Polarization correction of sun-light scattering for sky-scattered solar radiation based plume transmissivity measurements

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Characterization and quantification of PM emission in industry is required for scientific and legal purposes but there are critical gaps in the ability to accurately obtain these data for operating plumes and flares. An experimental procedure has been recently developed based on a line-of-sight attenuation (LOSA) method using sky light as reference source **[1]**. But in clear-sky conditions, the soot aggregates scatter the direct sun light in addition to absorbing sky-light; the plume intensity is overestimated leading to a corresponding underestimation of the plume attenuation and soot emission. The present study investigated various possibilities for the correction, including a discrimination of absorbed sky-light from scattered sun-light by using a light polarizer.
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PM measurement in industrial plumes

- **135 billions m³ of gas flared** in the world every year.
- PM emissions as primary health and environment concerns.
- But **no widely accepted diagnostic for PM emission in the industry.**
  - Regulatory diagnostic for plumes in the US: **EPA Method 9 [2].** plume opacity evaluated by trained observer → subjectivity
  - Recent improvement of Method 9 with acquisition by digital camera **[3,4].** but { **broadband opacity** → hard to quantify soot concentration; opacity is associated to **concentration**, not emission rate.

Sky-LOSA challenges

Obtaining accurate soot emission values from sky-LOSA.
- Accurate soot properties (optical properties & morphology).
- Accurate evaluation of plume velocity.

Other source of error: <u>**scattering caused by direct sun-light**</u>
→ **subject of the present study.**

Sky-LOSA principle

- **LOSA** = **L**ine-**O**f-**S**ight **A**ttenuation
  - commonly used for soot measurements in lab flame investigations **[5]**.
- **Sky-light** used as a light source.

} **SKY-LOSA**

- <u>**Soot emission rates from sky-LOSA**</u>:

$$\dot{m}_{soot} = \frac{-\rho_{soot}\lambda}{6\pi(1+\rho_{sa})E(m)_\lambda}\int u(y)\ln\left[\tau_\lambda(y)\right]dy$$

Soot properties
- ρ_{soot} soot density.
- ρ_{sa} scattering / absorption ratio.
- $E(m)_\lambda$ absorption function of the refractive index.
- Available in the literature (with uncertainty).
- Limit the accuracy of the method (±15%).

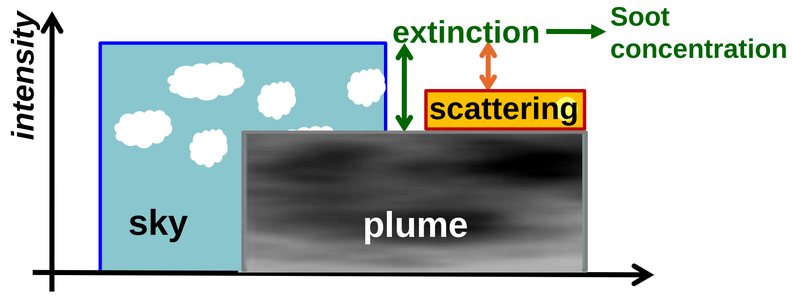
Transmission $\tau_\lambda(y)$
- Evaluated via sky-light interpolation algorithm.

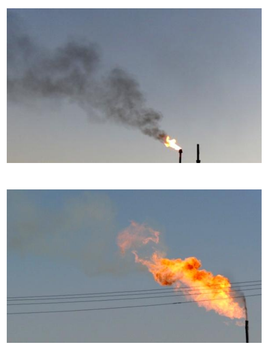
Plume velocity $u(y)$
- Required for conversion of concentration to emission rate
- Evaluated via image correlation from high-speed video.

Sun-light scattering error

- Soot aggregates scatter direct sun-light under clear-sky conditions.
- Sun-light scattering makes the plume appear brighter than for pure sky-light attenuation (plume turning 'white' under sun illumination).

→ **underestimation of light extinction & soot emission.**

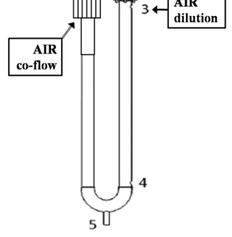


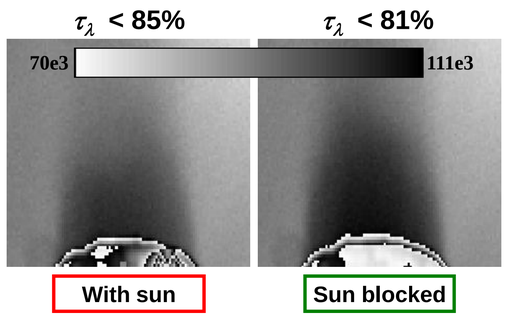


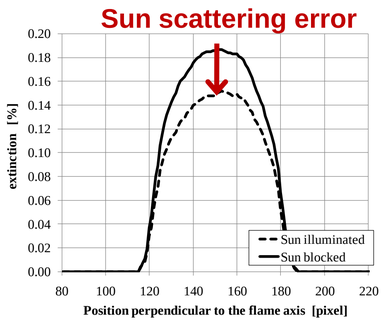
Experimental demonstration of the sun-light scattering effect

- Sky-LOSA measurements in a burner exhaust at **532 nm.**
  - **ethylene / air diffusion** flame in an inverted burner **[6]**.
- Outdoor measurements in Ottawa, Ontario, in late fall, 2009.
  - **With & without direct sun-light** illumination (sun blocked by plate).

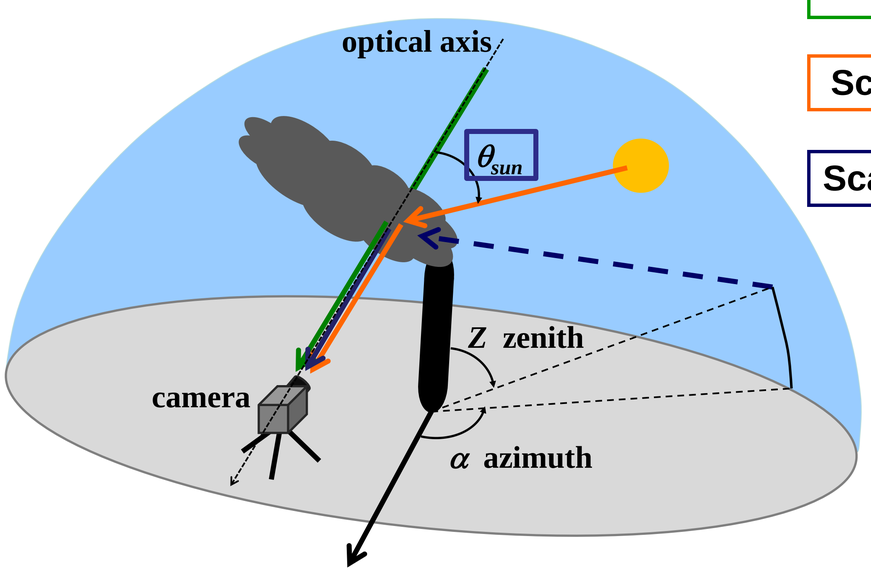
→ extinction & soot emission rate <u>**underestimated by 20%**</u>







Models for the light phenomena



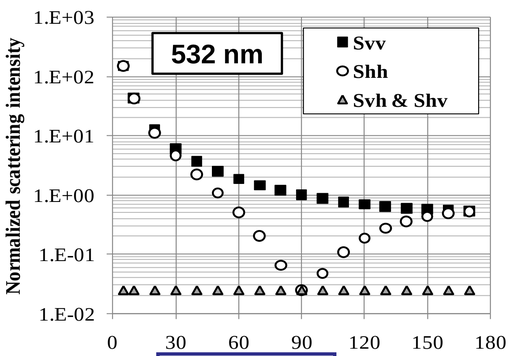
Sky-light extinction
$$S_{ext} \propto f_v I_{sky} G\left(p_{sky}, \gamma_{pol}\right)$$

Scattering of direct sun-light
$$Sc_{sun} \propto f_v I_{sun} G'\left(p_{sun}, \theta_{sun}, \gamma_{pol}\right)$$

Scattering of diffuse sky-light
$$Sc_{sky} \propto f_v \iint_{\alpha,Z} I_{sky}(\alpha,Z) G''\left[\theta_{sky}(\alpha,Z)\right]$$

- f_v soot volume fraction
- I_{sun} sun-light intensity
- I_{sky} sky-light intensity
- $G(\ldots)$ functions of soot prop.
- p degree of polarization
- γ_{pol} polarizer angle

- Light scattering by soot aggregates varies with the **scattering angle θ** (angle to the incident light) **[7].**
- The scattering intensity varies differently depending on the **polarization** of both incident and collected lights (***h***: horizontal, ***v***: vertical).
- **Incident sun-light is unpolarized** (50% ***h***, 50% ***v***).
  → sun-light scattering involves S_{hh}, S_{vv}, S_{hv} & S_{vh}



Correction approaches to sky-LOSA

- Corrections approaches aim at extracting the extinction data from the LOSA measurement, e.g. distinguishing it from both types of scattering.
- Various <u>approaches</u> can be used, involving
  - **filtering**
  - and/or **evaluation**

  } of both scattering signals
- All signals proportional to **soot volume fraction**: no effect of f_v on the error.

- <u>**Polarizer filtering**</u>: **Different polarization properties.**
  - Sky-light is partially polarized (p < 60%).
  - Light scattering is strongly polarized for θ = 90°.
  - Total scattering by sky-dome assumed unpolarized.

  → investigate polarizer use to suppress scattering bias
- <u>**Estimation of scattering contribution via models**</u>:
  In addition to soot morphology, various input data required
  - Direct sun-light intensity, measured or modeled.
  - Distribution of sky-light over the dome, modeled.

Future work

New outdoor measurements
- Image doubler for simultaneous sky-LOSA acquisitions with 1 or 2 polarizer filters.
- Sun-light measurements (pyrheliometer)

Scattering evaluation with various models
- Atmospheric models for sun-light intensity **[8]**.
- Spatial distribution of sky-light for various sky conditions **[9]**.

Error analysis for the various approaches.

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