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# CORRECTION DE L'AUTO ABSORPTION DANS LES MESURES DE DIFFUSION ANGULAIRE DE LA LUMIERE PAR LES PARTICULES DE SUIE

M. Littin<sup>1\*</sup>, G. Lefevre<sup>1</sup>, M. Mazur<sup>1</sup>, A. Fuentes<sup>2</sup> et J. Yon<sup>1</sup>

<sup>1</sup>INSA Rouen Normandie, Univ. Rouen Normandie, CNRS, Normandie Univ., CORIA UMR 6614, F-76000, Rouen France

<sup>2</sup>Departamento de Industrias, Universidad Técnica Federico Santa María, Av. España 1680, Valparaíso, Chile

\*Courriel de l'orateur: littinm@coria.fr

## TITLE

**Correction of angular light scattering signal trapping in soot measurements.**

## RESUME

La caractérisation expérimentale optique des particules de suie est essentielle pour améliorer la compréhension des mécanismes d'agrégation et d'oxydation mis en jeu. Dans ce travail, des mesures expérimentales de la diffusion de la lumière au sein d'une flamme académique à une longueur d'onde de 520 nm et à un angle de diffusion de 110,2° sont présentées. Ces mesures révèlent une dissymétrie significative du signal collecté causé par un piégeage optique du signal diffusé (auto-absorption). Un modèle de ce piégeage est donc proposé afin de corriger cet effet dans les mesures de diffusion. L'impact de la correction du piégeage du signal est présenté.

## ABSTRACT

Experimental characterization of soot is recognized as essential for enhancing the understanding of aggregation and oxidation mechanisms. In this work, experimental measurements of angular light scattering at a wavelength of 520 nm for a scattering angle of 110.2° on an academic flame are presented. Significant dissymmetry is observed in the measurements, due to a phenomenon known as signal trapping. A model to correct this effect in angular light scattering measurements is introduced. The quantitative impact of signal trapping correction is presented, highlighting the implications of not taking this effect into account.

**MOTS-CLES** : Particules de suie, Diffusion de lumière angulaire, Flamme axisymétrique, auto-absorption.

**KEYWORDS** : Soot particles, Angular light scattering, Axisymmetric flame, Signal trapping.

## 1. INTRODUCTION

Soot particles, resulting from the incomplete combustion of fossil fuels, are recognized as the second most significant anthropogenic contributor to global warming (Tollefson, 2013). Additionally, their adverse health effects continue to be documented (Rasking et al., 2023). Although the literature provides information on the soot volume fraction, temperature, and primary sphere diameter (Cortés et al., 2018; Hadeef et al., 2010; Michelsen et al., 2015), data on soot aggregates are still scarce, despite their relevance in validating aggregation and oxidation mechanisms. Consequently, the need to provide high spatial resolution data concerning the sizes of soot aggregates emerges as a crucial research question.

In the quest to characterize soot particles, significant efforts have been devoted to the development of in-situ optical techniques. For instance, recent advancements allow the determination of soot volume fraction, temperature, and maturity through multiwavelength line-of-sight attenuation (MW-LOSA) and Emission (Yon, Cruz, et al., 2021). To also characterize the aggregate size, number and diameter of primary spheres and number density, this technique can be coupled with Horizontal Planar Angular Light Scattering (HPALS) (Yon, Morán, et al., 2021).

Such optical techniques lead to inversion problems where a specific radial property of soot in axisymmetric flames needs to be reconstructed from a projection. A critical consideration in this inversion process is the correction for a phenomenon known as signal trapping. This refers to the attenuation of photons as they travel from their source to the point of detection. The attenuation occurs because soot particles within the medium have the ability to scatter and absorb light. Therefore, as photons move from their source, pass through the flame, and reach the detector, they experience attenuation along the line of sight. Two distinct signal trapping effects can be identified, each dependent on the path of the photons (c.f. Figure 3): 1. The original signal coming from the incoming light source via the flame to the scattering particle, and 2. The scattered light via the flame to the detector. There have been several attempts to correct the second effect, typically associated with emission measurements (Escudero et al., 2016; Legros et al., 2015). However, to the best of the authors' knowledge, the first effect, commonly linked to angular light scattering measurements and concerning the path from the flame to the detector, has not been thoroughly examined until now.

In the current study, extinction and angular light scattering measurements collected at 110.2° both at wavelength of 520 nm are presented. A significant signal trapping effect, indicated by pronounced dissymmetry of the scattered profile, is observed in these measurements. To address this, a methodology employing extinction reconstructions is introduced for the accurate reconstruction of the radial property associated with the scattering.

## 2. METHODOLOGY

### 2.1. EXPERIMENTAL SETUP

The current investigation examines an axisymmetric laminar ethylene-air diffusion co-flow flame using a Gülder-type burner operating at atmospheric pressure. The burner comprises a 10.9 mm inner diameter central tube for fuel injection and a 90 mm inner diameter co-annular tube for co-flow air supply. To maintain consistent flow rates, two mass flow controllers were employed to supply pure ethylene at 0.194 slpm and air at 150 slpm.

In order to capture images of extinction and emission, as well as angular and spectral scattering of the flame, an experimental campaign was conducted using the device illustrated in Figure 2. A continuous laser source (CELESTA) capable of producing light at 520 nm was used. The light was collimated with the aid of an achromatic lens ( $f = 300$  mm) positioned between the light source and the flame. For LOSA measurements (extinction) and angular scattering measurements, the light was filtered and captured with a CCD camera (Thorlabs) with an objective lens (Canon 200 mm). The LOSA measurements were performed in-line ( $0^\circ$ ), while the scattering measurements were taken at  $110.2^\circ$ .

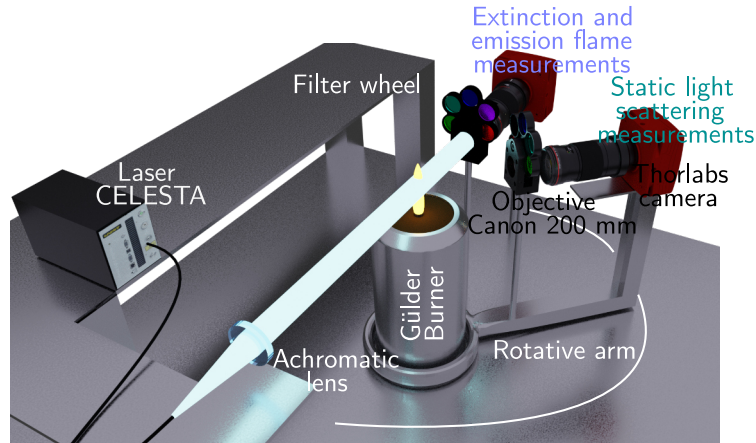


Figure 1: Experimental setup for measurement of extinction, emission, and angular and spectral scattering.

### 2.2. SIGNAL TRAPPING MODEL

Soot particles possess the capability to scatter and absorb light. As a result, when photons travel toward the detector, their intensity is reduced along the line of sight (LoS), a phenomenon known as signal trapping. In this section, a model is presented for correcting both scattering and absorption effects.

#### FROM THE FLAME TO THE DETECTOR

Suppose that the emission signal of the sooting flame is detected at a certain position  $x_s$  in the plane, as exemplified in Figure 2. The light detected at that position, undergoes attenuation, due to extinction, along the entire LoS as modeled in Equation 1.

$$F_s(x_s, y) = \exp \left[ - \left( \int_A^B \kappa_{ext}(r) dy + \int_B^C \kappa_{ext}(r) dy + \int_C^D \kappa_{ext}(r) dy \right) \right] \quad (1)$$

Here,  $F(x_s, y)$  is the coefficient that models the trapping effect up to the detector at  $x_s$ ,  $\kappa_{ext}$  is the extinction coefficient retrieved from LOSA measurements and  $y$  is the variable that represents the LoS. Figure 2 represents a top view of the flame; the colours are representative of the attenuation ( $F_s$ ) that much be considered for each position in the flame. The brighter corresponds to stronger trapping.

## FROM THE INCOMING LIGHT SOURCE TO THE DETECTOR

The methodology described can be extended to model the trapping from the incoming light source, as exemplified in Figure 3. It must now be considered that the incoming light source arrives with an angle  $\theta$ , as shown in Figure 3.

$$F_I^+(x_s, y) = \exp \left[ - \left( \int_E^G \kappa_{ext}(r) ds + \int_G^A \kappa_{ext}(r) ds \right) \right] \quad (2)$$

$$F_I^-(x_s, y) = \exp \left[ - \left( \int_F^{G^-} \kappa_{ext}(r) ds + \int_{G^-}^C \kappa_{ext}(r) ds \right) \right] \quad (3)$$

Here,  $F_I(x_s, y)$  is the coefficient that models the trapping effect from the incoming light source at  $x_s$  and  $ds$  represents the path of the incoming light.

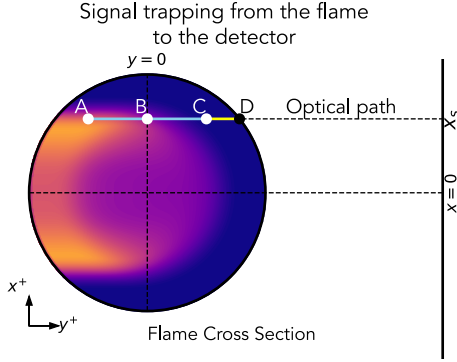


Figure 2: Schematic of signal trapping from the flame up to the detector.

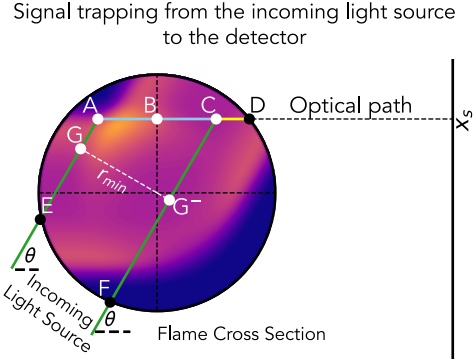


Figure 3: Schematic of signal trapping from the incoming light source up to the detector.

Finally, the signal trapping correction factor for the entire path corresponds to:

$$F(x_s, y) = F_s(x_s, y) F_I^+(x_s, y) F_I^-(x_s, y). \quad (4)$$

## 3. RESULTS

Figure 4a displays the measurements of transmissivity at a height of 30 mm above the burner for a wavelength of 520 nm. As these measurements represent a projection, a deconvolution process is necessary to extract the information on the radial extinction of the flame, as depicted in Figure 4b. Furthermore, the re-convolution of the extinction data is also presented in Figure 4a.

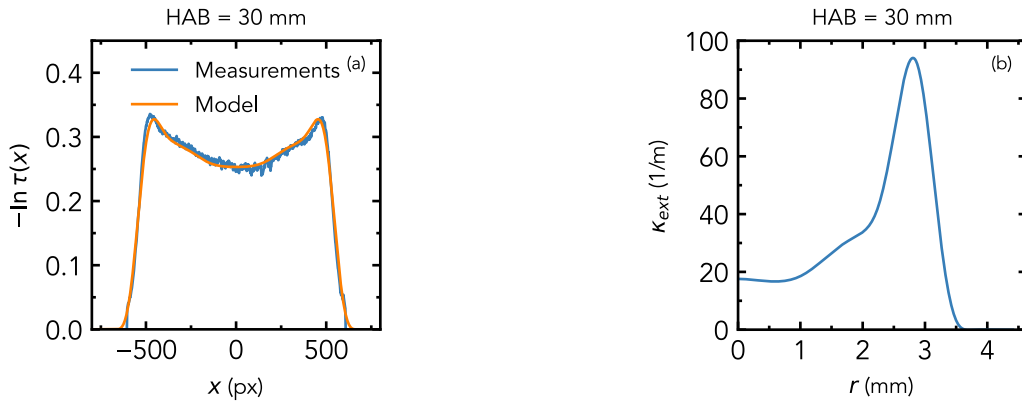


Figure 4: (a) Transmissivity data at 520 nm. (b) Corresponding extinction profile.

The extinction profile obtained is used as an entry to evaluate the signal trapping in light scattering measurements (computation of the F matrix). As previously described, by integrating the extinction along various paths, it is possible to generate a two-dimensional transmissivity map. To illustrate this approach, light scattering measurements were taken at a scattering angle of  $110.2^\circ$ . The transmissivity map produced is shown in Figure 5a. Note that the lower the value, the greater the correction of the effect. Additionally, the light scattering measurements are presented in Figure 5b. Figure 5c offers a comparison between the deconvoluted profiles, both with and without signal trapping correction (TC and NTC, respectively). Notably, when signal trapping is corrected, the model aligns well with the measurements. It is important to highlight that failing to correct for signal trapping results in a significant underestimation, specifically a 40% reduction at the peak value.

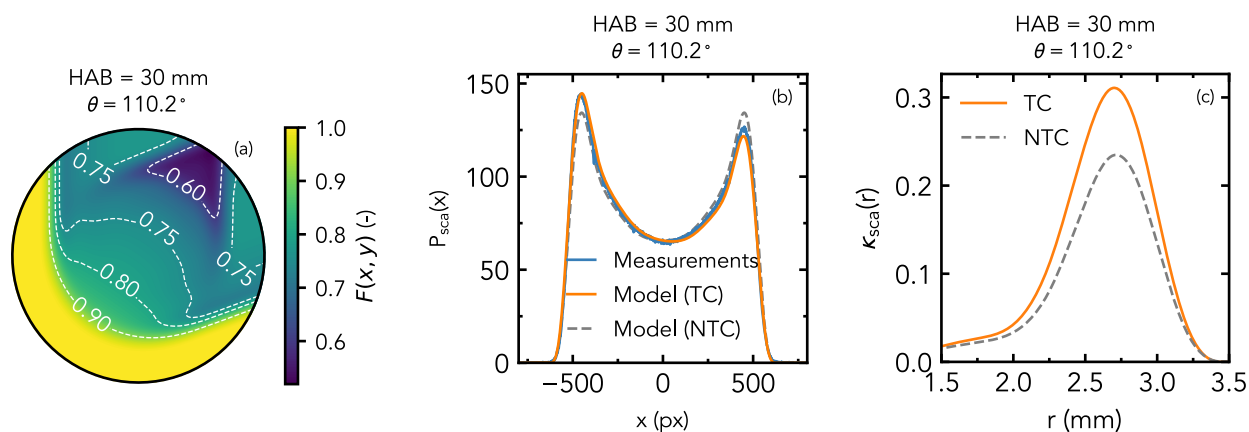


Figure 5: (a) Two-dimensional transmissivity map calculated 30 mm above the burner, using a scattering angle of  $110.2^\circ$ . (b) Representation of the scattered signal ( $P_{sca}$ ). (c) Comparative analysis of the radially retrieved property ( $\kappa_{sca}$ ), contrasting the results with trapping correction (TC) against those without it (NTC).

#### 4. CONCLUSIONS

In this study, a model has been developed for correcting signal trapping in angular light scattering measurements of soot, conducted in a laminar co-flow diffusion flame using a Gülder burner. Soot extinction has been recovered through the implementation of Line-of-Sight Attenuation (LOSA) measurements, allowing for the two-dimensional mapping of transmissivity for specified scattering angles. A significant dissymmetry in scattering profiles, indicative of a pronounced signal trapping effect, has been observed experimentally. This dissymmetry is effectively captured by the presented model. It has been found that when signal trapping is neglected, there is an underestimation reaching 40% in the maximum value for the studied case. Therefore, the inclusion of this correction when performing light scattering measurements is recommended. The application of this methodology at different angles is suggested to gather information about the impact of signal trapping on the measurement of the size of soot aggregates by the angular scattering response.

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