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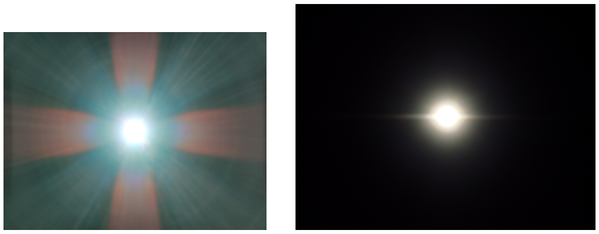
Evaluation of the Lens Flare

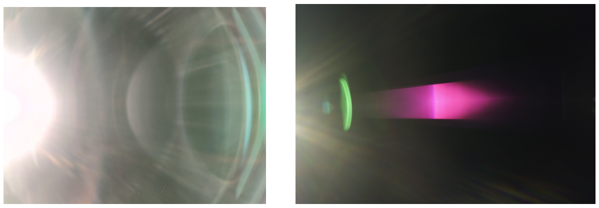
Elodie Souksava, Thomas Corbier, Yiqi Li, François-Xavier Thomas, Laurent Chanas, Frédéric Guichard
DXOMARK, Boulogne-Billancourt, France

Abstract

Flare, or stray light, is a visual phenomenon generally considered undesirable in photography that leads to a reduction of the image quality. In this article, we present an objective metric for quantifying the amount of flare of the lens of a camera module. This includes hardware and software tools to measure the spread of the stray light in the image. A novel measurement setup has been developed to generate flare images in a reproducible way via a bright light source, close in apparent size and color temperature to the sun, both within and outside the field of view of the device. The proposed measurement works on RAW images to characterize and measure the optical phenomenon without being affected by any non-linear processing that the device might implement.



(a) veiling glare (b) luminous halos



(c) haze (d) colored spot and ghosting

Figure 1. *Examples of flare artifacts obtained with our flare setup.*

Introduction

Flare is an optical phenomenon that occurs in response to very bright light sources, often when shooting outdoors. It may appear in various forms in the image, depending on the lens design; typically it appears as colored spots, ghosting, luminous halos, haze, or a veiling glare that reduces the contrast and color saturation in the picture (see Fig. 1).

With the exception of a deliberate use in the context of artistic photography, flare is generally considered an unwanted artifact in traditional photography, since its appearance reduces the quality of images, most notably by reducing the contrast. Importantly, while virtually all lenses can produce flare under certain conditions, the frequency and severity of this artifact's appearance vary significantly depending on the lens design. This motivates manufacturers to develop a measurement framework that would allow to compare different camera modules based on their flare performance.

Several attempts have been made to evaluate the flare on camera modules, most of them only focusing on a specific type of flare; in particular, the ISO 18844 measurement [1] reduces the flare measurement to the measure of the loss of contrast caused by the veiling glare at some points in the field. This standard approach is implemented by several commercial solutions in the industry, most notably Imatest [2] and Image Engineering [3]. While technically sound, this approach does not take into account other forms of flare and does not treat the case of directed light sources in the field.

In this article, we propose a more general approach by considering the amount of light reflections regardless of the particular form they take. Furthermore we perform our analysis for every position of the light source relative to the lens, within and outside of its field of view (or FoV).

Our goal is to provide a complete measurement protocol as well as a metric to quantify the lens flare in a complete camera module system. This protocol is to be used in our new DXOMARK RAW protocol based on [4]. This metric physically measures the optical phenomena caused by flare using RAW images from the device, and compares the amount of light originating from the scene to the amount caused by flare. Furthermore, another objective is to have a measurement protocol close to real use-cases with a very bright light source that has characteristics similar to those of the sun (simulating outdoor conditions), and being able to measure flare for all orientations of this source, both in and out of the field of view.

Our method is based on experimental prototyping and a theoretical analysis of different kinds of flare. We developed a hardware setup able to produce flare with a bright light source inside or outside the FoV of the camera, by rotating in every direction around the device to reproduce every situation the device could face in the real world. Taking RAW pictures, we measure the amount of light caused by flare at each point of the sensor, and compare it the amount received from the source.

One of the challenges is to properly identify the source when it is in the FoV so as not to consider it when measuring the lens flare. Furthermore, we propose a repeatable protocol to find the appropriate exposure times for every device to get directly comparable results among different devices.

The results of our work are reflected in the development of an automatic, reliable hardware setup that allows to generate flare artifacts (colored spots, veiling glare, haze, halo, gaze) and of a novel flare characterization metric, capable of quantifying the flare via an attenuation map as well as statistics (average and worst case) that illustrate visible degradations caused by the flare in camera modules.

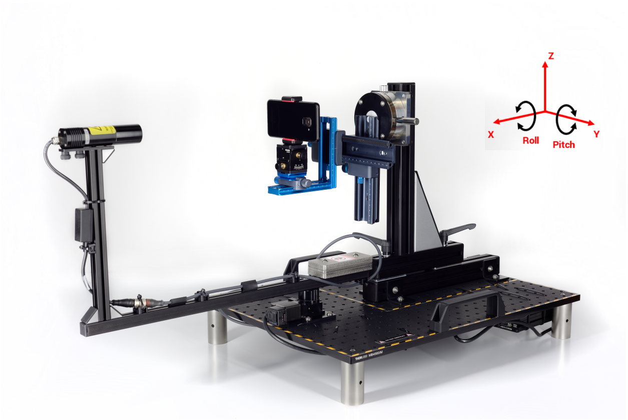


Figure 2. *Analyzer flare setup.*

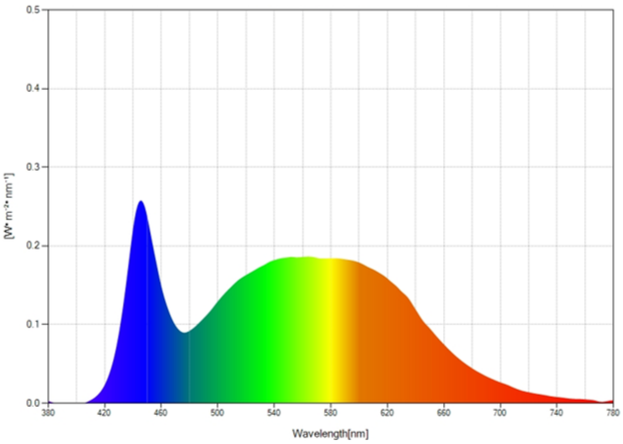


Figure 3. *Electromagnetic spectrum of the light source ($W \cdot m^{-2} \cdot nm^{-1}$ for each wavelength in nm).*

Flare Setup

The purpose is to propose a compact, accurate, user-friendly setup that simulate real-life use cases of flare. Our setup has been designed so that it is easy to use and to be able to reproduce any flare artifacts in camera lenses in a completely dark environment.

In addition to the fact that the setup is easily movable, the flare bench (see Fig. 2) is fully automated and can be controlled remotely. It includes a motorized rotary stage which allows a rotation angular range of 180° for the light source. The motorized arm allows the light source to rotate accurately around a device under test with a high angular resolution of 1.2 arc-minutes and a bi-directional precision of 1.6 arc-minutes. The motorized rotary stage is driven by software with a maximum rotational speed of 9°/s. The photo shooting session can be fully automated.

The device is installed on a platform that can be moved along three axes (X, Y and Z directions) with manual translation rails. Two other additional rotary stages allows the modification of the roll and pitch angles of the device to adjust the orthofrontality of the device with the light source more easily. The roll rotation, *i.e.* around the optical axis, of the device under test can be easily controlled, so as to cover the flare measurement in every desired orientation of the device, especially in vertical, horizontal and diagonal orientation.

In most cases, the flare appears when shooting with very bright sources like the sun. That is why the light source of the flare setup is designed in order to simulate the spectrum of the sun (see Fig. 3) with an apparent diameter of 0.95°. The collimated high-power LED can achieve an illuminance greater than 10000 lux with a color temperature between 5000 and 5500 K. To cover the entire surface of the camera, the light beam diameter on the device under test at measurement position is 25 mm. The uniformity of the area of interest which is a 10 mm diameter central zone is up to 98 %. A neutral filter is available with our setup to be placed in front of the source to shoot when the source is in the FoV. Otherwise, the scene would be over-exposed due to the high intensity of the light source.

Methodology

Many flare measurements have been proposed by ISO standard works. One of them is the ISO 9358 [5] that measures the glare spread function (GSF) in a dark environment with a collimated source as well. The problem of this standard is the fact that we can not extract a value to quantify the flare from their GSF measurement and their measure lens flare independently from the camera module system.

This is the reason why ISO 18844 [1] proposed another flare measurement for camera module systems. However, they only measure veiling glare and mainly focuses on the loss of contrast due to stray light produced at specific positions in the processed or unprocessed image by digital cameras.

Our proposed approach measure any flare effect caused by the lens in every point of the image by considering each photosite of the sensor as a light meter. Like the ISO 18844, our method measures lens flare in a complete camera module system but do not measure it on processed images. Our approach only uses unprocessed RAW images, which allows to compute the amount of light through the lens of the cameras in each point of the image. Processed images handle dark tones in unpredictable ways that can affect results, especially it can be critical to veiling glare measurements. This is why it is essential to measure on RAW images in order to be able to quantify as well as possible the real amount of light that arrives to the sensor. As we estimate the lux level at each point of the sensor, we return the flare spatial distribution in the image according to the position of the light source to the camera.

Proposed measurement

Our proposed measure originates from the ISO 12232 standard [6], which defines the ISO speed value from the mean focal plane exposure at saturation H_{sat} (in lux.s), for a scene luminance at saturation L_{sat} (in cd/m^2):

$$ISO = S_{sat} = \frac{78}{H_{sat}} = \frac{7800 \cdot Ap^2}{65 \cdot L_{sat} \cdot T_v}$$

with Ap the aperture and T_v the exposure time, parameters of the device.

Assuming a linear sensor, *i.e.* the normalized gray level intensity R is a linear function of the luminance received by the sensor until saturation, we measure the amount of flare received by the sensor as a *flare illuminance* value, as if the flare were coming from an additional light source in the scene, received as

E_{flare} and reflected on a Lambertian surface of 100% reflectance emitting L_{flare}:

$$E_{flare} = \pi \cdot L_{flare} = \pi \cdot \frac{7800}{65} \cdot \frac{Ap^2}{ISO \cdot T_v} \cdot R$$

Note that we linearize and normalize the RAW gray level R_{scene} measured on the sensor between 0 to 100%, by using the black level R_0 and value at saturation (or "white level") R_{sat} as follows:

$$R = \frac{R_{scene} - R_0}{R_{sat} - R_0}$$

In order to measure the impact of the flare generated into the sensor, we compare the *flare illuminance* defined above to the *source illuminance* received directly from the source.

We measure the *source illuminance* E_{source} with a light meter in a complete dark environment. We position the light source at 0° on the optical axis, corresponding to the position bringing the maximum illuminance on the device under test. We place the light meter in the plane of the device under test lens in front of the source and measure the received illuminance (in lux).

Consequently, the ratio between the *source illuminance* and the *flare illuminance* is called *flare attenuation*. It is computed in a linear scale, expressed in decibel (dB) defined as:

$$Flare_{attenuation} = 10 \cdot log_{10}\left(\frac{E_{source}}{E_{flare}}\right)$$

Find correct exposure parameters

The algorithm to evaluate the lens flare is the same regardless the light source is outside or inside the FoV of the device. However, we need to hide all the saturated pixels of the light source when it is within the field. It enables us to measure the flare on the rest of the image.

Accordingly, the choice of the exposure parameter is very important in our protocol to avoid flare saturation. As a reminder, the test setup is a powerful light in a completely dark environment. The main challenge is to find the best exposure parameters to capture this high dynamic scene. To do so, we use the linear region of the sensor's gray level dynamic for the source within and outside the field. Luckily, it is possible to use the entire dynamic range of the sensor with unprocessed RAW images which is much higher than the JPEG images one.

The main challenges were to find suitably repeatable protocols to determine a first exposure parameter when the source is in the FoV of the device and a second one when the source is out it. For both cases, we want to maximize the signal to noise ratio (SNR) to avoid drowning signal into the noise and be certain to detect properly the flare signal. Thus, the longer the exposure time, the more light will arrive to the sensor. Therefore the signal will be more distinguishable. Since our measurement works for devices with fixed aperture and the sensor sensitivity set to the minimum to limit the amount of noise in the image, the last parameter to determine is the exposure time which is a parameter that can affect the results.

When the source is in the FoV, the light source is saturated in the image due to its high level of illuminance. The exposure parameter must be chosen so that only the source is saturated in the image. As the measurement does not take saturated pixels into account, it was important to not mask eventual flare with the source while it could have been measured if it wasn't saturated. The results would be distorted by masking a part of the flare. The size of the circle to mask the light source is computed thanks to an optical formula, more precisely the Lensmaker's equation [7]. Since we know the light source diameter, its distance to the device under test and the device focal length, we can easily compute the expected apparent source diameter in the image.

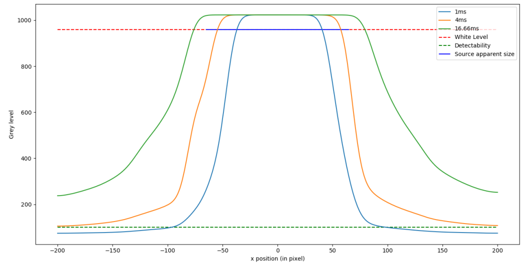


Figure 4. *Protocol selection between several exposure times when the source is in the FoV. The exposure time selected is 4ms which is the best compromise between the saturation and signal detectability.*

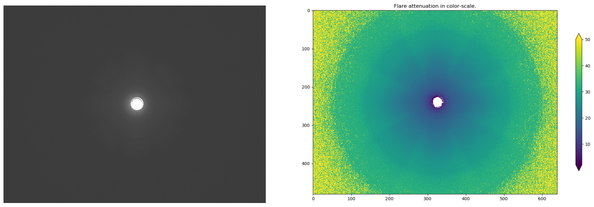
The protocol when the source is in the field consists in taking pictures at the position 0° for several exposure times (from the minimum exposure of the device to the exposure when the source blooms). Then, we mask the saturated pixels present in the image due to the source. The exposure time selected is the longest one that does not have saturated pixels after applying the mask and maximise the signal as shown in the Fig. 4.

Regarding the second case when the light source is out the FoV, we do not have saturation anymore. So our main challenge is to choose a second exposure time that provides a large gray levels range without reaching saturation. Remember that the longer the exposure time, the best the SNR will be. The optimal protocol would be to choose the right exposure time for each angle when the source is out the FoV. However, for practical reasons, we decided to use identical shooting conditions for all angles in order to simplify the process. The protocol consists in positioning the source outside the device FoV and to find the angle generating the highest intensity of flare. Then the exposure parameter is chosen according to the challenge explained before. The dynamics of the sensors are sufficient to have a valid measurement for all angles with a single exposure time when the light source is outside the FoV.

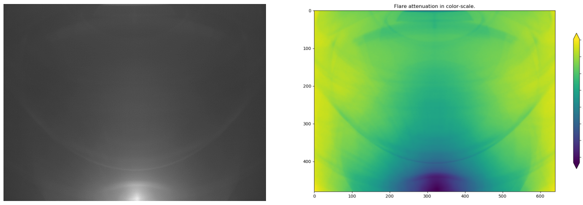
Key metrics

As we compute the illuminance for each photosite of the sensor, our measurement return a flare attenuation map in dB that can be used to analyze the spatial distribution of the flare according to the position of the light source (see Fig. 5). For more convenience, we decided to set the maximum value at 50 dB in the absence of flare. Indeed, 50 dB is a factor of 10^5 which is close to the max bit depth of RAW images that is at 16 bit.

In order to compare lens flare between devices, we introduce two key metrics: average flare attenuation and worst flare attenuation. Average flare attenuation helps to have a general idea of the flare distribution in the image, that is to say if the flare is centered



(a) source inside the field (b) attenuation map



(c) source outside the field (d) attenuation map

Figure 5. *Attenuation maps with the source inside and outside the FoV.*

in a part of the image or if it is diffused over the whole image.

$$Flare_{average} = 10 \cdot log_{10}\left(\frac{E_{source}}{mean(E_{flare})}\right)$$

The concept of the worst flare attenuation is used to specify the design of an optic. Indeed, it enables to assess the worst performance of the optics that corresponds to the biggest illuminance found on the sensor. The value of the metric depends on the analysis resolution, which is determined by the sub-sampling of the image chosen by the operator. The sampling can be chosen according to the applications. For the mobile world, we use a relatively low resolution. We recommend choosing a sample size of 40×30 or 80×60 pixels.

$$Flare_{worst} = 10 \cdot log_{10}\left(\frac{E_{source}}{max(E_{flare})}\right)$$

Results

Our work has led to the development of a new objective metric based on studying the lens flare on a complete camera module. First, we validated the exposure parameters in multiple devices in our database, which were then measured. Finally, we approached a real use-case by evaluating the impact that a damaged lens could have on the flare.

Exposure parameters

In order to validate our protocols, we have tested several devices on the flare bench. To have a representative panel of devices, we tested our protocols on different objectives.

We applied the protocols described previously to find the right exposure parameters when the source is inside and outside the FoV on two cameras (wide and ultra wide) of two devices. The Fig. 6 presents the results of exposure parameters selected for each camera. Remind that the light intensity of the source is lower when the source is in the FoV due to the addition of the filter in front of the source to reduce the light intensity by about 10 in order to avoid over-exposition of the scene. For all tested devices, the exposure time found when light source is in the device FoV is shorter than the exposure time found when light source is out of the device FoV. Indeed, the source no longer illuminates the lens, so it is necessary to have a longer exposure time to capture as much information as possible in the dark areas. Our protocols enable us to choose the best exposure times regarding the trade-off between the SNR and the saturation level for when the source is inside and outside the FoV. It will help us having a robust estimation of the lens flare.

Flare measurement

Our flare measurement is integrated in the new DXOMARK RAW protocol [4] to evaluate digital camera system performance. An aggregation is done for all source positions between 0 and 90 degrees in horizontal, vertical and diagonal directions. The Fig. 7 presents the result of the flare protocol on the camera B.

The curves presented in the Fig. 7 are continuous when switching to in and out the FoV. This validates our protocol when masking the source in the FoV and having two different exposure times. The variation of the average flare attenuation with the position of the source in the device FoV is quite constant in the first range of degree. Indeed, the same amount of illuminance is measured as the light source is in the FoV. When the light source comes out of the device FoV, the measured illuminance is lower. As a result, the average attenuation starts increasing. The higher the attenuation, the better the image quality with the fact of having a small amount of light arriving on the sensor. The gap between the angles 40 and 50 shows the position where the flare is important when the source is no longer in the field which is the position 44° (see Fig. 9). From 80 degrees, the flare attenuation remains constant at 50 dB. Indeed, from this angle, flare is no longer detectable.

In most devices, there is a significant gap between the average and worst flare attenuation when the light source is in the field, which can be explained by the large principle concentration amount of flare around the source light (see Fig. 8). The gap slightly decreases when the light source leaves the FoV of the device. The gap remaining up to 80 degrees is the consequence of the device noise.

In the Fig. 9, these two images were taken for two different positions of the light source outside the FoV of the camera. And as we can see, a slight change in the position of the source can change the amount of flare in the image.

Work on damaged lens

In additional, work has been done on two same lenses of a device but one of them has been damaged with some scratches on it. The main goal was to find out how the condition of the lens affects the lens flare. And the results in the Fig. 10 do show how

	Exposure Parameters			
	In FoV		**Out FoV**	
	Source Level	**Tv**	**Source Level**	**Tv**
Camera A	1440 lx	2 ms	13400 lx	4 ms
Camera B	1440 lx	8 ms	13400 lx	33 ms
Camera C	1440 lx	2 ms	13400 lx	6 ms
Camera D	1440 lx	4 ms	13400 lx	17 ms

Figure 6. *Exposure parameters when the source is in and out the field for two different devices on wide cameras $f/1.9$ (A and B) and ultra wide cameras $f/1.8$ (C and D), with ISO 50 set at the minimum.*

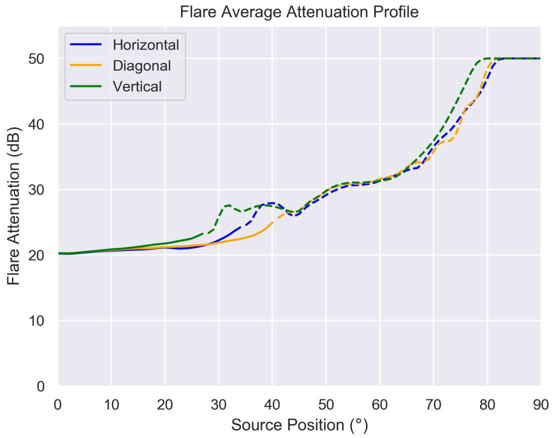


Figure 7. *Flare aggregation for average flare attenuation on the 3 orientations for camera B. Solid lines when source is in the field, dashed lines elsewhere.*

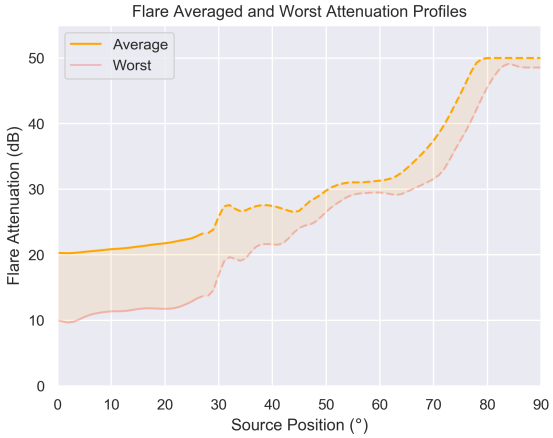


Figure 8. *Flare aggregation for average and worst flare attenuation for camera B in vertical orientation. Solid lines when source is in the field, dashed lines elsewhere.*

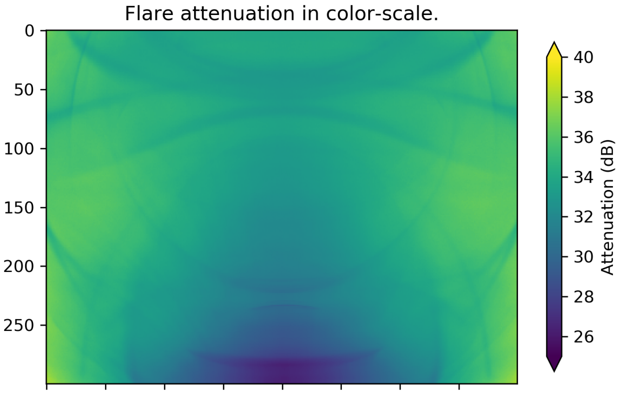
much the flare depends on the condition of the lens. When the camera lens has scratches on it, the amount of flare is greater than the camera without any damage, especially when the source is in the field since this is the case where the flare is the most important.

These results show how much important it is to have a lens without any dusts on it or defects which could increase the amount of flare on the image.

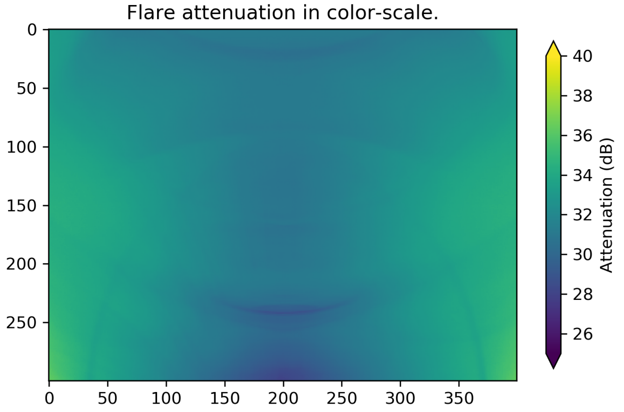
Conclusions and future work

Our work has led to an automated way to characterize and measure lens flare. Thanks to the flare setup and a rigorous protocol to get the correct exposure parameters, one can easily characterize the impact of the optical phenomenon in the image quality of a device, along all directions, with a light source in and out the device FoV. Unlike previous works, our measure takes any type of flare into account, as we consider the flare spatial distribution in the whole image.

However, today our measurement mainly relates to devices with small camera systems such as smartphones, automotive or drones cameras. Indeed, the light source of our setup is too small to cover devices with large sensor such as DSLR cameras. The second limit is related to the device under test itself. The measurement requires RAW as inputs, retrieving non processed RAW from the device is crucial to the evaluation. Moreover, access to the manual control of exposure parameters is primordial, as a matter of fact, the exact knowledge of ISO and shutter time values is necessary to guarantee the correctness of the results.



(a) position 40°



(b) position 44°

Figure 9. *Map attenuation with the source out the FoV for two different angles.*

This is why future works will be done to improve our measurement to evaluate colored lens flare [8] and on processed images, *i.e.* RGB pictures, without any manual control on the parameters (ISO and exposure time) of the device.

Acknowledgment

We want to thanks Alexandra Giraud who contributed to our work during her internship at DXOMARK. She is now at the Institut d'Optique Graduate School at Palaiseau in France.

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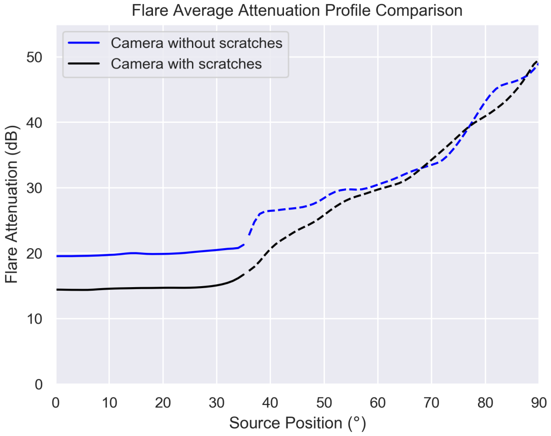

Figure 10. *Flare average attenuation on a damaged lens and on another normal lens of the same camera.*

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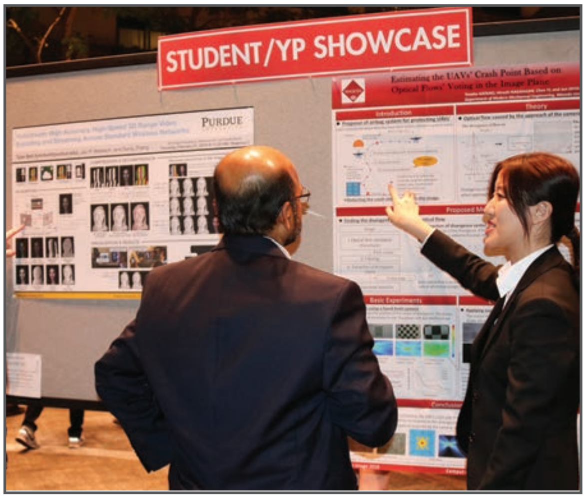

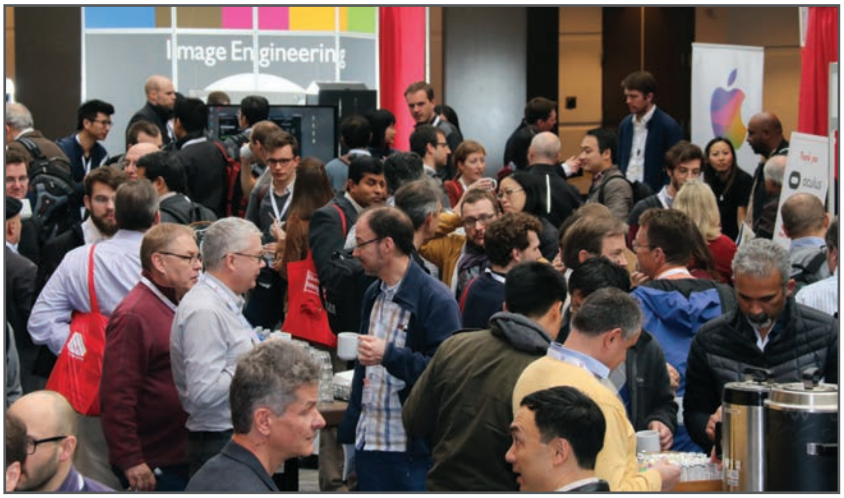

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