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Research Article

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Experimental SWIR gated viewing in accumulation mode

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Abstract: The recent availability of imaging sensors able to work in accumulation mode in the SWIR spectral range allows the realization of new efficient range-gated viewing systems. Such systems relax the illumination constraint so that the energy required to build an image can be distributed over several laser pulses. Semiconductor or fiber lasers can be used instead of high peak power solid state lasers. Such a system was realized in our laboratory, tested, and compared to a more classical flash system under outdoor conditions. In a first step, images of the same scenes recorded in the same weather conditions were compared to those recorded with a classical system working in flash mode. The MTF analysis shows an improvement of up to 40% with the system working in accumulation mode. In order to remove the influence of two different laser sources as well as of two different cameras, a second experiment was conducted. For this purpose, a shorter range and only one system were employed. Both operating modes, the flash and the accumulation mode, were examined. The second experiment confirms that accumulation mode can decrease significantly the value of the scintillation index resulting in a higher resistance to optical perturbations. These results increase the relevance of the accumulation mode for active imaging applications in the SWIR spectral region.

Keywords: gated viewing; laser illumination; SWIR imaging.

1 Introduction

Gated viewing in the SWIR spectral range has several advantages in comparison to the NIR domain [1]. Indeed, wavelengths over 1.4 μm are no longer focused on the eye retina, leading to a dramatical increase in ocular safety distances. Even if NIR wavelengths are theoretically not visible with the naked eyes, there is no difficulty to detect them with classical night vision goggles or cellphones. On the other hand, systems based on SWIR wavelengths increase the stealthiness of observation or detection operations [2].

Until recently, SWIR gated viewing systems were commonly based on a high-pulse energy low-repetition rate laser transmitter associated with a synchronized focal plane array camera. Such systems are efficient but suffer from two main limitations: the limitation of the detection range, which is proportional to the square of the laser pulse energy, and the limitation of the image quality, which is affected by the speckle noise initiated by the high coherence of solid state pulsed laser beams [3]. One pulse per image corresponds to the operating mode called ‘flash mode’.

Thanks to the recent availability of focal plane arrays such as electron bombarded CMOS (EBCMOS) able to accumulate multiple echoes synchronized with the illumination pulses, a new type of operating mode is possible. In this mode, called ‘accumulation mode,’ the illumination energy needed for reaching long ranges can be distributed during the integration time of a frame, leading to a dramatical decrease in peak power. By doing so, alternative laser technologies such as laser diodes [4] or fiber lasers [5], which are more efficient and more compact, can be used.

In active imaging, the image quality can also be degraded by the scintillation of the illumination beam due to atmospheric turbulences [6]. This point is particularly important, unlike conventional imaging systems, active systems are affected twice by atmospheric turbulence, first in forward motion when the laser beam propagates toward the target, and then in reverse motion when the echoes return to the sensor.

After a short description of the new developed system, several experimentations with the aim of quantifying and

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qualifying the accumulation mode under day and night conditions are presented. Using two different systems working in flash and accumulation mode, respectively, we compare the results obtained under different weather turbulence conditions on an open field. In a second step and with shorter distances inside an optical tunnel, flash and accumulation mode are compared with different perturbations.

2 System description

A new SWIR gated viewing demonstrator was designed and realized in our laboratory. This system shown on Figure 1 is based on a pulsed high-repetition rate semiconductor laser transmitter associated with a fast-gated camera able to work in accumulation mode (INTEVAC photonics, Santa Clara, CA, USA). Both transmitter and receiver are equipped with zoom lenses to cover a rectangular field of view from 0.28°×0.38° to 3.44°×4.58° with a perfect overlap of laser illumination and imaging field.

The laser diode stack (COHERENT-DILAS, Mainz, Germany) used for illumination has a wavelength centered at 1550 nm with a spectral bandwidth of 10 nm FWHM. A multimode optical fiber is used to connect the stack with the illuminator head as represented in Figure 1. The peak power is equal to 1 kW with a duty cycle of 2% allowing conduction cooling. Thanks to a high peak power driving electronics, the pulse duration could be reduced to an interval between 500 ns and 3 µs. The repetition rate is tunable up to 10 kHz. The camera, which is associated to this illuminator, has a maximum frame rate of 30 Hz. However, the global integration time for accumulation is limited to 22 ms for each frame. In this time window, the gate frequency is set to 6.5 kHz for a maximum of 7.5 kHz given by the manufacturer [7]. With these features, it is possible to integrate up to 143 laser pulses to build one image. Using one pulse per image, it is also possible to work with this system in the so-called flash mode. However, the available energy is highly limited, and this type of operation must be restricted to comparison purposes only. At maximum repetition rate, the available energy to record a frame is up to 300 mJ allowing an increase in the detection range.

3 Experimental results

Earlier work conducted inside an optical tunnel has shown a very good image quality in accumulation mode mainly due to the addition of several echoes for recording one image and also to the use of a low coherence laser illuminator [4].

Furthermore, the accumulation mode, which is more sensitive to parasitic lighting due to a greater integration time, was successfully tested under daylight conditions including direct sunlight [8].

With the new system presented in Figure 1, further experiments were conducted both inside an optical tunnel and outside, on a proving ground or in open urban environment.

3.1 Image quality comparison for flash vs. accumulation mode

The goal of the first experiment is to compare the results obtained with our new system based on accumulation mode to those achieved with a flash gated viewing system based on an OPO shifted Nd:YAG laser (Lumibird-Quantel, Les Ulis, France) [9]. The second system has a pulse energy of 65 mJ with a pulse duration of 9 ns and a maximum repetition rate of 30 Hz. This system is also equipped with an equivalent EBCMOS camera of an older generation working only in flash

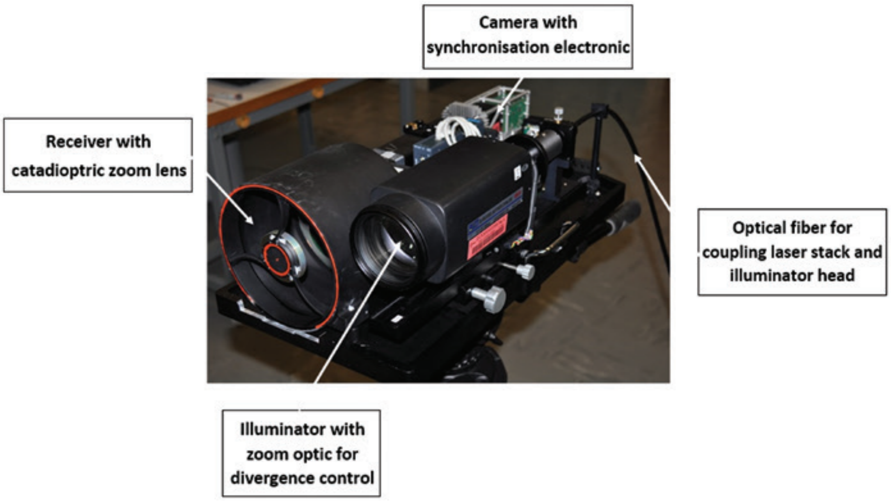


Figure 1: SWIR active imaging system based on accumulation mode for research purposes.

mode. The gate has a duration of 200 ns, which corresponds to the shortest value available for the camera. For the accumulation mode, laser pulses with a 2-µs duration and a repetition rate of 6500 Hz are used. This corresponds to a number of 143 pulses in a time frame of 22 ms. Both fields of view, input pupil and energy, are set equal to one another in both systems. On the target side, black and white charts with different spatial frequencies located at a distance of 500 m in open field are used. A scintillometer (Kipp & Zonen LAS large aperture scintillometer, Emerainville, France) is also placed close to the optical way in order to record the Cn^2 during experimentations (see Figure 2). The experimentations are conducted under daylight conditions between 10:00 am and 3:00 pm in the spring with light sunshine.

Several images of the scene are recorded and analyzed to determine the modulation transfer function MTF, which is deduced from the measured contrast transfer function CTF [10]. Figure 3 shows an example of the recording and corresponding line plot of the targets.

The results on the MTF are given in Figure 4 for three different measurements slots such as 10:07, 12:00 am, and 2:29 pm. As we can see, the results of MTF are very similar for the three cases; no real dependence on the Cn^2 value can be pointed out. The red line gives the spatial cutoff frequency Fc at 5% of the MTF. In all cases, the MTF of the pictures recorded with the accumulation mode system shows better results. This confirms the qualitative feeling coming from the pictures in Figure 3. For the system based on flash mode, the values are around 25 lp/mm, whereas for the accumulation mode, we are more around 35 lp/mm, resulting in an increase of 40%.

With a global integration time of 22 ms for accumulation mode and with this range of Cn^2 value, no blur effect on the images could be observed or measured on the frames.

These experiments are conducted with the same scene as well as the same turbulence conditions. Nevertheless, the use of two different systems with two different lasers and cameras does not allow us to conclude on the technique of accumulation mode itself. As demonstrated in an earlier work, the coherence length has a huge incidence on the image quality, which leads to a higher noise, called speckle contrast [11]. Unfortunately, for outdoor experiments with distances of 500 m, which is the minimum distance for measuring the Cn^2 with a scintillometer, there is no possibility to use a laser diode stack-based illuminator with only one pulse.

3.2 Scintillation index variation of accumulation vs. flash mode

The goal of the second experiment is to compare scintillation maps in flash and accumulation mode. Unlike the experiment presented in Section 3.1, we only use the system presented in Figure 1 to compare the flash and accumulation mode. The flash mode is obtained with one pulse. This could be possible by reducing the range to 270 m. The system is placed in an optical tunnel with a length of 135 m (see Figure 5).

A high-quality mirror reflecting the illumination beam to the receptor next to the transmitter is placed at one end of the tunnel. In the optical way, different types of perturbations, like water vapor, smoke, electrical heating mat, alcohol fire, generate absorption, diffusion, and air turbulences, which produce scintillation. Unfortunately, no Cn^2 measurements could be obtained on this short distance with the available equipment. Nevertheless, stringent comparison could be done for the same conditions between flash and accumulation mode. After recording and de-noising the illumination maps for different conditions, the scintillation index σ_I^2, which is defined as the normalized variance of the received intensity, is calculated [12].

$$\sigma_I^2(z)=\frac{\langle (I(z))^2\rangle}{\langle (I(z))\rangle^2}-1$$

In Figure 6, we can see different illumination maps recorded in accumulation mode with a pulse repetition rate of 1 kHz for five different types of perturbations and the corresponding scintillation index value. Each value corresponds to the average value of the scintillation index deduced from 100 maps recorded in a time frame of 5 s. This time frame must be long enough to smooth strong fluctuations and short enough to avoid long time deviations. Under these conditions, we start from a very low value of $\sigma_I^2=0.010$ for a tunnel free of perturbations to a value of 0.683 for the case of alcohol fire, which corresponds to a high perturbation strength. However, for a more rigorous and comparative study between flash and accumulation mode, only the case of perturbations generated by the 10-m electrical heating mat, which corresponds to the most stable case over the recording time, is taken into consideration.

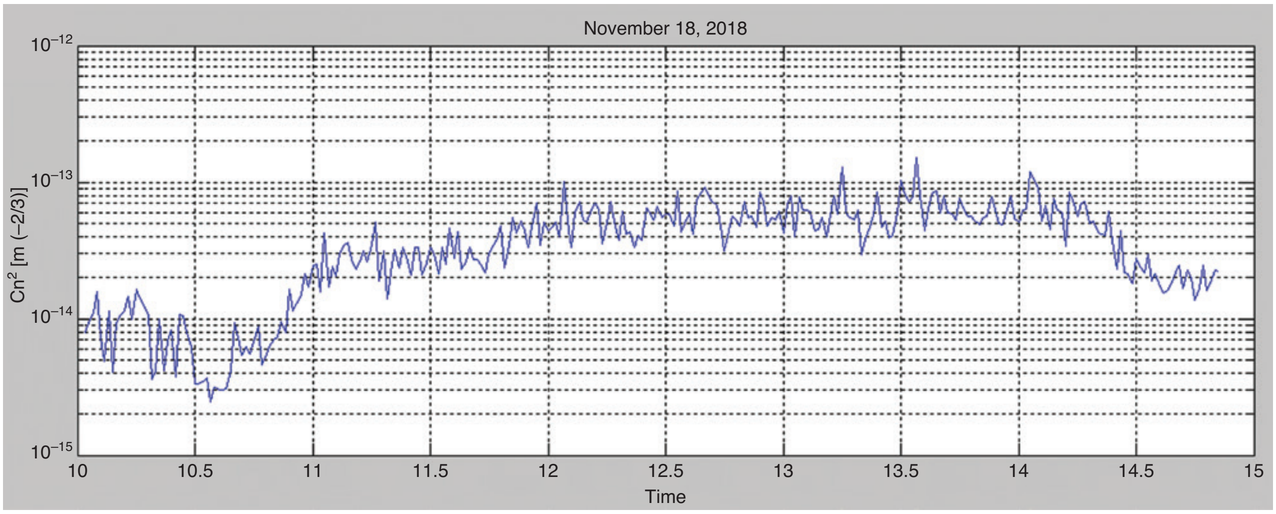


Figure 2: Cn^2 as a function of time recorded with the scintillometer.

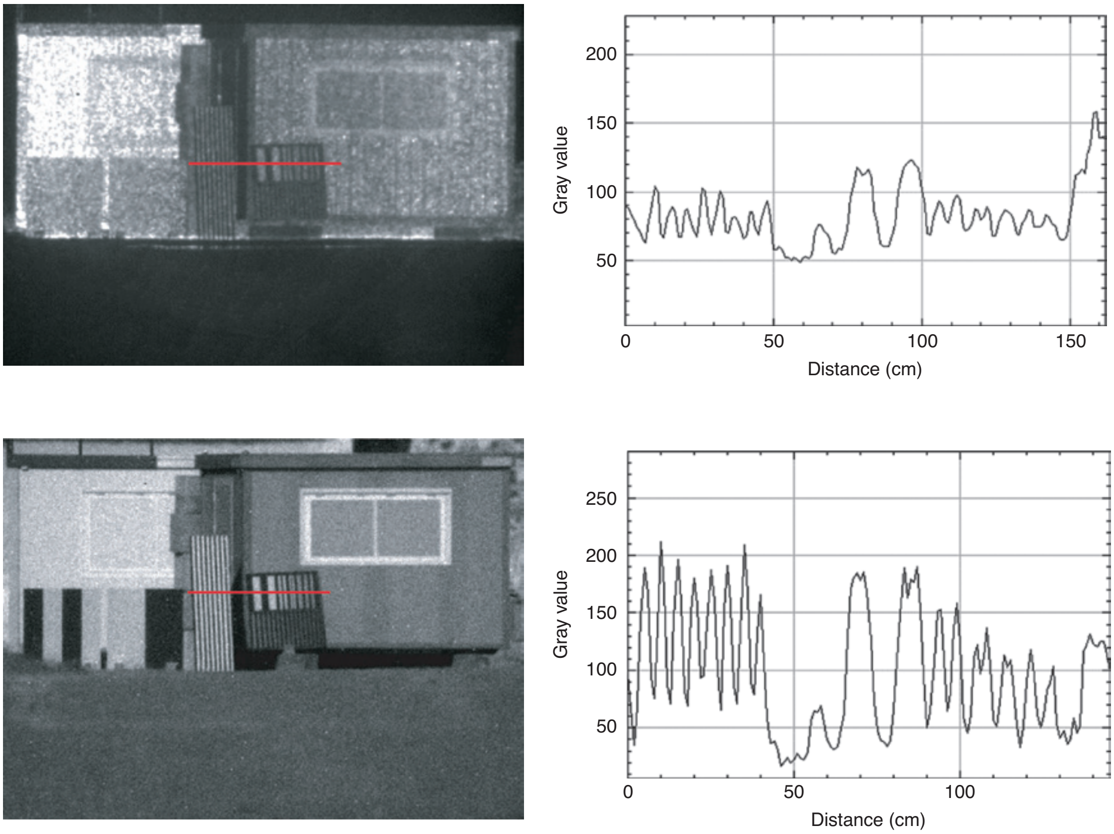
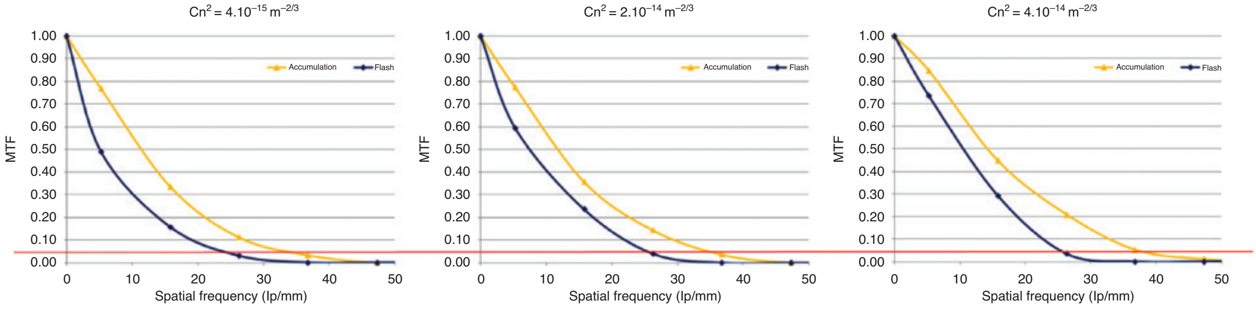


Figure 3: Pictures and plots of the targets (upper figure corresponds to the results obtained with the system working in flash mode and lower figure to those obtained with the system working in accumulation mode). Red lines represent the line scan over the bar charts.



F_{Cflash} = 24 lp/mm; F_{Caccu} = 34 lp/mm

F_{Cflash} = 25 lp/mm; F_{Caccu} = 35 lp/mm

F_{Cflash} = 26 lp/mm; F_{Caccu} = 36 lp/mm

Figure 4: MTF vs. spatial frequency for three different values of Cn^2.

In Figure 7, the results of the scintillation index vs. the number of pulses for one image are presented. One pulse corresponds to the flash mode, whereas 2–143 pulses correspond to the accumulation mode. The same series of measurements is performed several times corresponding to the represented fluctuation interval. As we can see on the curve, the global tendency is on the decrease in the scintillation index with the number of pulses. We start from an average value of $\sigma_I^2=0.048$ for one pulse and reach a value of $\sigma_I^2=0.012$ for 143 pulses. The scintillation index is reduced by a factor of four in this case.

Figure 8 illustrates the two border cases of this experiment, the scintillation map in 2 and 3D for one and 143 pulses, respectively. As we could expect, we can also observe a qualitative smoothing or averaging of the scintillation noise in accumulation mode. According to the observation of Goldberg, when the illumination pattern changes significantly during camera frame integration time, a significant reduction in the noise will occur due to the temporal averaging [13].

4 Conclusion and outlook

In this work, two main results have been obtained. They demonstrate the ability of the accumulation mode to

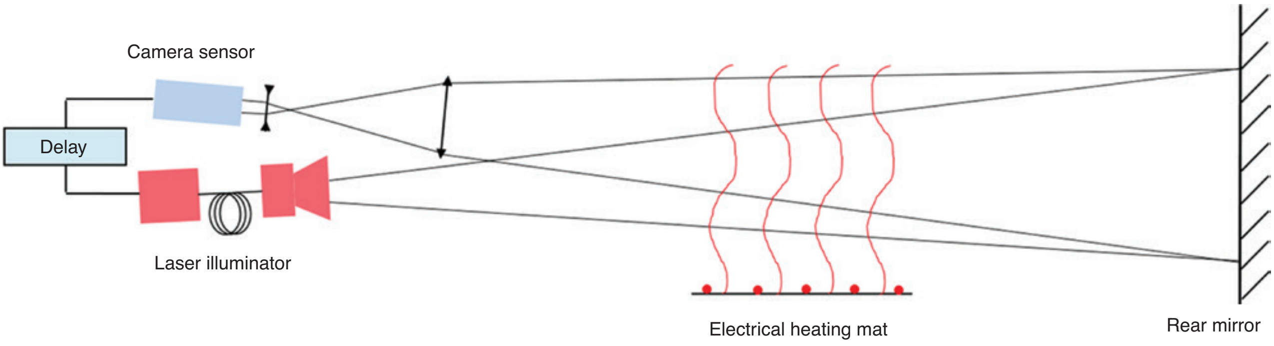


Figure 5: Experimental setup for scintillation map recording.

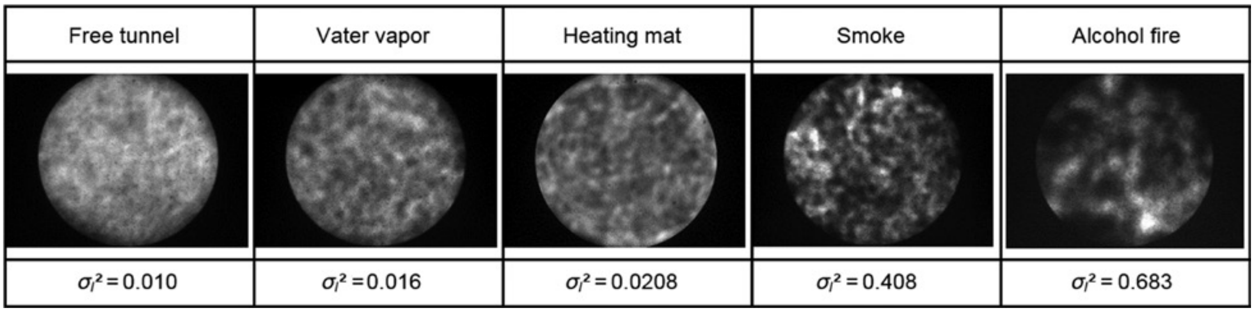


Figure 6: Qualitative scintillation maps and corresponding scintillation index for five different types of perturbations.

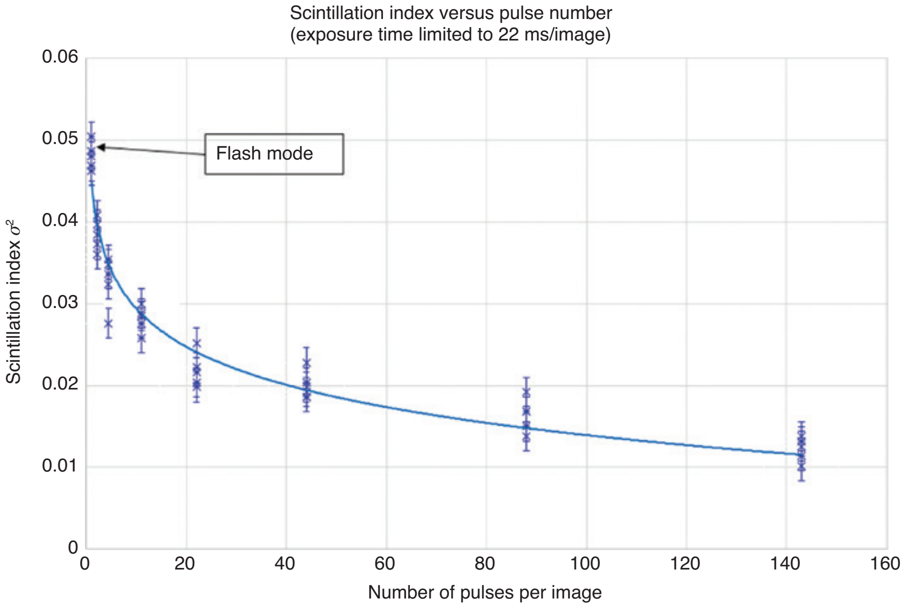


Figure 7: Scintillation index variation vs. pulse number starting from one pulse to 143 for a frame integration time of 22 ms.

produce images of high quality and to withstand optical perturbations. The images of the same scene recorded under the same conditions with a system working in accumulation mode exhibit a better quality in comparison to those recorded with a system working in flash mode. The MTF values are up to 40% higher, regardless of the Cn^2 value. The use of two different systems with two different lasers and cameras makes the interpretation more difficult. For this reason, a second experiment was conducted with only one system working in both modes but

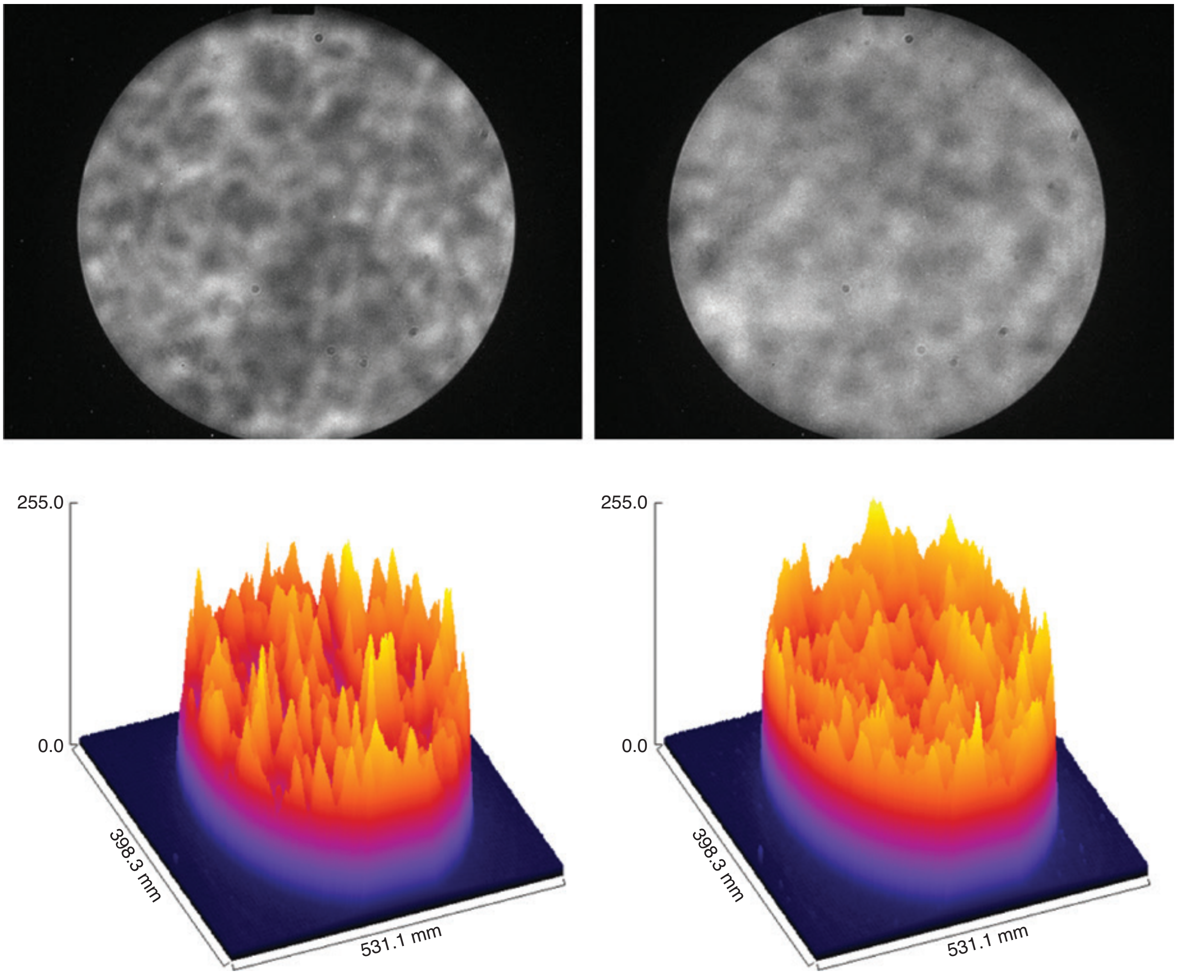


Figure 8: The 2D and 3D qualitative comparison of scintillation maps obtained in flash (left) and accumulation (right) mode, respectively.

with reduced range. For this experiment conducted inside an optical tunnel with different perturbations, it could be demonstrated that the scintillation index decreases with the increase in laser pulses. A decrease of a factor 4 could be measured between flash and accumulation mode in a specific condition. These results demonstrate the relevance of accumulation mode and open interesting perspectives for applications like long-range target detection and automatic target detection where image quality is of highest importance. For other special applications like high dynamic scenes, the accumulation mode can show some limitations due to longer integration time. Such types of experimentations are planned in the future in order to get an exhaustive overview of this technique.

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