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Ultrafast time-of-flight imaging for accurate determination of stray light origin

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Abstract. We demonstrate a new approach for stray light characterization of optical instruments, based on ultrafast time-of-flight imaging. A pulsed laser source and a streak camera is used to record and identify individual stray light contributors, taking advantage of the fact that each stray light path has its own optical path length and therefore arrives at the focal plane at a specific time. This method will allow to better understand the origin of stray light, thus rendering more straightforward improvement of the instrument by re-design or processing.

1 Introduction

The image formed by an imaging optical system is degraded when stray light (SL) reaches the detector. SL can appear through partial reflection between the lens interfaces (ghosts) or from scattering on the housing or due to the roughness of optical elements [1]. In the particular case of space optical instruments, SL is a key aspect as it can strongly affect the success of a mission.

In order to mitigate effect of SL, specific opto-mechanical principles must be followed. Sometimes the instrument hardware must be blackened with specific coating or incorporate obstacles, such as optical vanes, to prevent unwanted light (e.g. coming from out of field) to reach the detector by multiple scattering. Still, the optical instruments, once built, need to be experimentally calibrated to assess their actual performances. SL characterization is one of these activities which allows to evaluate if the SL aspects are conform to what is predicted.

In this work, we demonstrate how ultrafast time-of-flight imaging (ToF) based on streak camera and femtosecond lasers offers a new paradigm in SL characterization. As SL components have different optical path lengths (OPL), illumination with a pulsed laser beam and detection with an ultrafast camera with 2 ps resolution allows to characterize them separately, contrarily to current setup which integrate all SL contributions on a single frame.

2 Measurement principle and setup

The new SL measurement principle [2] has been demonstrated in the case of a simple refractive system consisting of two lenses and a window with different optical surfaces, labelled a to f, as is shown in Fig 1. A collimated beam reaches the system and converges to the

focal plane, while stray light coming from partial reflection by the different surfaces reach also the detector later and not necessarily converging.

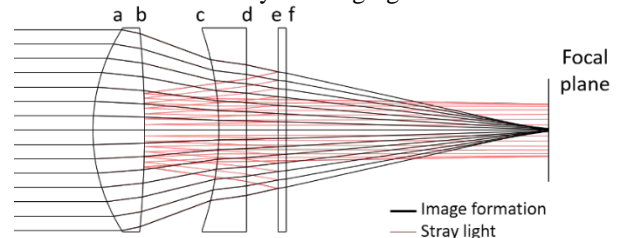


Fig. 1. Sketch of the tested optical instrument.

The experimental setup is shown in Fig 2. A fs-pulsed laser beam goes through a beam expander to form a large collimated beam, illuminating the optical instrument to characterize. The source is a Ti:Sapphire with repetition rate of 81.2 MHz and 100 fs pulses. A streak camera is placed at the focal plane of the tested optical instrument. The entrance slit of the streak tube is oriented along y.

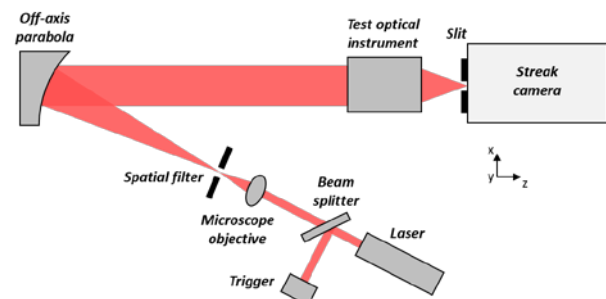


Fig. 2. Experimental setup for straylight characterization of an imaging optical instrument

The 100 fs light pulse entering the camera is mapped along the spatial direction x , in such a way an irradiance pattern is obtained in the form $I(t,y)$ along the slit. The different SL components have their own (x,y) extent at the

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focal plane and reach the latter at a specific time t . Therefore, if one wishes to reconstruct the full series of SL contributors irradiance $I_{SL}(x,y,t)$, one needs to scan the focal plane along x .

3 Results

Fig. 3 shows an example of $I(t,y)$ signal obtained at a particular x position in the tested optical instrument focal plane. The different SL components irradiances can be observed, each with a specific extent along y , with y_0 being the optical axis of the optical instrument tested.

On the figure, the different SL can be identified in function of the optical surfaces involved. For instance, "eb" at 120 ps is a ghost image arising from backward reflection first by surface "e" and second re-reflected by surface "b" towards the focal plane. It corresponds to the red rays shown in Fig 1. The labelling of the origin was made possible by raytracing, identifying the path length (and then the arrival time) of each possible ghost reflection. Some irradiance components appear to come from scattering by a specific element in the instrument.

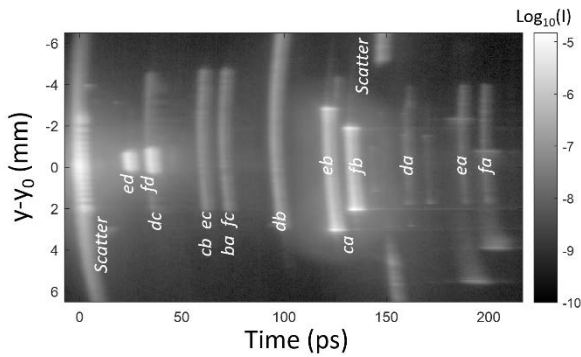


Fig. 3. Irradiance pattern $I(t,y)$ captured by the streak camera. Various stray light components are observed at different times.

After a scan along x (perpendicular to the streak camera slit) we obtain a series of irradiance values $I(x,y,t)$ containing all SL contributions in addition to the nominal image (here a point because the illumination is collimated). Fig 4(b) shows the experimental result for all the SL components and integrated on all the time frames. This shall be compared to the simulated irradiance pattern, Fig 4(a), that would appear in a traditional SL measurement facility where a classical camera is used instead of the streak camera. The black vertical stripe is located at the position of the nominal beam which is so intense that these positions were not measured.

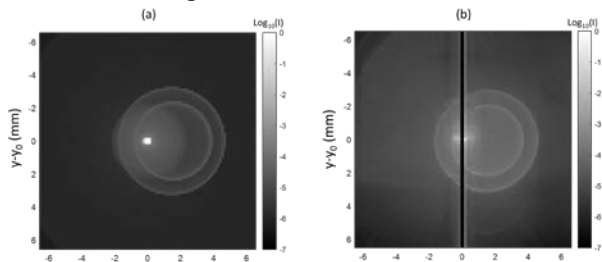


Fig. 4. (a) Irradiance pattern obtained by simulations with SL contributions of the optical system measured, (b) integration of all SL irradiances measured by time-of-flight.

Fig 5 shows some of the SL components extracted at different instants of the full temporal series. The (x,y) extent of each component were compared to the ones expected by simulation with very good agreement.

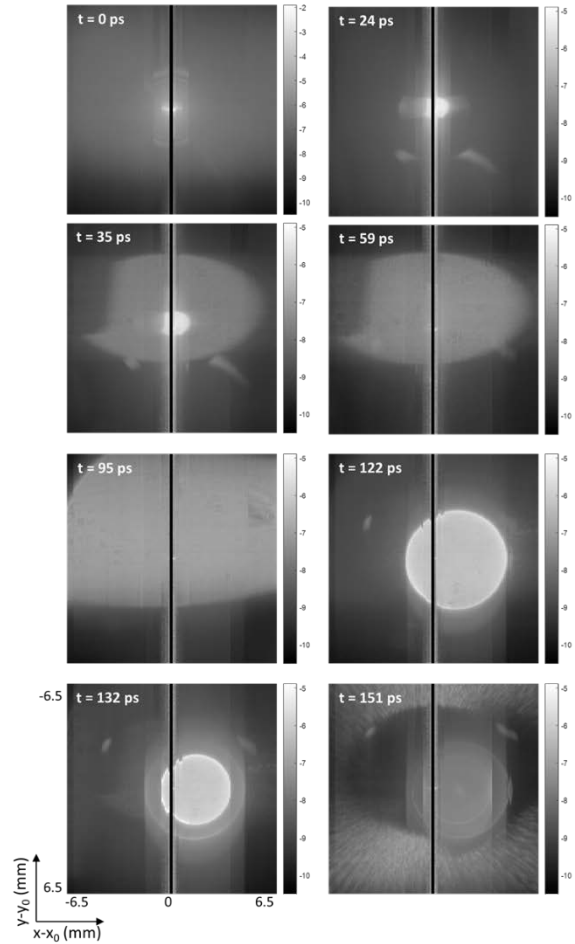


Fig. 5. Irradiance of SL components appearing at various times after the nominal image.

4 Conclusion

We have presented a novel method to characterize SL in optical instruments in view of uniquely identifying each SL component one by one, based on its specific arrival time at the detector plane. This method is based on ultrafast time-of-flight imaging, making use of streak camera and femtosecond pulse laser. The method is believed to become a new standard in SL characterization of space optical instruments.

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References

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2. L. Clermont, W. Uhring, M. Georges, *Sci. Rep.* **11**, 10081 (2021)