

# Sources of Error in HDRI for Luminance Measurement: A Review of the Literature

Sarah Safranek and Robert G. Davis

Pacific Northwest National Laboratory  
620 SW 5<sup>th</sup> Avenue, Suite 810  
Portland, OR 97204  
[Sarah.Safranek@pnnl.gov](mailto:Sarah.Safranek@pnnl.gov) (corresponding author)  
[Robert.Davis@pnnl.gov](mailto:Robert.Davis@pnnl.gov)

**This is an archival copy of an article published in *LEUKOS*. Please cite as:**

Sarah Safranek & Robert G. Davis (2020): Sources of Error in HDRI for Luminance Measurement: A Review of the Literature, *LEUKOS*, DOI: 10.1080/15502724.2020.1721018

## Abstract

Compared to the use of conventional spot luminance meters, high dynamic range imaging (HDRI) offers significant advantages for luminance measurements in lighting research. Consequently, the reporting of absolute luminance data based on HDRI measurements has rapidly increased in technical lighting literature, with researchers using HDRI to address topics such as daylight distribution and discomfort glare. However, questions remain about the accuracy of luminance data derived from HDRI. This article reviewed published papers that reported potential sources of error in deriving absolute luminance values from high dynamic range imaging (HDRI) using a consumer grade digital camera, along with application papers that included an analysis of errors in HDRI-derived luminance values. Four sources of significant error emerged from the literature review: lens vignetting, lens flare, luminous overflow, and sensor spectral responsivity. The cause and magnitude for each source of error is discussed using the relevant findings from previous research and any available correction methods are presented. Based on the review, a set of recommendations was developed for minimizing the possible errors in HDRI luminance measurements as well as recommendations for future research using HDRI.

Keywords: High Dynamic Range Imaging, luminance, measurement

## 1. Introduction

This article reviews literature related to possible sources of error when using commercial photography equipment for deriving luminance values from high dynamic range imaging (HDRI) in architectural applications. HDRI using a conventional digital single-lens reflex camera (DSLR) holds promise for collecting luminance measurements in a much shorter time and at a lower cost than is possible using traditional hand-held spot luminance meters. Because research into perceptions such as brightness, glare, and uniformity has used luminance as the most salient aspect of the lighting stimulus, the ability to quickly and accurately measure and calculate luminance has been a longstanding need. Recent technical literature on architectural lighting shows an expanded use of HDRI, with a growing number of researchers reporting luminance measurements that were captured through HDRI.

For decades, researchers studying human perceptual responses to lighting have explored luminances and the patterns of luminances in architectural environments. Some of this research has examined holistic environmental perceptions in the tradition of the Waldram (1954) “designed appearance” approach (Bernecker 1980; Davis and Bernecker 1984; Loe and others 2000; Loe and others 1994; Miller and others 1984). Other researchers have focused on using luminance data to predict perceptions of beam patterns produced by accent lighting systems (Simonson and others 2003; van Kemenade and Reker 1988; Wang and Davis 1996) or to predict human responses with analytical techniques derived based on visual processes, such as spatial frequency analyses (Davis and Harvey Jr 2007; Samuleson and others 1999) and retinal center-surround receptive fields (Scheir and others 2018). Generally, for this research, luminance values were measured using conventional spot or image-based devices, with measurement practices that could be very labor-intensive and expensive. The potential alternative of HDRI for these purposes was demonstrated by Van Den Wymelenberg and others (2010) who explored relationships between subjective preference ratings and the luminance patterns in a space.

Beyond these broad spatial perceptions, luminance serves as the foundation for glare metrics such as Visual Comfort Probability (VCP) and the Unified Glare Rating (UGR). (See Eble-Hankins and Waters (2005) and Ashdown (2005) for reviews of these metrics.) For daylighting, the development and initial evaluations of the Daylight Glare Probability (DGP) metric were based on images using a scientific-grade CCD camera (Wienold and Christoffersen 2006). Since then, other researchers have used luminance data derived from HDRI using commercial cameras for glare evaluations and the development of potential new metrics for glare (Cai 2013; Cai and Chung 2013; Suk and others 2013; Van Den Wymelenberg and Inanici 2014; 2016). Glare research, from electric lighting and from daylighting, appears to be the most common use of HDRI for luminance measurement.

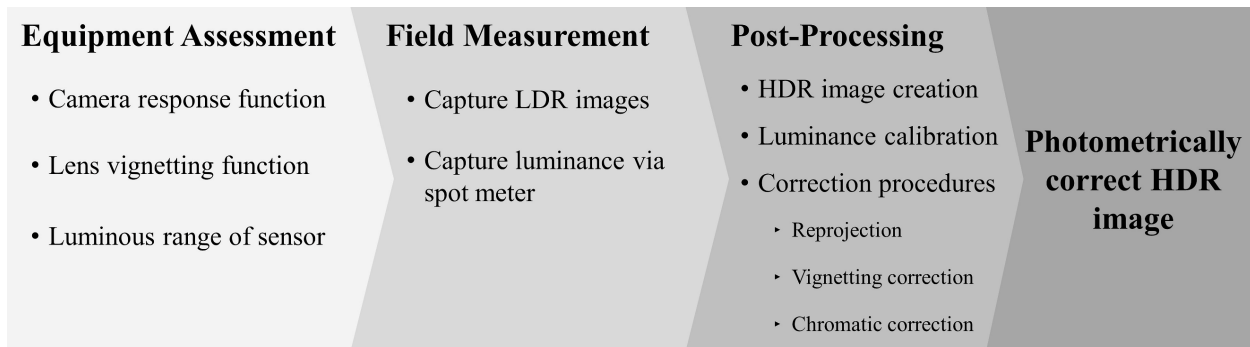
Other applications of using HDRI for luminance measurement include evaluating the uniformity of luminance across an LED chip (Tyukhova and Waters 2013), deriving the luminous intensity distribution of a luminaire by evaluating the luminaire’s delivered luminance pattern (Bellia and Spada 2014), modeling daytime sky luminances (Inanici 2010), testing the concept of using HDRI to replace the traditional photocell in a daylight control system (Sakar and Mistrick 2006), and approximating the spectral data at eye positions to predict quantities related to circadian physiology such as melanopic lux (Jung and Inanici 2018). These examples are included to demonstrate the breadth of the applications of HDRI for luminance measurement; many other examples exist in the literature of researchers reporting luminance data from HDRI techniques.

While HDRI offers advantages for luminance measurements in research, questions remain about the accuracy of luminance data derived from such techniques. Unlike conventional spot or imaging luminance meters, which can be calibrated through accredited testing using NIST-traceable light sources, HDRI luminance measurements derived from commercial photography equipment are often adjusted during image post-processing using field calibration techniques, and known sources of error are managed through a set of “best practices” that have been adopted within the related user community. This article reviews the body of literature where the potential sources of error and uncertainty in deriving luminance values from HDRI techniques were reported. Criteria for including a publication in this review included peer-reviewed articles or technical conference papers which had a focus on documenting the accuracy of HDRI for luminance measurement, and application articles that included an analysis of errors in HDRI-derived luminance values.

## 2. HDRI and Sources of Error

In photography, the term “dynamic range” describes the ratio between the brightest and darkest pixels in an image. The technique of HDRI combines the pertinent information from multiple low dynamic range (LDR) images of varying exposure to create a final image that more closely resembles the dynamic range of the human visual system. The most common method of HDR image creation begins by sequentially capturing three or more LDR images of a static scene. For each LDR image, the exposure of the image is altered by adjusting the shutter-speed, so that the camera sensor is exposed to the scene for different durations. These LDR images are then merged and tone-mapped, either onboard the camera body or using external software tools. While much of the on-board processes for LDR image capture remain proprietary and can vary among camera models, the camera response curve describes the non-linear mapping between an image sensor response and the recorded pixel value of compressed image formats (like JPEG files).

Creating HDR images has become relatively commonplace, with the capabilities now being found in consumer-grade digital cameras and smart phones. However, moving from an HDR image to the derivation of accurate luminance values at each pixel includes further calibration as illustrated in Figure 1. Luminance calibration is done by linearly scaling the recorded pixel values of the HDR image relative to a known reference luminance. At the time of image capture, a calibrated spot luminance meter is used to measure the reference luminance, which is typically a neutral grey calibration surface like a X-Rite ColorChecker Classic target. Once the HDR image is generated using the available software, details on how the HDR image was captured and created can be reviewed in the opening lines of the file header, accessible by opening the image file in a text editor. The header text describes the camera, LDR images and software used to create the HDR image as well as additional information on the image format, exposure, and view characteristics. Additional spatial calibration procedures, like correcting for camera perspective, lens distortion, and vignetting effects, are applied during the post-processing of the image. It is important to note that while specific information in the image header can be manually adjusted in preparation for the specific application of the HDR image, it is critical that the header remains intact throughout correction procedures like those described in the following sections of this article. Pierson and others (2017) recommend checking the image header before and after making significant modifications of the HDR image to ensure that the header is not corrupted or lost.



**Figure 1: Overview of the HDRI luminance measurement process as outlined by Pierson and others (2017). Before measurement in the field, the equipment should be assessed to determine potential limitations. During LDR image capture, a spot luminance meter is used to capture a reference luminance needed to calibrate the final HDR image. During post-processing, the HDR image is adjusted to correct for any defects resulting from the imaging/optical equipment.**

Early investigations into using imaging equipment for luminance measurements involved custom CCD devices capturing at least one LDR image of a lit scene (Bellia and others 2002; Rea and Jeffrey 1990; Uetani 2001; Xiao and others 2002). These investigations were limited by complex calibration procedures linked to the uniqueness of the equipment used. Inanici (2006) conducted some of the earliest investigations into using a consumer grade digital camera to capture HDRI luminance measurements, and her work often serves as the “recommended practice” for new HDRI users who wish to derive accurate luminance values from the HDRI images. After documenting calibrated luminance results for HDR images captured under several different lighting conditions, Inanici discussed the significance of relevant sources of error in the HDRI measurement process, including vignetting effects, lens flare artifacts, and spectral responsivity. Since 2006, further research focused on documenting and correcting for error found in HDRI luminance measurements has emerged. In this research, an assortment of camera models (the extent of which is exemplified in Table 1), lens models, camera settings and scene conditions have been used to document error in the HDRI measurement process.

The following sections consolidate the relevant findings from this research, review four major sources of error seen in the published literature (lens vignetting, lens flare, luminous overflow, and spectral responsivity), discuss available correction methods that have been reported for dealing with potential errors, and summarize recommendations for addressing the specific sources of error thought to be most consequential to the use of HDRI for luminance measurement. It is important to note that although this article is limited to discussing the most commonly reported sources of error affecting HDRI luminance measurements from the technical literature, the HDRI community has identified more sources of error inherent with the measurement process. Some of the additional sources of error have been listed in the final section of this article as recommendations for future research; a body of technical literature addressing these other errors has yet to emerge.

**Table 1:** Camera models used by different researchers to determine error in HDRI luminance measurements.

| Camera                            | References                                                      |
|-----------------------------------|-----------------------------------------------------------------|
| Canon EOS 1D                      | Stumpfel, 2004<br>Jakubiec, 2016b                               |
| Canon EOS 5D                      | Inanici, 2010<br>Jakubiec, 2016b<br>Jung & Inanici, 2018        |
| Canon EOS 7D                      | Tyukhova & Waters, 2013                                         |
| Canon EOS 20D                     | Bellia & Spada, 2014                                            |
| Canon EOS 40D                     | Cauwerts, 2012                                                  |
| Canon EOS 350D (Digital Rebel XT) | Moeck, 2007<br>Cai & Chung, 2011                                |
| Canon EOS 550D (Rebel T2i)        | Cai, 2013<br>Varghese, 2014                                     |
| Canon EOS 1000D                   | Varghese, 2014                                                  |
| Nikon Coolpix 5400                | Inanici, 2006<br>Anaokar & Moeck, 2005<br>Moeck & Anaokar, 2006 |
| Nikon D5200                       | Stanley, 2016<br>Teman, 2017<br>Safranek, 2017                  |
| Olympus C-5060                    | Moeck & Anaokar, 2006                                           |
| Panasonic Lumix DMC-LX7           | Varghese, 2014                                                  |

## 2.1 Lens Vignetting

Lens vignetting is one of the most documented sources of error in HDRI luminance measurement and can be corrected for during post-processing of an HDR image. Vignetting is the gradual decrease of captured luminance towards the edge of an image, where that decrease does not occur in the actual scene being captured. As light enters the lens, optical elements, such as the aperture diaphragm, obstruct off-axes rays, preventing incoming light from entirely filling the aperture and camera sensor. As a result, luminance values for points away from the center of an image measured by HDRI are systematically less than the actual luminances in the scene. The exact effect of vignetting can vary based on the structure of the lens optics and camera sensor, resulting in different magnitudes of luminance decrease depending on the camera/lens combination.

As illustrated in Table 1, many different camera bodies and lenses have been used to capture HDR images for luminance measurement. While fisheye lenses that capture a 180° field of view tend to be a popular choice, especially for architectural applications, different measurement techniques have included fixed focal length lenses, zoom lenses, and wide-angle lenses. The only observed trend when comparing the vignetting error across lens types is that fisheye and other wide-angle lenses exhibit more

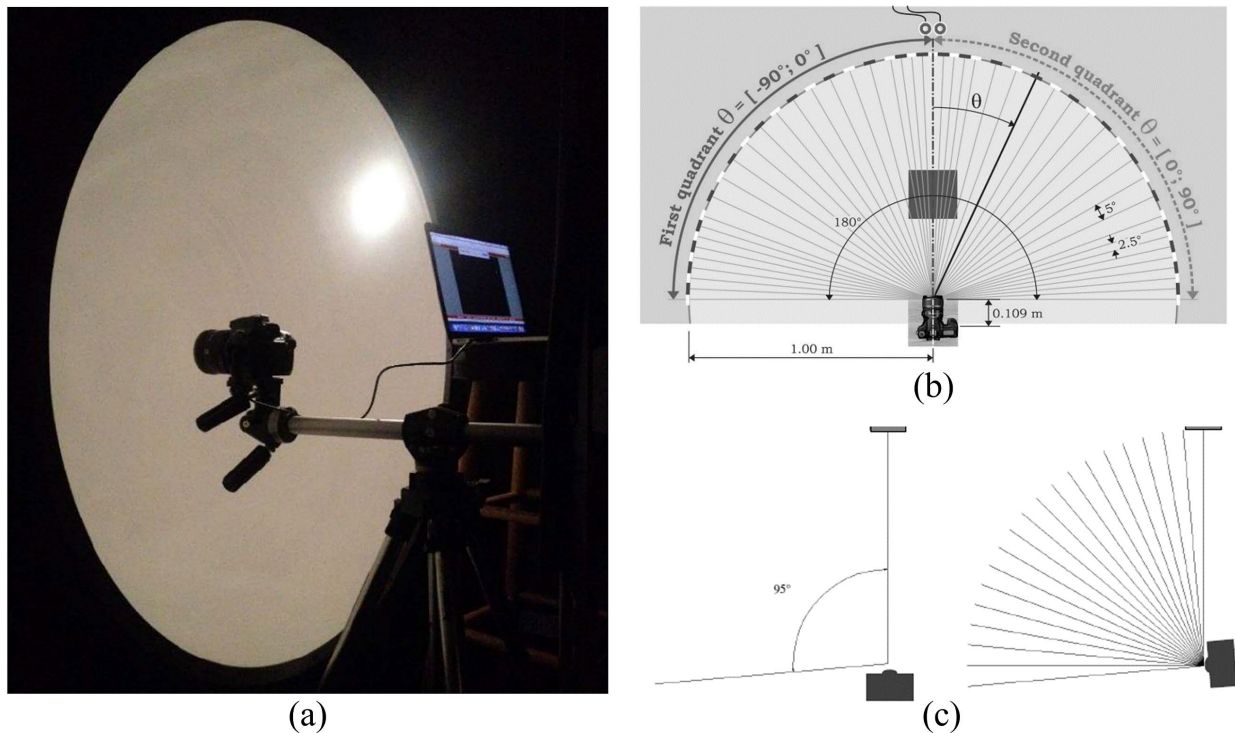
severe fall-off of luminance than other lens types. For example, Stanley (2016) compared the vignetting curves of three different lenses used in combination with a Nikon camera body and reported a maximum error 30% greater for the fisheye lens than the prime (fixed focal-length) or zoom lenses used. Separate evaluations done by Cauwerts and others (2012) and Jakubiec and others (2016b) found that vignetting effects are reproducible if the same camera and lens models are being used, indicating that the vignetting functions for a given combination can be shared with others using the same equipment.

Because optical vignetting is the result of the aperture diaphragm obstructing light rays, the camera aperture setting used for image capture affects the vignetting function. The construction of a typical lens causes vignetting effects to increase with larger apertures (smaller f-stop values). Cauwerts and others (2012) reported error in luminance values attributed to vignetting to be as high as 73% at the periphery of images captured using the largest aperture (f/2.8). For the same study, vignetting error decreased to less than 5% when using mid-range apertures or smaller (that is, f/6.3 and higher). While the decrease in vignetting effects with smaller apertures (larger f-stop values) is a general trend throughout the existing literature, Jakubiec and others (2016b) reported a contradictory finding of vignetting error 5% greater for an aperture setting of f/11 compared to a larger aperture of f/8. It is therefore worthwhile for HDR users to identify the unique vignetting trends for the equipment and aperture setting combinations that will be used for luminance measurement. Without correction, HDR images with vignetting present will underreport luminance values near the edges of the image. This underestimation may be consequential in applications such as determining the background luminance for glare evaluations, measuring the luminance uniformity ratios across a source, or deriving intensity distributions from the measured luminances.

There are three commonly used methods for determining the vignetting function for the specific aperture/camera/lens combination. For each method, luminance values of one or more targets in the field of view are captured using HDR and compared to values of the same target area captured using a calibrated luminance spot meter, creating a ratio between the two sets of luminance measurements. The most common method is to capture an HDR image of a surface lit as uniformly as possible and compare the derived luminance values to multiple spot measurements taken across the same surface. The more uniform the luminances across the scene, the fewer spot measurements required to establish the vignetting function. Several researchers reported photographing the interior of an integrating sphere, like that in Figure 2(a), to determine vignetting functions (Bellia and Spada 2014; Rea and Jeffrey 1990; Safranek 2017; Stanley 2016; Tyukhova and Waters 2013). This approach provides a very uniform luminance distribution and only requires one image per aperture of interest; however, it is difficult to obtain a surface that can be as uniformly lit as an integrating sphere. A related alternate approach uses a uniformly lit white paper as the subject (Anaokar and Moeck 2005; Moeck and Anaokar 2006). The option to use this method depends on the lens selected; a fisheye lens, for example, has a frame of view that extends beyond a flat sheet of paper.

A second method for determining vignetting functions is to capture an image with many targets placed at small increments ( $2.5$ - $5^\circ$ ) in a semi-circular frame around the camera, similar to Figure 2(b) (Cauwerts and others 2012; Inanici and Galvin 2004). Like the previous method, a spot meter is used to measure the luminance at each target and compare it to the derived target luminance of the HDR images. This method is well suited for fisheye lenses because the semi-circular frame of targets fills the view of the camera. Like the integrating sphere method, the set-up is somewhat intensive, but only one HDR image is needed to determine the vignetting function.

The third method used for vignetting function determination, demonstrated in Figure 2(c), is to take a series of HDR images of the same target of known luminance, rotating the camera about its focal point between images (Cai 2013; Cai and Chung 2011; Inanici 2006; Inanici and Galvin 2004; Jakubiec and others 2016b; Stumpf and others 2004). Throughout the determination process, the camera remains stationary for each capture but is rotated at small increments (typically 5°) between images until the camera's entire field of view has been covered with the series of HDR images. A calibrated luminance meter is used to obtain a spot measurement of the target perpendicular to the camera. The meter-measured luminance value of the target is compared to the luminance value of the target derived from the image; this process is repeated for each HDR image. The major drawbacks of this method are the need for a large number of HDR images to determine a single vignetting function as well as the potential to introduce error each time the camera is manually rotated. Depending on the number of apertures or lenses being considered for measurement, this method can be labor intensive. However, Inanici (2004) reported that this method may produce a smoother vignetting function than the previous method of fixed targets in the field of view.



**Figure 2: Examples of the methods used to determine the vignetting function for a given camera/lens combination using (a) an integrating sphere (Stanley 2016), (b) a semi-circular distribution of targets (Cauwerts and others 2012), and (c) rotation of the camera from 0° to 90° from a target (Inanici and Galvin 2004).**

Once the vignetting function is determined for a specific aperture/camera/lens combination, it can be used during the post-processing phase of HDRI analysis. Vignetting effects are expressed as a function of the radial pixel distance from the center of the image, as illustrated in Figure 3, and are typically characterized by a higher order polynomial function (Inanici and Galvin 2004; Safranek 2017; Stanley 2016). The inverse of the function is applied radially to the derived luminances, per pixel, from the center to the edge of the HDR image. Successful application of the vignetting function has been shown



to reduce the error in reported luminance values associated with vignetting to less than 10% for all apertures (Inanici and Galvin 2004; Stanley 2016).

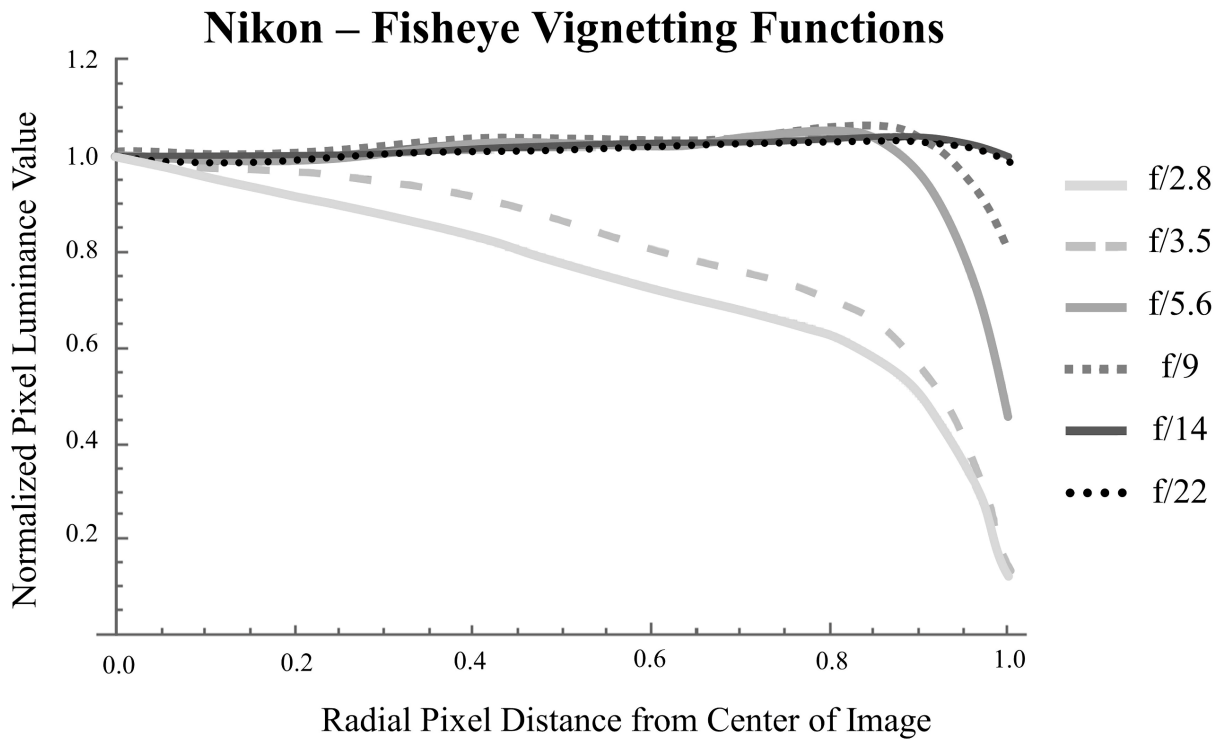


Figure 3: Example of a vignetting function for a Sigma fisheye lens at apertures from f/2.8 to f/22 (Stanley 2016).

## 2.2 Lens Flare

Like vignetting, lens flare stems from the optical structure of the camera lens. Any unwanted or stray light in the optical system of the camera lens, resulting from the internal diffraction of direct light rays, is considered to be lens flare. Lens flare is problematic in HDR luminance measurements because it overestimates the luminance values of the pixels around a source by including information that is not present in the scene. At larger aperture settings (lower f-stop values), lens flare is exhibited in HDR images as the blurring of pixels surrounding a light source, and as the aperture setting is increased, the blurring gradually changes to more dramatic star-like artifacts as seen in Figure 4 (left). The point spread function (PSF) is commonly used in optics to characterize lens flare, expressing an idealized scattering of light around a point source (Reinhard and others 2005). Factors determining the PSF include aperture size, exposure time, and eccentricity (Inanici 2006) as well as less-manageable factors like oil and dust built up within the lens (Reinhard and others 2005).



**Figure 4: Example of HDRI image demonstrating lens flare (left) and the same scene with all direct light blocked from camera lens (right).**

It is challenging to quantify the error in luminance values in HDR images pertaining to lens flare given its erratic behavior; it can vary based on the optical properties of the specific camera lens as well as the characteristics of the photographed scene. Luminance measurements of a simple scene taken using HDRI with the camera placed normal to a high-luminance LED indicated a maximum error of 62-100% in pixel values surrounding an LED (Safranek 2017). While the recorded error is significant, it only affects a small number of pixels around the source and rapidly decreases as the radial pixel distance from the source increases (Inanici 2006; Safranek 2017). Because lens flare has been found to affect a small percentage of the pixels from an overall image for most architectural applications, its error margin has been estimated as less than 10% on average (Inanici 2006). However, Safranek (2017) recommended further research to quantify the error associated with lens flare for applications where it may have more substantial effects on HDRI luminance measurements, such as those applications involving direct capture of the sun or one or more high-intensity point sources. The presence of lens flare in HDR images used for luminance measurements is particularly consequential in calculating glare metrics given that the existing metrics, such as UGR, rely on differentiating the average luminance across a light source as compared to the surrounding average luminance of the scene. If the luminances of the pixels pertaining to the background of a scene are overestimated as a consequence of lens flare, the increased values would lead to an underestimation of glare in the scene.

There are optical and computational photography techniques for mitigating lens flare, but at the time of this article there is no definitive correction method available. Given the dynamic nature of lens flare, it is most practical to attempt removal after the HDR image has been captured. The most readily available mitigation technique is a blind deconvolution algorithm applied during HDRI compilation in either

Photosphere (Ward 2018a) or *raw2hdr*<sup>1</sup>(Ward 2018b). The algorithm identifies pixels that exceed a certain threshold and estimates the PSF, which is then subtracted from the original image (Reinhard and others 2005). There is no evidence to confirm that the blind deconvolution removal method applied in Photosphere or *raw2hdr* reduces the error in HDRI luminance measurements; Safranek (2017) suggested investigating this technique under a small number of lens flare scenarios.

More research on the magnitude of error and correction methods is required before lens flare can be eliminated as a source of error from HDRI-based luminance measurements. In the meantime, there are several recommendations for minimizing the effects of lens flare beyond the post-processing algorithms. Jakubiec and others (2016b) visually assessed the lens flare across all of the available apertures available on their camera to determine a mid-range aperture (f/11) that balanced the negative effects of lens flare and vignetting. Tyukhova and Waters (2013) encountered significant lens flare when photographing an LED chip and recommended that the luminance spot measurement used for calibration be captured in an area of the scene where lens flare is not visually perceptible. Also, increased ambient light (which lowers the contrast between background and source) was observed to visually reduce lens flare (Stanley 2016). However, it was inconclusive whether the ambient light truly minimized the error in luminance measurements or simply minimized the visually perceived flare.

### 2.3 Sensor Blooming/Luminous Overflow

HDR images exhibiting lens flare from a strong contrast between source and background are also likely to experience blooming at the camera sensor. The pixels of the camera sensor have a limited charge capacity and once that capacity is met, the excess charge blooms onto surrounding pixels. This blooming causes underestimation of the overly charged pixel luminance and overestimation of the luminances of the surrounding pixels. The extent of the bloom depends on the size of the pixel, the level of excess charge, and the architecture of the imager used. Both CMOS and CCD sensors used in consumer-grade cameras are susceptible to blooming, and while anti-blooming structures can be added to the sensor, blooming effects cannot be eliminated entirely.

In studies where HDRI is used for luminance measurement, the term “luminous overflow” has been used to describe instances of sensor blooming where the maximum charge capacity of the pixels in the camera sensors has been met and as a result, the dynamic range of the final HDR image is less than the true luminous range (Jakubiec and others 2015). Luminous overflow can be detected in HDRI images when the pixel values of an LDR image have a measured RGB value of 255, 255, 255, even in the image with the minimum exposure. HDR images taken with a fisheye lens have been used to derive vertical illuminance measurements taken at the same location with an illuminance meter. In these instances, comparing the image-computed vertical illuminance to the meter-measured illuminance can also indicate the presence of luminous overflow (Jakubiec and others 2016a). Luminous overflow is common in HDR images with direct capture of the sun or other bright sources and causes the luminance values for the pixels corresponding to the light source to be underestimated. Underestimation of the light

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<sup>1</sup> Photosphere and *raw2hdr* are software tools available for combining multiple LDR images into a HDR image. *raw2hdr* accepts RAW image formats and operates from the command line. Photosphere accepts JPEG image formats and has a user interface. See Stanley (2016) for a more comprehensive comparison of available software tools used for HDRI creation and analysis. Both tools were created by Ward with the free versions limited to macOS. A Windows version of Photosphere can be purchased from Ward (2018a). Photosphere. <http://www.anywhere.com/>.

source is particularly problematic when HDR images are used to compute the luminance across a source or luminance ratios in existing glare metrics (Jakubiec and others 2015). In the application of glare metrics, such underestimation would result in predicted glare values that are less than what may be true in the scene.

Individual cameras have a specific peak luminance value, which is a function of the camera/lens combination as well as the ISO, aperture, and shutter-speed settings used for HDRI measurement. This peak value can be documented by photographing a very bright source (Jakubiec and others 2016a). One investigation found the peak luminance value of the camera being used was at the smallest aperture setting (f/22), maxing out at roughly 3 million  $\text{cd}/\text{m}^2$  (Jakubiec and others 2016a). As this peak value is significantly less than potential luminance values found in direct capture of the sun or LED packages, which can exceed 1 billion  $\text{cd}/\text{m}^2$ , methods to extend the luminous range of the sensor for the purpose of measuring luminance have been reported.

Studies have used neutral density (ND) filters over the camera lens to reduce the light reaching the sensor to as low as 0.1% (Jakubiec and others 2016a; Jakubiec and others 2016b; Stumpf and others 2004). ND filters extend the dynamic range of the HDR image but consequently reduce the mid-range luminance values (Jakubiec and others 2016b) and may introduce chromaticity shift to the image (Jakubiec and others 2016b; Stumpf and others 2004). The chromaticity shift can be corrected by comparing HDR images of a X-Rite ColorChecker Classic target with and without the ND filter and solving for the linear color transform that most closely matches the color samples between images (Stumpf and others 2004). The mid-range luminance values lost by using a ND filter can be recovered by taking HDR images of the same scene with and without the ND filter and combining the measured peak luminous range captured with the ND filter to the original image (Jakubiec and others 2016a).

Because the settings to minimize effects such as lens flare and vignetting affect the peak luminous value that the camera sensor will capture, an aperture setting can be selected that balances the potential error incurred from all three concerns. Although the ideal aperture setting may vary among cameras, mid-range apertures have been found to balance the potential error in HDRI luminance measurements (Jakubiec and others 2016b). Additional research into the relationship between lens flare and luminous overflow may be beneficial, because potential correction methods for one are likely to influence the other.

## 2.4 Spectral Responsivity of Sensors

Camera sensors have varying methods for capturing spectral information, contributing to error in the interpretation of color from the HDR images used to capture luminance measurements. The individual pixels of the camera sensor are unable to distinguish between wavelengths of incoming light, so to allow for color capture, red, green, and blue (RGB) filters are placed over the individual pixels. Typically, the RGB arrays are arranged in a Bayer pattern made of 25% red filters, 50% green filters, and 25% blue filters. A final RGB value for each pixel is determined during image processing on board the camera and involves multiple interpolations from surrounding pixels. The exact interpolation processes for a given camera models remain proprietary information, but are known to vary among manufacturers and sensors types (Teman 2017). While color sensors can distinguish between millions of colors, they cannot fully depict the color spaces corresponding to human perception. Color information is recorded differently depending on whether the image is saved in a RAW or JPEG format. RAW images contain the unprocessed image data directly from the camera sensor and consequently require considerable storage space. Although JPEG file sizes are smaller, the pixel values are compressed and correction adjustments like white-balancing, tone curves, and color saturation are applied. Both file formats are used often in

HDRI application studies, but RAW is recommended over JPEG, especially if there is significant color information in the scene (Stanley 2016; Teman 2017; Tyukhova and Waters 2013; Varghese and others 2014).

For colored, non-luminous surfaces, there are varying magnitudes of reported error in luminance values measured using HDRI. Early HDRI luminance evaluations used the X-Rite ColorChecker Classic target to determine the measurement accuracy of easily comparable colored surfaces (Anaokar and Moeck 2005; Inanici 2006; Moeck 2007). The average margin of error for colored surfaces was within 10% regardless of the lighting conditions and source types used in the scene (Inanici and Galvin 2004; Moeck 2007). However, surfaces that were dark and saturated tended to have greater magnitudes of error than lighter, more neutral surfaces (Anaokar and Moeck 2005; Inanici 2006; Moeck 2007). HDRI measurements of cooler colored surfaces, blue in particular, can have error as high as 53% (Moeck 2007). Moeck also reported that the luminance values of colored surfaces with high reflectance tend to be underestimated while those with low reflectance were overestimated. Given the errors associated with measuring the luminance of colored surfaces in HDR images, the reference target used to calibrate the final image should be a light grey surface.

HDR images capturing colored luminous surfaces introduce more severe errors. The general trends for measuring colored luminous surfaces are the same as those reported for non-luminous surfaces: blue, saturated sources have a larger magnitude of error compared to other regions of the visible spectrum (Stanley 2016; Teman 2017). But the magnitude of the errors for luminous sources may be much greater. For example, Stanley (2016) reported the error from a narrow-spectrum LED source could be as high as 730% depending on the HDR compilation software being used. An experiment by Teman (2017) found differences between the HDRI and meter luminance measurements to be over 500% for a source limited to emitting a narrowband spectrum peaking at 450 nm.

Teman ultimately determined that neither HDRI nor the Konica Minolta LS-110 luminance meter used were capable of accurately measuring the luminance of the narrowband luminous sources considered in her experiment. Comparison of luminance values captured with the LS-110 to luminance values derived from a CL-500 spectrophotometer confirmed that the LS-110 luminance meter used to calibrate HDR images recorded significant errors of saturated colored sources throughout the visible spectrum (Teman 2017). As standard luminance meters are calibrated to broadband light sources, measurement error in the meter for narrowband sources will be reflected in calibration of HDRI luminance values. Because the accuracy of commercial luminance meters at specific wavelengths is not published, it is difficult to accurately quantify the error or offer corrections for measuring the luminance of narrowband light sources using HDRI (Teman 2017).

For broadband sources such as daylight, Jung and Inanici (2018) identified a linear relationship between the average pixel RGB color space values from an HDR image and the same tristimulus values determined using measurements from a Konica Minolta CL-200A chroma meter. Based on this relationship, RGB values measured using a chroma meter were used to determine per-pixel RGB calibration equations to correct for differences in color between a camera sensor and the chroma meter. While this technique seemed effective for correcting possible wavelength-specific measurement errors for a broadband source and a simple three-channel measurement system, further research is needed to establish the suitability of this or similar correction methods for narrowband sources and more realistic discretization of spectral power distributions.

For applications of HDRI where the spectral composition of the scene being photographed may influence the resulting luminance values, spectral responsivity should be considered a significant limitation. This is a particular concern with the increasing use of narrow-band light sources. Given the potential severity of the error reported for the spectral responsivity of HDRI luminance measurements, digital cameras should be used with great caution for purposes of accurately measuring spectrum in the built environment, until further research on this topic documents the potential errors and remediation methods.

### 3. Recommendations for Minimizing Error

Based on this review of existing research on HDRI for luminance measurement, we recommend the following practices to help minimize measurement errors.

1. *Carefully select the camera, lens, and aperture setting(s) that will be used for the research.*
  - a. Select a mid-range aperture setting (f/5.6 through f/11) for balancing between the adverse effects of vignetting (worse with larger apertures) and lens flare (worse with smaller apertures).
  - b. Determine the vignetting function(s) specific to the equipment and aperture setting(s) used.
    - Use electric sources, not daylight, for establishing the vignetting function to maintain constant illuminance during sequential LDR image capture.
    - Avoid low luminances when establishing the vignetting function to help prevent noise in the HDR image from affecting the results.
  - c. Document the luminous range of the sensor specific to the equipment and aperture setting(s) used, to ensure that the maximum luminance expected in the measurements does not exceed the camera sensor's range.
2. *Use field measurement practices that help minimize errors.*
  - a. Mount the camera on a tripod and use tethering software to minimize movement of the HDRI setup. The tethering software allows for remote adjustment of camera settings during image capture.
  - b. Use RAW file formats to minimize error inherent with other compressed file formats, especially if the scene of interest includes saturated colors.
    - Although not recommended, if JPEG file formats are used, carefully record the camera response function before taking any HDRI measurements. Reference the procedure for determining the camera response function outlined by Reinhard and others (2005) and repeat for the available white-balance settings to determine which is best for the camera/lens combination being used (Stanley 2016).
  - c. Capture 12-14 LDR images to ensure no crucial information in the scene is excluded (Cai and Chung 2011; Teman 2017).
  - d. Ensure the luminance levels of the scene are within the luminous range of the camera sensor and remain relatively constant throughout LDR capture. This can be done by comparing the measured vertical illuminance at the camera, before and after the capture process. If the illuminance levels change significantly during LDR capture, as is possible with quickly changing daylight scenes, the capture sequence should be restarted.
  - e. Neutrally colored scenes will produce less error than scenes with saturated colors.

3. *Use calibration procedures that help minimize errors.*
  - a. To minimize vignetting effects, calibrate HDR images with a reference luminance measurement taken near the center of the scene.
  - b. To minimize lens flare effects, calibrate HDR images with a reference luminance measurement taken in an area of the scene remote from light sources.
  - c. When calibrating the HDR image with a luminance meter, record spot luminance measurements in an area of the scene with similar reflectance to the surfaces of the scene that are most important. Light grey surfaces are recommended.
4. *Ensure the header of the HDR image remains intact and accurate throughout post-processing calibration and correction procedures. Mismanagement or loss of the image header may incorrectly scale luminance data, making any other efforts to correct for errors in HDRI luminance measurements useless.*
5. *Document the equipment, settings, and correction methods used to obtain HDRI luminance measurements. Detailed reporting of HDRI luminance acquisition methods in future publications will aid researchers interested in establishing correction methods for the error associated with HDRI for luminance measurement.*

## 4. Recommendations for Future Research

Undoubtedly, HDRI for measuring luminance will continue to be used in lighting research, despite the potential errors of uncertain magnitude that have been explained here. Future research should address how the potential errors are managed and should follow the recommendations for minimizing errors provided in this article. In the meantime, future research can provide a greater understanding of the magnitude of possible errors and can investigate the importance of the various sources of error for different applications and conditions. Recommendations for further research include:

- Investigating additional sources of error than the four sources that qualified for this article. Other sources of error that have been identified by the HDRI community but have not been formally documented in published technical literature include (and are not limited to):
  - Projection method of the camera lens,
  - Viewing angle of the camera lens,
  - Measuring a light source that is flickering or dimmed with pulse width modulation,
  - Viewing angle of the light source,
  - Influence of using an unmodified image header,
  - Image cropping procedures,
  - Image scaling procedures.
- Exploring the relationship between lens flare and luminous overflow, including documentation of how correction methods for one may influence the other, and how the specific HDRI parameters may be optimized to manage both of these sources of error and their interactions.
- Quantifying the error associated with lens flare for applications where it may have large effects on luminance values, such as those involving direct capture of the sun or high intensity point sources. In these cases, the potential for large errors due to lens flare is present, as is the likelihood of those errors producing erroneous values of calculated glare metrics.
- Establishing calibration procedures for spectral responsivity at different wavelength bands. Based on the literature reviewed, the process to accomplish this must address adjustments not only for differences between the HDRI values and the measured values, but also for the possible

errors in the measuring devices being used for calibration. The combination of the increasing use of narrowband light sources and the increasing importance of accurately documenting the lighting spectrum to fully predict different human responses makes this topic particularly important for HDRI.

## 5. Conclusions

Compared to the use of conventional spot luminance meters, HDRI offers significant advantages for luminance measurements in lighting research. Consequently, the reporting of absolute luminance data based on HDRI measurements has rapidly increased in technical lighting literature, with researchers using HDRI to address topics such as daylight distribution, and discomfort glare, among others. However, questions remain about the accuracy of luminance data derived from HDRI. There are four significant sources of error reported in existing literature: lens vignetting, lens flare, luminous overflow, and spectral responsivity. While vignetting can introduce substantial errors to luminance values away from the center of an image, correcting for these errors by establishing a vignetting function is relatively straightforward, and sound research practices should minimize the errors. Correcting for the other sources of error mentioned in this article is less straightforward and requires further investigation. The practical means used to minimize the effects of either lens flare or luminous overflow may interact with each other in such a way that minimizing one may increase the errors from the other. Errors due to spectral responsivity may pose the greatest concern for HDRI, especially given the rapid deployment of narrowband LED light sources for general lighting.



## **Funding**

This work was supported by the Solid-State Lighting Program of the U.S. Department of Energy.

## **Disclosure Statement**

No potential conflict of interest was reported by the authors.

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