PA660 Instrument Manual

Diesel Particulate Matter Photoacoustic Instrument
University of Nevada, Reno

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Instrument Description

PA660 is designed to measure and monitor the concentration of diesel particulate matter (DPM) and other aerosol through light absorption due to the photoacoustic effect. The instrument utilizes a 660 nm laser as the source for light absorption. Essentially, in this photoacoustic instrument light-absorbing aerosol will heat up when illuminated, creating a pressure or acoustic wave that can be measured with a microphone. This microphone signal in combination with laser power can be used to determine the absorption coefficient of an air sample. The absorption coefficient can then be used to determine DPM concentration.

PA660 also measures the scattering coefficient of an air sample, which can provide insight about the composition of the sample aerosol. The absorption and scattering coefficient measurements in conjunction with a measurement of phase can provide insight about particle size.

The instrument operates using a Teensy 3.6 microcontroller programmed with Arduino in combination with the instrument software National Instruments LabVIEW for monitoring. LabVIEW can be used for monitoring on any laptop with USB ports and the capability to download the appropriate version of LabVIEW.

Instrument Components

Images of the instrument are shown in Figure 1-Figure 4. The operations of the photoacoustic instrument include the use of electrical, optical, and aerosol handling equipment as described in detail below.

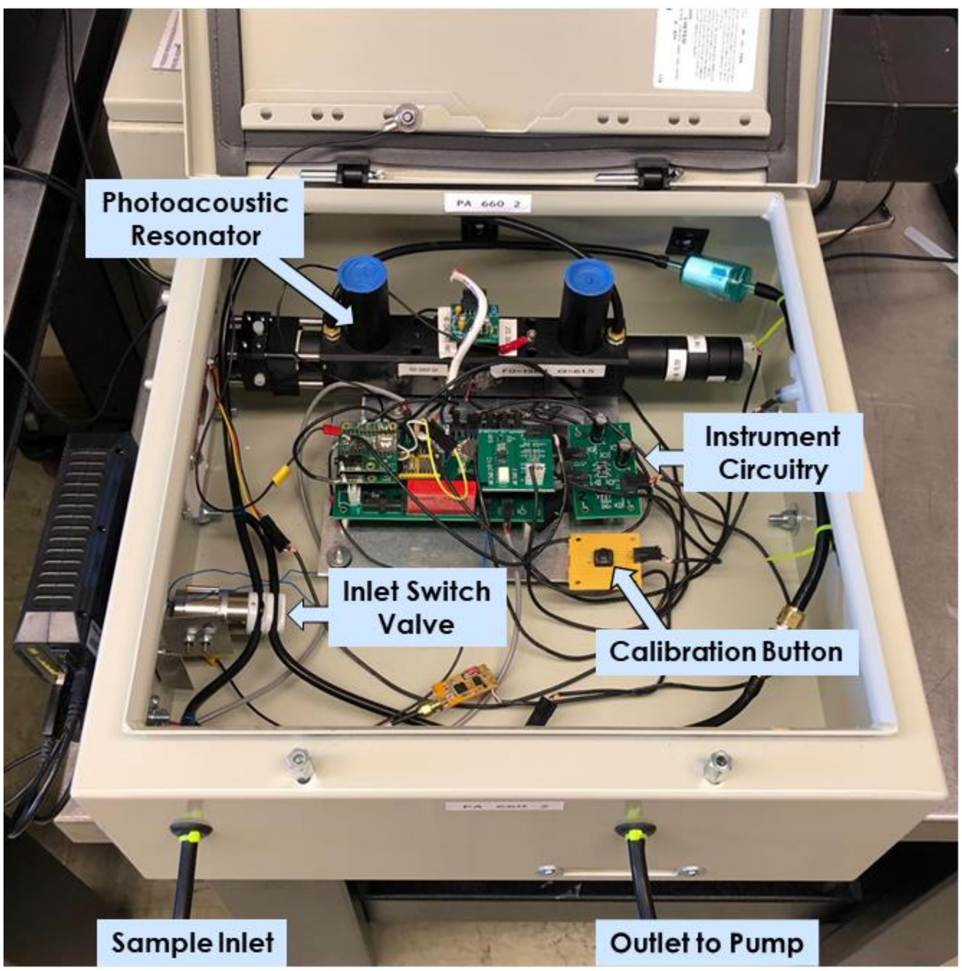


Figure 1. Photograph of the inside of the PA660 enclosure with its main components labeled.

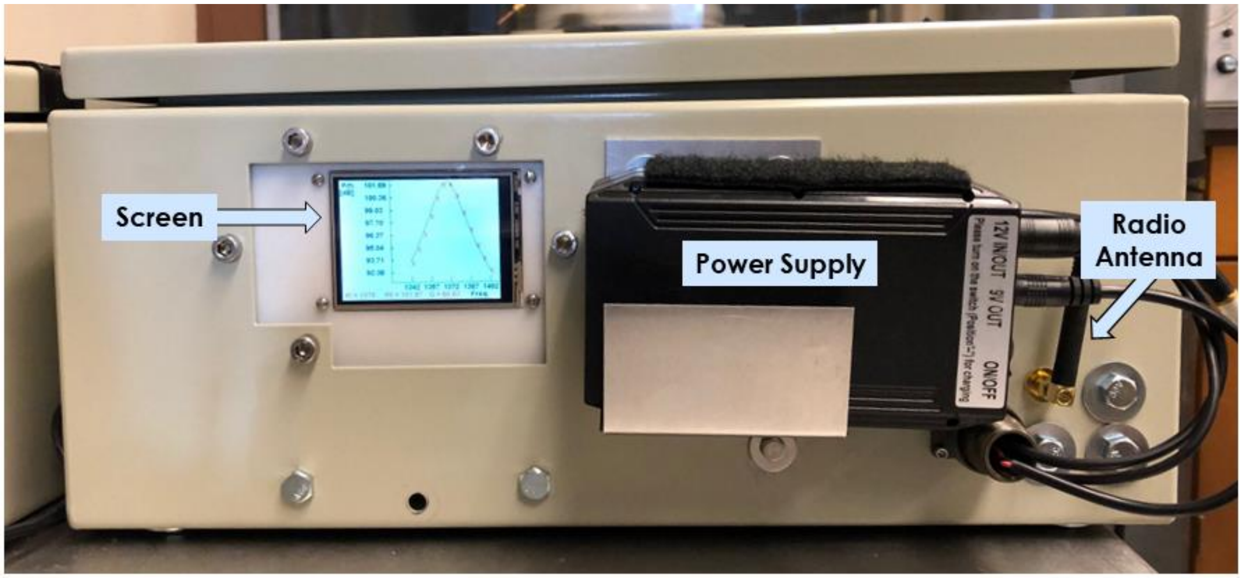


Figure 2. Photograph of the side of the PA660 enclosure with its main components labeled.

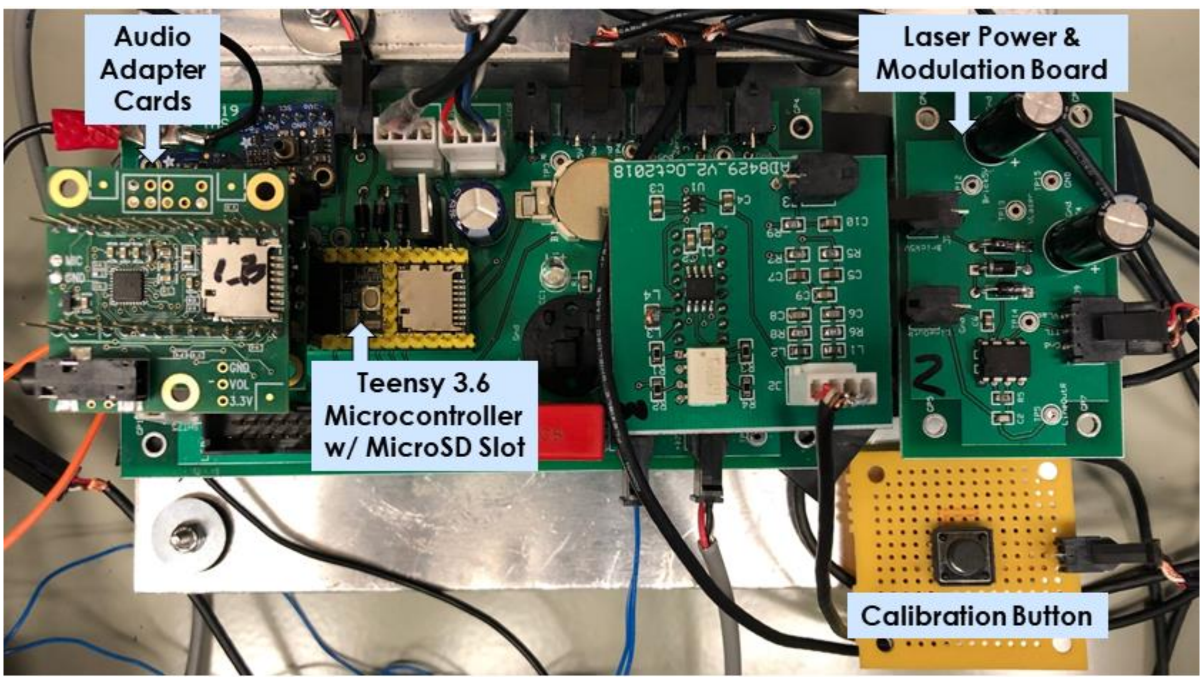


Figure 3. Photograph of PA660 circuitry with its main components labeled

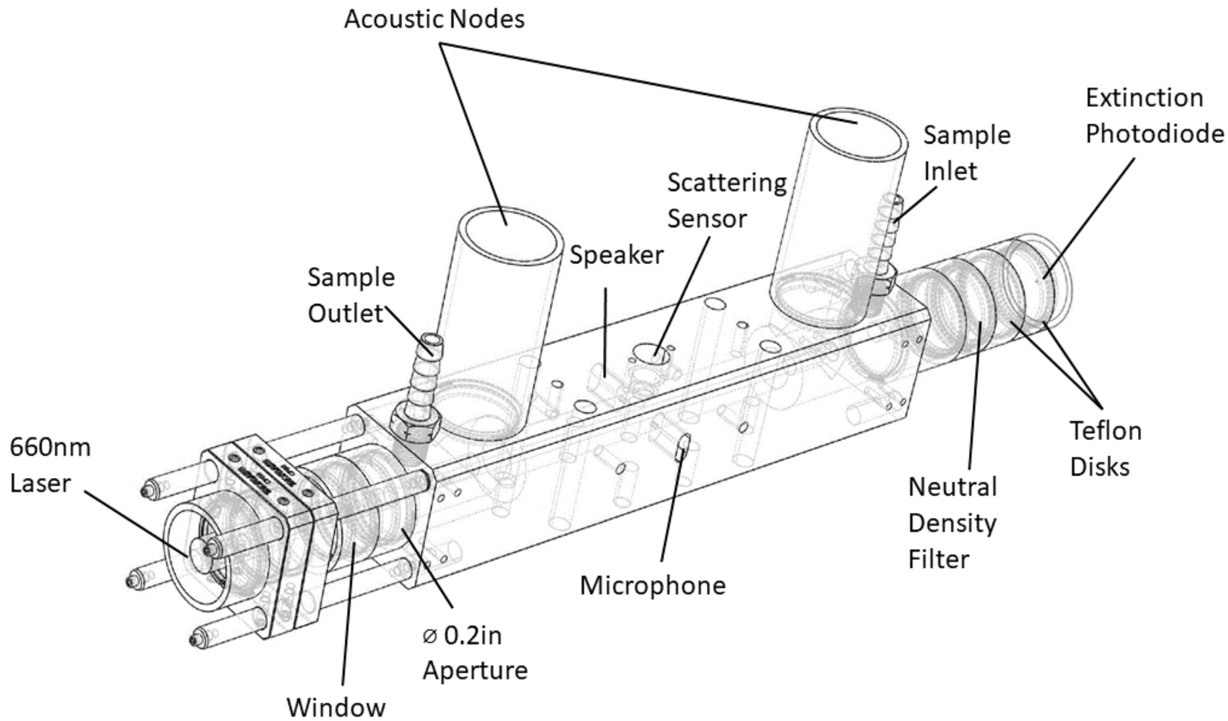


Figure 4. Diagram of PA660 acoustic resonator and optical components.

Electrical

The main electrical equipment utilized in PA660 includes:

- Teensy 3.6 microcontroller
    - The microcontroller is programmable and is used to calibrate and zero the instrument, to acquire and save data, and to perform calculations and data analysis on acquired data to determine concentration of diesel particulate matter in real time. The microcontroller communicates via radio to a LabVIEW program where the data is additionally saved and monitored.
- Rechargeable DC power supply
    - The rechargeable power supply can output 12V, 9V, and 5V and is responsible for powering everything onboard the instrument.
- 2 PJRC audio adaptor boards
    - The audio adaptor boards perform lock-in amplification to reduce noise on measured microphone, speaker, and extinction photodiode signals.

- Microphone
  - The microphone is used to measure the acoustic wave produced through the photoacoustic effect when aerosol light absorption occurs.
- Speaker
  - The speaker is used to calibrate the instrument. Calibration involves determining the resonance frequency (f_0), microphone pressure at resonance (P_0), and quality factor (Q) of the resonator for use in absorption coefficient measurements and for setting the lock-in amplification frequency.
- Pressure, temperature, and relative humidity (RH) sensors
  - These sensors are used to monitor pressure, temperature and RH during each measurement. The temperature sensor is particularly useful in estimating the initial resonance frequency used in calibration. The temperature is also monitored to determine if re-calibration is needed during instrument operation due to the temperature dependence of f_0 and Q.

Optical

The main optical equipment utilized in PA660 includes:

- 660 nm laser dot module
  - The laser module is used as the source for light absorption and is modulated at the resonance frequency with a square wave.
- AR coated window
  - The AR-coated window is located just after the laser inside an SM tube. The window hermetically seals the resonator and the anti-reflective coating reduces backscattering.
- Ø 0.2in aperture
  - The aperture is located on the laser side of the resonator directly following the window. It is used to reduce the scattering background in the resonator and to align the laser.
- Extinction photodiode
  - The extinction photodiode located directly across the resonator from the laser measures the portion of light not absorbed or scattered by the sample aerosol.
- ND filter
  - The neutral density filter is used to reduce the intensity of the laser light entering into the power meter.

- Teflon disks
  - The Teflon disks are also used to diffuse the laser light entering into the extinction photodiode.
- Scattering detector
  - The scattering detector is a photodiode located in the middle of the resonator, oriented perpendicular to the laser beam.

Aerosol Handling

The main aerosol-handling equipment utilized in PA660 includes:

- External AC vacuum pump
  - The pump is used for bringing sample air into PA660.
- Critical orifice
  - The critical orifice is located just upstream from the pump and is used to prevent pump noise from travelling back into the resonator.
- Inlet switching valve
  - The inlet switch valve is used during zeroing and allows the instrument to switch between sample and filtered air. The valve is located before the sample inlet to the resonator.

Operating the Instrument

Starting the Instrument

1. Ensure pump is connected to instrument outlet. Turn the external pump on.

2. Insert a micro SD card into the SD card slot located on the Teensy 3.6 microcontroller shown in Figure 3. There are additional SD card slots on each audio adapter card, however these are not programmed to save data so make sure you do not place the SD card in these slots.

3. Insert radio into a USB port on the computer. Ensure the radio antennae on the computer and the instrument are pointed in the same direction. If antennae are not aligned, LabVIEW may not receive any data.

4. Open LabVIEW program entitled “PA660_4_19_19.vi” (or most recent version) on computer. An image of LabVIEW is shown in Figure 5.

5. Under ***VISA resource name***, select the USB port to which the radio is connected. ex: COM1.

6. Under ***FILE NAME Babs Data***, choose a name for the file to which the instrument saves.

7. Ensure the ***SAVE DATA*** switch is set to ***YES***.

8. Click the ***Run*** button (a white arrow at the top right) to start the LabVIEW program. The program is now ready to receive data from the instrument.

9. Turn on the power supply on the instrument. The instrument is now on and will begin calibration.

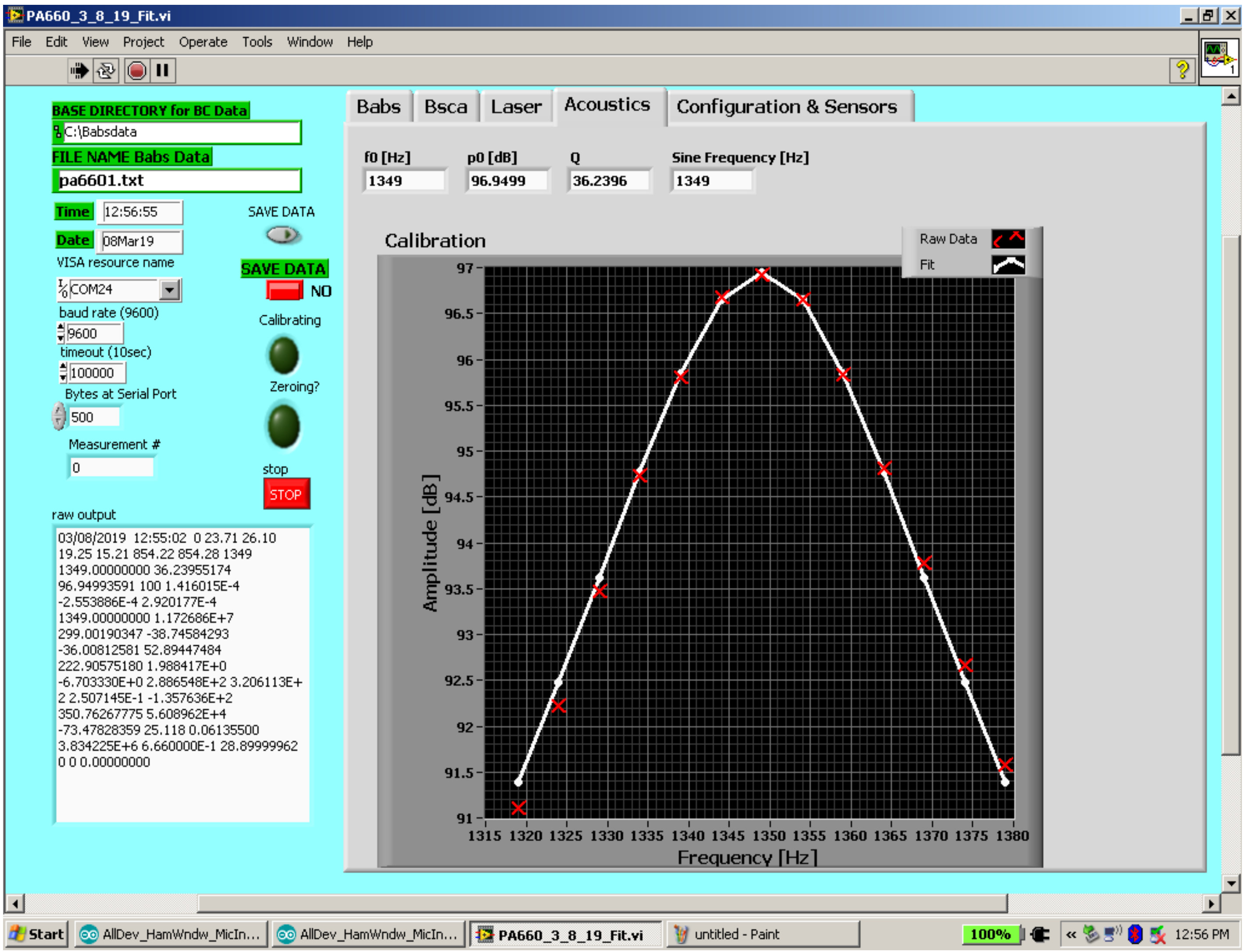


Figure 5. Screenshot of LabVIEW program to monitor and acquire data for PA660. The calibration resonance curve is displayed under the acoustics tab.

Monitoring Operation

Most instrument operations are programmed into the instrument's microcontroller. At power up, the instrument will automatically begin to conduct calibration, zeroing, and measurements. The operations currently being performed by the instrument are displayed on its screen. Measurements of absorption, scattering, laser power, etc. can be monitored on the following different tabs of the LabVIEW program:

- **Babs:** aerosol light absorption coefficient using the photoacoustic method
- **Bsca:** aerosol light scattering coefficient using the scattering sensor
- **Laser:** laser power as measured by the photodiode, as well as the laser phase and the net phase (microphone phase - laser phase)
- **Acoustics:** resonance curve collected during acoustic calibration
- **Configuration & Sensors:** calibration factors determined empirically, and on-board sensor data

Acoustic Calibration and Zeroing

Acoustic calibration and zeroing occur in the beginning of instrument operation and will be repeated after every 400 measurements. If additional calibration or zeroing is needed, the manual calibration button shown in Figure 3 can be pushed. The button may need to be held down for as long as 1 second. The button will initiate calibration followed by zeroing. Some reasons to recalibrate or zero the instrument may be:

- Drifting in Babs or Bsca measurements
- Suspiciously high Babs or Bsca background values
- Poor estimation of resonance curve fit or acoustic calibration values (acoustics tab)
    - Generally, f_0 = 1300-1400 Hz and Q = 38-60
    - If raw data acquired during acoustic calibration does not resemble a parabola

Stopping the Instrument

1. Power off the instrument by turning off its power supply.
2. Turn off pump.
3. Press the ***Abort Execution*** button (stop sign at the top right) or the rectangular ***Stop*** button to stop the LabVIEW program. Data is stored in the directory shown in the

program (C:\Babsdata by default). Data is also stored by the microcontroller into the on-board SD card.

Maintenance and Sensor Calibration

General Instrument Maintenance

1. The rechargeable power supply lasts approximately 10 hours during complete instrument operation, so it will need to be recharged after each day of use. There is a separate power supply that is used for the pump which will also need to be recharged each day.
2. After each use, data saved to the SD card should be duplicated and saved to a computer. Additionally, the user should ensure there is an adequate amount of memory available on the SD card for future data collection.

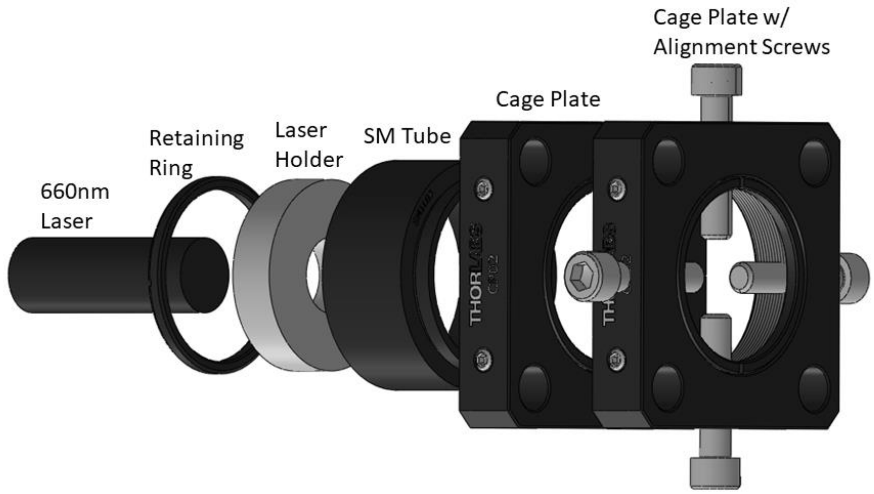
Instrument Sensor Calibration

If the laser is replaced or re-aligned, the scattering, absorption, and laser power measurements all need to be recalibrated. It is important that each of these are calibrated in the following order:

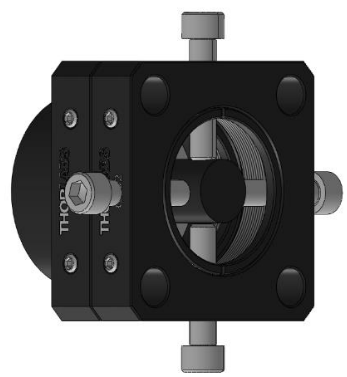
1. Laser Power
2. Scattering Coefficient
3. Absorption Coefficient

Laser Power Calibration

Each time the instrument's laser undergoes re-alignment or replacement it should be calibrated with a power meter. The process for alignment and laser calibration is as follows:



a)



b)

Figure 6. Laser setup with laser holder, SM tube, cage plates and alignment screws a) deconstructed for clarity and b) fully assembled.

1. In PA660's Arduino code, set the laser calibration factor "mVoltstomWatts" to 1.
2. Place the laser inside the SM tube containing the laser holder and inside a cage plate containing alignment screws as shown in Figure 6. The laser holder should position the laser centered about the aperture and power meter photodiode, although there is still room for small adjustments with the alignment screws.
3. Connect the laser to the pcb and turn it on (laser should be modulated with square wave/50% duty cycle). Use the alignment screws to fine-tune the laser alignment. You will need to wear laser safety goggles when aligning the laser. It may be helpful to use an iris or a beam stop on the power meter side of the resonator to look at the beam profile during alignment (the beam should be circular when aligned properly with the aperture).

4. Set up a power meter on the opposite side of the resonator as shown in Figure 7 to measure the beam's power output. The beam and power meter need to be aligned with each other for an accurate power reading.

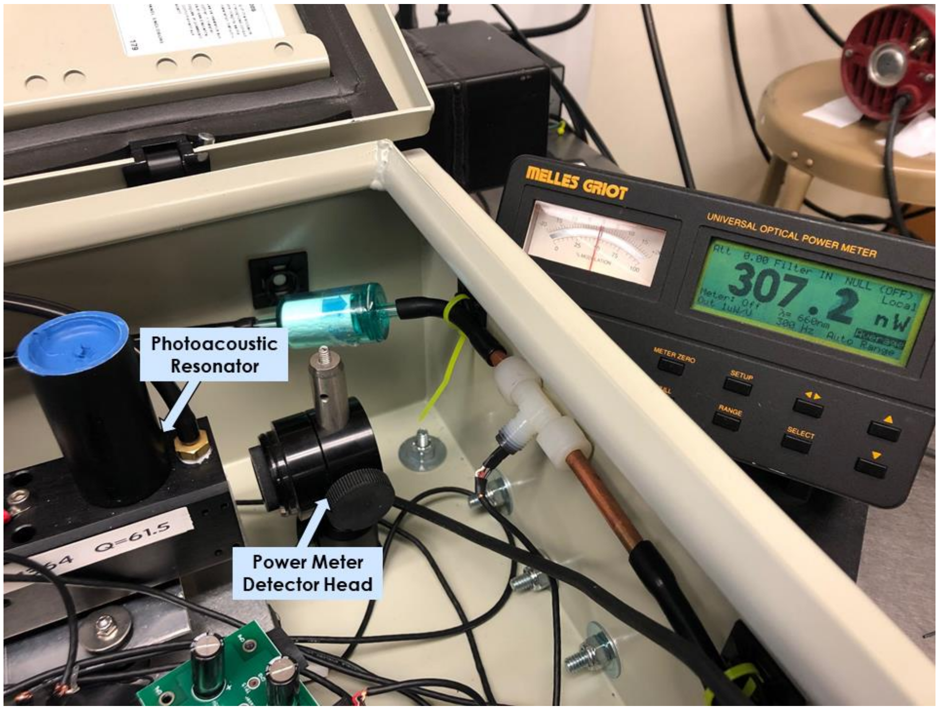


Figure 7. Optical power meter set up to measure laser power coming out of the photoacoustic resonator.

5. Record the laser power reading as P_{actual}.
6. Remove the power meter from the system and attach the extinction photodiode SM tube to the resonator following an empty SM tube, a neutral density filter, a thin Teflon disk, and a thick Teflon disk as shown in Figure 8.

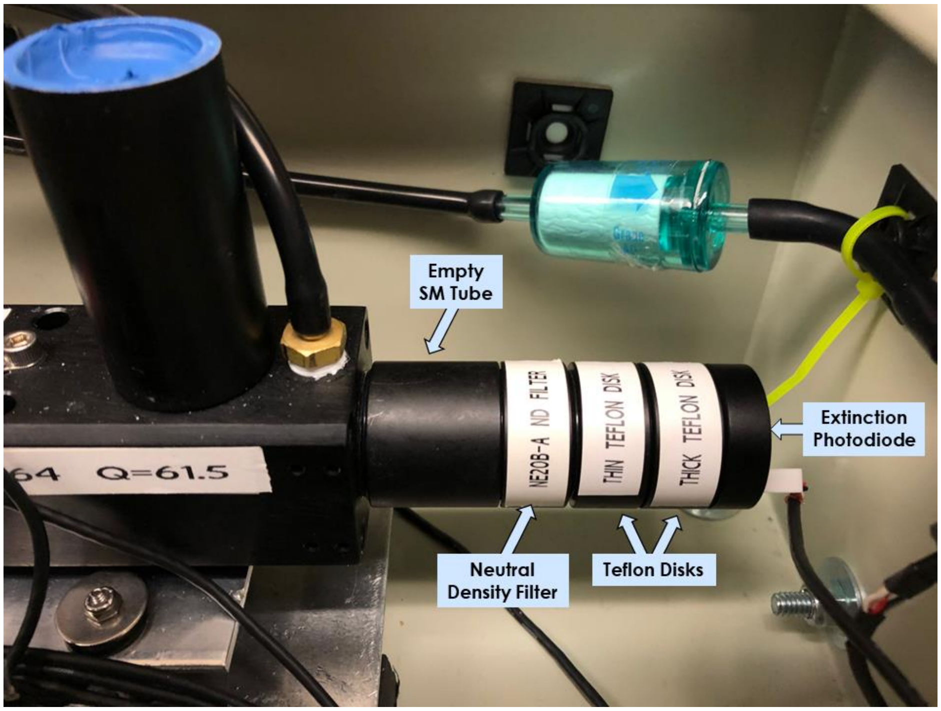


Figure 8. Extinction photodiode setup with an empty SM tube, neutral density filter, and Teflon disks attached to the instrument resonator.

7. Once all of the above components are in place, turn on the instrument and allow it to conduct acoustic calibration and zeroing.
8. Once acoustic calibration and zeroing are complete and the instrument has begun performing its regular measurements, record the instruments laser power reading as P_{ext}.
9. Now the new laser calibration factor can be calculated from the following relationship:

$$\frac{P_{actual}}{P_{ext}} = \text{ mVoltstomWatts.}$$

[1]

10. Update the laser calibration factor (mVoltstomWatts) in the instrument's Arduino code. Upload the updated code to the instrument's Teensy 3.6 microcontroller.

Scattering Sensor Calibration

PA660's scattering sensor will need to be calibrated each time the instrument's laser is replaced or realigned. Calibrating the scattering sensor involves sending a large quantity of light scattering aerosol through the instrument and determining the resulting extinction signal, described below:

$$\beta_{ext} = \beta_{sca} + \beta_{abs}.$$

[2]

β_{ext} is the extinction coefficient described by the following equations:

$$I = I_0 e^{-\beta_{ext} L}, \text{ so that}$$
[3]

$$\beta_{ext} = \frac{1}{L} \ln\left(\frac{I_0}{I}\right),$$
[4]

where L is the length of the cell, I_0 is the laser power detected by the extinction photodiode in the absence of aerosols, and I is the laser power in the presence of aerosols. I_0 can be considered to be the laser power just before scattering begins to increase, or it can be linearly extrapolated from the laser power before and after the high-scattering period, as shown in Figure 9. For PA660, L = 0.2032 m and calculating β_{ext} should result in units of [Mm^{-1}].

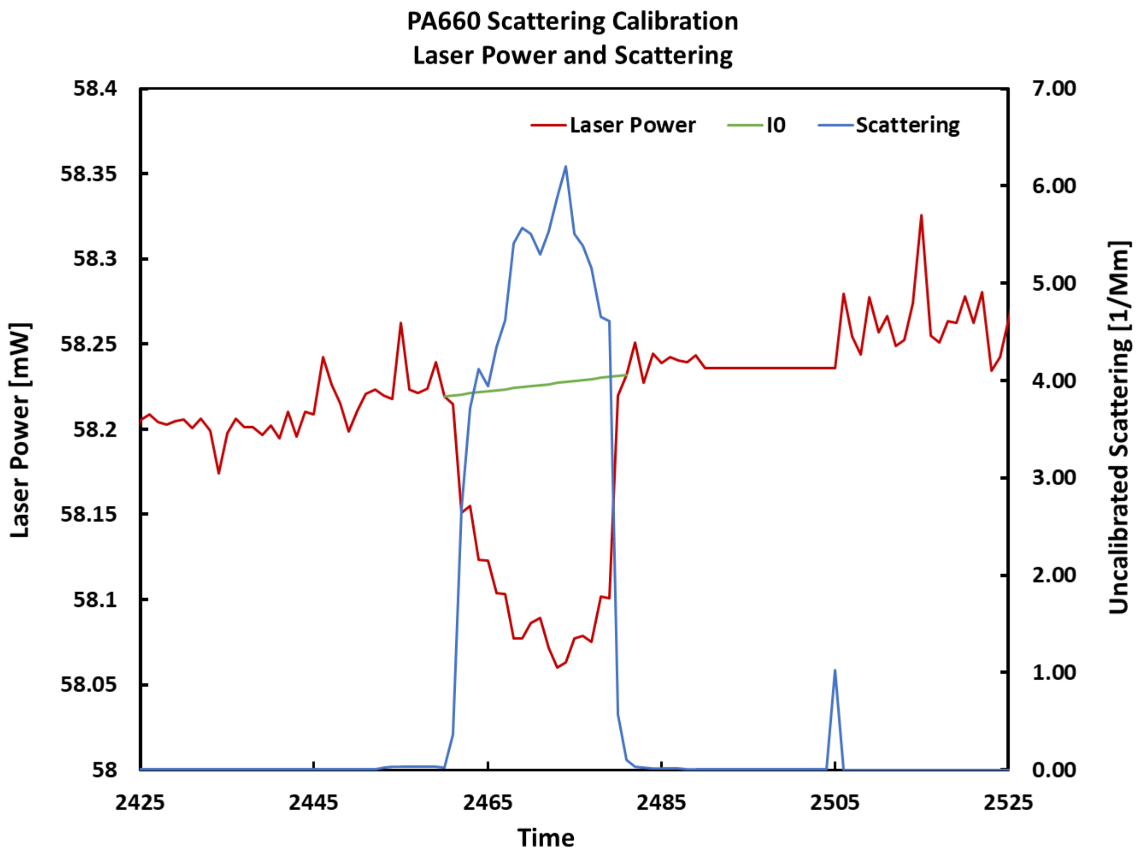


Figure 9. Example of Laser Power and Scattering Signal chart for scattering calibration. The laser power immediately before and after the high-scattering period can be used to extrapolate I₀ in order to calculate extinction.

For non-absorbing aerosols, $\beta_{abs} = 0$ and $\beta_{ext} = \beta_{sca}$, so the scattering signal can be plotted against the extinction signal and the slope of linear fit is the new scattering calibration factor (Sharma, Arnold, Moosmuller, Arnott, Mazzoleni). The scattering coefficient needs to reach up to 40,000-60,000 Mm^{-1} to obtain a large enough extinction signal for comparison. The process for scattering coefficient calibration is as follows:

1. In PA660's Arduino code, set the scattering calibration factor "ScatCF" to 1.
2. Set up the instrument near a fume hood or dust tunnel testing chamber.
3. Power the instrument on and allow it to conduct acoustic calibration and zeroing.
4. Once the instrument is on and has undergone acoustic calibration and zeroing, allow it to collect data until the laser power stabilizes.
5. While the instrument is running and the laser power is stabilizing, place incense inside the fume hood underneath a bucket as shown in Figure 10 to collect incense smoke. Incense smoke is highly scattering and a weak absorber, so it works well for scattering calibrations.

Figure 10. Incense stick lit beneath a bucket where smoke can accumulate. PA660 sample inlet will be connected to the bucket so that smoke can be drawn through the instrument.

6. Once the laser power stabilizes, attach a filter to the sample inlet.
7. Collect a few points of filtered air data.
8. After sufficient incense smoke has accumulated inside the bucket, remove the filter and connect the sample inlet to the sample outlet on the bucket so incense smoke is drawn into the instrument.
9. Collect 10-20 data points while the scattering signal is high.
10. After sufficient data has been collected with a high scattering signal, disconnect the instrument's sample inlet from the bucket and reattach the filter.

11. Collect a few more points of filtered air data.
12. Retrieve the saved data from the on-board SD card or from the computer running LabVIEW.
13. Import data into Excel and calculate the extinction signal using [3].
14. Plot the extinction signal vs. the scattering signal and perform a linear fit to the data.
15. The slope of this linear fit will be the new scattering calibration factor. Update the calibration factor in the Arduino code, then upload the program to the instrument.

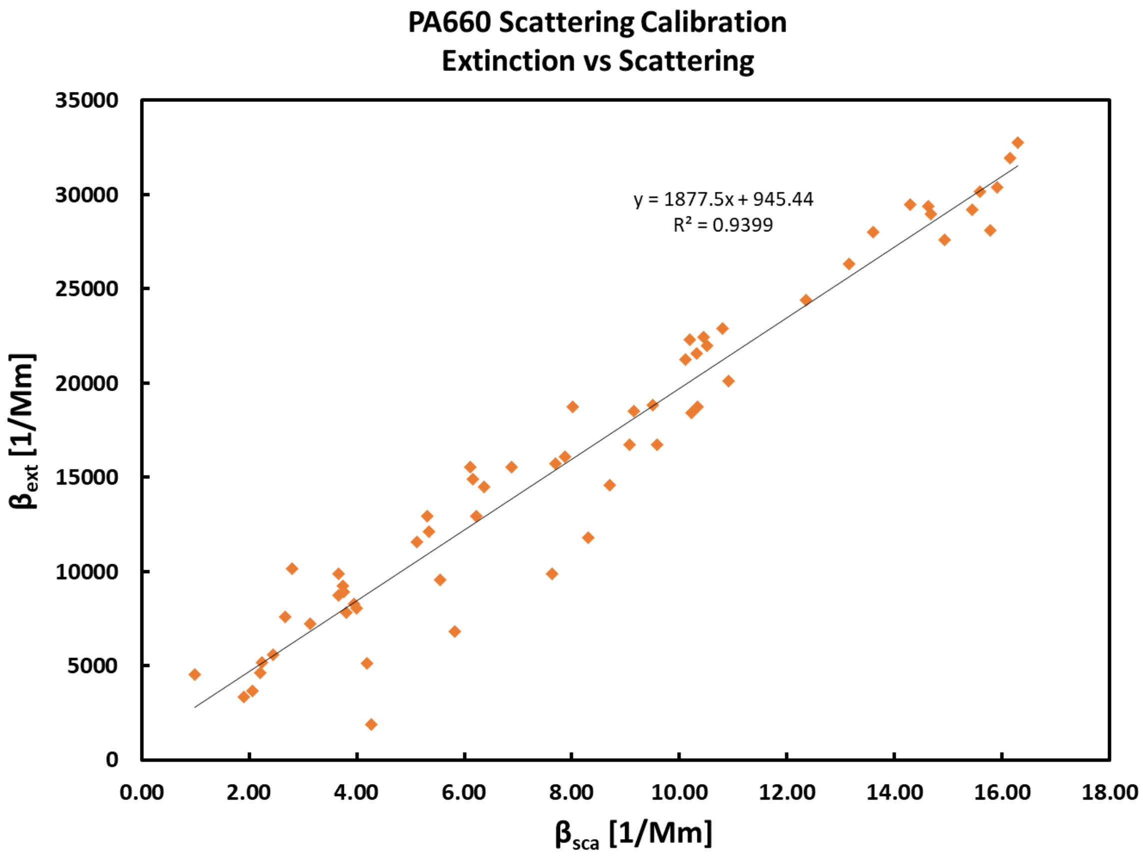


Figure 11. Example of Extinction vs. Scattering Signal chart for scattering calibration. The slope of the linear fit is the new scattering calibration factor.

Absorption Coefficient Calibration

Similar to the process for scattering calibration, calibrating the absorption coefficient for PA660 will involve passing highly absorbing aerosol through the instrument and determining the extinction signal using Equation [3]. In this case, the calibration factor will be determined by finding the slope of a linear fit of $\beta_{ext} - \beta_{sca}$ vs. β_{abs}. The net phase measured during the high-absorption period is considered to be the phase offset of the instrument. The absorption calibration procedure is as follows:

1. In PA660's Arduino code, set the absorption calibration factor "BabsCF" to 1 and set "PhaseOffset" to 0.
2. Set up the instrument near a fume hood or dust tunnel testing chamber.
3. Power the instrument on and allow it to conduct acoustic calibration and zeroing.
4. Once the instrument is on and has undergone acoustic calibration and zeroing, allow it collect data until the laser power stabilizes.
5. While the instrument is running and the laser power is stabilizing, light a kerosene lamp and place it inside the fume hood underneath a bucket to collect smoke as shown in Figure 12. Kerosene soot smoke is highly absorbing so it works well for absorption calibrations.

Figure 12. Kerosene lamp lit beneath a bucket where smoke can accumulate. PA660 sample inlet will be connected to the bucket so that smoke can be drawn through the instrument

6. Once the laser power stabilizes, attach a filter to the sample inlet.
7. Collect a few points of filtered air data.
8. After a sufficient amount of soot has accumulated inside the bucket, remove the filter and connect the sample inlet to the bucket so smoke is drawn into the instrument.
9. Collect 10-20 data points while the absorption signal is high.
10. After sufficient data has been collected with high absorption, remove the instrument's sample inlet from the bucket and reattach the filter.
11. Collect a few more points of filtered air data.
12. Retrieve the saved data from the on-board SD card or from the computer running LabVIEW.

13. Import data into Excel and calculate the extinction signal using Equation [3]. The absorption signal magnitude to be used during this calibration should be calculated with the following equation:

$$\beta_{abs}R = \sqrt{\beta_{abs}X^2 + \beta_{abs}Y^2}. \quad [5]$$

14. Plot the extinction signal minus the scattering signal vs. the absorption signal and perform a linear fit to the data.
15. The slope of this linear fit will be the new absorption calibration factor.

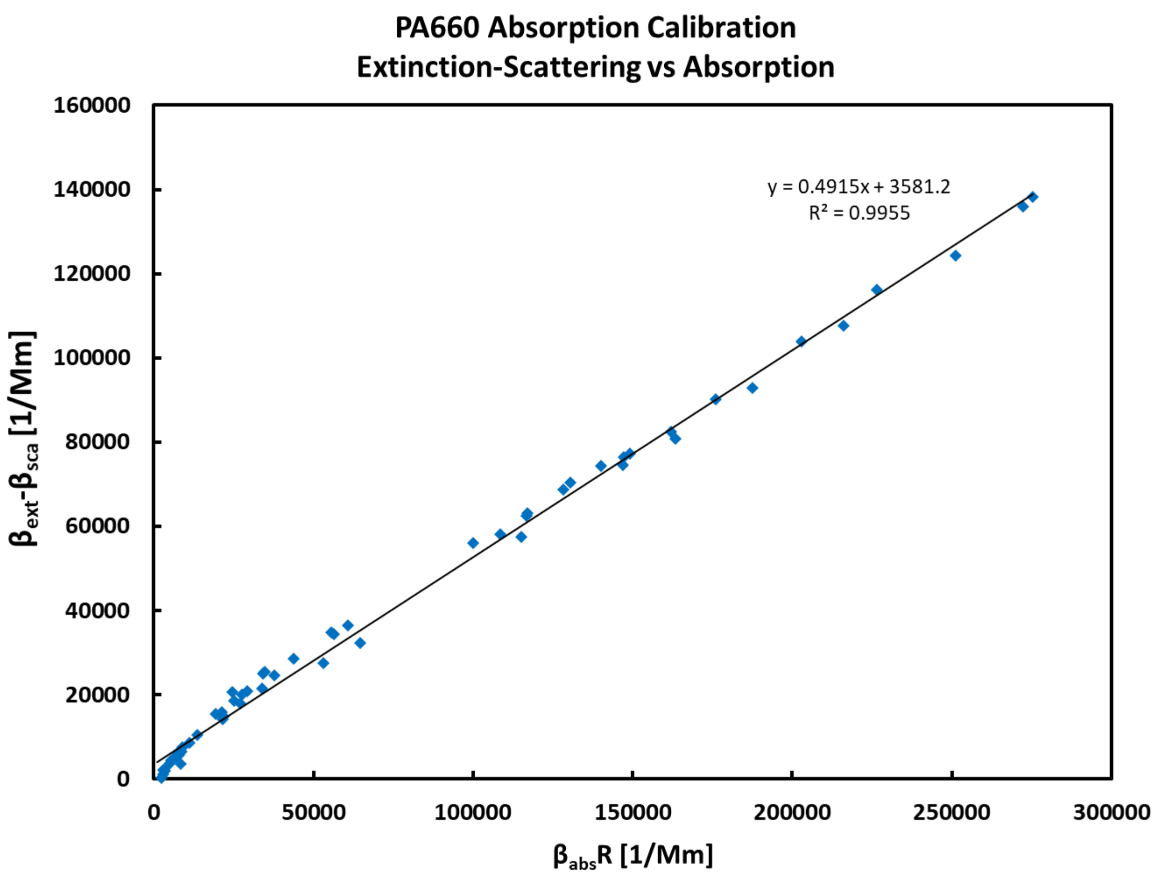


Figure 13. Example of Extinction minus Scattering vs. Absorption Signal chart for absorption calibration. The slope of the linear fit is the new absorption calibration factor.

16. Now create a plot of Net Phase vs. Absorption.

17. Find the net phase in degrees that correlates with the highest absorption coefficient values during the soot test. This net phase value will be the new phase offset.

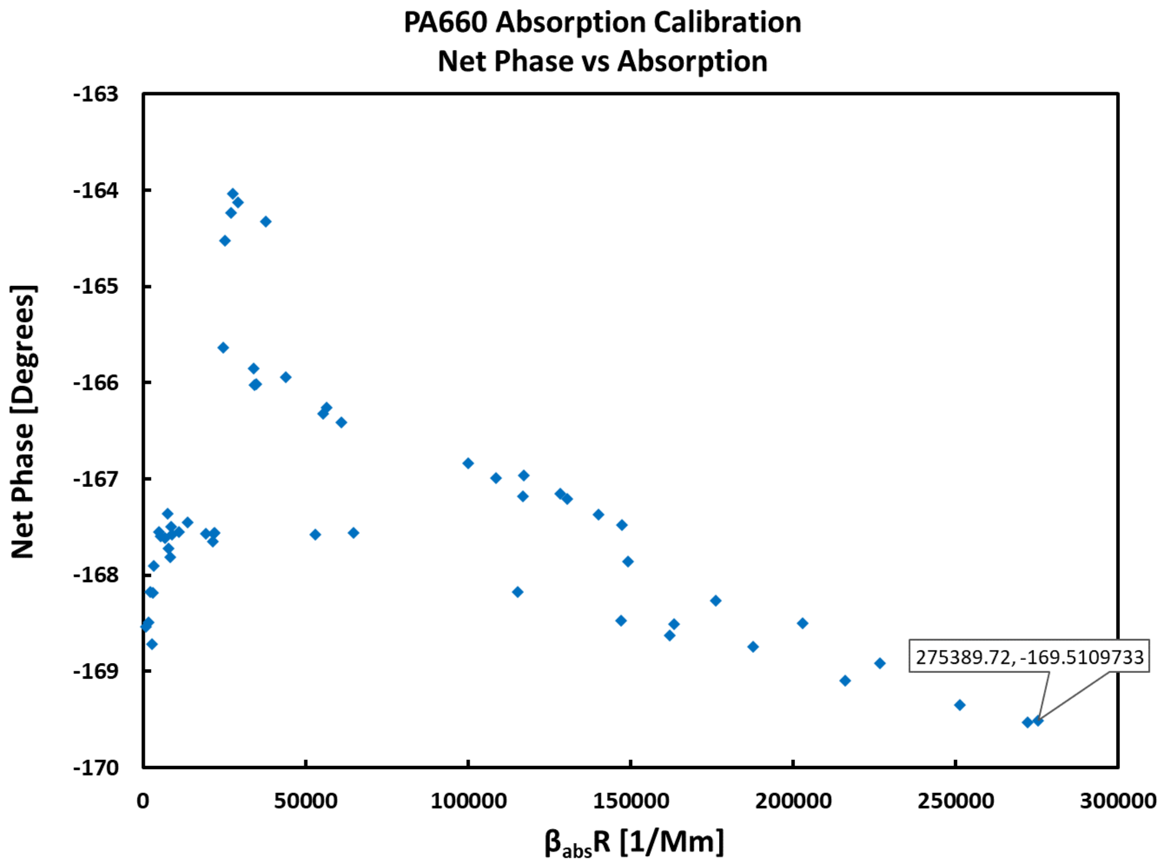


Figure 14. Example of Net Phase vs. Absorption Signal chart for absorption calibration. The phase which correlates with the highest absorption value is the new phase offset.

18. Update the value for absorption calibration factor “BabsCF” and phase offset “PhaseOffset” in the Arduino code and upload the Arduino code to the instrument.

Troubleshooting

Software Issues

- LabVIEW is not connecting to PA660’s radio:
    - Check to see if both radios are plugged into the computer and PA660 instrument correctly. If either antenna threaded connection is loose, the radios may not communicate.

- Check to see if the antennas are aligned properly (pointed towards the same direction).
- Check to see that the USB port selected on LabVIEW matches the USB port the antenna is plugged into.

- LabVIEW is not saving data:
  - Check to see if the **SAVE DATA** switch has been turned on in the top left section of the LabVIEW program. If LabVIEW continues to malfunction, the PA660 onboard SD card will save all data and can be used instead.
- Screen on PA660 is frozen:
  - Check to see that the instrument's power supply is on.
  - Try powering PA660 off and back on. These screens occasionally need to be restarted to work properly.
  - Check all wired connections from the screen to PA660 to ensure connectivity
- LabVIEW is receiving data incorrectly:
  - Check to see if the antennas are aligned properly and check to see if the antennas are making an adequate connection with PA660 and the computer's USB port.
  - Check to make sure the radio is plugged into the same USB port as selected under **VISA resource name** in LabVIEW.
  - Try restarting PA660 by powering off and on.
- Plots on LabVIEW aren't showing all data:
  - Try right clicking on both axes of the desired plot and make sure Auto Scale is selected.
  - Try restarting PA660.
- Instrument keeps calibrating:
  - Try restarting PA660.

Hardware Issues

- Pump is not turning on:
  - Check to see if pump is plugged into power supply completely.
- PA660 power supply is not turning on:
  - Check side of power supply and see how much charge the power supply has. If no green LEDs light up, it may need recharging.
  - If problem persists, contact PA660's lab members.
- PA660 is not powering up but power supply is on:
  - Try restarting PA660.

    - Open up the instrument and check the cable connections from the power supply to PA660's PCB.
    - If problem persists, contact PA660's lab members.
- Screen won't turn on:
    - Try restarting PA660.
    - Open up the instrument and check to see that cable connected from PCB to screen is adequate.
    - If problem persists, contact PA660's lab members.
- Laser power low message is being printed to LCD screen:
    - Open up the instrument and check the cable connections between the laser and the PCB.
    - Restart PA660.
    - If problem persists, contact PA660's lab members.

Theory of Operation

An illustration of the photoacoustic effect for aerosols is shown in Figure 15. Light is absorbed by the particle resulting in a temperature increase of the particle. Heat transfers by conduction from the particle to the surrounding air, expanding the air, and creating a pressure disturbance or sound wave. The volumetric expansion of the heated particle is negligible compared to that of the surrounding air. The conversion of light into sound is known as the photoacoustic effect. A microphone is used to quantify the sound wave. Aerosol light absorption can be quantitatively determined by use of a calibrated laser power meter and a microphone, as long as all the heat exits the particle to the surrounding air during the acoustic cycle.

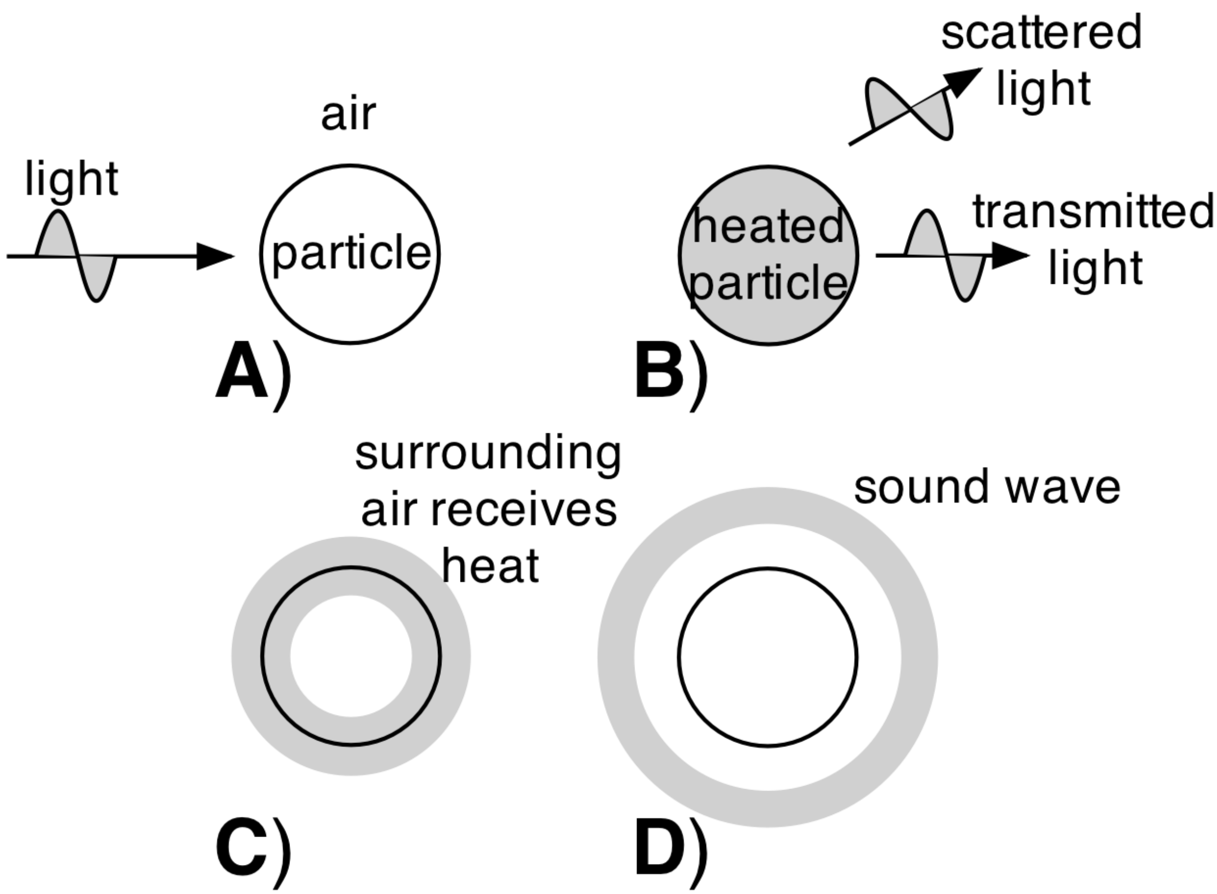


Figure 15. Diagram of photoacoustic effect. A) Light is incident on a particle. B) Some incident light is absorbed, transmitted, and scattered. The particle is heated by absorption. C) Heat transfers from the particle to the surrounding air. D) The surrounding air expands upon receiving heat, receiving heat, resulting in an outgoing acoustic wave.

Acoustic resonators are commonly used for photoacoustic measurements to increase the acoustic pressure at the microphone and to allow for coupling of laser beam and sample flow at pressure nodes, thereby reducing window noise due to light absorption on optical windows and flow noise due to pressure fluctuations of sample flow. Most acoustic resonators are cylindrical with radial, azimuthal, and longitudinal plane wave modes being used. Resonator design is a tradeoff between the need to allow laser beam and sample passage through the resonator and optimal acoustic pressure level for maximizing instrument performance.

Longitudinal mode plane wave resonators have been used with a resonator length of ½ wavelength or a full wavelength. The ½ wavelength longitudinal resonator has pressure nodes at the ends, and larger buffer volumes are used on the ends to simulate a pressure release boundary condition and to reduce flow and window noise. Figure 16 shows the schematic of the photoacoustic resonator used in this instrument. The aerosol light absorption coefficient β_{abs} for the resonator depicted in Figure 16 is expressed as:

$$\beta_{abs} = \frac{p_m}{P_L}\frac{A_{res}\pi^2 f_0}{(\gamma - 1)Q}.$$

[6]

In the above equation, p_m is the microphone pressure at the resonance frequency f_0, P_L is the Fourier component of the laser power at the resonance frequency, A_{res} is the cross sectional area of the resonator, *g* is the ratio of isobaric and isochoric specific heat, and *Q* is the resonator quality factor.

After aerosol light absorption is determined, the concentration of diesel particulate matter (DPM), black carbon (BC) or other aerosol can be calculated if the mass absorption efficiency (MAE) is known. In the case of utilizing PA660 to determine DPM concentration with a 660 nm laser, the MAE used is approximately 7.9 m^2/g. The expression for calculating aerosol concentration is as follows:

$$Aerosol\ Concentration\ \left[\frac{\mu g}{m^3}\right] = \frac{B_{abs}\left[\frac{1}{Mm}\right]}{MAE\left[\frac{m^2}{g}\right]}.$$

[7]

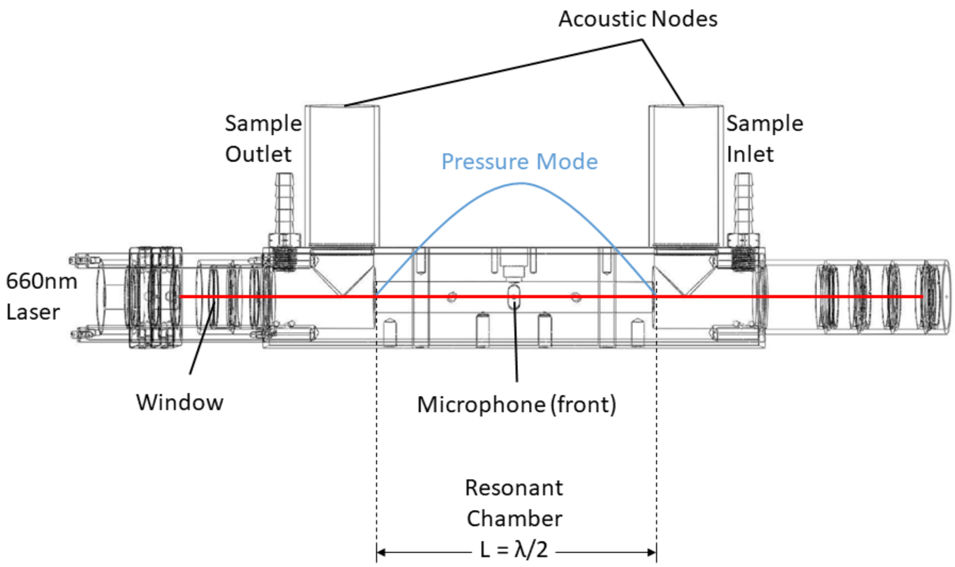


Figure 16. Schematic of the ½ wavelength longitudinal photoacoustic instrument with pressure nodes at the ends of the ½ wavelength resonator, and a pressure antinode at the microphone position.

Buffer volumes act as pressure release boundary conditions for the resonator, and they facilitate sample and laser beam passage through the resonator. The diameter of the acoustic resonator is as small as possible to maximize the microphone signal. A speaker is collocated with the microphone to be used in determining the resonator quality factor and resonance frequency. On the top of the resonator is an additional photodiode that is used as a scattering detector placed 90* degrees from the laser path. The scattering detector can give us insight about particle size and aerosol composition.

The scattering detector measures the power of scattered light inside the resonator. To normalize the scattering signal, the following expression is used:

$$B_{sca}\left[\frac{1}{Mm}\right] = \frac{R_{sca}[mV]}{P_{las}[mW]} * C_{sca}\left[\frac{mW}{mV * Mm}\right].$$

[8]

Where B_{sca} denotes the normalized scattering absorption coefficient, R_{sca} denotes the scattering signal from the photodiode, P_{las} denotes the laser power, and C_{sca} denotes the scattering calibration factor.

Appendix A. Instrument Parts List

On circuit board:

- Teensy 3.6 microcontroller
- MTU01D0505MC +-5V DC/DC converter
- AD8429 instrumentation amplifier
- PJRC audio adaptor boards for Teensy 3.6
- PJRC Arduino ILI9341 touch screen
- BME280 temp, pressure, and RH sensor
- MPRLS pressure sensor
- MCP6541 comparator op amp

On/in resonator:

- ICS-40730 MEMS microphone/EK23028 microphone
- Knowles FED30027 speaker
- OPT101 photodiode (extinction)
- FDS100 photodiode (scattering)
- 200 mW 660 nm laser dot module with focusing lens
- Newport 10QW20-30AR.14 parallel UVFS window
- Aperture
- ND filter
- Teflon disks

Plumbing & other hardware:

- Hammond Type 12 steel enclosure
- External 12VDC Boden vacuum pump (11 lpm)
- TalentCell Rechargeable 72W 132WH 12V/11000mAh 9V/14500mAh 5V/26400mAh DC power supply
- SHT75 temperature and relative humidity (RH) sensor
- Cole-Parmer EW-98302-46 inlet switch valve
- Critical Orifice # 13
- Balston filters 9933-11-AQ
- 1/8'' ID rubber tubing for main instrument plumbing
- 3/32'' ID rubber tubing for MPRLS pressure sensor plumbing

References

Moosmuller, H., R. K. Chakrabarty & W. P. Arnott (2009) Aerosol light absorption and its measurement: A review. *Journal of Quantitative Spectroscopy & Radiative Transfer,* 110**,** 844-878.

Sharma, N., I. J. Arnold, H. Moosmuller, W. P. Arnott & C. Mazzoleni (2013) Photoacoustic and nephelometric spectroscopy of aerosol optical properties with a supercontinuum light source. *Atmospheric Measurement Techniques,* 6**,** 3501-3513.