Numerical investigation of discriminated forward scattering: optimizing imaging optics for dense sprays

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Abstract
This work presents results from a validated numerical model for scattered light imaging systems applied to simulated media representative of different spray conditions. Three different particle size distributions are examined using two different ballistic imaging instruments, which discriminate imaging light using a combination of time-gating, polarization, and spatial filtering. Results from the simulations show advantages and drawbacks for both optical setups and highlight the importance of understanding the spatial and temporal distortion imparted to the source light, which has the potential to significantly change the nature of the collected light signal. The results presented in this work show marked differences in performance for the chosen optical arrangements, depending on the physical parameters of the spray under investigation.

Introduction

Optical diagnostics are important tools for understanding atomizing sprays, where the analysis of sensitive flow fields is often not possible using intrusive measurement methods. Increasingly, there is a need for measurements in adverse environments, e.g. in the near nozzle region of fuel injection sprays, where interference from light scattering presents significant challenges to conventional optical methods.

When light transits a highly scattering medium, most of the photons which make up that light participate in multiple scattering interactions. Each of these interactions has the potential to change the properties of the transiting photon in a manner which disturbs the fidelity of its optical information. Experimental work in turbid media has shown that transillumination images can be significantly improved by limiting light collection to a subset of photons which are minimally distorted by scattering. The literature includes numerous demonstrations of image contrast improvement by means of discriminating a small portion of the total transmitted intensity from the bulk of the light collected in a forward-scatter geometry, most often realized by time-gating or spatially limiting the detected light. When a pulse of light transits a turbid volume the majority of its constituent photons are altered by interactions with the medium. However, even in very dense media, a small percentage of photons transit the volume without being disturbed by scattering interactions and retain undisturbed optical information. The transmitted light pulse is therefore made up of a distribution of photons with different degrees of optical information fidelity which ranges from these undisturbed 'ballistic' photons to severely scattered photons which retain little or no optical information. These methods, which selectively partition and filter the transmitted light signal, are commonly referred to as ballistic imaging (BI) techniques.

Until recently, the complex nature of the detected signal has limited analysis of the effects of this filtering process to qualitative comparisons of image results. The advent of a validated numerical model for scattered light imaging systems provides a tool for detailed quantitative analysis of scattering, light collection, and the information obtained by an imaging instrument. The model simulates the relevant parameters of both the optics and the turbid measurement volume which constitute the imaging system by leveraging a Monte Carlo solution for light propagation in a random distribution of scatterers coupled directly to a ray-tracing implementation which tracks light information through the optical components to the detection plane. This enables analysis and optimization of the imaging system, and a direct means of calculating and understanding the image contrast enhancement produced by the instrument. This work presents an application of the validated model where representative configurations of sprays containing droplets with different sizes are examined using two different optical arrangements. Results from the simulations highlight the importance of understanding the spatial and temporal distortion imparted to the source light, which has the potential to significantly change the nature of the collected light signal.

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System model implementation

The system model presented here is a set of programs that work together to define a scattering volume, instrument optics and a light source. For a typical imaging application, an intense short pulse of source light is modeled by numerous “photon packets”, representing groups of photons that follow similar trajectories. This light is transmitted through the scattering volume and optics to form a spatial intensity profile at the detection plane of the system. Light propagation in the model scattering volume is calculated as the sum of many distinct photon-particle interactions.

The photon packets representing the source light are launched and tracked through the scattering volume using a validated Monte Carlo (MC) code designed for light scattering in random inhomogeneous media [1]. The information from this MC code is integrated with a custom ray-tracing model which implements spatial, temporal, and polarization filtering of the source light as it traverses the optical train to reach the output plane. This yields a spatial intensity profile, which is subsequently convolved with a Gaussian kernel representing the diffraction-limited spot-size of the optical system.

This scheme represents a computationally affordable approach for calculating photon trajectories in regions containing a large number density of spherical scatterers and allows the quantitative evaluation of different imaging instruments and light filtering schemes. This provides the opportunity to optimize individual components, identify problems in current systems, and test the feasibility of new measurement objects, light sources, or optical designs.

Monte-Carlo light scattering

The MC approach used to simulate the scattering volume determines likely values for the physical circumstances of each photon packet as it propagates from the source to its final position. This is accomplished by randomly sampling probability distributions for photon interaction and direction change, which are based on the mean free path in the medium and an appropriate scattering phase function determined by Mie theory, respectively.

The MC method relies on repeated random sampling. Individually, each randomly determined answer represents only a possible answer. Large numbers of randomly sampled values in aggregate, however, begin to portray a realistic picture of the physical system, as represented by the probability distributions. Provided a statistically significant number of samples can be evaluated, light propagation throughout the optical system can be accurately calculated.

Note that the use of the Mie scattering phase functions to represent the scattering medium implicitly restricts accurate simulation to situations where Mie scattering assumptions are valid. Here, we assume that scattering events in the simulation are mutually independent, the scatterers are approximately spherical, and that the wavelength of the incident radiation is small compared to the size of the scatterers. A full description of the MC implementation used in this work is given in [1,2].

Ray-tracing through system optics

While a MC approach is efficient and easily adapted for modeling light propagation in a volume of dense, randomly distributed scatterers, the same approach can be unwieldy and computationally expensive when the system includes complex light collection arrangements. For this reason, the system model presented here integrates the MC scattering implementation with a detailed ray-tracing model. Photon-packet information derived from the MC code is translated into light-source rays which can be efficiently traced through the optical components of the system.

The ray-tracing model is implemented in Rayica and Mathematica code [3], and consists of an array of surfaces, material properties, and interaction behaviors which describe each individual optical component. The pertinent information generated by the MC procedures, including optical path length, time, scattering order, position, direction and polarization for each simulated photon, form the basis for a source ray that can be explicitly traced through the surfaces representing the system optics.

This allows the light information handled by the MC code to be filtered to yield the spatial intensity incident on the detector in a physical imaging system. This arrangement further contributes to the utility of the model as an instrument design tool, since existing high-quality models of commercial optics, and ray-tracing optimization methods can be leveraged to refine the instrument response.

In practice, the computational model is applied to examine an optical system by defining a cubic volume representing the scattering medium and assuming an appropriate scatterer size and density distribution. Photon packets representing the source light are launched from the input face of this volume and propagate through the system according to Mie scattering theory until they reach the scattering volume boundary. At this point their properties are examined and those which meet the specified spatial and angular collection criteria are recorded. Rays representing photon packets from the Monte Carlo calculations are generated from the recorded MC data and traced through the system optics to the output plane where they are integrated to form a spatial intensity profile. This integrated intensity is then convolved with the diffraction-limited spot-size of the system optics to yield a signal representing the light imaged by the detector in the output plane of the physical system. A more detailed presentation of the complete system model is given in [4].

Image contrast evaluation

An essential aspect of an optical system is its ability to transmit spatial information. The relevant parameter for evaluating performance in this respect is the visibility, or image contrast [5]. For a single spatial frequency, this quantity is given by the ratio of the input modulation to the output modulation,

$$C = \frac{I_{max} - I_{min}}{I_{min} + I_{max}} \qquad (1)$$

Where the contrast, C, is given by relating the minimum and maximum intensities, I_{min} and I_{max}. By applying the system model and introducing a single frequency spatial modulation (by means of a test chart bar pattern) to light crossing the scattering medium at a specific location, the system response to a single spatial frequency can be calculated using Eq. 1.

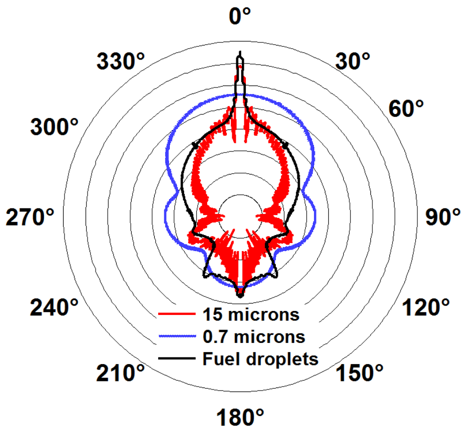
By modulating the light source at different spatial frequencies and applying the system model to calculate the instrument response, a series of simulations can be used sample the contrast transfer function (CTF) of the modeled instrument, yielding a quantitative metric for its performance as an imaging system. In addition, the point-spread function, representing the spatial distribution of irradiance produced by the instrument in response to a point source, can be calculated as the normalized modulus of the Fourier transform of the CTF. Validation results where system model analysis is compared with data from ballistic imaging (BI) measurements are given in [6,7].

Probing scattering conditions for spray imaging

The principal motivation for the development of a numerical scattering model which integrates the complete imaging system is to enable optimal diagnostics for the imaging of dense sprays. Ideally, one would like to provide a set of prescriptions for the imaging system based on pertinent spray parameters and the desired spatial resolution of the measurement results.

The scattering conditions for real sprays exhibit a large variability due to the diverse size distributions, optical depths, fluid properties, and physical dimensions intrinsic to sprays of practical interest. Hence, a fully prescriptive understanding of discriminated forward scattering in sprays will require a significant effort where the system model is applied to different imaging arrangements under a large range of scattering conditions. This work presents a preliminary effort where we examine and compare two different imaging arrangements under three different scattering conditions, at an optical depth (*OD*) of 14. These conditions were chosen specifically to provide insight for the application of BI to very dense sprays. In these simulations we examine two monodisperse droplet distributions at small (0.7 µm) and moderate (15 µm) sizes, and then apply the model to a polydisperse distribution of fuel droplets in air. The Lorenz-Mie phase functions which describe the scattering interactions in each of the simulated distributions are shown in Fig. 1, along with relevant parameters describing the simulation and spray conditions in each case.

The indications provided by these results are useful in framing the problem of fully prescriptive analysis, and give reliable insight for the specific conditions examined. However, one should take care to avoid drawing overly broad conclusions from these few test cases, as the interactions and competing influences of aggregate scattering effects, the physical dimensions of the system, and the filtering of the light collection arrangement can lead to non-intuitive effects on image contrast.



Droplet distribution:	***monodisperse*** $d = 0.7\ \mu m$	***monodisperse*** $d = 15\ \mu m$	***polydisperse fuel droplets***
Wavelength: λ **[nm]**	800	800	800
Refractive index particles: n_p	1.58+0.0i	1.58+0.0i	1.40+0.0i
Refractive index medium: n_m	1.33+0.0i	1.33+0.0i	1.00+0.0i
Anisotropy factor: **g**	0.845	0.920	0.920
Extinction cross-section: σ_e **[mm^2]**	3.390 10^{-7}	4.006 10^{-4}	4.280 10^{-4}
Number density at *OD* 14: N **[#/mm^3]**	4.130 10^{6}	3494	3270
Size parameter: $x = (\pi \cdot d / \lambda)$	2.75	58.9	55.0

Figure 1. Lorenz-Mie scattering phase function (logarithmic scale).

Simulation details—comparison of two optical arrangements

Source light in the simulation originates as a short (~100 fs) well-collimated laser pulse incident on the spray and collected in a forward-scatter geometry by the imaging optics. A nominal wavelength of 800 nm is assumed for the source, and the effects of absorption are assumed to be negligible. The spray structure or fluid dynamic features to be imaged by the optical system are represented in the simulations by a resolution test chart, which modulates the source light transmitted by the system with spatial information. This allows the effectiveness of the system for viewing specific spray features in the plane of interest to be quantified by the contrast, calculated according to Eq. 1.

Simulations for two optical arrangements are examined in this work. Both imaging systems eliminate a sizeable portion of the forward-scattered source light by time-gating and spatially filtering the collected signal. Each system includes an optical Kerr-effect (OKE) time-gate implemented using crossed Glan-polarizers which bracket a Kerr cell, consisting of a cuvette filled with liquid carbon-disulfide. Light which crosses the Kerr cell is subjected to a time-dependent birefringence which rotates its polarization, allowing transmission of the optical signal through the second polarizer during the a short (~2 ps) time window.

The first optical arrangement is shown in Fig. 2(a). This system is termed a "Projection" scheme, in reference to the action of the first lens, which is placed one focal distance from the plane of interest within the spray. This placement determines the efficiency of the light collection from the object plane. This results in a spatial filtering effect in which the collection of uncollimated light which has scattered prior to crossing the object plane is reduced, while the collection of well-collimated light remains unaffected. The source projection arrangement increases the amount of collimated light collected by the first lens from the object plane, which has the potential to increase image contrast when significant amounts of collimated light are present in the transmitted signal.

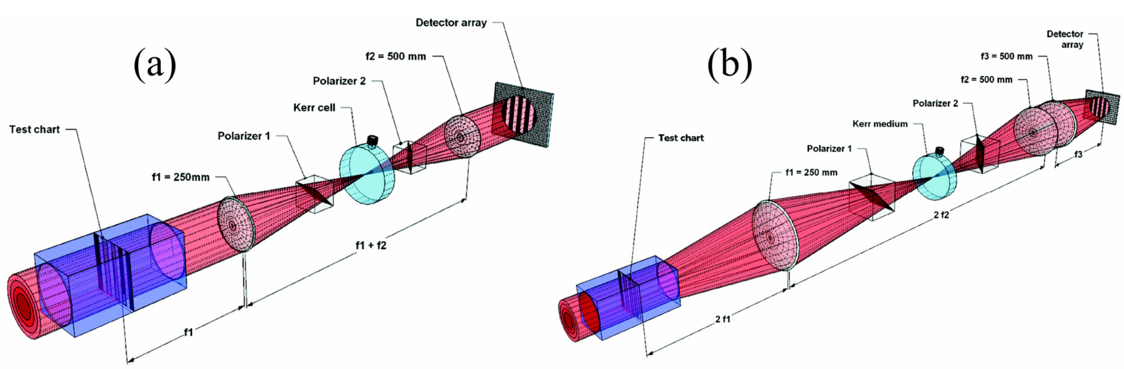


Figure 2. Simulated optical systems: (a) "Projection" light collection optics; first lens placed at 1 f, shadow image projected to detector. (b) "Imaging" light collection optics; first lens placed at 2 f, object plane spatial intensity imaged to detector at unit magnification.

The second optical arrangement is shown in Fig. 1(b). This system is termed the “Imaging" scheme, due to the arrangement of the collection optics which correspond to the conditions for imaging the object plane to the detection plane with unit magnification. Here, the first lens is positioned two focal distances from the object plane within the spray. This collection scheme reduces the amount of light contributed by each point in the object plane, since the irradiance filling the aperture of the lens decreases according to the inverse square of the distance from the object. However, this arrangement forms a spatial intensity at the detector which exhibits a conjugate optical relationship to the object plane, preserving a higher frequency spatial information, which can contribute to increased image contrast.

Monodisperse distribution results

Figure 3 compares the simulation results for the “Projection” and “Imaging” systems applied to a monodisperse distribution of 0.7 µm scatterers at *OD* = 14. Here the spatial filtering provided by the collection optics of the “Projection” system results in a greater relative contribution from photons with high spatial fidelity. This effect is partially explained by the shape of the scattering phase function, shown in Fig. 1., which indicates that scattered photons are very likely to experience large changes in direction at each interaction. The broad phase function results in scattering which increases the effectiveness of the spatial filtering from the “Projection” system collection optics. Under these conditions it is apparent that the “Projection” system outperforms the “Imaging” system throughout the range of the time-gating explored in the simulations.

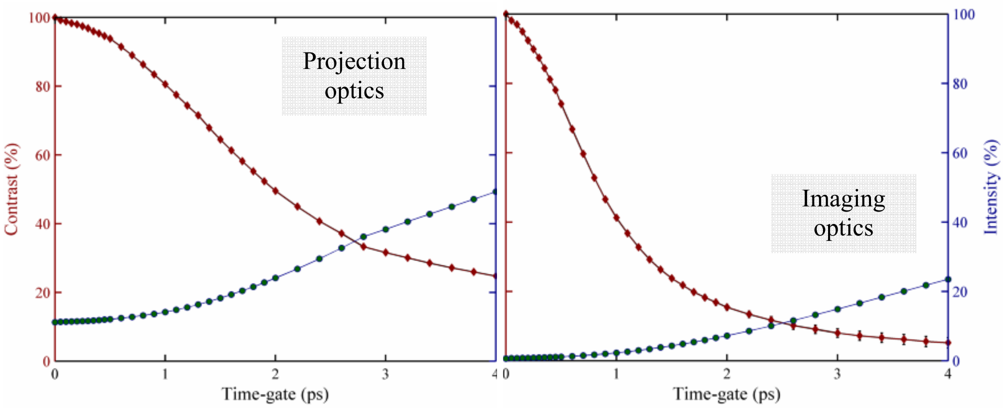


Figure 3. Simulation results for “Projection” and “Imaging” optical arrangements for 0.7 µm scatterers, at *OD* = 14.

Figure 4 compares the simulation results for the “Imaging” and “Projection” systems applied to a monodisperse distribution of 15 µm scatterers at OD = 14. Here the spatial filtering provided by the collection optics of the “Projection” system result in a much smaller relative contribution from photons with high spatial fidelity. Once again, this effect can be rationalized by observing the shape of the scattering phase function, shown in Fig. 1. In this case, the phase function exhibits a strong forward-scattering peak near zero degrees. This indicates that photons will often experience very small changes in direction with each individual scattering interaction. This type of scattering decreases the effectiveness of the spatial filtering from the “Projection” system collection optics, since many photons with large spatial disturbances are propagated in the forward direction to be collected by the optics. The “Imaging” system collects comparatively fewer low-fidelity scattered photons, due to the reduced collection acceptance angle of these optics. More importantly, the “Imaging” system is able to take advantage of the increased transmission of light due to forward-scattering in the medium, since collected light which has scattered from the object plane is correctly relayed to form an image at the detection plane. These results show that the “Imaging” system is capable of much higher contrast that the “Projection” system for the 15 µm conditions.

In general terms, the image contrast depends on both the light collection signal-to-noise ratio, and the spatial fidelity of the optical signal. Both of the light collection arrangements discussed in this comparison take advantage of the ballistic light transmitted by the spray, and apply identical temporal and polarization filtering. However, the systems implement different methods to gather and relay light to the detection plane, which results in marked differences in spatial filtering for each system. The performance differences exhibited by the systems are largely due to consequences of these spatial filtering effects, as detailed in Table 1.

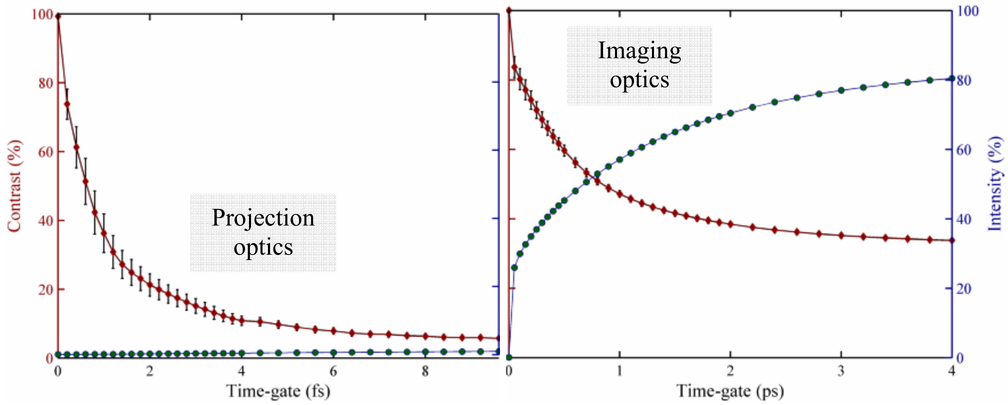


Figure 4. Simulation results for “Projection” and “Imaging” optical arrangements for 15 µm scatterers, at *OD* = 14. Note that the time scale shown in (a) is given in femtoseconds.

Table 1. Circumstances leading to performance differences between the “Imaging” and “Projection” systems.

	“Imaging” system	**“Projection” system**
Forward-scattered signal relative to ballistic signal	Forward-scatter contributes to signal as well as noise.	Forward-scatter contributes to image noise. High relative level of ballistic light essential for high image contrast.
Distortion of the forward-scattered light	Distortion limits achievable image fidelity.	Large distortion leads to better spatial filtering, increasing light collection signal-to-noise ratio.
Ability of the optics to reform scattered light from the object plane	This light is subject to distortion, but makes a positive contribution to image contrast.	This light contributes to the global background level at the detection plane, reducing image contrast.

Polydisperse fuel droplet spray results

A third set of conditions were probed to examine the performance of each light collection arrangement applied to a polydisperse, modified Rosin-Rammler distribution of droplet sizes with an average droplet diameter of 14 µm. In light of the results of the previous section and the similarities exhibited by the monodisperse 15 µm and polydisperse fuel phase functions, one expects the “Imaging” system to produce better image contrast for the polydisperse scattering conditions, and these expectations are borne out by the model.

Figure 5 shows the simulated spatial intensity results for the “Projection” system. Figure 5(a) shows the high-fidelity “first light” signal present if one were able to limit light detection to the first 100 fs of the transmitted pulse, resulting in ~90% contrast. The signal integrated at the detector using the simulated 2 ps time-gate is shown in Fig. 5(b). In this case, for a 2 ps gate, the contrast drops to ~1%.

Figure 6 shows the simulated spatial intensity results for the “Imaging” system. In this case the 100 fs time-gate signal (Fig. 6(a)), showing the test pattern with only high-fidelity light, yields a contrast of ~95%. The signal collected using the simulated 2 ps time-gate (Fig. 6(b)), results in a contrast of ~4%.

It is clear from these results that a spray reaching an *OD* of 14 would represent a very challenging measurement scenario, near the limit of what is possible to discern with the current BI implementations.

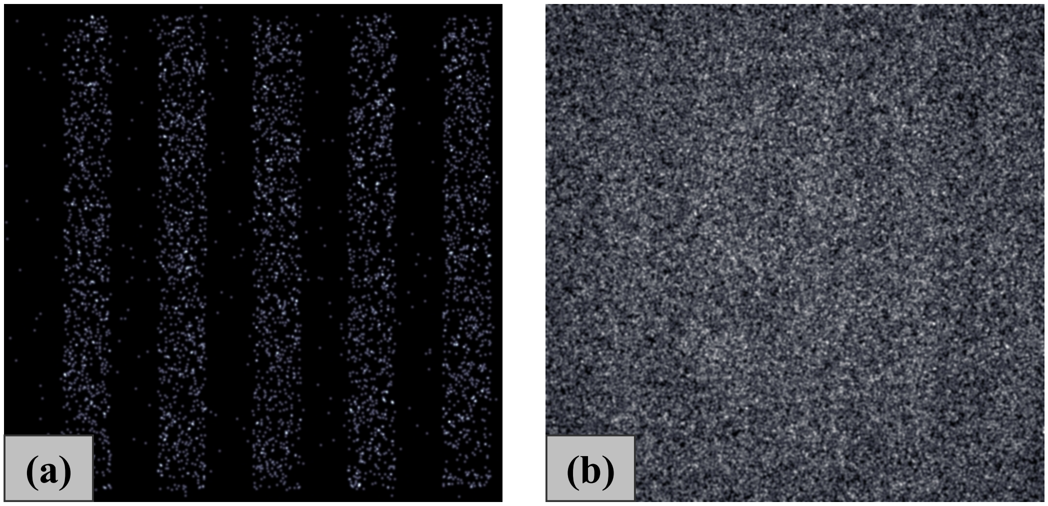


Figure 5. “Projection” optics simulation results for polydisperse fuel droplet distribution with mean diameter, d = 14 μm: (a) ‘first light’ signal corresponding to a 100 fs time-gate, resulting in 90% contrast. (b) signal integrated by the system optics corresponding to a 2 ps time-gate, resulting in ~1% contrast.

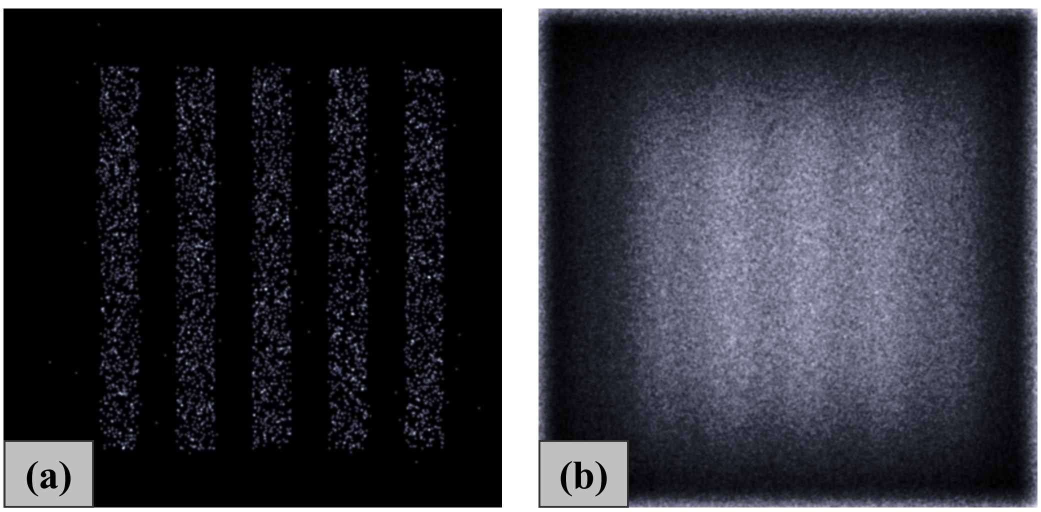


Figure 6. “Imaging” optics simulation results for polydisperse fuel droplet distribution with mean diameter, d = 14 μm: (a) ‘first light’ signal corresponding to a 100 fs time-gate, resulting in 95% contrast. (b) signal integrated by the system optics corresponding to a 2 ps time-gate, resulting in ~4% contrast.

Summary and conclusions

This work presented preliminary analysis providing insight for optimizing BI diagnostics for dense sprays. A validated “full system” model which tracks light through a complete imaging system was applied to two different imaging arrangements with fundamentally different light collection schemes. Three different scattering conditions were investigated, allowing the image contrast performance for each system to be quantified and compared over a range of conditions. Results from the simulations highlight the importance of understanding the spatial and temporal distortion imparted to the source light, which has a significant effect on the nature of the collected light signal. This determines which optical arrangement can be most effective for imaging in the spray.

Applying the validated model to a specific scattering medium allows the advantages presented by different arrangements of imaging optics to be quantitatively evaluated. Through a systematic investigation of imaging arrangements under a large range of scattering conditions, this analysis could be extended to provide more general prescriptions for the design of imaging optics suited to different spray conditions.

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