U.S. DEPARTMENT OF ENERGY | Office of Science

DOE/SC-ARM-TR-176

Particle Soot Absorption Photometer (PSAP) Instrument Handbook

SR Springston
C Hayes
R Trojanowski
C Flynn

May 2025

ARM

DISCLAIMER

DOE/SC-ARM-TR-176

Particle Soot Absorption Photometer (PSAP) Instrument Handbook

SR Springston, Brookhaven National Laboratory (BNL)
R Trojanowski, BNL
C Hayes, BNL
C Flynn, University of Oklahoma

May 2025

How to cite this document:
Springston, SR, R Trojanowski, C Hayes, and C Flynn. Particle Soot Absorption Photometer (PSAP) Instrument Handbook. 2025. U.S. Department of Energy, Atmospheric Radiation Measurement user facility, Richland, Washington. DOE/SCARM-TR-176.

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

Acronyms and Abbreviations

AAE	absorption Angström exponent
AMF	ARM Mobile Facility
AMF1	first ARM Mobile Facility
AMF2	second ARM Mobile Facility
AMF3	third ARM Mobile Facility
AOP	Aerosol Optical Properties
AOS	Aerosol Observing System
ARM	Atmospheric Radiation Measurement
ASCII	American Standard Code for Information Interchange
BNL	Brookhaven National Laboratory
CAPS	cloud aerosol and precipitation spectrometer
ENA	Eastern North Atlantic
EPROM	erasable programmable read-only memory
GUI	graphical user interface
HEPA	high-efficiency particulate air
LED	light-emitting diodes
lpm	litters per minute
MAOS	Mobile Aerosol Observing System
MFC	mass flow controller
MFM	mass flow meter
NetCDF	Network Common Data Form
OLI	Oliktok Point, mobile campaign
PASS3	three-wavelength photoacoustic soot spectrometer
PSAP	particle soot absorption photometer
QC	quality control
SAIL	Surface Atmosphere Integrated Field Laboratory, mobile campaign
SGP	Southern Great Plains
slpm	standard litters per minute
SSA	single-scattering albedo
STP	standard temperature and pressure
TRACER	TRacking Aerosol Convection interactions ExpeRiment, mobile campaign
VAC	volts alternating current
VAP	value-added product

Contents

Figures

1.0 Instrument Title

Particle soot/absorption photometer (3-λ PSAP). Instrument's front panel is pictured in section 4.0.

2.0 Mentor Contact Information

Rebecca Trojanowski
Lead Mentor
Building 815
Brookhaven National Laboratory
Upton, New York 11973-5000
Email: rtrojanowski@bnl.gov

Connor Flynn
Associate Mentor
School of Meteorology
University of Oklahoma
Norman, Oklahoma 73072
Email: connor.j.flynn@ou.edu

Chris Hayes
Associate Mentor
Building 815
Brookhaven National Laboratory
Upton, New York 11973-5000
Email: chayes1@bnl.gov

3.0 Vendor

Radiance Research
535 NW 163 Street
Seattle, Washington 98177

Ray Weiss
Phone: (206) 366-7981
Vendor does not have a web site

As of 2014, Radiance Research announced the PSAP would be discontinued and the company would no longer be available for support on a regular basis. Given the long history of PSAP operation in Atmospheric Radiation Measurement (ARM) (since 1992 at the Southern Great Plains [SGP] observatory), the ARM user facility will continue to operate the existing instrument until a substitute has been accepted.

4.0 Instrument Description

Radiance Research PSAPs as described in this handbook are deployed in the first ARM Mobile Facility (AMF1) Aerosol Observing System (AOS), which was formerly known as mobile aerosol observing system (MAOS)-A, AMF2 AOS, AMF3 AOS, Eastern North Atlantic (ENA) AOS, MAOS-A, and SGP AOS. An earlier version of the PSAP is currently operated in the ARM Aerial Facility. The original SGP AOS site (AOS00) used an older PSAP but has been discontinued.

Figure 1. Front panel (AMF2, AMF3, ENA, MAOS-A).

The PSAP determines the optical extinction coefficient for absorption at three wavelengths. The method is based on measuring optical transmittance through a glass/cellulose filter over time as particles are deposited.

As discussed elsewhere (Schmid et al. 2006, Virkkula et al. 2005, Anderson et al. 2003, Anderson et al. 1999; Bond et al. 1999), the PSAP technique measures the particle absorption coefficient (σ_{AP}) as a function of the decrease in transmittance, Tr, over time as particles accumulate on the filter; that is:

$$\sigma_{AP} \propto \frac{Tr_{t-\Delta t} - Tr_t}{\Delta t} \tag{1}$$

where Tr_t is the sample transmittance for the current averaging period and $Tr_{t-\Delta t}$ is the sample transmittance for the previous averaging period, Δt.

The filter transmittance is calculated (Virkkula et al. 2005) for each wavelength as:

$$Tr = \frac{\left(\Sigma Sig / \Sigma Ref\right)}{\left(\Sigma Sig / \Sigma Ref\right)_{t=0}} \tag{2}$$

where ΣSig and ΣRef are the detector outputs for the signal and reference channels summed over the same period, Δt. The reference channel includes an identical filter downstream of the sample channel and is illuminated by the same light source in order to further reduce certain common-mode noise sources such as light-emitting diodes (LED), output fluctuations, and changes in the optical properties of the filter media. The denominator of Equation 2 normalizes the transmittance to the value of a new filter. In operation, the filter is changed when $Tr < 0.7$ (Bond et al. 1999). Furthermore, the change in Tr over Δt is

<< 1 and therefore the simplification of $\ln \frac{Tr_{t+\Delta t}}{Tr_t} = Tr_{t+\Delta t} - Tr_t$ was used to derive Equation 1 from Beer's law.

A single, three-LED assembly provides light simultaneously through the sample and reference filter holder. The sample filter collects all the ambient aerosol. The reference filter is then exposed to the same (aerosol-free) air as the sample filter. This two-filter system removes all common-mode noise (such as humidity). In 2019, Emfab filters replaced the previous filter media (PALL Life Sciences [E70-2075W, VWR Part Number 21431-350]). The previous filters were specified by the vendor and correction factors in the processing were calibrated for this filter. However, the manufacturer discontinued the filter medium and four other potential replacement filter mediums were considered. The experiments and suggestions were documented in ARM's ENG0003846. In summary, the Pallflex Emfab media (Type: EMFAB TX40HI20-WW, 10 mm, Reorder No. 7228) were selected as the best candidate for ongoing ARM filter-based absorbance measurements as other media were ruled out due to particle capture efficiency for small particles. Details of the experiment and results are documented in a report (Springston, Filter Aerosol Measurements for ARM, 2019). E70 to EMFAB filter change for each site and campaign changes are shown below and captured in ENG0004067:

AOS07-SGP: March 1, 2020

AOS03-OLI: March 3, 2020 and any campaign going forward

AOS06-ENA: April 1, 2020

AOS02-SAIL: September 1, 2021 and also for pre-campaign set-up and any campaign going forward

AOS01-TRACER: October 1, 2021 and also for pre-campaign set-up and any campaign going forward.

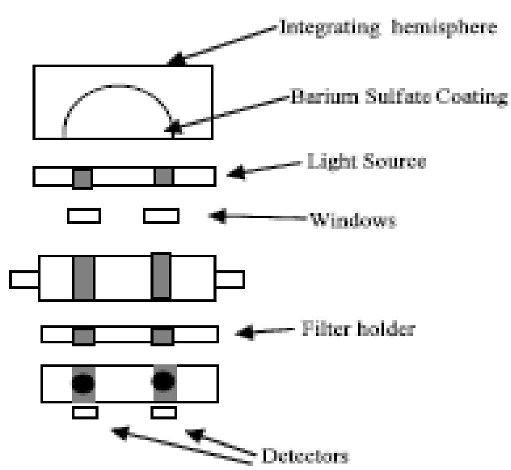

Figure 2. Optical assembly.

The three absorbances are measured by alternating between three illuminating LEDs. Nominally, the output of these three LEDs is listed as 470, 522, and 660 nm. Spectroscopic analysis of the output revealed a slightly different output:

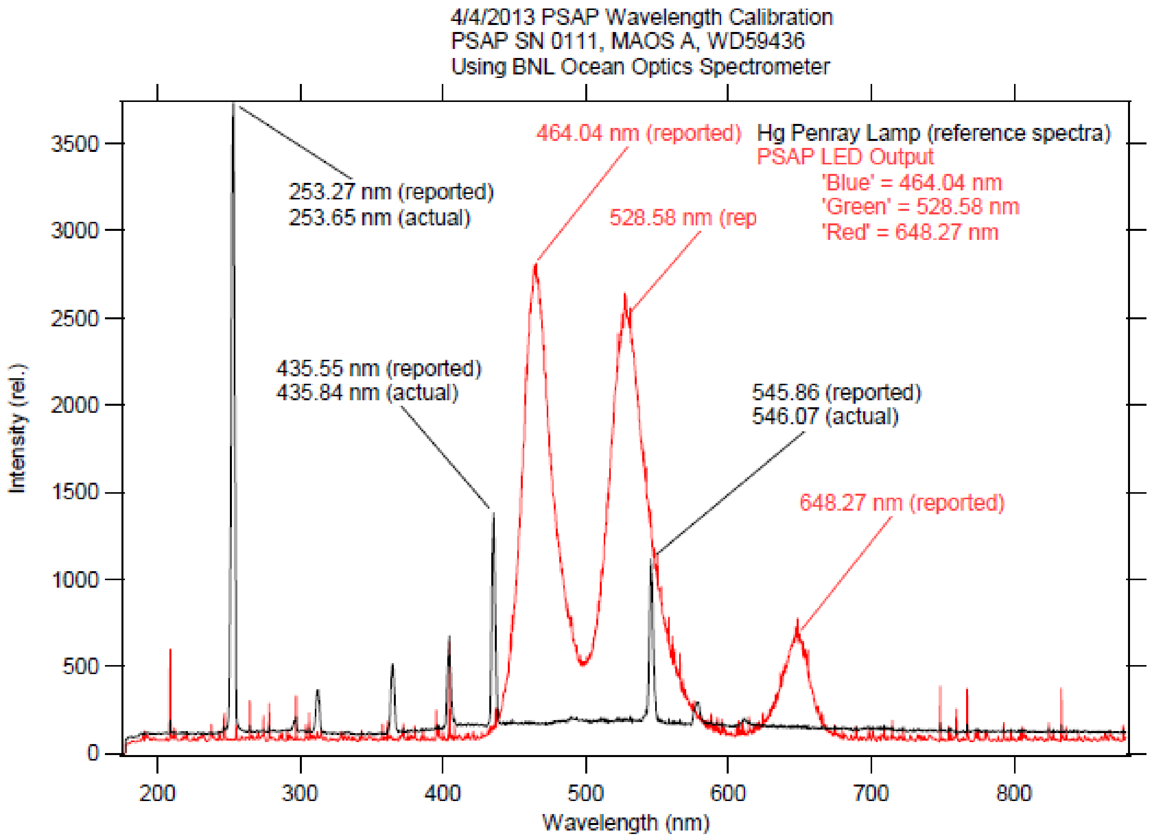

Figure 3. Measurement of LED outputs relative to Hg lamp.

The measured LED outputs shown here should be considered as the true absorbance wavelengths. These wavelengths are included in the metadata of all PSAP data files.

The 3-λ PSAP includes a mass flow meter (MFM) after the optical cell. All measured absorbances are scaled by the measured flow rate. A nominal flow rate of 1.0 slpm is maintained. The internal software of the PSAP uses a two-segment spline calibration fit of the MFM to calculate the true flow. In the AOS systems, a more accurate three-parameter parabolic fit is used to calculate the true flow. The MFM is calibrated annually or more frequently if circumstances change.

The internal software of the PSAP uses a nominal filter area to calculate the absorbance coefficient. This area is a default value assumed by the manufacturer. A more accurate measurement was made for each individual unit by the mentor.

The more accurate calibrated flow coefficients and filter area are used to calculate the absorbance coefficients.

In the field, the operator must monitor the front-panel read out to read the nominal transmittance of the filter.

The 3-λ PSAPs described here use EPROM version 2.03. This output includes a full 20-bit resolution measurement of the detector intensity at all three wavelengths plus the dark current of both the sample and reference light paths at 1-s resolution. Output of the PSAP is through an RS-232 serial port to the instrument computer. For historical reasons, the PSAP does not output all the relevant data in a single format. For this reason, three separate files are recorded, "O", "R", and "I".

Modifications of the stock instrument produced by Radiance Research include:

1. A slight easing of sharp edges in the filter holder to prevent o-ring tearing.
2. Replacing of the coarse metering valve with a micrometer driven flow valve (Swagelok) allowing the nominal flow rate to be adjusted to 1.000 ± 0.001 slpm.
3. Addition of an impactor and Nafion drier upstream of the sampling port.
4. Addition of a 0-2 slpm "dilution" mass flow controller (MFC) immediately upstream of the sampling port.

5.0 Measurements Taken

The primary measurement output from the PSAP is the light intensity at three wavelengths plus a dark current measurement for the sample and reference filters. An ancillary measurement of mass flow is also recorded. The addition of the dilution system adds a set point and read point from the dilution MFC.

6.0 Links to Definitions and Relevant Information

6.1 Data Object Description

The PSAP generates three separate serial packets that ARM collects and saves. These are named by the vendor as "I" (information), "O" (original), and "R" (raw). These serial streams are independently collected and saved as separate ASCII files, but only the "R" and "O" are converted to NetCDF and used in subsequent processing.

The "R" packets become the **aospsap3wr.a0** datastream where the "a0" data level indicates that this is raw/uncalibrated values such as A/D counts and millivolts.

The "O" packets become the **aospsap3w.a1** datastream where the "a1" data level indicates that the measurements are represented in physical units such as mass flow and dilution flow in LPM.

These two datastreams are processed together along with the **aosimpactor.b1** datastream to generate the **aospsap3w.b1** datastream in which the "b1" data level indicates the existence of QC (quality control) fields. Updated flow calibrations are also applied at this stage, as is identification of filter-change events and the calculation of full-precision filter transmittances.

Up to this point, all values are reported at the native 1-second resolution with the result that absorption values are quite noisy.

The **aospsap3w1s.b1** datastream is generated from **aospsap3w.b1** by applying the Springston-Sedlacek sliding boxcar average with a 60-second fullwidth, vastly improving the signal-to-noise ratio even at a 1second interval. In addition, the Wiess filter-loading correction is applied to yield partially corrected absorption coefficients. Additional QC tests are applied to assess filter stability and filter loading beyond optimal parameters. A final 60-second average is applied to **aospsap3w1s.b1** to yield **aospsap3w1m.b1**, the final b-level PSAP datastream.

The 1-minute b-level processing of the PSAP is followed by additional corrections and processing within the Aerosol Optical Properties (AOP) Value-Added Product (VAP). The AOP VAP combines the extensive aerosol optical properties of scattering and absorption from the nephelometer and PSAP, respectively, to apply additional corrections to the absorption measurements and ultimately generate a comprehensive set of extensive and intensive aerosol optical properties including scattering, absorption, Angström exponents, asymmetry parameter, single-scattering albedo, as well as sub-micron and supermicron fractions.

The AOP VAP consists of two primary outputs: 1-minute averages in **aoppsap1m.c1** and 1-hourly averages in **aoppsap1h.c1**. In the first stage, additional corrections are applied to the 1-minute b-level PSAP data. Two different approaches are implemented: the Bond/Sheridan/Ogren correction and the wavelength-averaged Virkkula correction. The Bond/Sheridan/Ogren corrections incorporate the Weiss filter-loading correction and a scattering subtraction. The Virkkula correction includes filter-loading, scattering, and single-scattering albedo (SSA) corrections. Because the SSA also depends on the resulting absorption, the Virkkula correction is applied iteratively until convergence is reached. It was observed that both of these correction approaches resulted in an artificial dependence of absorption Angström exponent (AAE) on filter transmittance, but fortuitously the dependence of each approach was noted to have similar magnitude and opposite sign. Thus, the AOP process takes the arithmetic mean of the two corrections to yield a combined result exhibiting negligible AAE dependence on transmittance.

The second stage of AOP processing produces hourly averages. Over the course of an hour, the AOS impactor alternates between a 1-um and 10-um size cut, permitting hourly averages to be generated and used to derive submicron fractions and super-micron components of the aerosol optical properties from the 1-minute output product.

6.2 Data Ordering

PSAP data collected are distributed through the ARM Data Discovery or can be ordered from http://www.arm.gov/instruments/psap. Data are organized by measurement location/campaign.

6.3 Data Plots

Figure 4 shows a month of ancillary PSAP measurements. The top frame shows the blue transmittance over time. The dotted lines at Tr = 1 and Tr = 0.7 indicate the proper bounds for operation to minimize multiple scattering and departures from Beer’s law. During episodes of high aerosol burdens, the filter may not always be changed frequently enough. The processing algorithm flags periods when Tr is not within bounds.

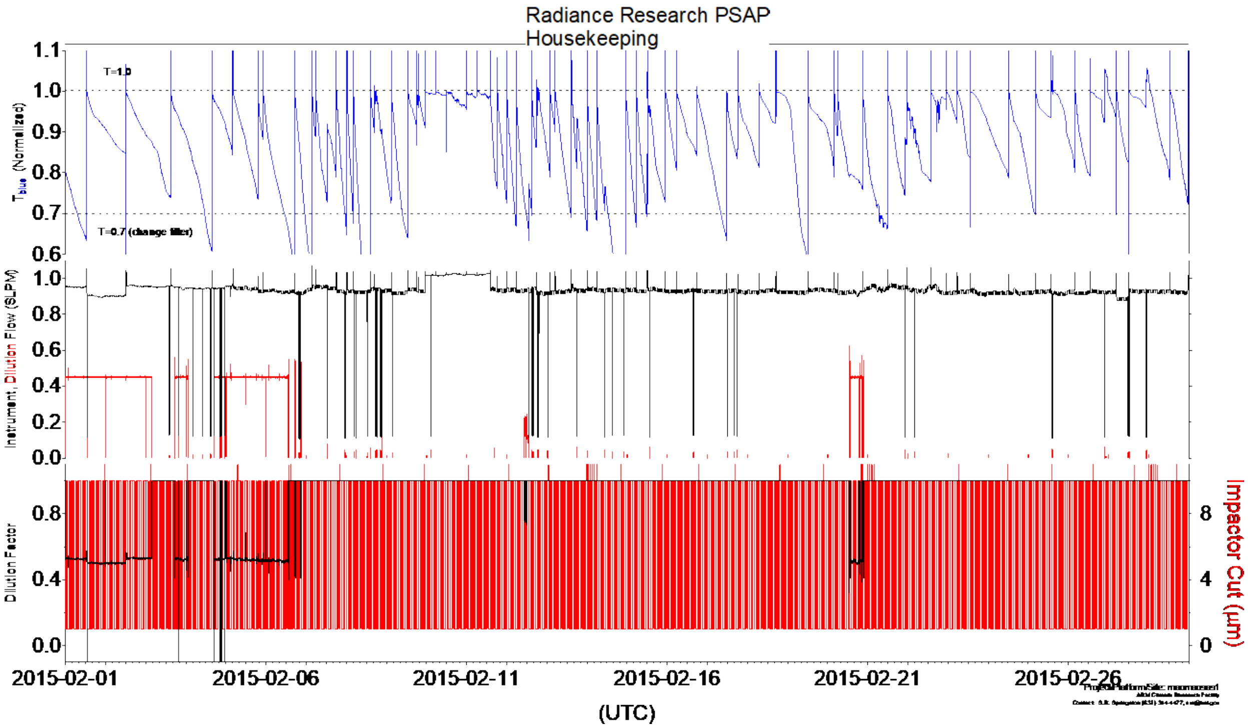

Figure 4. Housekeeping data for one month.

The second panel of Figure 4 shows the instrument flow (black trace) and dilution flow (red trace). This month illustrates when things go awry. The instrument flow goes >> 1.0 slpm during filter changes when the filter holder is opened. This allows the periods to be flagged as not valid. It also shows periods when the pump is off, usually due to site power failures. Even though the instrument is backed up with an uninterruptable power supply and the pump comes on once the site generator starts, there are two interruptions to the data: once when power goes down and another when power comes back up. There is roughly a 5-min period around each interruption where the data is flagged as not valid.

The fine structure (not readily apparent in Figure 4) of the instrument flow shows oscillations of ±0.03 slpm indicative of the impactor state. Although the impactor state is separately recorded, this oscillation confirms proper impactor operation. Periods (such as a two-day interval around 2015-02-11) where the impactor is not operating are readily obvious to the eye, and can be algorithmically flagged.

The red trace in the middle panel of Figure 4 is the flow of dilution. In this month, the source of filtered dilution air (the Pentras Drier) was failing. This is apparent in the gaps of dilution flow. However, as shown in the bottom panel of Figure 4, the dilution factor is automatically determined and is set to 1 (no dilution) if the dilution flow is not functioning.

The red trace in the bottom panel of Figure 4 shows the impactor state. A horizontal blow-up of this panel shows perfect correspondence with the flow changes discussed earlier.

After data quality checks (discussed above), the final data corrected for dilution factor are presented. A typical plot is shown in Figure 5.

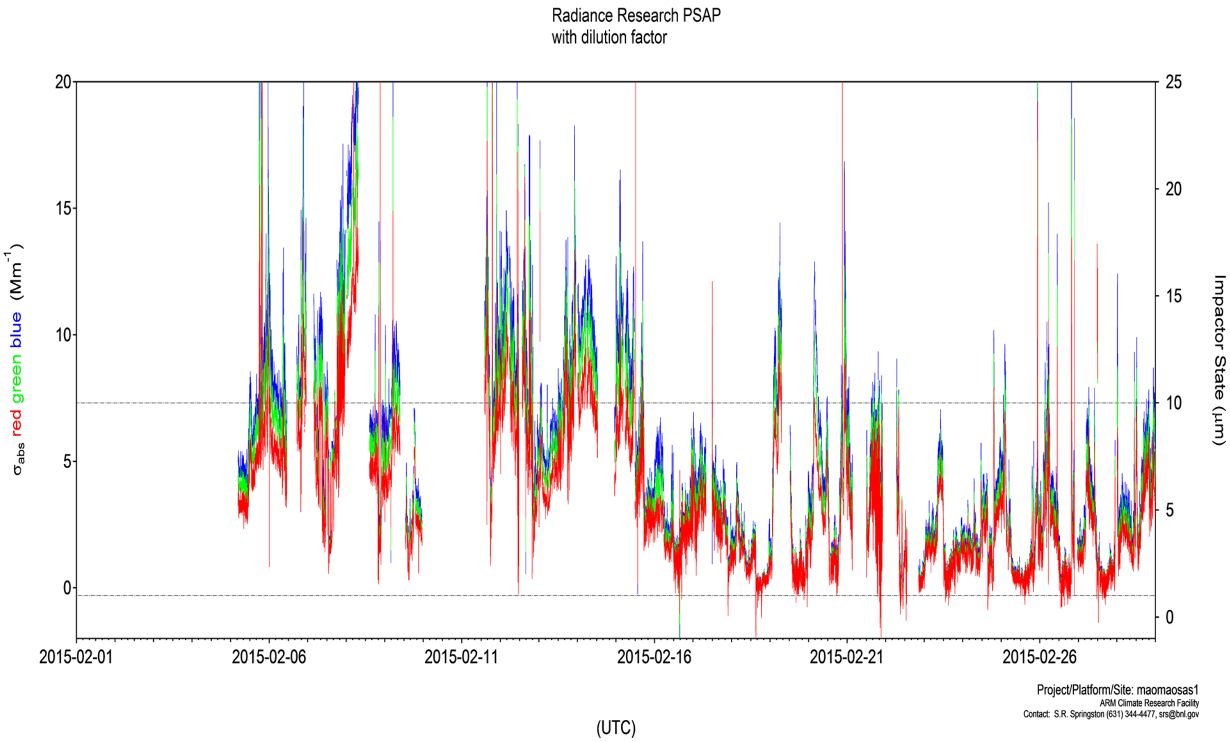

Figure 5. Processed data for one month.

6.4 Data Quality

The first level of data quality is the automatic flagging of data when transmittance decreases below 0.7, the pumps are off, or the filters are being changed. Most of these events can be identified algorithmically, but not all.

The final level of data quality is inspection of the plots for wild excursions (ringing). These are caused by momentary (~1 s) changes in intensity. It is not clear what causes these excursions. They are obvious in visual inspection, particularly due to the symmetrical nature about zero. They always occur near (just after) filter changes and also accompany power failures and resumptions. The automatic processing has relatively conservative (wide) bands around these events where data is invalid. However, occasionally the excursions are present outside even these wide bands. This can be due to line voltage instability, longer than normal filter changes, sudden excursions in the heating or air conditioning, or undocumented temporary changes in the sample inlet. Mentor judgment is exercised in identifying and flagging these periods.

6.5 Calibration Data Base

There is no effective way to calibrate the PSAP using a realistic absorbance standard. Instead, the absorbance of aerosols as measured by the PSAP is considered a first-principles measurement. The instrument, dilution flow rates, and spot size are all calibrated and used in processing the resultant data.

Spot size is measured upon receipt of the instrument. Flows are calibrated at the beginning of each deployment and generally at 6-12 month intervals in the field.

Zero checks are not considered appropriate given the nature of the measurement principle. Laboratory exercises involving putting a High-Efficiency Particulate Air (HEPA) filter on the inlet leads to zero response on all three channels.

7.0 Technical Specification

7.1 Units

The measured quantity of interest is the optical absorbance of aerosols. This is reported in units of reciprocal megameters (Mm^{-1}). The instrument measures transmittance as a ratio of intensities between the sample and reference cells. The first derivative of transmittance with time is absorbance. The instrument also reports instrument mass flow. Absorbance is reported at standard temperature and pressure (STP) (0ºC and 1 atm).

7.2 Range

The full range of this model is somewhat arbitrary. Ambient absorbance of aerosols in non-urban locations generally ranges from 0-50 Mm^{-1}, but can be much higher during biomass burn events or local contamination from the on-site generator.

7.3 Accuracy

The PSAP does not measure absorbance directly. What the PSAP measures is transmittance through an increasingly dirty filter. From the first derivative of transmittance over time, extinction is calculated, which is the sum of absorbance and scattering.

The accuracy of the PSAP is not generally agreed on in the community. Bond et al. discuss some of the many corrections of PSAP data. These corrections involve filter loading and inferring the scattering on the PSAP filter based on co-located nephelometry data, the so-called “Bond Corrections.” For aerosols with high single-scattering albedo, the scattering correction can be a sizable fraction of the original PSAP measurement, up to 50%.

At the end of the day, the PSAP measures what the PSAP measures.

7.4 Repeatability

Precision (repeatability) is given here as the noise of the 1-s signal. Under quiet ambient conditions, this is:

Absorbance $\sigma \sim 0.1$ Mm^{-1} without dilution for 60-s averaged intensity data.

This is a best case. A factor of 0.5 dilution (dilution air set to 50% of sample inlet flow) increases the standard deviation of the signal by ~2-3 X. The signal measured by instrument is reduced proportional to the dilution and there is additional uncertainty introduced by drift in the calibration of the dilution MFC.

Note that these Confidence Intervals represent repeatability over a relatively short period. Day-to-day and month-to-month repeatability has a larger confidence interval.

7.5 Sensitivity

Sensitivity with no dilution is taken as 3 X σ or 0.3 Mm^{-1} for 60-s averaging of intensities.

7.6 Uncertainty

Uncertainty is an integral of all errors. It is a combined measurement of accuracy and precision (repeatability) discussed above. Absent a true reference absorbance measurement, the uncertainty of the PSAP is ill-defined.

7.7 Output Values

Described in Section 6.0.

8.0 Instrument System Functional Diagram

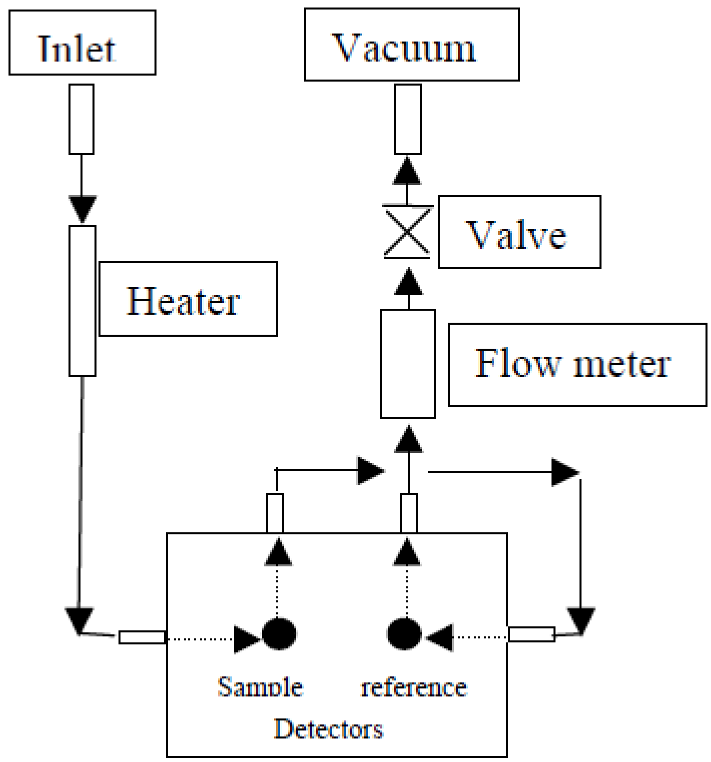

Figure 6. Flow schematic.

Air is sampled from the AOS high-flow aerosol inlet. A 1-/10-µm impactor is now used in all AOS systems. The impactor alternates between the two sampling cutoffs (all particles < 1 µm and all particles < 10 µm). The impactor output is shared between the PSAP, two nephelometers and, where present, the cloud aerosol and precipitation spectrometer (CAPS) and three-wavelength photoacoustic soot spectrometer (PASS3) systems. The impactor operates on a complicated switching schedule in accordance with other ARM instruments. A PermaPure Nafion drier is used upstream of the PSAP to dry the sample prior to entering the instrument. The PermaPure drier uses the counterflow of the PSAP exhaust at low pressure to dry the sample air. Because of the effectiveness of the drier, the heater shown in the flow schematic is NOT used in AOS sampling.

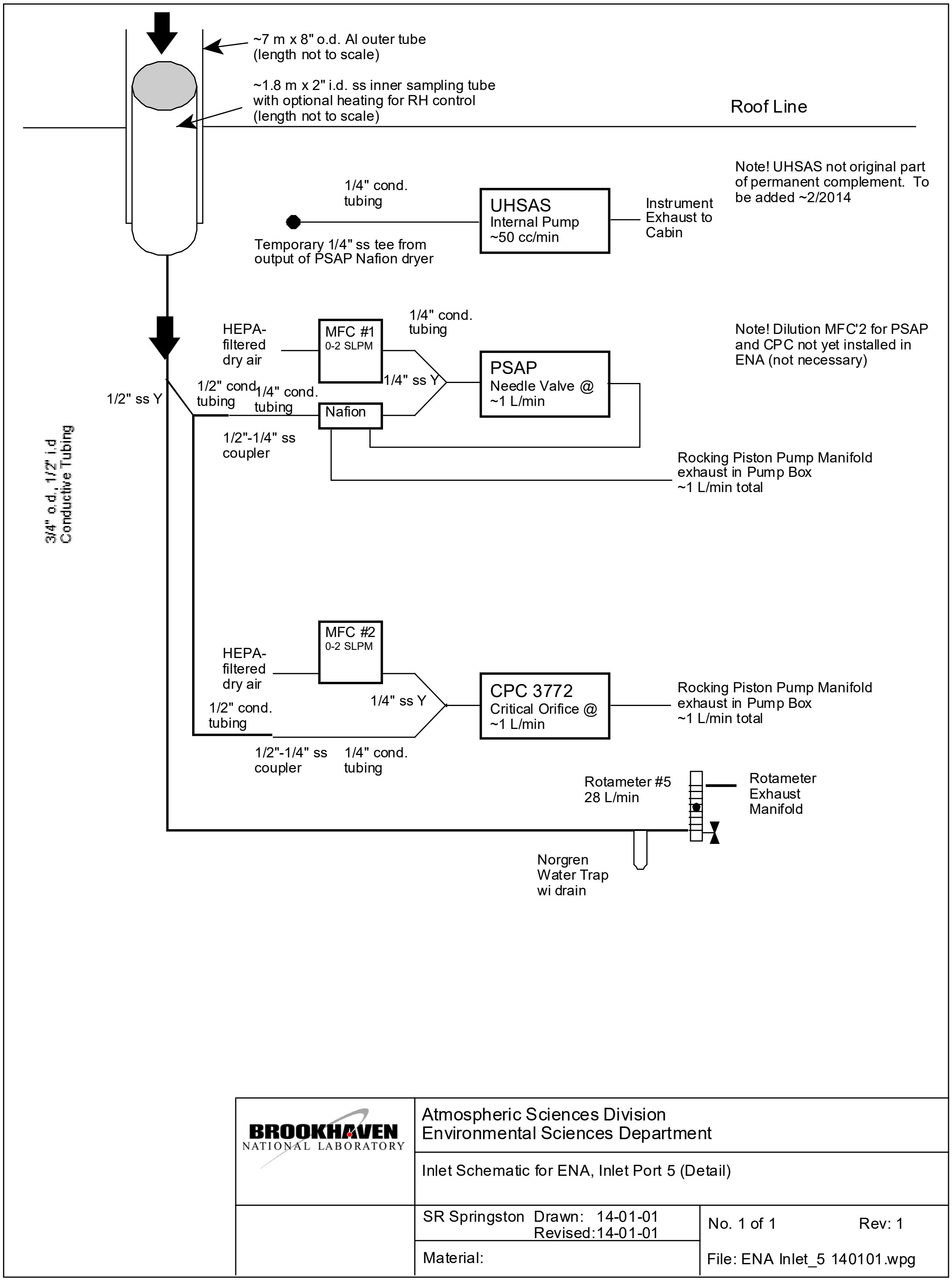

Figure 7. Ground inlet schematic.

9.0 Instrument/Measurement Theory

The following description is taken from the PSAP manual:

The method is based on measuring the optical transmittance at three wavelengths through a filter as particles are deposited. There are two optical paths: one through the filter with deposited particles, and a second path through a clean filter, used as a reference to determine transmittance, Tr. An experimentally determined transfer function, Fr, is used to correct the transmittance to the actual transmittance of the column of air drawn through the filter.

The absorption coefficient, σ_{ap}, is calculated from Beer's law using Tr, the flow rate and the area of the deposited spot on the filter.

10.0 Set-up and Operation of Instrument

Instrument is installed in the AOS systems. This includes:

1. Physical mounting of the instrument in a shock-isolated 19" instrument rack and electrical connection to the appropriate Power Distribution Unit.
2. Plumbing of the sample line into the fast flow ½" Silastic sample manifold line. Prior to the instrument, the sample goes through a 1/10 µm impactor, a Nafion drier, and optional dilution by HEPA-filtered dry air.
3. Setting of front panel settings (date/time are recommended to be set, but are not crucial as data is time stamped by the instrument computer) for file output. The MFM calibration settings, spot size, and Bond Correction coefficients are left in the default state (and the instrument values of these are not used in subsequent processing).
4. Connection of the dilution MFC to the RS-232 connection of the instrument computer.
5. Connection of the PSAP RS-232 output to the instrument computer, and
6. Connection of the 110-VAC power line to the appropriate Power Distribution Unit outlet.

After power is turned on, the instrument goes through self-checks and commences putting out data. After extended storage or transportation, the PSAP display occasionally comes up garbled. Reseating of all internal boards is the best remedy for this behavior.

11.0 Software

The instrument uses software in an EPROM version 2.03. This code is in assembly and is not available to users. Except for resetting the optical transmittance to 1.0 and adjusting the nominal flow rate to 1.0 slpm following filter changes, there is little interaction with operators.

Instrument control and data acquisition is performed by NI LabView-based software written by BNL. For the instrument operating with dilution, the flow is controlled in the same vi.

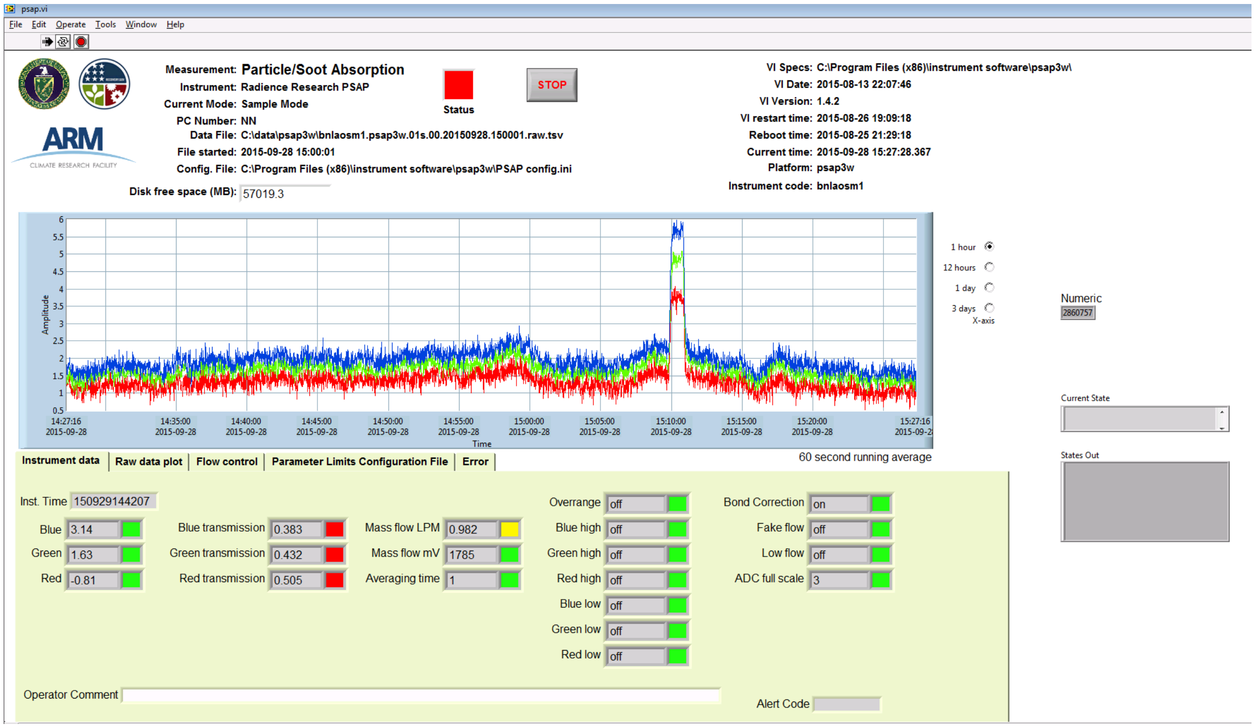

Figure 8. Graphical user interface (GUI) for operator.

The interface has multiple tabs of information. The default plot shows a 1-h, 12-h, 1-day, or 3-day time series plot. A local interference from transportation is evident at 15:10. The instrument parameters are color-coded based on limits contained in a configuration file. In this case, transmission is < 0.7 and the flow rate has decreased below 0.98 lpm. The green/yellow/red lights allow the operator to rapidly assess the operating conditions.

A section labeled "Operator Comment" allows free-form notes to be entered into the raw datastream with an accurate time stamp.

12.0 Calibration

Calibration procedures are described earlier. These include an initial measurement of spot size and regular calibrations of instrument and dilution flow rates.

Because the data processing requires knowledge of dilution and instrument MFC calibrations, these are calibrated during mentor visits. MFCs are calibrated with a 6-point calibration with triplicate measurements at each flow. Either a first-principles bubble flowmeter (with corrections for temperature, pressure, and water vapor concentration) or a dry gas meter (standardized against the bubble flowmeter) is used to calibrate the instrument and MFC flows.

13.0 Maintenance

This instrument requires minimal maintenance. Filter changes (sample and reference) are performed when the blue transmittance decreases below 0.7. After the filter change, the transmittance is reset to 1.00, and the flow is adjusted to a nominal 1.00 slpm. A procedure is given in the AOS Operating Procedures.

14.0 Safety

The unit has no safety concerns during normal operation. Inside the instrument, there is a 110-VAC power supply.

15.0 Citable References

Anderson, TL, DS Covert, JD Wheeler, JM Harris, KD Perry, BE Trost, DJ Jaffe, and JA Ogren. 1999. "Aerosol backscatter fraction and single scattering albedo: Measured values and uncertainties at a coastal station in the Pacific Northwest." *Journal of Geophysical Research – Atmospheres* 104(D21): 2679326807, doi:10.1029/1999JD900172

Anderson, TL, SH Masonis, DS Covert, NC Ahlquist, SG Howell, AD Clark, and CS McNaughton. 2003. "Variability of aerosol optical properties derived from in situ aircraft measurements during ACE-Asia." *Journal of Geophysical Research – Atmospheres* 108(D23): 8647, doi:10.1029/2002JD003247,2003

Bond, TC, TL Anderson, and D Campbell. 1999. "Calibration and intercomparison of filter-based measurements of visible light absorption by aerosols." *Aerosol Science and Technology* 3(6): 582–600, doi:10.1080/027868299304435

Schmid, O, P Artaxo, WP Arnott, D Chand, LV Gatti, GP Frank, A Hoffer, M Schnaiter, and MO Andreae. 2006. "Spectral light absorption by ambient aerosols influenced by biomass burning in the Amazon Basin. I: Comparison and field calibration of absorption measurement techniques." *Atmospheric Chemistry and Physics* 6(11): 3443–3462, doi:10.5194/acp-11-8861-2011

Springston, SR, and AJ Sedlacek. 2007. "Noise characteristics of an instrumental particle absorbance technique." *Aerosol Science and Technology* 41(12): 1110–1116, doi:10.1080/02786820701777457

Springston, S. 2019. "Filter Aerosol Measurements for ARM." OSTI Report United States: U.S. Department of Energy. doi:10.2172/1494998

Virkkula, A, NC Ahlquist, DS Covert, WP Arnott, PJ Sheridan, PK Quinn, and DJ Coffman. 2005. "Modification, calibration and a field test of an instrument for measuring light absorption by particles." *Aerosol Science and Technology* 39(1): 68–83, doi:10.1080/027868290901963

ARM

www.arm.gov

U.S. DEPARTMENT OF ENERGY

Office of Science