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Single-Particle Soot Photometer (SP2) Instrument Handbook

AJ Sedlacek

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Office of Science, Office of Biological and Environmental Research

Acronyms and Abbreviations

ACME-V	ARM Airborne Carbon Measurements V Field Campaign
AI	analog input
cm	centimeter
DMA	differential mobility analyzer
DMT	Droplet Measurement Technologies (manufacturer of SP2)
DVM	digital volt meter
fg	Femtogram (10^{-9})
Fullerene soot	Calibration standard for the SP2 incandescence channel
Incandescence	laser-induced black body emission from rBC particle
Hz	hertz
K	Kelvin
Kg	kilogram
Nd:YAG	Neodymium-doped yttrium aluminium garnet—crystal used as a lasing medium
NIR	near-infrared
ng	nanograms
ng/m^3	mass concentration
nm	nanometers
ns	nanoseconds (10^{-9} s)
PSL	PolyStyrene Latex spheres—calibration standard for particle scattering
QC	Quality Control
QA	Quality Assurance
rBC	Refractory Black Carbon
s	seconds
SP2	single-particle soot photometer
TPXXX	Test Point XXX
U	1U = 1.75-inches
UTC	Universal Time Coordinate
V	volts
VAC	volts alternating current
VED	volume equivalent diameter—a void-free sphere

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1.0 Instrument Title

Single-particle soot photometer (SP2)

2.0 Mentor Contact Information

Dr. Arthur J. Sedlacek
Brookhaven National Laboratory
Biological, Environmental, and Climate Sciences Department
Phone: (631) 344-2404
Fax: (632) 344-2887
Email: sedlacek@bnl.gov

3.0 Vendor/Developer Contact Information

Dr. Greg Kok; SP2 Instrument Developer
Droplet Measurement Technologies
2545 Central Avenue
Boulder, CA 80301
Phone: (303) 440-5576
Fax: (303) 440-1965
Email: gkok@dropletmeasurement.com

4.0 Instrument Description

The SP2 is an instrument that measures, in situ, the time-dependent scattering and incandescence signals produced by individual BC-containing particles as they travel through a continuous-wave laser beam. Any particle traversing the laser beam will scatter light, and the BC component of a BC-containing particle will absorb some of the laser energy until its temperature is raised to the point at which it incandesces (hereafter we adopt the standard terminology of the SP2 community and denote any substance determined by the SP2 to be BC as refractory black carbon (rBC)). The amplitude of the rBC incandescence signal is related to the amount of refractory material contained in the illuminated particle. By binning the individual incandescence signals per unit sample volume, the mass concentration [ng/m3] of rBC can be derived. By binning the individual signals by volume equivalent diameter the size distribution (dN/dlogDVED) per unit time can be derived. The rBC mass loading per unit time and the rBC size distribution unit time are the core data products produced by the SP2.

Additionally, the scattering channel can be used to provide information on the rBC particle population-based mixing states within ambient aerosols. However, this data product is produced on a requested-basis since additional detailed analysis and QC/QA must be conducted.

5.0 Measurements Taken

The measurement taken by the SP2 instrument include the rBC mass loading (ng/m3) per unit time and volume equivalent size distribution (dN/dlogDVED).

6.0 Links to Definitions and Relevant Information

6.1 Data Object Description

During normal operation the SP2 saves a housekeeping file, a log file, an initialization file, and a *raw* data file.

The housekeeping file (YYYYMMDDhhmmss.hk) containing several data fields relevant to data reduction as well as data streams to monitor the health status of the instrument. The housekeeping file is only important to the SP2 mentor and as such is not provided as a user data product. The log file (YYYYMMDD.log) contains logged information such as when the housekeeping file was created, when an individual raw binary data file was opened and closed, and any error or warning messages produced by the SP2 during operation. The initialization file (YYYYMMDD.ini) contains various SP2 configuration settings necessary to start the SP2 in a known state. These three files are ofnlyvaluable to the SP2 mentor and are not distributed to the end user.

The *raw binary* data files contain the raw SP2 signals. These *raw* data files contain data from eight channels:

- High- and low-gain broadband incandescence channels (wavelength range: ~350-800 nm)
- High- and low-gain narrowband incandescence channels (wavelength range: ~630-800 nm)
- High- and low-gain scattering channels
- High- and low-gain split-detector channels. (used to determine particle position within the laser beam.).

The utility of the high- and low-gain datastreams for all channels is to increase the particle detection dynamic range of the SP2. Each individual channel is made up of 100 points of data with a time resolution of 400 ns/pt. The raw SP2 data are stored in a binary format with the following naming convention: YYYYMMDDhhmmss.sp2b. The broadband channel is the datastream that is used to convert the incandescence signal to rBC mass owing to the increased sensitivity afforded by the wider spectral range. The narrowband channel is used in combination with the broadband channel to filter out non-rBC incandescence signals (e.g., from dust, metals, or spurious signals). The scattering channels are self-explanatory. The split-detector channel is used to provide information on a given particle's location within the laser beam relative to the center of the Gaussian laser.

Once the data is collected, it is processed offline using the DMT-developed PAPI analysis program (Probe Analysis Program for Igor).

6.2 Data Plots

Examples of a data plot:

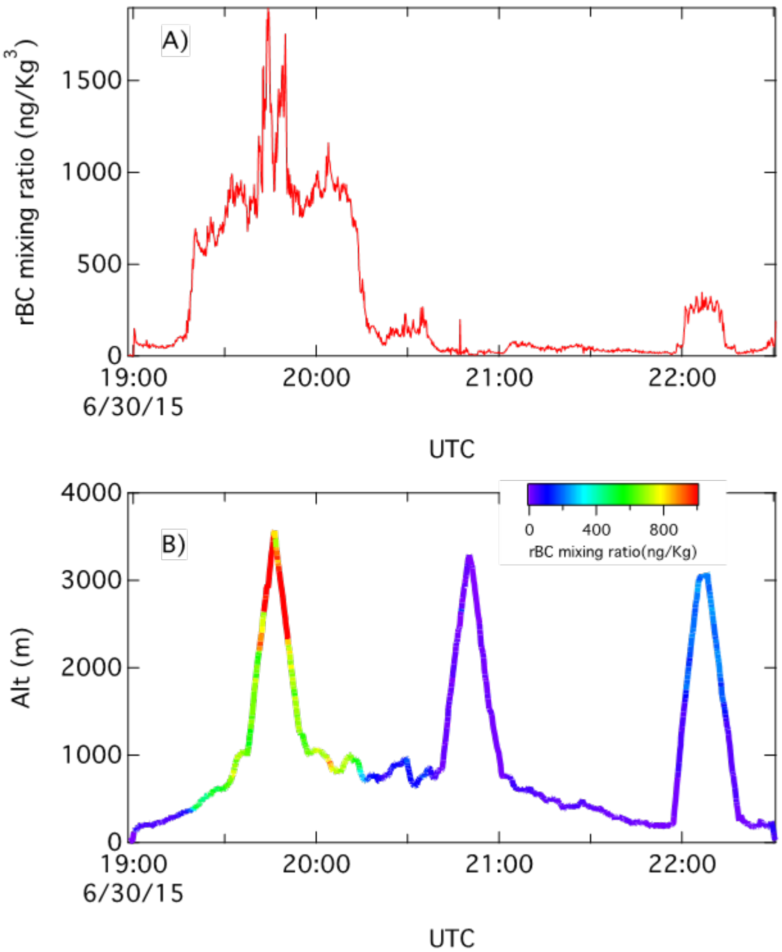

Figure 1. Top plot (A): the rBC mixing ratio time series measured during a flight conducted on June 30, 2015 as part of the ACME-V field campaign. Lower plot (B): the rBC mixing ratio as a function of aircraft altitude for the same flight.

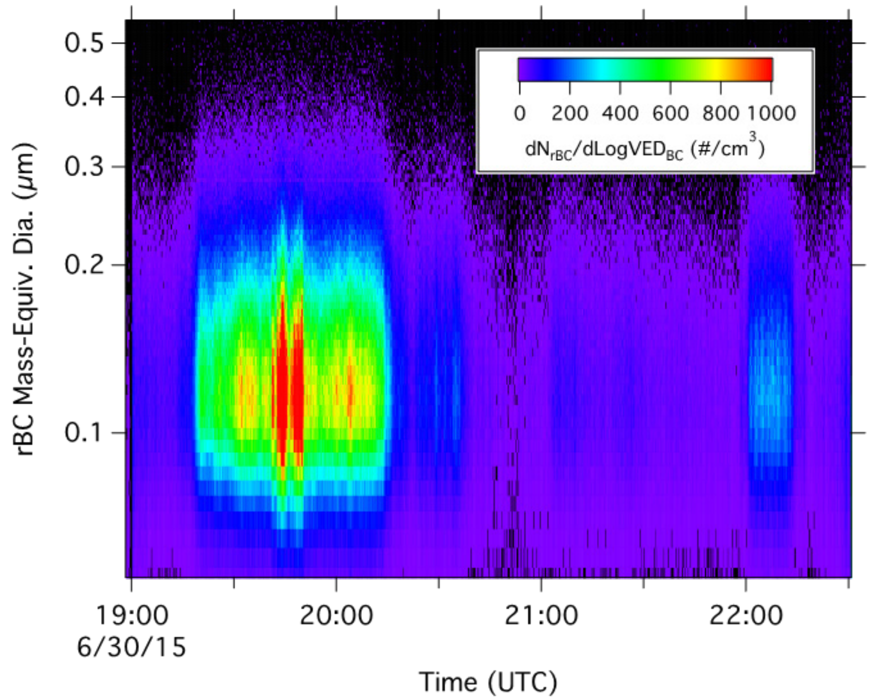

Figure 2. The rBC size distribution (dN/dLogD$_{VED}$) as a function of flight time for the ACME-V flight conducted on June 30, 2015.

6.3 Instrument Mentor Summary

Data is Quality-Controlled (QCd) by the mentor after an IOP-based field deployment before submission to the ARM Archive.

6.4 Calibration Data Base

The SP2 instrument requires incandescence and scattering calibrations. The incandescence calibration is accomplished using commercially available Fullerene soot and the scattering channel is calibrated using five different PSL standards. Figure 3 shows examples of the incandescence and scattering calibrations. See Section 12 for more details on the SP2 calibration procedure. Efforts are underway to transfer calibrations in the Operations Status System (OSS) database.

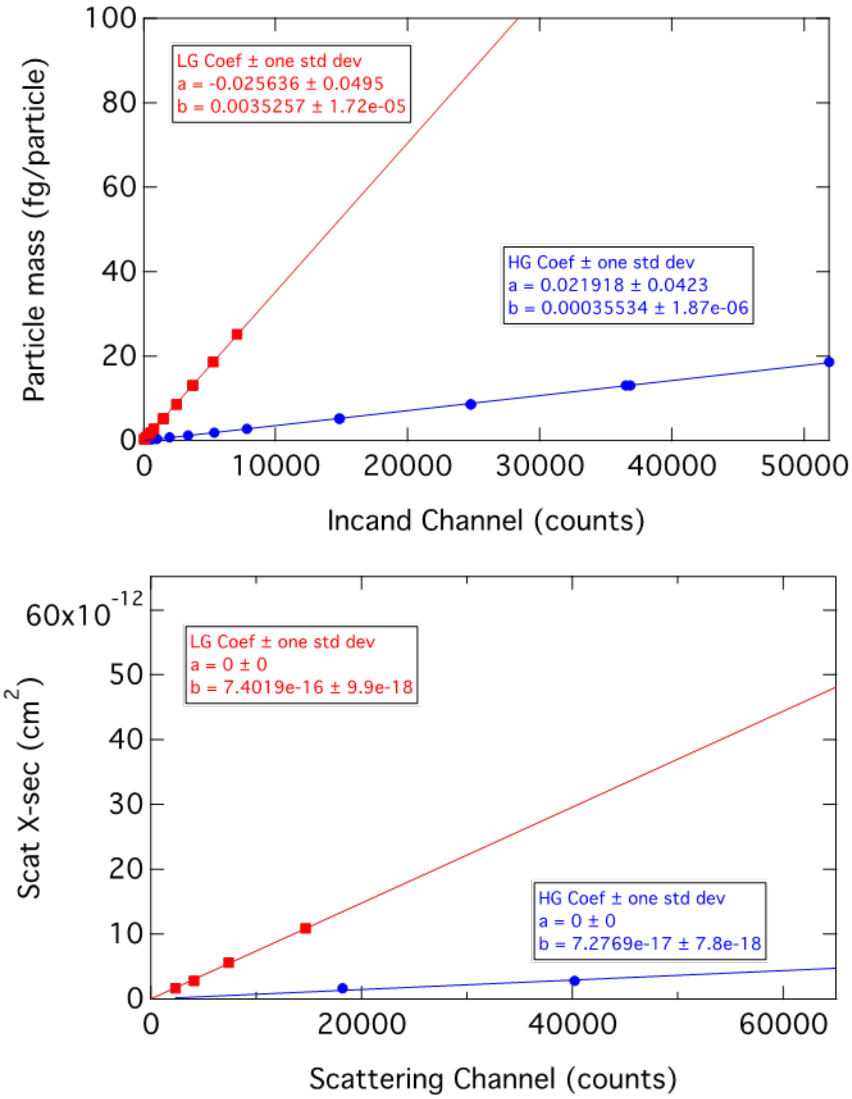

Figure 3. Examples of incandescence channel calibration (upper plots) and the scattering channel calibration (lower plot).

7.0 Technical Specification

7.1 Physical Specifications

Sample flow rate: 0.120 liters per minute (default; can be changed as necessary for loading conditions)

Purge flow: provided internally

Cell pressure: ambient

Power usage: ~ 300 watts (@120 VAC)

Weight: ~190 kg

Size: ~65 cm x 43 cm x 23 cm (length x width x height)

(19” rack mount, 5U, 24” deep)

Figure 4. Photos of single-particle soot photometer. The newer Revision “D” is shown on the left and the older Revision “C”—located in MAOS—is shown on the right.

7.2 Measurement Specifications

Measurement range: 1-12,500 particles/cc at 120 vccm (0 – 25,000 particles/sec; concentrations increases until particles become coincident)

Resolution: particle-resolved

Precision: < 20%

Time response: 10 seconds for aircraft-based deployments and 60-seconds for ground deployments.

Span drift: negligible

7.3 Range

Measurement range: 1-12,500 particles/cc at 120 vccm (0 – 25,000 particles/sec; concentrations increases until particles become coincident)

7.4 Accuracy

< 10%: Calibration dependent. Fullerene soot used (Laborde et al., 2012; Gysel et al., 2011)

7.5 Precision

30%; goes as $\sqrt{N}$, where N is the number of detected particles.

7.6 Sensitivity

10 ng/m^3

0.3 fg/particle

7.7 Uncertainty

~25% (May et al., 2014)

7.8 Input Voltage

~350 W; 100-250 VAC (50-60 Hz)

8.0 Instrument System Functional Diagram

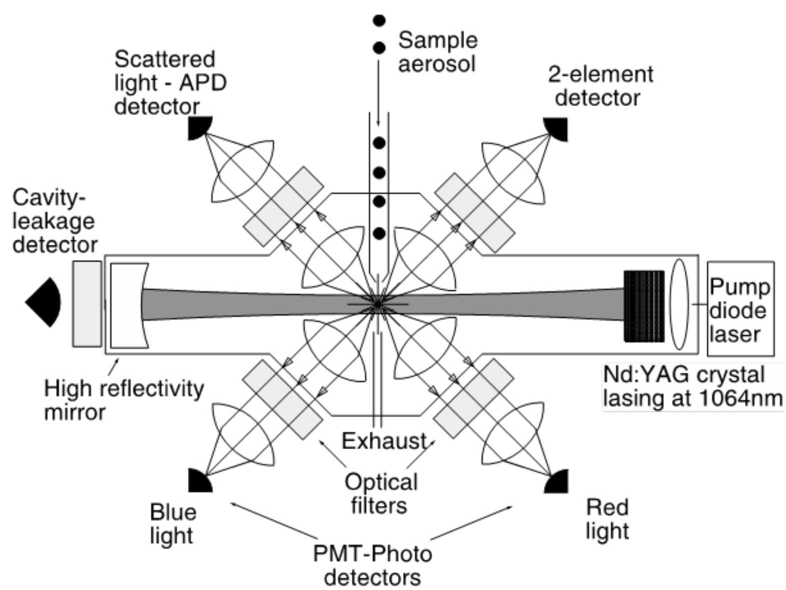

Figure 5. Schematic of the single-particle soot photometer (SP2). From Schwarz et al., 2006.

9.0 Instrument/Measurement Theory

The single-particle soot photometer (SP2) uses the high optical power available intra-cavity from an Nd:YAG laser. Light-absorbing particles, mainly black or elemental carbon in atmospheric measurements, absorb energy and are heated to the point of incandescence. The energy emitted in this incandescence is measured, and a quantitative determination of the black carbon mass of the particle is made. This mass measurement is independent of the particle mixing state, and hence the SP2 provides a reliable measure of the black carbon mass concentration. Since the SP2 detects single particles, the SP2 can also measure the black carbon number concentration.

All particles scatter light, regardless of whether or not they absorb light. A scattering detector is included in the SP2, which detects single-particle scattering at 1064 nm, and the scattering signal can be used to indicate the black carbon mixing state at the single-particle level. The scattering detector can also be used to detect non-BC-containing aerosol number and mass concentrations.

The SP2 measures the light scattering and/or incandescence of each particle. The full scattering and/or incandescence response of each particle is completely digitized for detailed analysis.

10.0 Set-Up and Operation of Instrument

10.1 Set-Up

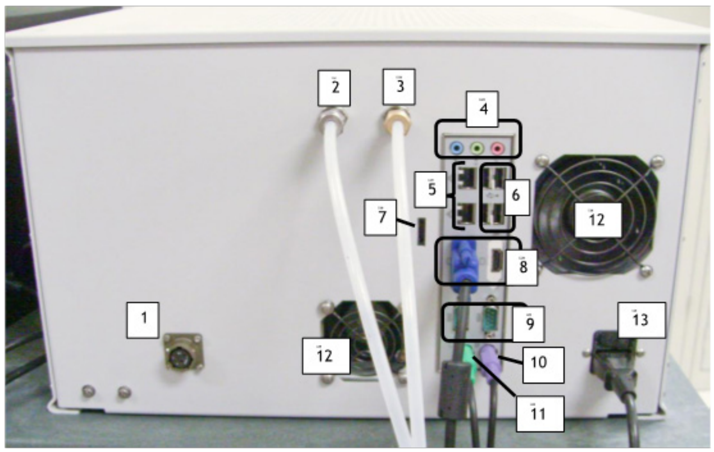

Figure 6. Rear panel of the SP2.

Table 1. Rear-panel components.

1	12 VDC pump power connection	8	Monitor ports (VGA on left, HDMI on right)
2	Purge flow	9	RS-232 serial port
3	Exhaust flow	10	Keyboard port
4	External speakers and microphone connections	11	Mouse port
5	Ethernet ports	12	Exhaust vents
6	USB 2.0 ports	13	System power connection
7	SATA port (external hard drive)		

To set up the SP2 purge and vacuum lines, follow the instructions below.

1. Using Poly tubing with 1⁄4” Swageloks, connect the exhaust port on the SP2 to the exhaust in-flow port on the SP2 pump (Figure 7).

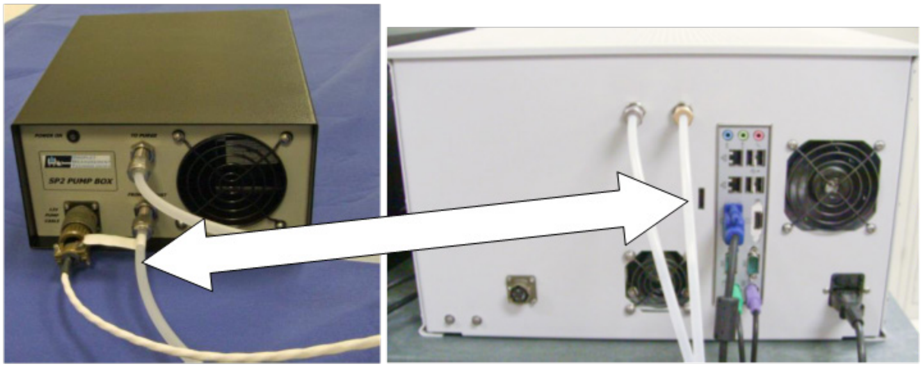

Figure 7. Connecting SP2 and SP2 pump exhaust valves.

2. If you want to connect a Drierite cartridge to the system, follow the steps below. (Both the Drierite and Nafion dryer are used to dry sheath and purge flow air in humid conditions.)
   a. Connect the Poly tubes exiting the SP2 purge port to the Drierite cartridge (Figure 8).

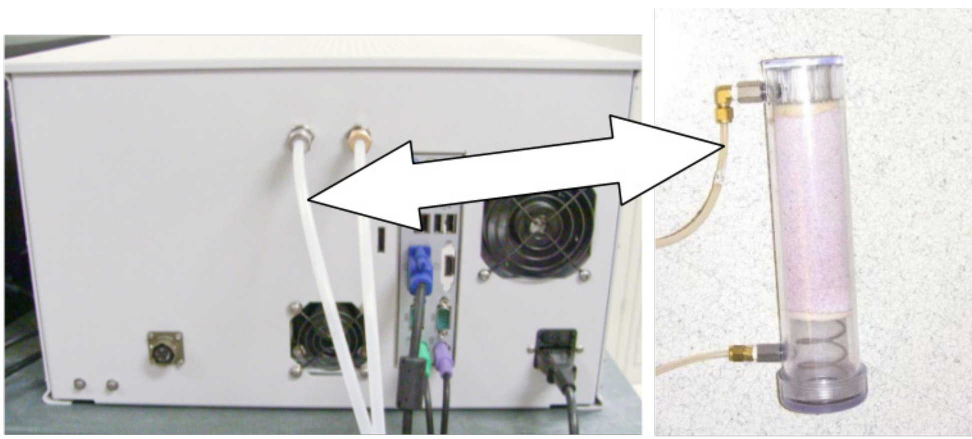

Figure 8. Connecting SP2 purge valve to DrieRite cartridge.

   b. Connect the Drierite cartridge to the out-flow purge port on the SP2 pump (Figure 9). The out-flow purge port is on the left side of the pump.

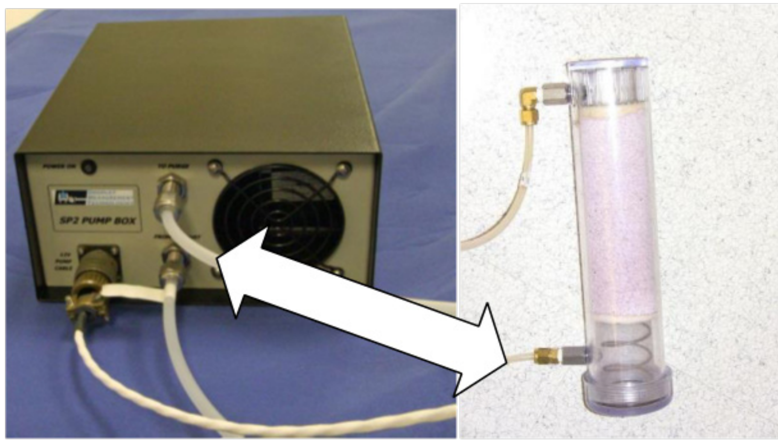

Figure 9. Connecting SP2 pump purge to DrieRite cartridge.

3. Plug in the power supplies for the SP2 and SP2 pump. The set-up is now complete.

10.2 Operation

The front panel of the SP2 instrument is devoid of any LED displays. Interaction with the SP2 must be conducted through the SP2 application software that is run on the Windows machine. The SP2 Application displays example signals from randomly chosen particles (e.g., high- and low-gain incandescence signals and high- and low-gain scattering signals) every second. In addition, the SP2 application displays a time series of the total number of raw incandescence and scattering signal counts every second. The units for the time series raw data signals are counts/cc.

To turn on the SP2, follow the instructions below.

1. Turn on the SP2 Computer using the Computer switch on the SP2.
2. Turn on the SP2 using the System Power switch on the SP2.[1]
3. Start the SP2 software by double-clicking on the SP2 icon on desktop.
4. In the software, go to **Config** tab and **Program** sub-tab.
5. Check to ensure *Config* File Being Viewed is set to the correct *Config* file. See Figure 10 for the location of this parameter. The name of the *Config* file may vary depending on your instrument. If the correct file is loaded, skip to step 10.

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[1] The SYSTEM POWER switch controls the power to the SP2 analyzer electronics, and is the master switch for the SAMPLE PUMP power. If SYSTEM POWER is off, the PUMP cannot be powered. The COMPUTER switch is independent of the other two switches, and turns only the computer on and off. For Revision “D” unit only.

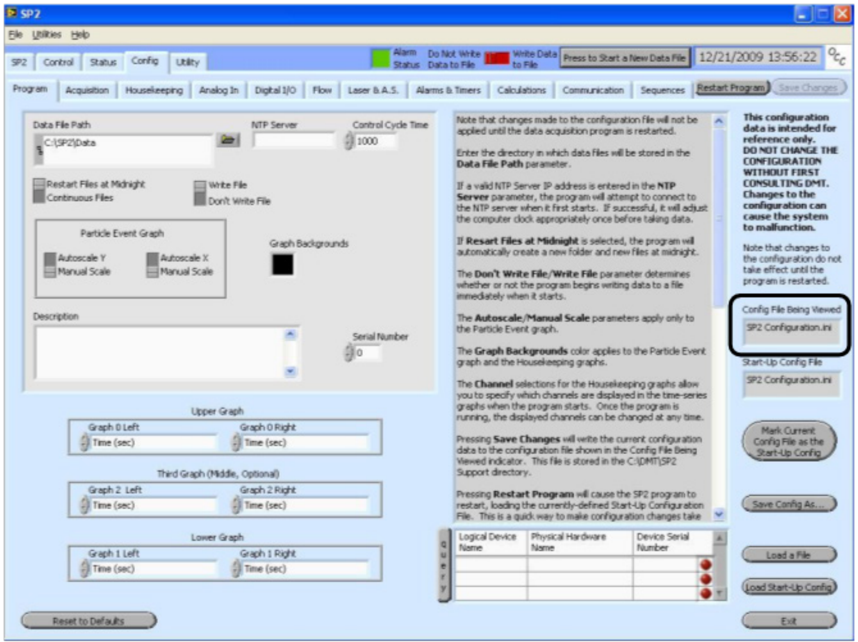


Figure 10. Verifying the *Config* File on the **Config** Tab.

6. If a different file is listed, press the Load a File button (Figure 11). Navigate to the directory `C:\DMT\SP2 Support`. Select the correct file and click OK.

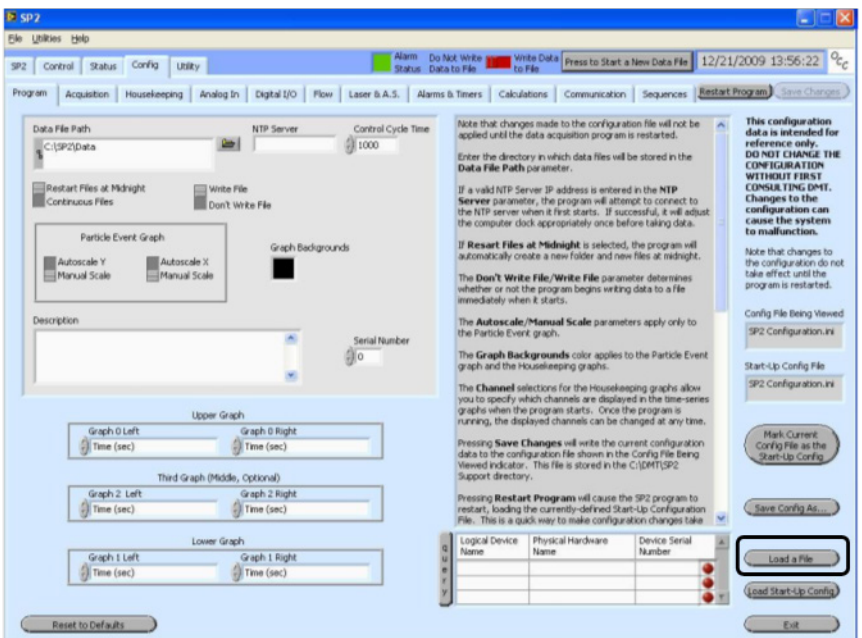


Figure 11. Loading a New Configuration File.

7. Click on the **Control** tab in the SP2 software. Move the Sample Pump Power Switch to ON (Figure 12). You will hear noise as the pump starts up.

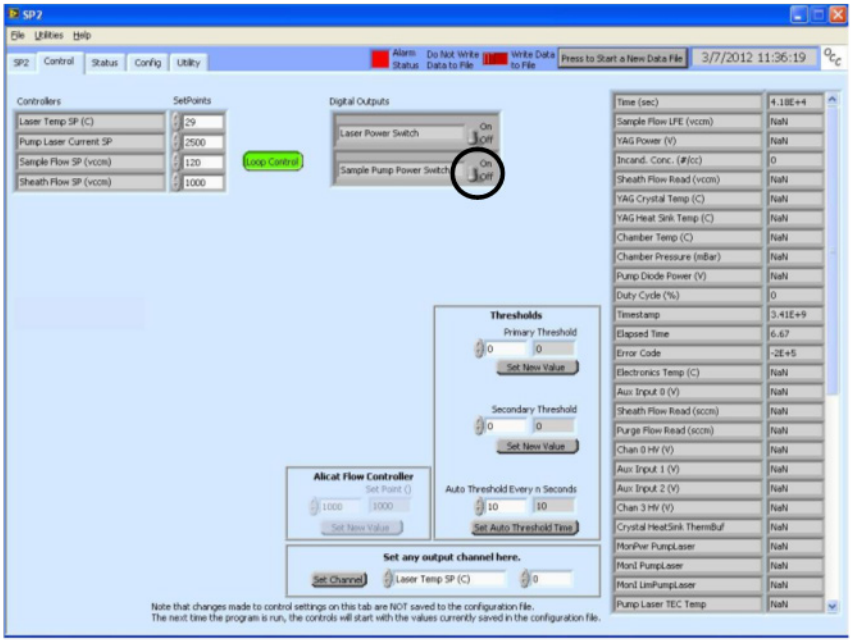


Figure 12. Sample Pump Power Switch.

8. Go to the **SP2** tab on software. Wait until the flow has stabilized. Sample Flow LFE should be approximately 120 vccm (Figure 13).

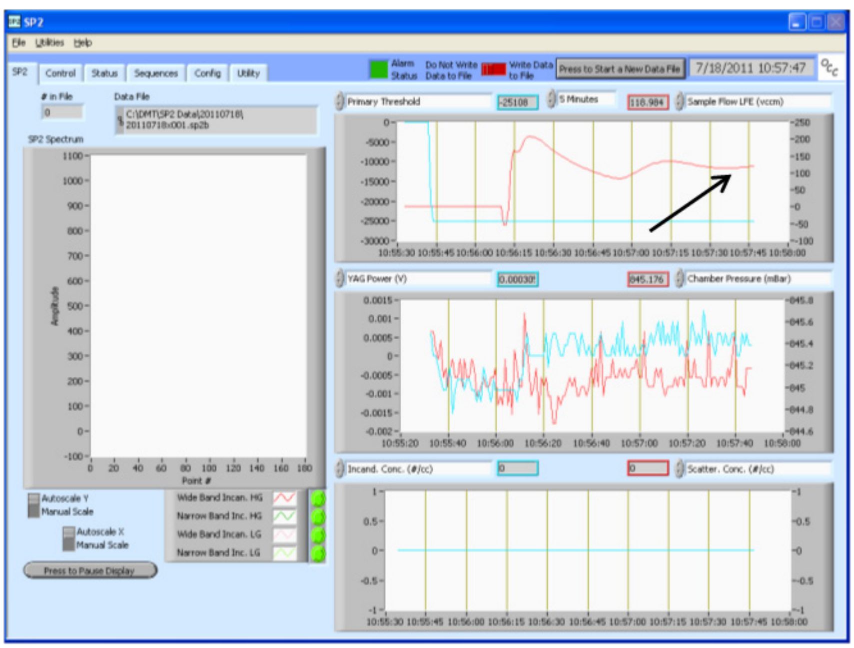


Figure 13. Sample flow stabilizing.

9. Click on the **Control** tab in the SP2 software (Figure 14). Move the Laser Power Switch to ON.

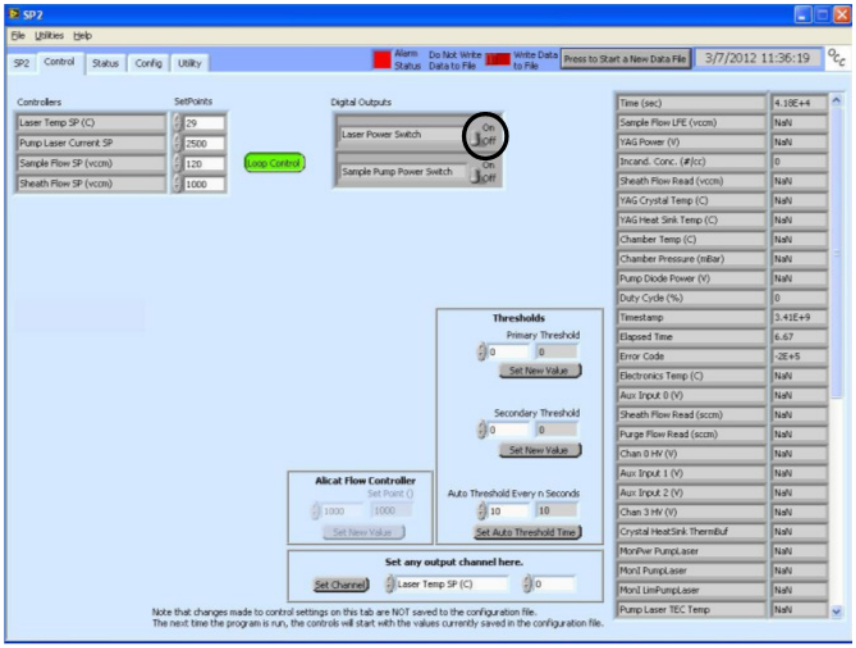


Figure 14. Turning on the laser from the Control Tab.

10. Go to the **SP2** tab in the software and verify the particle response (Figure 15).

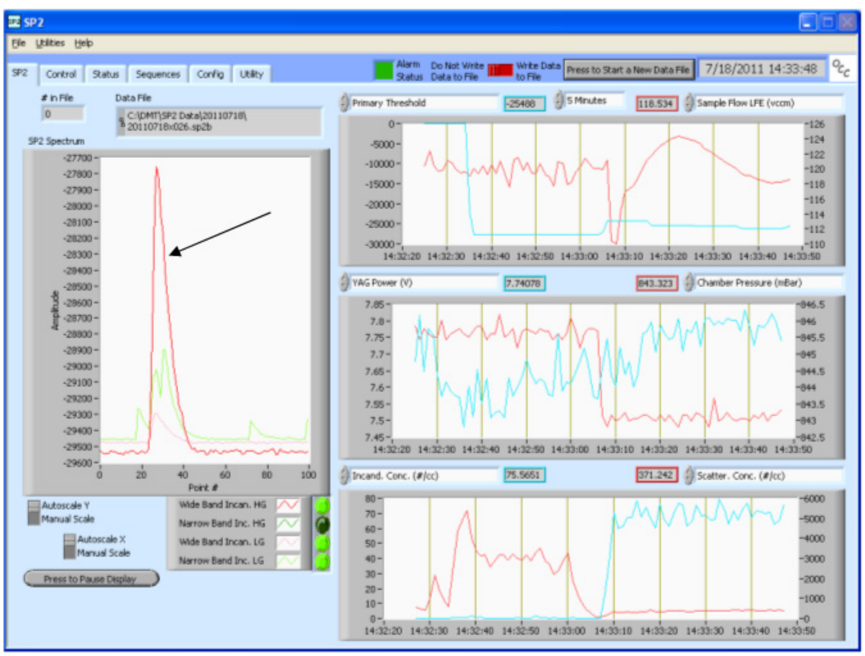


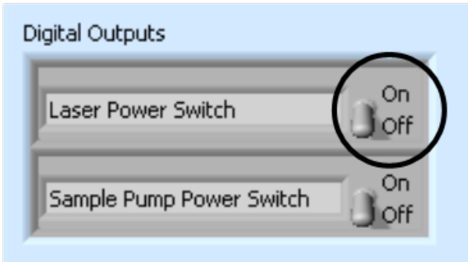
Figure 15. Verifying particle response.

11. Proceed with sampling and data recording. For details, see DOC-0092, the SP2 Software Manual.

To turn off the SP2, follow the instructions below.

1. On the SP2 software's **Control** tab, set the Laser Power Switch to Off (Figure 15). **WARNING:**

Laser Power MUST be turned OFF before the pump is turned off.



2. Turn off the Sample Pump switch on the SP2.
3. Shut down the SP2 software by selecting File > Exit.
4. Turn off the SP2 using the System Power switch on the SP2.
5. Turn off the SP2 Computer using the Computer switch on the SP2.

11.0 Software

See Section 10.2 on software control of the SP2 instrument.

12.0 Calibration

The instrument is routinely calibrated at the beginning, during, and at the end of a field campaign. If the campaign or deployment is longer than 12 months, the instrument is calibrated approximately every 6 months. While the manufacturer recommends Aguadag as the calibration material for the SP2, ARM uses fullerene soot. Fullerene soot is preferred because particle morphology more closely mimics that of ambient BC. However, in order to use Fullerene soot, it is necessary to know the particle density as a function of mobility size so that a good estimate of the actual particle mass can be derived. At this time there are no known mono-dispersed black carbon particles available for calibration of the SP2.

12.1 Required Equipment

Aerosol generator and an aerosol classifier that will provide particles in the 50-500 nm size range.

12.2 Calibration Procedure

To calibrate the instrument, follow the steps below. Figure 15 shows the typical set-up for the SP2 calibration using a DMA.

1. Start the SP2 and the DMA. Take approximately 10 data points, with nominal particle size between 80 nm and 500 nm. Generally two data files are taken at each setting.
2. Shut off the DMA and the SP2.
3. Process the data files and analyze the histograms generated for each of the particle sizes. Depending on the DMA used, several peaks with particles of charge 1, 2, 3, and on up can be seen. To avoid

confusion, we recommend that the first data analysis be conducted with mid-range-size particles, as the charge 1 aerosols will be seen clearly.

4. Calculate the particle mass for the each of the particle sizes and plot particle mass versus maximum peak height. This should be a polynomial function. The parameters of this function will form the calibration of the SP2. See the Probe Analysis Package for Igor (PAPI) Manual (DOC-0232) or contact DMT for details.

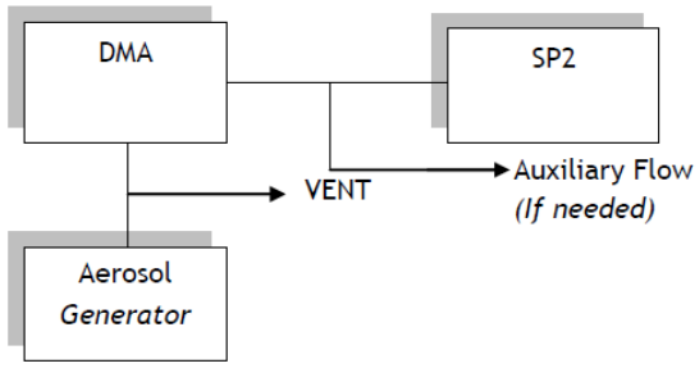


Figure 16. Schematic diagram for SP2 Calibration with DMA.

13.0 Maintenance

The only routine maintenance that the SP2 requires is to periodically refresh or replace the desiccant in the drying cartridge on the purge line. If the desiccant becomes saturated and the SP2 is operated in a very humid environment, condensation could build up in the purge line and possibly contaminate the flow controllers, which can cause them to fail.

An occasional particle zero check is also recommended; this is done by placing a HEPA or other high-efficiency filter on the SP2 inlet. After a few minutes, the instrument should record an occasional particle, but effectively the particle concentration measurement should be zero. If not, contact DMT for support.

If the SP2 is operated in a highly particle-laden environment, it may be necessary to check the calibration of the laminar flow element (LFE) on the sample inlet.

13.1 SP2-D: Procedure to Calibrate the Laminar Flow Element

1. Disconnect the proportional valve by unplugging the control board's J16 connector.
2. Connect a DVM to TPL22 (Ashcroft) and to the ground test point, TPL17 (GND).
3. Connect a bubble flow meter or volume-displacement flow meter to the sample inlet line on the SP2.
4. Start the SP2 data system, software, analyzer chassis power and sample pump—DO NOT START THE YAG LASER!
5. Take a series of readings with the bubble flow meter, over the range of 30-200 cc/min nominally. For each of these readings, record the voltage shown on the DVM (for best accuracy, average together 3-5

readings at each setting). Change the flow by manually adjusting the needle valve, which is in parallel with the proportional valve.

6. With this data, make a linear regression, with the flow rate on the Y-axis and the voltage on the X-axis. This should be very linear, with a slope of about 90 (+/-20) and an intercept close to zero (+/-5).
7. In the SP2 software, click the **Config** tab and the **Analog** In sub-tab. (This may require a password.) In the **AI Channels** table, find the **Offset** and **Linear** parameters for **Sample Flow**. These should read -1.1819 and 110.3629, respectively. Insert the value for intercept in the Offset field and the value for slope in the in the **Linear** field.
8. Shut down the SP2 sample pump, data software, and the analyzer chassis.
9. Reconnect the proportional valve cable at J16.

13.2 Procedure for Alignment of the YAG Laser

For complete instructions on aligning the laser, see DMT DOC-0229: SP2 Laser Alignment Manual.

13.3 Cleaning the Laser Optics

The optics used in the SP2 have reflectivity of 99.97% or better, and it is very difficult to clean them without damage or further contamination. If the laser power drops and it cannot be recovered by a minor alignment, and other parameters such as the pump laser power are verified, it is worth trying to clean the optics to recover laser power. Most likely the contamination will be on the surface of the coupler and this should be cleaned first. A full alignment system will be required to replace the coupler and get the YAG laser operational. It is also recommended that a replacement coupler be available; if the unit cannot be cleaned, it will need to be replaced. A separate manual, DOC-0229, gives information about optical cleaning and alignment of the YAG laser.

14.0 Citable References

Baumgardner, D, G Kok, and G Raga.2004. "Warming of the Arctic lower stratosphere by light absorbing particles." *Geophysical Research Letters* 31(6): L06117, doi:10.1029/2003GL018883, 2004.

Gao, RS, JP Schwartz, KK Kelly, DW Fahey, LA Watts, TL Thompson, JR Spackman, JG Slowik, ES Cross, J-H Han, P Davidovits, TB Onasch, and DR Worsnop. 2007. "A novel method for estimating light-scattering properties of soot aerosols using a modified Single-Particle Soot Photometer." *Aerosol Science and Technology* 41(2): 125-135, doi:10.1080/02786820601118398.

Gysel, M, M Laborde, JS Olfert, R Subramanian, and AJ Grohn. 2011. "Effective density of Aquadag and fullerene soot black car-bon reference materials used for SP2 calibration." *Atmospheric Measurement Techniques* 4(12): 2851-2858, doi:10.5194/amt-4-2851-2011.

Laborde, M, M Schnaiter, C Linke, H Saathoff, K-H Naumann, O Mohler, S Berlenz, U Wagner, JW Taylor, D Liu, M Flynn, JD Allan, H Coe, K Heimerl, F Dahlkotter, B Weinzierl, AG Wollny, M Zanatta, J Cozic, P Laj, R Hitzenberger, JP Schwarz, and M Gysel. 2012. "Single Particle Soot Photometer intercomparison at the AIDA chamber." Atmospheric Measurement Techniques 5(12): 3077-3097, doi:10.5194/amt-5-3077-2012.

May, AA, GR McMeeking, T Lee, JW Taylor, JS Craven, I Burling, AP Sullivan, S Akagi, JL Collett Jr., M Flynn, H. Coe, SP Urbanski, JH Seinfeld, RJ Yokelson, and SM Kreidenweis. 2014. "Aerosol emissions from prescribed fires in the United States: A synthesis of laboratory and aircraft measurements." *Journal of Geophysical Research - Atmospheres* 119(20): 11,826-11,849, doi:10.1002/2014JD021848.

Moteki, N, and Y Kondo. 2007. "Effects of mixing state on black carbon measurements by laser-induced incandescence." *Aerosol Science and Technology* 41(4): 398-417, doi:10.1080/02786820701199728.

Schwarz, JP, JR Spackman, RS Gao, AE Perring, E Cross, TB Onasch, A Ahern, W Wrobel, P Davidovits, J Olfert, MK Dubey, C Massoleni, and DW Fahey. 2010. "The detection efficiency of the Single Particle Soot Photometer." *Aerosol Science and Technology* 44(8): 612-628, doi:10.1080/02786826.2010.481298.

Schwarz, JP, RS Goa, DW Fahey, DS Thomson, LA Watts, JC Wilson, JM Reeves, M Darbeheshti, DG Baumgardner, GL Kok, SH Chung, M. Schulz, J Hendricks, A Lauer, B Kärcher, JG Slowik, KH Rosenlof, TL Thompson, AO Langford, M Loewenstein, and KC Aikin. 2006. "Single-particle measurements of midlatitude black carbon and light-scattering aerosols from the boundary layer to the lower stratosphere." *Journal of Geophysical Research – Atmospheres* 111: D16207, doi:10.1029/2006JD007076.

Schwarz, JP, AE Perring, MZ Markovic, RS Gao, S Ohata, J Langridge, D Law, R McLaughlin, and DW Fahey. 2015. "Technique and theoretical approach for quantifying the hygroscopicity of black-carbon-containing aerosol using a single particle soot photometer." *Journal of Aerosol Science* 81: 110-126, doi:10.1016/j.jaerosci.2014.11.009.

Sedlacek, AJ, ER Lewis, L Kleinman, J Xu, and Q Zhang. 2012. "Determination of and evidence for non-core-shell structure of particles containing black carbon using the Single-Particle Soot Photometer (SP2)." *Geophysical Research Letters* 39(6), doi:10.1029/2012GL050905.

Sedlacek, A, ER Lewis, TB Onasch, AT Lambe, and P Davidovits. 2015. "Investigation of refractory black carbon-containing particle morphologies using the Single-Particle Soot Photometer (SP2)." *Aerosol Science and Technology* 49: 872-885, doi:10.1080/02786826.2015.1074978.

Stephens, M, N Turner, and J Sandberg. 2003. "Particle identification by laser-induced incandescence in a solid-state laser cavity." *Applied Optics* 42(19): 3726-3736, doi.10.1364/AO.42.003726.

Subramanian, R, GL Kok, D Baumgardner, A Clarke, Y Shinozuka, TL Campos, CG Heizer, BB Stephens, B de Foy, PB Voss, and RA Zaveri. 2010. "Black carbon over Mexico: the effect of atmospheric transport on mixing state, mass absorption cross-section, and BC/CO ratios." *Atmospheric Chemistry and Physics* 10(1): 219-237, doi:10/5194/acp-10-209-2010.

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