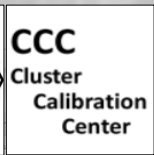
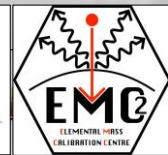
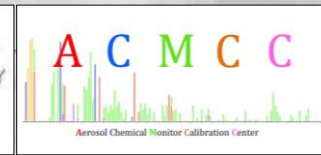


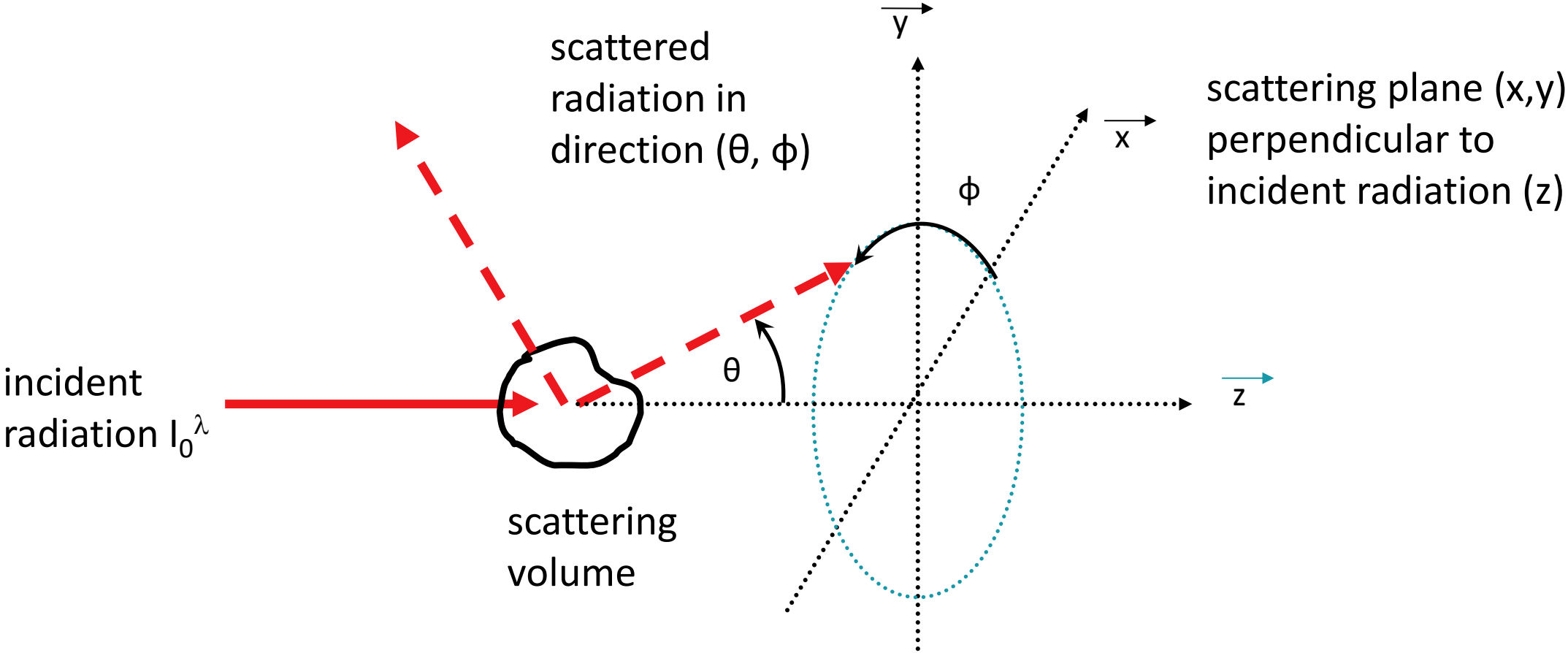
# Integrating Nephelometer - ITINERIS Training I

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# Particle Light Scattering Coefficient

# Principle of Light Scattering



## Scattering coefficient of light in a small volume:

- The integral of  $f^\lambda(\theta, \phi)$  over all directions is the spectral scattering coefficient.

$$\sigma_s^\lambda = \int_0^\pi \int_0^{2\pi} f^\lambda(\theta, \phi) \sin(\theta) d\phi d\theta$$

- The scattering function  $f^\lambda(\theta, \phi)$  gives the energy that is scattered into an increment of solid angle  $d\Omega$  in direction  $(\theta, \phi)$ .
- The dimension of  $f^\lambda(\theta, \phi)$  is  $\text{m}^{-1}\text{sr}^{-1}$ .
- The scattering angle  $\theta$  is measured from the initial direction of illumination.
- The problem for constructing a nephelometer is the correct integration including the term  $\sin(\theta)$  over the angular range  $0 \leq \theta < \pi$ .
- A nephelometer doing this integration is called an **integrating nephelometer**

## Integration for spherical particles

For spherical particles, the scattering function and the scattering coefficient simplify to

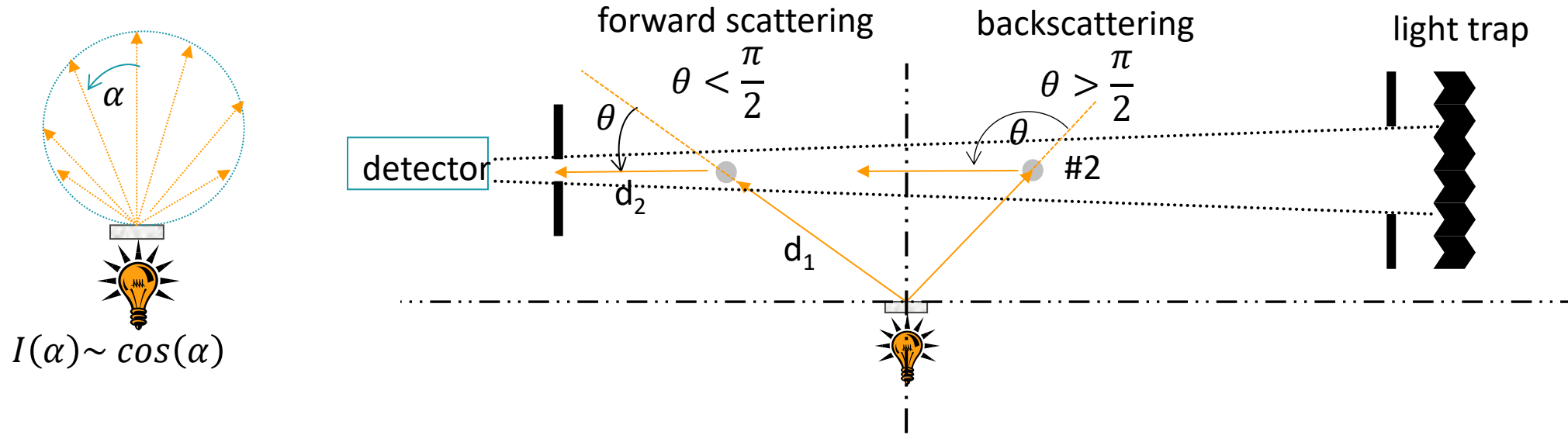
$$f^\lambda(\theta, \varphi) = f^\lambda(\theta)$$

$$\sigma_s^\lambda = 2\pi \int_0^\pi f^\lambda(\theta) \cdot \sin(\theta) \cdot d\theta$$

Based on the formula of the scattering coefficient, an integrating nephelometer can be designed.

# Principal of an Integrating Nephelometer

# Principal sketch of an integrating nephelometer with opal glass diffuser



- Integration over  $\theta$  is substituted by integration along the length of the measurement cell.
- The sinus is generated by the Lambertian radiation characteristics of the light source.
- The decrease of intensity with the square of distances ( $d_1$  and  $d_2$ ) is compensated by the opening of the cone (field of view of detector).

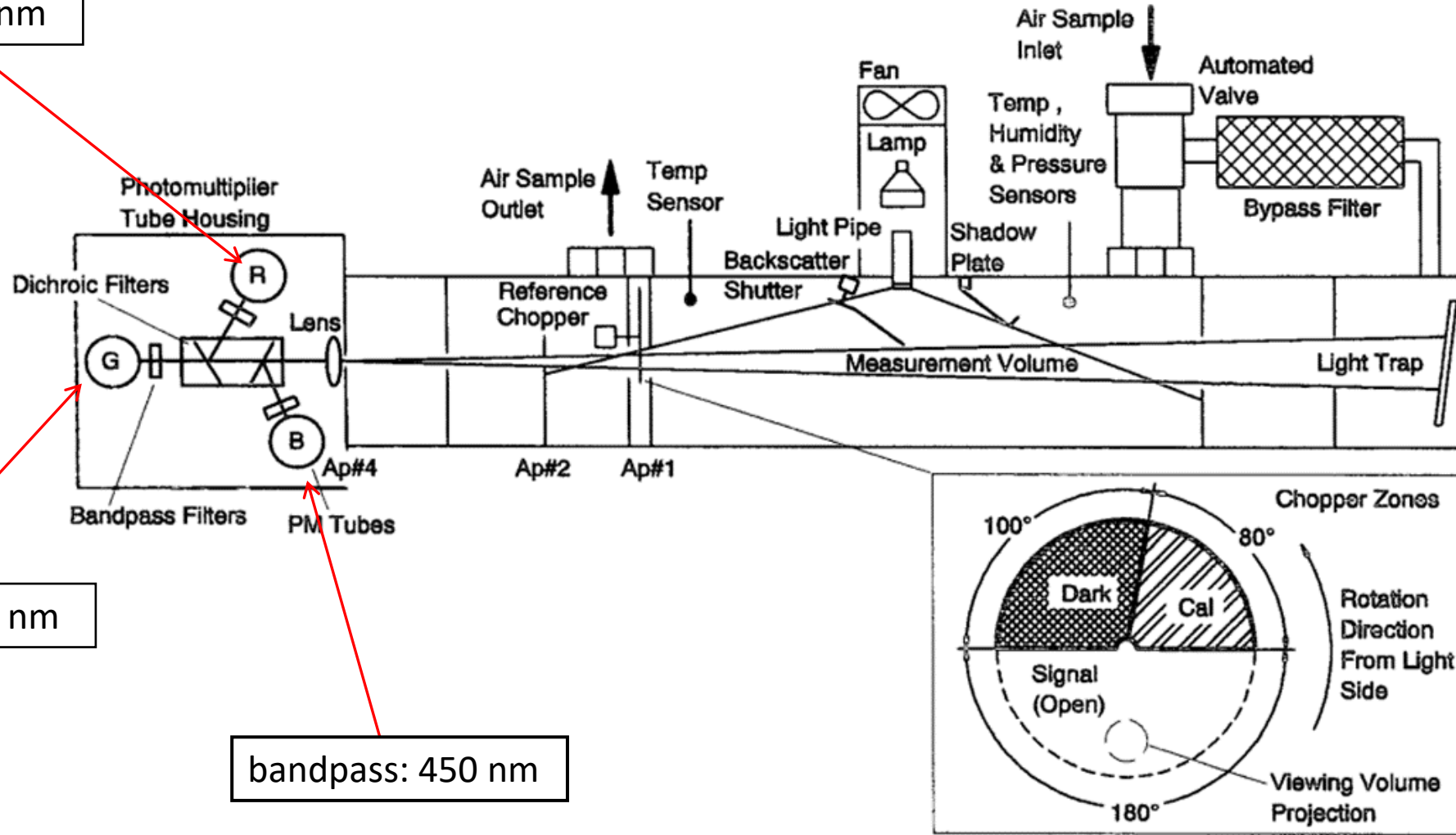
# TSI Integrating Nephelometer

# Example: TSI Integrating Nephelometer model 3563

bandpass: 700 nm

bandpass: 550 nm

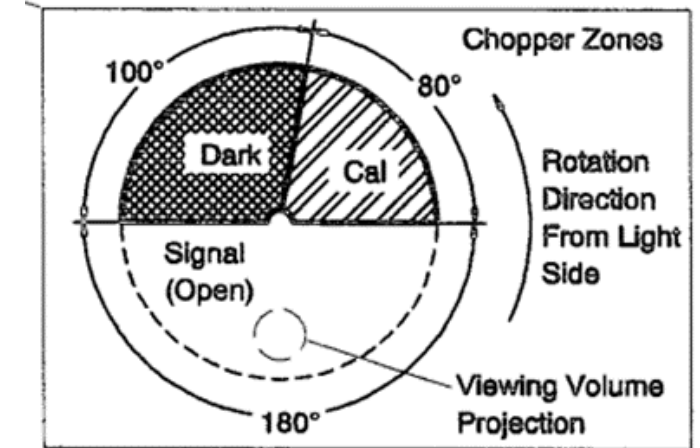
bandpass: 450 nm



## Reference chopper

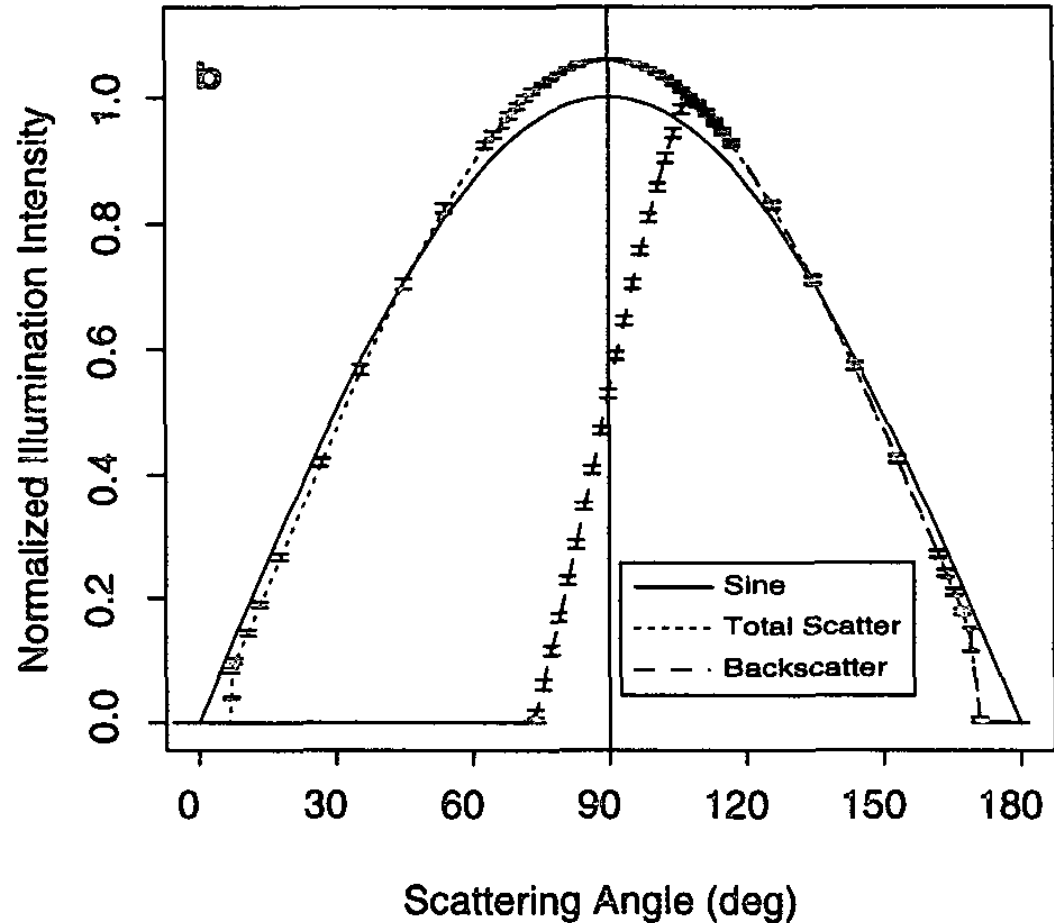
The reference chopper rotates with 23 Hz, consisting of three areas; signal, dark, calibration.

- Signal: all light can pass
- Dark: all light is blocked to provide the background noise of the photo multipliers.
- Calibration: a small fraction of illumination light can pass to check the stability of the light source



# Angular Truncation and Imperfect Illumination Function

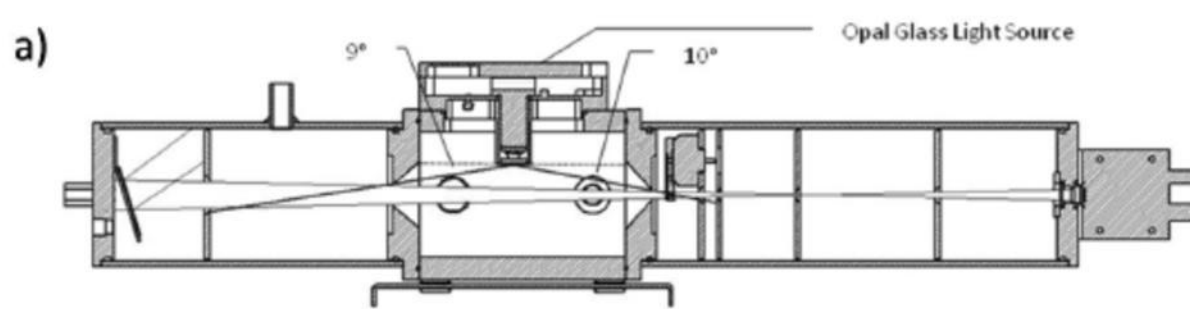
- The opal glass diffuser is not a perfect  $\sin(\theta)$ !
- Light scattered at angles smaller  $7^\circ$  and larger  $170^\circ$  can not be measured.
- These systematic uncertainties are combined in the illumination function  $Z(\theta)$ .
- The illumination function must be considered in calibrations and data evaluation.



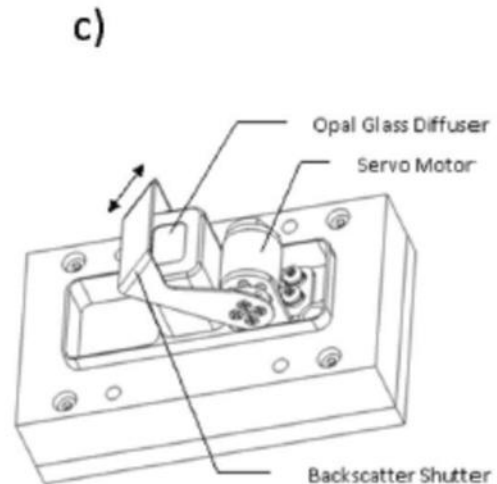
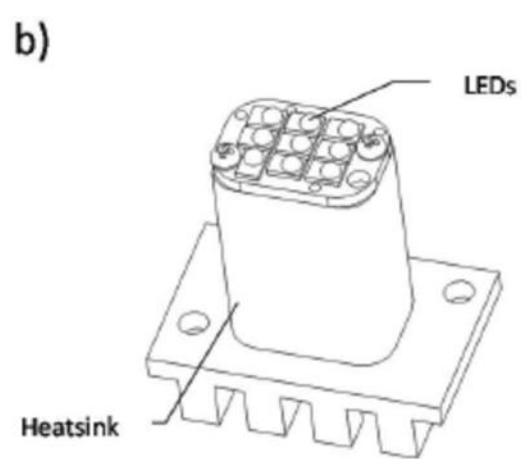
Anderson et al., 1996

# Ecotech/Acoem Integrating Nephelometer

## Example: Ecotech/Acoem 3000/4000

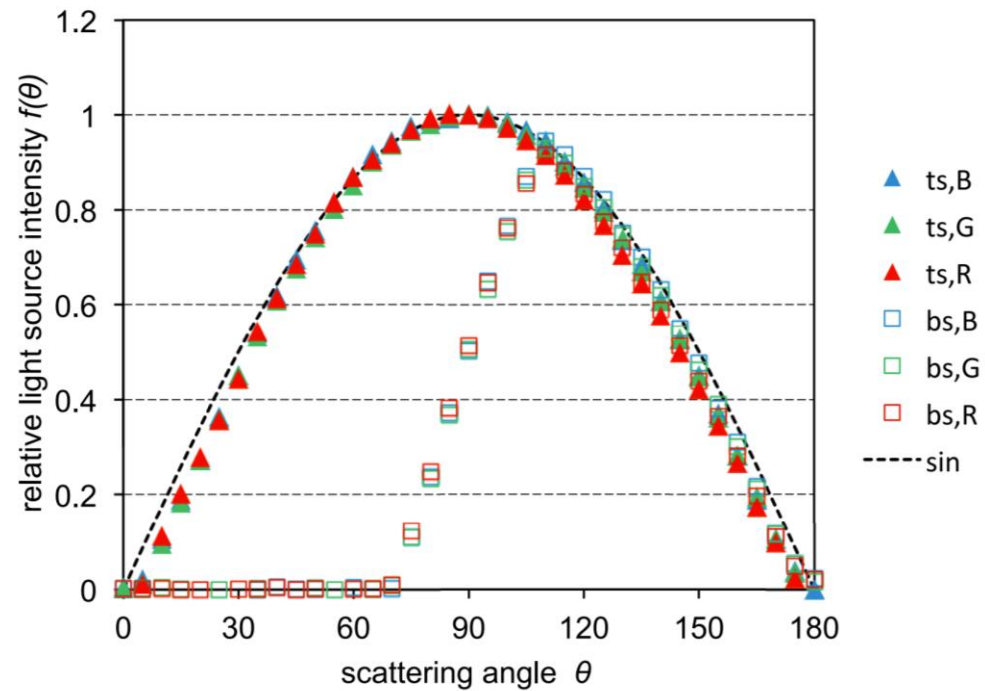


- a. Sensing volume and indicated truncation angles.
- b. Arrangement of LEDs
- c. Light source with motor-driven backscatter shutter



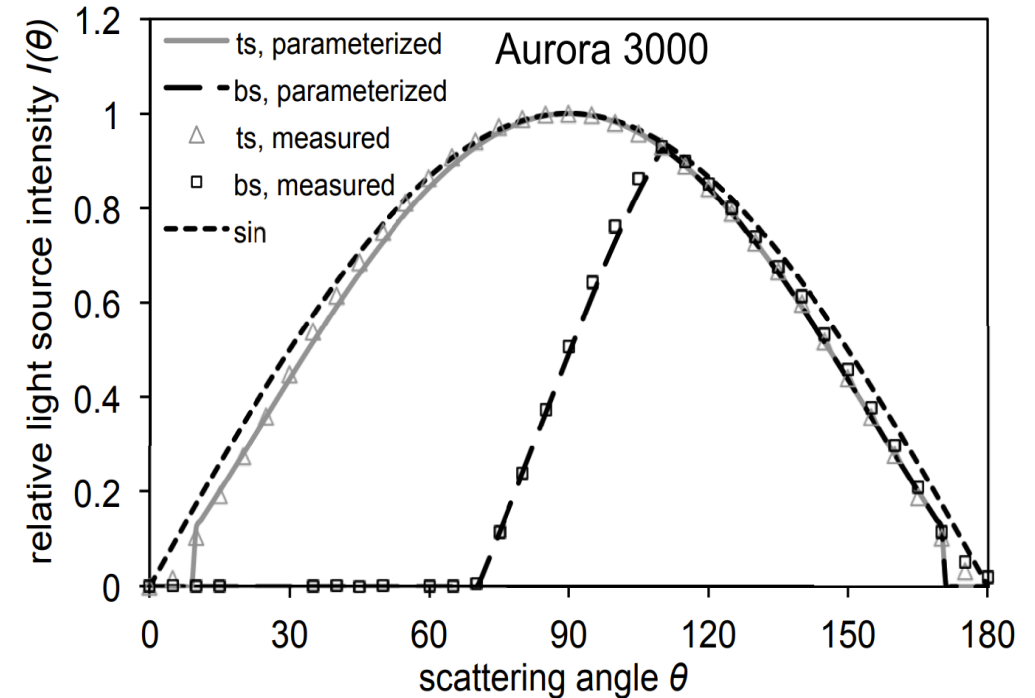
# Illumination Function and Angular Truncation

- Measured angular illumination function for total scattering and backscattering.
- The wavelengths are indicated by B (450 nm), G (525 nm), and R (635 nm)



Müller et al., 2011

- Measured angular truncation at  $10^\circ$  and  $170^\circ$ .



# Calibration of an Integrating Nephelometer

## Nephelometer Calibration

The measured scattering coefficient (photon frequency  $C_{meas}$  x calibration factor  $K_2$ ) is the sum of:

$\sigma_{sp}$  ... Particle scattering

$\sigma_{air}$  ... Rayleigh scattering of the air molecules

$W$  ... Wall scattering

$$\sigma_{sp} + \sigma_{air}(T, p) + W = K_2 C_{meas}$$

The particle scattering coefficient is then

$$\sigma_{sp} = K_2 C_{meas} - W - \sigma_{air}(T, p)$$

And the backscattering coefficient can be calculated to

$$\sigma_{bsp} = K_2 C_{meas,b} - W_b - K_4 \cdot \sigma_{air}(T, p)$$

Two particle-free gases are used to calibrate the integrating nephelometer: one low (air) and one high span gas (CO<sub>2</sub>)

**Step 1:** Scattering and backscattering is measured with particle free air. The measured signal is the sum of Rayleigh scattering of air molecules and the wall scattering.

$$\sigma_{\text{sp}} = 0 \rightarrow K_2 C_{\text{meas,air}} = W + \sigma_{\text{air}}(T, p)$$

$$\sigma_{\text{bsp}} = 0 \rightarrow K_2 C_{\text{meas,air,b}} = W_b + K_4 \cdot \sigma_{\text{air}}(T, p)$$

**Step 2:** Scattering is measured with CO<sub>2</sub>. The measured signal is the sum of Rayleigh scattering of CO<sub>2</sub> molecules and the wall scattering

$$\sigma_{\text{sp}} = 0 \rightarrow K_2 C_{\text{meas,CO}_2} = W + \sigma_{\text{CO}_2}(T, p)$$

$$\sigma_{\text{bsp}} = 0 \rightarrow K_2 C_{\text{meas,CO}_2,\text{b}} = W_b + K_4 \cdot \sigma_{\text{CO}_2}(T, p)$$

The four unknown parameters:  $K_2$ ,  $K_4$ ,  $W$ ,  $W_b$  can be calculated by the previous set of four equations.

$$K_2 = \frac{\sigma_{\text{CO}_2} - \sigma_{\text{air}}}{C_{\text{meas,CO}_2} - C_{\text{meas,air}}}$$

$K_2 \rightarrow$  the calibration slope

$$K_4 = \frac{C_{\text{meas,CO}_2,b} - C_{\text{meas,air,b}}}{C_{\text{meas,CO}_2} - C_{\text{meas,air}}}$$

$K_4 \rightarrow$  calibration factor for backscattering; Ideally  $K_4=0.5$

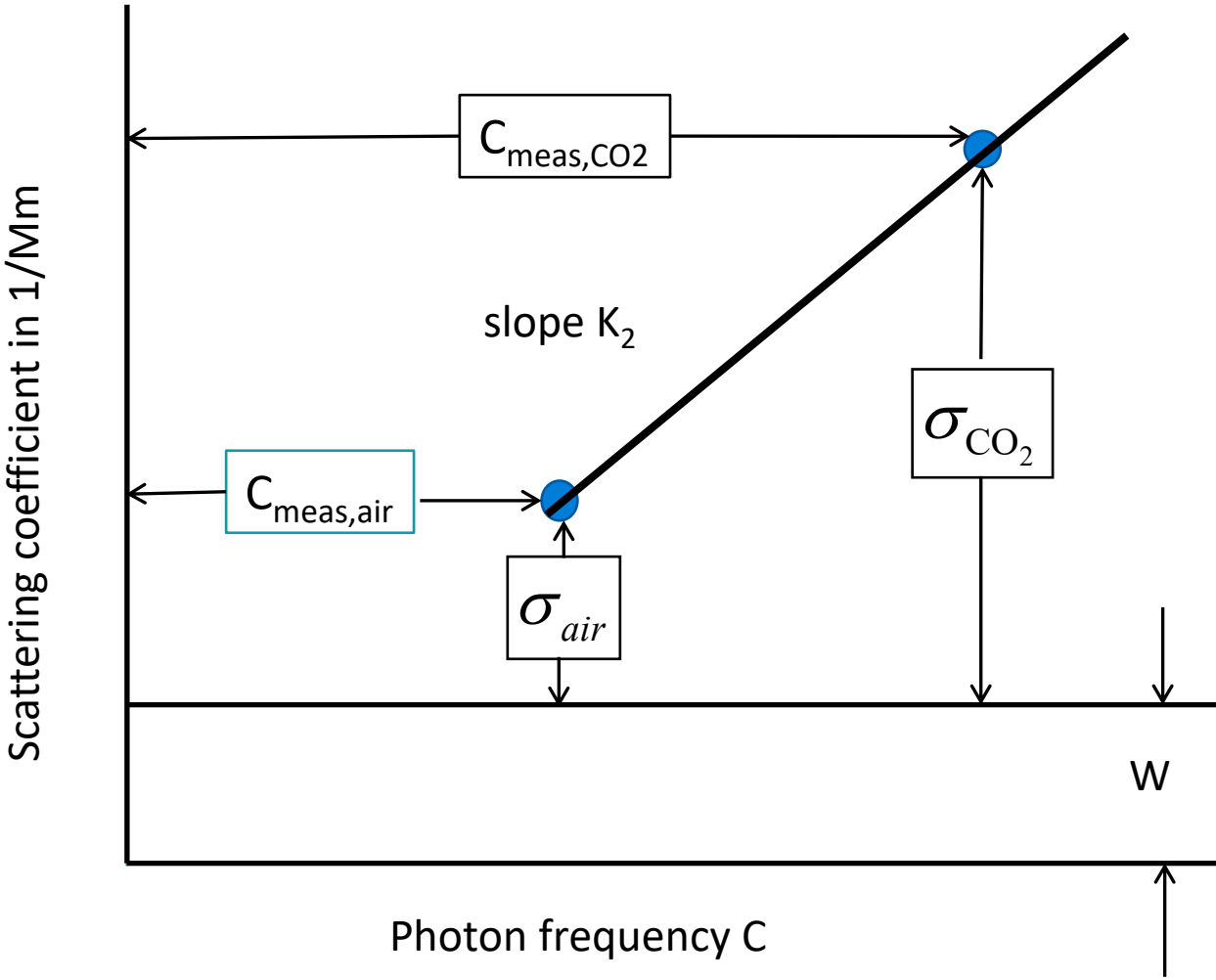
$$W = K_2 \cdot C_{\text{meas,air}} - \sigma_{\text{air}}$$

$W \rightarrow$  wall scatter constant for total scattering

$$W_b = K_2 \cdot C_{\text{meas,air,b}} - K_4 \cdot \sigma_{\text{air}}$$

$W_b \rightarrow$  wall scatter constant for backscattering

# Calibration function



# Scattering Ångström Exponent

## Scattering Ångström Exponent

Spectral behavior of particle scattering often is described by the Ångström exponent

$$\frac{\sigma_s^{\lambda_1}}{\sigma_s^{\lambda_2}} = \left( \frac{\lambda_1}{\lambda_2} \right)^{-\alpha}$$

The Ångström exponent depends on particle size distribution (aerosol type).

- urban aerosol:  $1.5 < \alpha < 2.5$
- rural aerosol:  $1.0 < \alpha < 1.5$
- mineral dust :  $-0.1 < \alpha < 0.5$
- Sea salt:  $0.2 < \alpha < 0.5$

# Correction for Truncation and Illumination

## Correction using Scattering Ångström Exponent

$$\sigma_{ts}^{corr}(\lambda) = \sigma_{ts}^{raw}(\lambda) \cdot C_{ts}(\lambda)$$

$$C_{ts}(\lambda) = a + b \cdot \alpha_{ts}^*$$

$$\alpha_{ts}^*(B/G) = -\frac{\log\left(\frac{\sigma_{ts}^{raw}(B)}{\sigma_{ts}^{raw}(G)}\right)}{\log\left(\frac{B}{G}\right)}$$

$$\alpha_{ts}^*(B/R) = -\frac{\log\left(\frac{\sigma_{ts}^{raw}(B)}{\sigma_{ts}^{raw}(R)}\right)}{\log\left(\frac{B}{R}\right)}$$

$$\alpha_{ts}^*(G/R) = -\frac{\log\left(\frac{\sigma_{ts}^{raw}(G)}{\sigma_{ts}^{raw}(R)}\right)}{\log\left(\frac{G}{R}\right)}$$

## Correction using Scattering Ångström Exponent

$$C_{ts}(B) = a + b \cdot \alpha_{ts}^*(B / G)$$

$$C_{ts}(G) = a + b \cdot \alpha_{ts}^*(B / R)$$

$$C_{ts}(R) = a + b \cdot \alpha_{ts}^*(G / R)$$

## Correction using Scattering Ångström Exponent

wavelength		B		G		R	
Ångström exponents		$\alpha^*ts(B/G)$		$\alpha^*ts(B/R)$		$\alpha^*ts(G/R)$	
parameters		a	b	a	b	a	b
TSI	no cut	1.345	-0.146	1.319	-0.129	1.279	-0.105
	sub- $\mu\text{m}$	1.148	-0.041	1.137	-0.040	1.109	-0.0033
Ecotech	no cut	1.455	-0.189	1.434	-0.176	1.403	-0.156
	sub- $\mu\text{m}$	1.213	-0.060	1.207	-0.061	1.176	-0.053

Correction factors for total particle light scattering coefficients as function of the Ångström exponents.

wavelength		total scattering			backscattering		
		B	G	R	B	G	R
TSI	no cut	1.300 +/- 0.250	1.290 +/- 0.240	1.260 +/- 0.210	0.984 +/- 0.041	0.984 +/- 0.041	0.988 +/- 0.043
	sub- $\mu\text{m}$	1.086 +/- 0.040	1.066 +/- 0.031	1.045 +/- 0.021	0.950 +/- 0.009	0.944 +/- 0.012	0.954 +/- 0.009
Ecotech	no cut	1.370 +/- 0.290	1.380 +/- 0.310	1.360 +/- 0.290	0.963 +/- 0.040	0.971 +/- 0.047	0.968 +/- 0.043
	sub- $\mu\text{m}$	1.125 +/- 0.059	1.103 +/- 0.046	1.078 +/- 0.035	0.932 +/- 0.012	0.935 +/- 0.017	0.935 +/- 0.014

Correction factors for angular non-idealities in TSI (450, 550, and 700 nm) and Ecotech (450, 525, and 635 nm) integrating nephelometers. They are used only for the particle backscattering coefficient if an Ångström correction for total scattering is applied.