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Structured Laser Illumination Planar Imaging: New horizons for the study of spray dynamics, thermometry and droplet sizing

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ABSTRACT

The first reported applications of laser sheet imaging for the study of atomizing sprays date from the mid-1980th. Since those early tries, blurring effects from the light being scattered multiple times by the surrounding droplets were already observed and reported. While strategies in suppressing part of this multiple light scattering contribution, were known for transmission imaging (e.g. spatial Fourier filtering, polarization filtering, time-gating) no robust solution was found for laser sheet imaging until the development of Structured Laser Illumination Planar Imaging (SLIPI) in 2008.

The originality of SLIPI resides in using a laser sheet with a spatially modulated light intensity. This light structure encodes the incident illumination beam which can be then decoded after image recording. As multiply scattered photons have "short memory" they do lose the modulation information while singly scattered photons fully preserve it. Therefore the two components, single and multiple scattering, can be separated using a demodulation post-processing algorithm on the recorded images.

This article is a review of the SLIPI technique from its earliest to latest developments. It describes the traditional way of applying structured illumination using three modulated sub-images and its use for averaged imaging of droplet sizes, extinction coefficients and spray thermometry. Recently the technique has been adapted for single-shot applications in order to study spray dynamics and liquid breakups. This is performed using two modulated sub-images instead of three, known as 2p-SLIPI, opening new horizons for the study of spray dynamics, single-shot droplet sizing and thermometry, even through optically dense situations.

1. Introduction

Laser sheet imaging for flow visualization possesses the advantage of generating an optical signal from a two-dimensional plan, sectioning a 3D flow in 2D. This optical sectioning illumination scheme does not suffer from the limitations commonly encounter with the line-of-sight configurations and has been extensively applied over the past three decades for PIV and LIF measurements. Laser sheet imaging was first used for flow and combustion applications in the early 1980th [1,2]. One of the earliest reported applications of laser sheet imaging for the study of atomizing sprays was presented by Melton and Verdieck in 1985 [3] for simultaneous imaging of vapor and liquid distributions in an evaporating fuel holow-cone spray using exciplex (excited state complex). Even though considered as an optically dilute spray, the presented photography were blurred as a consequence of the detectinon of multiple light scattering. Regarding this issue the authors reported:

- "optical thickness and intense scattering in dense sprays, such as found in diesel fuel injectors, will distort the spatial measurements"...."scattering from the numerous small droplets will remain a serious problem for any optical technique used with these dense sprays".

In 1989 Cavaliere et al. [4] tried to provide the first analysis of diesel sprays using two-dimensional laser sheet imaging of light scattering, mentioning:

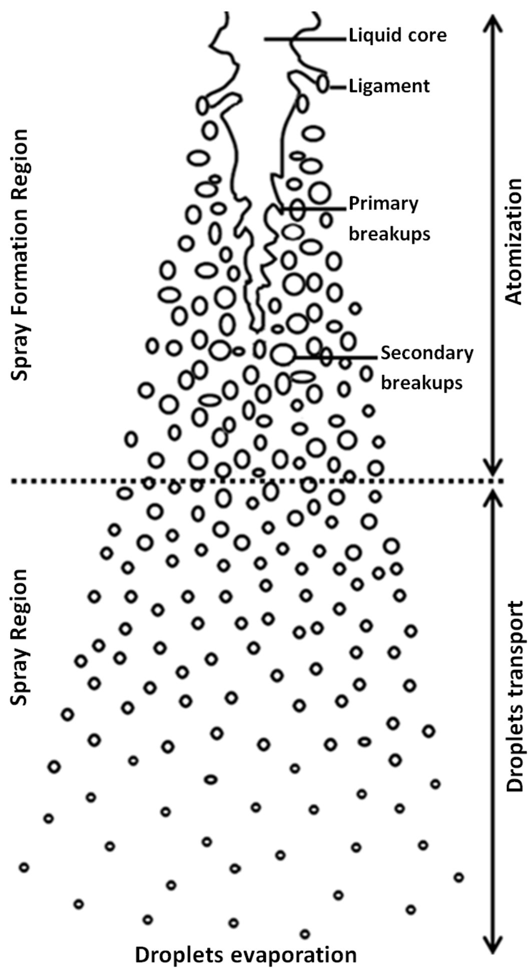
- "as a matter of fact the analysis of light patterns from scatterers with irregular shapes in the presence of multiple scattering effects presents challenges for the applicationof 2-D scattering techniques".

Despite those limitations, laser sheet imaging became in the early 1990th the preferred technique for diesel spray analysis, due to its capability in providing 2D spatially resolved information [5]. Particular attentions were given to the measurement of fuel mass distribution using fuel planar laser-induced fluorescence (LIF) [6] and of the droplet Sauter mean (SMD) diameter from the LIF/Mie ratio [7]. In the early years 2000, it was believed that the LIF/Mie ratio partly cancels out the multiple light scattering intensity detected on both images allowing denser sprays to be probed [8]. However, this assumption is not valid as the spatial contribution of multiple scattering differs strongly between the LIF and Mie images resulting in large inaccuracies for droplet sizing. A typical error is the observation of large droplets on one side of the spray, the entrance of the laser sheet, and small droplets on the other side at the exit of the laser sheet [9]. Experimental SMD results from LIF/Mie ratios, without any strategies for multiple scattering suppression remains, then, questionable.

While strategies in suppressing part of this multiple light scattering contribution, were known for transmission imaging (e.g. spatial Fourier filtering, polarization filtering, time-gating) no robust solution was found for laser sheet imaging until the development of Structured Laser Illumination Planar Imaging (SLIPI) in 2008 [10,11]. In Structured Illumination a recognizable pattern is added to the intensity profile of the light beam used to probe the sample of interest.

Although most patterns would suffice, it is mathematically convenient to use a sinusoidal structure. The purpose of the pattern is that only singly scattered and unperturbed photons will maintain this structural information while propagating through the spray. On the opposite, multiply scattered photons will ''forget'' the superimposed structure. With this feature, it becomes possible to reject the intensity contribution stemming from the multiply scattered light by post-processing the acquired data, thus allowing sprays with an optical depth exceeding unity to be investigated accurately. Since its creation the SLIPI technique has been used for many applications including qualitative single-shot spray imaging [12,13] and the measurement of:

- the extinction coefficient in 2D [14] and in 3D [15,16]
- the droplet SMD [9,17]
- the spray temperature [18]



Optically dilute spray systems		Optically dense spray systems	
Laser techniques	Quantity measured	Laser techniques	Quantity measured
• Shadowgraphy	2D droplet shape and size;	• Ballistic Imaging (at OD>5)	2D single-shot imaging, droplet shape and size; velocity vectors on double exposure
• High-resolution shadowgraphic imaging	velocity vectors on double exposure	• Light Sheet Fluorescence Microscopic imaging	
• Optical connectivity	2D Liquid core length and shape	• SLIPI - Single-shot	
Optically dilute situations: OD≤1		Optically dense situations: OD>2	
• Phase Doppler (PDA, PDI, PDPA)	0D data droplet size, distribution, number density & velocity	• SLIPI - Single-shot	2D single-shot imaging
		• SLIPI scan • Tomo-SLITI	3D extinction coefficient
• Laser diffraction	0D data spatially integrated; droplet size distribution	• Dual-SLIPI	2D extinction coefficient
• Interferome-tric Planar Imaging	2D droplet size and velocity	• SLIPI - LIF/Mie dropsizing	2D droplet Sauter Mean Diameter (SMD)
• LIF/MIe dropsizing	2D or 3D droplet SMD	• SLIPI Two-color LIF	2D spray temperature

Fig. 1 Characteristics of atomizing sprays showing both the spray formation region and the spray region (adapted from [19]). For each region, a categorization of the experimental laser techniques is indicated. In optically dense situations multiple light scattering effects must be suppressed. The SLIPI based techniques highlighted in blue are discussed in this article.

2. Description of the SLIPI technique

The method is based on using a laser sheet with a sinusoidal intensity pattern along the vertical direction. While the origin of multiply scattered light is independent of the modulation pattern the position of the first scattering events remains entirely faithful to it. This implies that the amplitude of the modulated component is a direct signature of the single light scattering while the non-modulated component is induced by multiple light scattering. Figure 2 shows the reduction of the modulation amplitude between position A and B, when a modulated laser sheet is crossing a homogeneous scattering medium (a water solution of 15 µm scattering polystyrene spheres). The SLIPI process consists in extracting, at each position along the direction of light propagation, the modulation amplitude of the laser sheet. To distinguish the modulated component from the non-modulated component, also named "*ac*" and "*dc*" [20] components respectively, several approaches can be employed.

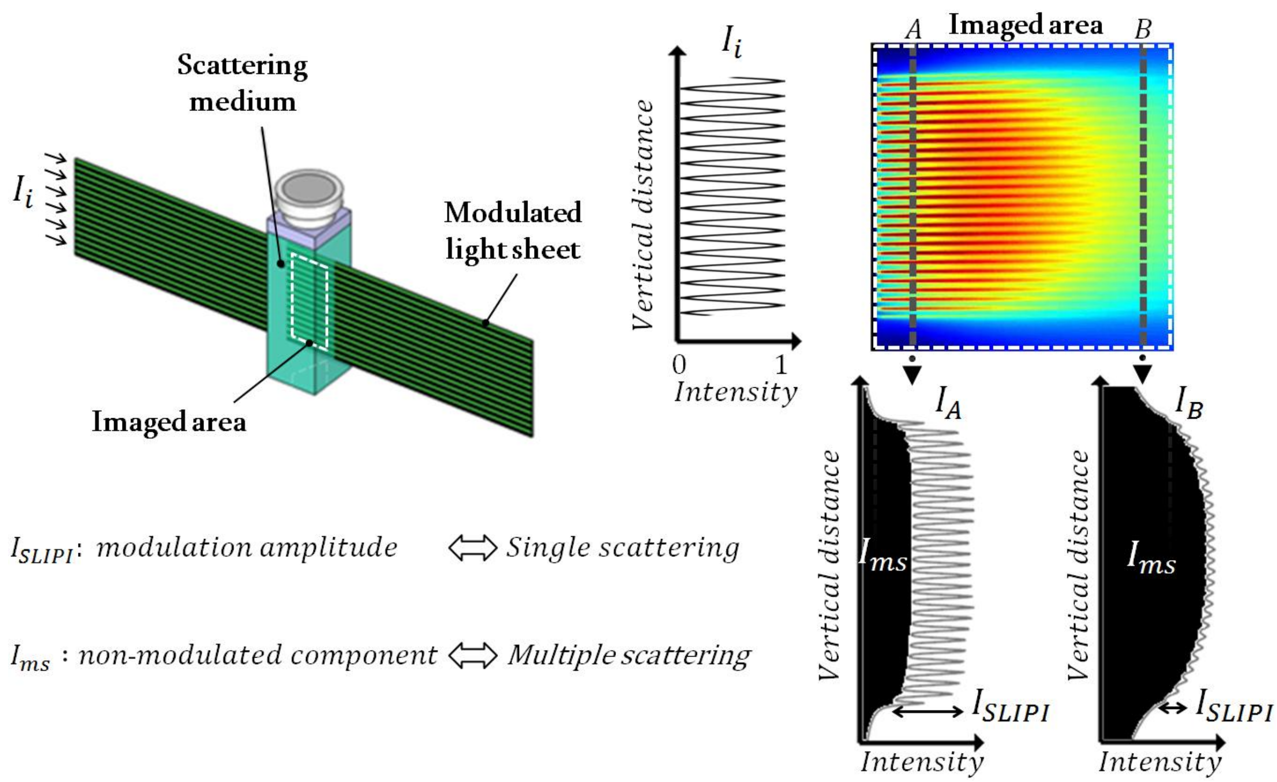


Fig. 2 Illustration of a spatially modulated light sheet crossing a homogeneous scattering medium consisting of a cuvette of 15 µm polystyrene spheres in distilled water. Due to multiple light scattering, the amplitude of the modulation decreases between position A and B. SLIPI aims to measure this amplitude which is a signature of the single light scattering. On the contrary, the multiple light scattering loses the modulation pattern and its intensity is mostly represented by the non-modulated component.

- **3P-SLIPI**

The most common approach to extract the amplitude of a sinusoidal modulation without any loss in resolution is to use three separated signals where a phase shift of one third of the period is implemented between them. This three phase (3P) approach together with the use of a sinusoidal spatial modulation is the standard Structured Illumination method [21,22]. This was implemented in the first SLIPI measurements [10,11] by recording three modulated sub-images I_0, I_{120} and I_{240} where the modulation is vertically shifted as shown in Figure 3. After each recordings the intensity modulation is moved along the vertical axis and a phase change of $\Delta\Phi$ = 120° is observed. However, the multiple light scattering, which is superimposed on the intensity modulation, is mostly unaffected by this shift. By then calculating the root mean square of the light intensity among the three images, the amplitude of the modulation can finally be obtained at a pixel level, corresponding to the final SLIPI image.

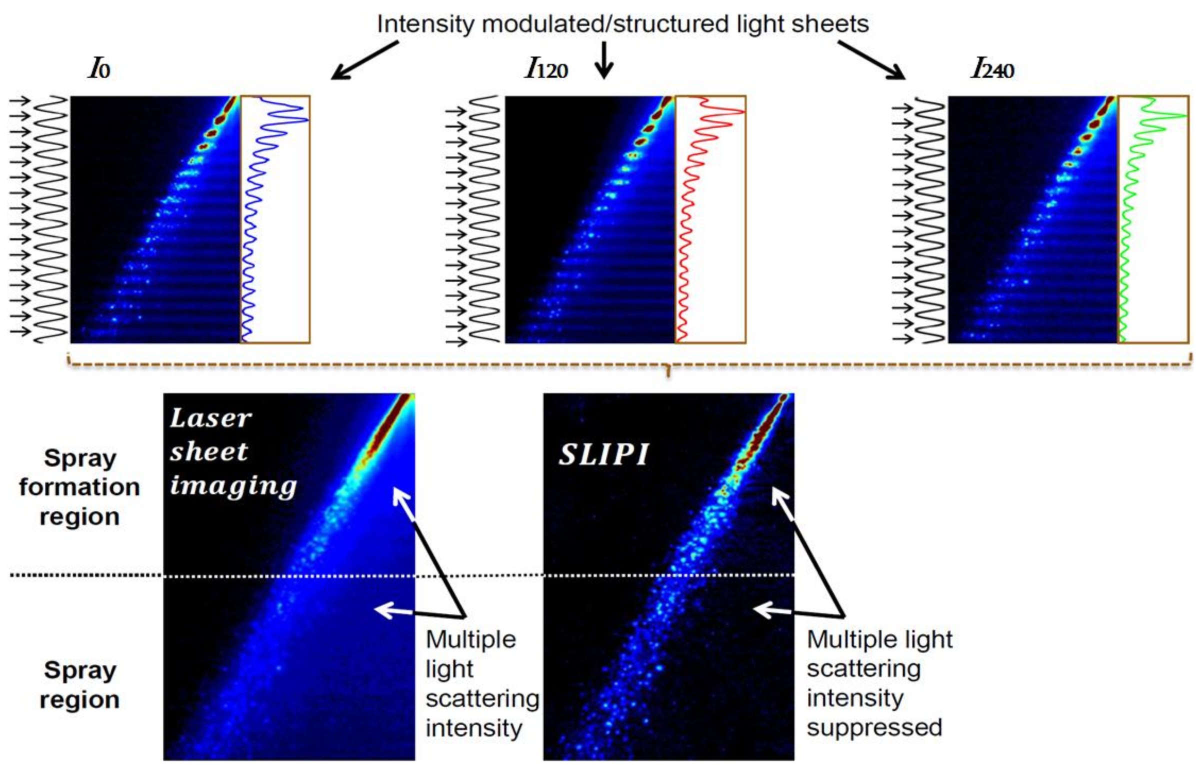


Fig. 3 Illustration of the 3P-SLIPI technique: Three successive images of a hollow-cone spray are taken using a spatially modulated laser sheet. Each laser sheet illuminates the spray differently by changing the spatial phase of the modulation. By averaging the sub-images, a conventional laser sheet image is obtained, in which the image is affected by multiple light scattering artifacts. By instead extracting the measurement of the modulation amplitude, the SLIPI image is formed. In this new image, the hollowness of the spray is now clearly visible. The removed intensity corresponds to the contribution from multiple light scattering (figure adapted from [19]).

This is done by applying the following equation:

$$I_{3P-SLIPI} = \frac{\sqrt{2}}{3} \cdot \sqrt{\left[(I_0 - I_{120})^2 + (I_0 - I_{240})^2 + (I_{120} - I_{240})^2 \right]} \quad (1)$$

Figure 3 shows the reconstruction of the SLIPI image and is compared with the conventional lser ser sheet imaging approach. In this example an a´verage of 50 images was considered. It is is observed that a significant contribution of unwanted light intensity has been removed on the SLIPI image, producing higher image contrast and faithful light signals.

Despite the advantage of having no losses in image resolution, the main drawback of 3P-SLIPI is the need in recording three sub-images, largely limiting the possibility in obtaining a single-shot spray images. Therefore, most of the initial SLIPI work was based on the averaged imaging [10,11,14-19]. Note nontheless, single-shot 3P-SLIPI has been achieved by Kristensson *et al*. [12] who have used three intensified CCD cameras together with three Nd:YAG laser systems. In addition to the complexity of the optical set-up, the cost of the equipment does not make it accessible to many research groups.

- **2P-SLIPI**

The idea of 2P-SLIPI, proposed in 2014 by Kristensson *et al.* [13], is to illuminate the sample with only two phase-mismatched modulated light sheets successively and to extract the absolute value of the intensity difference between these two sub-images I_0 and I_{180}. By mismatching the spatial phases, the overlap of the “line structure” is minimized. This approach will remove the image components that are identical in the sub-images, which is similar to what the standard three-pulse approach does. However due to the crossing of the two modulated signals at half of the modulation period, their substraction results in a “zero value” repeated at half the frequency of the incident modulation. The lack of information which was originally carried by the third sub-image, lead with 2P-SLIPI to an incomplete demodulation. This is visually observed by the appearences of black lines on the resulting SLIPI images as illustrated in Figure 4. The negative impact of these residuals often outweighs the improvement realized by structured illumination, which explains why the two-pulse approach has been avoided in the past. If one wants now to circumvent the visualization of those unwanted lines, the folowing procedure needs to be respected:

-1) To create an incident modulation of frequency as high as possible; as long as the modulation can be spatially resolved by the employed imaging system. This will push the residual lines at very high image frequencies and will affect only the tiny details on the image, which are sometimes not perceivable.

-2) To post-process the images and applying an adequate Fourier filter that will remove the residual lines from the final SLIPI images.

$$I_{2P-SLIPI} = \frac{\sqrt{2}}{2} \cdot \sqrt{\left(I_0 - I_{180}\right)^2} + \textit{Fourier filtering in post-processing} \quad (2)$$

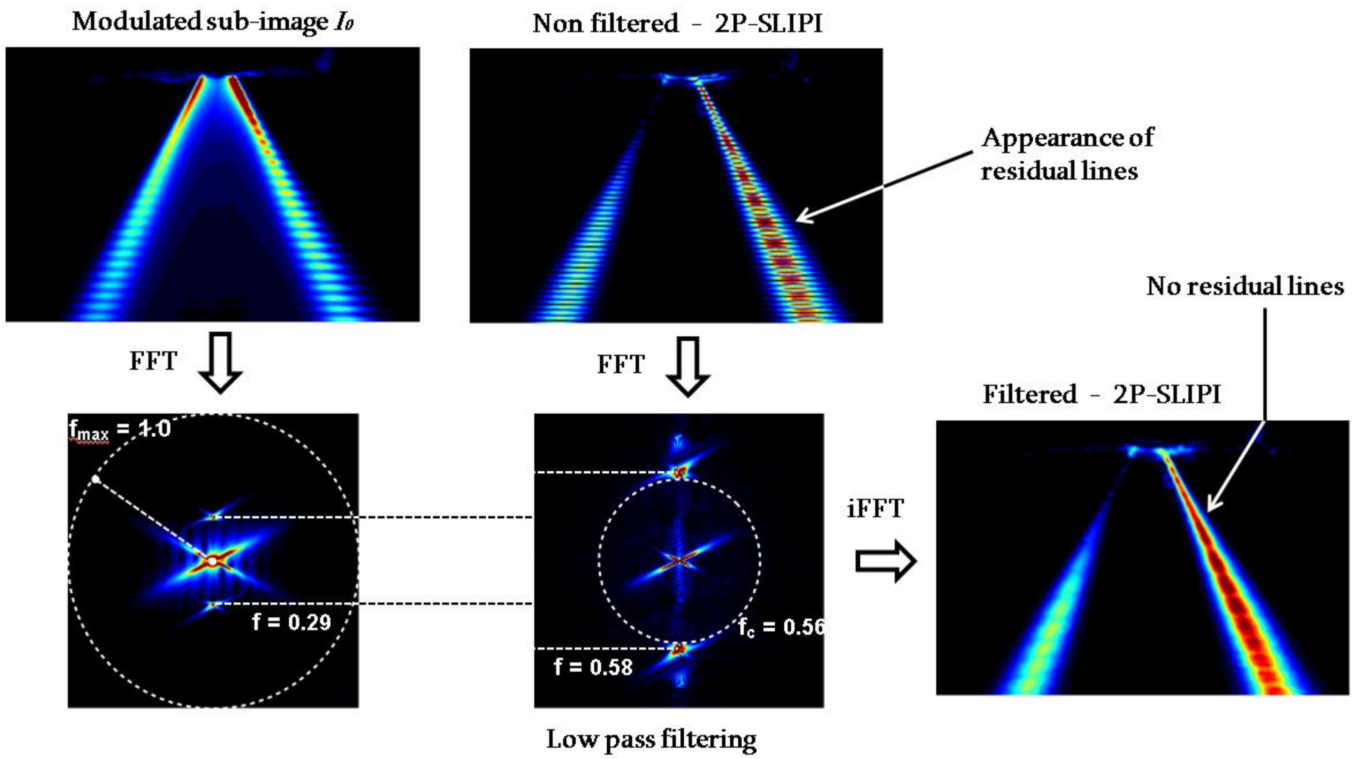


Fig. 4 Illustration of the 2P-SLIPI technique: Two modulated sub-images of a hollow-cone water spray I_1 and I_2 re taken with a spatial phase mismatched (ΔΦ = 180°). Here only the one sub-image is shown on the top-left, together with its FFT on the bottom left of the figure. By taking the absolute value of the differences between I_0 and I_{180} a non-filtered 2P-SLIPI image is obtained: Some residual lines are produced, here, at frequency f=0,58, which is twice as high as the incident frequency f=0.29 (where 1 equals the maximum frequency resolved in the image). By applying a low pass filter at f_c = 0.56 in the Fourier domain and applying an inverse-FFT the final filtered 2P-SLIPI is obtained with no observable residual lines. To reduce the amount of spatial frequencies which are suppressed on the final image, one should use frequencies as high as possible on the incident spatial modulation. The frequency limit is fixed by the imaging system employed and is respected as long as the line structure remains well imaged, with enough pixels to sample a single period.

In Figure 4, a 2P-SLIPI example is given based on averaged imaging, in order to clearly highlight the modulated structure of the modulation and the effects of the induced residual lines. The technique is then applied, in Figure 5, for single-shot Mie scattering of the same hollow cone spray.

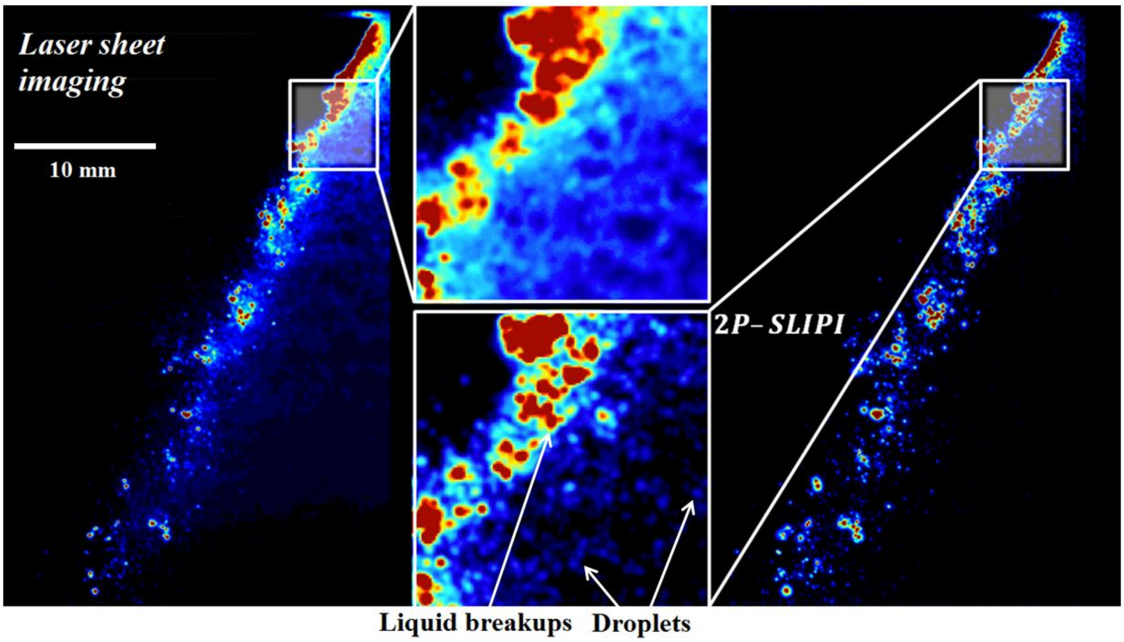


Fig. 5 Example of single-shot 2P-SLIPI for Mie scattering of the same hollow-cone water spray presented in Figure 3. A zoomed area highlights the differences with the conventional laser sheet imaging. The presence of individual drops which were hidden by blurs is now visible with single-shot 2P-SLIPI. Also the separation of liquid bodies is more apparent.

- **1P-SLIPI**

The amplitude of the modulation can also be recorded extracted from a single modulated light sheet. This has been first shown based on averaged imaging for the measurement of the extinction coefficient μ_e in homogeneous scattering solutions [23]. In this case the resulting losses in image resolution was not an issue to deduce accurate measurements of μ_e . The extraction of the amplitude of the modulation was done by deducing the maximas and the minimas of the signal along each pixel column as illustrated in Figure 5. It was demonstrated that the approach could be an efficient alternative to the standard transmission measurement especially when probing turbid media. To reduce the losses in image contrast, one should used frequencies as high as possible. In such case and if the probed medium consist of a smooth shape without too much high frequency information, then 1P-SLIPI for single-shot imaging is applicable as demonstarted in [24]. Note that the most efficient way in extracting the amplitude of the modulation from a single modulated image is to use can a lock-in amplification algorithm as detailed in [25].

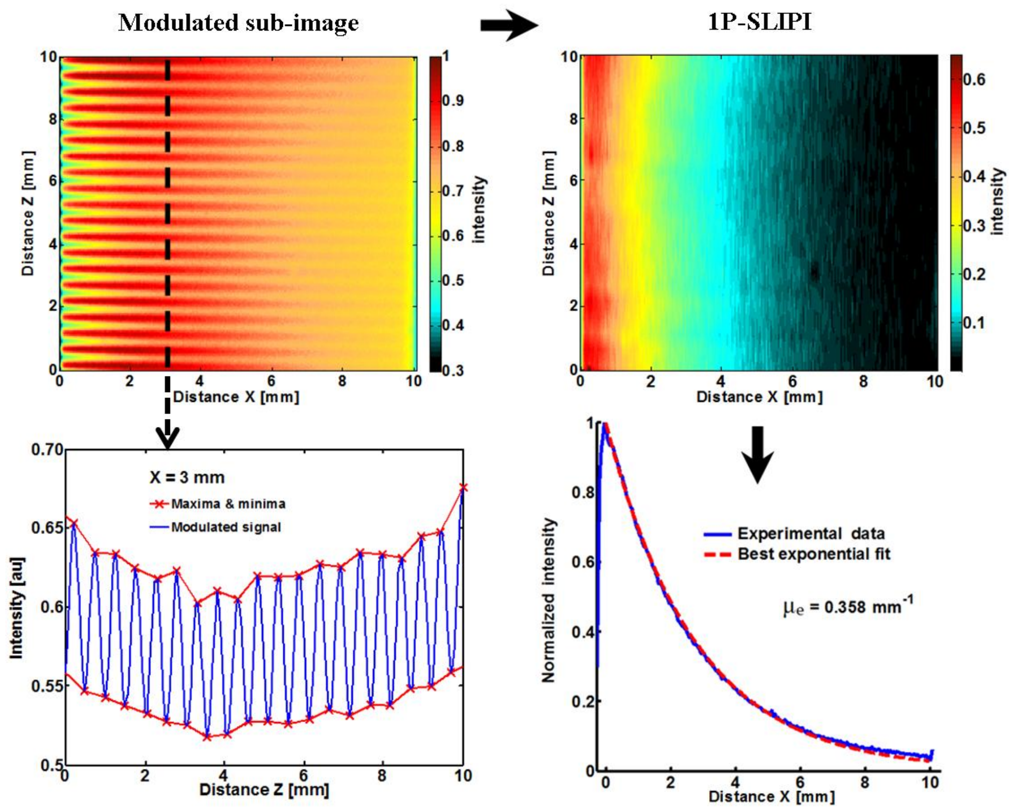


Fig. 6 Example of averaged 1P-SLIPI for the measurement of the extinction coefficient in a scattering solution of polystyrene spheres of 0,5 microns in size contained in a cuvette and illuminated at 532 nm [23]. Here the amplitude of the modulation from a single modulated sub-image is extracted using a peak detection algorithm. Losses in image resolution can be observed along the vertical direction on the 1P-SLIPI image. However in this application, this is not an issue as the medium is homogeneous and as the final signal is vertically integrated to observe the exponential intensity reduction, as predicted by the Beer-Lambert law.

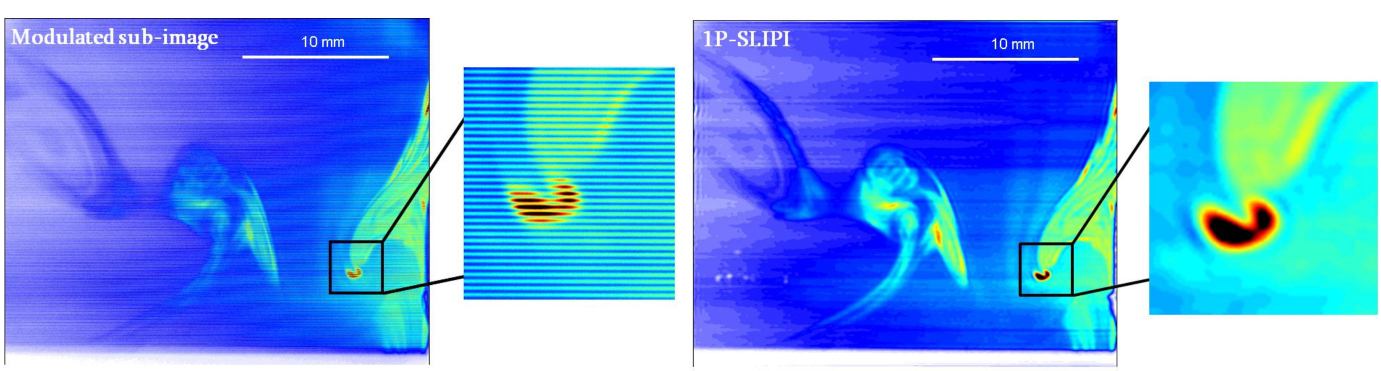


Fig. 7 Example of single-shot 1P-SLIPI for a drop of fluorescein dye mixing with water. Here it is observed that if the image contains mostly low frequency information, with large smooth features, and if a sufficiently high modulation frequency is applied, final reconstructed 1P-SLIPI is not too affected losses in image resolution.

3. Single-shot 2P-SLIPI for droplet sizing, thermometry and spray dynamics

An example of a 2P-SLIPI optical set-up is shown in Figure 8 for simultaneous LIF and Mie detection. This set-up and corresponding results have been produced at LTT Erlangen by Kögl *et al.* [26]. Two 532 nm Nd:YAG pulsed lasers are used where the time duration of each pulse is in the order of 6 ns while the repetition rate is 10 Hz. The linear polarization of the two laser beams are adjusted to be crossed one another and the beams are efficiently recombined using a polarization beam splitter. The time delay between the pulses generated from the two lasers is 750 ns, freezing the motion of the spray between the two exposures to generate the I_0 and I_{180} sub-images. The respective illuminations are recorded using LaVision sCMOS cameras running on double exposure mode. A single objective is employed here to reproduce the exact same image formation/magnification on the two separated cameras.

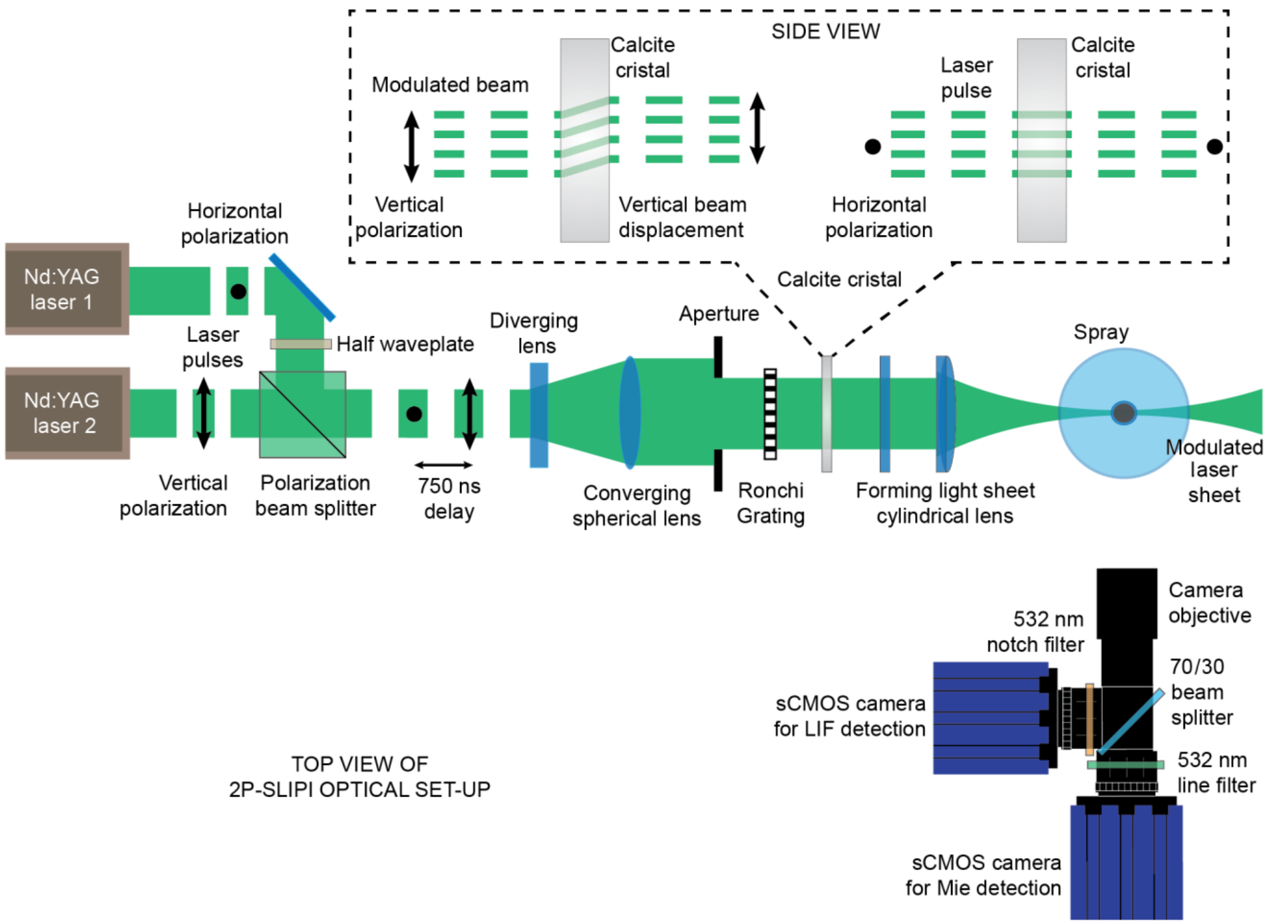


Fig. 8 Optical arrangement of the 2P-SLIPI set-up for simultaneous LIF and Mie detection. A time delay of 750 ns is set in between the pulses of the two lasers. This delay was short enough to freeze the spray motion and each pulse was recorded using LaVision sCMOS cameras running on double exposure mode. By using a temperature sensitive dye and replacing the filters by adequate bandpass filters accurate spray thermometry can be obtained using the same set-up.

This approach is found to be both more faithful in signal collection and easier to adjust than using two separated objectives where the field of view might differ. The optical filters are located in front of the detector arrays and consist of a 532 nm notch filter and a 532 nm line filter for the detection of the LIF and Mie signals respectively.

The structured light sheet is formed using a square Ronchi grating of 4 linepairs/mm, which is imaged along the vertical direction using a positive cylindrical lens. At the image plane a second positive cylindrical lens is used to focus the beam into a light sheet inside the spray chamber.

The displacement of the line structure must be operated at less than 750 ns which is not achievable mechanically. Instead, we operate the shift of the lines optically, using a birefringent calcite crystal. Due to the birefringent nature of calcite, the vertically polarized light (along the direction of the optical axis) propagates with a different index of refraction than the horizontally polarized light. This effect is depicted in Figure 8.

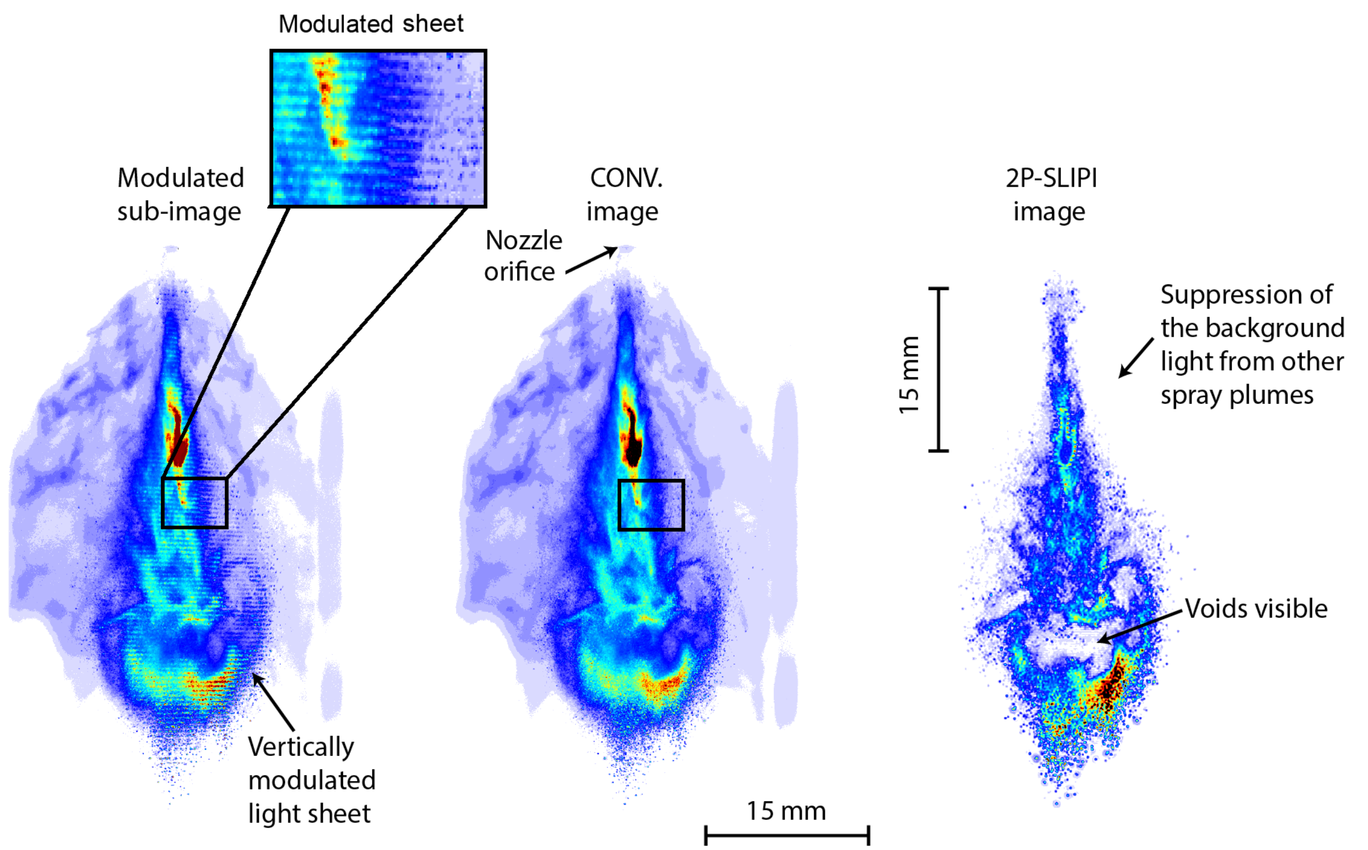


Fig. 9 Single-shot images of the LIF detection schemes adapted from [26]: By rapidly recording two modulated sub-image (with 750 ns time separation) where the "line structure" is shifted by half of the spatial period, a conventional light sheet image (picture in the middle) or a 2P-SLIPI (picture on the right side) can be reconstructed. It is seen that the 2P-SLIPI image shows significant improvements where voids in the spray are clearly visible and where the background light contribution induced by multiple scattering is efficiently suppressed.

The ordinary rays travel straight through the crystal while extraordinary rays exit the crystal displaced by a distance which depends on the wavelength of the incident light as well as the crystal thickness and the orientation.

The spray chamber is operated at 0.2 MPa and 298K representing high load engine operation. The fuel used here is ethanol, which is injected 16 MPa pressure. The injection duration is kept constant at 1.8 ms. A 5-hole DISI-injector from Bosch, was utilized, where one cone is centrally separated from the others allowing unrestricted optical access. The spray is investigated at 2300 µs after the electrical start of injection.

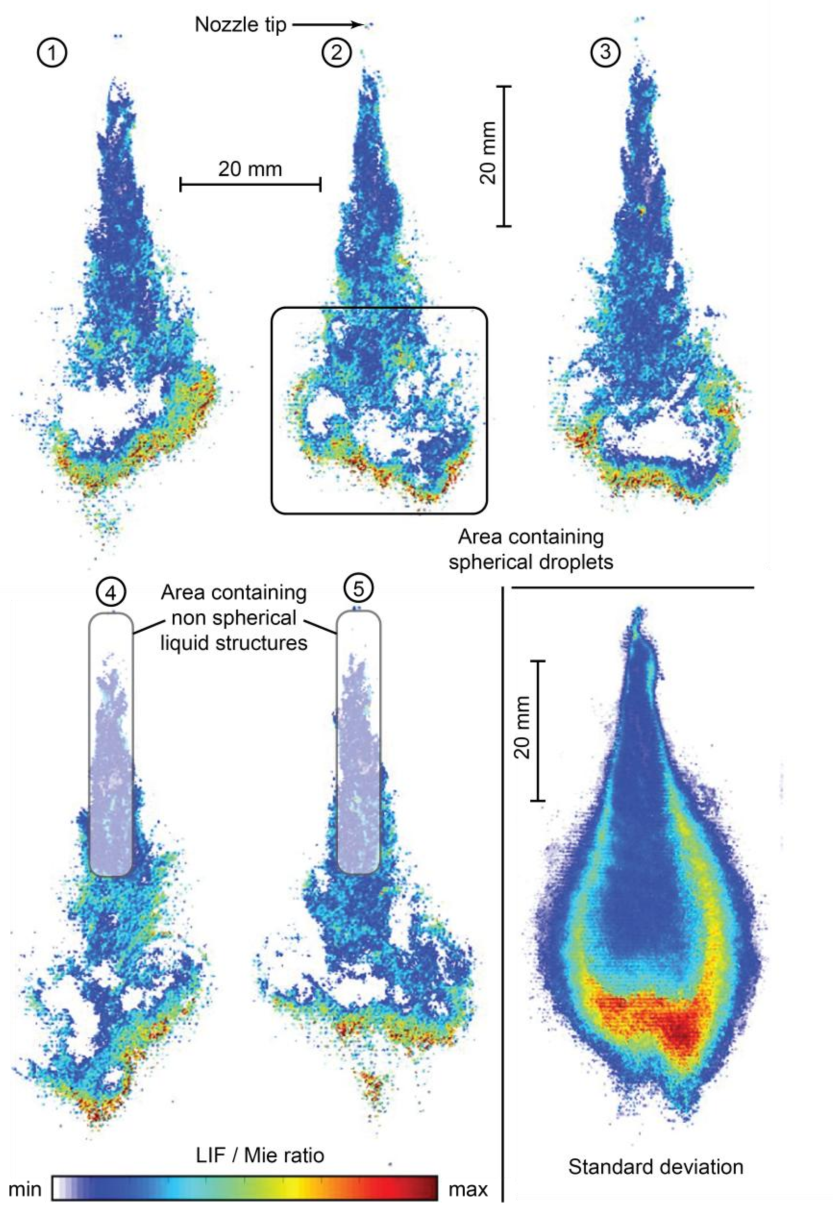


Fig. 10 Comparison of five single-shot images of the LIF/Mie ratio at 2300 µs after the electrical start of injection for an ethanol spray generated by a 5-holes DISI-injector (adapted from [26]). The standard deviation over 100 images is shown on the bottom right.

To induce fluorescence an organic dye, Eosin Y, is added to the injected ethanol fuel at 0.5 vol.-%. Eosin Y presents the advantage of being excitable at 532 nm and having a high quantum Yield when mixed with Ethanol. The broadband emission of the emitted LIF signal occurs between 500 nm and 620 nm. Five examples of single-shot LIF/Mie ratio recorded with 2P-SLIPI are shown in Figure 10 together with the standard deviation determined from 100 images. Note that the LIF/Mie ratio can be interpreted as a qualitative representation of the droplets Sauter mean diameter. Despite the fact that the maximum spray penetration length remains comparable between each recording, each spray image shows a non-symmetrical structure with large spatial variations in droplet distribution appearing. Large-scale vortices appear especially at the spray front, generated by large droplets with high droplet momentum. Those cyclic variations can be quantified by calculating the standard deviation of the LIF/Mie ratio images. The results reveals large inhomogeneities in droplet size at the spray front.

Conclusions

Since its creation in 2008 SLIPI has been largely developed and improved. Due to the prerequisite of standard Structured Illumination in generating three sub-images the technique was mostly limited to averaged imaging, which is a constraint in spray imaging and does not allow for the study of fluid dynamics. One significant progress on SLIPI is the recent possibility to obtain single-shot images by reducing the number of modulated sub-images to two and even one. This reduction in sub-image recordings simplify greatly the optical arrangement, but it ultimately affects the image resolution and add image artefacts consisting in residual lines on the final SLIPI image. To face those two issues, one has to apply a modulated incident light sheet with a modulation frequency as high as possible (still having the line struture being resolved by the employed imaging system) and to apply an adequate image Fourier filtering in the post-processing. It is found that this strategy allows applying SLIPI with two sub-image only with imperceptible, by human eye, image deteriorations: A technique called 2P-SLIPI.

Combining the approach with the existing Planar Drop Sizing or the two-color LIF thermometry, single-shot information on droplets size and spray thermometry can now be revealed without errors introduced by the contribution of multiple light scattering. Thus, 2P-SLIPI is a very attractive technique for the study of spray dynamics, thermometry and droplet sizing and might become the future method of choice for the study of the spray region.

It is also found that the use of a single modulated image, called 1P-SLIPI, can be applied to smooth flows that do not contain high frequency image information. Therefore the approach is recommended to the study of flames and single-phase flow mixing where small features and sharp edges do not need to be resolved.

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