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PER-PIXEL LIGHTING DATA ACQUISITION AND ANALYSIS WITH HIGH DYNAMIC RANGE PHOTOGRAPHY

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ABSTRACT

Recognizing the need for a tool that can capture the luminance values within a large field of view at a high resolution with a quick and inexpensive method, High Dynamic Range (HDR) photography technique has been evaluated. In HDR Photography, multiple exposure photographs are taken to capture the wide luminance variation within a scene. These photographs are used to automatically recover the camera response curve, and then used to fuse the multiple photographs into a single HDR image. Laboratory and field studies have shown that the pixel values in the HDR photographs can correspond to the physical quantity of luminance with reasonable precision and repeatability. The resultant HDR images are very useful for qualitative and quantitative lighting analysis since they can be post-processed with per-pixel data analysis techniques.

1. INTRODUCTION

Emerging technologies offer lamps, ballasts, control systems and strategies that allow opportunities for frequent switching and dimming applications, automated response for daylight harvesting, and individual addressability [1]. Hence, current lighting design trends promote dynamic lighting conditions by providing variability and easy control over the intensity, location, distribution and color of the lighting systems. Measurement and analysis of such environments come with challenges. There is a need for a data acquisition system that can capture the luminance values in:

- High resolution, that allows to study the temporal and spatial variability within the environment;
- High Dynamic Range (HDR); that covers the total human visual range from starlight to sunlight (10^{-8} to 10^{6} cd/m^2); and
- Large field of view, that covers the total human vision, which is 180° horizontally and 130° vertically.

HDR photography technique is presented here as a camera independent, low cost, and accessible solution for high resolution, HDR, large field of view luminance data acquisition.

2. HIGH DYNAMIC RANGE PHOTOGRAPHY

In HDR Photography, multiple exposure photographs are taken to capture the wide luminance variation within a scene. Each exposure captures a different luminance range. Camera response function is used to fuse the photograph sequences into a single HDR image (Fig. 1). The camera response function is a polynomial model that accounts for the accumulated radiometric non-linearities of the image acquisition process (such as gamma correction, A/D conversion, image digitizer, various mappings) without addressing the individual source of each non-linearity [2, 3]. The HDR images can be stored in image formats such as Radiance RGBE [4] and LogLuv TIFF [5].

A commercially available digital camera (Nikon Coolpix 5400) and fisheye lens (Nikon FC-E9 that has 5.6 mm focal length, 190 angle of view, and equidistant projection properties) is used to capture the multiple exposure photographs while the camera/lens system is mounted on a tripod. The white balance and contrast settings are kept constant for achieving consistent color space transitions. Although multiple exposures can be achieved either by changing the aperture size (f-stop) or the shutter speed (exposure time), photographs are taken with a fixed aperture size (f/4.0), and varying only the shutter speed in manual exposure mode (2 to 1/4000 sec). Shutter speed is reported to be a more consistent measure than the aperture size [2, 3].

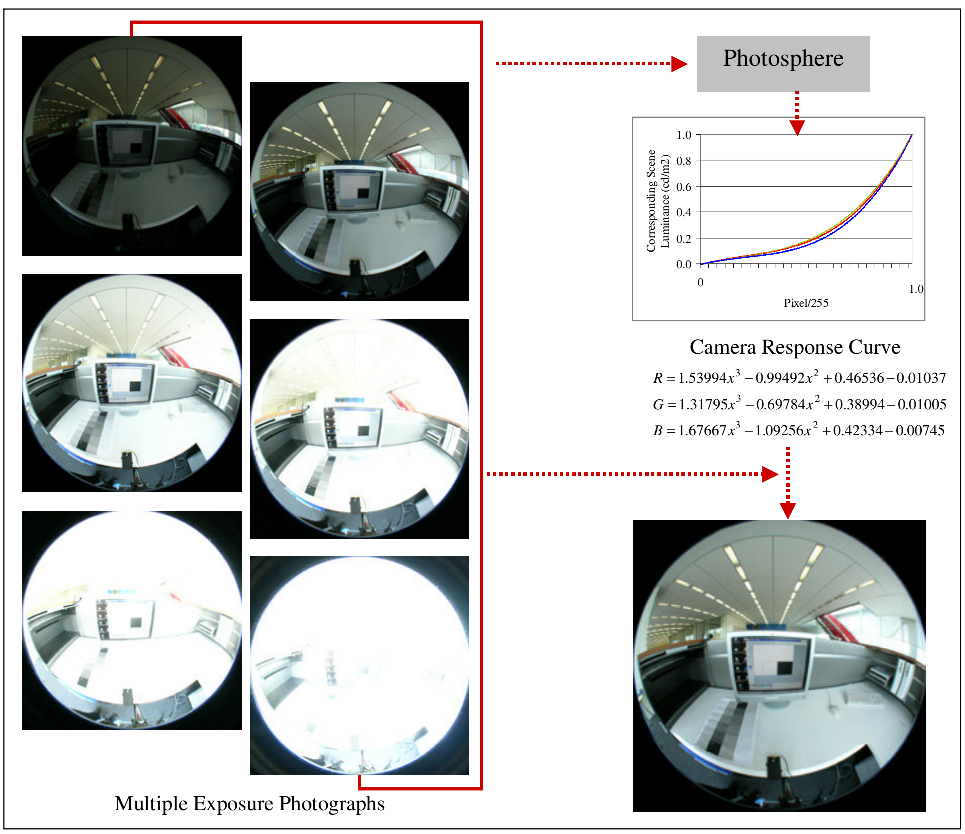
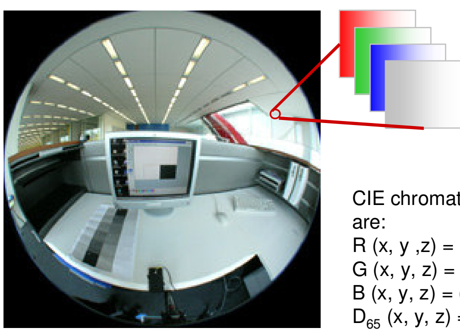


Fig. 1 Image assembly in HDR Photography

The photographs are fused into an HDR image using a software called Photosphere [6, 7]. Photosphere employs a radiometric self-calibration algorithm [2] that can computationally generate the camera response curve based on multiple exposure sequences. A daylit interior scene with large and smooth gradients throughout the interior and exterior views is captured with a 10 exposure set and used to computationally derive the camera response curve in three channels (RGB). It is important to emphasize that this approach is camera independent: it can work with any camera that has multiple exposure capabilities.

Luminance probe measurements are taken with a calibrated hand held Luminance meter with 1/3° field of view (Minolta LS110). Computational routines written in Matlab® allow the user to extract and process per-pixel lighting data from the HDR images that are saved in Radiance RGBE format. CIE XYZ values for each pixel are quantified from floating point RGB values based on the standard color space (sRGB) reference primaries [8], CIE Standard Illuminant D_{65}, and standard CIE Colorimetric observer with 2° field of view. The transformation process is illustrated in Fig. 2.



Red
Green
Blue
Exponent

$$red = \frac{R}{255} * 2^{(E-128)}$$

$$green = \frac{G}{255} * 2^{(E-128)}$$

$$blue = \frac{B}{255} * 2^{(E-128)}$$

CIE chromaticities for the reference primaries and CIE Standard Illuminant D65 are:
R (x, y ,z) = (0.64, 0.33, 0.03)
G (x, y, z) = (0.30, 0.60, 0.10)
B (x, y, z) = (0.15, 0.06, 0.79)
D_{65} (x, y, z) = (0.3127, 0.3290, 0.3583)

Conversion from RGB to XYZ: The RGB-to-XYZ matrix is constructed with the matrix of RGB chromaticities, which are differentially scaled to achieve the unit white point balance. Further information on RGB-toXYZ conversion can be found in [16, 17].

$$X = 0.4124 * R + 0.3576 * G + 0.1805 * B$$
$$Y = 0.2127 * R + 0.7151 * G + 0.0722 * B$$
$$Z = 0.0193 * R + 0.1192 * G + 0.9505 * B$$

In calculating luminance (L), CIE Y is multiplied by a constant value 'k', where k can be either a constant for the camera or determined for a scene based on a measurement of a selected region in the scene. It is recommended to determine 'k' based on a physical luminance measurement of a selected region in each scene.

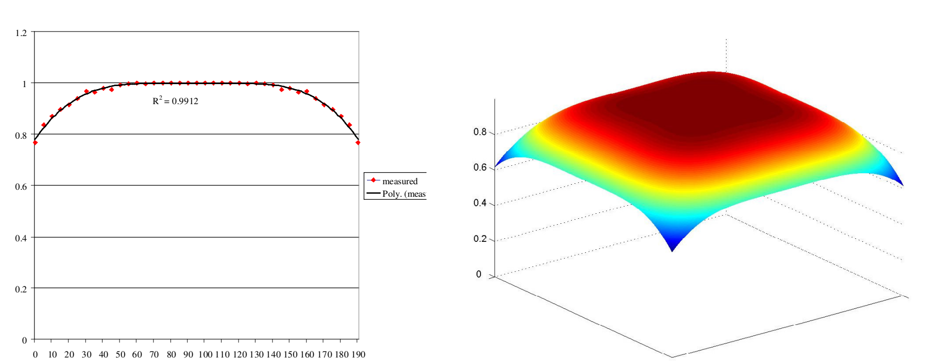
$$L = k * (0.2127 * R + 0.7151 * G + 0.0722 * B) \quad (\mathrm{cd/m^2})$$

Fig. 2 Conversion from RGBE to XYZ

3. VALIDATION

The calibration and validation studies of the HDR Photography technique involves the comparison of luminance values of various surfaces as determined from HDR images and the luminance meter. It is utmost important to understand the expected errors, error margins, and calibration opportunities in a data acquisition system.

There are two expected errors in HDR photography technique: vignetting effect and Point Spread Function (PSF). The Nikon FCE9 fisheye lens uses equidistant projection to produce an image. The equidistant fisheye lenses exhibit noticeable vignetting, i.e. light falloff for the pixels far from the optical axis. Although, the vignetting effects would be negligible in the center of the image, there will be increasing errors towards the peripherial pixels. The vignetting function of the Nikon FCE9 fisheye lens is determined through laboratory measurements done in 5° intervals and this function is used to devise a 'digital filter' in HDRLab to compensate for the luminance loss (Fig. 3). The maximum error caused by the vignetting effect is 23% loss at the periphery. The vignetting function is generated for an aperture size of f/4.0. It is important to note that vignetting is strongly dependent on the aperture size, and increases dramatically with wider apertures. The digital filter is a matrix that has the same resolution as the fisheye image and it compensates for the vignetting effect based on the pixel locations.



$$y = -1.28\text{E-}12 * x^4 + 3.43\text{E-}09 * x^3 - 3.38\text{E-}06 * x^2 + 1.45\text{E-}03 * x + 7.70\text{E-}01$$

Fig. 3 The vignetting function of Nikon FC9 a) measured data points b) digital filter developed based on the vignetting function (x corresponds the pixel location image) derived from (a);

Although it would have been very convenient to interpret each pixel in the photograph as a luminance measurement, it is important to recognize that some portion of the pixel signal comes from surrounding areas as light entering the camera is spread out and scattered by the optical structures of the lens (referred as point spread) [9]. A small point light source is used to quantify the PSF. The source is located far enough such that it covers less than one pixel area. Without any point spread, the image of the light should be equal to the original point of light, i.e. one pixel. The point spreading is illustrated in Fig. 4 (a, b are close-up views, c is the PSF). The aperture size, exposure time and eccentricity (distance from the optical center) affect PSF. The aperture size is kept constant throughout the capturing processes; therefore it is not a parameter affecting the luminance values. The effects of exposure time and eccentricity are studied. It is concluded that the spread is affecting a limited number of the neighboring pixels.

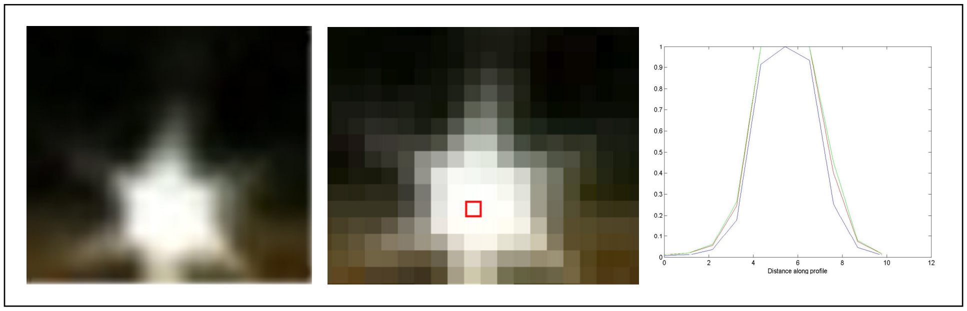


Fig. 4 a, b. Close-up views of point spreading: the red rectangle in b shows the pixel that corresponds to the actual light source c. PSF

The validation process involves the comparison of luminance values as determined from HDR images and a calibrated luminance meter. The center of each target is measured with the luminance meter and each measurement setup is captured with the HDR images that are generated from multiple exposure photographs using the camera response functions shown in Fig. 1. The luminance values are calculated with the transformation functions given in Fig. 2. The calibration feature of Photosphere is used for fine tuning the luminance values with a gray target in each scene. The vignetting effect is corrected by utilizing the function shown in Fig. 3. A rectangular block of pixels is extracted from the digital images for each target. This size of the block varies depending on the resolution of the target. The selection area fits inside each target and excludes the borders, where the luminance values may change drastically. The minimum, maximum, mean, and standard deviation of each block has been studied to ensure that the luminance values do not change significantly within the selected region.

The measurements have been repeated in different settings, which varied from controlled laboratory environments (black painted room without daylight) to office spaces and outdoors. The interior settings involve different light sources and different illumination levels. The measurements are done with 5 sets of paper targets: The first target consists of 24 squares (two sets of 12 squares) that have reflectances ranging between 4-87%. The other four targets have a gray square target in the middle with a 28% reflectance. This square is enveloped by a) white (87% reflectance); b) black (4%); c) white-then-black d) black-then-white surroundings. The Macbeth ColorChecker® chart is also used as a target.

When daylight was present in the setup, the probe measurements were done twice: before and after the multiple exposure photographs were taken. There is a time lag between the physical measurements and the multiple exposure photographs; therefore bracketing the photograph sequences with physical measurements allows characterizing the variation of the lighting conditions.

Figure 5 shows the accuracy results from a laboratory space, which is illuminated with different light sources such as incandescent lamp, projector (using a 500W tungsten lamp), fluorescent, metal halide (MH), and high pressure sodium (HPS) lamps; and an office spaces illuminated with daylight and electric lighting. The measurement setups shown here are chosen to provide a wide spectrum of the luminous environments. Additional setups have been measured and the results reveal similar error margins [10].

The luminance values extracted from the HDR images indicate reasonable accuracy when compared with probe measurements. Fig. 6 presents a histogram for error percentages for the 485 target points from different scenes. It involves a wide range of conditions with various light sources including daylight and electric lights, and various targets including colored and grayscale objects. The minimum and maximum measured target luminances are 0.5 and 12870 cd/m^2. The average error percentages for all, grayscale, and colored targets are 7.3, 5.8, and 9.3, respectively. The error margins for grayscale and colored targets vary depending on the spectral power distribution of the light sources. The overall error margin is quantified as less than 10% on average.

There is an increased error for the darker grayscale targets. The general scattering in the lens and sensor affects the darker regions of the images disproportionately. For instance, a bright background surrounding a dark target leads to over-estimation of the luminance values of the darker regions. Since the luminance level is quite low for these targets, small differences between the measured and captured values yield to higher error percentages.

The results also revealed increased errors for the saturated colors (Fig. 6b). In Photosphere, a separate polynomial function is derived fit to each RGB channel. However, it is important to note that the RGB values produced by the camera have been mixed between the different red, green, and blue sensors of the CCD. The CCD sensors have colored filters that pass red, green, or blue light. With the large sensor resolution, it is assumed that enough green (red, blue)-filtered pixels receives enough green (red, blue) light that the image would yield reasonable results. The sensor arrays are usually arranged in a Bayern (mosaic) pattern such that 50% of the pixels have green and 25% of the pixels have red and blue filters. When the image is saved in a file, algorithms built within the camera employ interpolation between the neighboring pixels [11]. The HDR algorithm assumes that the computed response functions preserve the chromacity of the corresponding scene points [2]. In an effort to keep the RGB transformations constant within the camera, the white balance setting is being kept constant throughout the capturing process. The camera response functions are generated with these constraints. Likewise, the luminance calculations are approximated based on sRGB reference primaries, with the assumption that sRGB provides a reasonable approximation to the camera sensor primaries.

The HDR technique requires reasonably stable conditions over the period of measurements. Dynamic lighting conditions resulting in significant light changes between differently exposed photographs can compromise the accuracy of the end result. It is strongly advisable to measure a single target in the scene, to be used as a calibration feature. As with any measurement and simulation tool, the user should be aware of the limitations and expected errors to be able to interpret the results meaningfully.

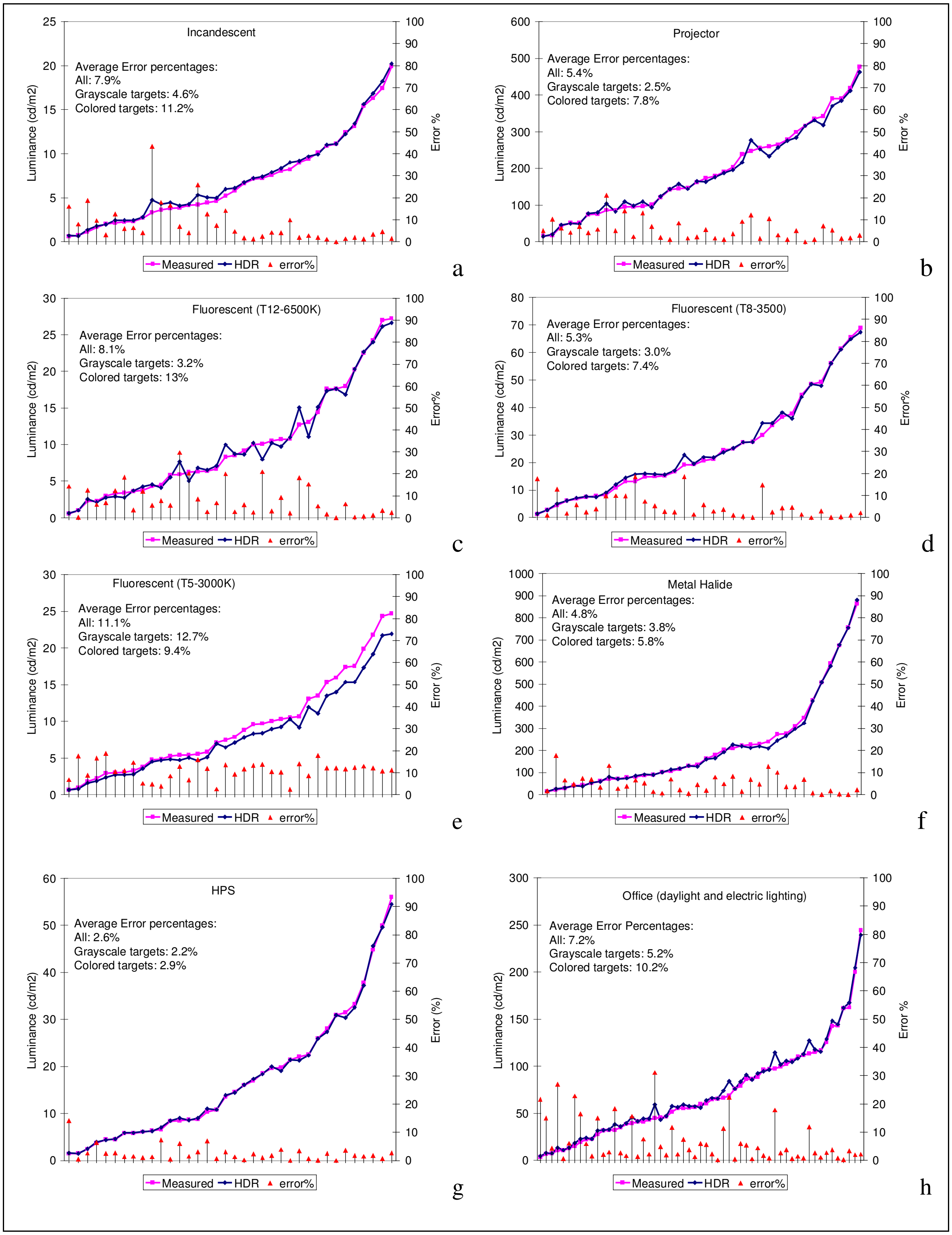


Fig. 5 Accuracy measurements with colored and grayscale targets in a laboroaty space with different light sources (a-g) and an office space (h)

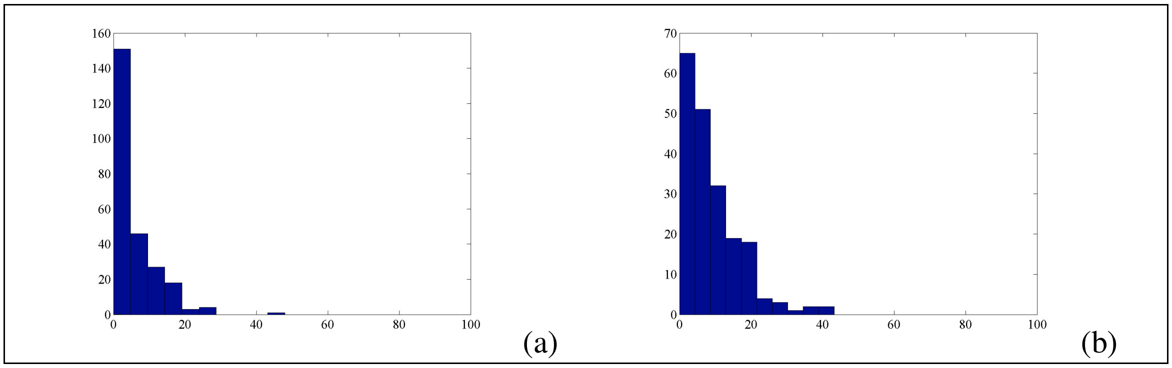


Fig. 6 Histograms for luminance error percentages between the measured and captured luminance values for grayscale targets (a) and colored targets (b)

4. REMARKS

The HDR photography technique is a useful tool that can capture HDR luminance values overall within 10% accuracy over a wide range of luminances. It is not suggested as a substitute for physical measurements. It requires calibration against a point and /or area of a reliable standard target with a reliable luminance meter to have absolute validity. Yet, it provides a measurement capability with the advantage of collecting high-resolution, HDR luminance data within a large field of view quickly and efficiently. It uses affordable equipment that is within the budgets of advanced lighting practitioners and researchers. Additionally, the self-calibration algorithm in Photosphere provides quick and easy camera response functions compared to the lengthy calibration measurements required in prior photography-based photometry [12 -14].

An HDR image is very useful for lighting analysis since it can be:

1. post-processed to
   a) extract photometric information on a pixel scale; this information can be utilized for statistical and mathematical analysis. A detailed documentation of various per-pixel analysis techniques can be found in [15].
   b) generate false-color image and/or iso-contour lines.
   c) simulate human visual sensitivity through a tone mapping operator.
2) studied for visual analysis by adjusting the exposure to different ranges.

Fig. 7 is an example of a parametric operation on shade fabric. The shade fabric has been operated in one of the 4 modes (a. open, b. drawn to cover the top portion of the window, c. drawn to cover the middle portion of the window, and d. fully drawn). The impact of the different operating modes of the shade fabric has been captured with HDR photographs and false color images are generated.

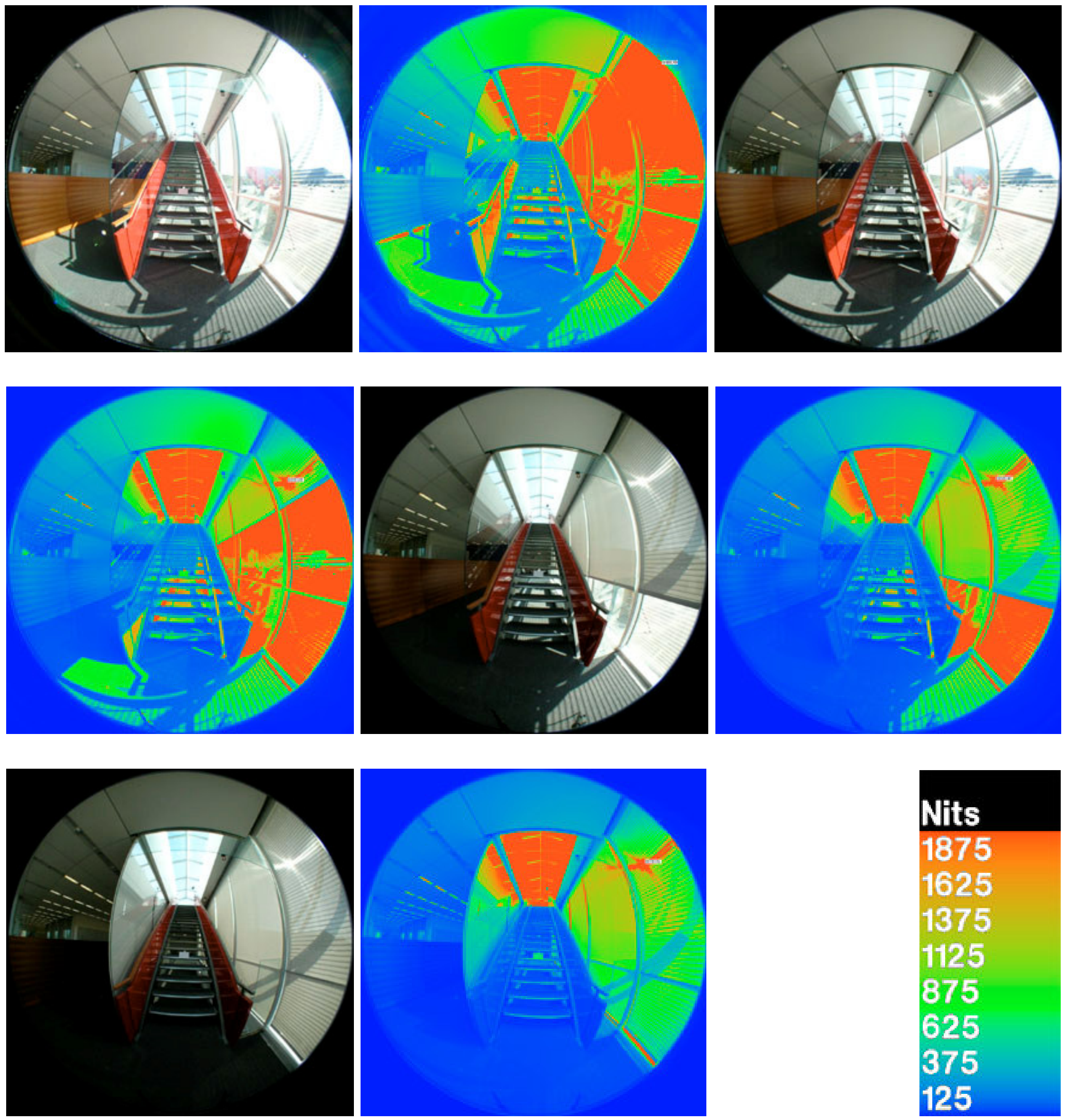


Fig. 7 False color images generated from HDR photographs

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