PM Light Extinction Monitoring* for a Possible Secondary PM NAAQS Based on Visibility-Related Welfare Effects

Prepared by Marc Pitchford for
Presentation at the AAMMS Subcommittee Advisory Meeting
Washington, DC – Feb. 24th & 25th, 2010

* While this presentation exclusively concerns PM light extinction monitoring, EPA is also considering PM mass concentration indicators for a possible visibility effects related to the secondary PM NAAQS. A more complete discussion is included in the PM Policy Assessment document (in preparation).

Background & Purpose

- As part of its PM NAAQS review, EPA is considering a secondary standard to protect against visibility based welfare effects that is different from the primary standard.
- Light extinction (i.e. fractional loss of light per unit distance caused by scattering and absorption by particles and gases) is more closely tied visibility effects than PM mass concentration.
- PM light extinction (component of light extinction caused by PM) is the largest contributor to light extinction during hazy conditions and it is directly measurable
- Purpose of this presentation is to introduce the monitoring goal and describe monitoring options that could be used to meet that goal
- Overall purpose of this AAMMS advisory is to seek feedback concerning PM light extinction monitoring approaches for use in implementing a possible PM secondary NAAQS
  - Establish a specific FRM, or specifications and procedures for approval of a FRM
  - Specifications and procedures for approval of a FEM
  - Provide network design and probe siting criteria

Monitoring Goal

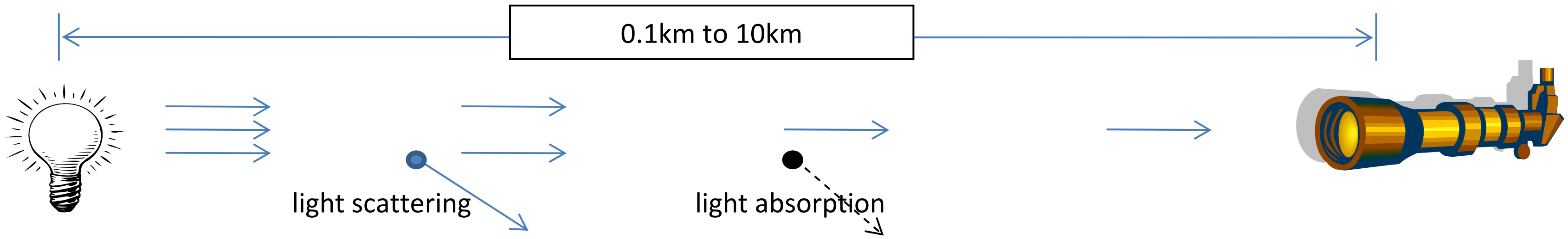
- Metric – Hourly averaged PM_{10} light extinction at 550nm wavelength
  - Haze impacts are instantaneous, but hourly data captures the generally more slowly changing urban haze levels throughout the day
  - Most PM light extinction is by $PM_{2.5}$, but for some cities $PM_{10-2.5}$ is a major contributor
  - Humans are most sensitive to light at ~550nm
- Range/Quality – 10 Mm^{-1} to 1000 Mm^{-1} with overall accuracy/precision of $\leq$ 10% (RMS)
  - NAAQS protection levels being considered are between 60 Mm^{-1} and 200 Mm^{-1} and maximum urban values above 1000 Mm^{-1}
  - A change of less than 10% in light extinction is typically imperceptible
- Constraints – Daylight hours with relative humidity $\leq$ 90%
  - Secondary NAAQS would only apply to daylight hours where visibility issues are best understood
  - High relative humidity is often associated with natural causes of haze (e.g. fog and precipitation)

Monitoring Options

- Multiple instrumental approaches, including commercially available units that can meet the goal
  - Light extinction (long-path transmissometer or folded path systems)
  - Separate measurements of PM light scattering and absorption
  - Both PM light scattering by nephelometer and light absorption by filter transmission monitoring have been used successfully in long- and short-term monitoring programs for several decades,
  - However other promising approaches might ultimately prove to be superior

Measurement Approaches

Long-Path Transmissometer



Advantages:

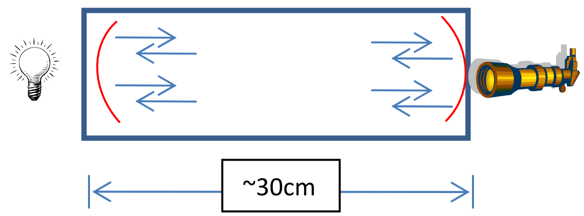
•One instrument measures light extinction (scattering and absorption)
•No particle modification caused by sample handling
•Path-averaged measurement may be more representative than point measurements
•Short and long-path versions are commercially available
•Can measure at selected wavelengths

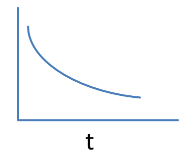
Disadvantages:

•Cannot exclude particles exceeding 10 µm, including fog, precipitation, etc.
•Calibration is problematic for long-path instruments
•Siting requirements for long-path instruments can be difficult to meet
•Cost can be high (> $25k)

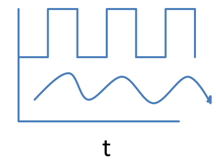
Measurement Approaches

Cavity Ring Down and Cavity Attenuation Phase Shift





Rate of pulse decrease related to light extinction



Frequency phase shift related to light extinction

Advantages:

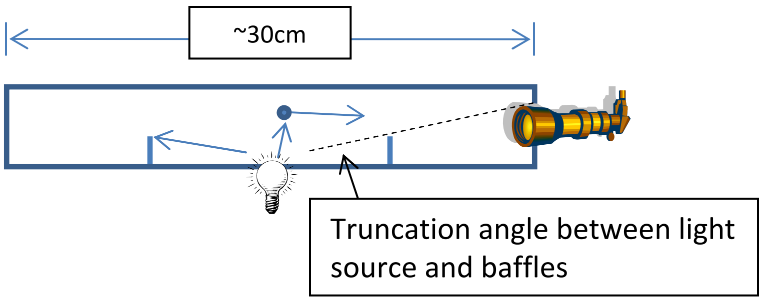
- One instrument measures light extinction (scattering and absorption)
- Can exclude particles larger than 10 µm
- Can be calibrated with well characterized standards

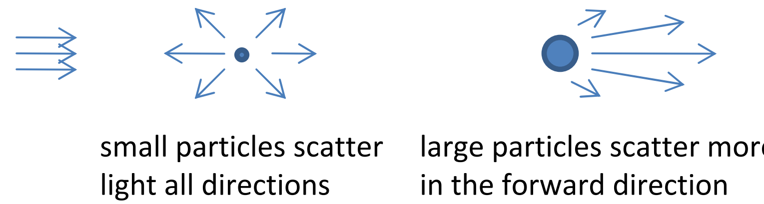
Disadvantages:

- Coarse particle sampling is a concern
- Relative humidity changes due to sample heating or cooling are a concern
- Laser-dependent wavelengths (e.g., 531 nm, but not 550 nm)
- Not currently commercially available

Measurement Approaches

Integrating Nephelometer for light scattering



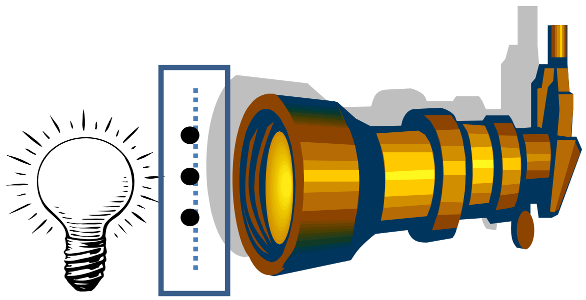


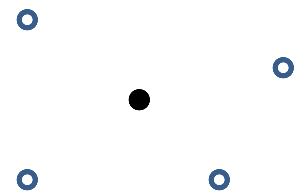
Advantages:
- Can exclude particles larger than 10 µm
- Calibration with well characterized standards
- Several commercially available instruments
- Has been used routinely for many years

Disadvantages:
- Only measures light scattering so absorption must be measured separately
- Coarse particle sampling is a concern
- Relative humidity changes due to sample heating and cooling is a concern
- Angular truncation causes underestimation of coarse particle scattering

Measurement Approaches

Filter Transmission for Particle Absorption





Optical interaction minimal in the atmosphere because of distances between particles

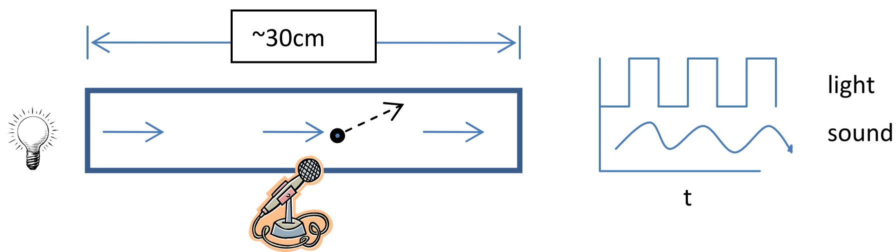
Close proximity of particles to each other and to filter fibers causes increased light absorption

Advantages:
•Can exclude particles larger than 10 µm
•Several commercially available instruments
•Has been used routinely for many years

Disadvantages:
•Only measures light absorption so scattering must also be measured
•Data adjustments required due to filter fibers and particles introduced biases
•Most existing units operate at a single wavelength far from 550nm wavelength

Measurement Approaches

Photoacoustic Absorption



Advantages:

•Can exclude particle larger than 10 μm

•Gives ambient PM absorption without adjustments (as required for filter transmission)

•Commercial units are available

Disadvantages:

•Only measures light absorption so scattering must also be measured

•Currently available commercial units are expensive (~$40k)

•Laser-dependent wavelengths includes 531nm, but not 550nm

Measurement Approaches

Nephelometer-Photoacoustic Hybrid Devise

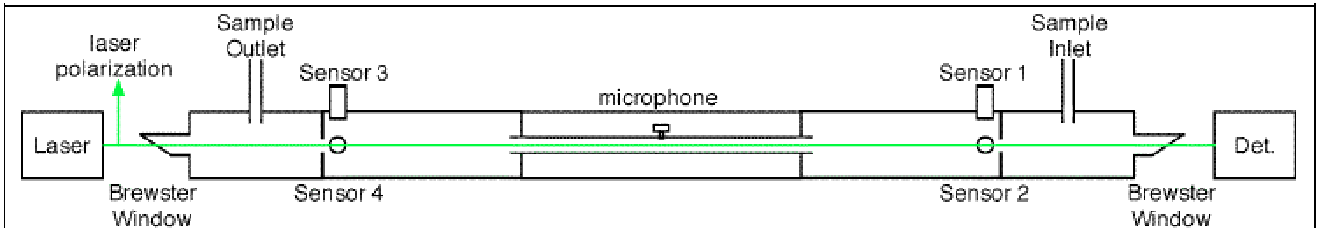


Figure 5. Schematic of the highly sensitive compact instrument for aerosol light absorption and light scattering measurements. The microphone is attached at the center of the ½ wavelength acoustical resonator. The operating frequency is 1500 Hz. The acoustical resonator diameter is ¼" and the adjacent buffer tubes have diameter 1". Brewster windows optimally pass the component polarization shown with little loss, and they prevent back reflection into the laser.

From Arnott, et al., 2009

Advantages:

•One instrument measures both light scattering and absorption

•Nephelometer has a very small cutoff angle (< 3.5 degrees) and makes separate forward and backscattering measurements

•Component cost is low so overall cost is expected to be reasonable

Disadvantages:

•Coarse particle sampling is a concern

•Relative humidity changes due to sample heating and cooling is a concern

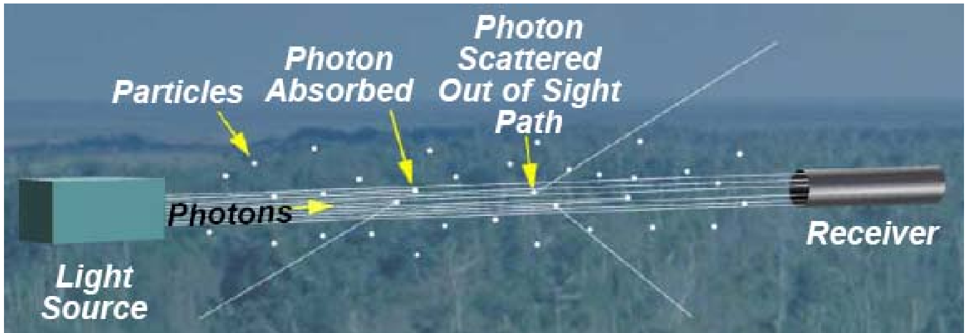
•Only prototype units have been built, not yet commercially available

Possible Next Steps*

- Compile and assess available information to determine most applicable approaches
  - Instrument reviews, and laboratory and field performance evaluations
  - Validation testing and operational experience
  - Use available information in error propagation analysis
- Measurement intercomparison studies
  - Field and/or laboratory environment selected to produce challenging conditions for the instruments
  - Would provide first hand operational and performance characteristic
- Deploy a modest prototype network of the most promising candidate instruments for a limited time
  - Operated by state/local agencies for most realistic operational and performance feedback
  - Would provide earliest light extinction data that could be helpful for the next PM NAAQS review
- Information gained in these steps* would guide selection of FRM device or preparation of performance standards/testing procedure

* The value of conducting each of these steps will be evaluated with respect to resource and time limitations.

Supplemental Information



The system consists of an incandescent light source (or transmitter), and a computer-controlled photometer receiver. The transmitter emits a uniform light beam precisely aimed at a receiver located from 1 to 10 kilometers away. The transmissometer receiver measures only the photons that successfully pass through the atmosphere. The receiver isolates transmitter light from ambient light and records the transmission of the intervening atmosphere. Visibility results are calculated and reported as visual range or extinction.

Receiver

Transmitter

The Optec, Inc. LPV-2 long path transmissometer has been used by IMPROVE since 1986. Transmissometers provide the most direct measure of the extinction properties of the atmosphere. Extinction is a measure of the number of photons both scattered and absorbed over a known distance through the atmosphere. Extinction data is useful for relating visibility directly to particle concentrations.

TABLE 1
Nephelometer models and specifications

From Mueller, et al., 2009

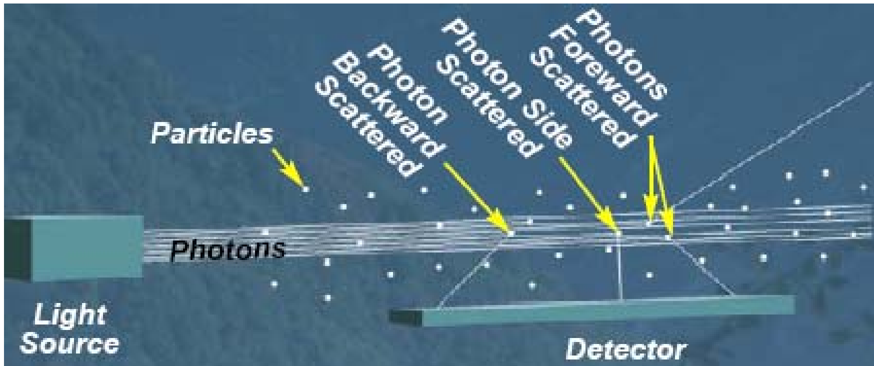
Manufacturer	Model	Number of units	Light source	Wave-length	Bandwidth FWHM	Angular integration range
TSI St. Paul, MN USA	3563	15 3/15 for illumination	Incandescent quartz-halogen, opal glass diffuser	450, 550, 700 nm	40 nm	7° to 170°
Radiance Research Seattle, WA USA	M903	2	Xenon flash lamp, opal glass diffuser	540 nm*	40 nm	10° to 170°
Ecotech Knoxfield, VIC Australia	9003	3	7 LED tuned array, ground glass diffuser	525 nm	60 nm	12° to 165°

*The wavelength of the Radiance M903 nephelometer with a Corion CA 550S interference filter is given as 545 nm in the manufacturer's manual. The value of 540 nm in Table 1 is from a measurement of the combined effective wavelength of light source, filter, and photomultiplier detector (Anderson et al. 2003).

1. Table 1. Integration angles for various integrating nephelometers.

ROVE web site.

Nephelometer	Integration Angle (deg)
Optec NGN	5 to 175
TSI 3563	7 to 170
Belfort 1590	8 to 170
Radiance Research M903	10 to 165



The Nephelometer draws ambient air into a chamber where light of known intensity is emitted over a path parallel to a photodiode detector. With this configuration only the photons that are scattered will be detected. The instrument is designed in such a way that the sampling chamber and light source are confined to a small volume so the instrument makes a "point" or localized measurement of scattering. A direct estimate of atmospheric scattering is made by measuring the light scattered from the front, back, and sides of the optical chamber. Because the scattered light is integrated over a large range of scattering angles, the instrument is referred to as an INTEGRATING nephelometer.

Standard nephelometer stations are mounted near the top of a 14-foot tower on the north face. A solar radiation and precipitation shield are installed to protect the instrument from severe precipitation (rain, hail, snow) and keeps direct sunlight off the monitor. This allows the instrument to be maintained at close to ambient temperatures. Temperature and relative humidity sensors are often installed as part of the standard nephelometer configuration.

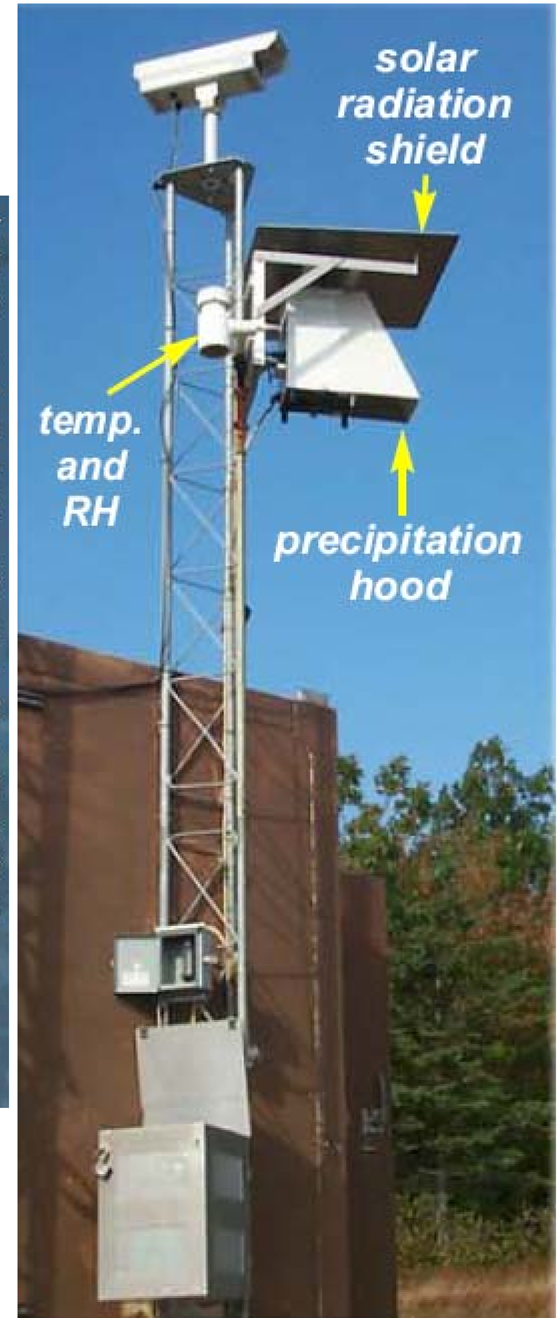


Table 3
Some commercially available instruments related to the measurement of aerosol light absorption.

Instrument name	Company	Principle	Nominal wavelength(s)
Aethalometer (AE22 & AE31 & AE42 & AE45)	Magee Scientific Company, 2020 Stuart Street, Berkeley, CA 94703, USA. Tel.: +1510-845-2801. http://www.mageesci.com	BC mass density from real time filter transmission, automatic filter change	880 nm (AE45) 370 & 880 nm (AE22) 370 & 880 nm (AE42) 370 & 470 & 520 & 590 & 660 & 880 & 950 nm (AE31)
Particle Soot Absorption Photometer (PSAP)	Radiance Research Inc., 535 N.W. 163rd Street, Seattle, WA 98177, USA. Tel.: +1206-366-7981	Aerosol absorption coefficient from real time filter transmission	565 nm
Micro Soot Sensor (AVL 483)	AVL LIST GMBH, Hans-List-Platz 1, A 8020 Graz, Austria, Tel.: +6143 316787x0. info@avl.com. http://www.avl.com	BC mass density (for source characterization) from real time, in-situ photoacoustic signal	808 nm
Multi-Angle Absorption Photometer (MAAP model 5012)	Thermo Fisher Scientific Inc., 81 Wyman Street, Waltham, MA 02454, USA. Tel.: +1866 2820430. http:// [illegible]	Aerosol absorption coefficient, BC mass density from real time filter transmission with scattering correction, [illegible]	670 nm
Photo-Acoustic Soot Spectrometer (PASS-1 & PASS-3)	Droplet Measurement Technologies, 5710 Flatiron Parkway Suite B, Boulder, CO 80301, USA. Tel.: +1303 440 5576. info@dropletmeasurement.com. http://www.dropletmeasurement.com	Aerosol absorption coefficient from real time, in-situ photoacoustic signal	781 nm & custom (PASS-1) Three custom wavelengths (PASS-3)

From Moosemuller, et al. 2009.

Aethalometer Optical Schematic

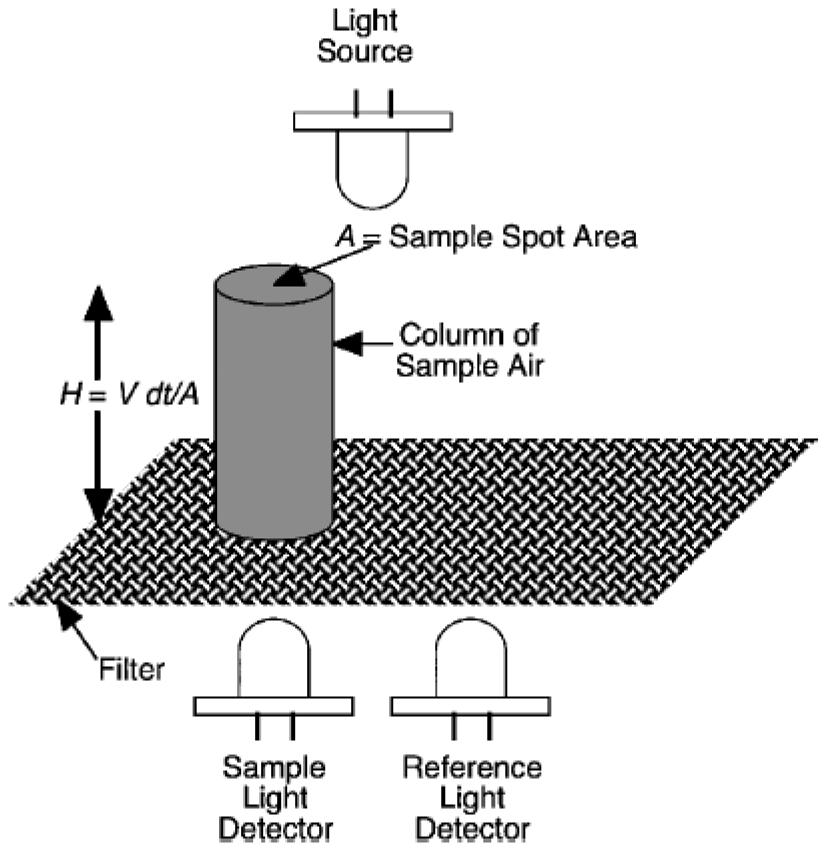


Figure 1. A column of aerosol-laden sample air of height H is deposited on the filter in time dt. Then the light source and detector are used to measure the filter transmission. Filter transmission at time t and at time $t + dt$ is used to estimate aerosol BC concentration as described in the text. A reference light detector over a pristine portion of the filter is used to measure variations in the source output. From Arnott, et al., 2005.

Particle Soot Absorption Photometer (PSAT)

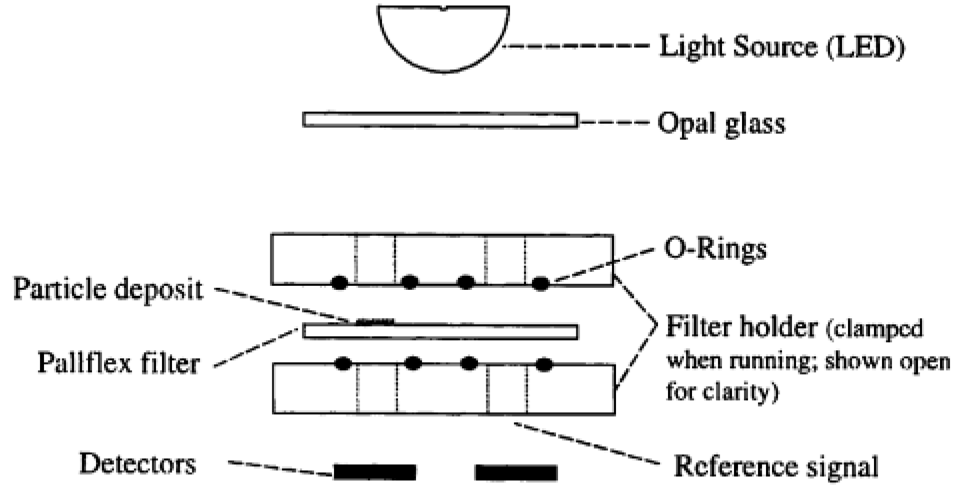


Fig. 5. Cross-section of the filter setup in the PSAP. The sample is drawn through one of the holes, shown on the left, and the particles are deposited on the filter. Filtered air is drawn through the hole shown on the right for a reference measurement (from [37], Aerosol Science & Technology: Calibration and Intercomparison of Filter-Based Measurements of Visible Light Absorption by Aerosols. (30):582–600. Copyright 1999. Mount Laurel, NJ. Reprinted with permission).

Multi-Angle Absorption Photometer (MAAP)

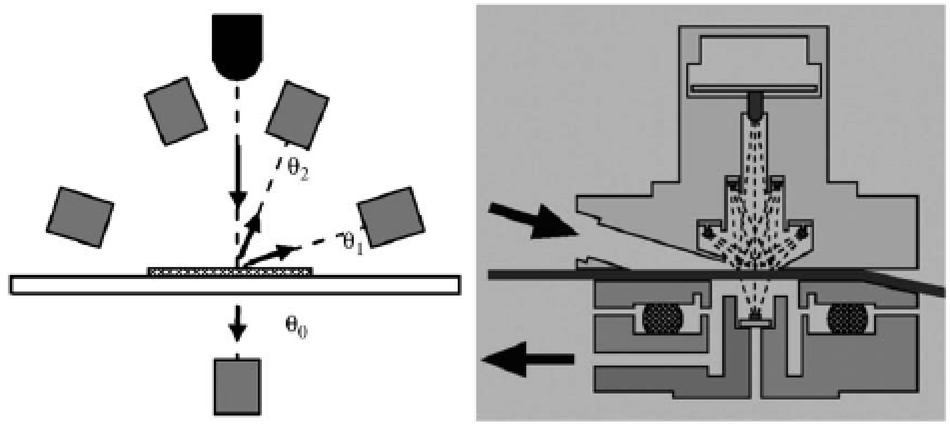


Fig. 6. Optical sensor of the MAAP. Left: position of the photodetectors at detection angles $\theta_0 = 0°$, $\theta_1 = 130°$, and $\theta_2 = 165°$ with respect to the incident light beam ($\lambda_{MAAP} = 670$ nm). Right: layout of the MAAP sensor unit, arrows indicate the airflow through the sensor unit across the filter tape (from [41], Aerosol Science & Technology: Evaluation of Multiangle Absorption Photometry for Measuring Aerosol Light Absorption. (39):40–51. Copyright 2005. Mount Laurel, NJ. Reprinted with permission).

From Moosemuller, et al. 2009.

Model 5012 MAAP *Continuous Black Carbon Monitor:*
***M**ulti-**A**ngle **A**bsorption **P**hotometer*