DOE/SC-ARM-TR-259

Portable Optical Particle Spectrometer (POPS) Instrument Handbook

F Mei M Pekour

November 2020

DISCLAIMER

DOE/SC-ARM-TR-259

Portable Optical Particle Spectrometer (POPS) Instrument Handbook

F Mei
M Pekour
Both at Pacific Northwest National Laboratory

November 2020

Work supported by the U.S. Department of Energy,
Office of Science, Office of Biological and Environmental Research

Acronyms and Abbreviations

3D	three-dimensional
AAF	ARM Aerial Facility
AMF3	third ARM Mobile Facility
ARM	Atmospheric Radiation Measurement
DAQ	data acquisition
DMA	differential mobility analyzer
DQ	Data Quality
HEPA	high-efficiency particulate air
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
POPEYE	Profiling at Oliktok Point to Enhance YOPP Experiments
POPS	portable optical particle spectrometer
SMPS	scanning mobility particle sizer
TBS	tethered balloon system
UAS	unmanned aerial system
UHSAS	ultra-high-sensitivity aerosol spectrometer
UTC	Coordinated Universal Time
YOPP	Year of Polar Prediction

Contents

Figures

1.0 Instrument Title

The U.S. Department of Energy Atmospheric Radiation Measurement (ARM) user facility portable optical particle spectrometer (POPS) is a lightweight particle spectrometer designed for aerosol particle size distribution measurement. Several POPS of different versions have been procured to serve as routine instruments for the ARM Aerial Facility (AAF) unmanned aerial systems (UAS) and tethered balloon system (TBS) deployment since 2018.

POPS measures the aerosol particle size distribution approximately between 0.13 and 3 μm.

2.0 Mentor Contact Information

Fan Mei
Pacific Northwest National Laboratory
902 Battelle Boulevard
P.O. Box 999, MSIN K4-28
Richland, Washington 99352
Tel: 509-375-3965
fan.mei@pnnl.gov

3.0 Vendor/Developer Contact Information

Handix Scientific Inc.
5485 Conestoga Count, Suite 104-B
Boulder, Colorado
Tel: 720-724-7658
http://www.handixscientific.com/

4.0 Instrument Description

POPS used a 405-nm laser diode as a light source, as shown in Figure 1. A laser heater has been added to the commercial (Handix) version, as well as to later National Oceanic and Atmospheric Administration (NOAA)-produced systems, to maintain the laser operating temperature at a minimum of 35 °C, which becomes essential in cold weather applications.

The sampling flow is sheathed in clean air. It enters the optical chamber to maintain a laminar state and prevent particles from entering the fringe area of the sampling volume, where sizing becomes biased. Nominal (on the ground) sampling and sheath flows are 3 cm^3/s and 9 cm^3/s, respectively. When operated on an aircraft or UAS platform, where the inlet lines' pressure may differ from the cabin and/or ambient pressure, the POPS sample and sheath inlets are connected to the same inlet manifold to minimize the flow distortions. The exhaust line also needs to be balanced with a similar pressure as the inlet line to reduce the miniature rotary vane pump load.

An additional temperature sensor is installed after the optical chamber's exit port to monitor the operational temperature, as discussed in section 3. When deploying to an icy environment, an insulated enclosure was designed to keep the POPS internal temperature around 15 °C.

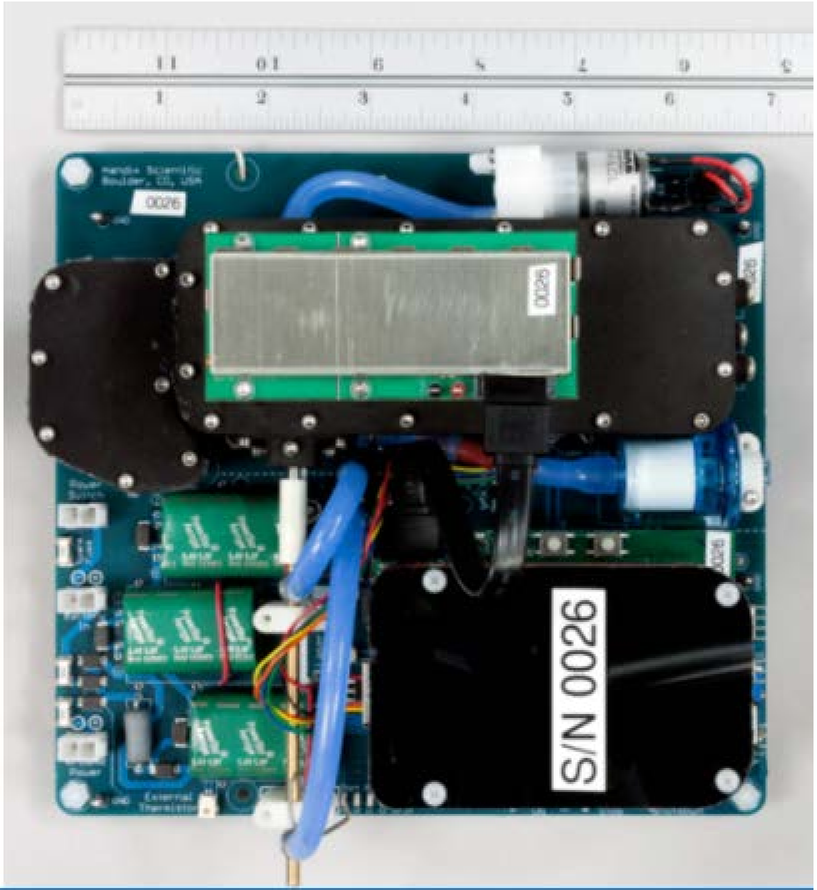

Figure 1. POPS photograph from the manufacturer's website (http://www.handixscientific.com/pops).

5.0 Measurements Taken

As shown in Figure 2, sample particles enter the optical chamber through an inlet sheathed by a clear air and transit the laser beam, scattering light collected by a spherical mirror on the bottom of the optical chamber. Light is focused onto the detection region of a photomultiplier tube and scaled to particle diameter using a theory-based calibration response function.

The POPS design has evolved and differs in minor ways from the original system described in Gao et al. (2016). Changes include modification to the inlet/exhaust mechanical design, implementation of round-versus-square optical elements, and improvements to circuit board design, software, and firmware. More recent changes include replacing several 3D-printed components for mounting the laser and optical elements with machined aluminum parts, which was done to reduce contamination of the optical surfaces by apparent outgassing of plastic material. The AAF also manufactured different enclosures to meet deployment needs.

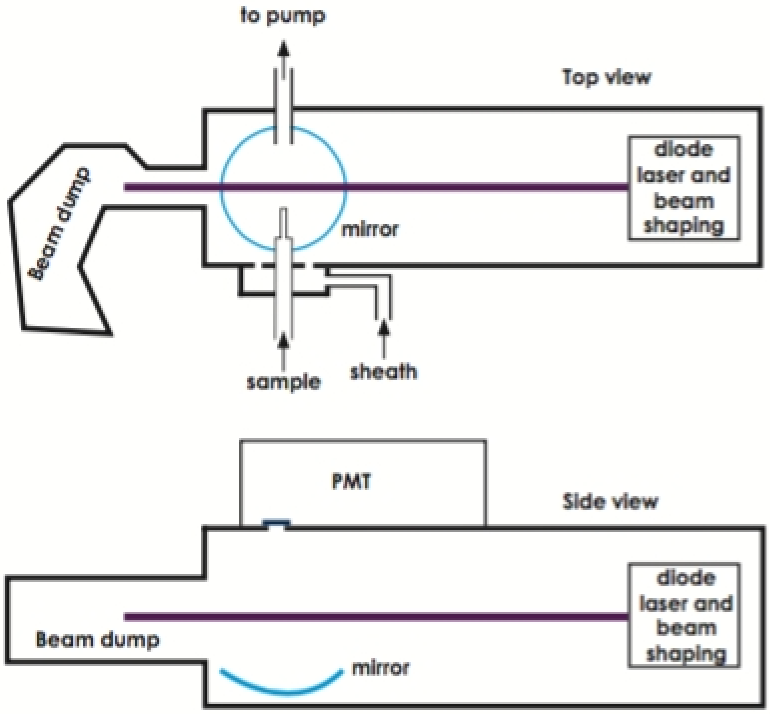

Figure 2. Schematic of POPS optical chamber, showing 405-nm laser diode and beam dump. Information from the manufacturer's website (http://www.handixscientific.com/pops).

6.0 Links to Definitions and Relevant Information

6.1 Data Object Description

The POPS's processed data include the measurement date/time, the total number concentration, and the aerosol particle size distribution for 12 size bins.

The raw data from the POPS include three types of data files. The housekeeping file is recorded in column format with appropriate headers specifying the data and units of measurement. The data fields recorded include:

> Measurement date/time, status, particle counts, particle concentration, the current baseline of the detector, the threshold for particle counting, standard deviation of baseline, ambient pressure, onboard temperature, sample flow, pump feedback, the temperature of laser diode control board, laser feedback, laser diode output power monitor, external temperature, battery voltage, laser current, pump set point, baseline start point, the multiplier threshold, number of bins for particle raw peak signal, minimum particle signal bin, maximum particle signal bin, “skip_save” parameter, minimum number of peak points above threshold, maximum number of peak points above threshold, number of points saved for any raw data recorded, N bins columns.

The peak files contain several parameters describing the raw particle peak signals recorded by the photodetectors. This file is useful for re-binning the raw data to different size bins. The RawBL and Raw

Peak files contain high-speed raw signals recorded during particle and baseline periods and are mainly used for system diagnosis.

Output data are recorded after every sample, typically every second. A new data file is started every time the system is restarted or the file size reaches the threshold.

This data object description is subject to change with future revisions of the instrument software.

6.2 Data Ordering

Data from the ultra-high-sensitivity aerosol spectrometer (UHSAS) can be ordered from https://adc.arm.gov/discovery/#/. Data are organized by measurement location/campaign.

6.3 Data Plots

Figure 3 shows the total number concentration data for the POPS as a function of time. These plots were generated using the ARM user facility Data Quality (DQ)-Zoom Plotter.

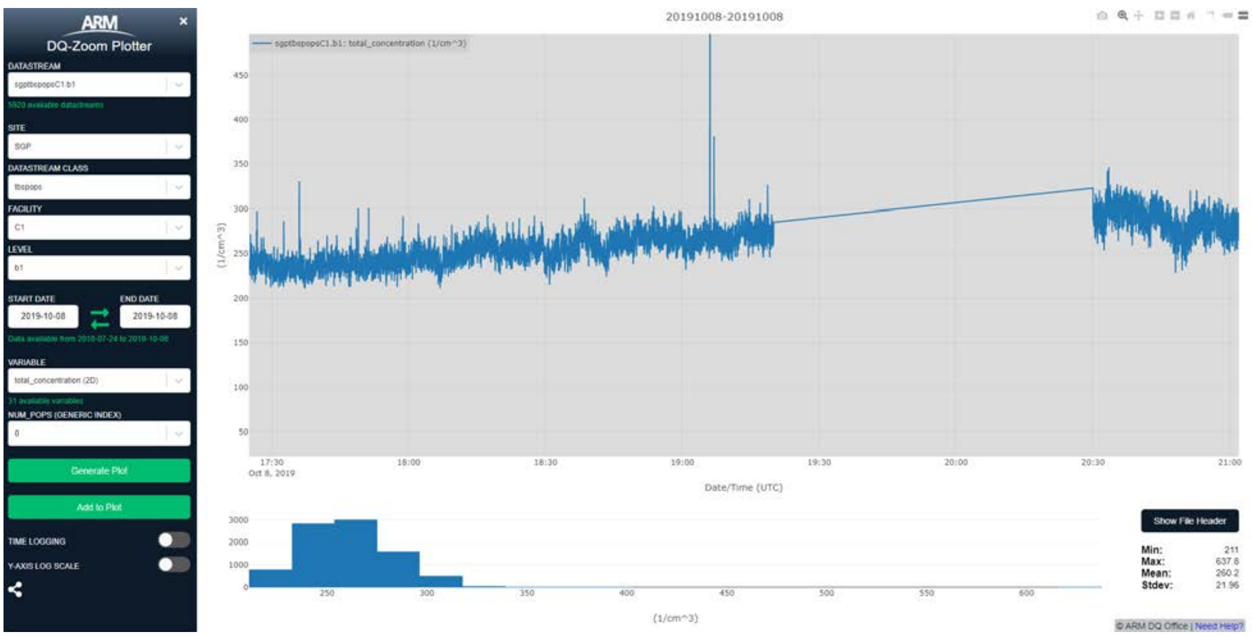

Figure 3. Sample plot of the POPS total number concentration shown in the ARM DQ-Zoom Plotter.

6.4 Data Quality

Data quality evaluation involves the automatic generation of the housekeeping plots by a mentor (see also Figures 4 and 5):

- Aerosol particle size distribution as a function of time: low counts or noisy signal may indicate issues with the POPS optics block (misalignment, contamination) or air flows (low or unstable sample flow).

- Comparing particle number concentration measurements from the POPS and several co-located instruments such as a UHSAS or scanning mobility particle sizer (SMPS): the total concentration measured by the UHSAS should follow the same general trend as other instruments if the data are integrated with the same size ranges.
- Sample flow rate: low or unstable flow rate indicates a blockage in the sample line or a failing pump.
- Laser temperature. A value out of the range 25-65 ℃ will cause more considerable uncertainty in the size determination.

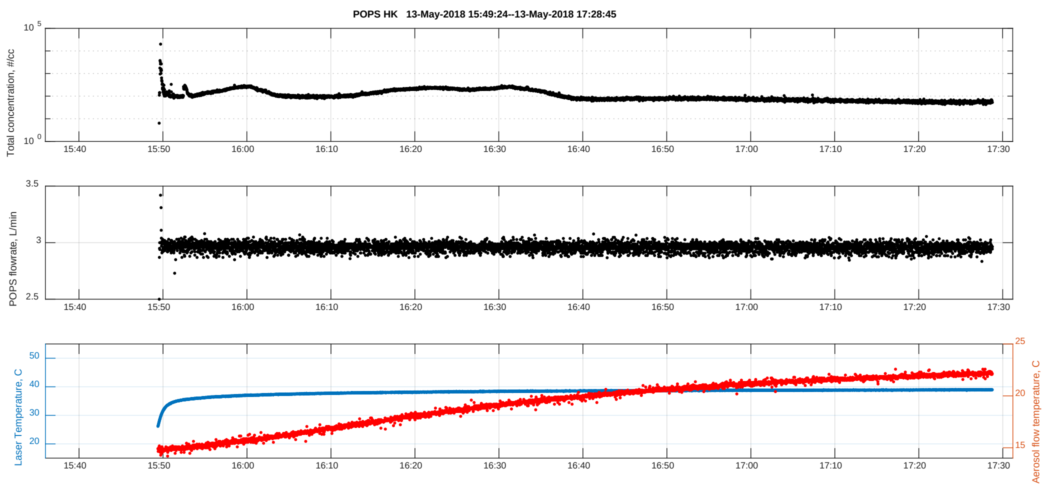

Figure 4. Housekeeping plot for POPS operation monitoring.

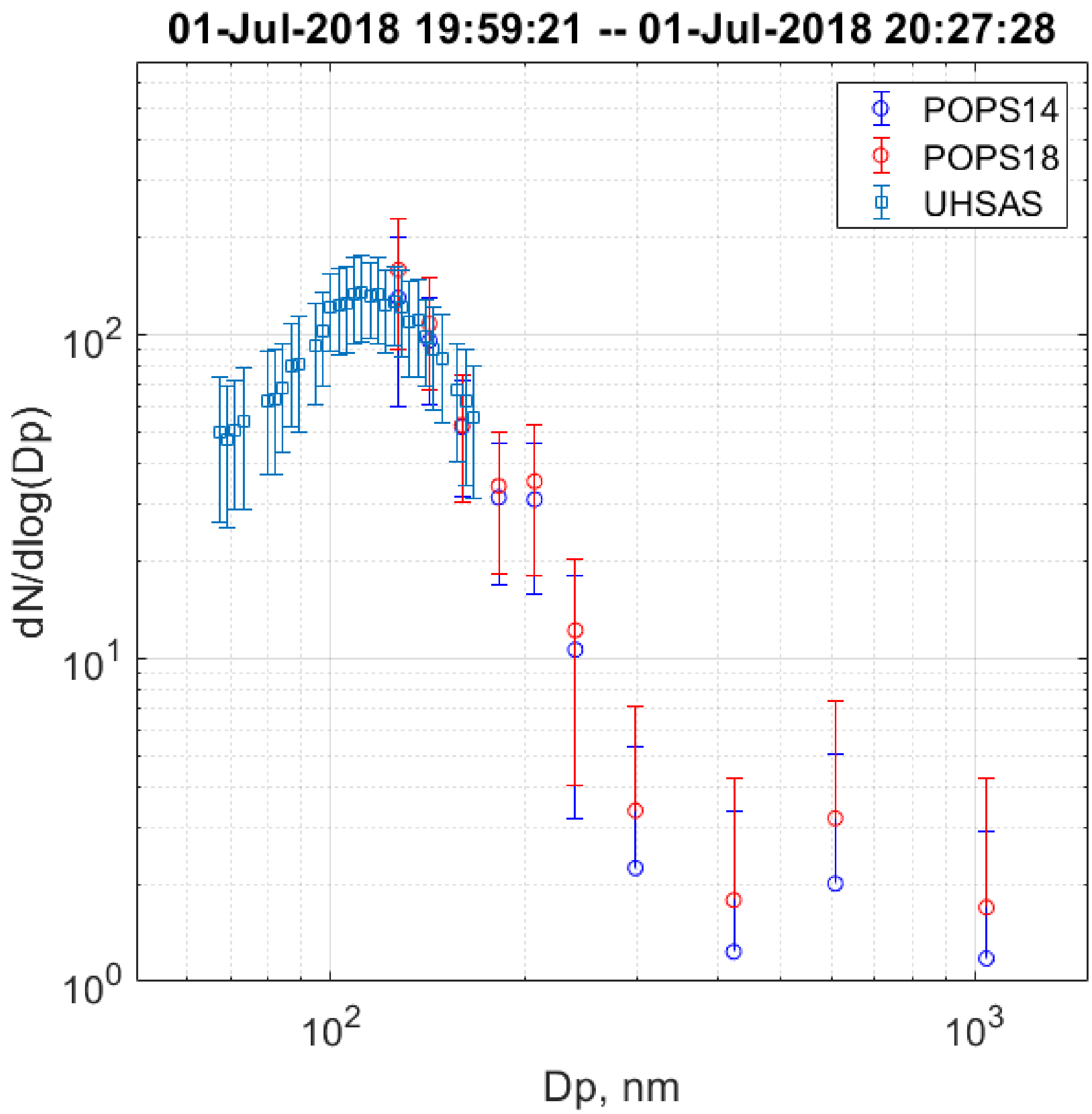

Figure 5. Comparison of the size distribution between two TBS POPS and the UHSAS from the third ARM Mobile Facility (AMF3) during the Profiling at Oliktok Point to Enhance Year of Polar Prediction (YOPP) Experiments (POPEYE) deployment in July 2018.

6.5 Calibration Database

During deployment, the POPS calibration is periodically verified by the instrument mentors. This activity includes using the POPS to measure the size distribution of a PSL particle or monodisperse aerosol particles with a known mean particle diameter (electrical mobility) generated by a differential mobility analyzer (DMA) and comparing the measured geometric mean particle size to the DMA selection size. Additionally, more information such as the size determination and the counting efficiency can be found in Mei et al. 2020 [1]. Calibration verification data is collected and maintained by the instrument mentors.

7.0 Technical Specification

7.1 Units

Units include aerosol particle size, nanometers (nm), aerosol particle number concentration, particles per cubic centimeter (cm^3), or raw counts (dimensionless).

7.2 Range

Particle size can be measured from 130 to 3000 nm. Total particle number concentration (per unit time) can be measured from 0 to 3000^{s-1} (4000 cm^{-3} with 25% uncertainty—the maximum number of particles per unit volume depends on the instrument's sample flow rate).

7.3 Accuracy

Accuracy of particle sizing depends mainly on the accuracy of the particle size look-up table that is calculated during instrument calibration with monodisperse calibration aerosols. The look-up table relates particle size to pulse height of scattered light for a calibration aerosol, usually PSL. Ambient aerosol particles with a non-spherical shape or refractive index different from PSL can be thus sized incorrectly. In general, the instrument sizing accuracy is within 5%, as seen from comparison experiments with an SMPS [2]. This applies to the instrument's normal operating mode where the total particle counts are below 3000 $^{s-1}$ and no significant particle coincidence occurs.

7.4 Repeatability

Repeatability of particle sizing mainly depends on the inherent noise in the response of the electronics that measure the pulse height of the scattered light. In general, the repeatability is within 1% [2]. This repeatability applies to the instrument's normal operating mode where the total particle counts are below 4000 cm^{-3} and no significant particle coincidence occurs.

7.5 Sensitivity

Aerosol particle size and concentration measurement are sensitive to particle concentration (due to particle coincidence during counting at higher concentrations). The operating speed of the detector electronics sets the upper limit of total particle counts for reliable single-particle detection at around 4000 cm^{-3}. No corrections for particle coincidence are made by the instrument, and a dilution system should be used when sampling aerosol particles at concentrations higher than the upper limit specified above.

Particle sizing is also sensitive to the particle refractive index if it differs from that of the calibration aerosol particles (PSL). If the ambient particle refractive index is known, corrections can be applied to the measurement data [2, 3].

7.6 Uncertainty

Uncertainty for particle sizing is largely determined by the instrument's sizing resolution, which depends on the geometry of the optics system, i.e., the diameters of the laser beam and the particle jet. The manufacturer specifies the uncertainty of particle sizing as within 2.5% of particle size.

7.7 Input Values

Parameters set by the user include measurement range, number of size bins, upper and lower boundaries of each size bin, and sample flow rate.

7.8 Output Values

See section 6.1.

8.0 Instrument System Functional Diagram

See section 5.0 and Gao et al. 2016 [4].

9.0 Instrument/Measurement Theory

See section 5.0 and Mei et al. 2020 [1].

10.0 Setup and Operation of Instrument

In general:

1. Switch on the instrument and wait for the internal computer to boot up.
2. Start the measurement software by double-clicking on the “POPS” icon on the computer desktop screen. The software may be configured to start automatically in the future, in which case skip this step.
3. The instrument is now ready to operate automatically.

Before each flight:

1. Check the battery:
    a. Install the charged battery to the instrument.
2. Check the instrument time: make sure it is synchronized with UTC.
3. Check the POPS status:
    a. Check the POPS display tab, and make sure POPS is on and communicating with the data acquisition (DAQ) computer.
    b. Check that the flow is around 3 cc/second.

4. Daily Zero check – verify that the instrument is operating normally.
   a. Turn on the instrument and let it warm up (approximately 600 seconds).
   b. Attach the supplied HEPA zero filter assembly to the inlet screen assembly.
   c. The particle concentration should go to zero in approximately 5 to 10 seconds. Leave the HEPA zero filter attached to the instrument for 30 seconds to ensure the zero reading is stable.

11.0 Software

For further details, consult the manufacturer's manual.

12.0 Calibration

The POPS system is calibrated by the manufacturer before delivery to the user and during instrument maintenance at the manufacturer's facilities. The instrument mentors perform calibration verification that checks for conditions requiring a full calibration, typically once every 12 months or as needed, e.g., before deployment. No corrections to the data are derived from calibration verifications. In case of verification failure, the instrument would be size-calibrated by the mentors or sent to the manufacturer for maintenance.

The manufacturer's calibration includes:

- Measuring the size distribution of the National Institute of Standards and Technology (NIST)-traceable calibration aerosols PSL with known mean particle sizes.
- Calibrating the gain of the four internal pulse-height measurement ranges, i.e., recording the light detector electronics' responses to aerosols with known particle sizes. Calibration values are recorded in the software and applied automatically.
- Calibrating the inlet flow rate with a precision flow meter. Calibration values are recorded in the software and applied automatically.
- Zero counts verification by operating the instrument with a high-efficiency particulate air (HEPA) filter attached to the inlet.

Calibration verification done by instrument mentors was documented in Mei et al. 2020 [1].

13.0 Maintenance

Consult the manufacturer's manual for cleaning the laser optics, cleaning the mirror, and laser alignment.

14.0 Safety

The POPS is a Class I Laser Product. During regular operation, the user is not exposed to laser radiation.

15.0 Citable References

[1] Mei, F, G McMeeking, M Pekour, R-S Gao, G Kulkarni, S China, H Telg, D Dexheimer, J Tomlinson, and B Schmid. 2020. "Performance Assessment of Portable Optical Particle Spectrometer (POPS)." *Sensors* 20(21): 6294, https://doi.org/10.3390/s20216294

[2] Cai, Y, D Montague, W Mooiweer-Bryan, and T Deshler. 2008. "Performance characteristics of the ultra-high-sensitivity aerosol spectrometer for particles between 55 and 800 nm: Laboratory and field studies." *Journal of Aerosol Science* 39(9): 759−769, doi:10.1016/j.jaerosci.2008.04.007

[3] Ames, RB, JL Hand, SM Kreidenweis, DE Day, and WC Malm. 2000. "Optical measurements of aerosol size distributions in Great Smoky Mountains National Park: Dry aerosol characterization." *Journal of the Air and Waste Management Association* 50(5): 665−676, doi:101080/10473289.2000.10464128

[4] Gao, RS, H Telg, RJ McLaughlin, SJ Ciciora, LA Watts, MS Richardson, JP Schwarz, AE Perring, TD Thornberry, AW Rollins, MZ Markovic, TS Bates, JE Johnson, and DW Fahey. 2016. "A light-weight, high-sensitivity particle spectrometer for PM2.5 aerosol measurements." *Aerosol Science and Technology* 50(1): 88−99, https://doi.org/10.1080/02786826.2015.1131809

ARM

www.arm.gov

U.S. DEPARTMENT OF ENERGY

Office of Science