Manual

Photoacoustic Instrument Aerosol Optics Measurement
Instrument Serial # 20

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Brief Instrument Description

A photoacoustic resonator is used to aerosol light absorption, and a reciprocal nephelometer is used to measure aerosol light scattering. A 532 nm laser is used. In the photoacoustic measurement, light absorbing aerosol heat when illuminated with a laser beam. The heat transfers rapidly to the surrounding air. The surround air expands, producing sound. The sound is measured with a microphone. The laser power is measured as well. Light absorption can be converted to equivalent black carbon mass concentration using a light absorption efficiency factor of 8.8 $m^2 g^{-1}$.

The computer operating system is Windows XP 32 bit. The instrument software was written using National Instruments Labview.

What to do and not to do

- If the instrument is stored in a very cold place, let it warm to room temperature before starting it up. Depending on the relative humidity, when you move an instrument from cold to hot you can get serious amounts of condensation inside. Allowing the instrument to come to ambient temperature before operation will allow the condensation to harmless evaporate before the instrument is energized. Energizing an instrument coated with condensation could short out some components and cause failure.

- Do not thump on the instrument case. Mount the instrument on foam if you can as a preventative measure. The microphone used is very sensitive and can pick up sounds coupled in through vibrations. Vibration isolation has been installed, but you can get best performance by not pushing the issue too much.

- Give the instrument about 10 minutes to warm up after you have started it before taking data if possible. It will settle in nicely to a routine during this time.

- Turn off and unplug the instrument if you need to open it.

- Be sure to leave the inlet switch on the instrument front in the computer control setting. Do not leave it in the filtered air setting for longer than 5 minutes as the controller gets hot. If the controller gets too hot, a thermal switch will cut power to the instrument. If you need to use filtered air for an extended period of time, use a filter on the inlet rather than the internal filter.

- Do ask questions, and enjoy the instrument. It has very good sensitivity for light absorption and scattering measurements and has a very large dynamic range of operation. Contact the manufacturer if the instrument has problems. Self repair would likely not be effective and is discouraged.

Quick Start Guide

1. Connect the pump to the outlet. See Figure 1.

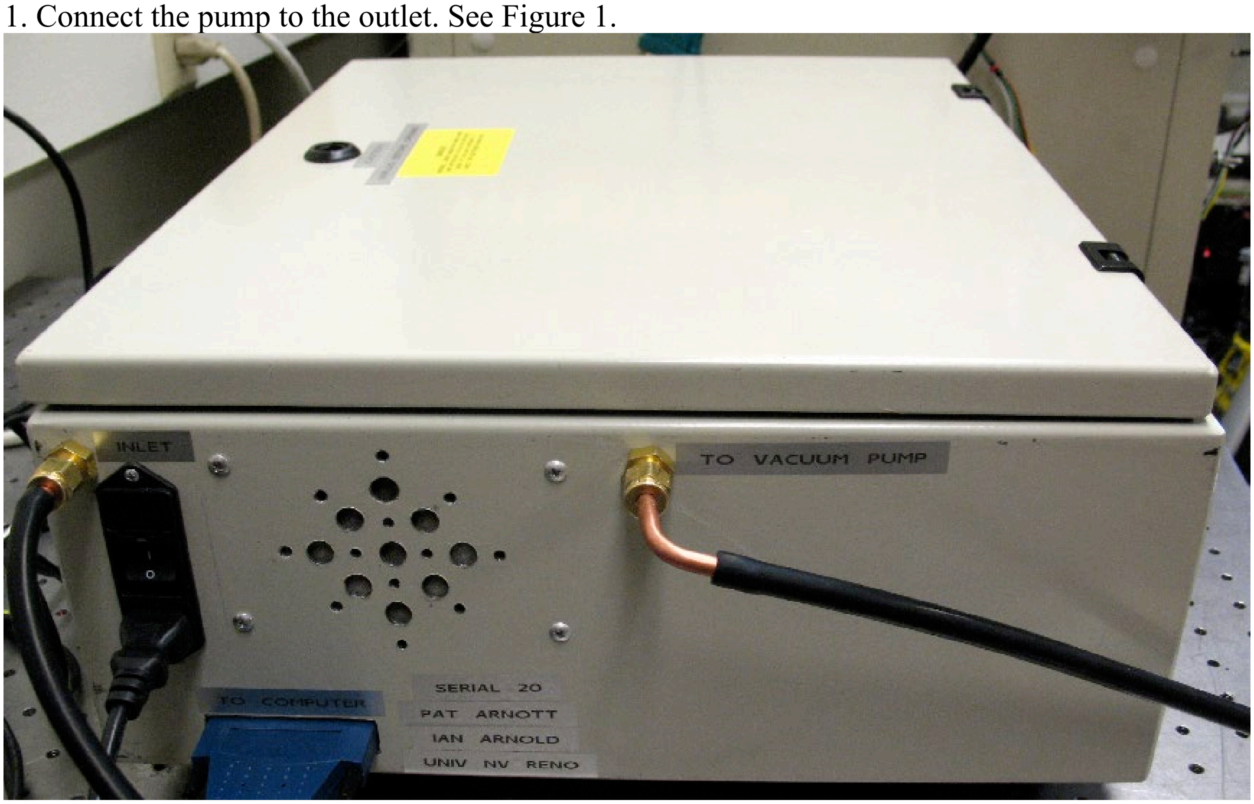


Figure 1. Rear of instrument showing the sample inlet and the outlet to the pump as well as the cable for the computer.

2. Connect your sample line to the inlet. See Figure 1.

3. Turn on the pump. Confirm pump adequacy by noting the vacuum pressure reading on the gauge on the right side of the instrument. See Figure 2.

Figure 2. Pressure gauge indicating vacuum level. For proper operation the pressure should be between 15 and 30. If it is below 15, check to make sure the pump line is not leaking.

Figure 3. Computer connections. All are standard except for the data acquisition card on the right. It is a 68 pin connector. Exercise caution when plugging it in as it is fragile. The other end of the data acquisition cable goes to the instrument as shown in Figure 1.

4. Plug in the computer as shown in Figure 3. Connect the computer and the instrument with the supplied cable. Be very gentle as you connect the data acquisition cable between the computer and the instrument as it has many fragile pins. The power cord connects to the port in the back of the computer. Turn the instrument on with the rocker switch on its back panel. Turn the computer on with the button on its front panel.

5. The computer and instrument can be operated with the touch screen monitor and/or the trackpad keyboard. Plug in the keyboard if desired.

6. The computer automatically loads the instrument control program. When ready, start the program by clicking on the arrow in the upper left corner of the program.

7. Be sure the front panel switch is in the computer control setting. See figure 4. The instrument periodically has filtered air pass through it for zeroing the instrument. The light is bright when the instrument is zeroing.

CAUTION: When the switch is in either the middle or lower position, the sample air / zero air inlet switch is not being controlled by the computer, so that erroneous data may result. Use the filtered air setting for only a few minutes at a time as the inlet switching device gets very warm after 30 minutes, and will shut down the instrument. If you want to have only filtered air enter the instrument, put a filter on the inlet and then let the instrument operate with sample air.

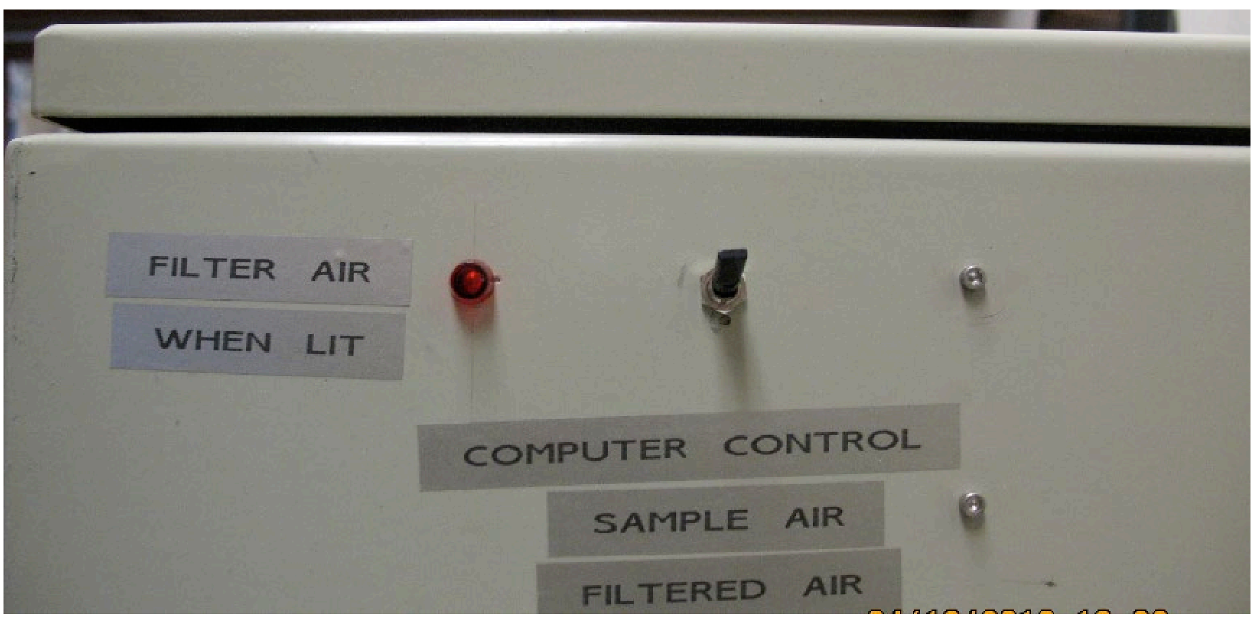


Figure 4. Instrument front panel. The switch has 3 positions. When up, the computer controls the inlet switch choice between sample air and filtered air. When in the middle position the inlet is set for sample air. When down, the inlet is set for filtered air. The inlet switching device in the instruments gets hot when left on the 'filtered air' setting for longer than 10 minutes, and the instrument will shut down when a thermal switch activates. It is generally best NOT to use the filtered air setting, except for brief periods of a few minutes.

Operating the Instrument.

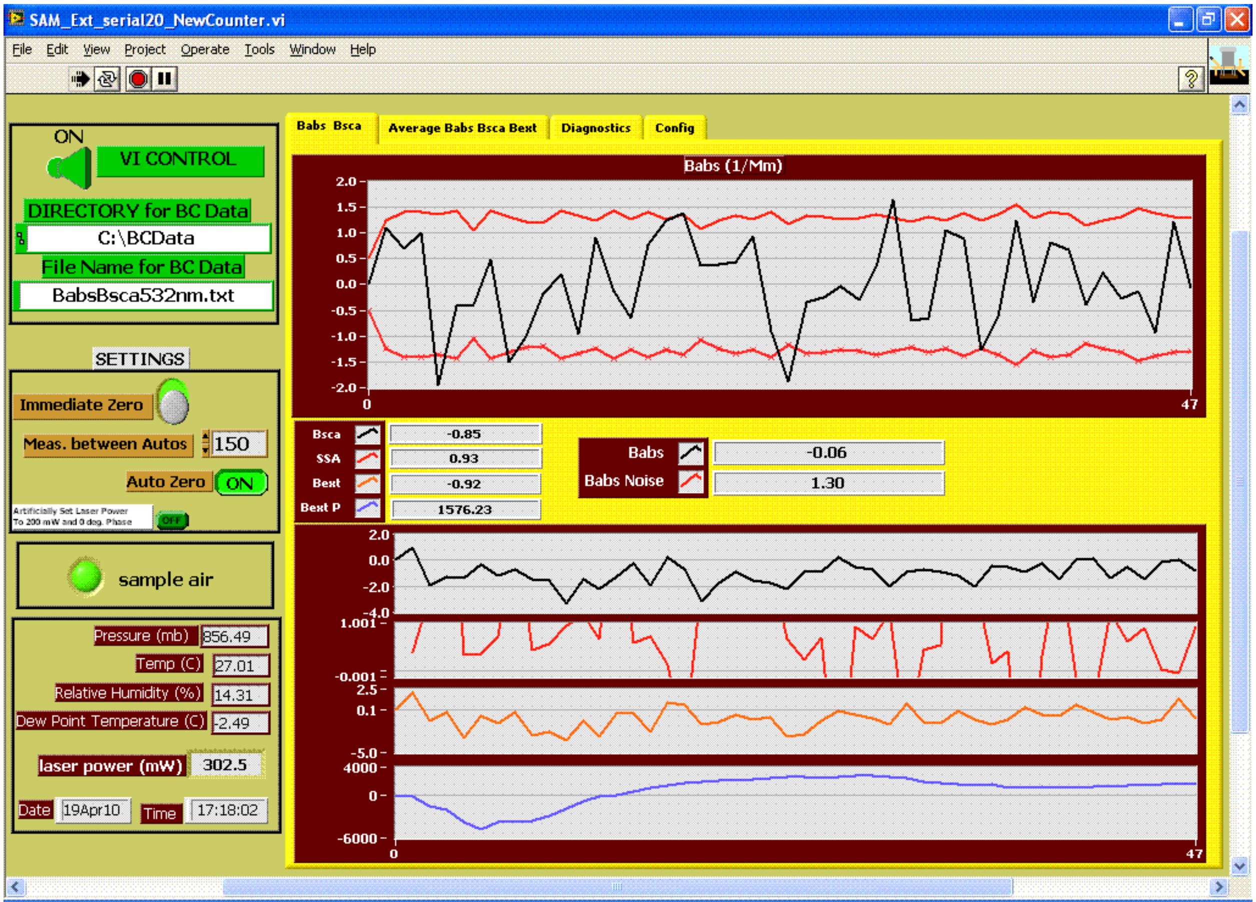


Figure 5. Detailed view of the program to run the instrument. You can tab between “Babs Bsca” that presents the raw data, “Average Babs Bsca Bext” that presents 1 minute time averaged data, “Diagnostics” that presents the laser power, and “Config” that has a few user controllable choices for averaging the raw data.

The instrument measures aerosol optics at 532 nm ± 0.5 nm as follows:

- **Babs** -- aerosol light absorption using the photoacoustic method.
- **Bsca** -- aerosol light scattering using the reciprocol nephelometer.
- **Bext** -- Babs + Bsca.
- **Single Scattering Albedo** – Bsca/(Bsca+Babs).
- **BextP** - Extinction obtained from the use of laser power attenuation over the path length of both the photoacoustic cell and the nephelometer. This measurement has low accuracy, but is very useful when performing a particle calibration of the instrument.

You can change the values in the ‘SETTINGS’ box, and the ‘VI CONTROL’ box. The rest of the values are measurements. Additional settings can be found in the ‘Config’ tab. Settings are as follows:

- **Immediate Zero** -- pressing this forces the instrument to perform a zero. It is most useful when doing laboratory tests (rather than ambient measurements). It is often convenient to use this switch to zero only when you want to, for example after a test of some kind, and to also use "Auto Zero" in the 'off' setting.

- **Auto Zero** -- When measuring ambient air or very long samples of relatively constant plumes, this switch, when 'on' will automatically zero the instrument every 150 measurements.

- **Meas. Between Autos** – sets the measurement interval between instrument zeros.

- **Artificially Set Laser Power To 200 mW and 0 deg. Phase** -- this is a diagnostic and should not generally be used.

Figure 6 shows the 1 minute time average tab for the program. Data presented in this tab are time averaged over a minute, and it excludes instrument zeros.

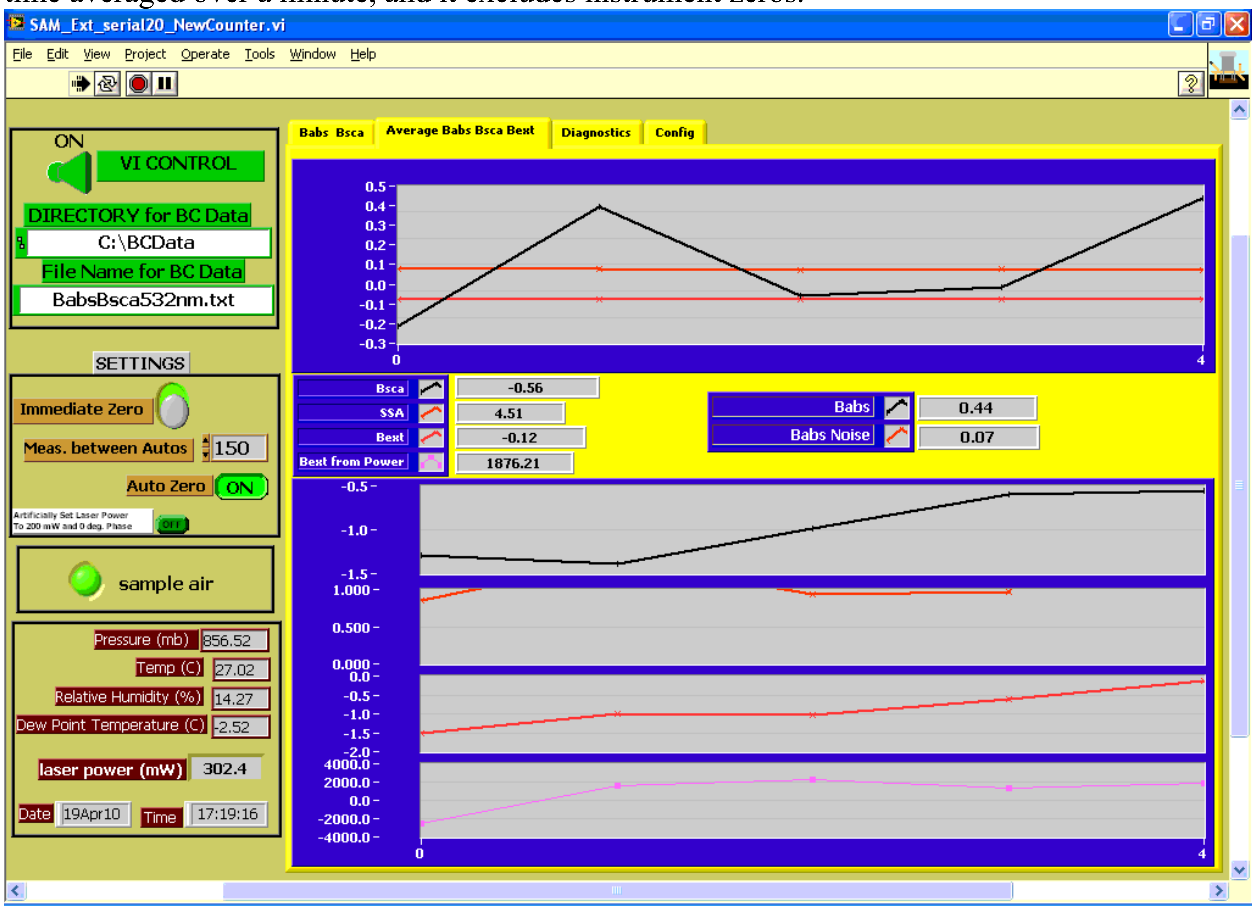


Figure 6. Tab showing the 1 minute time averaged data. This panel is similar to the "Babs Bsca" panel.

In the absorption plot, the red curves represent the fundamental limit of photoacoustic sensitivity for this instrument.

Figure 7 shows the "Diagnostics" tab. Here the laser power is presented as a time series. This panel gives a good idea of the values of the parameters, and can be used to check the instrument at other times. It is normal for the laser power to fluctuate, and this fluctuation is taken into account in the instrument as light absorption and scattering measurements are normalized by laser power.

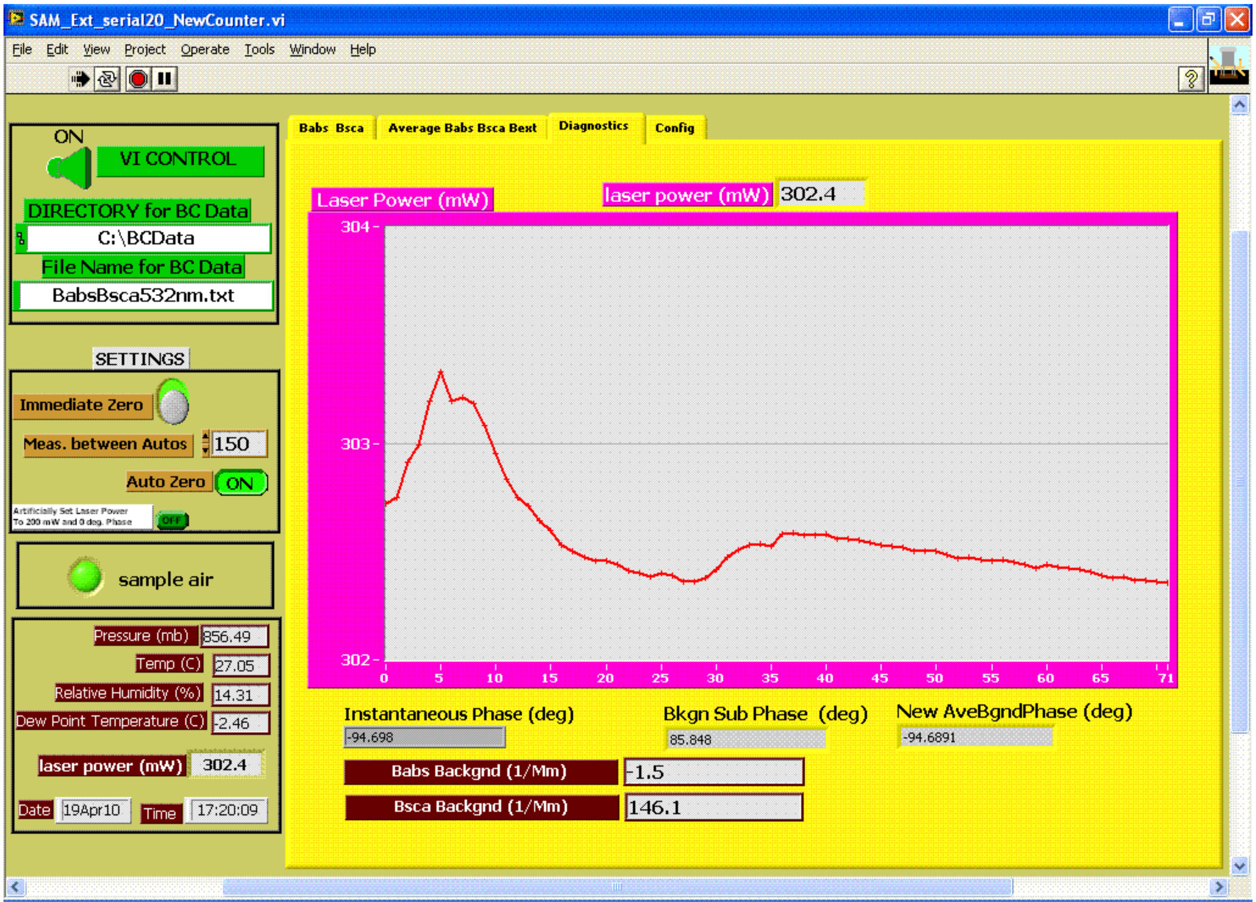


Figure 7. Panel showing diagnostics.

Figure 8 shows the instrument "Config" panel. You may choose different averaging time for each measurement, though recommended values are shown and probably should be used. The acoustic calibration of the photoacoustic cell is also shown. Acoustic calibration is accomplished by broadcasting sound through a miniature speaker in the frequency range of the acoustic resonator and recording this sound with the microphone attached to the resonator.

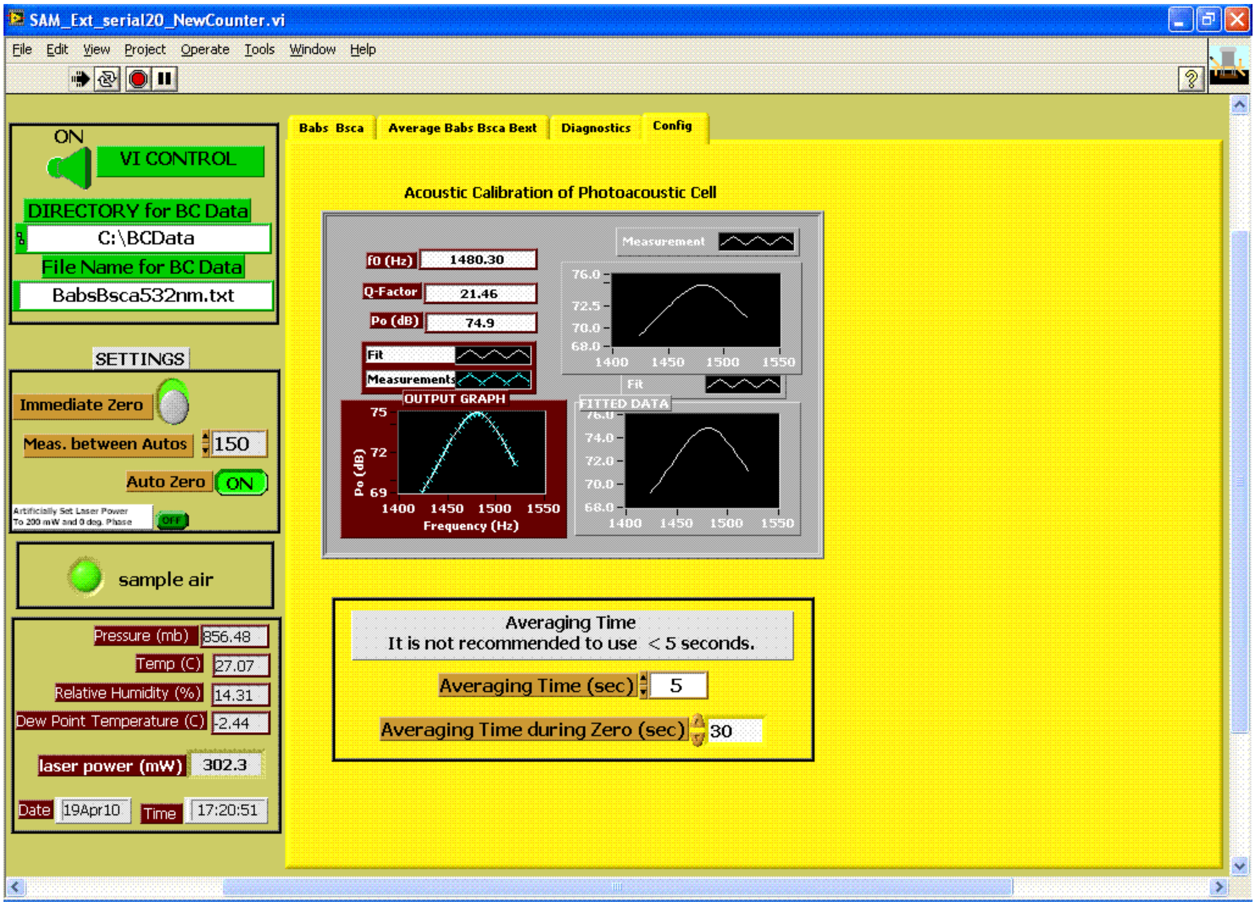


Figure 8. "Config" panel. The user may choose averaging time for each 'raw' measurement, and the averaging time during instrument zero. Recommended values are given. The acoustic calibration of the photoacoustic cell is also presented. Typical values are shown. The resonance frequency f_0 and the quality factor Q are used to when obtained aerosol light absorption.

Stopping the instrument

1. To stop the instrument in a graceful manner, toggle the green VI CONTROL to off. The program will finish what it is doing, and the run arrow in the upper left will change from solid black to an outline. See Figure 5.

2. The data is stored in a folder with the date as a name in the directory C:\BCData. Two files are stored, a 'raw' file containing raw and diagnostic data, and a file containing 1 minute data. You can retrieve the data with a USB drive placed on a USB port on the front of the instrument.

3. Then go to the Windows start menu and shutdown the computer. After it shuts down, turn off the toggle switch for power in the back. Disconnect the power cord.

4. Turn off the pump and disconnect it. You are now ready to move the instrument to a new location.

Instrument Components

A photograph of the instrument is shown in Figure 9 with the major components listed. The instrument comprises three systems:

Optics -- laser light is steered by mirrors first through the nephelometer for measurement of aerosol light scattering, and then through the photoacoustic cell for measurement of aerosol light absorption. Laser power is measured after the photoacoustic cell. Total attenuation of the laser beam is determined with the laser power measurement, and is used to calculate the extinction coefficient. A schematic of the optical system is shown in Figure 10. Important details of the scattering sensor head design are given in Appendix 1.

Air Handling -- After the inlet, aerosol flow is split into two paths, the sample air path and the filtered air path. The inlet switching device is AC power activated as controlled by a manual switch on the front panel of the instrument or by the computer through use of a 5 volt logic relay. After the inlet switching device the air flow is split between the photoacoustic cell and the nephelometer. Tubing lengths have carefully been chosen to ensure that the flow rate through each cell is about the same so that the time constant of each cell is similar. After each cell is a filter to remove particles, a pressure transducer and a temperature and RH sensor are used to characterize the sample air thermodynamics, and a critical orifice to control flow speed. The flow rate through the photoacoustic cell is about 0.8 LPM and is about 1.5 LPM through the scattering cell. The scattering cell receives sample air at its center and it exits from the ends to minimize particle path length in the cell.

Electrical -- The instrument uses 110 Volt 60 cycle AC supply, and is electrically grounded to the ground lead from the wall supplied current. A DC power converter follows immediately after the AC inlet. The DC supply delivers -12 VDC, signal ground, and 12 VDC to the preamplifier boards for the microphone, scattering sensor photodiode, and laser power meter photodiode. The DC supply also provides 5 VDC for the pressure sensor and for the laser modulation card. Two other power supplies convert AC to DC for powering the laser and powering the exhaust fan. A thermal switch is attached to the inlet switching valve to cut AC power to the instrument when it becomes warmer than 45 C inside of the enclosure. This also protects the laser from thermal damage.

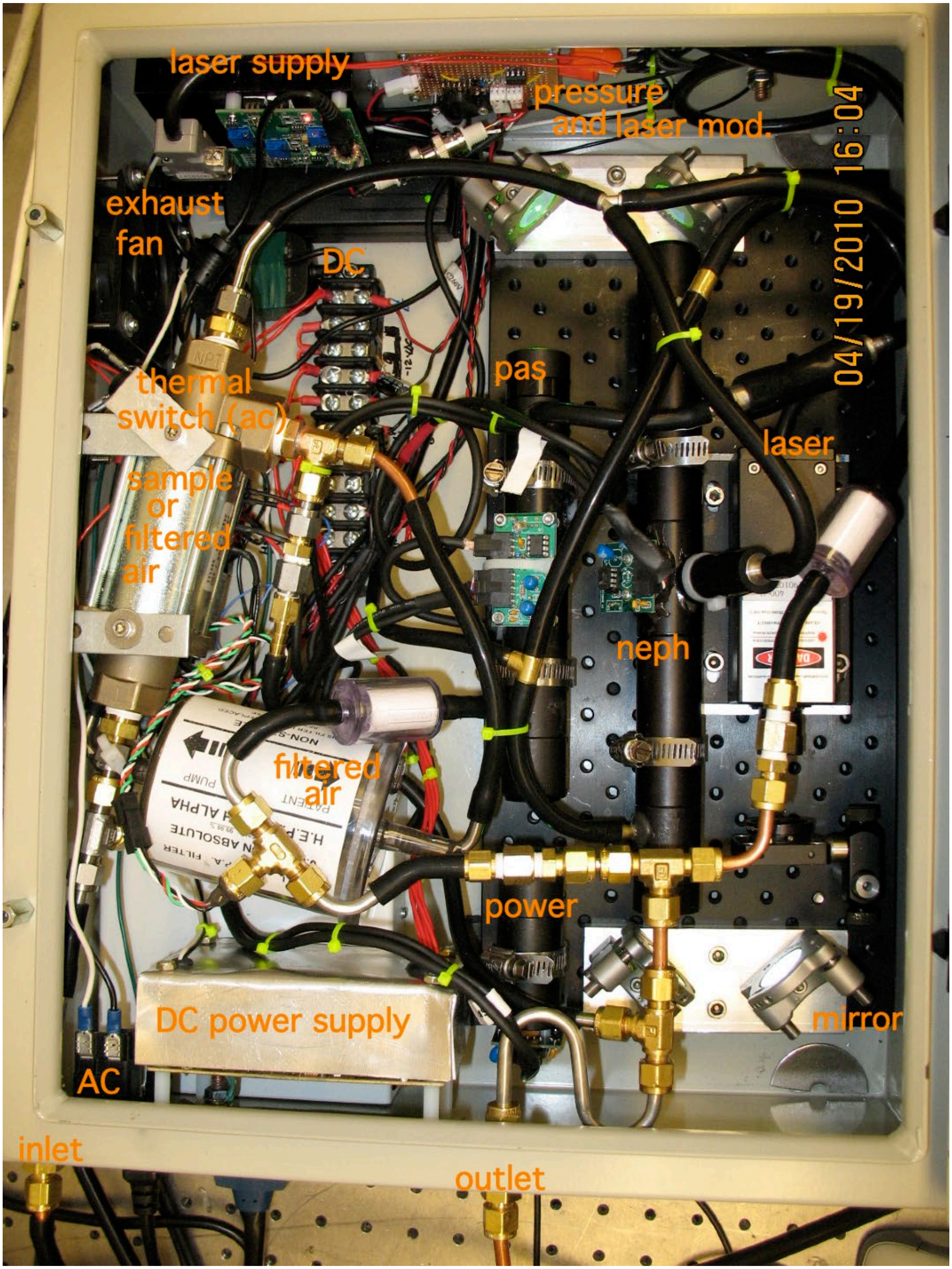


Figure 9. Instrument details.

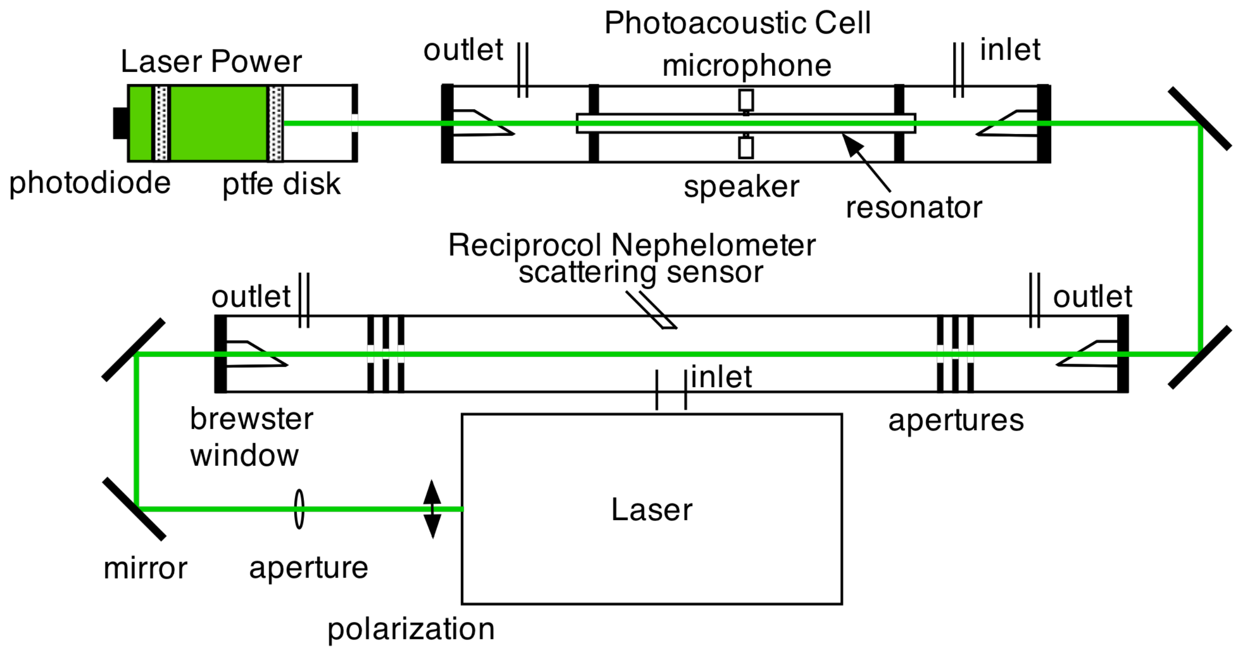


Figure 10. Schematic of the optical system. Starting at the laser, the horizontally polarized beam reflects from the first mirror, then the second mirror, and then it passes through the reciprocol nephelometer for the scattering measurement. The scattering sensor is at an angle of 45 degrees to the plane of the figure so that it measures the average cross section for polarization states parallel and perpendicular to the scattering plane. Apertures are used to reduce effects of background scattering. The truncation angle for the sensor geometry is 3.6 degrees in forward and backward directions. Angular truncation, while small, is partially compensated by the angular response of the sensor head. After leaving the nephelometer, the laser beam reflects from two more mirrors and enters the photoacoustic cell. Aerosol light absorption is performed on this cell. Then the laser beam is dumped in the laser power measurement optic.

Theory of Operation

Photoacoustic measurement of aerosol light absorption.

Photoacoustic spectroscopy is a widespread and practical tool for trace detection and characterization of all phases of matter, but especially useful, practical, and robust for quantifying light absorption by gases and aerosols as demonstrated by the balloon borne detection of trace gases in the stratosphere, by sensitive respiration measurements of trace gases by tomatoes and cockroaches, and by aircraft borne measurements of aerosol light absorption. The photoacoustic measurements of aerosol light absorption has been accomplished now for more than 30 years and differs from photoacoustic trace gas detection with respect to the time response of heat transfer from deposited electromagnetic energy by particles and gases, and because particles deposited on instrument optical surfaces may absorb light if precautions against this interference are not taken.

An illustration of the photoacoustic effect for aerosols is shown in Fig. 11. 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. Particle temperature increase is typically less than 1 K for typical aerosol size and laser power used in photoacoustics.

Heated particles can also relax to ambient conditions through evaporation of semi-volatile compounds such as water vapor. Mass transfer accompanying evaporation also contributes to the acoustic pressure, though less efficiently than does heat transfer because some of the laser energy is needed as latent heat to provide the transformation from liquid to vapor phase. Water is the most common semi-volatile compound, so to avoid ambiguity between heat and mass transfer it is best to dry the aerosol first, preferably with a semi permeable membrane dryer rather than by heating the aerosol. This still leaves open the question of aerosol light absorption by particles with a significant semi-volatile component.

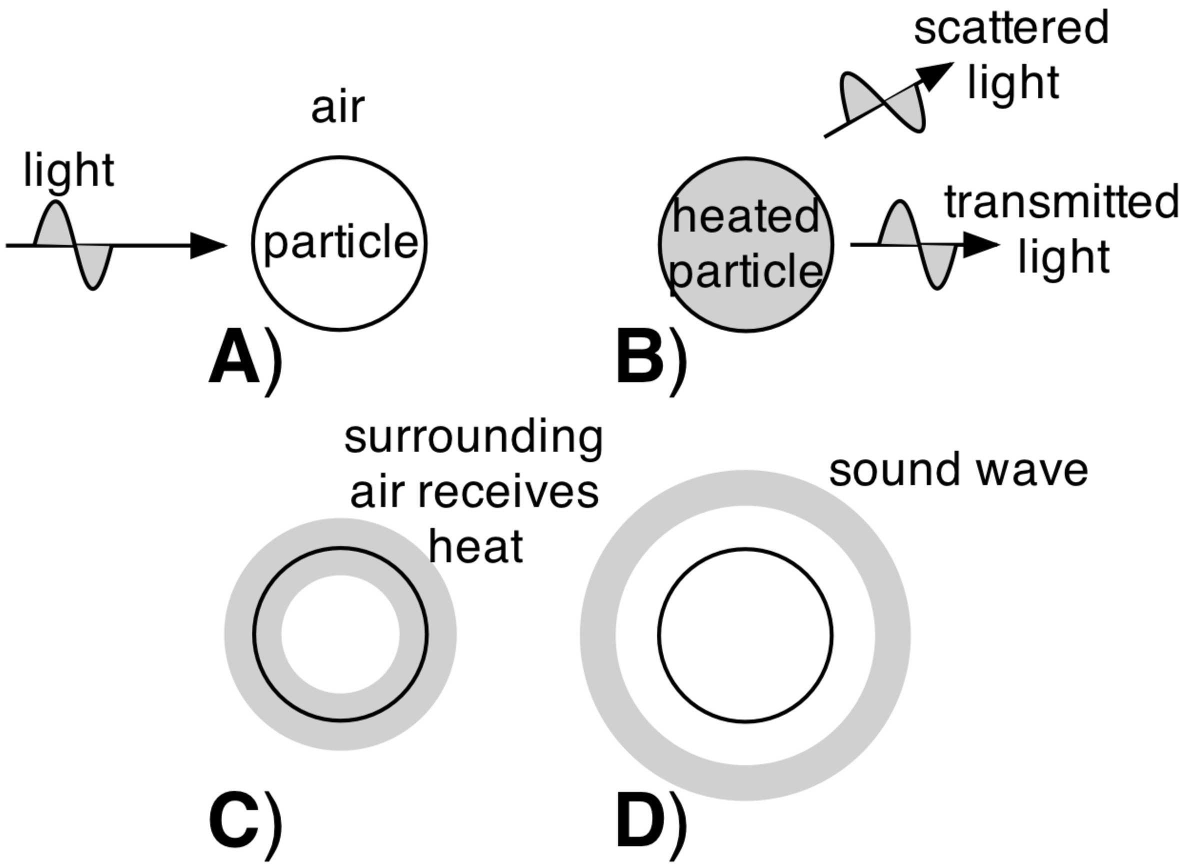


Figure 11. A) Light is incident on a particle. B) Some of the incident light is absorbed by the particle, some is transmitted, and some is scattered. The particle is heated by light absorption. C) Heat transfers from the particle to the surrounding air. D) The surrounding air expands upon receiving heat, resulting in an outgoing acoustic wave.

A small dry particle illuminated by a laser beam begins to heat throughout its volume and to simultaneously transfer that heat to the surrounding air through its surface. The temperature change $\Delta T(t)$ of a particle of radius r illuminated by a laser beam of irradiance I at time $t = 0$ is given by as function of time as

$$\Delta T(t) = T_\infty \left[1 - \exp(-t/\tau)\right], \tag{1}$$

where the T_∞ is the eventual particle temperature change with

$$T_\infty = \Delta T(t = \infty) = \frac{I Q_{abs} r}{4 \kappa_a}, \tag{2}$$

where Q_{abs} is the aerosol light absorption efficiency, κ_a is the thermal conductivity of air, and the time constant τ for the particle to heat up (or cool to ambient once the beam is turned off) is

$$\tau = \frac{r^2 \rho_{particle} c_{p\_particle}}{3 \kappa_a}, \tag{3}$$

where $\rho_{particle}$ is the particle mass density and $c_{p\_particle}$ is the particle heat capacity per unit mass. Thermal relaxation (i.e., the time it takes to have heat transfer out of a particle compared to the frequency v used to modulate laser beam power in continuous wave photoacoustics) induces a reduction of the photoacoustic signal by a factor of f, with

$$f = \frac{1}{1 - i 2\pi \nu \tau} = |f| \exp(i\theta) , \tag{4}$$

where θ is the phase shift between the light modulation and the resulting microphone signal. Table 1 gives a range of signal reduction factors f as function of particle diameter d (= 2 r) for typical parameters.

Table 1. Signal reduction factors f as function of particle diameter d (= 2 r) for typical parameters (i.e., laser wavelength of 532 nm, laser beam power of 0.1 W, laser beam diameter of 2 mm, laser modulation frequency of 1500 Hz, particle complex refractive index of (1.75, 0.75i), particle mass density of 2 g/cm^3, particle heat capacity per unit mass of 710 J/(kg K), thermal conductivity of air of 0.0257 W/(m K).

***d* (µm)**	**Q_{abs}**	**T_∞ (mK)**	**τ (s)**	**→*f*→**	**θ (deg)**
0.01	0.0688	0.1	4.6×10^{-10}	1.00	0.0
0.1	0.844	13.1	4.6×10^{-8}	1.00	0.0
1	1.25	194	4.6×10^{-6}	1.00	2.5
2.5	1.03	400	2.9×10^{-5}	0.97	15
5	0.94	727	1.2×10^{-4}	0.68	47
10	0.88	1366	4.6×10^{-4}	0.22	77

Soot particles commonly consist of monomers with $d < 0.1$ µm making up fractal-like chain aggregates. For spherical particles with a diameter ≤ 0.1 µm, the particle temperature change is much less than 1 K, and there is no reduction of the photoacoustic signal and no phase shift. Spherical particles with a diameter > 5 µm have a substantial reduction of photoacoustic signal (i.e. $|f| < 0.68$) due to thermal relaxation and a very measurable phase shift of $\theta > 47$ deg. The manufacturers have not observed such large phase shifts in all their aerosol sampling with instruments that operate at 1500 Hz, and thus it is likely that most ambient and source sampled aerosols dominating aerosol light absorption behave thermally as if the particles were spheres with diameters less than 1 µm. Another message from Table 1 and Eq. 3 is that for typical 0.1 µm diameter light absorbing particles, a typical photoacoustic system raises the particle temperature by about 0.01 K.

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. Microphones have a very large dynamic measurement range and provide ideal "color-blind" sensors for photoacoustic instruments.

Full wavelength plane wave longitudinal mode resonators have been used for trace gas detection and aerosol light absorption measurements. These resonators are commonly bent to allow laser light to enter and exit at pressure nodes and thereby greatly reduce window noise. The aerosol light absorption coefficient β_{abs} measured with this resonator is given as

$$\beta_{abs} = \frac{P_m}{P_L}\frac{A_{res}}{\gamma - 1}\frac{\pi^2 f_0}{Q} \quad (6)$$

where 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, γ is the ratio of isobaric and isochoric specific heat, and Q is the resonator quality factor.

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 (Fig. 12). This is the schematic of the photoacoustic resonator used in this instrument.

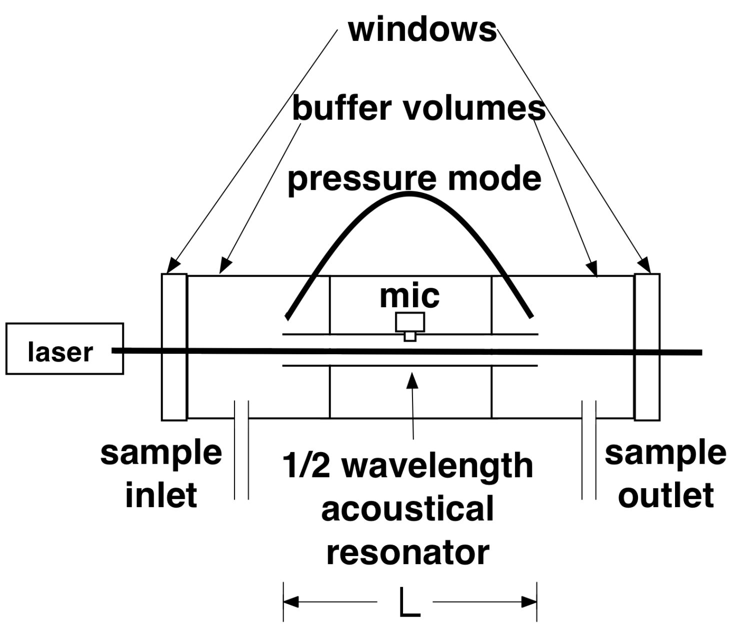
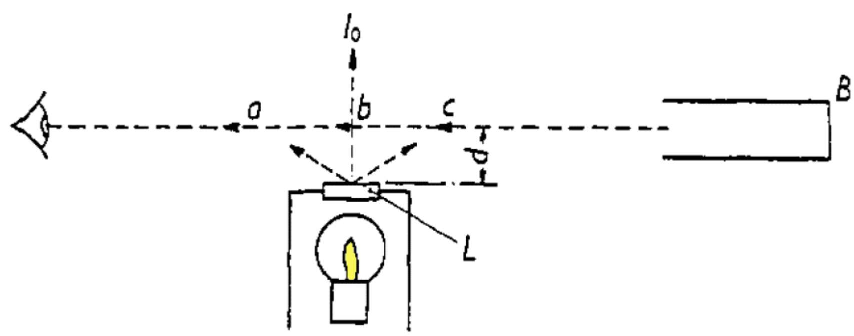


Figure 12. Schematic of a ½ wavelength longitudinal photoacoustic instrument with pressure nodes at the ends of the ½ wavelength resonator, and a pressure antinode at the microphone position. Buffer volumes act as pressure release boundary conditions for the resonator, and they facilitate sample and laser beam passage through the resonator. The diameter of the acoustical resonator is as small as possible to maximize the microphone signal. This is the schematic of the photoacoustic instrument acoustical resonator. A speaker (not shown) is collocated with the microphone to be used in determining the resonator quality factor and resonance frequency. The windows are actually Brewster windows as shown in Figure 10.

History and theory of nephelometers

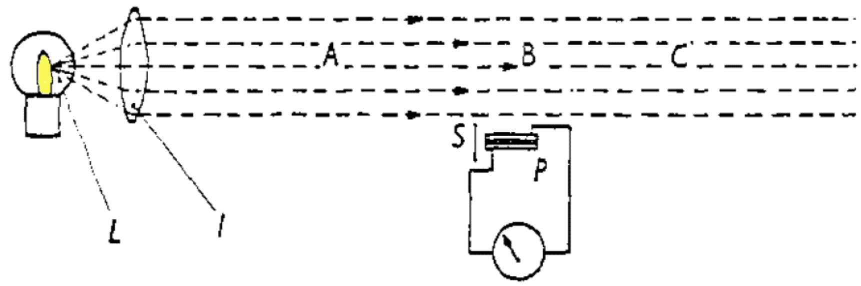
The nephelometer part of the instrument described herein directly measures aerosol light scattering in real time and in situ, i.e. with aerosol in their natural state, not collected on filters or substrates. Concentrating on the light scattering measurement, these instruments are conventionally called nephelometers because they measure properties of particles suspended in a gas, also known as aerosol. Figure 13 shows one of the earliest schematics (Beutell and Brewer 1949) of a nephelometer that later was popular with researchers from the University of Washington, and is now commercially available from TSI.



Scattering at *a*, *b* and *c*. (The black body *B* appears to have brightness due to light scattered at points such as *a*, *b* and *c*. The brightness is a measure of the visibility)

Figure 13. Basic schematic of a nephelometer with an eye on the left as a detector and a candle flame shown as a source. A cosine-weighted diffuser provides Lambertian (uniform) illumination of sample air between the detector and the black target labeled 'B'. Light scattered from the forward hemisphere is labeled 'a', and 'c' is refers to light scattered from the backward hemisphere. This was originally figure 2 in Beuttell and Brewer's paper. Brewer thankfully had the insight to posthumously publish the ideas of Beuttell after he died in a plane crash.

Comes now that the terminology 'reciprocal nephelometer' is used to refer to Beuttell's design illustrated here in figure 14, even though this was the first nephelometer described in his work. It is the policy in this manual to follow modern terminology for the nephelometer herein thereafter referred to using the same name. Many have improved upon the technology available in times of Beuttell and Brewer for successively better reciprocal nephelometers (Sepucha and Mann 1975; Gerber 1979; Gerber 1982; Mulholland and Bryner 1994; Peñaloza 1999; Rahmah, Arnott et al. 2006).



Light scatter at *A*, *B* and *C*. (Light from approximately parallel beam *ABC* is scattered by haze into the photocell *P*. The illumination of the photocell is a measure of the visibility)

Figure 14. Schematic of the Beuttell nephelometer design now known as a reciprocal nephelometer since the location of the source and detector is reversed from that of the design shown in Figure 1. The detector is at P. Aerosol are illuminated by the light source and scattered light falls on P.

The reciprocal nephelometer design is ideal for use with laser beam sources since they are easy to collimate for illuminating particles. Forward and backscattered light are from particles at positions 'A' and 'C', respectively, shown in figure 14. One central assumption of nephelometery is that a representative, randomly oriented distribution of aerosols uniformly fills the nephelometer volume during the averaging time of a single measurement, typically 1 second.

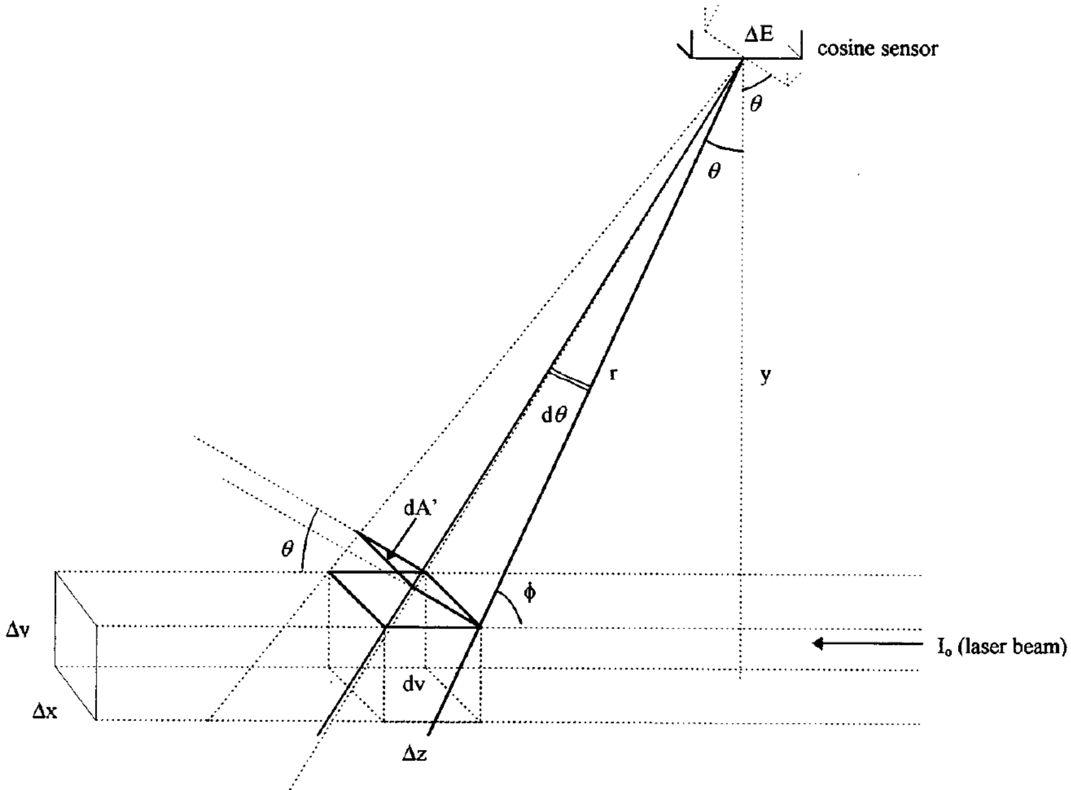
Peñaloza provided an excellent tutorial on nephelometers (Peñaloza 1999). The principle of operation for a reciprocal nephelometer for aerosol light scattering coefficient measurement can be quantitatively understood first by considering figure 15. Accordingly, the total scattered irradiance ΔE falling on the sensor is given by

, (7)

where $F_0 = (I_0\ \Delta x\ \Delta v)$ is the optical power (Watts) illuminating particles, F=($\Delta E\ S$) is the optical power received at the sensor having area S, β_{sca} is the total scattering coefficent (units of inverse distance) for particles and gases that co mingle with the laser volume, and y is the perpendicular distance from the laser beam to the sensor. Equation (7) has the characteristic inverse with distance spreading factor of a line source. The *key message* is that the scattering coefficient can be obtained from

, (8)

where A is a calibration constant with units of (Mm^{-1} Watts $volt^{-1}$) to be determined, and F_0 is the laser beam power, measured, for example, with the photodetector shown in figure 10.



Geometrical details of the cell-reciprocal integrating nephelometer.

Figure 15. Geometry used by Peñaloza to describe operation of the reciprocal nephelometer (originally figure 5 of his paper). An ideal sensor is simply a hole oriented parallel to the laser beam so that the projection of the hole-area with angle varies as the cosine of the angle. Aerosol co mingles with the laser beam.

Noise reference measurements with 1 minute time averages

Figures 16-18 show histograms of 1 minute time averages of absorption, scattering, and extinction measurements obtained with a filter over the sample inlet. These measurements provide a quantification of instrument sensitivity. Note that extinction was obtained from laser power, and therefore is not anywhere near as precise as absorption and scattering measurements.

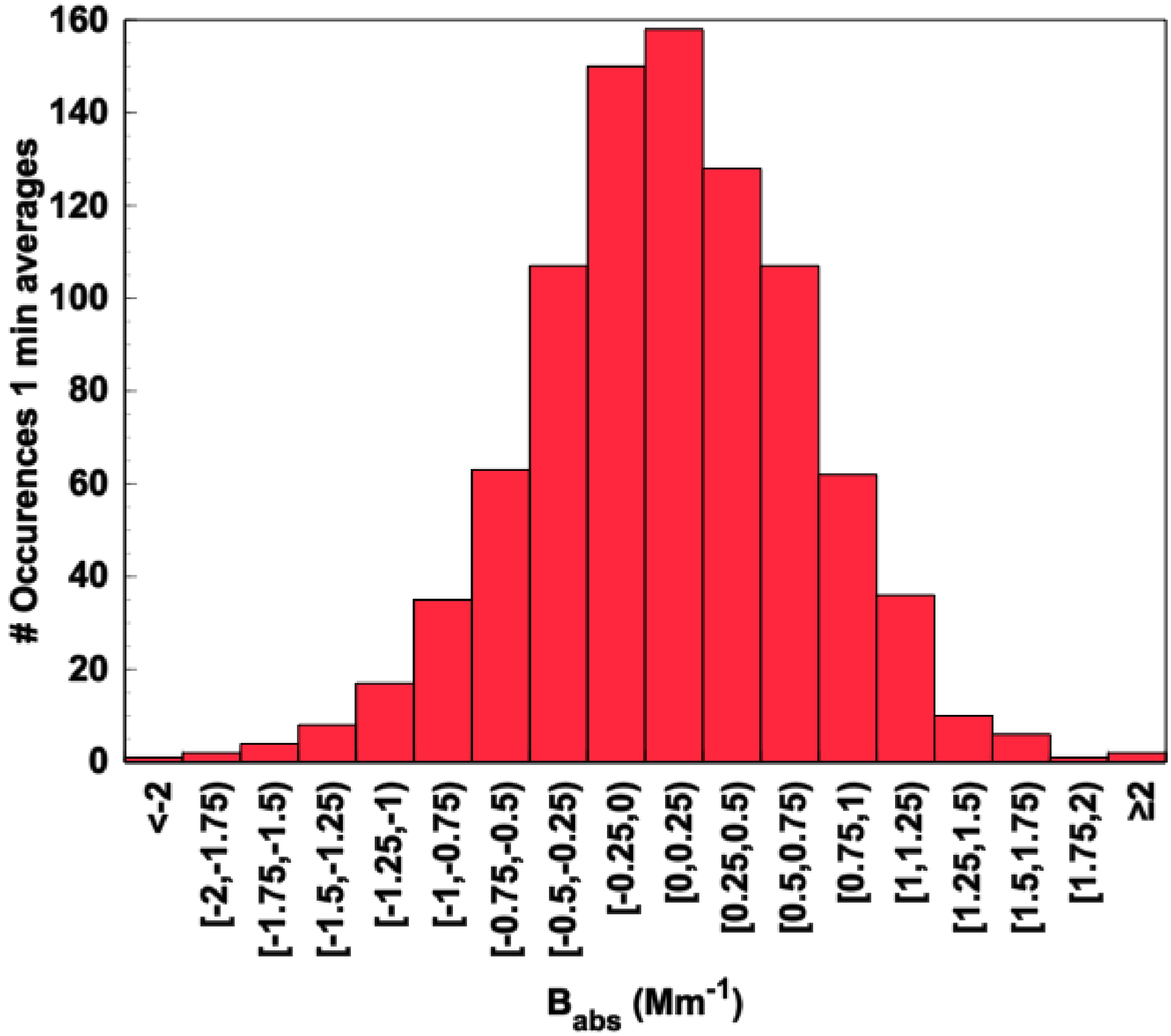


Figure 16. Histogram of 1 minute time averaged photoacoustic measurements with a particle filter over the inlet.

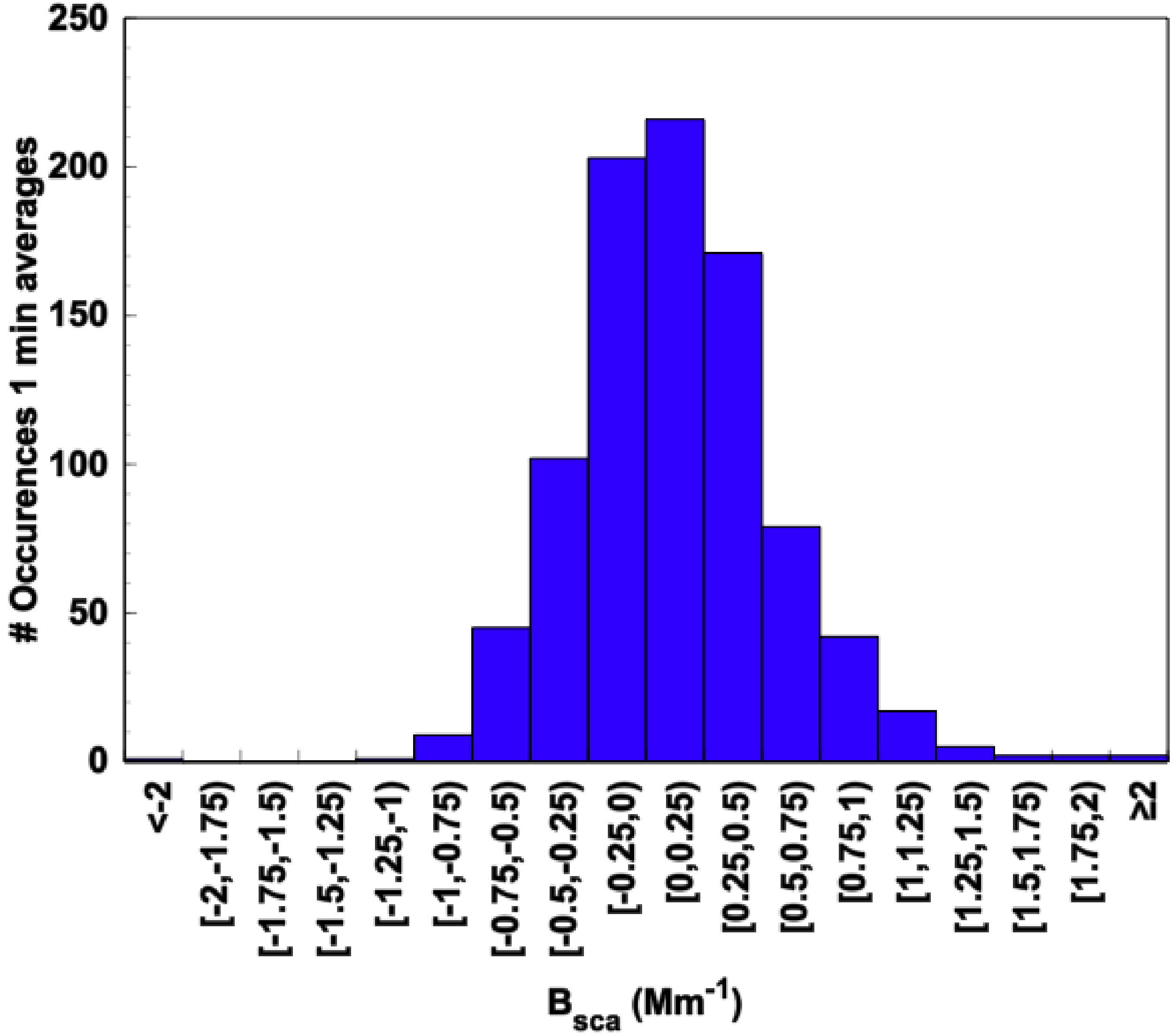


Figure 17 Histogram of 1 minute time averaged aerosol scattering measurements with a particle filter over the filter inlet, to investigate the instrument noise performance.

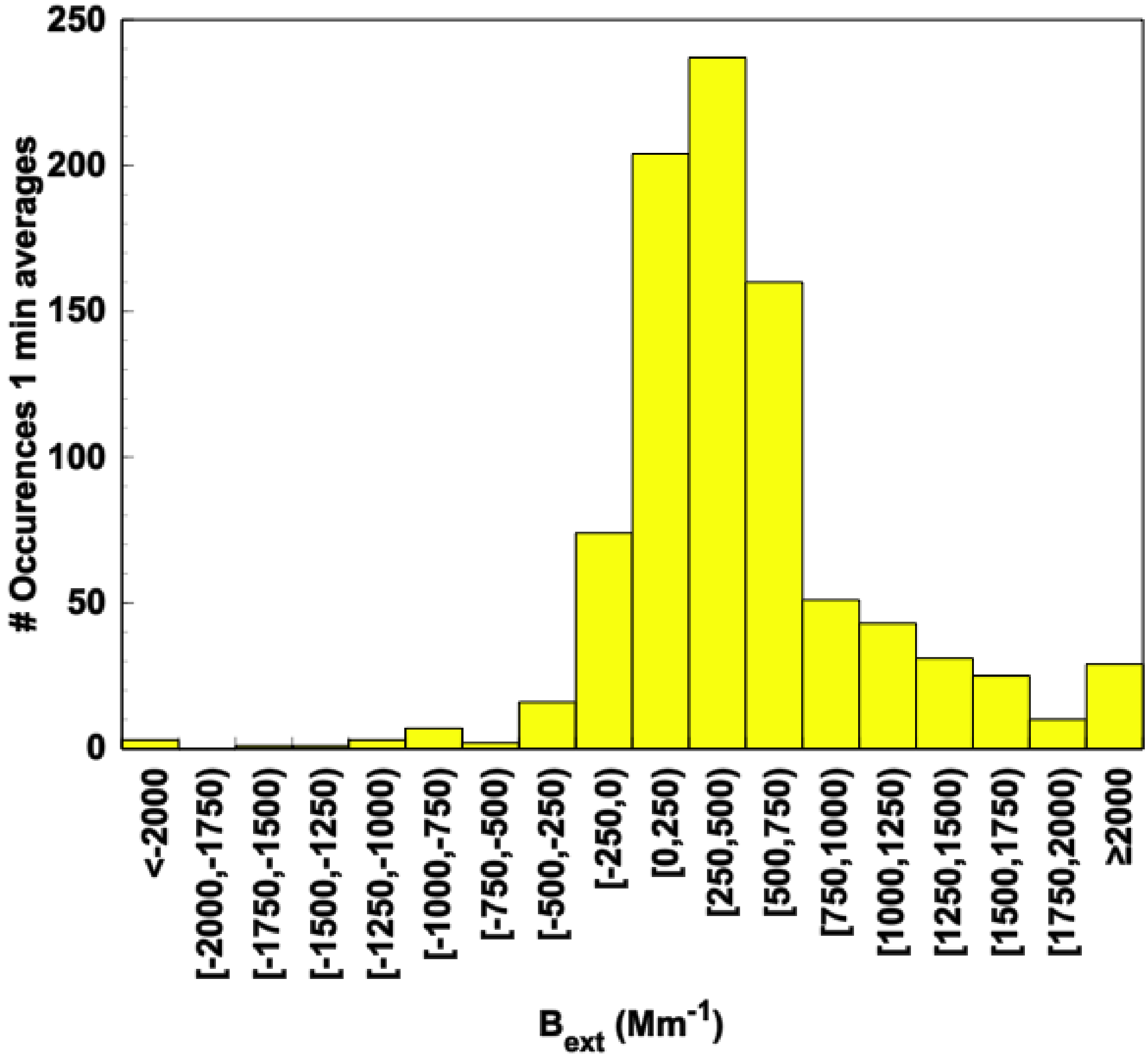


Figure 18. Histogram of 1 minute time averaged extinction measurements obtained with a filter over the instrument inlet to investigate noise performance. Note that extinction was obtained from the laser power, and is fundamentally not as precise as extinction obtained from the sum of scattering plus absorption. However, it is very useful for quantifying instrument calibration at levels of extinction greater than 10,000 Mm^{-1}.

Appendix 1. Details of the Scattering Sensor Design

Figure 15 illustrates one important idealization of nephelometers, that the sensor head has an exact cosine response to radiation coming in at an angle relative to the sensor surface normal. In practice, the sensor head design is made to best approximate the cosine response. Deviations from cosine are termed 'angular nonidealities' of the nephelometer.

Figure 19 shows our ptfe (Teflon) sensor head design, and figure 20 shows the aluminum housing that adapts the sensor to the sample tube. Figures 19 and 20 together constitute the 'scattering sensor' in the optical layout for the instrument given in Figure 10.

A goniometer setup was devised to measure the angular response of the sensor head. A green LED light source was used, and the angle of light from the LED to the sensor head normal was adjusted between 0 and 90 degrees. Figure 21 shows the measurements of angular response along with the theoretical cosine curve that it should match. The truncation angle of the sensor head is determined by the location of the apertures in the scattering sensor in Figure 10, and the location of the sensor head. The truncation angle is 3.6 degrees, and so a lot of the angular nonideality near 90 degrees induced by using a cone shaped sensor is removed by angular truncation, and is labeled 'truncation loss' in figure 21. However, at the same time, angular nonideality produces additional contribution in scattering from about 72 degrees to 86 degrees. The additional scattering helps offset the loss due to truncation.

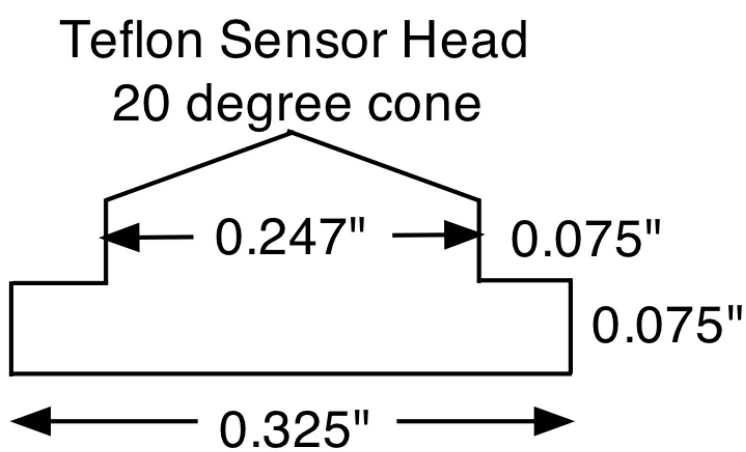


Figure 19. Scattering sensor head design for the nephelometer. Material is ptfe (Teflon).

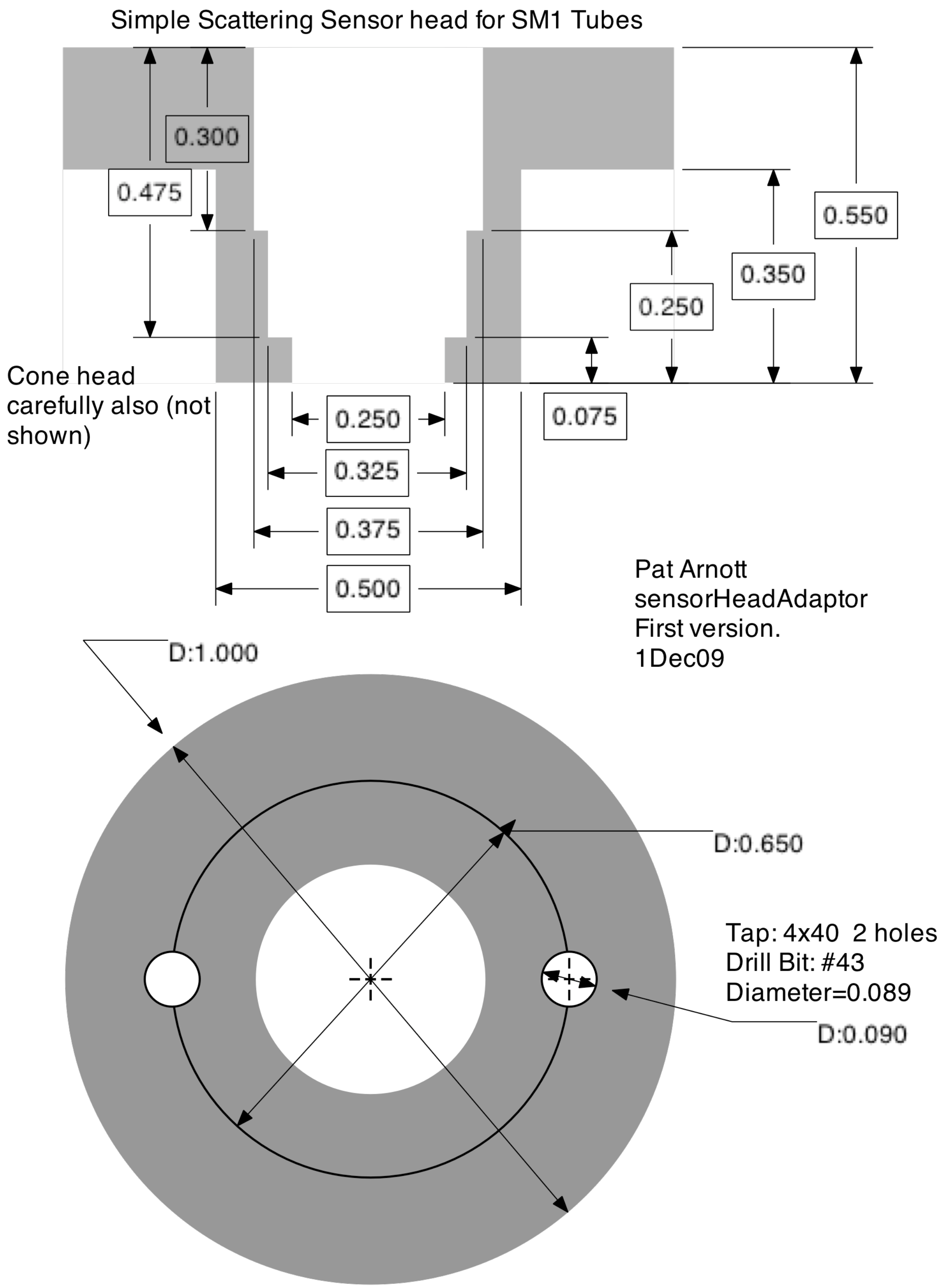


Figure 20. Scattering sensor head housing.

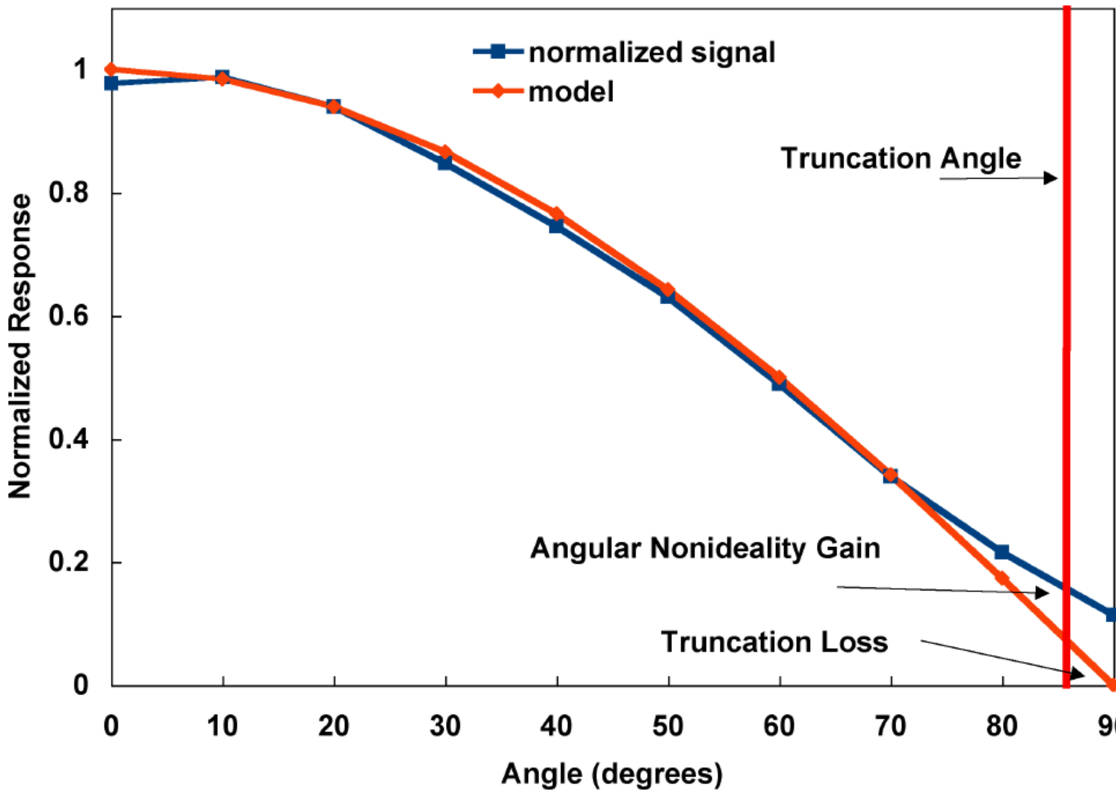


Figure 21. Measured angular response of the sensor head and holder show in Figure 19 and 20. The sensor head conforms closely to the model curve (cosine function) until an angle of about 70 degrees. Then the sensor head receives more radiation than the model suggests. However, the apertures in Figure 10 cause angular truncation and cut off of response all together at angles larger than about 86 degrees. The actual amount of signal lost or gained is determined by the product of the normalized response times the aerosol scattering phase function that tends to be a strongly increasing function of angle as the angle approaches 90 degrees (corresponding to exact forward or backward scattering.) Therefore, angular truncation losses are partially offset by the angular nonideality gains, making the nephelometer closer to an ideal instrument that measures at all angles.

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