer (SMPS) measures the size distribution of aerosols ranging from 10 nm up to 1000 nm. The SMPS uses a bipolar aerosol charger to keep particles within a known charge distribution. Charged particles are classified according to their electrical mobility, using a long-column differential mobility analyzer (DMA). Particle concentration is measured with a condensation particle counter (CPC). The SMPS is well-suited for applications including: nanoparticle research, atmospheric aerosol studies, pollution studies, smog chamber evaluations, engine exhaust and combustion studies, materials synthesis, filter efficiency testing, nucleation/condensation studies, and rapidly changing aerosol systems.

5.0 Measurements Taken

The primary SMPS measurement output is particle number-size distribution, ($dN/dlogD_p$,), measured in units of #/cc. Additional recorded instrument outputs include: sample temperature and pressure, the gas mean free path and viscosity, particle diameter (size bin) median values, scan up time, retrace time, scans per sample, impactor type, sheath flow rate, aerosol flow rate, CPC inlet flow rate, CPC sample flow rate, scanning voltage minimum, scanning voltage maximum, minimum particle diameter, maximum particle diameter, particle density, status flag, transport time through the classifier and downstream tubing, transport time through the classifier, impactor cut size, median particle diameter, mean particle diameter, geometric mean particle diameter, mode particle diameter, geometric particle diameter standard deviation, total integrated number concentration, and DMA sheath temperature and relative humidity.

6.0 Links to Definitions and Relevant Information

6.1 Data Object Description

Output data from the SMPS is recorded in column format with the following headers and units:

- Sample #: unit-less
- Date: month/day/year
- Start Time (UTC): hours:minutes:seconds
- Sample Temperature: °C
- Sample Pressure: kPa
- Mean Free Path: m
- Gas Viscosity: kg/(m*s)
- Diameter: nm
- Particle Number-Size Distribution: #/cc
- Scan Up Time: seconds
- Retrace Time: seconds
- Scans Per Sample: unit-less
- Impactor Type: cm (nozzle size)
- Sheath Flow Rate: lpm
- Aerosol Flow Rate: lpm
- CPC Inlet Flow Rate: lpm
- CPC Sample Flow Rate: lpm
- Low Voltage: volts

- High Voltage: volts
- Lower Size: nm
- Upper Size: nm
- Density: g/cc
- Title: empty
- Status Flag: Normal Scan/Failed Scan
- td (transport time through the classifier and downstream tubing): seconds
- tf (transport time through the classifier): seconds
- D50 (impactor cut size): nm
- Median (particle diameter): nm
- Mean (particle diameter): nm
- Geo. Mean (particle diameter): nm
- Mode (particle diameter): nm
- Geo. Std. (of the particle number-size distribution): unit-less
- Total Concentration: #/cc

A separate program reads data collected from the temperature/relative humidity probe installed in the sheath flow path of the long-column DMA and outputs the following data in column format:

- Temperature (sheath flow): °C
- Relative Humidity (sheath flow): %

6.2 Data Ordering

Data from the Model 3936 SMPS can be accessed and ordered through the ARM website. Data is organized by measurement location.

6.3 Data Plots

A plot of representative Model 3936 SMPS data is presented in Figure 1. Particle number-size distribution measurements (#/cc) are presented as a function of sampling time for typical samples obtained during the GoAmazon field campaign on October 10, 2014.

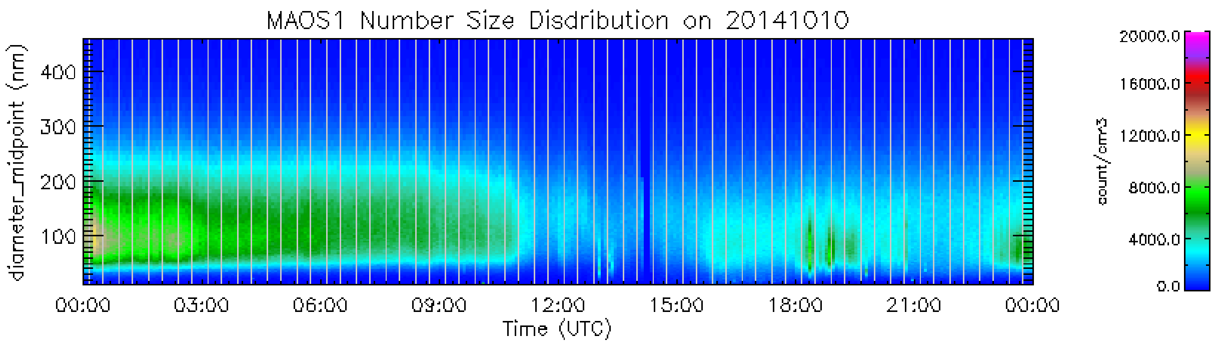

Figure 1. Particle number-size distribution data contour plot, presented as a function of particle diameter and sampling time, as measured by the Mobile Aerosol Observing System Model 3936 SMPS deployed at Manacapuru, Brazil, during the GoAmazon campaign on October 10, 2014. Plot was generated using the ARM Program Data Quality Diagnostic Plot Browser.

6.4 Data Quality

The first level of data quality evaluation consists of automated data flagging by the Data Quality Office, based on mentor-supplied evaluation criteria. Flags are generated whenever measured data (primary output and/or meta-data such as instrument housekeeping) are above, below or outside defined maximum threshold ranges. Examples of these thresholds and ranges are listed below; intended to be illustrative rather than definitive.

- Sample Pressure Minimum = 97 kPa: when sampling downstream of the inlet impactor, the sample pressure provide indication of the degree to which the impactor is being clogged by debris. Sample pressures below this minimum value will generate an alarm and alert the operator to clean the inlet impactor.
- Status Flag = 1: the status flag (0 or 1) provides a binary indication of measurement status. A value of 0 indicates a normal measurement, while a value of 1 indicates a failed measurement. This failed measurement status can be due to instrument faults in the CPC (e.g., lack of sufficient vacuum, saturator/condenser/optics temperatures not at set point values) and/or the electrostatic classifier.
- Sheath Flow Relative Humidity Maximum = 20%: sampling aerosol at a relative humidity above 20% could result in sampling of "wet" aerosol that could be incorrectly mobility classified (sized) due to diameter changes resulting from ambient water uptake.
- Please refer to the manufacturer's manual for examples of data quality flags triggered for the CPC.

The second level of data quality evaluation involves automatic generation of the following plots, in collaboration with the Data Quality Office:

- Comparison of co-located 3772 CPC and integrated SMPS particle number concentration measurements as a function of time. Since the SMPS uses a 3772 CPC as the particle detector, then co-located, concurrently sampling 3772 CPC and SMPS models should generate number concentrations nominally within ±10% of each other when sampling ambient aerosol with the majority of the particle numbers between 10 and 500 nm. This comparison provides quick assessment of SMPS performance, compared to the 3772 CPC.

6.5 Calibration Database

The Model 3936 SMPS is calibrated prior to instrument installation and deployment. Calibration activities include verifying sheath flow rate with a low pressure-drop bubble flow meter, verifying high-voltage power supply performance using a high-voltage probe, verifying the accuracy of mobility classifier particle sizing using polystyrene latex particle standards, and determining the CPC (particle detector) particle size-dependent counting efficiency. SMPS calibration data is collected and maintained by the instrument mentor.

7.0 Technical Specification

7.1 Units

The measured quantity of interest is the particle number-size distribution ($dN/dlogD_{p,}$); with units of particles per cubic centimeter (#/cc) measured as a function of time, and particle mobility diameter measured in units of nm.

7.2 Range

The ARM SMPS utilizes a Model 3772 CPC as the particle detector. Under this configuration with typical operating parameters, the measured particle number concentration range is between 1 to $1x10^7$ #/cc, and the measured particle diameter range is from 10 nm (detection limit of 3772 CPC) to 500 nm (mobility diameter corresponding to maximum applied voltage of 10,000 volts and an operating sheath flow rate of 5 lpm).

7.3 Accuracy

Ambient size distribution measurement accuracy is primarily a function of the aggregate contributions from uncertainties in the size-dependent aerosol charging efficiency, mobility particle classification accuracy, single particle counting associated statistical counting error, and variability in the CPC sampling flow rate. The size-dependent aerosol charging efficiency (which itself is a function of flow rate and sample relative humidity) is typically characterized by an accuracy of ±10% (Jiang et al. 2014). Operating a long-column DMA at a typical sheath flow rate of 5 lpm with a flow rate variability of ±2% results in particles being sized with an accuracy of < ±2%. The statistical noise associated with particle counts n has a relative uncertainty of $1/\sqrt{n}$. With a 3772 CPC as the particle detector, the aerosol sample flow rate is not monitored on-line and thus assumes a fixed value of 1 lpm, which can, in practice, vary by as much as ±5%. As a result of these individual contributing uncertainties, a typical ambient particle size distribution measurement will have an accuracy limited primarily by aerosol flow rate and charging efficiency uncertainties.

7.4 Repeatability

Particle size distribution measurement repeatability is a function of the 3772 CPC sample flow rate variability (±5%), long-column DMA sheath flow rate variability (±2%), and single particle counting associated statistical noise n, resulting in a relative counting uncertainty of $1/\sqrt{n}$, which itself is concentration-dependent. Particle concentration measurements in typically clean environments (~100 #/cc) have a counting uncertainty of 2.5%, while measurements in typically polluted environments (~5000 #/cc) have a counting uncertainty of 0.3%. Particle size distribution measurement repeatability, therefore, is primarily a function of 3772 CPC sample flow rate variability.

7.5 Sensitivity

SMPS sensitivity to measuring particle size is ±2% under typical operating conditions and is a function of the concentration linearity, as measured by the 3772 CPC; accounted for in the CPC signal-processing electronics.

7.6 Uncertainty

Ambient size distribution measurement uncertainty is primarily a function of the aggregate contributions from size-dependent aerosol charging efficiency uncertainties, mobility particle classification accuracy, single particle counting associated statistical counting error, and CPC sampling flow rate variability. The size-dependent aerosol charging efficiency (which itself is a function of flow rate and sample relative humidity) is typically characterized by an accuracy of ±10% (Jiang et al. 2014). Operating a long-column DMA at a typical sheath flow rate of 5 lpm with a flow rate variability of ±2% results in particles being sized with an accuracy of < ±2%. The statistical noise associated with particle counts n has a relative uncertainty of $1/\sqrt{n}$. With a 3772 CPC as the particle detector, the aerosol sample flow rate is not monitored on-line and thus assumes a fixed value of 1 lpm, which can, in practice, vary by as much as ±5%. As a result of these individual contributing uncertainties, a typical ambient particle size distribution measurement will have an uncertainty dominated primarily by aerosol flow rate and charging efficiency uncertainties.

7.7 Output Values

Output data from the SMPS is recorded in column format with the following headers and units:

- Sample #: unit-less
- Date: month/day/year
- Start Time (UTC): hours:minutes:seconds
- Sample Temperature: °C
- Sample Pressure: kPa
- Mean Free Path: m
- Gas Viscosity: kg/(m*s)

- Diameter: nm
- Particle Number-Size Distribution : #/cc
- Scan Up Time: seconds
- Retrace Time: seconds
- Scans Per Sample: unit-less
- Impactor Type: cm (nozzle size)
- Sheath Flow Rate: lpm
- Aerosol Flow Rate: lpm
- CPC Inlet Flow Rate: lpm
- CPC Sample Flow Rate: lpm
- Low Voltage: volts
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- Lower Size: nm
- Upper Size: nm
- Density: g/cc
- Title: empty
- Status Flag: Normal Scan/Failed Scan
- td (transport time through the classifier and downstream tubing): seconds
- tf (transport time through the classifier): seconds
- D50 (impactor cut size): nm
- Median (particle diameter): nm
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- Total Concentration: #/cc

A separate program reads data from the temperature/relative humidity probe installed in the sheath flow path of the long-column DMA and outputs the following data in column format:

- Temperature (sheath flow): °C
- Relative Humidity (sheath flow): %

8.0 Instrument System Functional Diagram

The 3936 SMPS consists of three subsystems: the inlet impactor, electrostatic classifier, and the CPC. Polydisperse. Aerosol first enters the impactor, (which removes particles above a known particle size through inertial impaction), before entering the electrostatic classifier, which selects a known size fraction from the incoming polydisperse aerosol. The resulting monodisperse aerosol then enters the CPC where it is counted. The flow schematic for the inlet impactor and electrostatic classifier is shown in Figure 2, and the flow schematic for the CPC is shown in Figure 3.

In the electrostatic classifier, the aerosol enters a Krypton-85 bipolar charger (or neutralizer), which exposes the particles to high concentrations of both positive and negatively charged ions. Through frequent collisions with the bipolar ions, the particles quickly achieve a state of charge equilibrium; well-predicted by theory. The charged aerosol then passes into the long-column DMA, within which a user-set electric field causes particles of a particular electrical mobility to exit the column and enter the particle detector, which, in this particular SMPS, is a Model 3772 CPC.

The particle detector grows sampled particles into larger droplets, which are detected optically. Laminar aerosol flow is sampled through the inlet and enters the saturator, where evaporated butanol liquid saturates the aerosol flow with butanol vapor. The combined flow of aerosol and butanol vapor then enters the condenser, which is cooled with a thermo-electric device. Here, the butanol vapor becomes super-saturated and condenses onto the aerosol particles to form larger droplets. These butanol droplets pass through a nozzle into the optical detector comprised of a laser diode, various focusing and collecting lenses, and a photodiode detector. Butanol droplets that pass through the laser will scatter light which is then detected by the photodiode and converted into electrical pulses that are counted and, at high particle concentrations, corrected for particle coincidence.

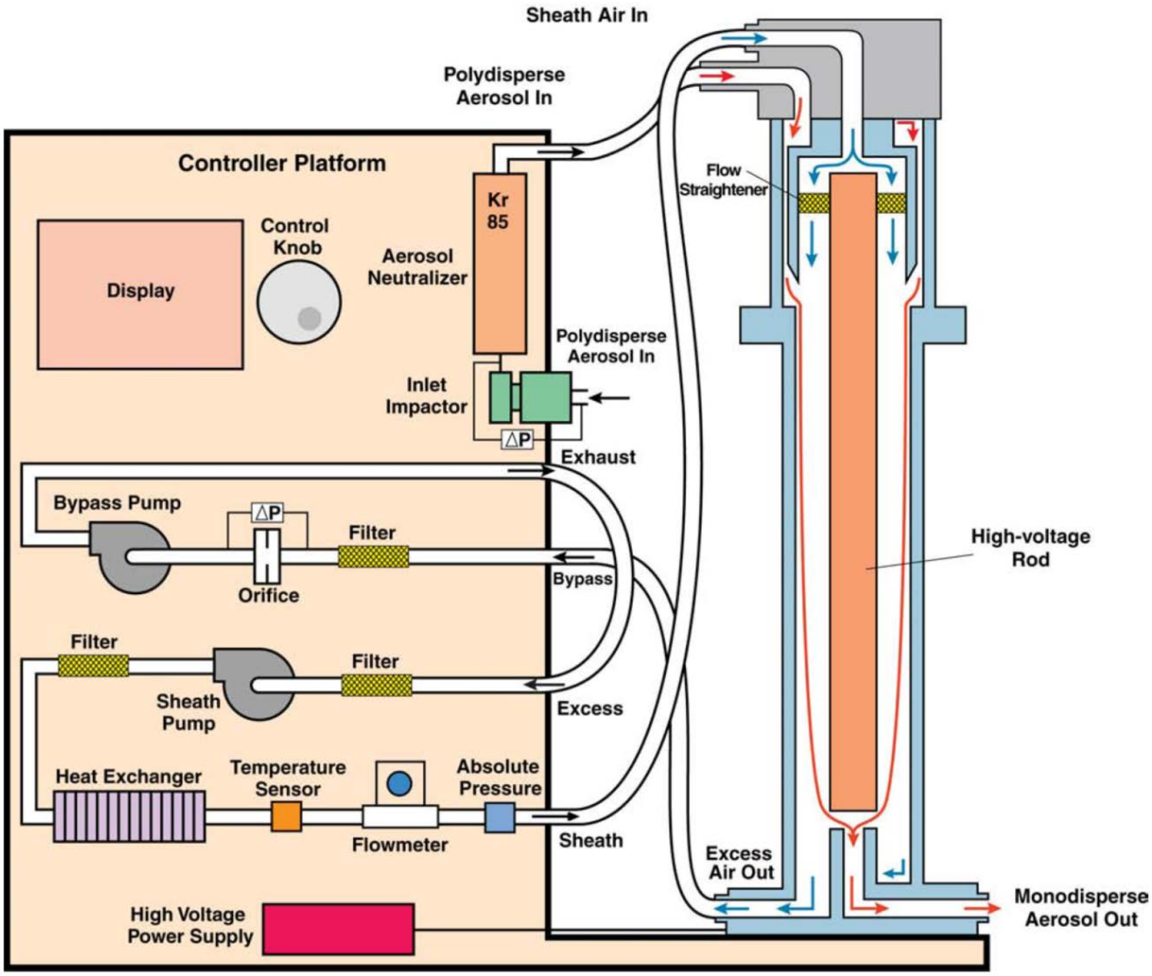

Figure 2. Flow schematic for the inlet impactor and electrostatic classifier with a long-column DMA, adapted from the manufacturer's manual.

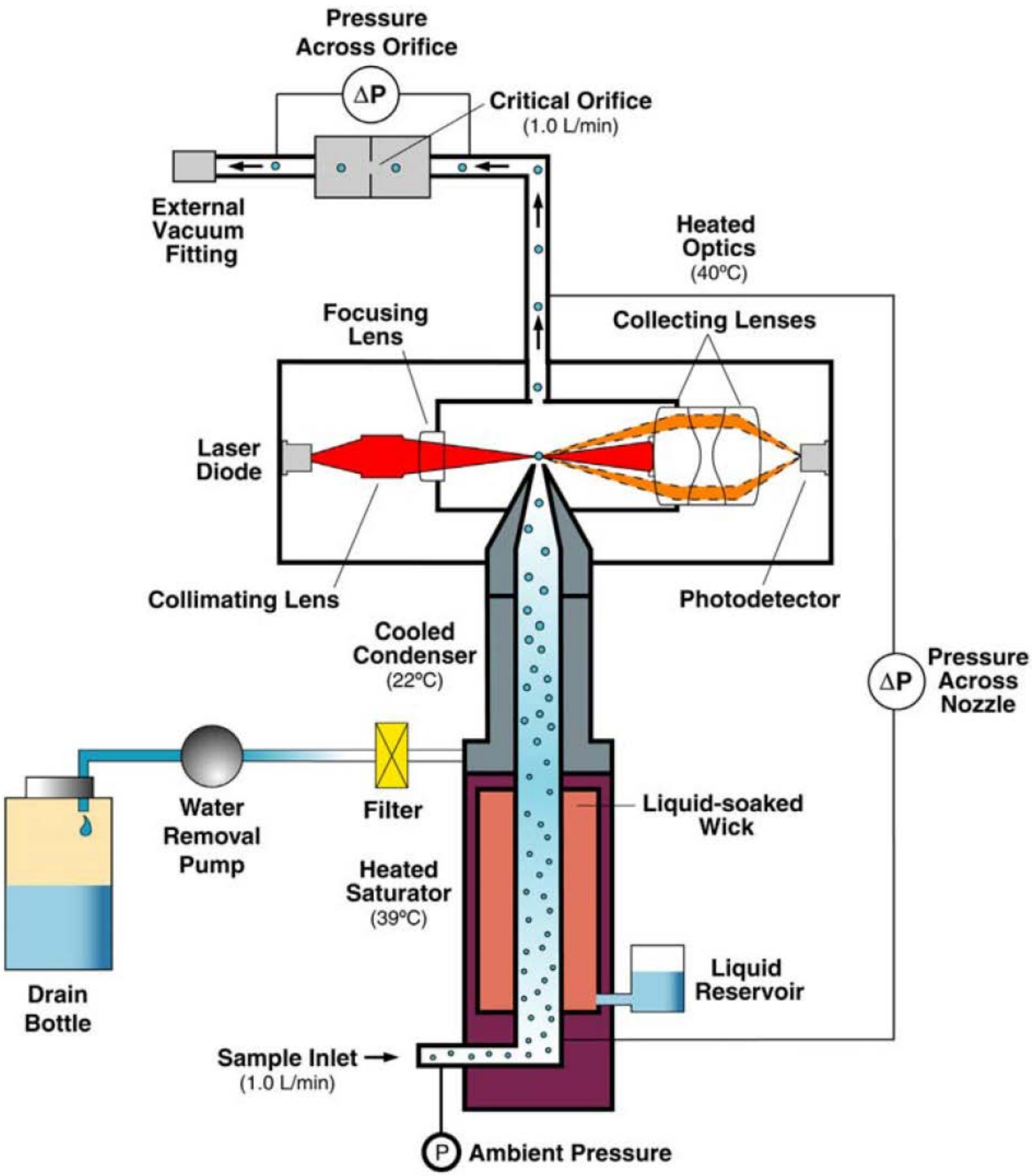

Figure 3. Flow schematic of the Model 3772 CPC, adapted from the manufacturer's manual.

9.0 Instrument/Measurement Theory

In the impactor, aerosol flow is accelerated through a nozzle directed at a flat plate. The impaction plate deflects the flow to form a 90° bend in the flow streamlines. Particles with sufficient inertia are unable to follow the streamlines and, consequently, impact on the plate. Smaller particles with less inertia, however, follow the streamlines, avoid contact with the plate, exit the impactor, and enter the electrostatic classifier. Further details regarding impaction theory can be found in (Hinds 2012).

The method of data inversion to recover the ambient size distribution from raw measurements of particle counts and particle diameter assumes that the polydisperse aerosol entering the DMA has reached charge equilibrium prior to electrical mobility classification. This process of achieving charge equilibrium is accomplished with a Krypton-85 bipolar charger (neutralizer). In the charger, the sampled aerosol undergoes frequent collisions with bipolar ions and quickly reaches an equilibrium charge state, with a distribution of particles carrying no charge, a single charge, or charges of both positive and negative polarities. This charge distribution is well predicted by ion charging theory (Fuchs 1964, Wiedensohler 1988).

The charged particles then enter the DMA into the presence of an electric field, in which they experience an electrical force which propels them through the gas in which they are suspended. The measure of a charged particle's ability to move within an electrical field is known as electrical mobility; a function of the particle charge state, diameter, and experienced drag force (Friedlander 2000). After exiting the DMA, charged particles are classified according to their electrical mobility; determined based on derived relationships between particle electrical mobility and DMA operating parameters (e.g., applied voltage) (Knutson 1976, Knutson and Whitby 1975).

As the instrument name indicates, the essential feature of the CPC is the ability to grow sampled particles through working fluid condensation before optically counting them. When the vapor surrounding particles reaches a certain degree of super-saturation, the vapor begins to condense on the particles; a process known as heterogeneous nucleation. If super-saturation levels are too high, however, vapor condensation can take place even without sampled particles present; a process called homogeneous nucleation. During homogenous nucleation, working fluid vapor molecules collide and form clusters. Counting particles in droplets generated through homogeneous nucleation will result in instrument noise and should be avoided. Optimal CPC performance is achieved by operating at a super-saturation level just below the homogeneous nucleation limit. The particle size detection limit is a strong function of the super-saturation ratio operating value and can be calculated from theoretical predictions relating particle diameter and vapor super-saturation ratio (Ahn and Liu 1990).

10.0 Setup and Operation of Instrument

Setup of the 3936 SMPS involves the following:

1. Make the necessary cable connections between/from the 3772 CPC and electrostatic classifier (BNC cable, serial cables, and power cables).
2. Apply the correct power sequence.
3. Install the proper tubing connections in the electrostatic classifier and between the 3772 CPC and electrostatic classifier.

Further details regarding the installation of the SMPS can be found in the manufacturer's manual.

The Model 3936 SMPS operates nominally within the following environmental conditions and ranges:

- Altitude: Up to 2000 m (6500 ft)
- Inlet Pressure: 75 to 105 kPa (0.74 to 1.05 atm)

- Operating Temperature: 10 to 35°C
- Ambient humidity: 0 to 90% relative humidity non-condensing

The nominal environmental operating range is limited primarily by the particle detector used in the SMPS; the 3772 CPC.

During ARM deployments, the 3936 SMPS samples within an environmentally controlled measurement container, in accordance with the manufacturer's environmental requirements.

For further details and instructions, please consult the manufacturer's manual.

11.0 Software

SMPS data acquisition and instrument control is accomplished through the manufacturer's data acquisition software program, Aerosol Instrument Manager. DMA sheath flow relative humidity and temperature data is gathered using a LabView based program, written at Brookhaven National Laboratory. Once collected, the data is parsed and saved in hour-long text files on the instrument computer. Instrument firmware commands for the CPC (particle detector) and electrostatic classifier are listed in the manufacturer's manuals.

12.0 Calibration

The Model 3936 SMPS undergoes calibration prior to installation to characterize the electrostatic classifier and the CPC.

Electrostatic classifier characterization includes verifying the DMA sheath flow rate control, voltage control, and particle sizing. The sheath flow rate control (nominally 5 lpm) is verified with a low pressure-drop bubble flowmeter. Voltage control is verified with a high-voltage probe, capable of measuring up to 10,000 volts. DMA Particle sizing is verified with National Institute of Standards and Technology-certified polystyrene latex particle size standards (150 nm).

CPC characterization includes verifying the inlet flow rate and determining the size-dependent particle counting efficiency. The inlet flow rate is measured with a low pressure-drop bubble flow meter, which nominally yields an inlet flow rate of 1.0 lpm, with a variability of up to ±5%. The 3772 CPC has a nominal cut size of 10 nm; with the cut size defined as the particle diameter at which 50% of sampled particles are detected. The 3772 CPC counting efficiency is a function of particle diameter (and, to some extent, particle composition); determined by using the calibration protocol described in Hermann et al. (2007). Calibration aerosol is generated in a tube furnace via the evaporation-condensation method and size classified with a TSI Model 3080 Electrostatic Classifier and Model 3085 Nano DMA. Counting efficiency is calculated by comparing CPC readings to a TSI Model 3068A Aerosol Electrometer. An example of a 3772 counting efficiency curve from Hermann et al. (2007) is presented in Figure 4.

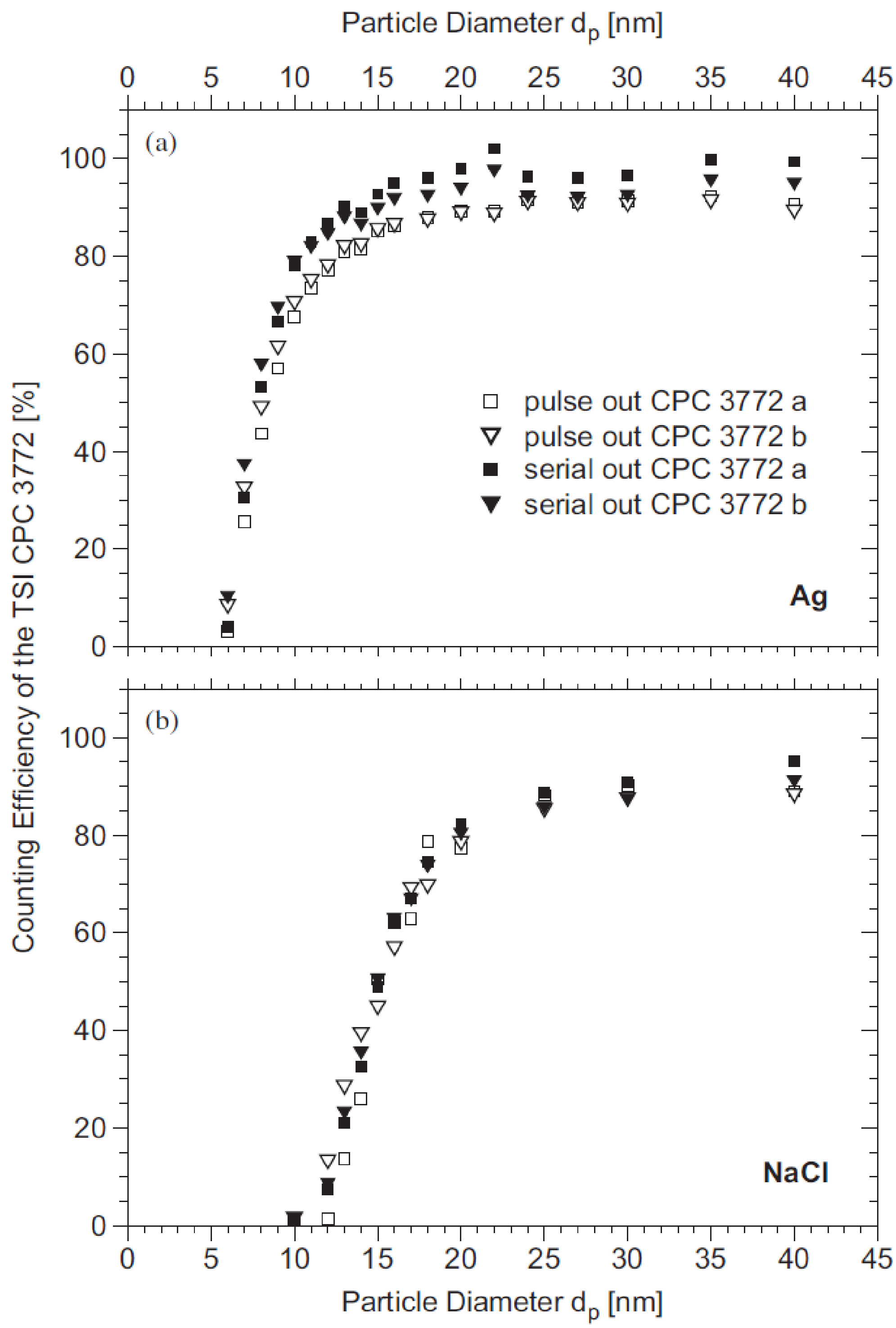

Figure 4. CPC 3772 counting efficiencies for (a) silver and (b) sodium chloride particles, as presented in Hermann et al. (2007).

13.0 Maintenance

The following maintenance activities are required to ensure proper functioning of the 3936 SMPS.

- Clean the impactor nozzle when there is indication of significant pressure drop. See manufacturer's manual for impactor cleaning instructions.
- Drain butanol from the butanol reservoir in the CPC prior to instrument shipment.
- Correct flooded optics when there is any indication of flooding.
- Clean clogged nozzle when the nozzle pressure is > 3 kPa and has been steadily increasing over time. This procedure is outlined in more detail in manufacturer's manual.

Refer to the manufacturer's manual for a detailed description of the procedures associated with each of the maintenance actions.

14.0 Safety

The SMPS particle detector (3772 CPC) is a Class I laser-based instrument. During normal operation, the user will not be exposed to laser radiation. However, the 3772 CPC uses n-butyl alcohol (butanol) as a working fluid which is flammable and toxic, if inhaled.

The electrostatic classifier has high-voltage points within the cabinet/case. The electrostatic classifier contains a Krypton-85 source in the aerosol neutralizer. Under normal circumstances, the user will not come into contact with hazardous radiation.

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