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# Advances in stray light characterization by ultrafast time-of-flight imaging

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## ABSTRACT

Stray light characterization using ultrafast time of flight imaging was demonstrated recently for the testing of refractive telescopes, using a streak tube with a femtosecond laser. It was shown that individual contributors such as ghost reflections and scattering features can be measured individually and identified, allowing unprecedented understanding of stray light properties in telescopes. This opens the door to the development of higher performing instruments, with stray light properties significantly reduced compared to the state of the art. In this paper, we will present the latest advances in the domain of stray light characterization by ultrafast time-of-flight imaging. This includes the characterization of imaging instruments, and the use of the time-of-flight measurements for reverse engineering instruments properties. In addition of using the time-of-flight approach for characterizing instruments, we will show that this method can be used to validate and improve conventional stray light measurement devices and facilities. In the case of large facilities, the typical optical path lengths is of the order of several centimeters to tens of meters. Therefore, in that case streak cameras can be replaced by a less expensive alternative, namely SPAD detectors. We will present the dedicated SPAD detector that we developed and the results obtain in the validation and improvement of the stray light facility for the FLEX Earth observation instrument. This system will be also used in the near future also for the NAC instrument in the ERO mission to Mars.

**Keywords:** stray light, time of flight, lidar, ghost, scattering, telescope

## 1. INTRODUCTION

In an optical instrument, stray light is unwanted light reaching the detector [1]. For this to happen, light follow a path or process different than the image forming beam. This can be ghost reflections, scattering on optical surfaces or non-optical surfaces, as well as straight shots. Figure 1 illustrates these different effects [2]. Stray light is a critical effect to take care in optical instruments, and in particular in the case of space applications. It degrades the performances of the system by decreasing the signal to noise ratio, decreasing the resolution, adding artefact features. Figure 2 shows an example where a simple point like source object is observed, for example a star [2]: the left figure shows how the image is supposed to look like while the image on the right shows an example of stray light features superposed to the nominal image.

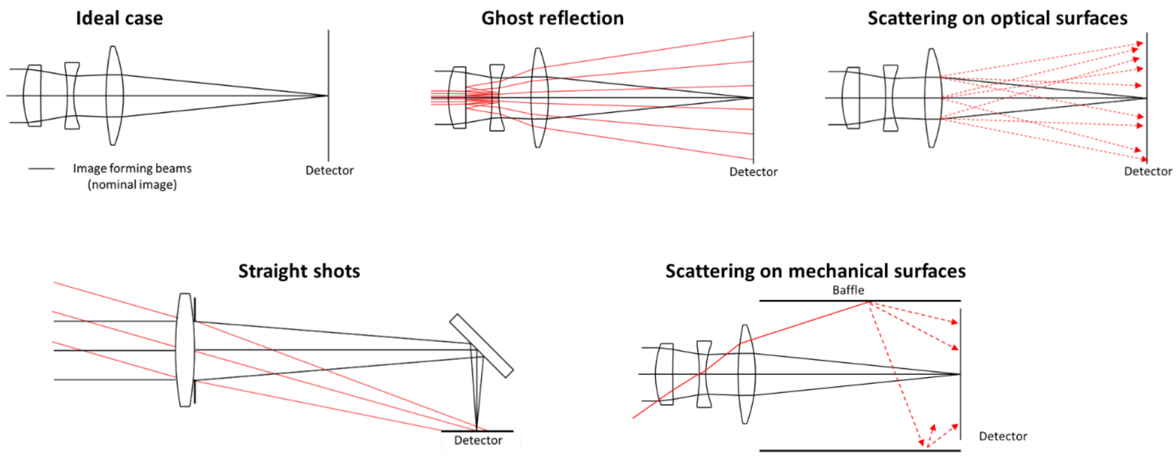



*Figure 1: Illustration of different kind of stray light effect*

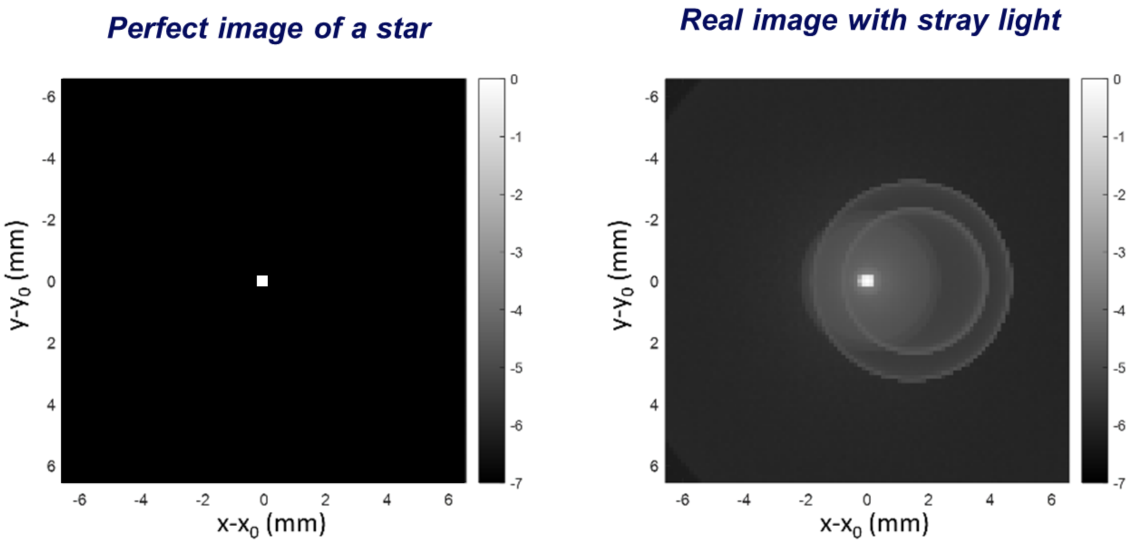



*Figure 2: (left) Perfect image of a star. (right) More realistic image of that star when considering also the stray light*

As stray light is a critical effect in space instruments, it must be controlled by design [3] and characterized experimentally. The characterization is meant to verify the performances, as an error discovered once the system is sent to space could not be corrected at that stage. It is important to identify any stray light issue on ground so that appropriate actions can be taken if necessary. Furthermore, characterization can be done to be used as an input for stray light correction algorithms [4][5][6][7].

The method for stray light characterization has been essentially unchanged since several decades. Typically we illuminate the instrument with a point like source and we look at the signal at the detector. Any signal away from the nominal pixel is stray light (at least if above the dark current signal). This pattern is often called the spatial point source transmittance or SPST. When integrated on a given zone, either a pixel or the full detector area, we talk simply the point source transmittance of PST [1].

The issues with the conventional approach is the following [8][9]. First, **stray light measurements are hard to interpret**. When looking at Figure 2 for example all we see is the superposition of multiple ghosts. Here only three are clearly visible, but even here more are actually present. In more complex situations we can have several hundreds of stray light features superposed. Next, **stray light origin is not identified**, therefore when any issue is encountered it is very hard to find the origin and thus the solution. All that can be said is the level of stray light and if it is within specification or not. If the performance is acceptable then the instrument can be sent to space. If the performance has any discrepancy with what is expected, we need to find the origin of the discrepancy so that we can understand what should be done to correct the issue. However when we don't know the origin of a problem, it is not possible to determine a solution. This is therefore a tricky, time consuming and expensive process. Finally, **stray light could come from the measurement device**. This means that the performance that we predict is not necessarily the one of the instrument under test, but the combination of the instrument and the measurement device itself. For example we could have a situation where the instrument has acceptable performances but the measurement device increases the measured stray light to a level above specifications. In that case we will look to solve a problem which does not exist in the first place.

A new paradigm is required to solve these issues. It is not just above optimizing the capabilities of the conventional methods, but instead of using a new approach. If we could solve the three issues described above, it would open the door to the development of instruments with higher performance, with design and test timeframe and cost reduced. In that frame we proposed the stray light characterization by ultrafast time of flight imaging. Let's assume we would illuminate the instrument under test with a pulsed laser beam, as shown on Figure 3. Then, the image forming beam and the different stray light paths would all have a specific optical path length, therefore a specific time of flight. At the focal plane, each path arrives at a specific time. While with a regular detector the difference of time of flight is so small it cannot be distinguished, using an ultrafast sensor would enable to measure each path separately. This would allow to decompose the different stray light contributors, and to identify them based on their time of flight. This would solve the three fundamental issues of conventional approaches, it would make the interpretation easier, would allow to identify the origin of potential problems, and it would discriminate the stray light from the measurement device. This is exactly what we have done recently and demonstrated with a refractive optical system [8], with a streak camera setup. This will be described in the next section. Furthermore, we show in this paper that this approach can be used also to characterize and validate the stray light performance of an optical measurement device. In that case a spad-sensor setup can be used as the difference of time of flight is smaller.

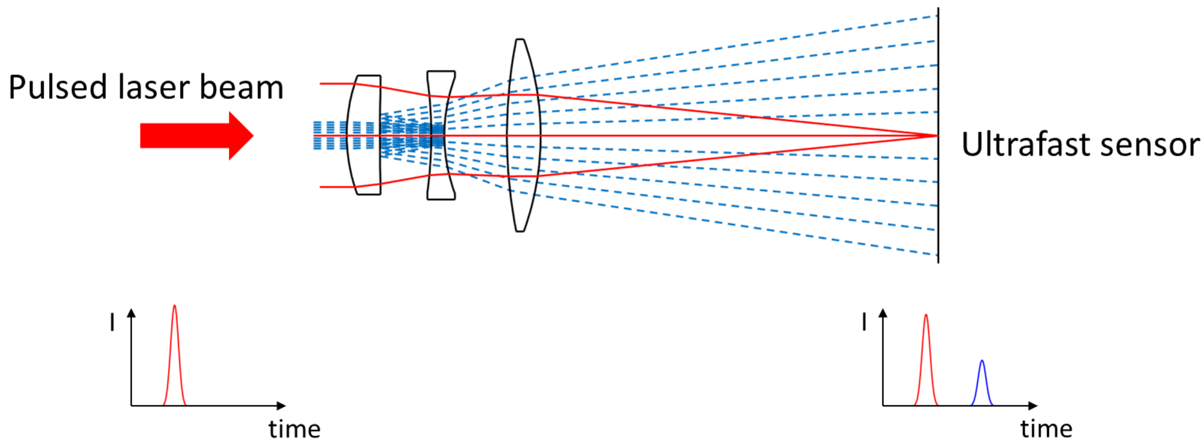



*Figure 3: When an optical system is illuminated by a pulsed beam, the nominal beam and the different ghost paths reach the detector with a different time as their optical path length is different. An ultrafast sensor can be used to resolve temporally these paths*

## 2. STRAY LIGHT CHARACTERIZATION IN AN IMAGING INSTRUMENT WITH A STREAK CAMERA SETUP

In the case of instruments with small differences in optical path lengths for stray light contributors, a femto-second laser used in combination with a streak camera is necessary. This allows to discriminate paths with typically sub-millimeter differences. We developed such a setup to characterize the stray light in refractive systems with lenses of few mm thicknesses [8][9]. Figure 4 shows the sketch of the setup. A collimated beam is formed with a femto-second laser and off-axis parabola to illuminate the optical instrument under test, which could be any kind of telescope looking at an object at infinite distance. At the focal plane of the telescope, we put a streak camera. Streak camera measure the light over a slit and decompose temporally the photons along that slit, by transforming the photons in photoelectrons which are then deviated with a deflection plate whose tension is time dependent. With this setup, we decompose temporally the stray light arriving at the detector along a 1 dimensional spatial dimension.

Figure 5 shows an example of optical system tested and the associated results. Here we consider a simple two lenses system, with a configuration typical of a simplified telescope. With 2 lenses and therefore 4 interfaces, we get a total of 6 ghosts paths plus the scattering on the lenses interfaces. The graph shows the PST, so the stray light integrated spatially (0 spatial dimension), as a function of the time. The blue curve shows the experimental results, while the red curves are the simulations. As we see, the experimental results presents several distinctive peaks, with remarkable similarities with the predicted results obtained by simulation. Each peak is identified based on the theory, for example around 30 ps time we have path “dc”, which is a ghost reflection between interface d and c as labelled on the optical sketch. At 0 ps, we have the scattering combined for each interface, as scattering path don’t have optical path length difference like for ghosts.

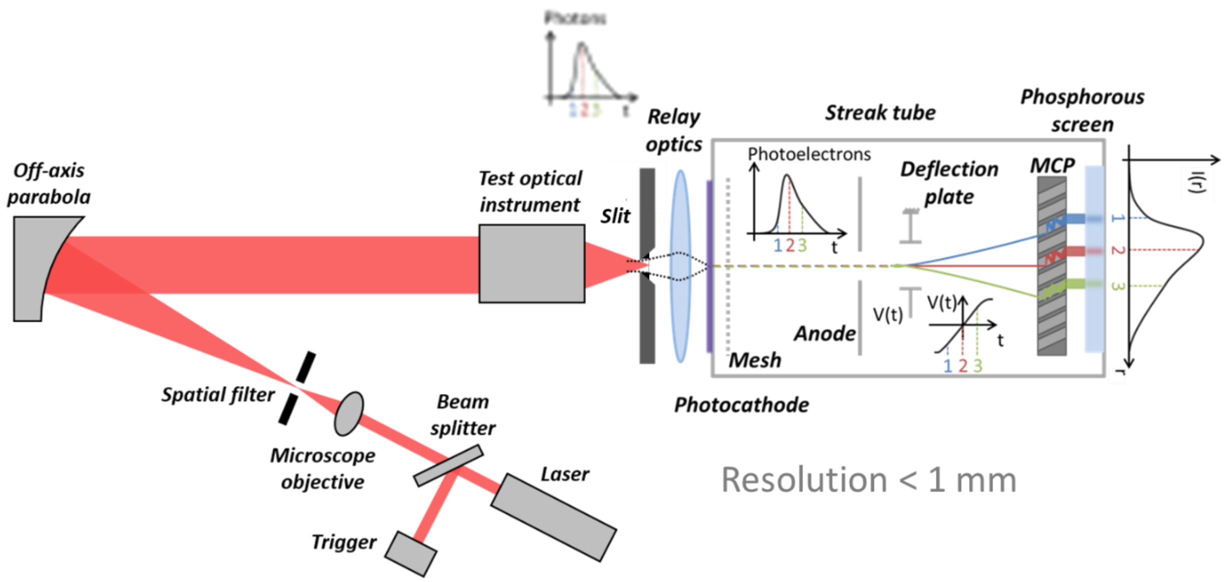



*Figure 4: Sketch of a streak=based setup for characterization setup by ultrafast time of flight imaging, for an imaging system*

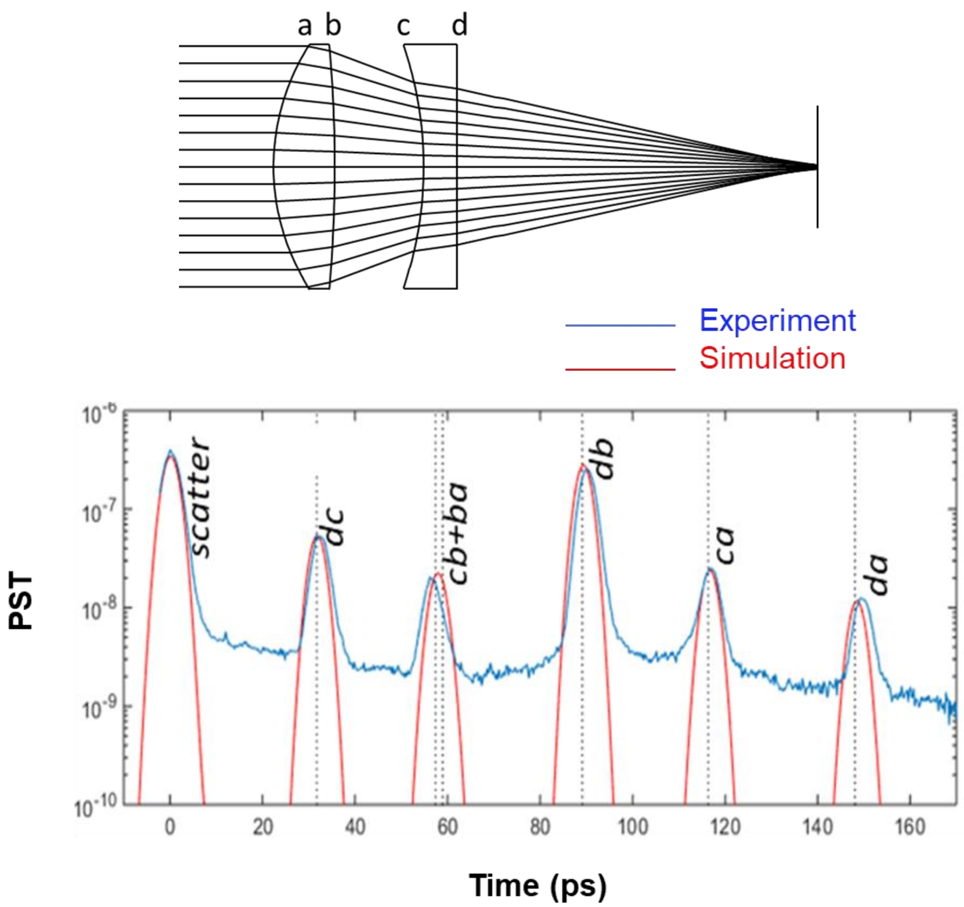



*Figure 5: (Top) Decomposition of the stray light by the time of flight, considering the spatially integrated stray light as defined by the point source transmittance function (PST), for ghost in the optical system shown on the bottom illustration. Experimental and theoretical results are displayed.*

The results from Figure 5 obtained by time of flight characterization brings significant added value compared to the conventional approach. In the conventional approach the PST would have been a single number, while here we have the PST decomposed for the different contributors. With the conventional approach, the value of the PST is compared to the required value, and all that can be said is if it is above or below the expected value. With the time of flight approach, we can compare each contributor with the expected value, and the sum with the total required value. If the PST is above the performance requirement, we can look at every different peak and identify which is the problematic contributor, and therefore we know what actions should be taken to improve the performances.

In addition of the PST, the time of flight approach can be used to measure the SPST, or the 2D spatial distribution of the stray lith decomposed by the time of light. Figure 6 to Figure 8 show experimental results where this is put in place. The idea is to perform 1D spatial acquisition as a single shot measurement, with the measurement along the slit, then we scan spatially the slit in the direction perpendicular to the slit direction. We then recombine the different acquisitions to reconstruct 2D spatial images.

Figure 6 (top) shows the system which is considered, which is similar to Figure 5 but with an additional optical window to increase the number of ghosts, and thus the complexity of the stray light patterns. The Figure 6 (bottom) shows first the result obtained in a single shot, with the stray light decomposition along the slit. Here also we can identify each different feature by comparing the results with the theory obtained by simulation. Figure 7 shows the 2D results obtained by scanning the slit spatially. As we can see, we obtain the spatial distribution of individual stray light features. With this approach, we obtain the full spatial power distribution together with the information of the origin of the contributor.

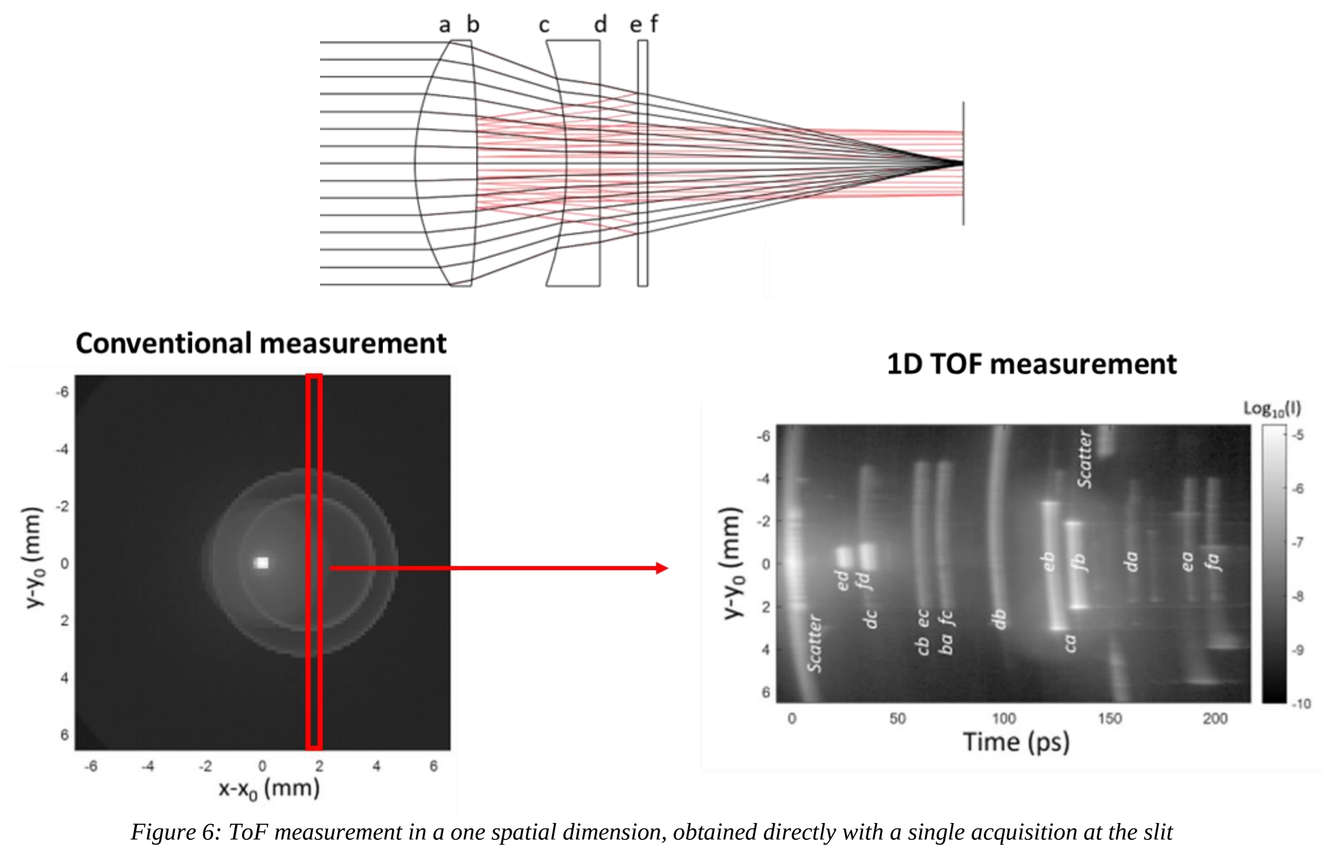



*Figure 6: ToF measurement in a one spatial dimension, obtained directly with a single acquisition at the slit*

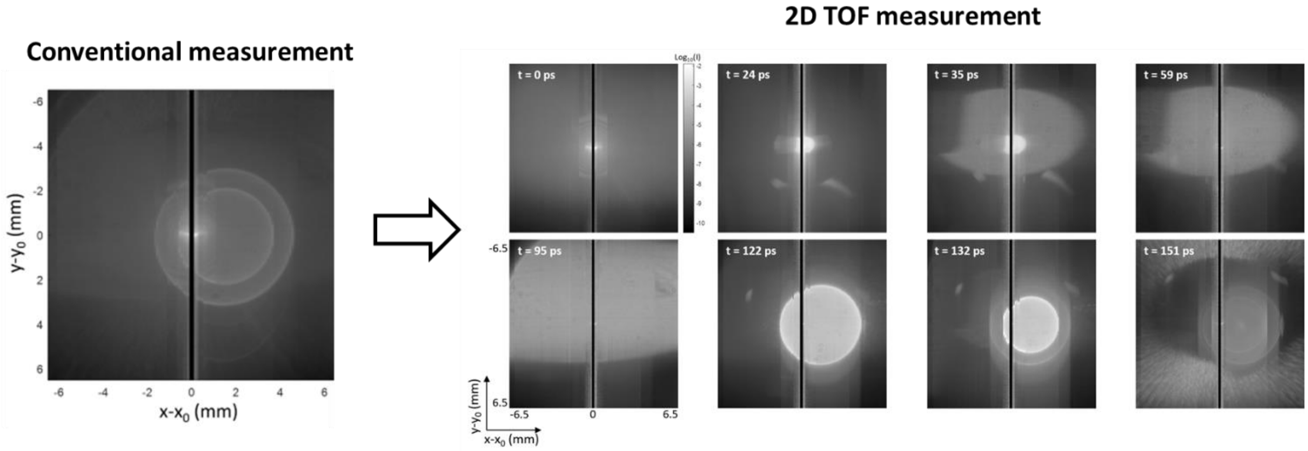



*Figure 7: Reconstruction of 2D spatial distribution of individual ghosts, achieved by scanning the slit in the spatial direction.*

A remarkable capability of the time of flight approach is that it enables reverse-engineering of the telescope properties. For example, Figure 8 shows the profile of two different contributors, namely the optical surface scattering and the ghost eb which are also shown on Figure 7. In the case of optical surface scattering, no theoretical result was initially available as the roughness properties of the lenses were unknown. Therefore we used the experimental results to determine the BSDF of the lenses by iterating on the ray tracing, each time comparing the simulation result with the experiment and adjusting the BSDF until we reach a result which fits the experiment. On the figure we overlay in black continuous line the result, which is extremely similar to the experiment.

About the ghost eb, we directly compared the experiment with the simulation (black continuous line). Both were extremely similar except that the experiment presented a tail around the ghost. It was found that this actually came from scattering of the rays involved in the ghost reflection. By simulating the ghosts considering also the scattering, used the reverse engineered BSDF of the optical surfaces, we obtained results in excellent agreement as shown by the black dotted lines.

These results are extremely promising to demonstrate the potential of the time of flight approach for developing higher performance space telescopes with lower stray light, also in a more efficient way considering both timing and costing.

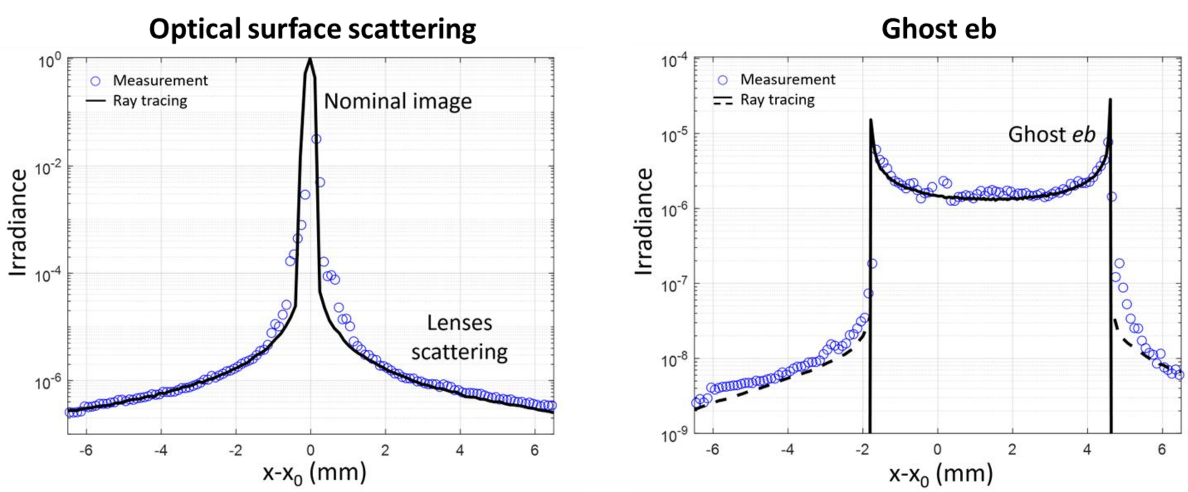
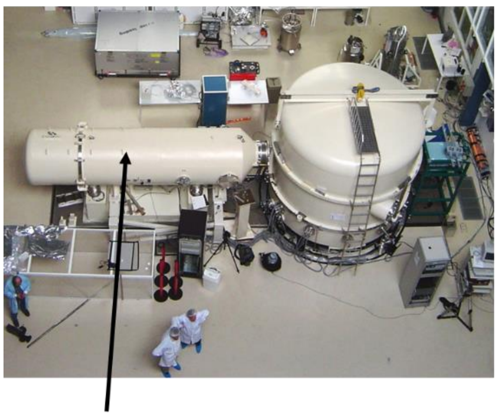



*Figure 8: Profile of the scattering by the lenses surface roughness (left) and profile of a single ghost (eb). The blue dots show the experimental results, the ray tracing is overlayed to show the reverse engineering capabilities for scattering or comparison with theory for the ghosts*

## 3. STRAY LIGHT CHARACTERIZATION OF AN OPTICAL FACILITY WITH A SPAD SENSOR

When an instrument is characterized in stray light with traditional methods, we need a measurement device which presents a stray light significantly lower than what we want to measure. Nevertheless, as the stray light requirement of instruments becomes always more stringent, this induce even more stringent stray light requirements for the measurement device. Therefore, achieving such stray light performance for the facility is extremely difficult, and verifying its level is very hard if not impossible as it would require another measurement device to measure that measurement device, itself better than the latter. Often the only alternative is to perform a verification by simulation [10]. With time of flight characterization, we can overcome these challenges.



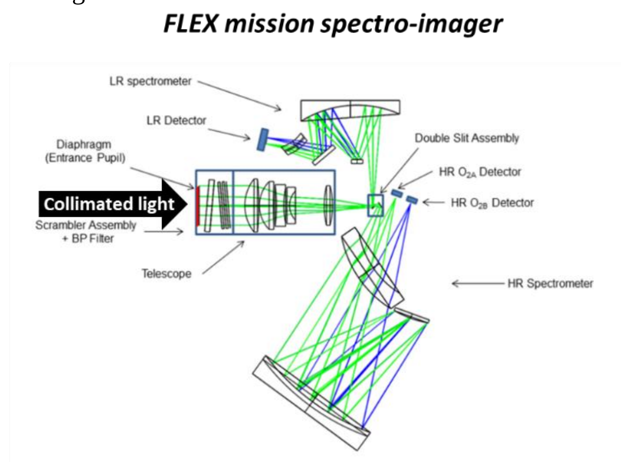




*Figure 9: (left) Optical calibration facility in a vacuum chamber for space instruments. (right) sketch of the FLEX mission spectro-imager, which will be tested in the calibration device*

Figure 9 (left) shows the picture of the optical characterization facility at CSL, which is placed inside a vacuum chamber to simulate the space conditions. A large collimator is used to reproduce a quasi-point light source illuminating the instrument. Figure 9 (right) shows an example of instrument tested in that facility, namely the FLEX Earth observation instrument. Figure 10 shows the 3D sketch of the facility with the instrument.

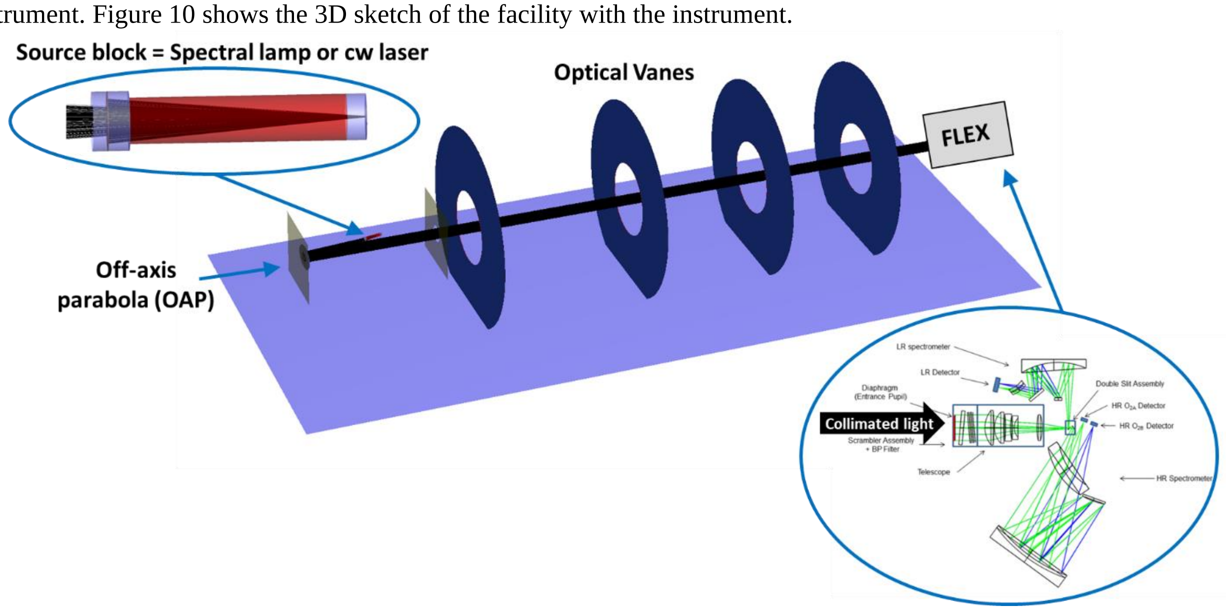



*Figure 10: Sketch of the interior of the calibration device as used for FLEX*

The time of flight stray light characterization method is applied to characterize and validate the stray light performances of the facility. For that, we replace the instrument under test by an ultrafast sensor, as shown on Figure 11. The goal is to measure the stray light generated by the facility and illuminating the instrument, and to discriminate it spatially and temporally. Here the spatial dimension is in the angular domain.

In this situation, the facility have large dimensions, with about 5 meters between the collimator and the sensor. Therefor the stray light paths to characterize have difference of optical path lengths typically large, up to several meters. Hence a streak camera could be used but would overkill. Instead, we can use a lower temporal resolution sensor: single photon avalanche detector, or SPAD. For this application, a specific SPAD system was developed specifically with resolution of the order of the cm, and with a window up to tens of meters.

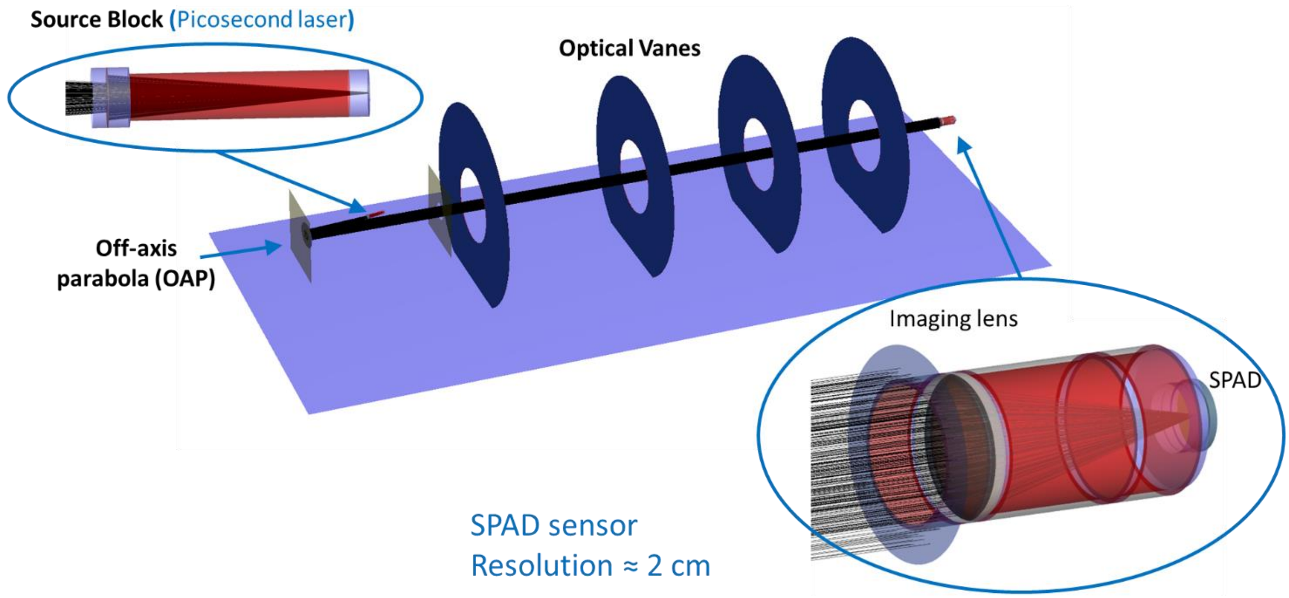



*Figure 11: Sketch of the interior of the calibration device with the spad detection system replacing the FLEX instrument, used fo time-of-flight characterization and validation of the facility*

In this setup, the measurement goes as follow. The SPAD has a single pixel, instead of a 1D array like the streak camera. Therefore, we use an imaging lens in front of the SPAD to reproduce the effect of the telescope. This means that the SPAD only receive the light coming directly toward the optical axis of the imaging lens, and within a very small angular range (called the detector field of view, or detector FOV). Then, the detector system is placed on an hexapod which allow to perform an angular scan in 2D. By combining the images together, we get the angular mapping of stray light, decomposed by the time of flight.

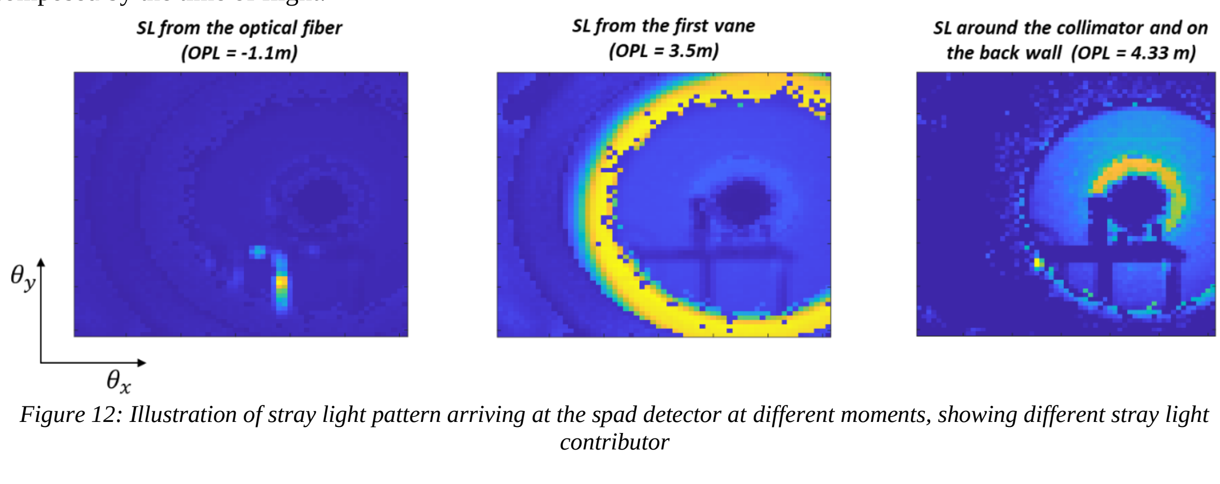



*Figure 12: Illustration of stray light pattern arriving at the spad detector at different moments, showing different stray light contributor*

Figure 12 shows example of experimental results obtained with the angular scan of the SPAD, with the angular distribution of stray light with different optical path lengths. For example, we show at the left the stray light arriving with an optical path length 1.1 meter shorter than the nominal. We find that this path is actually coming from light directly illuminating the optical fiber before the collimator. We also show the stray light from individual vanes, or from the wall behind the collimator. These different images, and others from the different time of flights, gives the stray light angular distribution of the different paths, and allows to identify each of them by their time of flight.

Figure 13 shows the near field stray light mapping, temporally integrated. This is the stray light directly in the vicinity of the image forming beam. The image on the left emphasize multiple features, in particular tilted squares and some spider-like features. At the center we have the bright signal coming from the nominal image. A zoom on that area (in linear scale) is shown on the right image, it shows indeed the nominal signal with an angular extend predicted by the angular extend of the collimator, and some broadening due to the finite extend of the detection FOV.

Regarding the square and spider features, we were able to find thanks to the time of flight information that they came from the ghost reflection in the SPAD itself. Indeed, Figure 14 shows a picture of the SPAD which presents exactly these features. What happens is that direct light illuminating the size of the SPAD is reflected back and creates a ghost in a window in direct vicinity of the sensitive area. This means that the SPAD seas itself and it could blur the signal and therefor prevent us to detect fainter signals. For that reason it was decided to place a mask before the SPAD so that only the sensitive area is illuminated.

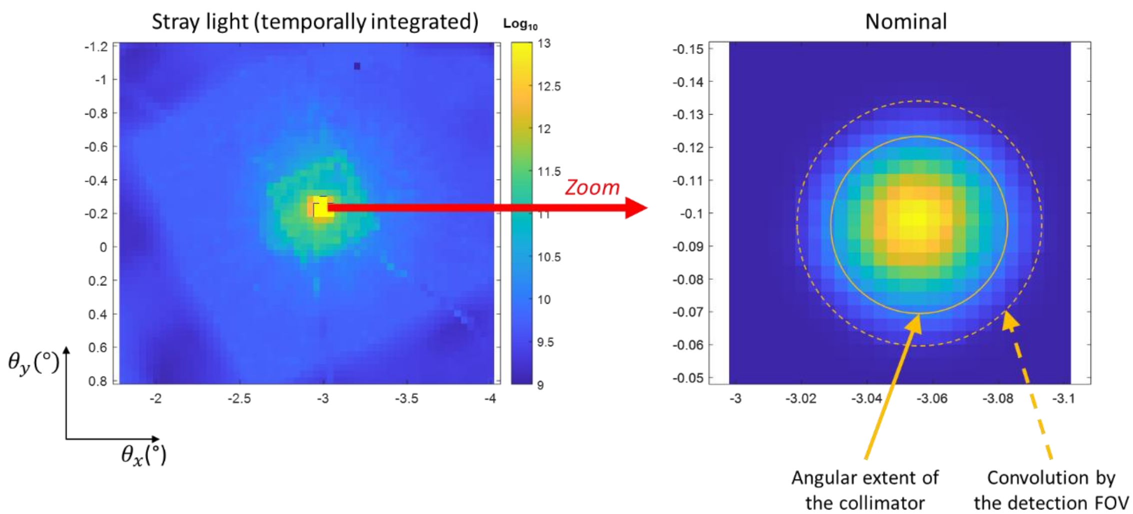



*Figure 13: Stray light from the facility arriving at the same moment than the nominal*

*Figure 14: Picture of the SPAD*

Figure 15 shows a profile of the stray light angular distribution along one direction, for different optical path lengths. The left figure is a semi-log diagram, while the right figure is a log-log diagram as a function of the sinus of the angle, a frequent approach for plotting stray light curves. What can be seen is for example the narcissus: as light illuminated the SPAD, it is reflected back toward the collimator and up to its focal plane. This can be extremely problematic as when the SPAD is replaced by the instrument under test, the reflectivity of the instrument detector is unknown and it could create an unwanted stray light path that will be detector among the actual stray light path of the instrument. Therefore, to minimize this path we placed a light trap at the focal plane of the collimator to block the light back reflected. Other kind of improvements are possible by using the time-of-flight approach to identify the cause of the issues, ultimately converging toward an optimal facility in terms of stray light control. The limitation is that when the telescope to test will replace the SPAD, light will illuminate its lenses, mirrors and mechanical elements and it can be back reflected or scattered toward the facility. This will create additional cross-talk paths involving pairs of surfaces between the telescope and the facility, which will not actually be part of the instrument stray light. For that reason we must minimize as much as possible the potential for cross-talk, which is why the measurement with the SPAD is performed with a baffle in front of its entrance aperture. Therefore during the characterization we also measure cross-stray light, even though the scattering properties of this baffle might not be exactly the same as for the telescope. The goal is to minimize all potential sources of stray light, by identifying the most critical and taking action on those.

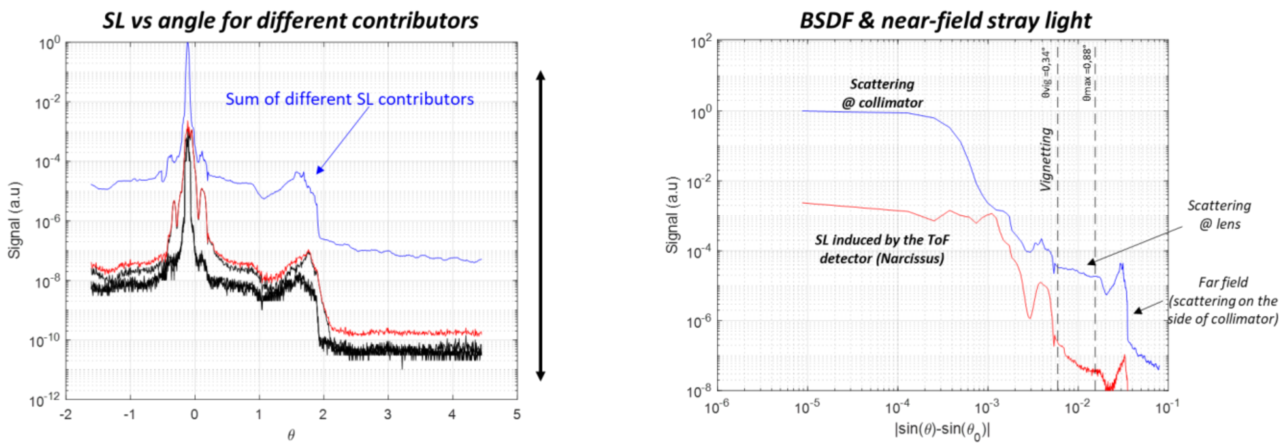



*Figure 15: Stray light profile for different optical path lengths, around the nominal*

## 4. CONCLUSIONS

We have developed a new approach for stray light characterization which allows to decompose and identify stray light contributors: the time-of-flight (ToF) characterization method. It solves the three main issues of conventional approaches, which were that stray light measurements are hard to interpret, origin of problems is hard to impossible to determine and measurements contain the contribution of the measurement device itself. With the time of flight approach, we decompose each contributor so we can compare them to the expected level, and if the total level is higher than expected we are able to determine which is the contributor responsible of the discrepancy. We have demonstrated the method experimentally and by simulation, with a streak camera setup to measure scattering and ghosts in a refractive telescope. We have also demonstrated the applicable of the method to validate and characterize the performance of an optical measurement device, using a space based configuration. The method could be applied in a large number of situations, from instrument characterization to facility characterization, including over a broad range of wavelengths. For example, Takakura et al. applied that approach in the TeraHz domain for the LiteBird mission [11].

## AUTHORS CONTRIBUTIONS

Lionel Clermont, Wilfried Uhring and Marc Georges are the authors of the first work done on stray light characterization by time of flight using a streak camera, also published in www.nature.com/articles/s41598-021-89324-y
The characterization with SPAD based sensor involved in three additional scientists, Wassim Khaddour, Pascal Blain and Emmanuel Mazy.

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