U.S. DEPARTMENT OF ENERGY | Office of Science

DOE/SC-ARM-TR-262

Single-Channel Tricolor Absorption Photometer (STAP) Instrument Handbook

F Mei
C Flynn

LA Goldberger
M Pekour

November 2020

ARM

DISCLAIMER

DOE/SC-ARM-TR-262

Single-Channel Tricolor Absorption Photometer (STAP) Instrument Handbook

F Mei, Pacific Northwest National Laboratory (PNNL)
LA Goldberger, PNNL
C Flynn, University of Oklahoma
M Pekour, PNNL

November 2020

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

Acronyms and Abbreviations

AAF	ARM Aerial Facility
ACCESS	aerosol counting, composition, extinction, and sizing system
ARM	Atmospheric Radiation Measurement
ASCII	American Standard Code for Information Interchange
CACTI	Cloud, Aerosol, and Complex Terrain Interactions
DAQ	data acquisition
DQ	data quality
G-1	Gulfstream-159
GUI	graphical user interface
HEPA	high-efficiency particulate air
MCPC	mixing condensation particle counter
MFC	mass flow controller
MIST	multiple instruments stackable tower
MOPC	miniaturized optical particle counter
netCDF	Network Common Data Format
PNNL	Pacific Northwest National Laboratory
PSAP	particle soot absorption photometer
STAP	single-channel tricolor absorption photometer
STP	standard temperature and pressure
UAS	unmanned aerial system
UAV	unmanned aerial vehicle
UTC	Coordinated Universal Time
VDC	volts direct current

Contents

Figures

Tables

1.0 Instrument Title

The U.S. Department of Energy Atmospheric Radiation Measurement (ARM) user facility's aerosol counting, composition, extinction, and sizing system (ACCESS) includes a base module (9400), a filter sampler (9401), an advanced mixing condensation particle counter (MCPC, 9403), a miniaturized optical particle counter (MOPC, 9405), and a single-channel tricolor absorption photometer (STAP, 9406).

This handbook describes the principles and operations of the single-channel tricolor absorption photometer, Model 9406.

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

Brechtel Manufacturing, Inc.
1789 Addison Way
Hayward, California 94544
bmi_info@brechtel.com
Tel: 510-732-9723
Fax: 510-732-9153
Website: https://www.brechtel.com/products-item/stap/

4.0 Instrument Description

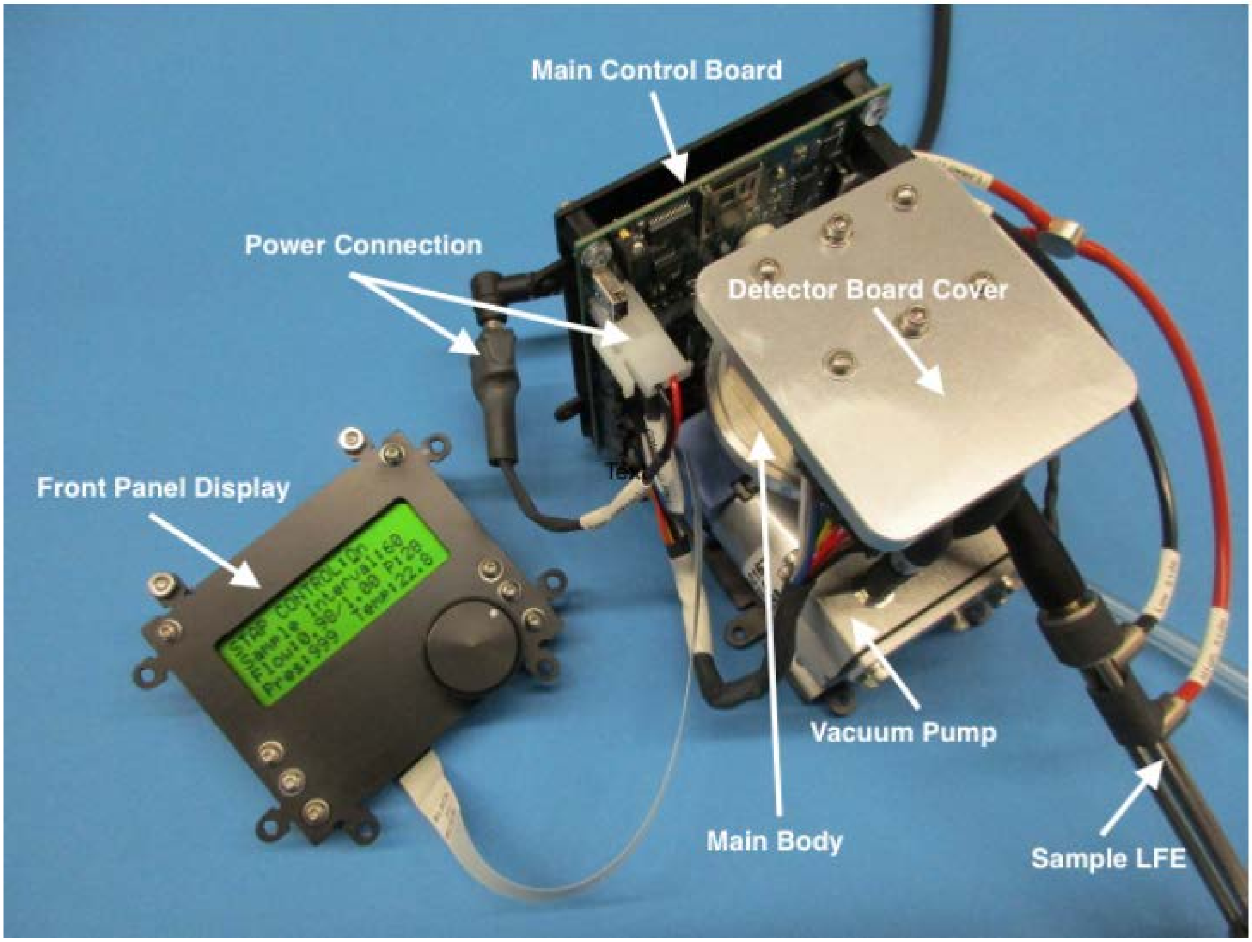

Figure 1. Major components of the STAP (figure adapted from manufacturer's manual).

The STAP used the same measurement technique as the ARM particle soot absorption photometer (PSAP), which is based on optical transmittance measurement through a filter over time as aerosol particles are deposited on the filter.

The determination procedure of the particle absorption coefficient ($\sigma_{AP}(\lambda)$) was both described in the ARM PSAP handbook and the Brechtel instrument manual (see references in section 13). The basic principle of both the PSAP and STAP techniques is based on measuring the particle absorption coefficient as a function of the decrease in transmittance with the increase of aerosol particle loading. However, for field operations, data processing should consider the filter material difference, the aerosol flow fluctuation, and the artifact from aerosol deposition. Thus, a filter-loading correction factor was determined empirically and applied to the absorption photometer's operation.

5.0 Measurements Taken

The STAP's primary measurement output is similar to the PSAP, which includes 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 mass flow controller (MFC).

6.0 Links to Definitions and Relevant Information

STAP manufacturer's webpage: https://www.brechtel.com/products-item/stap/

Pikridas, M, S Bezantakos, G Mocnik, C Keleshis, F Brechtel, I Stavroulas, G Demetriades, P Antoniou, P Vouterakos, M Argyrides, E Liakakou, L Drinovec, E Marinou, V Amiridis, M Vrekoussis, N Mihalopoulos, and J Sciare. 2019. "On-flight Intercomparison of three miniature aerosol absorption sensors using unmanned aerial systems (UASs)." *Atmospheric Measurement Techniques* 12(12): 6425−6447, https://doi.org/10.5194/amt-12-6425-2019

6.1 Data Object Description

The raw data from the STAP are recorded in *.dat file with appropriate headers specifying the data and units of measurement. The diameter array is written as one of the header rows in the file. The data file column definitions are included in Table 1.

ARM archived data are available in both netCDF format and ASCII format.

Table 1. Data file column definitions.

Variable	**Description**
`YY/MM/DD HR:MN:SC`	Time, UTC
`invmm_r`	Red absorption coefficient, Mm^{-1}
`invmm_g`	Green absorption coefficient, Mm^{-1}
`invmm_b`	Blue absorption coefficient, Mm^{-1}
`red_smp`	Red sample, Mm^{-1}
`red_ref`	Red reference, Mm^{-1}
`grn_smp`	Green sample, Mm^{-1}
`grn_ref`	Green reference, Mm^{-1}
`blu_smp`	Blue sample, Mm^{-1}
`blu_ref`	Blue reference, Mm^{-1}
`blk_smp`	Black sample, Mm^{-1}
`blk_ref`	Black reference, Mm^{-1}
`smp_flw`	Sample flow, ms^{-1}
`smp_tmp`	Sample temperature, C
`smp_prs`	Sample pressure, kPa

Variable	Description
pump_pw	Pump power, W
psvolts	Power supply voltage, V
err_rpt	Error report, int (1-13: refer the manual for detail)
cntdown	Countdown, int
fltstat	Flow status, int
flow_sp	Flow set point, float
intervl	Interval, int
stapctl	STAP control, int

Data Processing

Due to computational limitations in the onboard STAP firmware, the firmware's particle absorption coefficient values calculated in real time have higher uncertainties (15%). Thus, the post-processing of raw data is recommended. Brechtel has developed an Igor-based software routine for post-processing. For ARM-mentored instruments, a MATLAB-based software routine was developed by Connor Flynn for both PSAP and STAP. The future b-level data will adapt a similar approach to PSAP to process the STAP data.

The data is read in and managed by handling chopped records and possible decimal formatting errors and status flags. Then, after providing the input about the filter spot area and the sample flow rate correction and using the measured light intensity through the particulate filter (over a specified time duration), the smoothed transmittances are computed. Afterward, the 'uncorrected' absorbance coefficients are computed via Beer's Law. Finally, the absorbance coefficients are calculated via the Bond/Ogren algorithm (Bond 1999, Ogren 2010), which uses the normalized filter transmittance and the aerosol scattering coefficient to account for apparent absorption from aerosol scattering.

$$\sigma_0 = \frac{A}{Q\Delta t} \ln\left(\frac{I_{t-\Delta t}}{I_t}\right)$$

(1) Beer's Law

$$\begin{aligned}\sigma_{AP,O2009} &= \frac{1}{1.22}\left(\frac{0.97 \cdot 0.873}{1.0796 \cdot Tr + 0.71}\sigma_0 - 0.02 \cdot \sigma_{SP}\right) \\ &= \frac{1}{1.5557 \cdot Tr + 1.0227}\sigma_0 - 0.0164 \cdot \sigma_{SP} \\ &= \frac{1}{2.58} \times \frac{1}{.6Tr + .4}\sigma_0 - 0.0164\sigma_{sp}\end{aligned}$$

(2) Bond/Ogren

The absorption coefficient, σ_{ap}, is calculated from Beer's Law using T_r, the flow rate and the area of the deposited spot on the filter and the T_r correction function, F_r,

$$\sigma_{ap} = \frac{area}{flow \times \Delta T} \times ln\left({}^{T_{rt}}/_{T_{r0}}\right) \times F_r$$

where flow is the flow rate determined with a mass flow meter, ΔT is the sample time period, T_{rt} is the sig/ref at time t, and T_{r0} is the sig/ref of a clean filter.

6.2 Data Ordering

The collected STAP data are distributed through the ARM Data Center and are presently updated after each unmanned aerial system (UAS) daily flight.

6.3 Data Plots

Figure 2 shows the housekeeping plots that the ARM Aerial Facility (AAF) field crew use to check the instrument health during flight operation.

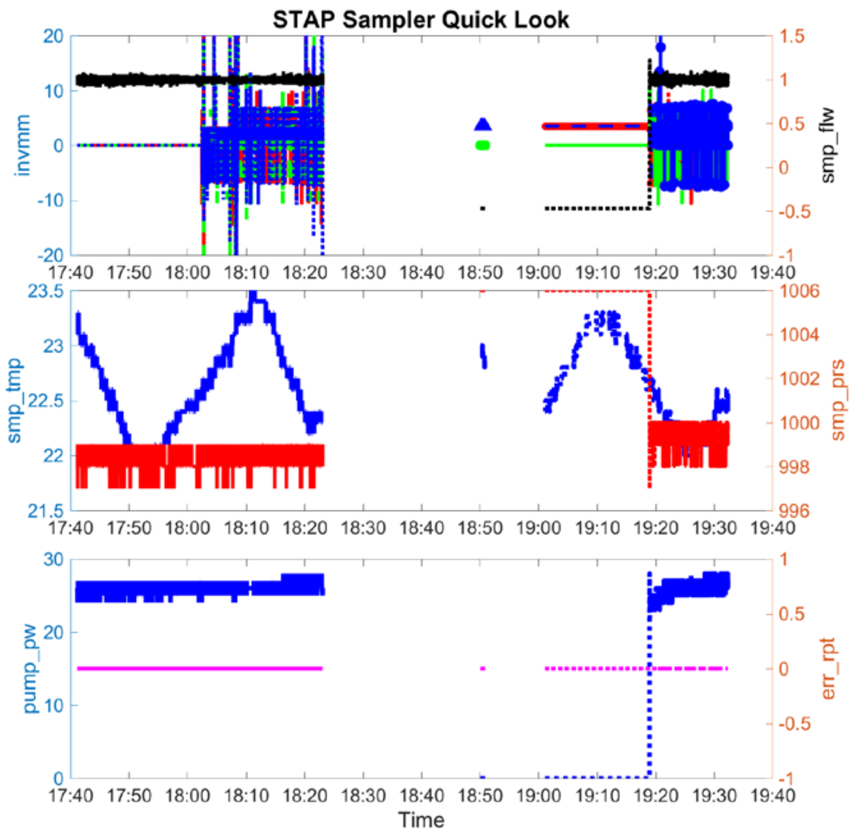

Figure 2. An example of the housekeeping data from STAP.

Figure 3 shows the data visualization option using the ARM Data Quality (DQ)-Zoom Plotter tool from the ARM Data Center. The example shown is from the PSAP data plot. The STAP data plot is under development.

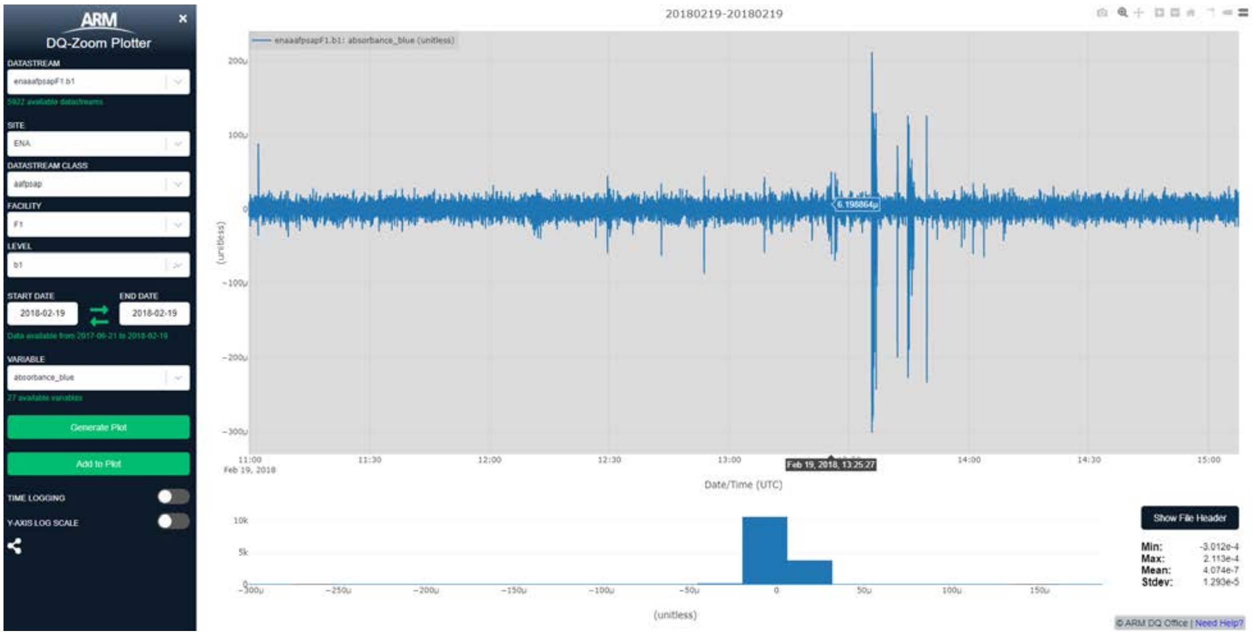

Figure 3. ARM Data Center DQ-Zoom Plotter.

6.4 Data Quality

In 2018, the AAF's flying laboratory, the Gulfstream-159 (G-1), was deployed to Argentina for the Cloud, Aerosol, and Complex Terrain Interactions (CACTI) field campaign. Both the STAP and PSAP were deployed after the G-1 isokinetic inlet inside the aircraft cabin. This deployment gave us a good opportunity to compare both instruments with the same filter media.

Figure 4 shows the good correlation of the absorption coefficients between the PSAP and STAP in cloud-free air. This figure included the data from all the "level" flight legs from CACTI. Both PSAP and STAP data used similar MATLAB processing routines. The "level" flight periods have been defined as when the aircraft maintained at an altitude within ± 40-m variation. The data were colored with the flight average altitudes, which did not significantly affect the STAP performance.

Multiple factors were also analyzed to assess whether they affected PSAP and STAP agreement, including the ambient temperature, the static pressure, the differential pressure (rates of ascent and descent), and vertical wind speed. None of these factors had a significant effect on PSAP and STAP differences.

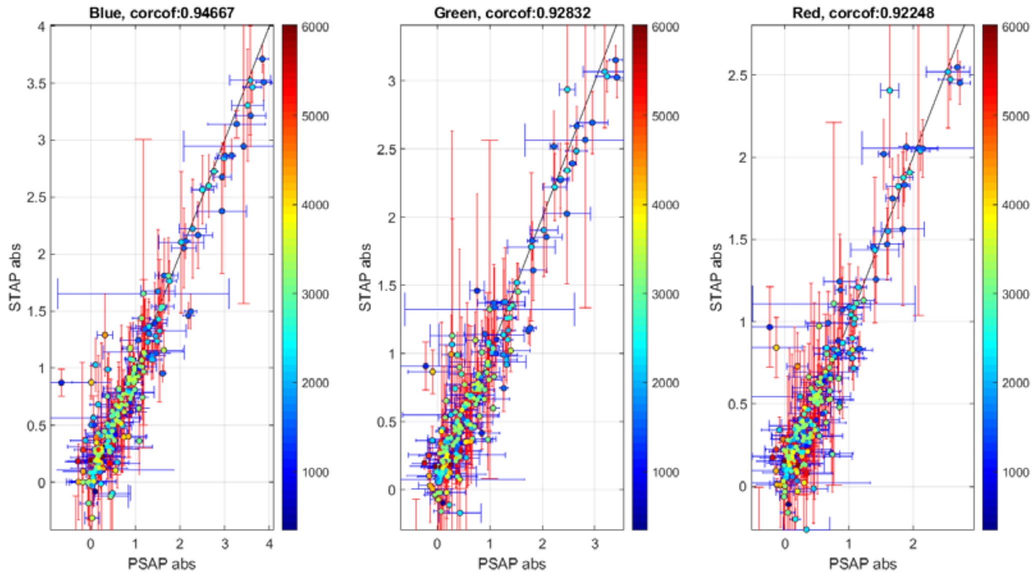

Figure 4. The particle absorption coefficients comparison between PSAP and STAP during the CACTI "level" flight leg. The data was colored by the flight altitude (m).

Furthermore, the same analysis was applied to periods of flight when ascending and descending to characterize STAP and PSAP comparison during flight maneuvers. The p values are in the top left box in Figure 5 below. A smaller p value indicates that the STAP and PSAP values agree with each other because the measurements are comparable, not just by happenstance. Based on the comparison, the PSAP and STAP behaved similarly during the different flight maneuvers.

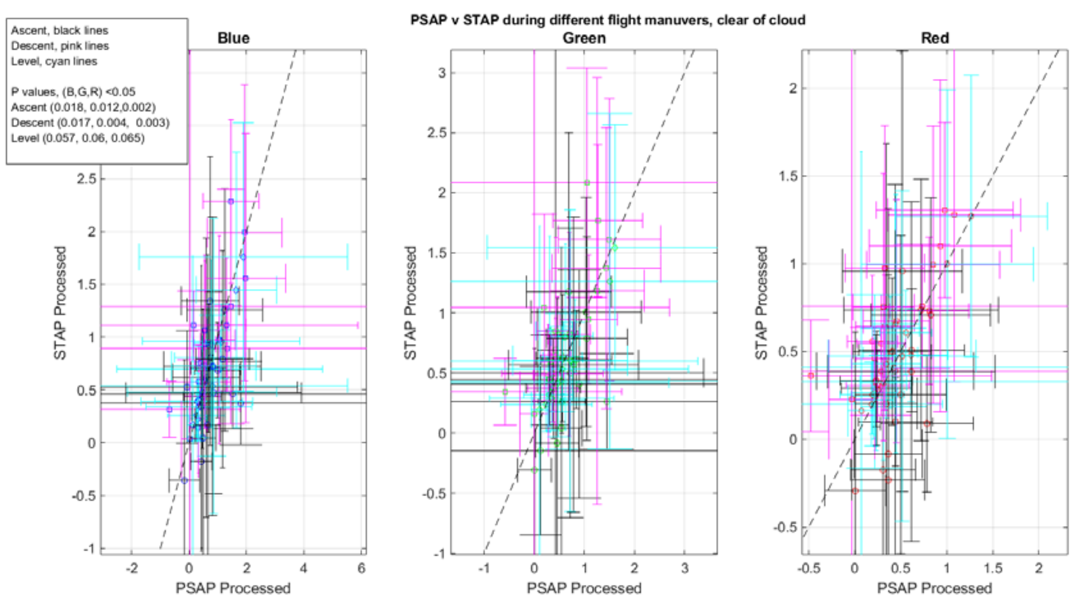

Figure 5. The particle absorption coefficients comparison between PSAP and STAP during different flight maneuvers in CACTI.

6.5 Calibration Database

Similar to the PSAP, there is no effective way to calibrate the STAP using a realistic absorbance standard. Instead, the absorbance of aerosols, as measured by the STAP, is considered a first-principles measurement. The instrument and dilution flow rates and the spot size are all calibrated and used to process 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 lead to zero response on all three channels.

7.0 Technical Specification

Table 2. STAP parameters and values.

Parameter	Value
Wavelengths	450, 525, 624 nm
Sample flow	0.5 to 1.7 lpm
Noise level (1 sigma)	+/- 0.2 Mm^{-1} (0.02 $\mu g/m^3$ black carbon mass)
Filter	Glass fiber, 10-mm dia
Size	5.3 x 4.3 x 3.9 in/13.5 x 10.9 x 9.9 cm
Weight	1.45 lbs/0.66 kg
Supply voltage	12 VDC
Power	10 Watts
Mounting	Multiple hard mounting points through metal body brackets

7.1 Units

The measured quantity of interest is the optical absorbance of aerosols, which 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 onsite generator.

7.3 Accuracy

The STAP does not measure absorbance directly. What the STAP 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.

Accuracy of the STAP is not generally agreed on in the community. Bond et al. discuss some of the many corrections of STAP data. These corrections involve filter loading and inferring the scattering on the STAP 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 STAP measurement, up to 50%.

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 for the best-case scenario.
- A factor of 0.5 dilutions (dilution air set to 50% of sample inlet flow) increases the standard deviation of the signal by ~2-3 X. The signal measured by the instrument is reduced proportional to the dilution, and additional uncertainty is 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 STAP is defined the same as PSAP.

7.7 Output Values

Described in section 6.0.

8.0 Setup and Operation of Instrument

Deployment on a TigerShark or ArcticShark UAS

The ACCESS STAP is installed on the multiple instruments stackable towers (MIST, as shown in Figure 6) in the main payload bay of the ArcticShark. The MIST itself is seated in the payload bay connected by four vibration isolators to reduce noise. Outside air is brought into the payload via a universal inlet installed on the nose of the UAS. As shown in Figure 7, the inlet is pumped actively via a scroll pump and controlled with a mass flow controller during the flight. The instrument is initialized by an onboard data acquisition (DAQ) system that operates the Brechtel LabVIEW software. The data are transmitted to scientists on the ground in real time.

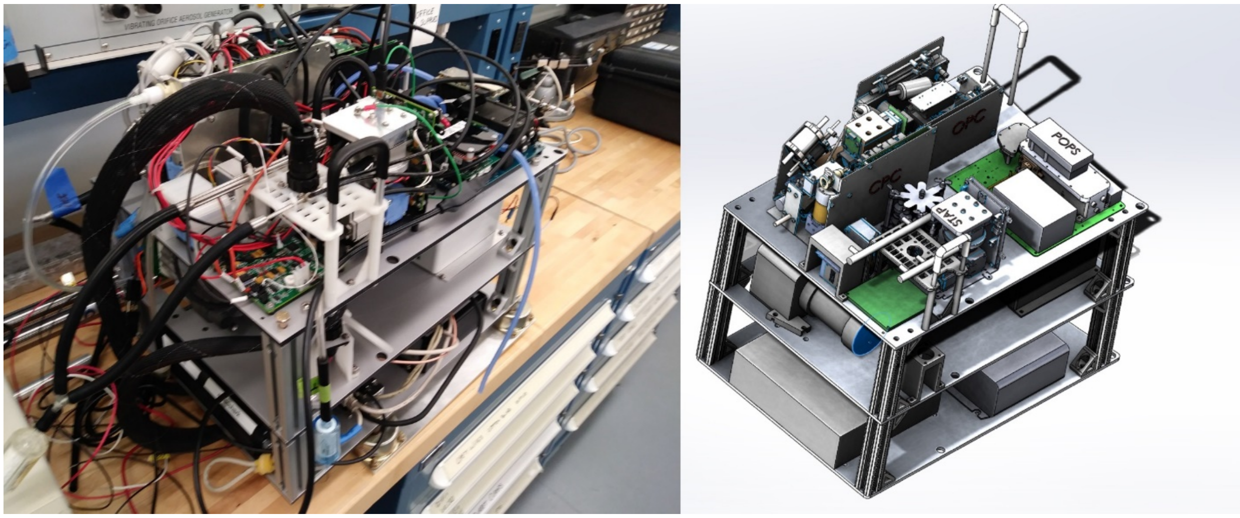

Figure 6. MIST instrument payload tower. Left: On laboratory bench. Right: Schematic with instrument placement clarified.

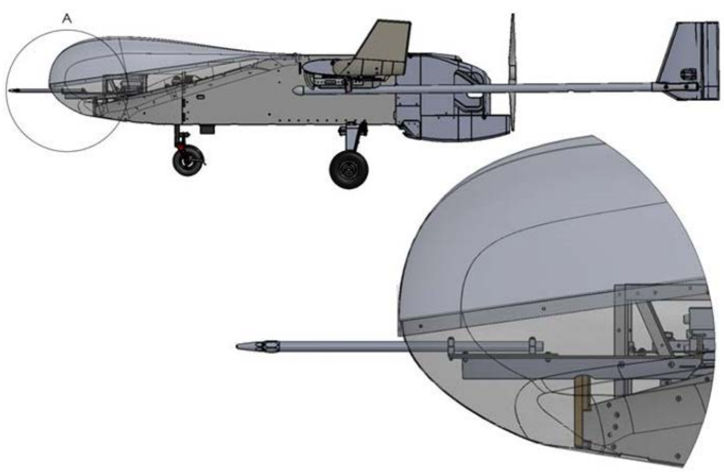

Figure 7. ArcticShark with nose inlet installed.

9.0 Software

The Brechtel unmanned aerial vehicle (UAV) reader software has been designed to allow multiple instruments to be connected simultaneously, and it controls the data logging and instrument performance monitoring at the same time. The UAV reader is installed on the DAQ computer aboard the ArcticShark and provides a graphical user interface (GUI) to view and monitor the STAP operation. Detailed information about the software and various instrument settings can be found in the manufacturer's STAP manual.

10.0 Calibration

Calibration procedures are similar to the ARM PSAP instrument. These include an initial measurement of spot size and regular calibrations of instrument aerosol flow rates.

11.0 Maintenance

Maintenance is minimal on this instrument. Filter changes (sample and reference) are done 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.

12.0 Safety

This unit has no safety concerns during regular operation.

13.0 Citable References

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* 30(6): 582–600, https://doi.org/10.1080/027868299304435

Lin, C-I, M Baker, and RJ Charlson. 1973. "Absorption coefficient of the atmospheric aerosol: a method for measurement." A*pplied Optics* 12(6): 1356–1363, https://doi.org/10.1364/AO.12.001356

Ogren, JA. 2010. "Comment on 'Calibration and intercomparison of filter-based measurements of visible light absorption by aerosols'." *Aerosol Science and Technology* 44(8): 589–591, https://doi.org/10.1080/02786826.2010.482111

Springston, SR. 2018. Particle Soot Absorption Photometer (PSAP) Instrument Handbook. U.S. Department of Energy. DOE/SC-ARM-TR-176.

STAP Brochure. https://www.brechtel.com/wp-content/uploads/2017/08/Brechtel_Model_9406_STAP_Brochure1.pdf Accessed 5 July, 2020.

STAP 9406 Instrument Manual Ver. 3.4. Brechtel. October, 2020.

www.arm.gov

U.S. DEPARTMENT OF ENERGY

Office of Science