Atmospheric Aerosol Physics, Physical Measurements, and Sampling

Filter-Based Absorption Photometers

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European Center for Aerosol Calibration

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World Calibration Centre for Aerosol Physics

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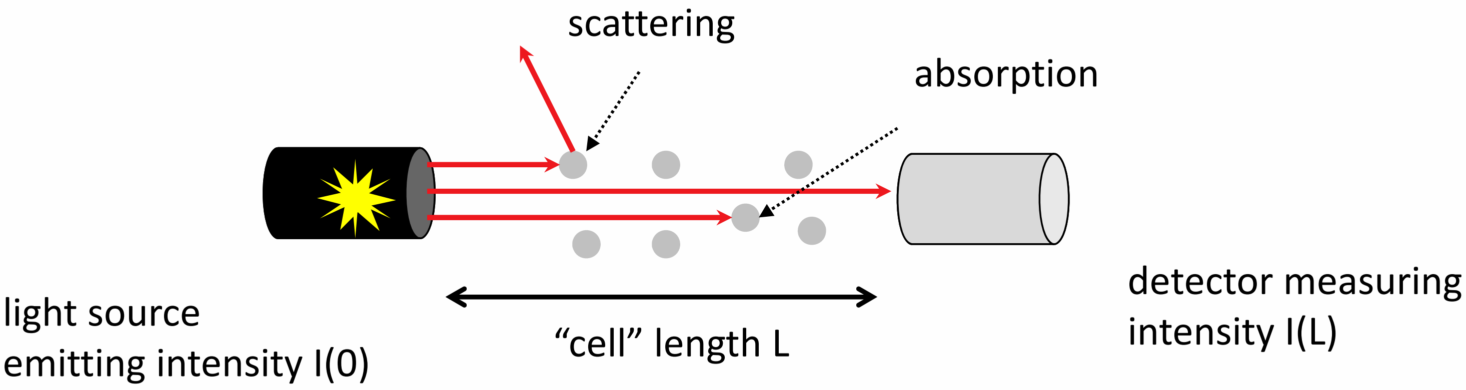
Particle Light Absorption

- Absorption is the process by which the energy of a photon is taken up by another subject (here particles).
- The photon is destroyed.
- In the atmosphere, light is absorbed by both gas molecules and by aerosol particles.
- Absorption by gases is usually weak compared to absorption by aerosol particles.
- The use of Absorption Photometers is:
  - to measure the particle light absorption coefficient
  - to estimate a corresponding particle mass concentration of Black Carbon

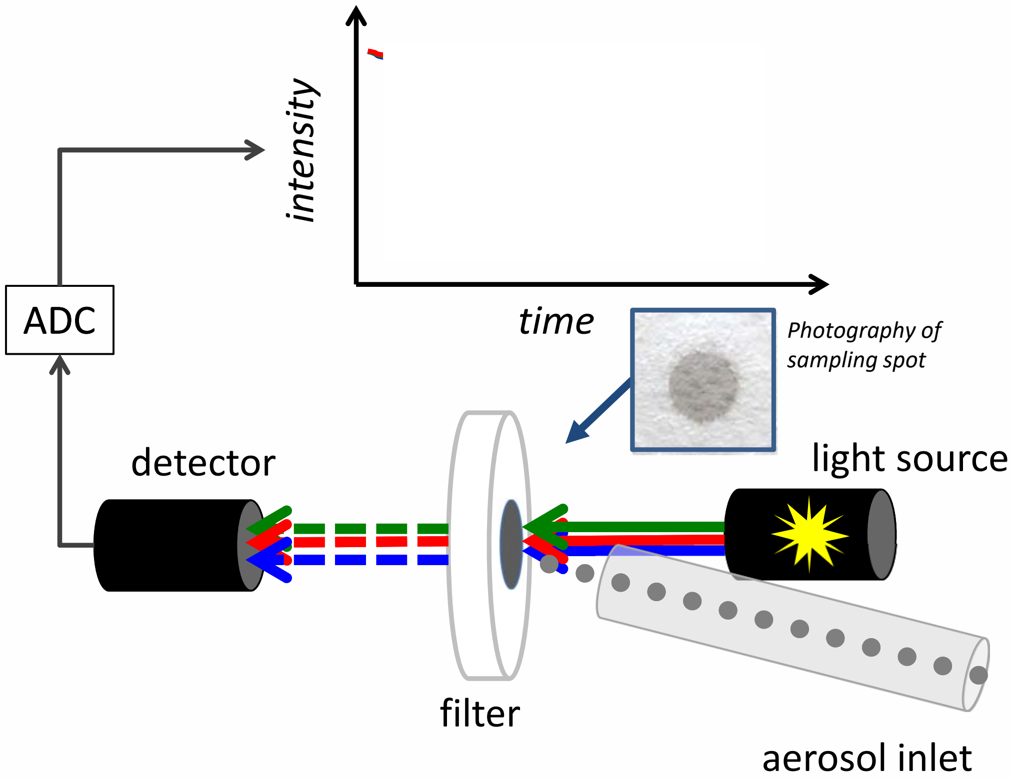
Lambert-Beer Law



$$\frac{I(L)}{I(0)} = e^{-\sigma_{ext} \cdot L} \quad \Leftrightarrow \quad \sigma_{ext} = \frac{-\ln \frac{I(L)}{I(0)}}{L}$$

Filter-Based Absorption Photometers

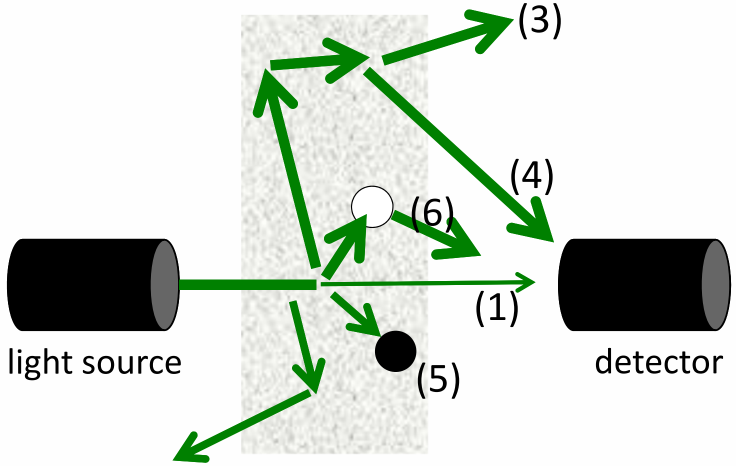
- A fibre filter is loaded with particles
- **Transmitted intensity** through system of **particle and filter** is measured
- Intensities after the filter for one or more wavelengths are recorded



Radiative transfer through a particle free filter

Light is scattered several times by the filter matrix

1. very little light passes the filter without scattering
2. light is scattered back
3. light is scattered forward
4. multiple scattered light reaches the detector



Radiative transfer through a particle loaded filter

Additionally to scattering by the particle free filter matrix, light is scattered and absorbed by particles

5. light is absorbed by particles
6. light is scattered by particles (additionally to scattering by the filter)

- The exact description of the radiation transfer is complicated. The following is a simplified description of the main points.

- Light scattering by the filter is order of magnitudes larger than scattering by particles. The internal radiation field does not change much by loading with particles.

  →The effect of additional particle scattering on the transmission of light is greatly reduced.

- Because of multiple scattering by the filter, the light path length inside the filter is larger than the filter thickness.

  → The light path enhancement factor depends on filter type and amounts between two and four.

- Light absorbed by particles reduces light transmittance. Furthermore, the enhanced light path length causes a higher probability for a photon to be absorbed by particles.

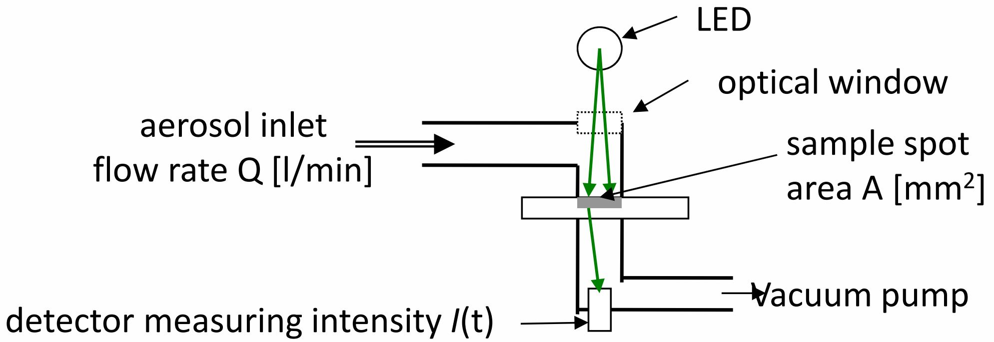
  → Light absorption is magnified by the light path enhancement factor.

Commonly used terms for particles in their airborne state and collected onto a filter

Transmittance: $\tau = \frac{I}{I_0}$. With actual intensity *I* and a reference intensity I_0.

Air-borne state (e.g. extinction cell)	Collected in a filter
Reference intensity: *Intensity before entering the cell*	Reference intensity: *Intensity through a particle free filter*
Optical depth: $OD = -ln(\tau)$	Attenuation: $ATN = -ln(\tau)$
Extinction coefficient: $\sigma_{ext} = \sigma_{sca} + \sigma_{abs}$	Attenuation coefficient: $\sigma_{atn} = f(\sigma_{sca}, \sigma_{abs}) \approx f_1 \cdot \sigma_{sca} + f_2 \cdot \sigma_{abs}$
***OD* and *ATN* are the integral values of σ_{ext} and σ_{atn}, respectively**	
$OD(L) = \int_0^L \sigma_{ext}(l)\, dl$ $\sigma_{ext}(l) = \frac{d\ OD(l)}{dl}$	$ATN(L) = \int_0^L \sigma_{atn}(l)\, dl$ $\sigma_{atn}(l) = \frac{d\ ATN(l)}{dl}$

Determining the particle light absorption coefficient using an Absorption Photometer



While loading the filter with particles the intensity *I*(t) and is measured and Attenuation is calculated by $\boldsymbol{ATN = -ln(\tau)}$

Here, *dl* is the increment of the column of air sucked through the filter is $\boldsymbol{dl = \frac{Q}{A} \cdot dt}$

Substituting the path length *l* by time *t* (equation from previous slide)

$$\boldsymbol{\sigma_{atn}(l) = \frac{d\,ATN(l)}{dl} \quad \Rightarrow \quad \sigma_{atn}(t) = \frac{Q}{A}\frac{d\,ATN(t)}{dt}}$$

Then, the absorption coefficient is (c.f. equation from previous slide):

$$\boldsymbol{\sigma_{abs} \approx \frac{\sigma_{atn} - f_1 \cdot \sigma_{sca}}{f_2}}$$

Particle Soot Absorption Photometer

- The absorption needs to be calibrated because of
  - the increased sensitivity (light path length enhancement) to particle absorption
  - the remaining cross sensitivity to particle scattering
- Calibration of this type of absorption photometers (Bond, 1999):

$$\sigma_{abs} = \frac{\sigma_{atn}}{1.317\,\tau + 0.886} - 0.016\,\sigma_{sca}$$

The dependence on the transmission τ is called *loading effect*.

For an unloaded filter (τ=1) The sensitivity to absorption is increased by a factor of 2.18.

The sensitivity to scattering is approx. 1.6 %.

For most atmospheric aerosol types, the particle light scattering coefficient is up to 10 times higher than the particle light absorption coefficient.

We need to correct for the particle light scattering coefficient.

Aethalometer AE31

- The functional principle of the Aethalometer is similar to that of the PSAP.
- The Aethalometer AE31 measures the absorption coefficient at 7 wavelengths

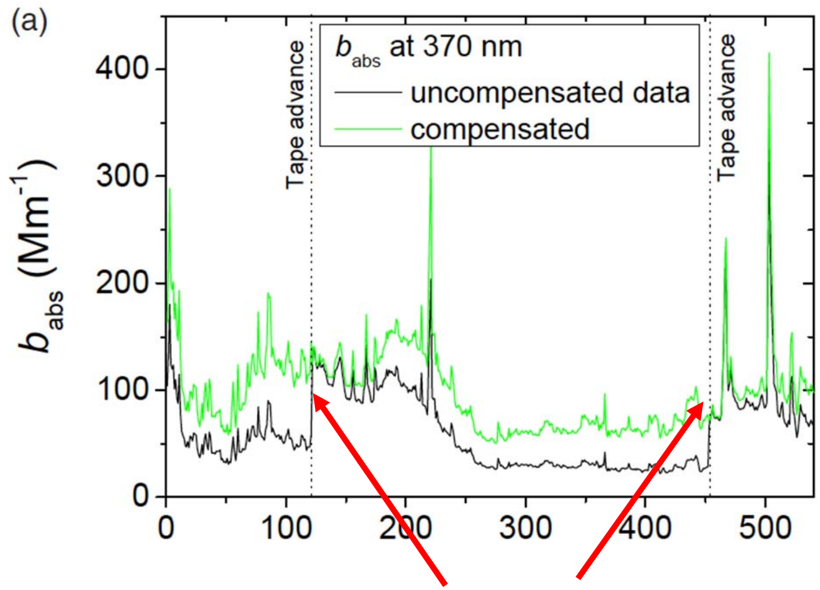
  → 370, 470, 520, 590, 660, 880, and 950 nm
- The calibration is different to the PSAP because of the use of a different filter tape.
- The calibration function of the instrument is:

$$\sigma_{abs} \approx \frac{\sigma_{atn}}{3.5\ (\pm 25\%)}$$

- Cross sensitivity to particle scattering can be neglected.
- The light path enhancement factor varies a lot depending on aerosol type.
- A loading effect was omitted in the calibration function, since the uncertainty due to the a priori unknown aerosol type is comparable large.

Aethalometer AE33

- The aethalometer AE33 is a further development of the AE31.
- The main feature is the dual spot technology to compensate for loading effects.



The particle light absorption coefficient is calculated by

$$\sigma_{abs} = \frac{d\ OD(t)}{d\ t},$$

with an empirically determined loading function of the form:

$$ATN = \frac{1}{k}\left(1 - e^{-k\ OD}\right).$$

The compensation parameter *k* is determined by the dual spot technology (shown on next slide).

Without compensation: Jump in time series occurs, when changing to an new, unloaded spot

Drinovec, et al. The "dual-spot" Aethalometer: an improved measurement of aerosol black carbon with real-time loading compensation, Atmos. Meas. Tech., 8, 1965-1979, https://doi.org/10.5194/amt-8-1965-2015, 2015.

Aethalometer AE33 dual spot compensation

Two spots are loaded simultaneously with different aerosol flows Q_1 and Q_2, respectively. Therefore, one spot has a higher loading than the other spot.

$$ATN_1 = \frac{1}{k}\left(1 - e^{-k\,OD_1}\right)$$
$$ATN_2 = \frac{1}{k}\left(1 - e^{-k\,OD_2}\right)$$

ATN_1 and ATN_2 are measured. k, OD_1 and OD_2 are unknown.
Can we solve this system of two equations for OD_1 and OD_2?

We have one more information! The ratio of the optical depth equals the flow ratio:

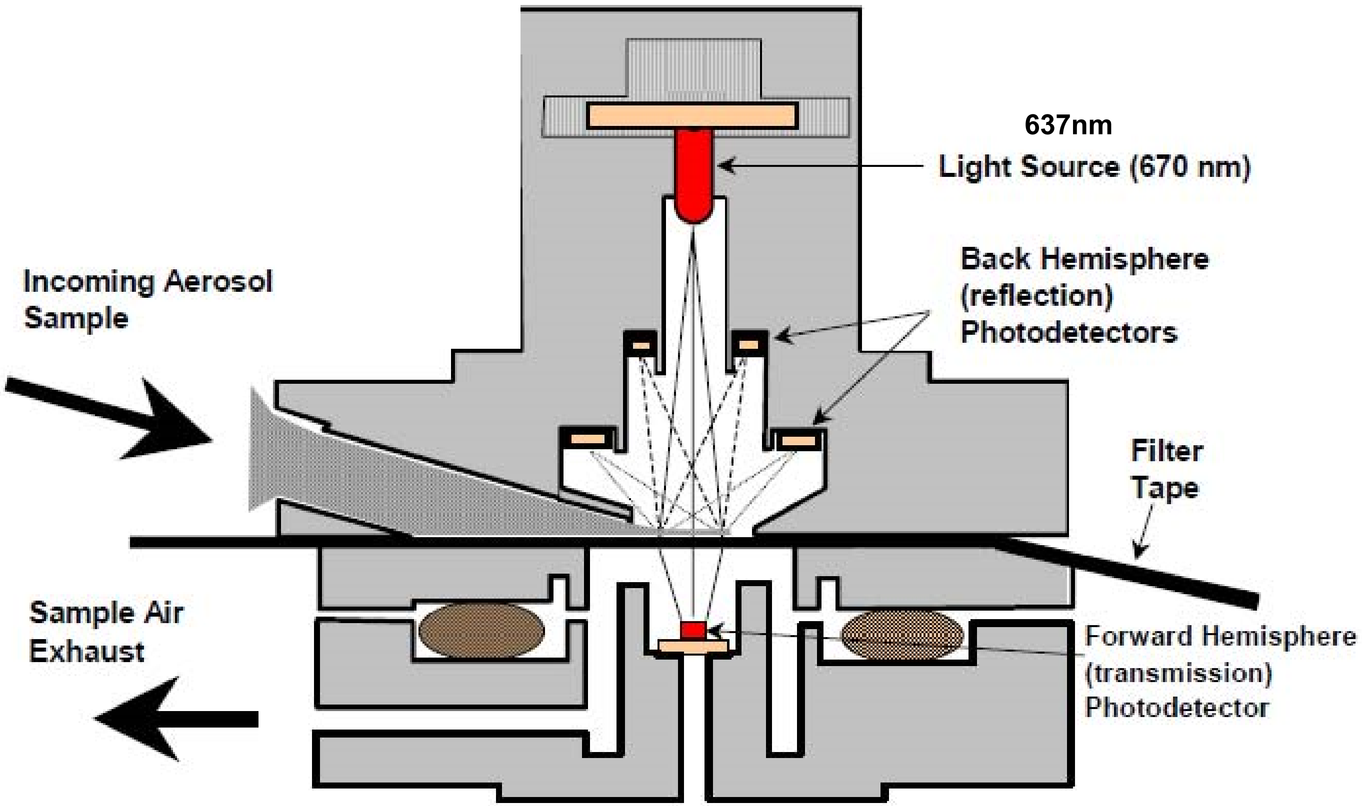
$$\frac{Q_1}{Q_2} = \frac{OD_1}{OD_2}$$

Now it is just mathematics to solve the equation for k, and OD_1 and OD_2.

Combining the information from two spots, a compensation for the loading effect can be derived while collecting particles and taking data.

Multi Angle Absorption Photometer (MAAP)

- The MAAP is another instrument with a build in loading correction.
- Intensities are measured in forward and in backward direction.



Petzold et al. 2004 JAS 421-44

Properties of MAAP

- Scattering artifacts are reduced.
- Method is based on radiative transfer calculations.
- Calculation of the absorption coefficient requires a rather complex algorithm (not explained here).
- The MAAP overcomes most problems, which occur for PSAP and Aethalometer.