Luminance maps from High Dynamic Range imaging: calibrations and adjustments for visual comfort assessment

Clotilde Pierson
Magali Bodart
Architecture et Climat
UCL
Louvain-la-Neuve, Belgium

Jan Wienold
Laboratory of Integrated Performance in Design
EPFL
Lausanne, Switzerland

Axel Jacobs
GIA
London, United Kingdom

***Abstract*—Luminance maps created on the basis of High Dynamic Range Imaging (HDRI) is a technique increasingly used to study the visual environment. But creating HDR images with commercially affordable equipment requires an extensive calibration process to ensure that luminance data and derived spatial information is correct. This paper aims to provide an overview of the necessary steps for the most commonly used HDR calibration process, based on the self-calibration routines in hdrgen/Photosphere. It also addresses commonly made mistakes and aspects requiring special attention. The described steps are: the capture of multiple exposure photographs, the response curve derivation, the HDR image generation, the vignetting and neutral density filter correction, the calibration adjustment by spot luminance measurement and the geometrical reprojection. A detailed description of the geometrical reprojection is included in this paper, since this topic has not yet been described in the literature relating to HDRI, although needed for certain lens types and glare analysis.**

***Index Terms*— calibration; daylighting; High Dynamic Range Imaging; luminance maps; visual comfort assessment**

I. Introduction

In the field of lighting, HDRI is a technique increasingly used to study the visual environment with affordable equipment. HDRI allows to create luminance maps of the visual field, namely 180° views including luminance value of each pixel of the fisheye view. The technique consists in capturing multiple exposures of a scene and merging them in an HDR image with a higher range of luminance. When calibrated, these HDR images can be used to derive much useful information such as glare sources or vertical illuminance. However, the calibration process is tedious and error-prone since a lot of steps could go wrong. Therefore, this paper aims to present a synthetic overview of the HDRI calibration process, based on the most common tools hdrgen and Photosphere [1], which use self-calibration algorithms. From the capture of multiple exposure photographs to the calibration adjustment by spot luminance measurement, each stage is addressed. A special focus is laid on the geometrical calibration, as this topic has seen little attention in the HDR literature. A thorough description of each manipulation applied to an HDR image is provided, as well as several requirements, options, and common mistakes. References are also made to useful literature.

II. Calibration of High Dynamic Range images

A. Equipment characteristics assessment

The first step, before starting to create any HDR image, is to get to know the equipment used. Some basic but useful characteristics should be determined for each camera/lens association, as they will be required in later steps.

The no-parallax point, which is the centre of the lens's entrance pupil, can be defined using a tripod with a panoramic rotation unit and a sliding plate on which the camera is set out. Two vertical markers align with the centre of the rotation unit in such a way that when looking into the camera, the rear marker is hidden by the one in front. The camera position has then to be adjusted with the sliding plate so that when it rotates, the rear marker is still hidden by the one in front [2]. In future steps, the camera should be rotated around this no-parallax point to avoid parallax error.

The real viewing angle of a fisheye lens is not always exactly 180°, and the centre of a fisheye view is not exactly at the centre of the image [2]. In order to determine the total viewing angle of a lens and crop the fisheye view images to a square encompassing this total viewing angle, the camera no-parallax point has to be positioned between two reference grids. The no-parallax point should be aligned with the middle vertical lines of both grids, and centred at equal distance from these grids, so that the spacing between two vertical lines of a grid corresponds to one degree at the no-parallax point. When the camera is looking at 0° and 180°, the two middle vertical lines should appear at the borders of the fisheye view image and the distance in pixels between these lines in both pictures should be the same. If additional vertical lines –over the 180° middle lines– appear in both pictures, the total viewing angle is over 180° and can be defined according to the number of additional lines. The image cropping values are defined as the pixel coordinates of the most peripheral lines and the centre of the fisheye view image is in the middle of these coordinates.

The camera luminous range, or the camera maximum luminance capture, should be determined for each specific ISO/shutter speed/aperture combination used [3]. By capturing an image of a very bright light source such as the sun, the maximum luminance capture can be defined as the peak luminance in this image. In any HDR image created using the same equipment and settings, if the peak luminance is near the camera maximum luminance capture and the HDR-computed vertical illuminance is below the measured one, the picture most probably exhibits luminous overflow.

At last, the camera sensor should be checked once in the beginning for stuck or hot pixels [4]. Stuck pixels will always appear over-exposed, even if no light reaches the sensor. Hot pixels, however, are not permanently stuck, but will appear deficient during long exposures when the sensor heats up. To detect stuck and hot pixels, a picture should be taken with the lens cap closed using a long exposure. Every non-black pixel is a defective one and should be replaced, for instance by interpolation using the jpegpixi command, provided that the image quality is preserved.

B. Capture of multiple exposure images

To capture a sequence of multiple exposure photographs, the most common method is the automatic exposure bracketing (AEB). The AEB feature is often included in the camera, but can generally not manage to capture more than five images in a sequence. Software’s such as *DSLRRemotePro* or *qDSLRdeshboard*, allows to remotely control the camera and capture over 15 exposure bracketed images in one sequence. In addition to this remote control, the camera should be set on a tripod to avoid alignment problems during HDR generation [5].

A sequence of multiple exposure images has to be taken by varying the exposure time between photographs, since changing the aperture would increase problems associated with vignetting [5] and shutter speed is a more reliable measure than aperture size [6]. A sequence should include as many images as possible, separated by one or more EV-stop. If the sequence is captured under daylighting conditions, the longest exposure time should not exceed a few seconds to ensure stable conditions throughout the sequence. The aperture should be set according to the scene, although it is recommended not to use extreme aperture sizes. On the one hand, small aperture sizes (high numerical apertures) are correlated with greater potential for lens flare [7]. On the other hand, large aperture sizes (small numerical apertures) suffer from a low maximum captured luminance value [3] and a large vignetting effect [8]. A mid-range aperture size, such as f/8 or f/11, can be used as a trade-off. The film speed should be set on ISO 100 and the white balance on daylight [9]. The light metering method is irrelevant and the exposure mode is manual since the aperture and mean exposure time are defined through the remote control software. The focus should be set manually (on the infinite) and locked, to prevent the camera to refocus between each exposure. The image size should be the largest and all other settings should be disabled or set to neutral [5].

Moreover, when the solar disk is in the field of view, it is recommended to insert a neutral density filter between the lens and the sensor to increase the captured range and avoid pixel overflow. For instance, the Kodak WRATTEN 3.0 Neutral Density (ND) filter allows 0.1% of the light to pass through [10]. Although these filters are said to be neutral, they introduce a chromatic shift, especially for the blue channel [11], that could slightly affect the luminous ranges [3]. A solution is proposed later in this paper to counterbalance this chromatic shift.

C. Response function derivation

The camera response function relates pixel values to relative radiance [12] and is specific for each camera, even from the same model [13]. To approximate the camera's response function, several algorithms have been developed, amongst which the one from Debevec and Malik [14] (later modified by Mitsunaga and Nayar [15]) and the one from Robertson [16] are the most widely implemented. The software *Photosphere* and the hdrgen command from *Radiance* can approximate the camera response curves using Mitsunaga and Nayar’s method [1] whereas the software *PFStools* offers the option to choose between Robertson’s and Mitsunaga and Nayar’s algorithms. Both software’s and the hdrgen command require as input a sequence of LDR images separated by one EV-stop. These images should represent an interior daylit scene with large and smooth gradients throughout interior and exterior views, and with very bright and dark areas [5], [6], [17]. To limit the vignetting effect on the LDR images used to derive the response function, it is suggested to use a small aperture (such as f/16) to capture the sequence. Three response curves are then derived from this sequence for the red, green and blue channels. A text file is issued, containing the polynomial order of these curves and the coefficients, which are in a reverse order between hdrgen command and *Photosphere*. If several response functions are derived for the same camera, either the smoothest RGB curves are taken or compound curves are produced for the three channels from the average of the coefficients.

D. HDR image generation

1) Exposures selection

To ensure that over- and under-exposed photographs are captured, it is recommended to take the largest bracketed sequence possible [18]. But in order to facilitate and accelerate the HDR creation process, only LDR images bringing useful information should be used. The –x option in *Photosphere* and hdrgen command to ignore unnecessary exposures should, however, not be applied since it was developed as a time-saver function and lacks accuracy Selection of LDR images has to be made manually in such a way that the darkest exposure has no RGB value greater than 228 and the lightest exposure has no RGB value below 27. These threshold values are preferred over the 20-200 RGB values as they have been empirically recognized to achieve better results. When working on visual discomfort due to glare, it is especially important to make sure that the darkest exposure has no white pixel. This means that the total luminance of the brightest light source in the field of view was captured by the selected sequence.

To select the sequence of useful exposures, a mask should first be applied to the LDR images, so that all pixels outside the fisheye view are set to a neutral colour (such as black) [18]. A script could then automatically count the pixels in the usable region of the image that are below 27 and over 228, and select the right sequence, from the first over-exposed image having no pixel below 27 to the first under-exposed image having no pixel over 228. If over-exposed images all contain black pixels (or inversely), they will all be included in the selected sequence.

2) LDR images merging

With the derived camera response function and the selected sequence of LDR images, a HDR image can be created using a software such as *Photosphere*, or more directly through a command line like hdrgen or pfshdrcalibrate. Choosing between one of these tools should have no impact on the quality of the HDR image created, since both Debevec and Malik's and Robertson's algorithms have been proved to perform equally well [4]. In *Photosphere* and hdrgen, the default value of automatic exposure alignment and exposure adjustment options is on. But when taking a tripod-stabilized sequence, the automatic alignment option could be turned off to restrict images manipulations. If the captured scene is prone to lens flare, namely scattered light which results in a slightly fogged appearance in HDR images, or ghosts, i.e. moving objects or subjects, options can be selected to remove these artefacts.

E. Chromatic correction (ND filter)

In addition to the reduction of luminances in the image, ND filters have been acknowledged to introduce a chromatic shift, especially in the blue channel [11]. This chromatic shift can be corrected for the visible portion of the ND filter spectrum, by devising a colour transform that maps the RGB components of an image with the filter to the RGB components of an image without it [10], [11], [19], [20]. For this purpose, a Macbeth colour chart has to be photographed under constant daylight conditions with and without the ND filter. By comparing the RGB values of the two pictures, a transformation function can be computed for each channel. These transformation functions account for the chromatic shift and the brightness scaling caused by ND filters. To correct the filtered HDR images, a .cal file containing the three RGB mapping functions should be applied with pcomb command of *Radiance*. Moreover, when using pcomb command, the –o option should be used to ensure conservation of original pixel values and exposure.

F. Vignetting correction

The vignetting effect is the light falloff that can be observed toward the edges of an image, especially when a fisheye lens is used [5]. This light falloff can be as high as a 70% luminance loss at the periphery of the fisheye image for large apertures [8]. The vignetting effect depends on the aperture of the lens, with small apertures yielding less vignetting than large ones [9]. Although it seems like lenses of a same model have a similar vignetting effect [7, 8], it is recommended to derive proper vignetting curves for the lens in use. There are two common ways of deriving the camera vignetting curves. The first one [8] consists in taking, for each studied aperture, one HDR image of uniform targets having the same reflectance and located at known angles in the 180° field of view of the lens under constant and uniform indirect lighting. The vignetting curves can be defined for each aperture on the basis of the ratios of the HDR-derived luminance values of each target on the HDR-derived luminance value of the central target. These curves should be approximated by an even-order polynomial since odd-order polynomials are not possible with actual optical systems. The second method [6], [7], [12], [17], [18], [21] requires only one constant and uniform target, which could be a grey card in a stable and uniform lighting environment, or a stable and uniform light source (such as halogen lamp) in a darkroom. The camera is rotated with respect to the target in intervals (e.g. in 5° steps) until the camera field of view is covered. The HDR-derived luminance value of the target in each HDR image can be compared to the HDR-derived luminance value of the target when it is at the centre of the fisheye view. The vignetting curves can then be derived similarly to the first method, but this second method should provide smoother curves [17].

The vignetting correction of an HDR image can be achieved by applying a digital filter on the fisheye view. More precisely, a .cal file is applied to the HDR image using the pcomb command of *Radiance*, so that each pixel of the HDR fisheye view image is divided according to its radial position, by the right vignetting function.

G. Reprojection

Fisheye lenses project 3D scenes on 2D images with a specific projection method (Fig. 1) amongst equidistant (i.e. equiangular), equisolid-angle (i.e. equal-area), orthographic (i.e. hemispherical), and stereographic (i.e. planispheric) [8]. The two most widely implemented projections in commercially available fisheye lenses nowadays are the equidistant and equisolid-angle methods. Each lens model is related to one theoretical projection but in practice, the implementation of the projection method is not perfect and suffers from small inaccuracies.

When working on visual comfort and glare, geometrical calibration of HDR images is an essential step. The evaluation of vertical illuminance or glare indices, which can be made through the *Radiance* tool Evalglare [22], depends on the solid angle and the position index of each pixel of an HDR fisheye image. But depending on the projection method, the solid angle and the position index vary and should thus be calculated differently. Evalglare is currently able to devise the solid angle and position index from equidistant (-vta) or orthographic (-vth) HDR fisheye images as well as for perspective lenses (-vtv).

Since on one hand, each lens has its own non-perfect projection function and on the other hand, Evalglare does not support equisolid-angle HDR fisheye images, an image correction is generally necessary. The first step consists in defining the exact projection function of the lens used. One relatively easy way to determine the real projection function of a fisheye lens is to take a picture every 5° of a vertical marker on the horizon line of a fisheye view. The camera should rotate around the no-parallax point until the lens field of view is covered. The radial position of the vertical marker in each picture can then be related to a certain angle of the lens field of view. By computing the Mean Squared Error (MSE) of each theoretical projection function against the measured values, the projection type of the studied lens can be defined as the one producing the smallest MSE. The exact projection function can then be approximated (Fig. 1) from the measured values with a regression model based on the known projection type. Other methods [8], [23] exist to devise the real projection function of a fisheye lens, but require very specific equipment.

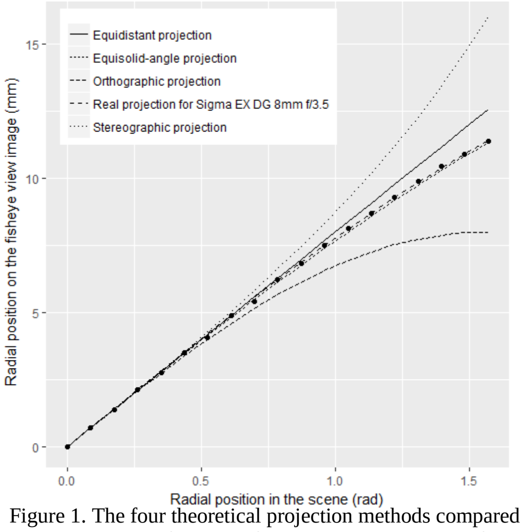

Figure 1. The four theoretical projection methods compared to the projection of a Sigma fisheye lens EX DG 8mm f/3.5

Once the real projection function has been defined, two options can be considered. If the projection of the lens is not the equisolid-angle method and if the real projection function does not differ much from the theoretical one, then the theoretical projection function can be used and the HDR image does not need to be geometrically corrected. Otherwise, a distortion function has to be derived to map the pixels of the original fisheye image to the pixels of an equidistant fisheye image. The distortion function transforming an equisolid-angle projection into an equidistant one has already been implemented in Ward's fisheyecorr.cal file. For all other cases, the method consists in approximating the projected relative radial positions (i.e. the radial positions in the fisheye image, on a [0;1] scale, corresponding to each 5° angle, going from 0° to 180°, when using an equidistant projection type) from the original relative radial positions (i.e. the radial positions in the fisheye image, on a [0;1] scale, corresponding to each 5° angle, going from 0° to 180°, when using the lens original projection type) with a second-order polynomial. At last, the reprojection of the HDR image is made through the pcomb command with Ward's fisheyecorr.cal file. Since the fisheyecorr.cal strictly handles the transformation from a theoretical equisolid-angle projection to a theoretical equidistant one, the mapsolid variable of the file should be modified to implement the derived distortion function.

H. Calibration adjustment by spot luminance measurement

The HDR imaging technique allows to collect the relative luminance value of every pixel in the lens field of view. In order to retrieve the real luminance values of the scene, a calibration adjustment has to be done. For this purpose, at least one spot luminance value should be measured on a mid-range grey card in the scene during the LDR sequence capture, using a luminance-meter. The final HDR image is achieved by scaling the relative luminance values of the HDR image with a factor. This factor is the ratio between the measured and HDR-derived luminance values of the grey card [13], and should be around 1.0. It is recommended to collect a spot luminance measure for each HDR image [18]. The software *Photosphere* can be used to calibrate an HDR image by implementing the spot luminance measure.

To check the validity of a 180° fish-eye HDR image, it is necessary to first check the luminous balance. Therefore, the integration of all luminance values over the hemisphere should corresponds to the illuminance value measured by a sensor placed besides the lens [24]. Using the Evalglare tool, the vertical illuminance of the calibrated HDR image can be derived and compared to the illuminance reading of the sensor. If the two values do not match, some areas in the HDR image are over- or under estimated. An HDR-derived vertical illuminance lower than the measured vertical illuminance could indicate pixel overflow in the HDR image.

An additional recommended way of checking the validity of calibrated HDR images is to take more than one spot luminance measure in the scene when capturing the sequence, especially on low- or high-range grey card. The measured values should be similar to the ones derived from the calibrated HDR image [6].

I. Evalglare-ready images

Frequently, luminance maps created on the basis of HDR images are processed by the Evalglare tool to devise some useful information, such as glare indices or vertical illuminance. But in order to be correctly implemented in Evalglare, a few more steps and verification are required.

1) Cropping

HDR images have to be cropped to a square, encompassing the circular fisheye view. By using the predetermined cropping values (as explained before), an HDR image can be cropped with the pcompos command of *Radiance*.

2) Resizing

Evalglare's performance drops when processing large HDR images. Thus, the final HDR images should not exceed 1500x1500 pixels (minimum size: 1000x1000). The resizing of HDR images can be done by using pfilt.

3) View type and exposure modification

Although a calibrated HDR image should have been reprojected to an Evalglare-supported image, the view type information has most probably not been modified in the header of the image [25]. The header of an HDR image is the location where all settings and parameters of the image are stored [13]. Evalglare, which reads the information of the header, will therefore wrongly evaluate the projection type of the image and produce incorrect results. The view type information should be modified in the header using the getinfo command of *Radiance*, not only for the projection type, which generally is equidistant (-vta), but also for the extent of the fisheye view, which should correspond to the total viewing angle of the lens. E.g. for a 180° lens, both directions should be set to: -vv 180 –vh 180.

Moreover, several *Radiance* commands modify the header information, especially the view and exposure information which is essential to Evalglare [25]. Evalglare expects a valid view type and exposure value, which correspond to the real lens type and real exposure of the image. The pcompos and pcomb commands mark the view information line in the header as “invalid” by adding a tab. The view type modification should therefore be done at the end of the process, so that it is still valid when running Evalglare. These two commands also mark the exposure information as “invalid”, so that it is not possible to retrieve absolute luminance values from the modified HDR image. This can be avoided applying pcomb command with the -o option as the very first command from those two (pcomb -o before pcompos), since this option “includes” the exposure into the pixel values. In that case, the remaining “invalid” exposure line has to be deleted. It is also advised to use the pfilt command only with the -1 option to avoid additional exposure lines entry. In any case it is recommended to check the header before and after using a command.

III. CONCLUSION

In this paper, the various stages required to create and calibrate an HDR image are described. These stages comprise the equipment characteristics assessment, the capture of multiple exposure images, the response function derivation, the HDR image generation, the ND-filter chromatic correction, the vignetting correction, the reprojection, and the calibration adjustment by spot luminance measurement. The authors believe that conducting the calibration process step by step allows to have a better understanding of the transformations applied to HDR images.

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