Tristimulus Color Accuracy in Image-based Sky Models: Simulating the Impact of Sky Spectra on Daylit Interiors

Mehlika Inanici¹

¹University of Washington, Department of Architecture, Seattle, WA, USA.

Abstract

Spectral properties of daylight surpasses any other light source. Its dynamic intensity and spectra across the full spectrum facilitates sustainable daylighting practices, produces best color rendition, and regulates circadian rhythms in all living beings. However, simulation models do not typically include spectral variability; daylight is modelled as a uniform, equal energy white source. In this paper, tristimulus calibration procedures are utilized to create spectrally accurate High Dynamic Range (HDR) photographs. HDR photographs of skies are collected and utilized as an input to image based lighting (IBL) simulations. The impact of color variations across the sky dome and between different sky conditions are studied. Per-pixel photopic luminances, tri-stimulus chromatic distributions, Correlated Color Temperatures (CCT) and circadian luminance and illuminance values are quantified for image-based daylighting simulations, and compared with standard colorless Perez skies.

Introduction

Color content of the indoor light is important to evaluate the color appearance, perceptual and aesthetic considerations, circadian lighting, and plant (horticulture) lighting. Daylight availability and luminance variability across the sky have long been measured and simulated. However, spectral content and its distribution is not well known.

Photopic lighting units and measurement devices are based on the CIE 1924 Standard Observer response curve, $V(\lambda)$. It is the spectral efficacy for photopic vision in human beings (Wyzecki and Stiles, 2000). Although CIE Standard Colorimetric Observer (XYZ) was adopted in 1931 for color and heterochromatic brightness matching properties in human beings, daylight metrics and simulations (luminance and illuminance calculations) singularly focus on CIE Y, which is the CIE 1924 Standard Photopic Observer.

The recent studies in non-visual (circadian) responses of light and the photobiological interactions in plants (photosynthesis, circadian and circannual rhythms) point to a need for simulating spectral properties of light beyond human visual responses. Photopic and circadian measurement units are derived from 380 to 780 nm range in the electromagnetic radiation. While the photopic response ($V(\lambda)$) is most sensitive at 555 nm (green region), circadian response favours the blue rich light at

480 nm (Lucas et al., 2014). The action spectra for plant photosynthesis is different from human visual and non-visual responses (ANSI/ASABE, 2017). It extends beyond the human range and favours both the blue and red regions of spectra. Therefore, it is necessary to augment the current simulation practices with the ability to generate spectrally accurate raw data to study the impact of lighting on human visual and non-visual systems along with plant photosynthesis.

One of the major obstacles is the lack of quantitative data on the color distributions across the sky dome. The simulated models typically treat daylight as equal energy white source. CIE and Perez sky models in Radiance software (Ward, 1999) are modelled with RGB values of (1, 1, 1), which yields to a sky and sun with the Correlated Color Temperatures (CCT) of 5,453 K. This is close to the generalized classification that “daylight with sunlight present at noon” typically produces around 5,000- 5,500 K (Lechner, 2014). Overcast skies are reported to typically have CCT of 7,000 K and blue skies in summer range between 10,000 to 25,000 K. Yet, even when the color of the sky is considered, 6500 K is assumed to approximate daylight, and the spectra of the sky dome is modelled as uniform.

There are very few spectral measurements of the skies around the world. These measurements are usually limited to global horizontal CCT measurements in Kelvin (Chain et al., 1999; Hernandez-Andres et al., 2001). One of the significant CCT data collection studies includes 2,600 daylight spectra measured in a two-year period in Granada, Spain (Hernandez-Andres et al., 2001). The dominant CCT value for this location was 5,700 K, but the data clearly affirms a wide variation between 3,758 K and 34,573 K.

More recently, affordable hand held spectrophotometers facilitate the measurement of global horizontal spectra in $W/m^2/nm$, but these measurements are sporadic at best. Even scarcer, is the variability of spectra across the sky dome as typical sky scanners do not include narrow field spectrophotometers. 145 patch sky spectra measurements are collected in one location (Knoop et al., 2014). Other researchers focus on developing spectral photographing methodologies. Efforts include scanned fish-eye photographs (low dynamic range (LDR) images) of the sky and color-calibration with cards of known spectral power distributions (Hernandez-Andres et al., 2003) or digital LDR images calibrated with broadband color

filters (Nieves et al., 2005; Uetani, 2014); the results are useful for reporting relative chromaticities and luminances.

High Dynamic Range (HDR) image-based skies have been used to simulate indoor and outdoor scenes with naturally occurring conditions (Inanici, 2010; Inanici and Hashemloo, 2017). However, previous work focused on luminance distributions rather than the color accuracy.

Analytical models (Bird and Riordan, 1986; Lee and Hernandez-Andres, 2005) provide simulations for clear or overcast skies, leaving out any other sky type. Computer graphics models include Preetham et al. (1999), Hosek and Wilkie (2012), and Kider et al. (2014). Two recent circadian simulation software allow for multi spectral simulations (Lark, 2015 and ALFA, 2018). Lark simulates uniformly colored skies based on global horizontal CCTs, and ALFA simulates the spectra of the sun and the sky using U.S. Air Force Geophysics Laboratory's atmospheric constitute profiles. A comparison study has been performed (Balakrishnan, 2018), but the validation of these theoretical models are difficult, as long-term measurements are scarce.

The objectives of this paper are:

- i) To demonstrate the tri-stimulus calibration of HDR images to achieve color accuracy: Absolute per-pixel luminances, tri-stimulus chromatic distributions, CCTs, and circadian luminance and illuminance values can be accurately derived from color calibrated imagery.
- ii) To analyse sky images to provide an empirical and accessible methodology to study the color variation across the sky dome; and
- iii) To quantify color based metrics for indoor simulations using image-based skies, and to compare them with the standard colorless Perez skies.

Methodology

High Dynamic Range Sky Imagery

Measuring and simulating spectra at each wavelength is generally expensive. In many practical applications, colorimetric measurements are done in three-dimensional (sRGB or XYZ) color space. The methodology presented here demonstrates a practical workflow to incorporate tri-stimulus calibration of HDR images.

Two different categories of data have been collected. Long-term data are captured with HDR images of the sky dome between December to June, on one day of the month in hourly intervals.

It is important to note that intensity and spectra of daylight reaching the eye is dependent not only on the sky, but on the reflections from the surrounding surfaces. Daylighting in urban settings is a product of i) the variability of the intensity and the spectra of the sun and the sky (as a function of location, position of the sun, weather, cloud cover, turbidity, and seasonal variations), and ii) the reflections and shadows from the surrounding (as a function of urban density, spectra and reflectivity of urban fabric, vegetation, and terrain). As the second category, four sets of sky models have been captured along with

accompanying four vertical orientation imagery. The HDR images of the sky dome and four vertical orientations (with 90° increments) are collected in a successive manner using a Canon EOS 5D fitted with a Sigma 8mm F3.5 EXDG fisheye lens.

Standard capturing practices were followed with an aperture size of f/11, white balance of daylight and ISO of 100. Luminance variations are captured by changing the shutter speed [15 – 1/8000s]. As each capture can be completed under a 2-minute period, all five images were captured under a 10-minute duration. A sixth HDR image (of the sky) is taken to confirm that the sky conditions did not change significantly between the first and last image capture.

Each series of multiple exposure photographs are accompanied with two scientific grade measurements at the camera lens level: Konica Minolta LS-110 Luminance is used to measure the luminance meter of a grey scale card from the position of the camera lens. An UPRtek MK350S Spectrophotometer was placed on the camera lens, horizontal for sky measurements and vertical for the other scenes, to align with the same view as the 180° fisheye lens. The spectrophotometer measurements included CIE human tristimulus values (CIE XYZ), CCT, and normalized spectral power distributions between 380 – 780nm at 1nm intervals.

Sigma fisheye lens exhibits a projection that is similar to an equidistant projection up to 60° from the center and diverges towards an equisolid angle between 60° and 90°. This aberration was corrected using a python code so that the images exhibit an equidistant projection.

Each series of exposures were merged into HDR image using Photosphere (Ward 2005). The post processing procedures include i) vignetting correction for the aperture of f/11; ii) luminance calibration based on a grey scale card in the scene for vertical scenes; iii) direct and diffuse irradiance/illuminance calibration for sky images; iv) luminous overflow correction based on global illuminance measurements; and v) tristimulus color calibration using CIE XYZ measurements.

A number of previous publications focus on standard capturing practices and post-processing operations (such as vignetting corrections, luminance and illuminance calibrations, and overflow corrections); and they are understood and accepted as best practices (Inanici 2006, Jakubiec et al., 2016a, b). However, tristimulus color (CIE XYZ) calibrations is a recent research focus and it deserves further discussion here.

Tristimulus Color Calibration

The color space in digital photography is the standard RGB space (sRGB) with CIE standard illuminant D65 (IEC, 1999). The reference primaries (x,y) for the sRGB channels and CIE standard illuminant D65 are (0.64, 0.33), (0.3, 0.6), (0.15, 0.06), and (0.3127, 0.329) respectively. Using these primaries, RGB values can be used to calculate the XYZ values (1) (Glassner, 1995).

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.4124 & 0.3576 & 0.1805 \\ 0.2127 & 0.7152 & 0.0722 \\ 0.0193 & 0.1192 & 0.9505 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} \quad (1)$$

Radiance software has a different color system. The reference primaries (x,y) for the RGB channels differ minimally (0.64, 0.33), (0.29, 0.6), (0.15, 0.06) from the sRGB primaries, but the standard light source is defined as equal energy white (0.33, 0.33). Equation (2) shows the linear transformations of Radiance RGB values to XYZ. RGB to XYZ transformations are performed at a per-pixel scale.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.5142 & 0.3239 & 0.1620 \\ 0.2651 & 0.6701 & 0.0648 \\ 0.021 & 0.1228 & 0.8530 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} \quad (2)$$

The illuminance meters and spectrophotometers are cosine corrected devices. Figure 1 demonstrates the difference between the equidistant projection and cosine corrected hemispherical fisheye projection. The fisheye images collected in this study align with an equidistant projection after corrected for geometric aberrations. Scientific grade illuminance meters and spectrophotometers collect data through a hemispherical projection.

Hemispherical projection follows the cosine law. Averaging the luminance of pixels in a cosine corrected imagery and multiplying it with Π yields to the resulting illuminance from the hemispherical light source.

Figure 1: Equidistant and hemispherical (cosine corrected) projections

If the per-pixel values in a cosine corrected HDR photograph are processed with $(179 \cdot (0.2127 \cdot R + 0.7126 \cdot G + 0.0722 \cdot B))$, multiplying the average pixel values (luminance in cd/m^2) in the circular fisheye region with Π yields to illuminance (CIE Y) in lux (1). Similarly, processing pixel values with $(179 \cdot (0.4124 \cdot R + 0.3576 \cdot G + 0.1805 \cdot B))$ and multiplying average pixel values with Π , yields to CIE X. Average pixel values processed with $(179 \cdot (0.0193 \cdot R + 0.1192 \cdot G + 0.9505 \cdot B))$ and multiplied with Π , yields to CIE Z. If the color calibration of the camera is accurate, the tristimulus values derived from these HDR images will match to the measured tristimulus values of the spectrophotometer.

A recent research (Jung and Inanici, 2018) demonstrate the calibration procedures with HDR imagery to capture spectrally accurate data. This research focuses on developing a tristimulus calibration functions for a given camera. Following the same methodology, a database of HDR images are utilized to compare the CIE XYZ data derived from HDR images and the measured values. Three channels in HDR images have consistent color aberrations, which make it possible to correct for them. Since luminance and illuminance calibrations are

performed in HDR photographs prior to color calibration, derived CIE Y values match the spectrophotometer measured Y channel. However, CIE X is typically underestimated and CIE Z is overestimated. Following the reverse transformation equation from XYZ to RGB (3), correction factors are derived for each channel of RGB color space of the camera through a regression analysis. Derived color calibrations are camera specific, therefore, they can be reliably utilized for any image taken with that camera. The camera color calibrations are derived using this methodology for the camera used in this research, and applied to long term sky data. Camera calibration in this method yields to average errors of 10%.

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 3.2406 & -1.5372 & -0.4986 \\ -0.9689 & 1.8758 & 0.0415 \\ 0.0557 & -0.2040 & 1.0570 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \quad (3)$$

For the second category of data with sky and vertical images, CIE XYZ values were measured in situ. Each HDR image is further calibrated and fine-tuned to keep errors within 1% error margin.

CCT

CCT values are measured in-situ with the spectrophotometer at the position of the axis of the fisheye lens. CCT values from the HDR imagery have been calculated using the McCamy (1992) method at a per-pixel scale (3-6). As the HDR images are color corrected, the spectrophotometer measured and color calibrated CCT values align, as they should.

$$x = \frac{X}{X+Y+Z} \quad (3)$$

$$y = \frac{Y}{X+Y+Z} \quad (4)$$

$$n = \frac{x-0.3320}{y-0.1858} \quad (5)$$

$$CCT = 437n^3 + 3601n^2 - 6861n + 5514.31 \quad (6)$$

Equivalent Melanopic Lux (EM.Lx)

The human ocular system facilitates vision and regulates circadian rhythms (i.e. synchronizes the internal body clock with the local time). The photoreceptors and neural pathways are different for these two mechanisms. As a result, their computation methods are different. CIE XYZ defines the spectral efficiency for the visual response. There is not a standardized circadian efficiency function yet. However, the melanopic curve (Enezi et al. 2011) that is scaled to match the photopic curve (Lucas et al. 2014) is the most commonly used circadian metric and its unit is Equivalent Melanopic Lux (EM.Lx).

For sRGB color space, melanopic curve yields to RGB coefficients as seen in (7) (Jung and Inanici, 2018). In a cosine corrected, color calibrated HDR imagery, the per-pixel values are processed with equation (7), and multiplying the average pixel values with Π , yields to Equivalent Melanopic Lux (EM.Lx). The pixel values are Equivalent Melanopic cd/m^2 (EM.cd/m²). Radiance RGB values can be used to calculate EM.Lx as shown in (8).

$$\begin{aligned} EML_{sRGB} &= \\ 179 * (0.0013 * R + 0.3812 * G + 0.6175 * B) & \quad (7) \\ EML_{RadRGB} &= \end{aligned}$$

$$179 * (0.0023 * R + 0.3911 * G + 0.6066 * B) \quad (8)$$

Tristimulus Analysis of HDR Sky Models

Six sky images are selected to demonstrate significant spectral variability across different skies, and within each sky dome (Figure 2). For each set, false color legends show per-pixel variations (cd/m^2 for photopic luminance, Kelvin for CCT, and EM.cd/m^2 for circadian luminance). The global horizontal photopic illuminance, CCT values, and EM.Lx are derived from the HDR photographs. The advantage of HDR image skies is that color variations across the sky dome can be easily studied through the CCT maps. Although a previous research (Chain et al., 1999) suggest that high luminance values of sky correspond to low CCTs, and low luminance values correspond to high CCTs, both the HDR measurements and the spectrophotometer measurements done for this research do not always support this proposition.

The sky in Set 1 (Figure 2.a) is taken in May at 9:00 under cloudy sky conditions. Global horizontal measurement is 16,111 Lx. The CCT is low at 4,797 K. The circadian stimulus is lower than the photopic illuminance at 11,820 EM.Lx. This is expected, as a low CCT point to a blue

deficient sky spectra. Under mostly cloudy sky conditions, the color variation across the sky dome is not significant. Orientation does not create luminance variations under overcast skies, as the sky luminance is symmetric on a plan view. A similar pattern is observed with the spectra.

The sky in Set 2 (Figure 2.b) is taken on the same day at 16:45 under partly cloudy sky conditions. The global horizontal illuminance is quite high at 90,536 Lx, and CCT is 5,630 K. The circadian stimulus is lower than the photopic illuminance at 64,085 EM.Lx. In general, the EM.Lx values are lower than the photopic values up to CCT values of 6,000 - 6500 K; and they are above the photopic values with CCTs exceeding 6,500 K. More importantly, the CCT map in this set shows the color variations across the sky dome. The results from this sky and other skies where the solar corona is visible, agree with findings from Hernandez et al. (2003). The highest luminance values and the lowest CCTs are observed near the solar corona. The spectral distributions in non-overcast skies are neither uniform nor symmetrical.

Figure 2: A Selection of HDR Sky models that are collected under naturally occurring sky conditions. Per-pixel photopic luminance maps are plotted in false color in cd/m^2 ; CCT images demonstrate per-pixel CCT variations in Kelvin, and reveal the color variations across the sky dome; and circadian luminance images are plotted in false color in EM.cd/m^2 . Global photopic illuminance (Lx), CCT and EM.Lx values are derived from the HDR sky models.

The sky in Set 3 (Figure 2.c) is an example of a cloudy sky in January at noon. Global horizontal measurement is 4,591 Lx. With 6,539 K, the Em.Lx values are similar to the photopic lux at 4,581. There are luminance variations across the sky dome, but color variations are relatively uniform. In other words, simulations of building spaces with orientations will have different daylight availability, but not different spectral content. The November overcast sky (Figure 2.d) demonstrates a similar pattern, though the global illuminances are higher.

February sky at noon (Figure 2.e) yields to a photopic illuminance of 13,389 Lx, and a high CCT of 12,511 K. The most chromatic sky colors are across and away from the sun. The circadian stimulus is 16,891 EM.Lx.

The last set (Figure 2.f) is taken on December 4 at 14:20. The low sun in the sky produces a global illuminance value of 3,725 Lx and a high CCT of 22,686 K. High CCT points to a blue rich light, and as a result, circadian stimulus has increased more than double to 8,206 Em.Lx. The variability of sky spectra is significant, thus the spectra of indoor spaces with different orientations will vary substantially.

In sum, current practices that consider a uniform spectra across the sky dome has dual oversimplifications. Fluctuations among different sky types, dates, and times, and variations across the sky dome are not appropriately modelled.

Tristimulus Analysis of HDR Sky Models and Vertical Orientations

Although sky models are important to simulate the daylight source, global vertical light values at the eye level are orientation specific and modified with the reflections from the surrounding surfaces. The image sets with HDR images of the sky dome and four vertical orientations are collected in November and December to study the spectral variations at the eye level (Figure 3).

For the data sets in Figure 3, a standard (colorless) Perez sky is simulated with the same direct and diffuse irradiances as the HDR sky image. The photopic luminance distributions between the actual HDR skies and theoretical Perez skies do not always match (due to the cloud cover and other atmospheric conditions), but since the same direct and diffuse irradiance measurements are used to generate the Perez skies, similar global horizontal illuminances are achieved between HDR skies and Perez models. The similarities end there. As Perez skies are colorless (i.e. equal energy white), CIE X and Z values are always equal to CIE Y. The circadian stimulus is always equal to photopic stimulus, and CCT is always fixed at 5,453 K regardless of date, time, and sky condition in Perez skies. They do show significant variability in HDR skies, as they should.

In set 1 (Figure 3.a), sky is dominantly cloudy. Both the sky image and the four vertical orientations provide similar photopic, circadian, and spectral data.

The data sets are collected with low altitude sun angles that yield to large incidence angles with a horizontal

surface. In contrast, the low sun strikes vertical surfaces with a small incidence angle. As a result, there are significant differences between the global horizontal and vertical measurements with sunny skies, especially for orientations facing the solar corona. The differences are not limited to photopic luminance and illuminances, they are observed with CCT and EM.Lx and EM.cd/m², as well. The spectral power distribution curves in 1nm intervals between 380-780 nm clearly demonstrate the color differences between the sky dome and the four vertical orientations.

Sky in Set 2 (Figure 3.b) yields to global horizontal measurements of 27,481 Lx, 5797 K, and 25,603 EM.Lx. The first vertical orientation directly faces the solar corona and yields to global vertical measurements of 96,323 Lx, 5,150 K, and 86,896 EM.Lx. The deficiency of color around the solar corona decreases the CCT and EM.Lx values. In contrast, the second vertical orientation produces a much lower photopic illuminance of 5,993 lx with a much higher CCT of 10,264 K, and as a result circadian stimulus is higher than the photopic one.

Global horizontal illuminance is associated with a high CCT in the sky of Set 3 (Figure 3.c), but all vertical orientations have much lower CCTs than the sky dome. Two vertical orientations that include the solar corona have much higher photopic and circadian stimuli, and the other two orientations have lower photopic and circadian stimuli than the sky.

The fourth set (Figure 3.d) demonstrates the bluest sky among the studied scenes. Once again, the intensity and spectral variability between the sky and the vertical orientations are significant based on orientation. The Perez sky simulations do not incorporate this variability.

Analysis of Image based Simulation Results

Image based lighting (IBL) is a simulation technique that utilizes 180° HDR images as light sources instead of theoretical sky models (Debevec, 2002; Inanici, 2010). A sidelit space (with room dimensions of 6 x 14 x 4.5 m) has been simulated in Radiance software for four orientations. The floor, wall, and ceiling materials have 20%, 70%, and 70% reflectivity (Figure 4). Since the simulated space has a single window with one orientation, vertical HDR images in four cardinal orientations are utilized as light sources so that the spectra of both the sky and the surrounding could be incorporated in simulations. The simulations are repeated under Perez skies, as well.

Figure 5 demonstrates the differences under colorless Perez sky and color-calibrated HDR skies. The HDR sky and the orientations utilized in IBL simulations are the image probes shown in Figure 3.b (Nov 17th, at 12:02). With Perez sky, the variations between four cardinal orientations are simply based on sky luminance distributions. The sun positions align in both sky models, but Perez sky has a wider solar corona. The wider corona and a relatively uniform sky model throughout the rest of the dome, favours the south orientation, but the photopic illuminances at the eye level do not vary significantly in other orientations.

Figure 3: HDR images of the sky dome and four vertical orientations are given along with the Perez sky simulations that produce the same global horizontal illuminance as HDR imagery. CIE XYZ, CCT EM.Lx and photopic:melanopic ratios are provided for each scene. False color images for the scene show photopic cd/m^2 ; normalized spectral power distributions show the global spectral measurements taken at the lens level. Global horizontal illuminance values varied 2.1%, 0.8%, 10%, 2.7% before and after total image capture duration in scenes a,b,c, and d, respectively.

Figure 4 The setting used for simulations

In HDR capture, solar corona is more compact and intense. HDR images are taken in a relatively empty urban setting, distant vegetation are visible in the images covering lower portions of the sky towards the horizon. It can be seen from the vertical HDR imagery in Figure 3.b that the sun indeed casted long and sharp shadows during the data capture. The intense directional light source in IBL simulation creates a much intense south facing room as observed in Figure 5.b. The photopic illuminance outside the window is 96,323 Lx; the illuminance inside at the camera level is 62,440 Lx. This orientation has a low CCT due to the relatively colorless nature of the solar corona. In contrast, the west facing room has much lower vertical illuminances with a high CCT. The interior photopic illuminance, CCT values, and EM.Lx values mirror the outdoor conditions that were captured in vertical HDR images. They contrast sharply with relatively uniform CCT values in colorless Perez skies.

Perez skies yield to similar circadian and photopic stimuli in each orientation, as a result of colorless sky model. The spectral variation across the sky dome in HDR images yield to a much variable circadian stimulus as a dependent of orientation in IBL simulations.

Conclusion

This research demonstrates that actual skies have significant variations for spectra across the sky dome. The spectra also differs considerably based on date, time, and sky type. Although similar dynamics of luminance variations are well understood and adequately modelled, standard simulation models do not address spectra. Therefore, they are not adequate for calculating color-based metrics. The color metrics utilized in this paper include the standard human tristimulus response (XYZ), CCT, and equivalent melanopic stimuli.

The first step in developing theoretical spectrally accurate models is to measure them on a long-term and in different geographies around the world. Such information was instrumental in developing the sky luminance distribution models. The methodology presented in this paper can be utilized for measuring and understanding the variability of sky spectra based on location, date and time, and atmospheric conditions. Meanwhile, the HDR images captured under naturally occurring sky conditions, and calibrated with the tristimulus techniques discussed here, can be reliably used to simulate and calculate color metrics.

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	Sky	Orientation 1: South	Orientation 2: West	Orientation 3: North	Orientation 4: East
a. Perez sky, Nov 17 12:03	 CCT = 5,453K X = 28,905 Y = 28,905 Lx Z = 28,905 28,905 EM.Lx	 CCT = 6,454 K X = 23,767 Y = 25,002 Lx Z = 27,040 24,810 EM.Lx	 CCT = 6,351 K X = 3,651 Y = 3,825 Lx Z = 4,101 3,798 EM.Lx	 CCT = 6,430 X = 2,992 Y = 3,162 Lx Z = 3,383 3,310 EM.Lx	 CCT = 6,365 K X = 3,506 Y = 3,686 Lx Z = 3,938 3,641 EM.Lx
b. HDR Sky, Nov 17, 12:03	 CCT = 5,797 K X = 26,509 Y = 27,481 Lx Z = 27,343 25,603 EM.Lx	 CCT = 5,056 K X = 64,954 Y = 62,440 Lx Z = 62,581 57,020 EM.Lx	 CCT = 15,015 K X = 1,282 Y = 1,360 Lx Z = 2,339 1,949 EM.Lx	 CCT = 8,384 K X = 1,261 Y = 1,284 Lx Z = 1,769 1,515 EM.Lx	 CCT = 9,088 K X = 673 Y = 695 Lx Z = 991 849 EM.Lx
Sky Luminance Maps: 1 100,000 cd/m ²		Interior Luminance Maps: 1 10,000 cd/m ²			

Figure 5 A sidelit room with a single window has been rotated to four orientations. Top row shows the traditional Radiance simulations under colorless Perez sky, bottom row show the image based lighting simulations with color corrected HDR imagery. CIE XYZ, CCT and EM.Lx are provided for each scene. False color images for the scene show photopic cd/m²

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