Developing High Dynamic Range Imaging Procedures for Luminance Uniformity Measurement

Lia Irvin
Benjamin Feagin Jr.
Eduardo Rodriguez-Feo Bermudez
Michael Royer

Pacific Northwest National Laboratory
620 SW 5th Avenue, Suite 810
Portland, OR 97204
anne.irvin@pnnl.gov

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Developing High Dynamic Range Imaging Procedures for Luminance Uniformity Measurement

Lia Irvin*[1], Benjamin Feagin Jr.[1], Eduardo Rodriguez-Feo Bermudez[1], Michael Royer[1]

[1]Pacific Northwest National Laboratory
*anne.irvin@pnnl.gov (ORCiD: 0000-0002-7238-4299)

Abstract

Documented procedures for high dynamic range imaging (HDRI) for the purpose of measuring luminance are largely focused on situations in which the luminance range is large, such as in a room. There is no clear consensus on procedures for cases in which average luminance is high and the range is small, such as assessing luminaire luminance uniformity. This work proposes saturation limits for low dynamic range (LDR) exposures combined in HDRI for this specific application. Also in this paper, different numbers of LDR exposures (ranging from 2 to 16) used to generate high dynamic range images were analyzed for their effects on a variety of luminance uniformity metrics. Fewer exposures resulted in more noise in the final high dynamic range image, which in turn caused unpredictable inaccuracies in metrics representing luminance uniformity. Using a higher quantity of LDR exposures for HDRI produced a final product with less noise, resulting in more reliable luminance uniformity metric values. More research is needed to determine metric relation to human perception of luminaire luminance uniformity.

1 Introduction

High dynamic range imaging (HDRI) is an emerging technique for evaluating luminance over an area, with particularly valuable characteristics for evaluating luminaire luminance uniformity across its optical material, where the optical material is either diffusing or focusing. When calculating luminance uniformity metrics, it is important to be able to capture spatial luminance patterns with an array detector, such as a digital single-lens reflex (DSLR) camera, for a variety of reasons. The first reason is that an array detector captures data with high fidelity, gathering a greater number of measurements per area than is practically possible with a spot luminance meter, providing more information for analysis. The second reason is that an array detector retrieves the high-fidelity data with a spatial relationship, allowing for easier spatial frequency analysis with respect to data taken by a spot luminance meter, for which hundreds to thousands of readings would have to be obtained to rival data taken by an array detector. This high-fidelity spatial relationship is important because it allows for the straight-forward calculation of uniformity metrics that consider human sensitivity to visual patterns (Moreno 2010). In order to compare metrics that are sensitive to visual patterns and metrics that are not, it is important to have high quality, spatially related data.

HDRI using a common DSLR camera is the most accessible approach to array detector luminance measurement. For this reason, it is the focus of this analysis, although other calibrated array-detector measurement systems are available. HDRI using commercial cameras does have shortcomings, as there are many sources of error that are poorly quantified (Safranek et al. 2020), but in some cases these errors can be managed with calibration and other measurement and analysis practices (Pierson et al. 2020).

HDRI is a frequently used method for capturing luminance data in the architectural lighting industry (Cauwerts et al. 2019). It is most often used by researchers to image entire rooms and exterior scenes where the luminance variation is large, allowing for the calculation of metrics related to such phenomena as glare (Cauwerts et al. 2019; Pierson et al. 2020). By taking a series of low dynamic range (LDR) images to generate a high dynamic range (HDR) image, proper exposure can be achieved for both high-luminance sources (such as interior luminaires and windows permitting daylight into a space) and low luminance areas. The procedure to do this is well defined by Pierson (2020).

The procedures explored in this work relate to a task that is defined by different parameters than the usual use-case for HDRI. The large range of luminance resulting from imaging an entire room is not relevant to measurement of the luminaire discussed in this paper. This use-case refers to luminaires utilizing optical materials to diffuse light from LED arrays with the intention of creating a uniform pattern across the aperture, thus narrowing the range of luminance measured, and therefore necessitating evaluation of the performance of existing HDRI protocols.

When measuring high average luminance with a small range, it is still important to take a series of exposures. Because of the narrow luminance range, the accepted LDR limits for longer and shorter exposure times used in general area lighting cannot be used. At such a high luminance, it is easy to oversaturate the camera sensor. At the shortest possible exposures, the highest range of luminance is not adequately captured due to noise in the data exceeding the measured values. For these larger luminance ranges, it is understood that for the longest exposure, there should be no red, green, or blue (RGB) pixel values below a saturation of 27, and the shortest exposure should have no RGB pixel values above 228 (Cauwerts et al. 2019; Pierson et al. 2020). This paper will propose different limit values for narrower luminance ranges.

At least one extensive study reported that 15 exposures total (the two corresponding to the defined exposure limits and 13 between) be combined to generate an HDR image (Pierson et al. 2020). This paper seeks to determine whether it is necessary to use so many exposures for smaller luminance ranges when the purpose is to evaluate luminaire luminance uniformity.

1.1 Luminance Uniformity Metrics

Although an HDRI procedure for narrow luminance ranges could be useful for other applications, this paper focuses on the luminance uniformity of luminaire optical materials. Currently, the most widely used metric for luminance uniformity is maximum-to-minimum luminance ratio (max:min). When utilized within architectural lighting, there are typically no controls for what the spot measurement size needs to be, nor for how the measurements are obtained. However, since max:min only relies on two points of measurement, it does not describe the complex spatial patterns that emerge as a result of LEDs behaving as point sources (Moreno 2010). A few other statistical metrics improve on this quantification of luminance uniformity.

One alternative that has emerged is avg:min, the ratio of the average luminance to minimum luminance. For both max:min and avg:min, a lower ratio implies a more uniform pattern.

Coefficient of variation, represented as CV, is another alternative, and is the ratio of the luminance pattern standard deviation to the mean. Because the standard deviation is taken, the entire image is sampled, producing a more stable metric that is less likely to be affected by photometric measurement errors or deviations from practice (Moreno 2010). To a lesser extent, the same is true for avg:min. For CV, a lower number implies a more uniform pattern.

Entropy uniformity (Yao et al. 2016), or EU, is more complicated. It is based off equations for entropy; the range is from 0 to 1, with 1 being entirely uniform. In Equation 1, n is the number of luminance points measured (referring to the number of pixels in an HDR image) and p_i is the probability of the i^{th} measured luminance value (the ratio of the i^{th} luminance value to the total luminance). An EU value closer to 1 implies a more uniform pattern.

$$EU = \frac{1}{n} \cdot \exp\left(-\sum p_i \ln(p_i)\right) \tag{1}$$

The metric hypothesized by Moreno (2010) to be most representative of human perception of luminance uniformity is U_{HVS}, uniformity based upon the human visual system. In Equations 2 and 3, k, α, β, and C are constants, ω_n is each individual spatial frequency present in the data, NU stands for non-uniformity metric (another term for CV), and NU_{HVS} is the non-uniformity based on the human visual system. NU_{HVS} weights the the Fourier transform of the luminance pattern $F(\omega_n)$ by the human visual contrast sensitivity function $CSF(\omega_n)$ and sums the results. It is then divided by the addition of a constant C added to the sum of the Fourier transform (the magnitudes of all spatial frequencies present in the data). A U_{HVS} value closer to 1 implies a more uniform pattern.

$$U_{HVS} = \frac{1}{1 + k \cdot NU^{\alpha} \cdot NU_{HVS}^{\beta}} \tag{2}$$

$$NU_{HVS} = \frac{\sum_n F(\omega_n) CSF(\omega_n)}{C + \sum_n F(\omega_n)} \tag{3}$$

$CSF(\omega_n)$ describes the human eye's sensitivity luminance contrast as a function of spatial frequency. Sensitivity increases up to about three cycles (spatial wavelengths) per degree in the visual field, and then decreases slowly to a low sensitivity at ten cycles per degree and higher (Moreno 2010). This means that although the presence of high frequencies may indicate a less uniform image with more drastic changes in luminance, the human eye requires greater contrast at these frequencies to be able to detect the changes. In future experiments, the ability of these metrics to represent human perception of luminance uniformity will be analyzed, while this paper focuses specifically on how varying HDRI procedures affect the calculation of these metrics for an example luminaire.

2 Methods

The DSLR camera selected for this test was a Canon 5D Mark II used with a 17-40mm zoom lens (maximum aperture f/4). The target luminaire aperture was that of a nominal 2'×2' luminaire containing an LED array and diffusing optical material. The luminaire (USLED, model GTR2-22-40-0) was operated via Power over Ethernet (PoE). It is dimmable and color-tunable, although the color-tunable properties were not utilized. The CCT used in this work was 4000 K, and the specified lumen value at full output was 4,250 lm.

Before images were captured of the luminaire optical material, a calibration plate was placed in front of the luminaire. The calibration plate was transparent aside from a labeled grid, which used to record the singular location near the center of the luminaire of three repeated spot luminance measurements (taken with a Konica Minolta LS-160 at 6' from the luminaire) and the camera center. It was used to focus the camera and was removed before the spot measurements and HDRI sequence of exposures were taken to avoid a falsely low reading caused by light blockage from the black lines making up the grid and text. The camera was placed such that the sensor was at the same distance and height as that of the luminance meter, and an image was taken of the calibration plate to both test for focus and have a reference for later calibration.

All images for the HDRI sequence were taken at an ISO of 100 and an aperture of f/11, 6' from the luminaire. An HDRI sequence was captured at three different output (luminance) levels, which was adjusted utilizing the manufacturer's interface; the actual output was not validated because the absolute values were not relevant to the tests. Level 1 was set to 100% output, Level 2 to 59% output, and Level 3 to 20% output. These levels were used to investigate if overall light level would affect the exposures needed to generate the optimal luminance data.

Fifty-two exposures were obtained for each of the three output levels, with the longest exposure at 15 seconds and shortest at 1/8000 of a second. The other 50 exposures were taken at shutter times between, as permitted by the camera. The images were recorded in both RAW and JPEG format. The JPEGs were only used for visual assessment by the researchers, and the RAW formats were used in calculation to avoid data loss that would be present in JPEGs due to compression inherent to the format.

A MATLAB script was written to iterate through LDR exposures and determine the longest and shortest exposures needed to fit the following pixel value criteria. The shortest exposure was chosen such that every pixel in the image had no RGB values greater than 228. The number 228 was chosen because it allowed for all the highest luminance pixels to be reliably captured by the camera sensor and avoided oversaturation and blooming. The longest exposure was chosen such that every pixel in the image had no RGB values less than 250. This value was chosen because it allowed for the lowest luminance pixels to be the only pixels that were not saturated, ensuring that minimum values were not lost.

A range of LDR exposure quantities (ranging from 2 to 16, referred to in the paper by "case" and appending a dash and the exposure quantity to the level number) were then chosen between the exposure limits from the total of 52 captured LDR images. HDR images were generated from these LDR images using the radiance-based program *raw2hdr* with the RAW images of the selected exposures.

A MATLAB script was written using Equation 7 to transform the RGB values of the HDR image into luminance, where L is luminance, and R, G, and B are the red, green, and blue saturation values, respectively (Jung et al. 2018).

$$L = 179 * (0.2127 * R + 0.7152 * G + 0.0722 * B) \quad (7)$$

The HDR image and the calibration images were cropped because the surrounding background was not needed, as only the uniformity of the luminaire optical material was within the scope of this investigation. The pixels that fell within the measurements by the spot luminance meter were isolated using the cropped calibration image, and the pixel values averaged. The three spot luminance measurements were all taken at the same location, and the values averaged to provide a more accurate value. The ratio of this spot luminance average to the related pixel average was determined, and the HDR image was calibrated by multiplying each pixel in the image by the ratio. The cropped and calibrated HDR image was then used to calculate the five different uniformity metrics detailed in Equations 1-6.

3 Results

Table 1 shows the number of LDR exposures used to generate an HDR image at each light output level. The cropped and calibrated HDR images for Cases 1-12, 2-12, and 3-12 are shown in Figure 1. The luminance is shown in false color, with the color scale determined by the range of luminance values in each image. Although the relative luminance patterns look similar, the absolute luminance values are very different, as shown by the accompanying scales.

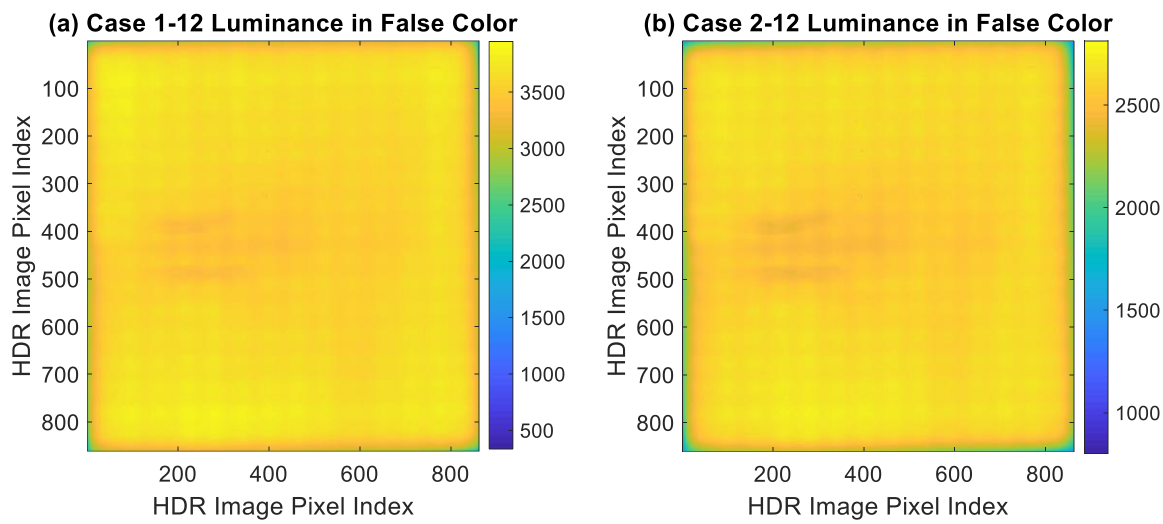
As seen in Figure 1, the luminance of the luminaire’s optical material matched the expected repeating pattern. Across tests at different levels, the relative HDRI patterns appear visually similar. This was expected, as the geometry of the luminaire did not change between levels. The calculated luminance uniformity measures, shown in Table 2 and Figure 2, varied with level and to some degree with number of exposures.

Table 1: Determining Low Dynamic Range (LDR) Exposure Limits for High Dynamic Range (HDR) Image Generation

Level	LDR Exposure Quantities for HDRI	Luminance measured by Luminance Meter [cd/m^2]	Shortest Exposure [s]	Longest Exposure [s]
1	2, 4, 6, 8, 10, 12, 14, 16	3,502	1/80	8/5
2	2, 4, 6, 8, 10, 12, 14, 16	2,540	1/60	5/2
3	2, 4, 6, 8, 10, 12, 14, 16	685	1/15	8

Table 2: Averages and Standard Deviations of Luminance Uniformity Metrics Across Exposure Quantities

Level	Averages Across Exposure Quantities					Percent Difference Across Exposure Quantities (%)				
	Max:Min	**Avg:Min**	**CV**	**EU**	**U_{HVS}**	**Max:Min**	**Avg:Min**	**CV**	**EU**	**U_{HVS}**
1	11.8281	10.6589	0.0476	0.9988	0.8670	4.6	4.1	10.5	0.02	1.3
2	3.5122	3.2015	0.0464	0.9989	0.8713	4.5	2.6	10.1	0.03	1.4
3	9.6837	8.7344	0.0475	0.9988	0.8690	6.8	5.7	8.2	0.02	1.0



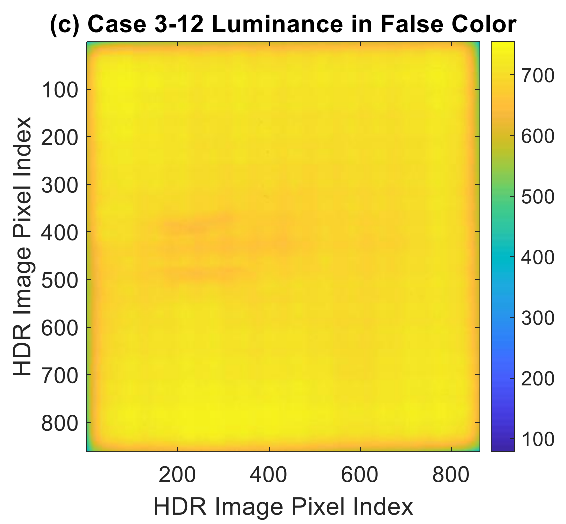


Figure 1: Luminaire luminance false color. (a), (b), and (c) correspond to the luminance measured by the high dynamic range (HDR) image generated from Cases 1-12, 2-12, and 3-12, respectively. Each HDR image was generated with 12 low dynamic range (LDR) exposures.

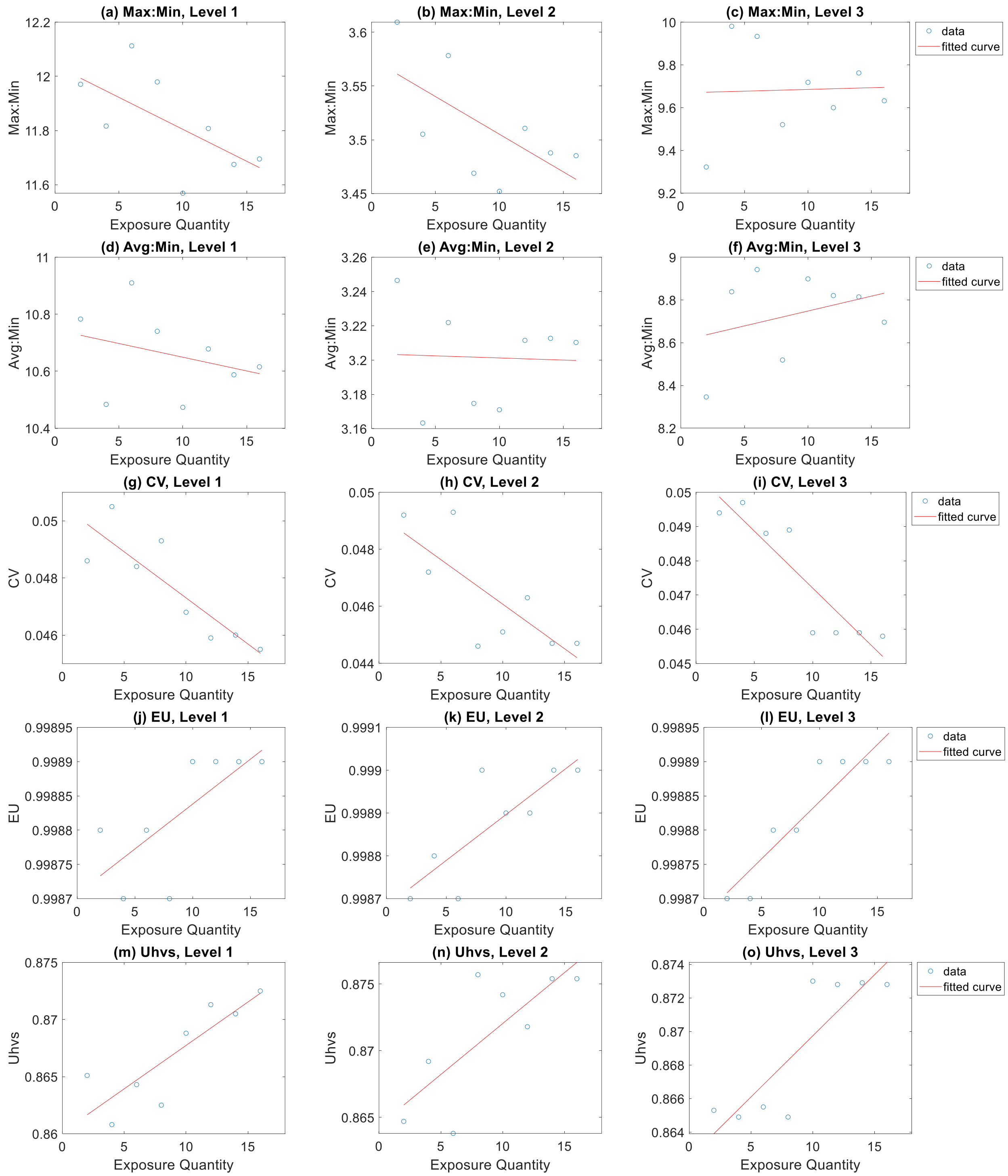


Figure 2. Luminance uniformity metrics calculated from HDR images generated from various exposure quantities. Each row of plots is a different metric, and each column is corresponding output levels. Note that the ranges of the y-axes are small, especially in (j), (k), and (l), which plot EU.

4 Discussion:

There are several important considerations to discuss that can inform recommended procedures for this application and recommended metrics for assessing luminaire luminance uniformity. First, the irregular areas of lower luminance on the left side of the luminaire were not caused by the LEDs but rather are a result of an aberration on the optical material diffusing the light. Given this aberration, some of the uniformity metrics responded to more than simply the regular pattern projected by the LED array.

Second, as seen in Figure 1, the edges of the luminaire were less luminous than areas within the extents of the LED array. By taking measurements with the DSLR camera, the array detection capabilities allowed these edge conditions to be considered. When calculating max:min, the minimum is therefore on the edge of the optical material. The resulting max:min value is hypothesized to understate the overall perceived luminance uniformity, as it weights the quantification towards a condition that only exists along the edge.

Max:min also is susceptible to errors in image cropping that could artificially inflate or deflate the ratio. For example, the luminaire used in this experiment was manufactured in such a way that the luminous area was not perfectly square to the outside dimensions. Therefore, despite efforts to crop the image so that the same area of the luminaire optical material was visible in each test level, the algorithm for cropping chose slightly different pixels in each test. For example, in Level 1, the area of the HDR image cropped was a few pixels above that of the other two levels, including a series of less luminous areas on the edge of the luminaire. The minimum luminance value was extracted from these edge conditions and caused the max:min ratio to inflate compared to that of the other levels, as seen in Table 2. By this same reasoning, avg:min was also inflated.

Figure 3 compares a cross section of each HDR image generated from the exposures taken in Level 3 by extracting corresponding rows of luminance values from the HDR images. The HDR images produced with fewer LDR exposures had more noise in the luminance values, although from a visual analysis, the noise reached a consistent minimum for HDR images produced with 10 exposures or more. As seen in Figure 2, using a higher quantity of exposures tended to alter the luminaire luminance uniformity metrics to indicate increased uniformity in CV, EU, and U_{HVS}. For these three metrics, the values associated with Level 3 tended to converge starting at exposures 10 and greater. This implies a correlation between the metric values and the visual assessment of noise in the HDR images, but further investigation is necessary to determine if it is a causal relationship. The quantity of exposures had varying effects on max:min and avg:min; the representation by the metrics of the luminaire luminance uniformity could either be inflated or deflated – there is no clear trend. As seen in Figure 2, the metrics indicate a trend to greater uniformity with an increase in exposures in Levels 1 and 2, while the opposite is true in Level 3.

The percent difference between the maximum and minimum values was calculated across uniformity metric data for each level to determine how much of a difference changing the quantity of exposures makes on the metrics. The effect on CV was the largest, but the values themselves are small enough in relation to the equation that the percent difference provides little issue. The effects on max:min and avg:min were the next largest, with the percent difference reaching 6.8% and 5.7% respectively. The effect was the smallest on EU, at a fairly consistent

0.02% and 0.03%. The HDRI luminance data supports the assertion that avg:min and max:min are not as reliable as other assessed metrics for luminance uniformity, as they are most affected by noise.

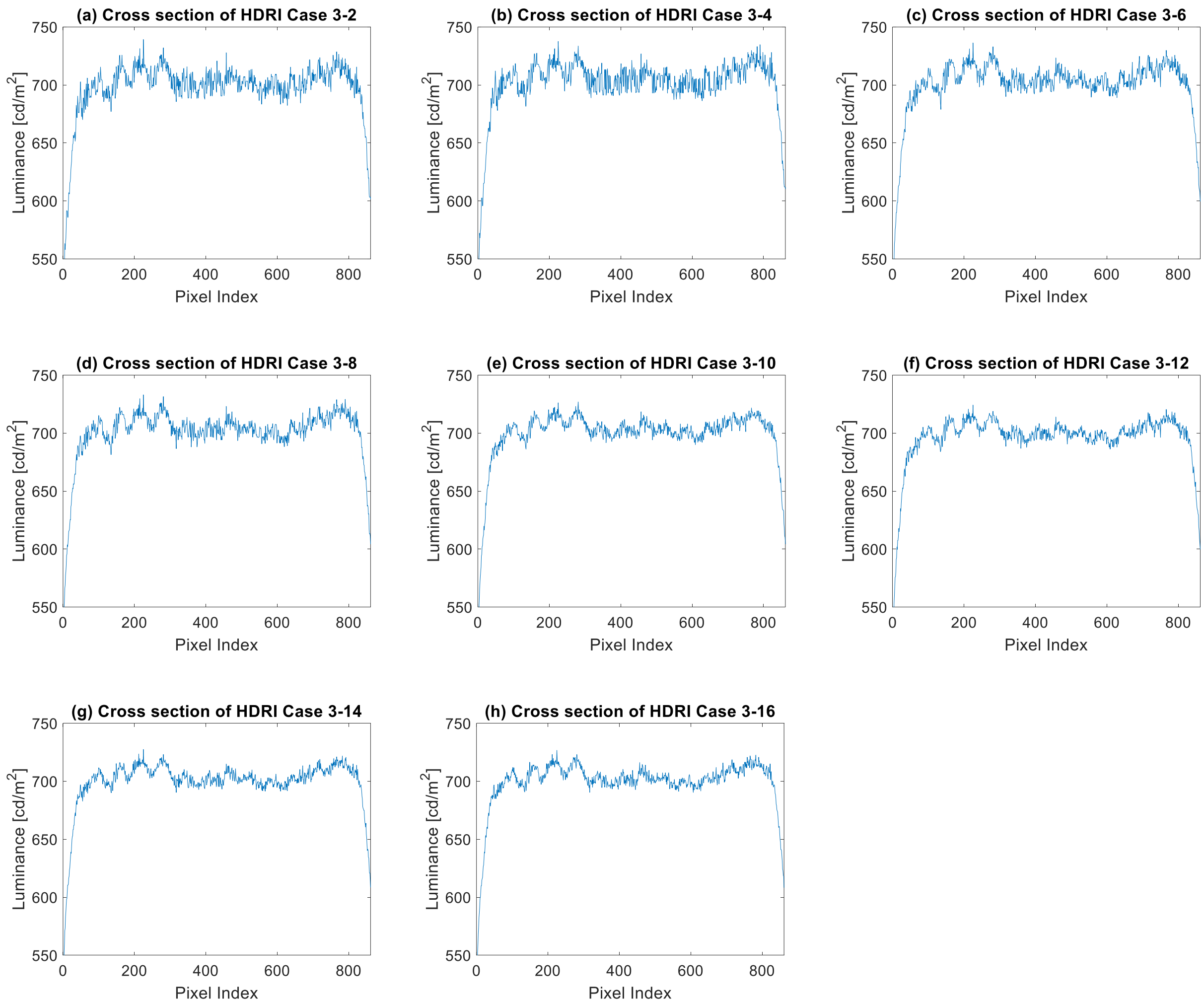


Figure 3. Noise effects of fewer exposures at Level 3. Corresponding rows of HDR images from Level 3 generated with different quantities of LDR exposures. The HDR image represented in (a) uses 2 LDR exposures, and each subsequent plot uses two more, until (h) uses a maximum quantity of 16. The y-axes are truncated to better illustrate the decrease in noise that results from using a higher quantity of exposures.

4.1 Limitations and Future Work

This work examined the effect of absolute light level and exposure quantity on luminance uniformity metrics calculated from HDR images of one luminaire. Evaluation of many more luminaires is necessary before a set of recommended procedures can be generalized.

This work was conducted in preparation for experimental work on human perception of uniformity using a newly designed apparatus (Feagin Jr. et al. 2020). This apparatus will allow for variable spatial luminance patterns to be created from a mock luminaire with an LED array backlighting interchangeable optical materials from various depths. It will also facilitate rapid imaging of the optical material with multiple types of meters, which will enable further work to refine procedures and recommendations for using HDRI to characterize the luminance uniformity of luminaire optical materials.

5 Conclusions

When using HDRI for luminance measurement of luminaire optical materials with a limited luminance range and high average luminance, it is suggested that LDR exposure limits need not be those defined by applications that vastly differ in luminance parameters. For this work, the LDR exposure limits were set such that the shortest exposure had all individual RGB values below 228, and the longest exposure had all individual RGB values above 250. This allowed for all pixels to be depicted in the HDR image at a reliable saturation point, at which no pixel was oversaturated. Future work comparing different exposure limits for this application is necessary before recommendations can be made.

For this example scenario, using a higher quantity of exposures resulted in less noise, which correlated with a convergence in metric values within CV, EU, and U_{HVS}. In this specific use-case, fewer than 15 exposures were necessary, as the luminaire luminance uniformity metric values tended to converge at a quantity of 10 or more exposures, which correlated with the point at which the noise effects on the luminance data appeared to reach a consistent minimum. Further investigation is necessary to determine if the relationship between noise and metric convergence is causal. Light level did not influence these results, although variations in image processing, which confounded with light level, substantially altered the max:min and avg:min characterizations. More work is needed to generalize these conclusions for practical use.

It was determined that in this scenario, max:min and avg:min were not reliable in HDRI analysis of the situation in which the average luminance is high and the luminance range is limited. More research is needed with human subjects to determine whether CV, EU, or U_{HVS} can provide a more accurate representation of human perception of luminaire luminance uniformity.

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