

Photometric measurement of visibility in case of fire

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Offen im Denken

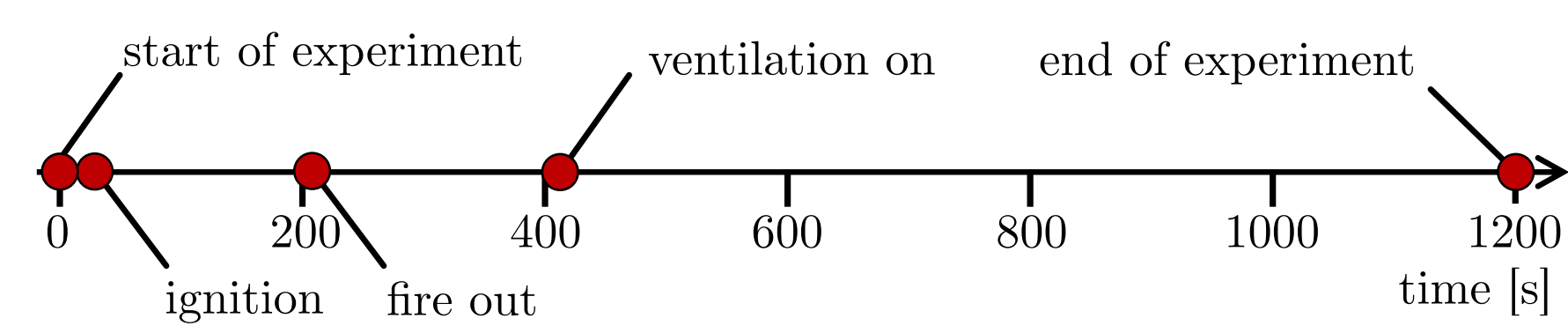
Limited visibility in case of fire is a major tenability criterion in performance-based safety concepts. The smoke density can be calculated with CFD codes, yet there are many indicators that the light extinction is overestimated [1]. A new photometric measurement method for the spatial and time resolved determination of light extinction coefficients within the scope of laboratory fire experiments was recently presented [2]. A camera captures the relative change in intensity of individual light sources (LEDs) due to the fire smoke. Based on geometrical optics and the Beer-Lambert's law, an inverse model deduces the local values of the extinction coefficient. By using multiple LED strips and a second camera the analysis has been extended to a two-dimensional scale while local deviations of the smoke density can be recognized.

EXPERIMENTAL APPROACH

Light transmission T depends on the extinction coefficient σ as a product of the extinction cross section c_{ext} and particle number density n along the light path Δs through a homogenous medium. It indicates the ratio between the initial I_0 and the reduced intensity I and can be expressed as a function of the optical depth τ :

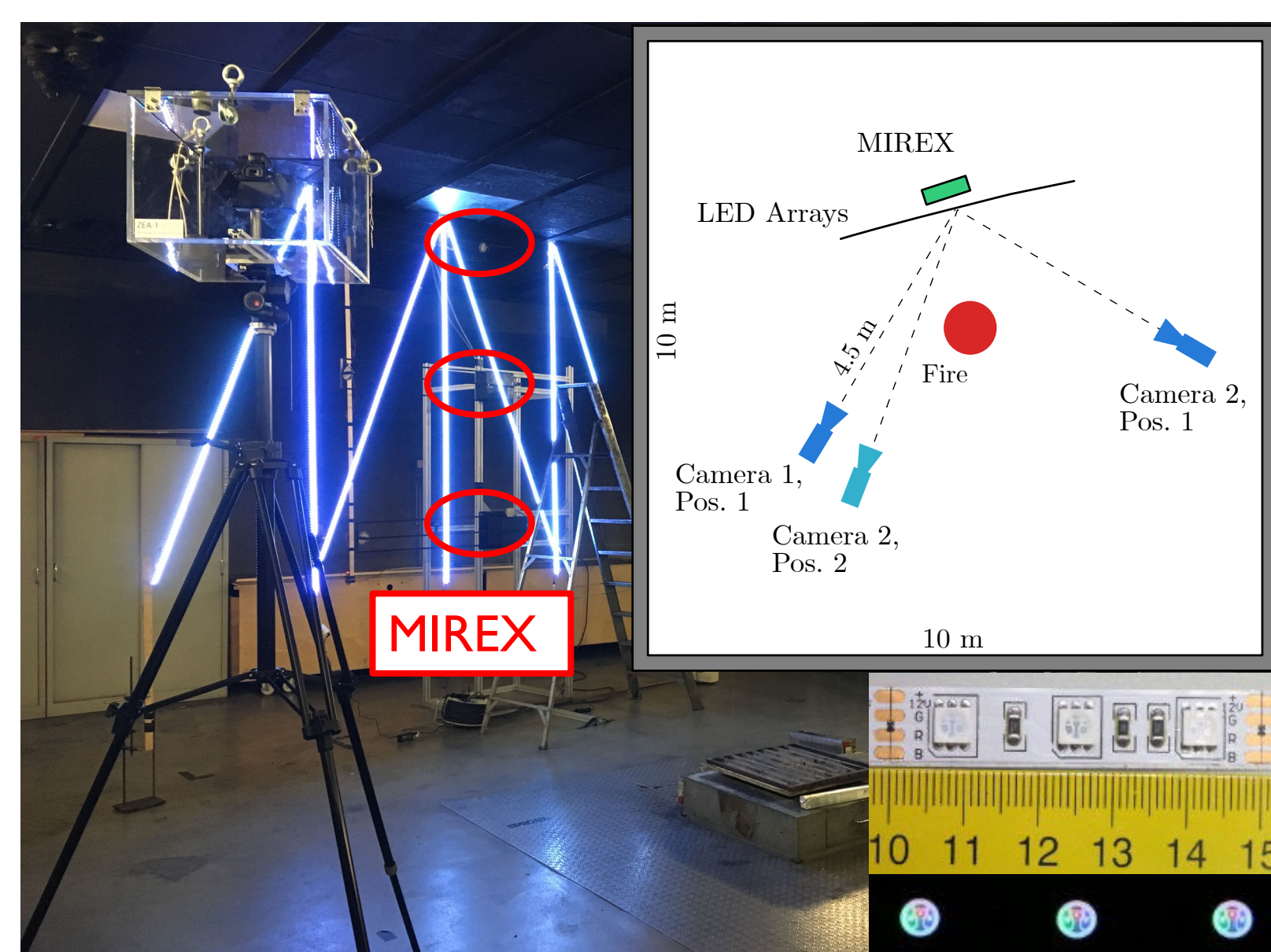
$$T = \frac{I}{I_0} = \exp(-\tau) \quad \tau = \int_s c_{\text{ext}} n(s) ds = \int_s \sigma(s) ds$$

A series of experiments was conducted at the Heinz-Luck fire detection laboratory at the University of Duisburg-Essen in order to compute spatiotemporal resolved extinction coefficients based on the photometric observation of RGB LEDs.



The experimental procedure is as follows:

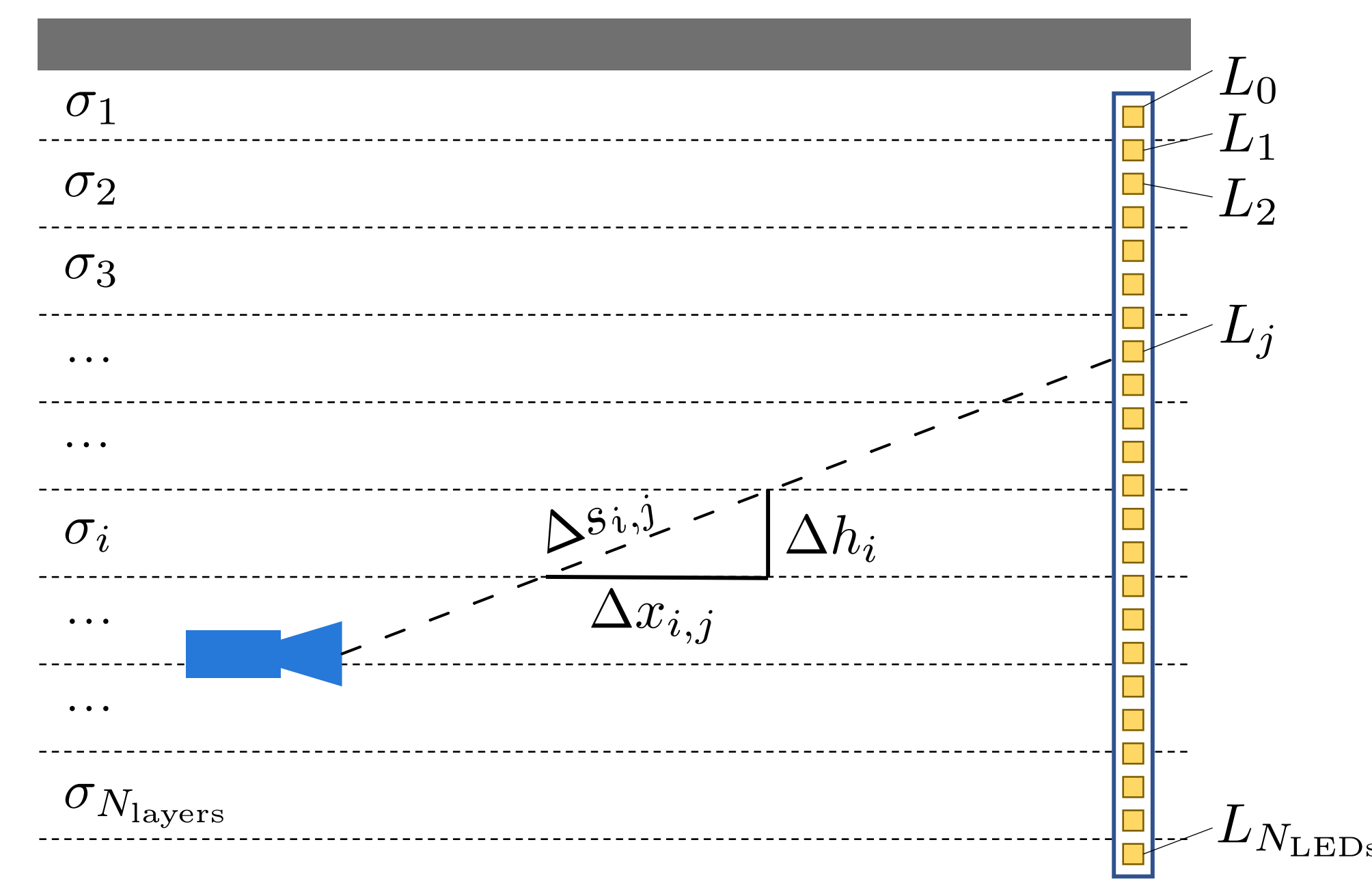
- Continuous image series captured from two consumer digital cameras at a rate of 1 Hz
- Extinction coefficients in the camera's line of sight can be deduced from measured drops in intensity
- Results were compared to the local measurements of the well established MIREX system



METHODOLOGY

Based on a layer model the intensity $I_{m,j}$ of the individual LEDs $L_{N_{\text{LEDs}}}$ can be described as:

$$I_{m,j} = \exp\left(-\sum_{i=1}^{N_{\text{layers}}} \sigma_i \Delta s_{i,j}\right)$$

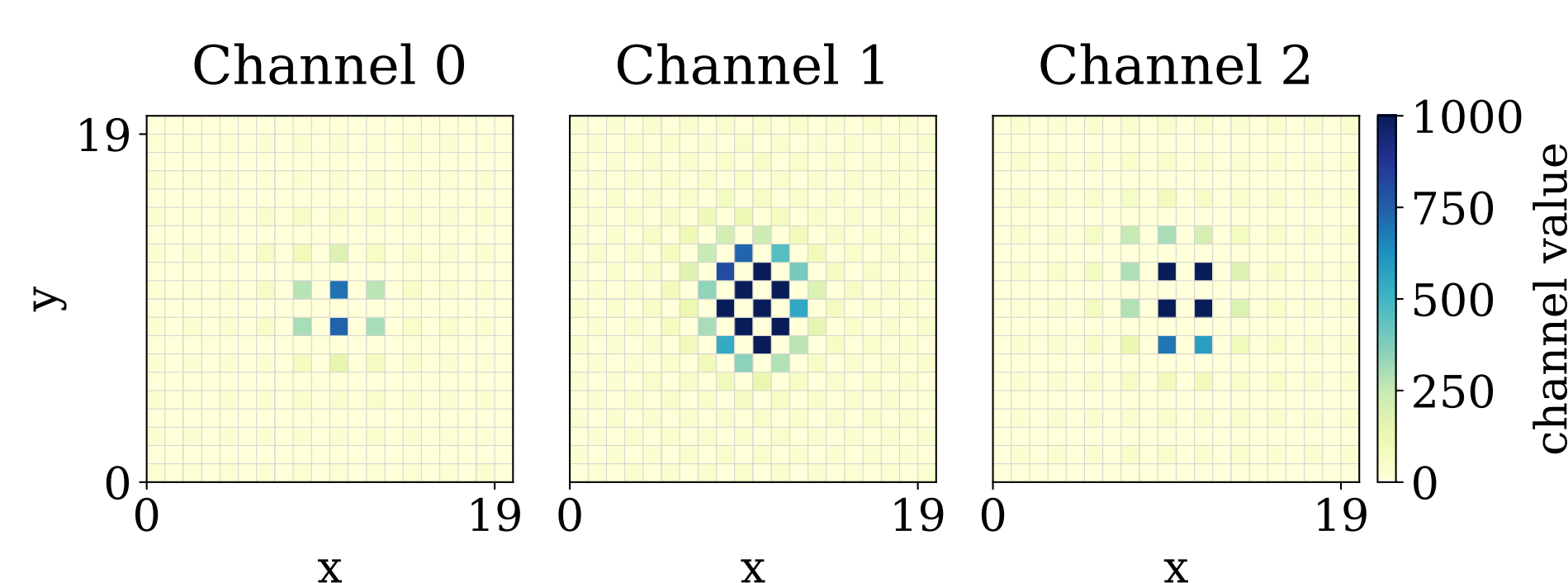


A cost function Ω_σ based on three contributions is defined to find extinction coefficients σ_i that match the experimental intensities $I_{e,j}$:

$$\Omega_\sigma = \underbrace{\sum_{j=1}^{N_{\text{LEDs}}} (I_{m,j} - I_{e,j})^2}_{1} + \underbrace{\phi_s \sum_{j=2}^{N_{\text{layers}}-1} (\sigma_{i-1} - 2\sigma_i + \sigma_{i+1})}_{2} + \underbrace{\phi_a \sum_{i=1}^{N_{\text{layers}}} \sigma_i}_{3}$$

1. L2 Norm between model and experimental intensities
2. Numerical approximation of the second derivation to serve the smoothness of the solution
3. Control of the minimalization process to choose low or high values of the extinction coefficient

The LED intensities are measured, separated for the color channels (0 : red, 1 : green, 2 : blue) of the camera, by a summed value of a 20 x 20 pixel section of the RAW images.



The analysis covers following procedure:

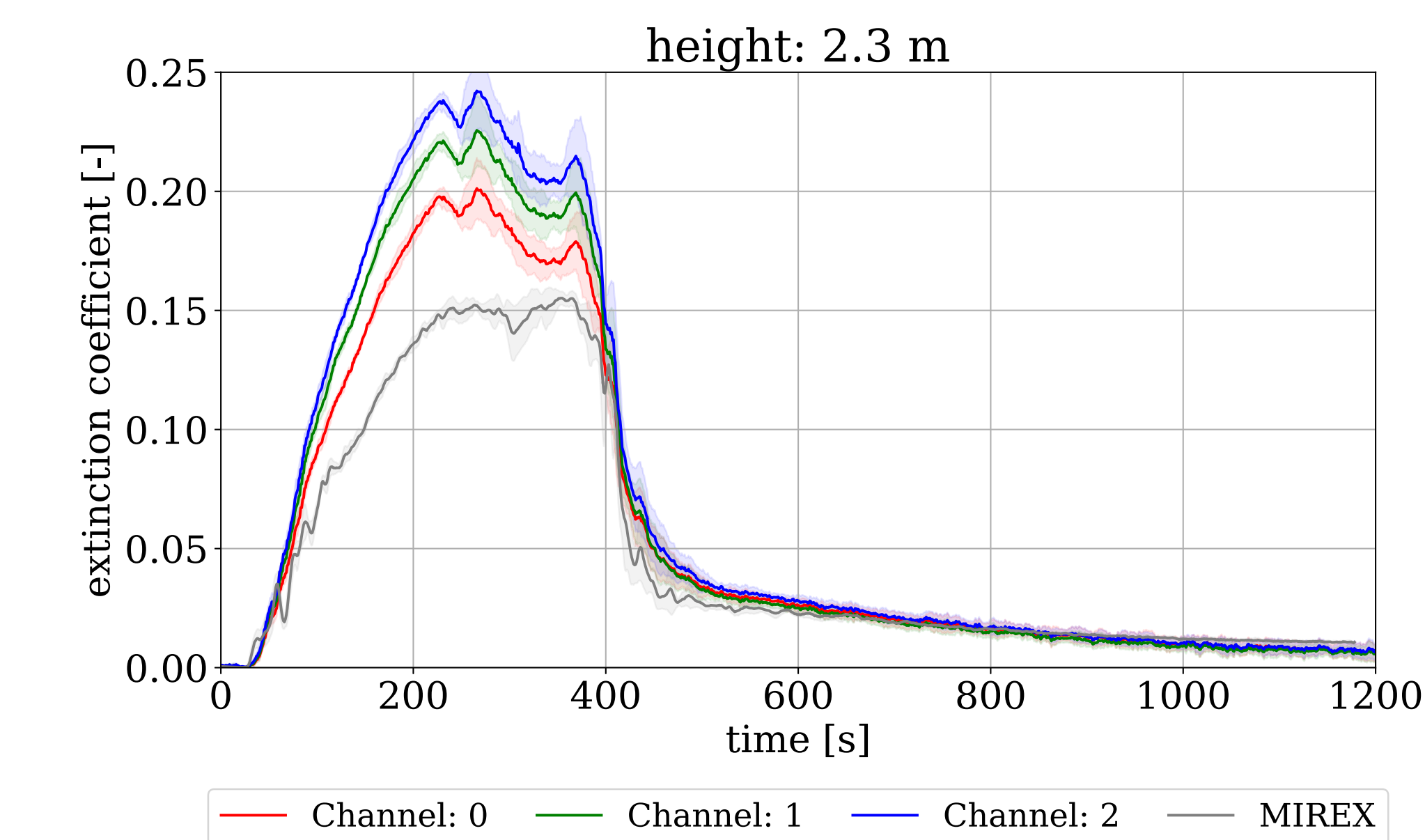
1. Detection of the LEDs via a threshold channel value
2. Assignment of the LEDs to the respective arrays
3. Temporal determination of the relative change in intensity of each LED
4. Calculation of the spatial LED coordinates
5. Computation of the extinction coefficients at the individual layers and color channels

RESULTS

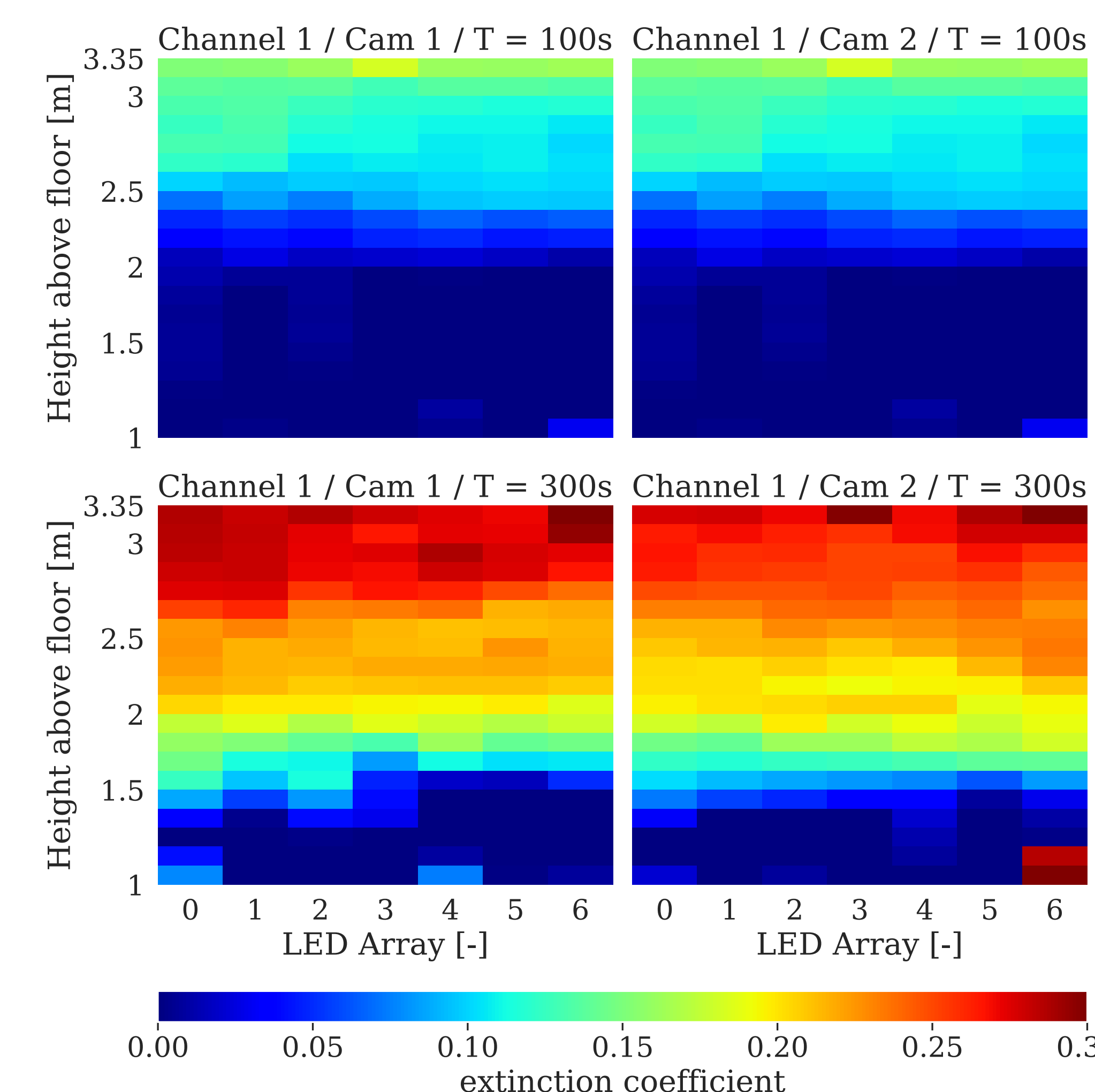
The applied model relies on the following boundary conditions and parameters:

- Series of six experiments of 500 g n-heptane fire in style of EN 54 [3] / TF-5
- Seven arrays with a total of approx. 1,000 RGB LEDs
- Extinction coefficients computed for three color channels at 20 uniform layers with constant thickness

The following figure shows the mean value and the standard deviation for the computed and measured (MIREX: infrared) extinction coefficients:



The analysis of several LED arrays distributed in the experimental space allows, to some extent, not only a temporal but also a spatial resolution of the extinction coefficients. However, it should be noted that up to now such a representation serves more for the investigation of a homogeneous layer than for a true-to-scale representation of the smoke distribution.



CONCLUSION

The extinction coefficients computed with the presented method already show a reasonable agreement with the MIREX measurement which operates at infrared regime. An increase towards the blue channel corresponds to the known correlation that the light-obscuring effects of smoke increase exponentially at decreasing wavelengths.

Due to the spatiotemporal resolution, the approach can be referred to as a reliable basis for the validation of numerical simulations. Nevertheless, the hypothesis of homogeneous layers requires further investigation, as the comparison of data from two independent image sources reveals.

The presented methodology provides several advantages

- Easy applicability, since there is no need for complex experimental setups or expensive measurement devices
- Photometric accuracy of the used consumer cameras can be considered as adequate, as calibration is automatically achieved by capturing the initial state of the experiment
- Highly robust against minor changes in the setup such as the failure of individual LEDs, since the procedure is essentially based on data analysis

OUTLOOK AND IMPROVEMENTS

One of the primary objectives is to extend the procedure to the investigation of other test fires, including smouldering fires in accordance with DIN EN 54.

In particular, the following impacts and phenomena require further investigation:

- Thermal stability of LEDs in terms of light intensity and spectral range
- Deducing particle size distribution from the extinction coefficients at different wavelengths
- Separation of absorption and scattering effects
- Quantifying effects of deposition and agglomeration

REFERENCES

- [1] McGrattan K, Hostikka S, Floyd J, McDermott R and Vanella M., "Fire Dynamics Simulator (Version 6): Technical Reference Guide Volume 3: Validation", August 21, 2020.
- [2] Arnold, L, Belt, A, Schultze, T and Sichma, L. "Spatiotemporal Measurement of Light Extinction Coefficients in Compartment Fires", Fire and Materials, May 22, 2020.
- [3] The European Committee for Standardization., "EN 54 - Fire detection and fire alarm systems - Part 7: Smoke detectors - Point detectors using scattered light, transmitted light or ionization", 2000.

