Luminance, Reflectance, and Chromaticity from RAW Scene Capture

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Abstract

This paper measures the effect of increased dynamic range on the accuracy of scene radiance measurements made from photographs of scenes. The experiment uses a constant scene with constant illumination and constant camera exposure settings. A small lightbox in the scene had luminances that varied from off to 19200 cd/m². It varied the dynamic range of the scene, while leaving the rest of the scene radiances unchanged. Optical veiling glare altered a image's radiances on a camera's image plane. The camera's optics spread some of the light from the lightbox into the rest of the camera image. This article measures how optical glare affects camera-based calculated luminance, reflectance, and chromaticity values.

Introduction

Cameras can be used for different purposes. Mostly, cameras capture scene information for reproductions that are designed for human viewing. Alternatively, camera images are also used for capturing information for scientific and engineering applications. These applications are interested in the numerical values of camera response as input to computer algorithms designed to calculate information about the scene in front of the camera.

This paper studies the limits imposed by camera optics on the capture of scene radiance. The dynamic range of camera image measurement is limited by both sensor dynamic range and camera optics. Glare is unwanted spatial distortion of scene radiance information from every point of light in the scene. Light scatter, multiple reflections between lens surfaces, reflections from lens barrels and camera body parts, and sensor surfaces all contribute to glare.[3] Glare sources include all radiances imaged on the sensor (camera field of view) as well as any source of light outside that field of view that reaches the camera lens.[10] Every pixel in the sensor image is the recipient of glare distributed from the entire scene. While the individual glare contribution from another pixel's light is very small, the sum from all the millions of glare contributions is substantial.

While glare limits are an important part of scene reproduction, the human visual system provides spatial image processing that mediates glare.[3] Human viewing introduces another layer of its own spatial image processing that counteracts glare.

There are many calculations in digital image processing that are indifferent to the accuracy of individual pixel values. Computational object recognition is a good example. Here the relationship of image contours is critical. While optical fisheye distortion is harmful, object recognition is largely indifferent to optical glare.

The type of calculations we study in this paper require radiometric accuracy. Using a camera to find the reflectance properties of objects in a scene, or the scene's illumination are common, often ill-posed problems. Perhaps the largest use of computational scene radiances is High-Dynamic Range (HDR) imaging using multiple exposures. Debevec and Malik [1] described a digital algorithm based on camera reciprocity to measure a Camera Response Function (CRF). They calculated and applied an inverse CRF to extend the dynamic range of scene information.

Figure 1. Illustration of the experiment. (top) Photograph of scene with lightbox off. (middle) Diagram identifying RoomCC, HallCC and Lightbox image sectors. (bottom) Photograph with maximal lightbox luminance.Two ColorChecker test targets (RoomCC and HallCC) were photographed with constant exposure using RAW data format. Variable luminances from the lightbox changed the dynamic range of the scene without changing the radiances from the rest of the scene. The experiment measured how optical veiling glare on the camera's sensors affected calculations of scene radiances, reflectances and chromaticities.

HDR imaging [2,3] incorporates scenes with dramatic, nonuniform illumination. Scenes with bright highlights and dark shadows have very large ranges of radiances coming to cameras. HDR techniques claim to extend the dynamic range of captured scene radiances. The best of these techniques uses RAW digital camera formats with LibRAW data extraction[4] to access, as closely as possible, the actual response of the sensor without camera firmware signal processing. Ideally, LibRAW camera digits are the linear response to the quanta catch of the camera sensor. However, the light falling on the sensor is the sum of scene radiance plus optical veiling glare resulting from the content of the scene in front of the camera.[5] Therefore, optical veiling glare can set the lower limit of accurate camera response. This paper reports the effects of optical glare on the sensor using LibRAW extraction. It reports the effects of glare for all calculated camera-based luminances, reflectances and chromaticities in two ColorCheckers® from their photographs.

A Variable Dynamic Range Scene

This paper measures the effects of increased glare caused by a large, variable-luminance scene element. The control scene includes a pair of ColorChecker reflectance targets in a living room. A small Aladdin A-Lite® lightbox[6], with variable intensity, and constant color temperature, was placed in the scene near the camera. The ambient illumination in the room was a mixture of daylight and tungsten light sources. The lightbox color temperature was set between daylight and tungsten.

This small (7 by 14 cm) LED lightbox covers 12 percent of the area of the camera image's field of view.(Figure 1) The surface of the lightbox measured 15.6 cd/m^2 (53% max luminance) with its LEDs shut off. The lightbox is near the center of the image. The experiments compares LibRAW digits recorded from the control scene and four different levels of lightbox output. The lightbox was placed halfway between the camera and the RoomCC ColorChecker with opaque baffles to blocked any light leaking out of the back of the lightbox. Any nonuniform illumination from the lightbox falling on the ColorCheckers would disrupt the reflectance and chromaticity measurements. None of the light emitted from the small lightbox fell directly on either ColorChecker. Obviously, the lightbox added light to the room. The small lightbox with a diffusing surface has an area of 0.01 m^2. It illuminated the furniture and wall (area =14 m^2) behind the camera and the ceiling (22 m^2). The lightboxes emission adds light that can reach the ColorCheckers after multiple diffuse reflections. The A-Lite added illumination to the room that acted as an integrating sphere, returning a very small increment of indirect uniform illumination. We compared luminance measurements from five regions of a uniform white paper placed in front of the RoomCC ColorChecker (lightbox-off). The white paper averaged 24 cd/m^2 ± 2.2, with a range of 6.0. Turning the lightbox on with its maximum luminance added increased the RoomCC illumination. The white paper measured 25.6 ± 2.2, with the same nonuniform luminance pattern. The individual luminances increase ratios for the 5 regions of white paper were +1.06, +1.09, +1.07, +1.04, +1.07 (average=1.07 ± 0.01). This extreme comparison of lightbox-off and lightbox-max increased illumination uniformly by a small amount. Uniform illumination increments have no effect on reflectance and chromaticity calculations. The increments in uniform illuminance were smaller than the variability of luminance measurements from the white paper. covering the ColorChecker. Even in this extreme case, the lightbox's maximum addition to room illumination has minimal effect on the experimental results.

The lightbox emission increased the dynamic range of the scene in front of the camera. With LED's off the scenes dynamic range was 128:1. HallCC had less illumination than RoomCC. Camera exposure was optimized for this scene. Camera setting of ISO, exposure time, and aperture were held constant for the other images with four different lightbox luminances. Turned on, the center of the lightbox surface had luminances of 469, 1850, 3950, 19200 cd/m^2. These lightbox settings increased the dynamic range of the scene by factors of 16, 63, 134, and 652. This paper studies the effects of glare produced by higher lightbox luminances on the rest of the scene, particularly the low-reflectance, and low-illumination scene segments.

Vary Dynamic Range

The first step in vision and reproduction is imaging. Optical veiling glare limits the dynamic range of the image on sensors.[7]

Figure 2 (top left) is a segment of the Jpeg photograph of a Low-Dynamic-Range (LDR) scene using a Canon D60 camera with Canon EF 50 mm F/1.8 II primary lens having only five optical elements (so as to minimize glare).[11] The left side of the image is a ColorChecker® reflection target; the right side has an Aladdin® LED lightbox turned off. The center of the lightbox with all LEDs off is 15.6 cd/m^2.

Figure 2 (top right) was taken with the same exposure, but with the lightbox on maximum output. The lightbox was placed several feet in front of the ColorChecker, with an opaque light shield behind it. None of the light from the lightbox fell directly on the chair, the wall and the ColorCheckers.

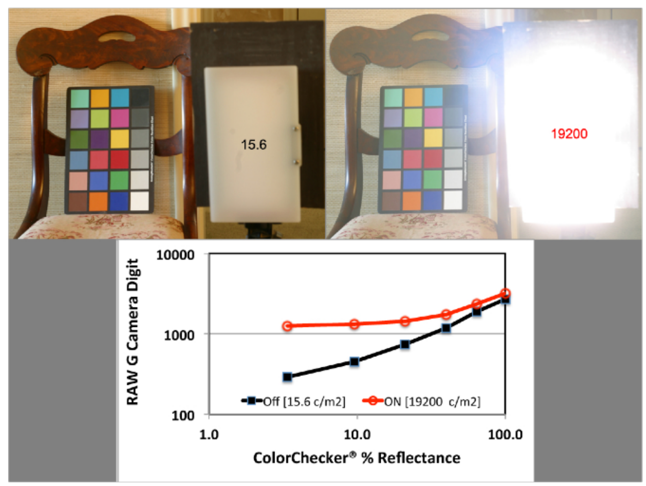

Fig.2(top) LDR Jpeg photographs of ColorChecker® and an Aladdin® LED lightbox (left) turned off; (right) turned on with maximal output.
Fig. 2(bottom) plots the RAW G camera average digits (log scale) extracted by LibRAW for the six achromatic squares.

The maximum luminance at the lightbox center (turned on) was 19,200 cd/m^2, as measured with a Konica Minolta C100 spot radiometer. The bright lightbox has increased the scenes dynamic range by three log units.

The Jpeg photographs in Figure 2 provide an illustration of the effects of glare, but they also introduce nonlinear transformations of sensor response, namely tone scale and color enhancement.[5] In order to measure the light falling on the camera's sensor we extract data from RAW format images. Figure 2 (bottom) plots LibRAW digits extracted from Green RAW images made with the same camera. By using RAW we remove most of the signal processing in the cameras firmware, and get to see the spatial effects of glare on the camera sensor. The data plotted in black in Figure 2 (bottom) shows the RAW G camera digits for the 6 achromatic squares in the ColorChecker with the lightbox off.

Turning on the lightbox added glare light to the other parts of the scene. The increase in the scene's dynamic range added glare to the image of the ColorChecker on the sensor, as seen in the red curve in Figure 2 bottom). The camera digits from identical scene radiances have much higher values. The camera's optical glare added only 20% to the RAW G digits for the White square. It added 90% to the middle-gray (4th) square, and 334% to the Black. The Black square with glare is slightly higher digit than the third gray square with the lightbox off. The black square digit changed from digit 290 to 1259 with glare.

Figure 2 demonstrates that when a very bright object is added to an LDR scene, it can alter the camera's response to the entire LDR portion of the HDR scene.

White Gray and Black in RoomCC and HallCC

The range of digits in the control image with lightbox off was 4005 to 162. The average digit value was 709.

Table 1 lists the increase in RAW digit values for White, Gray, and Black squares in RoomCC and HallCC image sectors with increase of lightbox luminance.

Lightbox	15.6 off	469	1850	3950	19200
RoomCC Digit					
19 White 9.5	2696	2661	2689	2757	3181
22 Gray 5	753	757	803	882	1433
24 Black 2	291	312	380	474	1229
W/B ratio	9.3	8.5	7.1	5.8	2.6
HallCC Digit	3.8	3.6	2.9	2.4	1.4
19 White 9.5	601	660	718	800	1423
22 Gray 5	241	273	335	426	1121
24 Black 2	158	182	245	336	1035
W/B ratio	3.8	3.6	2.9	2.4	1.4

Table 1. Comparison of RAW digit values of White, Gray, and Black squares for the RoomCC segment (top); and the HallCC segment (bottom). W/B ratio is the range of digits calculated as the ratio [19White / 24Black].

The RoomCC digits fall in the middle of the exposure range. The HallCC digits fall near the bottom of the range. The digit values in Table 1 were LibRAW extracted values with a camera with documented linear response to light. Pascale's measurements [9] of the ColorChecker report a W/B reflectance ratio of 29. The RoomCC data reports a smaller ratio of 9.3; and HallCC report a ratio of 3.8. The fact that the RoomCC has a range of 9.3, just means that the camera's linear response has a slope less than 1.0. Using this data to define and implement an inverse CRF should correct the range calculation.

The unexpected result was the HallCC data for the identical ColorChecker, in less illumination. It reported a range of 3.8. That means the inverse CRF for that part of the lightbox-off scene has a very different slope. The HallCC inverse CRF slope is higher by a factor of 2.5.

Our initial assumption that glare would be minimal in the control indoor scene was wrong. We assumed that the low-dynamic-range scene, with a range of 128:1, would display modest changes from glare. Even though the lightbox was off, glare generated by the entire control scene has substantially changed the camera's CRF for the HAllCC part of the image. The LDR scene itself is a much larger source of glare that expected.

In RoomCC, the lightbox luminance 469 causes no effect on white and gray squares, and minimal increase of 12 digits on black. That has a W/B ratio of 8.5, which is somewhat smaller. Higher lightbox luminances decrease those W/B ratios to 7.1, 5.8, and 2.6. With maximum lightbox luminance 19200, white digits increase by 485; gray digits increase by 680; black digits increase by 938.

In HallCC the lightbox luminance 469 causes small increases of digits. That has a W/B ratio of 3.8. Higher lightbox luminances decrease those ratios to 2.9, 2.4, and 1.4. With maximum lightbox luminance 19200, white digits increase by 822; gray digits increase by 880; black digits increase by 877. The two image segments RoomCC and HallCC have very different changes in camera digits from glare. RoomCC has more illumination, with the lightbox off, white to black covers digits 2696 to 291. HallCC has less illumination. With the lightbox off, white to black covers digits 601 to 158.

Camera digit is the sum of scene luminance plus glare. Glare is a complex function of scene content. Camera digits do not correlate with scene luminances.

Calculated Scene Reflectances

The Canon D60 camera has a linear response to light, even with very low digits. We can use the achromatic ColorChecker reflectances[8] to find the slope of the camera's G RAW linear response in the LDR case of lightbox off (15.6 cd/m^2). We used this *digit-to-reflectance* calibration to calculated reflectance value for the four images with lightbox glare. Figure 3 shows the calculated reflectances for all 5 images for both RoomCC and HallCC.

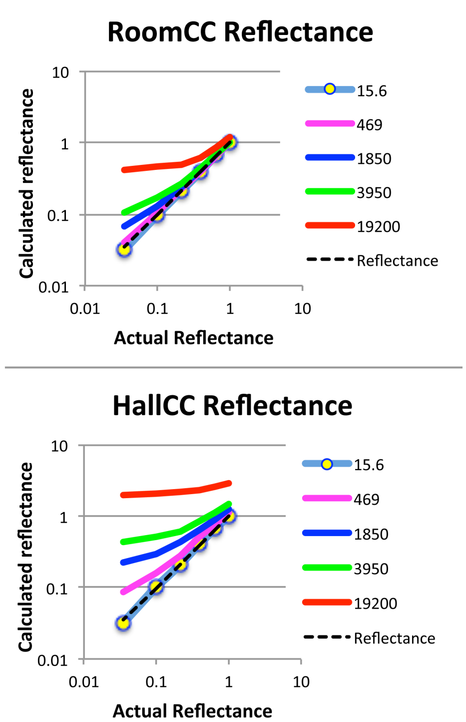

Figure 3. Plot of Calculated G Reflectances with different Lightbox luminances for RoomCC (top), and HallCC (bottom).

Figure 3(top) plots the ColorChecker's actual reflectances with black dashes. It shows that the control (15.6 lightbox-off) digits data falls on these measured reflectance values. The 15.6 data created the CRF used to calculate the reflectances in the other RoomCC images. As the luminance of the lightbox increases the digital values of the low-reflectance papers increase faster than those of the white. A constant inverse CRF calibration for RoomCC cannot recover accurate reflectance values. The target has a reflectance range of 29.[9] Using the inverse CRF for RoomCC calculates a range of 31 for 15.6; 24 for 469; 15 for 1850; 10 for 3950; 2.9 for 19200 cd/m^2.

Figure 3(bottom) shows the data for HallCC. It used a different inverse CRF defined by HallCC 15.6 data to calculate the reflectances in the other HallCC image sectors. The target has a reflectance range of 29. Using the HalCC calibration calculates range of 31 for 15.6; 13 for 469; 6 for 1850; 3.4 for 3950; 1.4 for 19200 cd/m^2. The effect of glare is distinctly different in RoomCC and HallCC.

Figure 3 uses an impractical calibration process. Its two parts use distinctly different CRF calibrations. The top graph uses the achromatic data from RoomCC squares, while the bottom graph uses data from HallCC. The camera response is linear in both, but with very different slopes. Even though we used different CRFs for different parts of the same image, we were unable to measure reflectances accurately because of glare.

Using two very different inverse CRF functions, we found different, variable glare distortions with increased dynamic range. Glare prevented us from using camera digits to measure reflectances in scenes.

Chromaticity vs. Lightbox Luminances

Chromaticity is the projection of the three-dimensional color solid onto a plane defined by the RGB color separation data. Position in the plane, defined by **r, g** are calculated

$$\mathbf{r = R / (R + G + B)}$$
$$\mathbf{g = G / (R + G + B)}$$

where **R, G, B** are the digital color values from the camera image These chromaticity values are specific to the camera system and file format (e.g. Jpeg, or RAW). Chromaticity is the ratio involving a sum. That requires strict linearity of input information.[5,8] Camera chromaticity should not be confused with CIE colorimetric chromaticities (x, y).

The RAW **R** digits for each of the 24 squares were normalized by dividing their value by the RAW **R** value of 19(White). The same normalization [Gdigit/ G 19(white)digit], and [Bdigit/B19(White)digit] was used. This served to color balance the data and assigned 19(white) square chromaticity 0.33, 0.33. Chromaticities **(r,g)** were calculate using this normalization to the 19(White).

High-Chroma Squares

Figure 4(top) plots the chromaticities of 11 high chroma ColorChecker squares for RoomCC segment. As well, it plots the chromaticity of the 19(White) square. With increase in lightbox luminance, the calculated camera chromaticity showed a decrease in chroma.

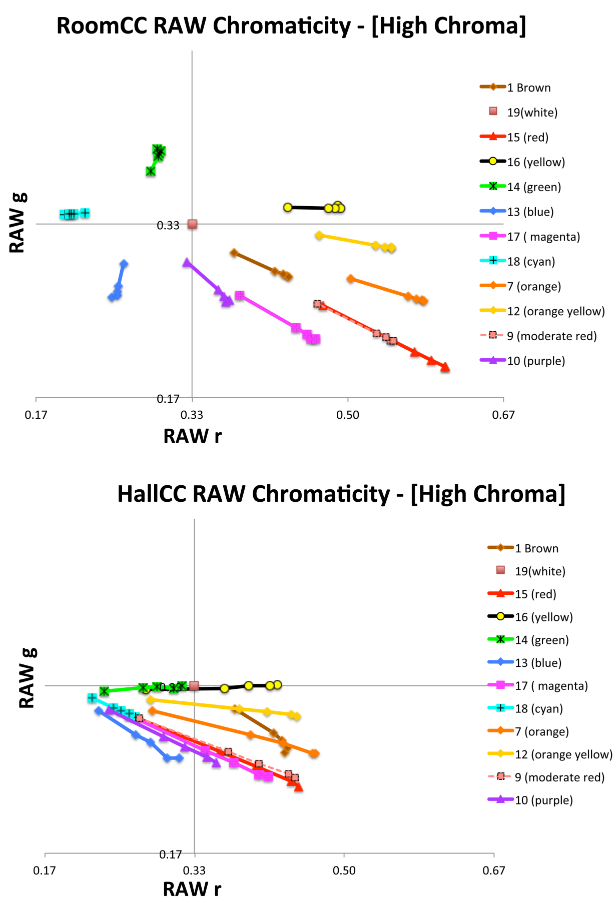

Figure 4 Calculated camera chromaticities for high-chroma ColorChecker® squares in RoomCC and HallCC

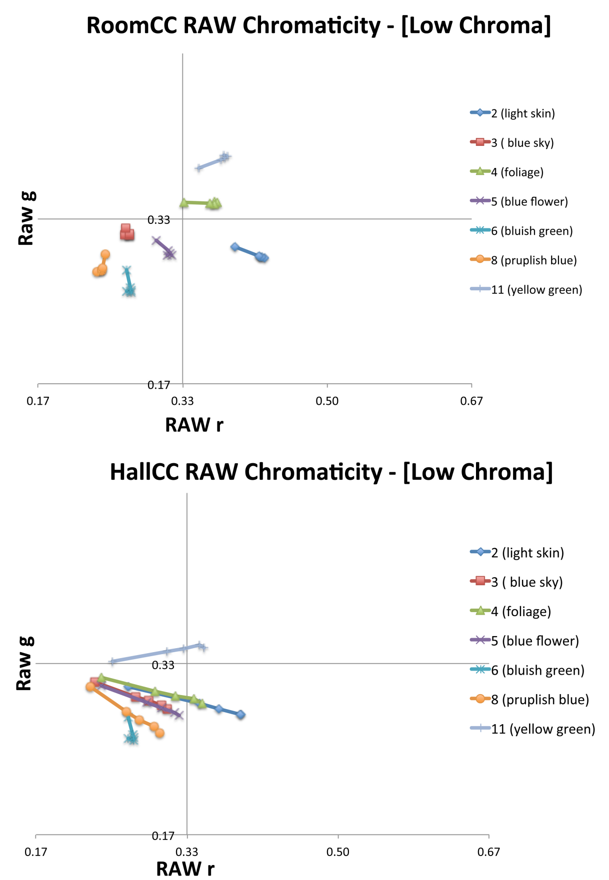

Figure 5. Calculated camera chromaticities for low-chroma ColorChecker® squares in RoomCC and HallCC.

Most plots traced a line toward the chromaticity of white, maintaining a constant hue angle. The exceptions were 13(blue) and 14(green). They moved perpendicular to hue angle. Also 10(purple) moved in a different direction.

Figure 4(bottom) plots the chromaticities of the same color squares for HallCC segment. The color balance step used 19(White) data from the HallCC segment. As shown in Table 1, this ColorChecker is darker, and has smaller range. That smaller range contributes to the the magnitude of uncertainty of data recording. Figure 4 (bottom) chromaticity data covers a much smaller range and is much less systematic.

The effect of increased scene dynamic range was to alter calculated chromaticities in a complex manner. RoomCC and HallCC showed different patterns of chromaticity distortion.

Low-Chroma Squares

Figure 5 plots the corresponding data for the remaining seven low-chroma squares. The data was processed in the same way as with High-Chroma Squares.

In the HallCC segment, camera chromaticities were less consistent. They showed greater distortion.

In the RoomCC segment, Figure 5 colors showed almost no shift in calculated chromaticity, with the exception of the highest lightbox luminance. These low-chroma papers have much smaller differences between R, G, and B reflectances. Their camera chromaticities are more stable.

Combining the results from Figures 4 and 5, glare distorts RoomCC camera chromaticity values for many, but not all color samples. For HallCC, glare distorts chromaticity for all colors.

Discussion:

This paper describes the camera responses to all 24 reflectance squares to two identical ColorChecker targets. Glare in the control scene, with the lightbox off, created two different inverse CRF corrections. Further, the data showed increased lightbox luminance added more glare to the other parts of the images. Lightbox glare adds light to all areas of the scene depending on the angular separation between the glare pixel and the receiving pixel. By increasing the dynamic range of a scene with a small lightbox, we found LibRAW extracted camera digits did not correlate with scene luminances. We measured the large percentage changes in camera digits for low-reflectance ColorChecker squares, such as black.

Using multiple CRF calibrations, in different parts of the same scene, did not generate accurate calculated reflectances.

We also measured the complex glare distortion on camera chromaticity. Some color samples with very high chroma have high reflectances in some wavebands, and very low reflectances in others. By adding light to low-reflectance wavebands, glare distorts camera chromaticity values for some, but not all squares.

Camera chromaticity data is an unreliable correlate with spectral reflectance in high-glare, and high-dynamic-range natural scenes.

The interesting property of glare is that its effects are constant with exposure. When we hold the camera's aperture constant and vary the time of exposure, the image on the sensor is fixed. It has a constant spatial luminance pattern on the sensor. Scene degradation by the optical system is constant with exposure time. Changing exposure time changes illuminant flux. The sensor image moves up and down the camera's RAW linear response. Changing exposure time adds, or subtracts a constant RAW value to all pixels. Image segments affected by glare have a fixed spatial relationship to other segments regardless of exposure time. More exposure cannot add more information about the darker segments. The dark values in HallCC have already reached their glare limit.

Glare is the very small fraction of each scene segment's light that gets spread over all the other sensor pixels. The glare contribution from a donor pixel depends on its radiance and the angular separation between this donor and the receiving pixel. The total amount of glare falling on a receiving pixel is the sum of glare from millions of other pixels. In other words, glare depends on the radiance content of the scene, and the local distribution of those radiances in the individual scene. This is the reason that the ISO 9358:1994 Standard states unequivocally that: "the reverse [deriving luminance from camera response] calculation is not possible"[9]

Conclusions

The control experiment used two identical ColorCheckers in different regions of a scene. Glare distorted the inverse CRF for the colorChecker in lower illumination. Additional experiments found that glare from a variable luminance lightbox added light to camera images from an otherwise constant scene. Glare is unique for each part of every image. For darker squares, glare distorts calculations of scene radiance from camera data. The effects of glare increases when scene dynamic range increases. Glare distorts image processing algorithms that require accurate scene radiance information. Glare makes camera calculated luminance, reflectance and chromaticity data unreliable.

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Acknowledgements

The author thanks Vassilios Vonikakis for LibRAW data extraction and Mary McCann for discussions of this work.

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John McCann received a B.A. degree in Biology from Harvard University in 1964. He worked in, and later managed, the Vision Research Laboratory at Polaroid from 1961 to 1996. He currently consults and continues to do research on color. He has studied human color vision, digital image processing, large format instant photography and the reproduction of fine art. His 140 publications have studied Retinex theory, color from rod/Lcone interactions at low light levels, appearance and intraocular scatter, and HDR imaging. He is a Fellow of the Society of Imaging Science and Technology (IS&T) and the Optical Society of America (OSA). He received the SID Certificate of Commendation, and is the IS&T/OSA 2002 Edwin H. Land Medalist, and IS&T 2005 Honorary Member. He is past President of IS&T and the Artists Foundation, Boston. He served as Secretary of the Inter-Society Color Council, the USA Member body of AIC. In 2012, he and Alessandro Rizzi published the Wiley/ IS&T book, The Art and Science of HDR Imaging. He was a papers chair of the first CIC conference in 1992.