International Commission on Illumination
Commission Internationale de l'Eclairage
Internationale Beleuchtungskommission

OP89

COLORIMETRIC ACCURACY OF HIGH DYNAMIC RANGE IMAGES FOR LIGHTING RESEARCH

Coralie Cauwerts et al.

DOI 10.25039/x46.2019.OP89

from

CIE x046:2019

Proceedings
of the
29th CIE SESSION
Washington D.C., USA, June 14 – 22, 2019

(DOI 10.25039/x46.2019)

The paper has been presented at the 29th CIE Session, Washington D.C., USA, June 14-22, 2019. It has not been peer-reviewed by CIE.

CIE Central Bureau
Babenbergerstrasse 9
A-1010 Vienna
Austria
Tel.: +43 1 714 3187
e-mail: ciecb@cie.co.at
www.cie.co.at

COLORIMETRIC ACCURACY OF HIGH DYNAMIC RANGE IMAGES FOR LIGHTING RESEARCH

Cauwerts, C.[1], Jost, S.[2], Deroisy, B.[3]
[1] Université catholique de Louvain, Louvain-la-Neuve, BELGIUM,
[2] University of Lyon, ENTPE, LGCB, Vaulx-en-Velin, FRANCE,
[3] Belgian Building Research Institute, Brussels, BELGIUM

coralie.cauwerts@uclouvain.be

DOI 10.25039/x46.2019.OP89

Abstract

High Dynamic Range (HDR) imaging techniques are frequently used in lighting research for measuring luminance. The main objective of this work was to determine to what extent they can also be used for measuring colours. Three professional digital single-lens reflex cameras fitted with fisheye lenses were used for taking HDR pictures. The scene, containing a Macbeth chart and additional Munsell samples, was lit by a LED equi-energy spectrum source. The set of colour samples had first been characterized using a spectrophotometer. This article presents and compares two calibration methods, a conventional and an alternative one. It was demonstrated that the second method is necessary to achieve an acceptable colorimetric accuracy for lighting design of interior environments, and that it improves the luminance accuracy. The study also shows that one of the studied devices has higher accuracy performances.

Keywords: High Dynamic Range (HDR), colorimetric calibration, fisheye

1 Introduction

High Dynamic Range (HDR) imaging techniques are frequently used in lighting research for measuring luminance. Part of their success lies in the opportunity to capture quickly a large field of view. HDR images are created by combining multiple images with different exposures. Various merging algorithms and tools exist. In the lighting community, the most widely used tools take jpeg or raw files as input and produce HDR images stored in the Radiance RGBE format (.hdr) as output. The luminance of any pixel of these HDR camera-based images is then computed using the standardized sRGB to CIE-XYZ colour transformation matrix (IEC, 1999). The Y channel corresponds to the luminance. To ensure photometric accuracy, a luminance calibration factor is calculated for each scene as the ratio of the HDR luminance of a grey target to the luminance measured with a spot luminance meter. Previous works (Inanici, 2006, Cai and Chung, 2011) report average relative differences of luminance values of approximately 10% for coloured targets and 5% for grey surfaces under various lighting conditions. While this procedure ensures photometric calibration, it does not necessarily lead to colorimetric accuracy.

The objectives of this work are:

- Assessing what level of colorimetric accuracy is achievable with the conventional calibration method, for three digital cameras fitted with fisheye lenses;
- Testing alternative calibration methods to improve colorimetric accuracy.

2 Material and method

A Macbeth colour chart and 33 additional colour samples from the Munsell Book of Colour (see Fig.1) were placed in a booth lit either by a cool incandescent source (source_1) or by a LED equi-energy spectrum source (source_2). The correlated colour temperatures (CCT) of the sources were 5 050K and 5 400K respectively. The luminance range of the scene was 1 250:1 under source_1 and 520:1 under source_2. The horizontal illuminance in the booth, measured at floor level, was 750lx and 2 500lx respectively. Source_1 was chosen for calibration because of its continuous spectrum between 380 and 780nm and for the presence of energy in the blue part of the spectrum. Source_2 was used for validation purposes.

Figure 1 – Experimental set-up

The scene was captured with three cameras fitted with three fisheye lenses:

Canon EOS 5D Mark II fitted with a Sigma 8mm F3.5 EX DG fisheye lens (device_5Dfe8);

Canon EOS 40D fitted with a Sigma 4.5mm F2.8 EX DC fisheye lens (device_40Dfe45);

Canon EOS 50D fitted with a Sigma 4.5mm F2.8 EX DC fisheye lens (device_50Dfe45).

The cameras were mounted on a tripod. For minimizing vignetting effect (Cauwerts et al., 2012), aperture was set to f/16 for the 5Dfe8 device and to f/10 for the two other devices. Colour samples were placed in the centre of the picture where the effect is negligible. The camera sensitivity setting was fixed to ISO 100. Shutter speed bracketing was performed for 1-stop increments. Pictures were taken in raw format and the multiple exposure images were combined using *raw2hdr* Perl scripts under Linux (Ward, 2011). Floating point RGB values after exposure compensation were extracted from the HDR file using the Matlab *hdrread* program, and were then corrected with the exposure value extracted from the header with the Matlab *textscan* program (MathWorks, 2017). The reference CIE XYZ coordinates were measured with a Jeti Specbos 1211UV Spectroradiometer calibrated less than two months prior the study.

2.1 Calibration

Two colour transform matrices were investigated for computing CIE XYZ coordinates from camera-based images (see Eq.1).

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = M \times \begin{bmatrix} R \\ G \\ B \end{bmatrix} \tag{1}$$

where

R, G, B are linear sRGB values before exposure compensation retrieved from HDR picture;

X, Y, Z are CIE 1931 XYZ values;

M is either the standardized sRGB to CIE-XYZ colour transform matrix (method_1, see Eq.2) or a colour transform matrix determined by minimizing the least square error in the XYZ colour space i.e. the error between values retrieved from HDR photography and CIE XYZ values that are physically measured with the spectroradiometer (method_2, Eq.3).

$$M1 = \begin{bmatrix} 0{,}4124 & 0{,}3576 & 0{,}1805 \\ 0{,}2126 & 0{,}7152 & 0{,}0722 \\ 0{,}0193 & 0{,}1192 & 0{,}9505 \end{bmatrix} \tag{2}$$

$$M2 = \left(\left(RGB^t \ RGB \right)^{-1} \ RGB^t \ XYZ \right) \tag{3}$$

where

RGB	is a 18-by-3 matrix containing the linear RGB values of the 18 colour patches of the Macbeth chart lit by source_1 extracted from the HDR file;
XYZ	is a 18-by-3 matrix with the CIE XYZ values of the same colour samples lit by the same light source measured with the spectroradiometer.

Both conversion methods were followed by an adjustment either by a single calibration factor (method_1a and method_2a, see Eq.4) or a triplet of re-scaling values (method_1b and method_2b, see Eq.5). Calibration factors were determined using a grey target (Macbeth chart, patch #22, Neutral 5, reflectance=19,8%). Method_1a (sRGB matrix followed by a photometric calibration) is the method which is mostly used in lighting research when working with HDR pictures.

$$\begin{bmatrix} X_{adj} \\ Y_{adj} \\ Z_{adj} \end{bmatrix} = \frac{Y_{grey,spectro}}{Y_{grey,HDR}} \times \begin{bmatrix} X_{HDR} \\ Y_{HDR} \\ Z_{HDR} \end{bmatrix} \quad (4)$$

where

X_HDR, Y_HDR, Z_HDR	are XYZ values retrieved from HDR picture, before adjustment;
$Y\_grey,spectro$	is the luminance of the grey target measured with the spectroradiometer;
Y_grey,HDR	is the luminance of the grey target retrieved from HDR picture, before adjustment;
X_adj, Y_adj, Z_adj	are calibrated XYZ values.

$$\begin{cases} X_{adj} = \frac{X_{grey,spectro}}{X_{grey,HDR}} \times X_{HDR} \\ Y_{adj} = \frac{Y_{grey,spectro}}{Y_{grey,HDR}} \times Y_{HDR} \\ Z_{adj} = \frac{Z_{grey,spectro}}{Z_{grey,HDR}} \times Z_{HDR} \end{cases} \quad (5)$$

where

X_HDR, Y_HDR, Z_HDR	are XYZ values retrieved from HDR picture, before adjustment;
$X, Y, Z\_grey,spectro$	are tristimulus values of the grey target measured with the spectroradiometer;
X, Y, Z_grey,HDR	are tristimulus values of the grey target retrieved from HDR picture, before adjustment;
X_adj, Y_adj, Z_adj	are calibrated XYZ values.

2.2 Accuracy assessment

Accuracy of photometric and colorimetric data retrieved from HDR photography was assessed using the complete set of colour samples (57 patches) lit by the LED source (source_2).

To quantify the error between luminance retrieved from HDR pictures and luminance captured with the spectroradiometer, the mean absolute percentage error (MAPE) was calculated with respect to the luminance measured with the spectroradiometer (see Eq.6).

$$\mathrm{MAPE_{lum}} = \frac{100}{\mathrm{n}} \sum_{\mathrm{i=1}}^{\mathrm{n}} \left| \frac{\mathrm{Y_{i,HDR}} - \mathrm{Y_{i,spectro}}}{\mathrm{Y_{i,spectro}}} \right| (\%) \quad (6)$$

where

$MAPE\_lum$	is the mean absolute percentage error;
n	is the number of colour samples;
Y_i,HDR	is the luminance of the colour sample i retrieved from HDR picture;
$Y\_i,spectro$	is the luminance of the colour sample i measured with the spectroradiometer.

Based on the literature (Inanici, 2006, Cai and Chung, 2011), within the studied luminance range [10-400cd/m²], luminance errors are expected to be below 10% with peak values reaching up to 20% or exceptionally more.

For assessing colorimetric accuracy, colour differences were calculated in the CIE 1976 L*a*b* Colour Space (ISO/CIE, 2008). Spectroradiometer measurements were used as the reference. While it is recognized in the literature that perceptibility and acceptability of colour difference vary with the application, few data are available regarding colour difference thresholds. In the present study, we fixed the following thresholds based on the works by Mokrzycki and Tatol (2011) and by Meyer (1988) cited in (Finlayson et al., 2004): mean ΔE_{ab}^{*} < 3,5 units (threshold between a noticeable and a clear colour difference) and max ΔE_{ab}^{*} < 6 units (perceptibility threshold of colour difference in complex images). For comparison with the literature (Varghese et al., 2014, Kim and Kautz, 2008), mean, median and maximum CIEDE2000 (CIE, 2018) were also calculated.

NOTE The tristimulus values of the white reference measured with the spectroradiometer was used as the reference for calculating L*a*b* values.

3 Results

3.1 Photometric accuracy

Figure 2 illustrates the relative differences between the luminance value extracted from the HDR image (for each device), and the luminance measured with the spectroradiometer (57 colour samples). The conventional calibration model (method_1a/b) leads to the expected luminance accuracy for the three tested devices.

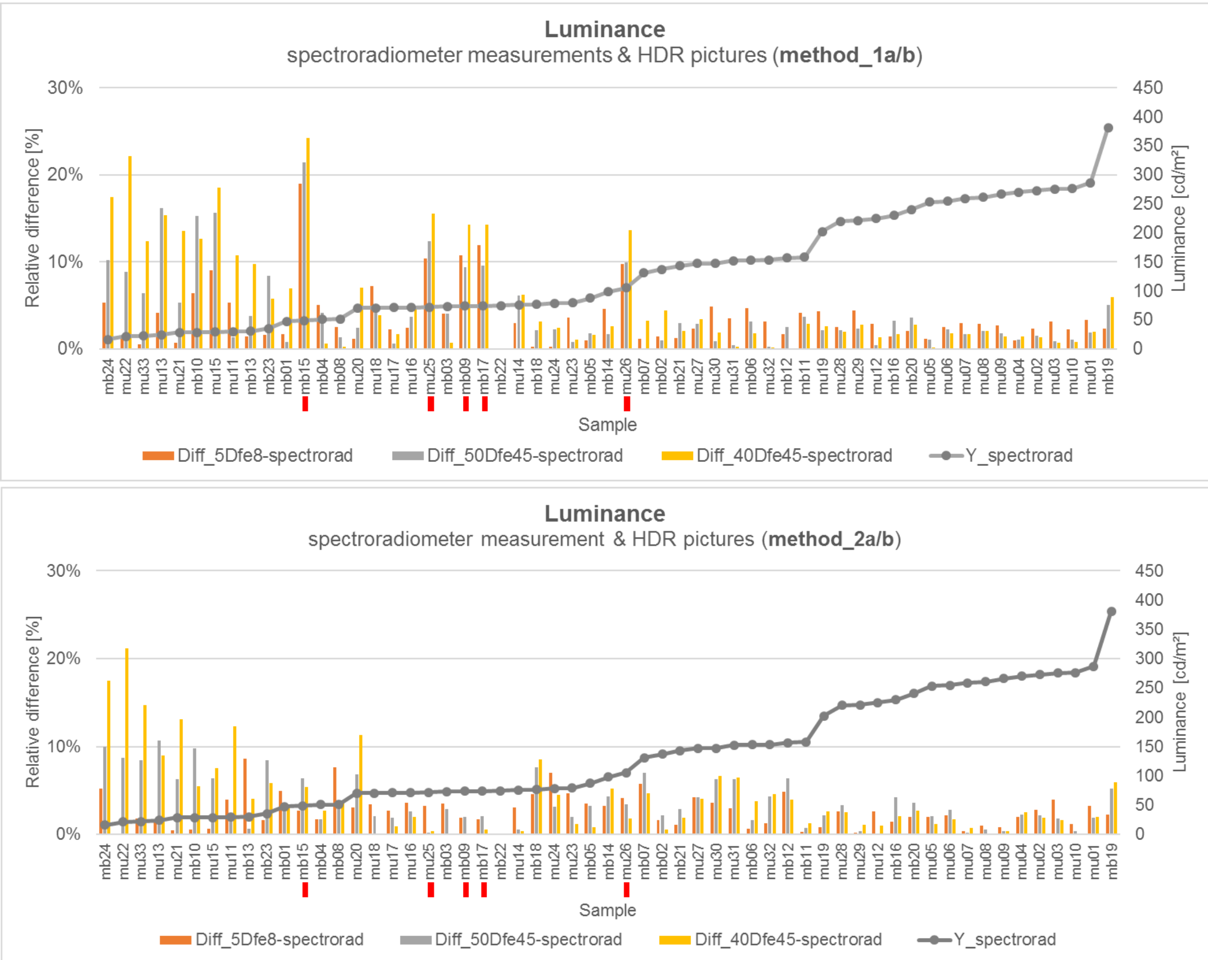

Figure 2 – Relative differences between luminance values taken with the three devices using conventional calibration method (top) and alternative calibration method (bottom).

We observed an average relative difference of luminance (57 samples, source_2) of 5,5% for the 40Dfe45 device, 4,2% for 50Dfe45 and 3,6% for 5Dfe8. Large discrepancies are observed on red samples (mb15, mu25, mb09, mb17, mu26) whatever the device. Relative errors on darkest samples are larger than 10% with the 40Dfe45 device; they are also large with the 50Dfe45 device. The alternative calibration model reduces the average relative difference of luminance. We obtained 4,1%, 3,6% and 2,7% for the 40Dfe45, 50Dfe45 and 5Dfe8 devices respectively. We noted that relative errors are below 11% for all samples captured with 50Dfe45 and 5Dfe8. Relative errors observed on red samples are reduced. Large discrepancies are still observed on dark samples with the 40Dfe45 device.

3.2 Colorimetric accuracy

Colour differences computed for the three devices, in CIELAB, are given in Table 1. With the standardized sRGB to CIE-XYZ colour transform matrix (method_1), whatever the adjustment method (a or b), none of the tested devices fulfils the requirements we fixed above for mean and maximum (see Section 2.2). With method_2a it is possible not to exceed the thresholds we set, but only when the samples are captured with the 5Dfe8 device. With method_2b, all devices meet our acceptability criteria for colorimetric accuracy.

Table 1 – Colour difference (ΔE^*_{ab}), by device and calibration method. Values are mean +/- standard deviation (maximum). Bold values fulfil our requirements.

	40Dfe45	50Dfe45	5Dfe8
method_1a	5,4+/-2,3 (11,6)	3,8+/-2,3 (9,7)	4,0+/-1.6 (7,9)
method_1b	4,0+/-2,7 (10,6)	3,6+/-2,6 (11,2)	3,1+/-2.2 (8,1)
method_2a	3,2+/-1,2 (6,6)	3,1+/-1,2 (7,4)	**2,0+/-0.8 (4,3)**
method_2b	**1,9+/-1,4 (5,9)**	**1,7+/-1,1 (5,7)**	**1,7+/-0.9 (4,3)**

For comparison with the values given in the literature, CIEDE2000 were computed for method_2b (see Table 2). The values obtained are in the same range or even lower than those observed in previous works. These works assess HDR pictures taken with cameras fitted with traditional lenses and calibrated with a matrix determined either in minimizing XYZ values similarly to what we did (Kim and Kautz, 2008) or in minimizing CIEDE2000 (Varghese et al., 2014).

Table 2 – CIEDE2000, by device, for method_2b. Values are mean; median (maximum).

	40Dfe45	50Dfe45	5Dfe8
method_2b	1,2; 1,0 (2,9)	1,3; 1,2 (3,1)	1,3; 1,2 (2,4)

4 Conclusions and further work

Previous works validated HDR photography for luminance measurement within 10% accuracy and with peak errors up to 20% or even more. These works use the standardized sRGB to CIE-XYZ colour transform matrix followed by a photometric adjustment (method_1a) for calibrating the HDR data.

The first objective of the present study was to evaluate the level of colorimetric accuracy achievable with this conventional calibration method, and fisheye lenses. Colorimetric accuracy is, in the present work, assessed through the computation of colour differences in CIELAB on 57 colour samples (a Macbeth chart and additional Munsell samples) lit by a LED equi-energy spectrum source. Luminance values of the samples are between 10 and 400cd/m². The second objective of the work was to investigate alternative calibration methods. We tested an adjustment by channel, similarly to what is done in Jung et al. (2018). We also tested the advantage of using a colour transform matrix specifically determined for each camera by minimizing the least square error in the XYZ colour space, similarly to the work of Kim and Kautz (2008). For determining the colour transform matrices, we used the 18 colour samples of a Macbeth chart lit by a cool incandescent source. Three professional digital single-lens reflex (DSLR) cameras fitted with fisheye lenses were studied.

The present study shows that in comparison to the conventional method (method_1a), using a colour matrix specifically determined for each camera to transform RGB values to XYZ triplet (method_2a/b) improves the luminance accuracy and makes it possible to reduce the large relative differences of luminance observed on red samples. Errors on red samples are indeed between 9 and 24% with method_1 and, between 0.2 and 6% with method_2. Moreover, using a colour matrix specifically determined for each camera is necessary to meet the acceptability criteria for colorimetric accuracy we fixed (mean ΔE^*_{ab} < 3,5 and max ΔE^*_{ab} < 6).

Among the three devices we tested, the Canon EOS 5D Mark II fitted with a Sigma 8mm F3.5 EX DG fisheye lens presents the best performances for both photometric and colorimetric accuracy. It is also the only device among the three we tested to achieve the requested level of colorimetric accuracy with calibration method 2a. This means that if a user knows the specific colour transform of his device, he does not need to have a chromameter in the field. Indeed, a (il)luminance meter will be sufficient for determining the single calibration factor required for adjusting data.

The general light scattering in the lens and sensor mentioned by McCann et al. (2017) and Inanici (2006) could be the reason for large luminance errors observed on dark samples. The quality of optics and sensors could explain the differences we observed between devices.

Validation should be pursued with various light levels, spectra and sets of colour samples, both in controlled laboratory environments and in real world. It should also be checked if the colour transform matrix determined for one device (a camera and an associated lens) can be used for calibrating similar photographic material (same brand and same model).

Acknowledgements

This work was partially supported by the Belgian Fund for Scientific Research (FNRS) through the postdoctoral fellowship of Coralie Cauwerts.

References

CAI, H. & CHUNG, T. 2011. Improving the quality of high dynamic range images. *Lighting Research and Technology,* 43**,** 87.

CAUWERTS, C., BODART, M. & DENEYER, A. 2012. Comparison of the Vignetting Effects of Two Identical Fisheye Lenses. *LEUKOS The Journal of the Illuminating Engineering Society of North America,* 8**,** 181-203.

CIE 2018. CIE 15:2018 Colorimetry. 4th ed. Vienna: CIE.

FINLAYSON, G. D., HORDLEY, S. D. & MOROVIC, P. 2004. Using the spectracube to build a multispectral image database. *Conference on Colour in Graphics, Imaging, and Vision, Society for Imaging Science and Technology, Aachen, Germany***,** 268-274.

IEC 1999. IEC 61966-2-1: Multimedia Systems and Equipment-Colour Measurement and Management-Part 2-1: Colour management-Default RGB Colour Space-sRGB. Geneva: IEC.

INANICI, M. 2006. Evaluation of high dynamic range photography as a luminance data acquisition system. *Lighting Research and Technology,* 38**,** 123-136.

ISO/CIE 2008. ISO 11664-4:2008/CIE S 014-4:2007 Colorimetry – Part 4: CIE 1976 L*a*b* Colour Space. Vienna: CIE.

JUNG, B. & INANICI, M. 2018. Measuring circadian lighting through high dynamic range photography. *Lighting Research & Technology***,** doi: 10.1177/1477153518792597.

KIM, M. H. & KAUTZ, J. 2008. Characterization for High Dynamic Range Imaging. *Computer Graphics Forum,* 27**,** 691-697.

MATHWORKS 2017. MATLAB Release 2017a. The MathWorks Inc., Natick, MA.

MCCANN, J. J., VONIKAKIS, V. & RIZZI, A. HDR Scene Capture and Appearance. 2017. Society of Photo-Optical Instrumentation Engineers (SPIE).

MEYER, G. W. 1988. Wavelength selection for synthetic image generation. *Computer Vision, Graphics, and Image Processing,* 41**,** 57-79.

MOKRZYCKI, W. & TATOL, M. 2011. Color difference Delta E - A survey. *Machine Graphics and Vision,* 20**,** 383-411.

VARGHESE, D., WANAT, R. & MANTIUK, R. 2014. Colorimetric calibration of high dynamic range images with a ColorChecker chart. *Proceedings of HDRi 2014, Second International Conference and SME Workshop on HDR imaging, Sarajevo, Bosnia and Herzegovina***,** 17-22.

WARD, G. 2011. *raw2hdr Perl script* [Online]. Available: http://www.anyhere.com/gward/pickup/raw2hdr.tgz [Accessed 24th April 2019].