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Comprehensive Stray Light (Flare) Testing: Lessons Learned

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Abstract

Stray light (also called flare) can adversely affect the image quality or application performance of a camera system. Testing for stray light is critical for understanding limitations of camera system performance. Stray light is any light that reaches the detector (i.e., the image sensor) other than through the designed optical path. Depending on the mechanism causing stray light, it can introduce false colors and phantom objects (ghosts) within the scene, reduce contrast over portions of the image (veiling glare), and effectively reduce system dynamic range.

In this paper, we present an overview of stray light testing for digital camera systems, as well as lessons learned and various technical elements to consider. These elements include the radiometric (e.g., brightness) and geometric (e.g., size) properties of the light source and test setup. We focus on a test approach that involves illuminating the camera with a small, bright light source and describe how certain elements of the test can impact a measurement.

Introduction

Within the context of this paper, “stray light” and “flare” are synonymous. However, the term “lens flare” may more specifically refer to stray light caused by the camera lens, while the term “stray light” may be caused by other components of a camera system, such as layers on top of or within the image sensor. Stray light can be thought of as scene-dependent optical noise.

Optical engineers typically design for the imaging path, that is, the path that directly transforms world space into image space. However, this path is not necessarily the only path from the scene to the sensor. These non-design paths are stray light paths. Note that not every stray light path is contained within the field of view (FOV) of the camera. Figures 1 and 2 show examples of how stray light can manifest itself in images from real cameras.

As we move to higher dynamic range sensors, optical design imperfections that cause stray light will have more of an impact on the image relative to the noise floor of the sensor. Therefore, stray light is now more of a problem than ever before and is also impacting more critical systems as we use cameras for more applications (i.e., automotive).

Stray light can limit the dynamic range capability of a camera system by obstructing or adversely affecting the information in the image. For some cameras, such as those with automotive-related applications, stray light may potentially lead to system failure scenarios by obstructing the system’s ability to identify objects in the scene or by introducing new false information (e.g., ghosts) into the scene. However, stray light is not always a negative as it can be used for artistic purposes, such as with the common use of diffraction spikes (or “sun stars”) in landscape photography.

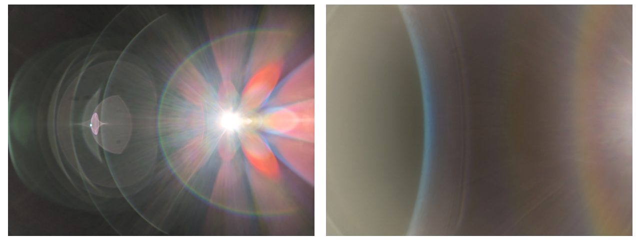

Figure 1. *Two examples of test images showing stray light manifesting itself in different forms. The left image shows a small, bright light source within the camera FOV resulting in clear examples of petal flare and other ghost artifacts. The right image shows significant veiling glare and other artifacts caused by a small, bright light source outside the FOV of the camera. Both images were captured in a completely dark lab using a Google Pixel 6 Pro camera.*

Figure 2. *An image of a traffic intersection captured through a windshield using a Google Pixel 6 Pro camera. Stray light artifacts emanating from the Sun obstruct the view of the traffic light. Some of these artifacts are caused by the windshield. Separately, some stray light caused by the camera is manifested as a ghost in the form of a peculiar green dot.*

Camera System-Level Stray Light Testing

A system-level test is one that is conducted on a complete integrated system which, in the case of a camera system, includes the optics (or any medium in front) and sensor, with the end result (and test subject) being the image. We provide an overview of two different approaches to system-level stray light testing for cameras, primarily focusing on the second approach. We first briefly describe a “patch-based” approach to testing. We then describe a second “small, bright light source” approach, with additional description and consideration of the test methods associated with this approach.

Patch-based Test Approach

The patched-based test approach involves capturing images of a backside-illuminated chart (or dome) with black patches (light traps) on it [1]. The camera device under test (DUT) is positioned such that chart overfills the camera's FOV. The camera is used to capture images of the chart while the chart itself is backside-illuminated with measurable light level. In the resulting images, the black patches are analyzed to measure how "not dark" they are. Figure 3 shows an example test chart design that could be used for this approach. The test chart can alternatively consist of light patches with a black background, or other patterns providing different light source extent (light region) and sampling/measurement area (black region) for the test.

The patch-based approach can provide measurement of the camera's low spatial frequency stray light (veiling glare) performance and is overall a valid approach to measuring stray light in a camera. However, the method has some limitations. It provides limited analysis points and can be difficult to use for fisheye camera devices. It also does not reveal all kinds of stray light or potential application-based failure scenarios. Namely, the patch-based approach may not entirely describe what happens when a small, bright light source (e.g., the Sun) illuminates the camera at varying angle, which can be a common scenario in the application of real camera systems.

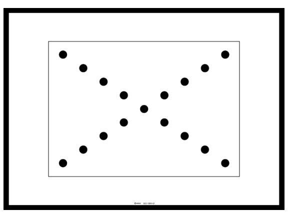

Figure 3. *An example of an Imatest-branded backside-illuminated chart design that could be used for the patch-based approach to stray light testing. The design is meant to be compliant with ISO 18844:2017.*

Small, Bright Light Source Test Approach

The small, bright light source test approach involves capturing images of a small bright light source in a dark (black) room. To build test coverage, the DUT can be rotated to change the angle of the light source with respect to the DUT. Alternatively, the light source can be moved in an arc around the DUT. The test can and should include angles where the light source is outside the FOV of the DUT. The captured images are then analyzed as-is, or normalized to represent a metric. This approach is an extension of the optics-only test approach described by the ISO 9358 standard [2].

For this approach, the angular size of the light source (relative to the FOV and viewing distance of the camera DUT) should be small, or similar to the size of the source(s) of concern for the application (e.g., the Sun). The angular size of the source can affect the appearance of stray light, which is a fundamental reason for why this test may be necessary in the first place. The concept of angular size and its effects are elaborated on in the *Light Source Angular Size* section.

In principle, the small, bright light source approach is simple. We are capturing and analyzing images of a small, bright light in a completely dark room. However, we learn that there are many factors to consider for this test approach. We begin by describing the concept of test coverage and then explore the concept of normalized stray light.

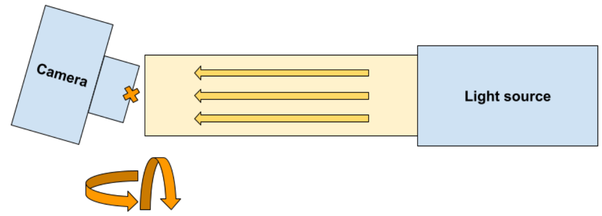

Figure 4. *High level diagram of the small, bright light source approach. The light source projects a small, point-like source as a collimated beam of light that overfills the front of the DUT. The DUT is rotated (or the source moved) to change the angle of the light source with respect to the DUT. The DUT is rotated about its front to avoid inducing a lever arm, minimizing the necessary area of the projected beam.*

Test Coverage: Extent and Sampling

Perhaps the most important test factor for the small, bright light source approach is the overall concept of test coverage. Test coverage describes both extent (range) and sampling (delta). The concept relates to how many images or source angles one is willing to capture and analyze for the test. Specifically regarding the source angle, the test coverage extent is the range of angles being tested inside and/or outside the FOV of the DUT, while the sampling is the delta or magnitude of angular increments.

For example, a test plan could involve performing a single-axis sweep of the light source angle described by an extent (range) of 180 degrees across the horizontal FOV of the DUT, with a sampling interval of 0.1 degrees. This test plan would require 1,800 image captures in total. Still, this is not a comprehensive test plan as it does not cover all azimuth angles and, therefore, assumes some aspect of radially symmetric performance.

Certain camera system asymmetries may result in asymmetric stray light performance, such as dust/debris, lens surface roughness/defects, or any asymmetric optomechanical components of the camera system. Some stray light features may only appear at very specific source angles. For some systems, additional source angles (both azimuth angle and field angle) may need to be tested, for instance by using a combination of horizontal, vertical, and diagonal sweeps of the source angle.

Overall, the concept of test coverage is a complication because there is a trade-off between the fidelity of the measurements and the time taken to perform the measurements. Better test coverage requires a longer time for data capture and analysis. See [3] for more details about test coverage.

Normalized Stray Light

The images captured for the small, bright light source approach may be normalized to represent a metric, where the method of normalization determines the metric. Equation 1 shows that, overall, the calculation of normalized stray light simply involves taking the image data under test and dividing by a normalization factor.

$$\text{Stray Light} = \frac{\text{Image Data}}{\text{Normalization Factor}} \tag{1}$$

The goal with normalized stray light is usually to normalize out the level of the light source from the images. This provides a compensation for the level of the light source, allowing for easier comparison of results. With that, the method may also require that the direct image of the light source be masked out (ignored) because it is technically not stray light. The direct image of the source is the small region in the image that represents the actual size of the source (i.e., if there were no stray light or blooming in the image).

Therefore, the calculation fundamentally results in a normalized stray light metric image, where each pixel value in the image is representative of a metric. These images can be analyzed subjectively to identify noteworthy features that could be linked to application failure scenarios. Additionally, one could derive various statistics (e.g., mean, max, 95th percentile, etc.) from the metric image data to summarize the results. These statistics could be plotted as a function of light source field angle, for example. It may also be useful to identify and analyze specific regions of interest in the metric images, or known problematic areas. However, derived summary metrics will not illustrate the whole picture, whereas the metric images themselves do.

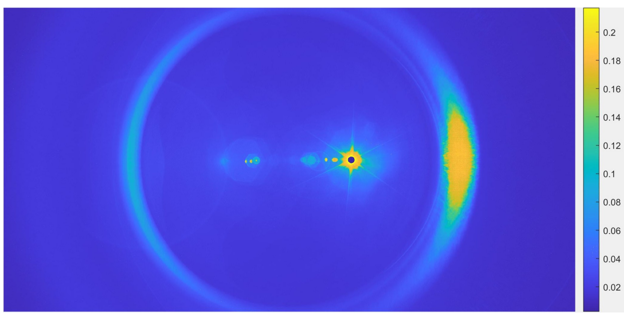

Figure 5. *An example of a normalized stray light metric image showing a point-like source and resulting stray light artifacts. The plotted metric is Point Source Rejection Ratio (PSRR) and has normalized values ranging from 0 to 1. The direct image of the source is saturated and is masked out (small blue dot) because it is not stray light. The color bar shows that the level of stray light in the image is around 20% or less than the level from the direct image of the on-axis light source. We know the theoretical (above-saturation) level of the source because we captured a separate on-axis reference image where the source was not saturated and then compensated for the difference in light level with the normalization method. This method assumes the data is linear.*

Regardless of the normalization method or what measurements the method requires, we recommend keeping track of the light level at the location of the DUT (e.g., irradiance) along with any camera setting that influences response level (exposure time, aperture, gain, image signal processing settings, etc.). We summarize and describe considerations for several normalization methods in the following subsections.

Normalization Method: None

The method of using “no normalization” provides the benefit of having easier access to stray light feature and color analysis, i.e., analyzing the as-is images of the light source captured from the DUT. This is the easiest method and requires no extra measurements. It provides a direct way to see how the stray light manifests itself in real images from the camera.

Note that using no normalization inherently lacks any within-test compensation of light level, in that the test itself will not be aware of any change in light level. Light level can change due to drifting level over time, changes in the setup, or by use of a different light source.

Normalization Method: Direct Image Level

The direct image level normalization method uses the level (in pixel value or digital number) of the direct image of the source to normalize the data. This method normalizes out the image level of the light source from the images under test. This level could be derived from an on-axis image of the source (global normalization) [4] or it could be derived on a per-capture/source angle basis. On its own, this method does not require any external measurement equipment. However, we learn that in practice this method may require extra steps and/or equipment so that the level used for normalization is not saturation level.

A method described in [4] involves capturing an on-axis reference image of the source and then using the image level within the direct image of the source to normalize the images under test including images captured at other (off-axis) angles. The direct image of the source is masked out (ignored) in the resulting metric images as it is not stray light. If testing with a point light source, this would provide a metric image showing Point Source Rejection Ratio (PSRR). If testing with a non-point source (i.e., an extended source) which is the case in most real testing, the metric would be Extended Source Rejection Ratio (ESRR). Figure 5 shows an example of a normalized stray light metric image showing PSRR (or ESRR).

Normalization Method: Lambertian Image Level

The lambertian image level normalization method uses the level (in pixel value or digital number) of the image of the light source with a neutral diffuser between the source and the camera [5].

This normalization method is a step in the process to compute the Flare Attenuation metric described in the IEEE P2020 pre-release [6].

Normalization Method: Radiometric/Photometric Level

The radiometric/photometric level normalization method uses measured light source radiometry/photometry to normalize the data. This method may require extra measurement equipment, such as a spectroradiometer or light meter to measure absolute light level(s). This method may often be accompanied with a form of radiometric calibration for the DUT.

For example, if testing with a point light source, the irradiance caused by stray light at the focal plane divided by the irradiance at the front of the DUT would provide a metric image showing the Point Source Transmission (PST) metric in units of irradiance (watts per unit area) [7, 8].

Normalization Method: Combined Factors

Normalization methods may utilize a combination of factors to compute a metric. For example, a method could involve using Image Level-based normalization in combination with Radiometric Level-based normalization to provide a metric akin to PSRR and PST in units of normalized irradiance.

The Flare Attenuation metric described in the IEEE P2020 pre-release [6] is a result of a method that utilizes a combination of factors to normalize the data. The Flare Attenuation metric effectively uses the reciprocal of Equation 1 and is in units of decibels.

Linearization and calibration

An underlying assumption of the stray light test is that the data are linear. If the data are non-linear (e.g., gamma encoded or companded), then the image data may need to be linearized. Without linearity, the test method may not provide an objective or comparable metric. For example, if doing Image Level-based normalization on 8-bit images with a saturation level of 255, the normalization may involve dividing the data by a theoretical value greater than 255. For that theoretical value to be true, the data must be linear.

Some normalization methods require the data to be in radiometric/photometric units. For these methods, a radiometric/photometric calibration for the DUT can be used to convert the image data into the proper units for analysis (e.g., irradiance).

Reference Image Attenuation and Compensation

Separate reference images can be used in the process of normalizing the images under test. When using reference images to compute a normalization factor, there is the assumption that the data are below the saturation level of the camera. Once saturation is reached, the data cannot be used to determine if the light source was just above or very far above saturation level. The normalization and resulting metric loses some of its meaning if saturation level is used to normalize.

Depending on the controls available to the camera, there are different techniques that can be used to compute an unsaturated image of the source and an "analysis image-equivalent" normalization factor, such as:

- Adjust the exposure time (T)
- Adjust the system gain (ρ)
- Adjust the source light level (L), e.g., with ND filters and/or direct control of light source power

These techniques can be used individually or combined to form a compensation factor (C) serving as a multiplier for the normalization methods described in previous sections.

$$C = \frac{T_{analysis}}{T_{reference}} \cdot \frac{\rho_{analysis}}{\rho_{reference}} \cdot \frac{L_{analysis}}{L_{reference}} \tag{2}$$

Note that these techniques assume that the camera data is linear or linearizable and that the reciprocity law holds.

Considerations for light source masking

Regardless of the exact normalization method in use, it may be necessary to mask out or ignore the direct image of the source in the metric images. Again, we mask the direct image of the source because it is not considered to be stray light. However, in some circumstances, accurate masking may be difficult due to certain ambiguities in the geometry of the light source in the images under test. For example, the direct image of the source may not always be circular. Figure 6 shows two examples where the apparent location and shape/size of the direct image of the source may be considered ambiguous due to a combination of factors including lens distortion, coma smearing, blooming, and stray light.

Special attention should be paid to the logic and robustness of any mask method. To the benefit of control and repeatability in the measurement, we want to accurately track the location/angle of the source with respect to the DUT in the image. The accuracy of the mask may have an effect on the accuracy of the resulting metric images or any derived summary statistics, as well as the appearance of stray light surrounding the direct image of the source. We consider three potential mask methods.

Figure 6. *Two cropped images of a small, bright light source demonstrating that the shape, size, and location of the direct image of the source may be ambiguous. The ambiguity can be caused by lens distortion, blooming, coma, and stray light. The red ellipsoids illustrate the question of where and what the actual direct image of the source is (and the overarching question of what is stray light).*

A first mask method involves using a level threshold where any image value above that level is considered the mask [6]. Additional image processing steps can be applied to improve accuracy, such as localization via centroiding, image close morphology, connected component analysis, or more. A level threshold method can fail in the presence of high levels of stray light (i.e., saturation), noise, blooming in the sensor, or if the source is outside the camera FOV.

A second mask method could involve using the geometric properties of the light source and camera to project the size and location of the source in the image [6]. This could involve the use of a geometric camera model for the DUT (intrinsic parameters including distortion) in combination with the pose (extrinsic parameters) of the setup. This method can fail if the geometric model is inaccurate or in the presence of non-geometric factors that affect the appearance of the light source in the image, such as irregular lens point spread function (PSF) manifested as coma smearing.

A third mask method could involve capturing separate well-exposed reference images for each of the images/angles under test, wherein the direct image of the source is not saturated or is not blooming enough to affect its apparent geometry in the image [6]. The location and shape/size of the source in these separate well-exposed images may be easier to identify than in the over-exposed stray light images. A level threshold-based mask method may be more successful on these well-exposed image(s) and the resulting binary mask(s) could then be applied to the separate over-exposed images under test.

The answer to what is and is not stray light in the metric images is fundamental to the test. Blooming, which is largely caused by electrical cross-talk in the sensor, may or may not be considered stray light depending on the intention of the test or who's being asked. Overall, a key challenge of the test is quantifying the stray light paths while not penalizing the direct path.

Stray Light Test Factors

The principle of the small, bright light source approach is relatively simple, but the method can can be challenging in practice due to the inherent high dimensionality of the problem. Stray light is a high dimensional problem, in that many factors can affect the magnitude and form of stray light in the camera including:

1. Light source angle with respect to camera
2. Light source brightness/level
3. Light spectrum
4. Light polarization
5. Light source distance and focus (i.e., collimated vs. diverging light)
6. Light source angular size with respect to the camera's instantaneous FOV
7. Bundle intersection (fill factor) of light with respect to camera lens
8. Any added filters, mediums (e.g., windshields), or contaminants
9. Environmental factors (e.g., temperature and haze)
10. Camera exposure time and sensitivity (linked with #2)
11. Camera focus and depth of field (linked with #5)
12. Camera lens aperture setting

A comprehensive testing scheme will include coverage of all factors. However, in practice, sampling within each dimension is not feasible, so limited sampling is used instead (e.g., testing with a broadband light source instead of monochromatic light).

We recommend considering the properties of the light sources of concern and scenarios for the application of the camera. For example, the sources of concern for a camera with the automotive application may include the Sun, car headlights, reflections off of the environment (e.g., other cars), and/or other environmental sources like building or street lights.

The Sun and other small, bright light sources may be common sources of concern for a camera. Therefore, the test approach could involve attempted emulation of their properties. In the following subsections, we describe some additional factors to consider, especially with respect to physically emulating these properties in a lab environment. See [3] for more details about stray light test factors.

Light Level and Reciprocity

Consider the case where the Sun is the source of concern for the application. We may want to try testing with the same level (or intensity/brightness) as the Sun. However, this can be difficult in practice (in a lab environment) and may not actually be necessary. Assuming reciprocity, or the inverse relationship between the intensity of light and the duration of light, one can simply test using a longer camera exposure time than that which is used in the application or in presence of the source of concern. This assumption requires that the camera exposure be fixed or fixable for the test and that the image data is linear or linearizable.

For example, one could consider a camera that operates with exposure time T while the Sun has an average irradiance of E on the camera. If one's intent for the test is to simulate the application stray light performance, but one's test light source level is measured to be E / 10, then one could simply test the camera with exposure time $T \times 10$ (assuming reciprocity).

Nevertheless, it may be desirable to test with multiple light levels or camera exposure times to identify different magnitudes of stray light or different stray light scenarios. Figure 7 shows three images captured with different camera exposure time. If the

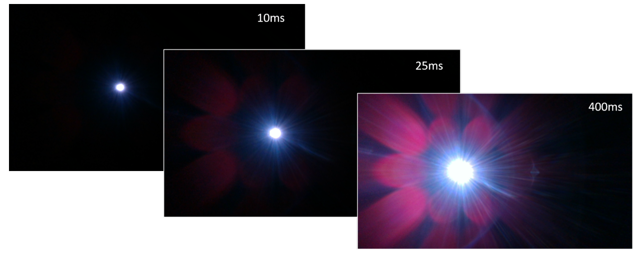

Figure 7. *Three images captured with the same camera using different integration time to show different levels of stray light. In the rightmost image which was captured using the longest integration time, fainter levels of stray light are revealed, but the ability to measure stray light close to the direct image of the source is limited due to saturation and significant blooming.*

image is saturated and/or if the image of the source is significantly blooming (such as in the third image from Figure 7), one may lose the ability to measure intense stray light or stray light that is near the direct image of the source. Therefore, the dynamic range of the camera sensor determines the dynamic range of the test.

Light Source Optomechanical Considerations

We present several considerations relating to the optomechanical design and function of the light source that is used for the test. We first provide a few underlying recommendations for the light source and setup.

We recommend using a beam of light that can overfill the entire front of the DUT, including any surface that can "see" the front lens, as these surfaces can act as an origin for a stray light path. Overfilling the front of the DUT avoids the need to sample within the fill factor dimension (factor #7 from the *Stray Light Test Factors* section).

We also recommended using the front of the DUT as the center of rotation for the test. The first reason for this is that it can minimize the area of the projected beam needed to overfill the front of the DUT. Rotating about another point may induce a lever arm that requires a larger beam to overfill the front of the DUT at all source angles. A second reason is that the front of the DUT is often the measurement datum for light level (e.g., measured irradiance at the front of the DUT).

Finally, we recommend that the beam of light at the DUT location be spatially uniform, such that the entire front of the DUT is exposed to the same or similar intensity of light. This is for the benefit of control and repeatability.

Collimation and Divergence

Ideally, the focus of the light illuminating the DUT should be similar to the source of concern. This relates to the distance of the light source and also the divergence of the light (whether the light is diverging in all directions, focused, or "collimated"). In general, it is recommended to use collimated light for this test, but there are some exceptions.

A first reason to use collimated light is for the benefit of control and repeatability. If the DUT is translated within a collimated beam, theoretically, all of the rays are still coming from the same direction and are at the same angle with respect to the DUT. Additionally, the intensity of collimated light will not fall off as significantly as diverging light (or not at all with perfect collimation in a vacuum), which is more forgiving for light level measurements and repeated positioning of the DUT. A second reason for using collimated light would be if the source of concern is at “infinity”.

However, diverging light can still be useful. If the front of the DUT is significantly large, it can be difficult to overfill with collimated light. For example, if testing through a car windshield, it may be more practical to use focused, diverging light to overfill the windshield (e.g., with an actual car headlight as the source). A second reason for using diverging light would be if the source of concern is not at “infinity”.

The camera’s focus distance and depth of field should be considered in tandem with the focus of the light source. For all intents and purposes, the test does not distinguish blur or bokeh from stray light. Overall, the focus of the light and the camera may be an important test dimensions to consider because they can affect the appearance of stray light in the image, or whether the resulting stray light are focused or defocused.

Extraneous reflections

We recommend that the test environment be completely dark and that surfaces in the test environment be black or have minimized reflectance in the spectral bandpass of the DUT. Any extraneous reflections or light that is detected by the DUT will show up as stray light in the measurement images. This includes reflections off of the DUT itself. The test assumes that only light emitted directly from the source is illuminating the DUT.

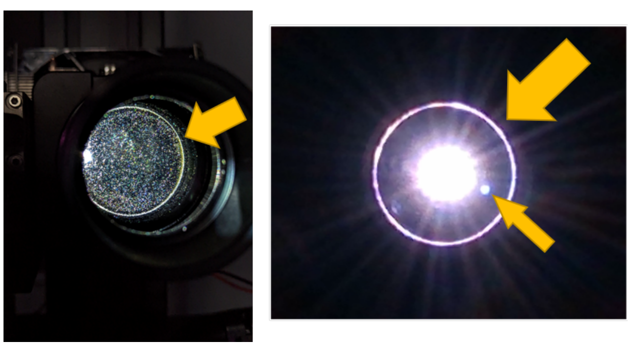

Figure 8. *Example images showing how extraneous reflections from inside a refractive collimator (left) can show up as stray light in the image under test (right). In the latter image (which is significantly cropped), a halo surrounds the direct image of the source – a result of extraneous reflections inside the collimator. In addition, dust and smudges on the collimating lens surface can appear surrounding the direct image of the source.*

For some collimator designs, extraneous reflections from within the collimator can influence the measurement. This is stray light from within the light source or setup that can show up as stray light from the camera in the images under test. It can be caused by internal reflections and scattering from the optomechanics of the light source or the collimating lens (CL) surfaces.

A common artifact is the appearance of a halo/ring of stray light surrounding the direct image of the source. This halo is caused by reflections off of a critical stop in the light source. The critical stop can be an actual stop/baffle, or it can be the edge of the CL or the lens barrel housing it.

Additionally, any dust and smudges on CL surfaces can induce extraneous reflections that show up in the images under test. We recommend testing in a clean room or dustless environment [9]. Figure 8 shows an example of how extraneous reflections from inside a refractive collimator can appear in the images under test.

These extraneous reflections are not collimated, so their size and position in the image may be sensitive to translation of the DUT. Therefore, extraneous reflections can affect the repeatability of the stray light measurement. For example, moving the DUT perpendicular to the direction of the beam will change the position of the halo with respect to the direct image of the source. Moving the DUT away from the light source will reduce the size of the halo, up until the point where the direct image of the source encompasses the halo.

In Figure 9, we show a simple refractive collimator design consisting of an LED light source, a pinhole (which acts as a lens), and a CL. In this case, the critical stop causing a halo is the lens barrel or the edge of the CL. Increasing the distance between the LED and pinhole results in a narrower projection that doesn’t overfill the CL. This eliminates the halo in the resulting images because the critical stop is removed. However, by not overfilling the CL, the output beam will have a narrower diameter and shape resembling an image of the LED instead of a circle. With this, it’s important that the light source itself (LED) be spatially uniform so that the output beam is also spatially uniform.

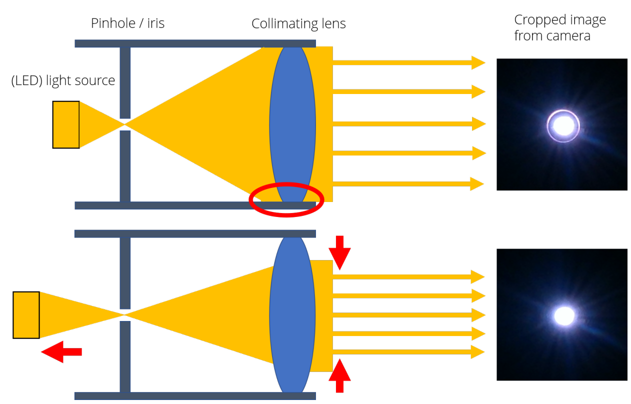

Figure 9. *An example of a simple refractive collimator design composed of an LED light source, a pinhole (which behaves as a lens), and a collimating lens. The top diagram shows that extraneous reflections off of the collimating lens barrel or the edges of the collimating lens itself can cause a “halo” artifact to appear in the resulting images under test (shown in the cropped images to the right of the diagram). Increasing the distance between the LED and pinhole provides a narrower projection, eliminating the critical reflections and the resulting halo (bottom diagram).*

An inherent drawback to this design is that collimation suffers with use of a larger pinhole, which leads to a trade off between pinhole size, angular size, collimation, and brightness. Additionally, collimation and spatial uniformity can suffer due to light from the LED source and the pinhole being focused by the CL at different distances, resulting in non-uniformity within the beam of light, or imperfect collimation. Another valid design could be to not use a pinhole at all, but this may be more likely to have internal reflections if the LED has a wide viewing angle as opposed to narrow focus.

A workaround for the halo issue is to mask out (ignore) a larger portion of the image when measuring the stray light, including any extraneous reflections from the source or CL. However, this leads to an underestimation of the overall amount of stray light in the image and also prevents measurement of stray light near the direct image of the source.

Overall, standardization of optomechanical designs for light sources, test setups, and test schemes could be beneficial to the repeatability of the test and the community at large, due to the potential effects they can have on the metric images.

Light Source Angular Size

A factor related to the design of the light source and the size of the source in the images is the angular size (or angular diameter/extent) of the source. This is the apparent size of the source relative to a camera's viewing distance and instantaneous FOV. This factor is separate from the diameter of the beam of light. For a diverging source, angular size will shrink when viewed from further away. For a collimated source, angular size is constant with distance.

The Sun, for example, is an extended source at "infinity" and has an angular diameter of approximately 0.53°. For a refractive collimator design, the angular size is proportional to the size of the pinhole or LED source. A bright light source that has small angular size may result in different forms of stray light than one that is large.

Figure 10 demonstrates how the angular size of a source affects the appearance, or specifically the "sharpness", of resulting stray light features. Smaller angular size (i.e., point sources) may result in high-frequency stray light while, conversely, larger angular size (i.e., extended sources) may result in low-frequency stray light that is more akin to veiling glare.

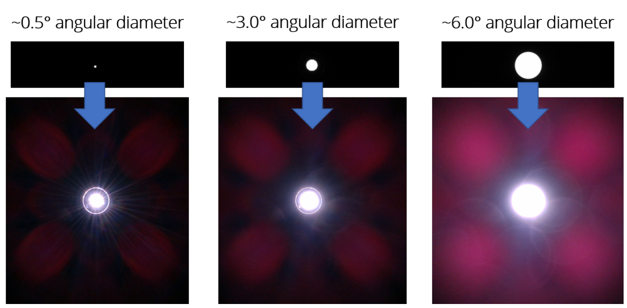

Figure 10. *Example showing the effect of light source angular diameter on the appearance of stray light. The cropped images on top were well-exposed to show the actual size of the source in the image without any blooming. The cropped images beneath were captured with longer exposure to reveal stray light. The halo surrounding the direct image of the source is caused by reflections from within the light source collimator.*

In essence, the stray light from an extended source is the convolution of the stray light features from a point source over the area that the extended source subtends. We can deduce that the patch-based approach results in low-frequency stray light (e.g., veiling glare) instead of high-frequency stray light (e.g., ghost objects) because the light region of the test chart is an extended source. Note this is not to say that smaller sources cannot cause veiling glare.

By understanding that the relative "size" of the light source can result in different forms of stray light, we see the fundamental reason for performing the small, bright light source test approach. However, we also see that the test itself may be sensitive to the exact type of light source or setup in use.

Conclusions

In this paper, we provide an overview of stray light (flare) testing for digital camera systems and explain a multitude of factors to consider when performing the small, bright light source test approach. We describe the concept of normalized stray light and consider factors related to several normalization methods. We recommend taking into account attributes related to the design of the light source and setup by showing how some of these factors can affect the appearance of stray light or the repeatability of the measurement.

Camera system stray light testing is a relatively new focus for some industries and communities. Therefore, further development of the normalization methods and measurement may be necessary. Future work for the community includes settling on meaningful summary metrics with application-specific focus, such as ways to identify, classify, and quantify different kinds of ghosts. Additionally, due to the effects that it can have on the measurement, it may be beneficial to standardize designs for light sources and test setups.

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