Using High Dynamic Range (HDR) Photography to Capture Visual and Non-Visual Stimuli in Built Environments

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Outline

1. HDR photography concepts: Measuring Light with HDR photography
2. HDR photography rules: How is it captured?
3. Generating the HDR image
4. Post-processing: Correcting for aberrations and Accuracy
5. Applications: Visual stimuli
6. Applications: Non-Visual stimuli
7. Concluding remarks
1. Measuring Light with HDR Photography

- Collecting a record of lighting at a point-in-time

- Storing light in original units ( Cd/m\(^2\) )

- Post-processing per-pixel luminance measurements for analysis
1. Measuring Light with HDR Photography

- Digital and chemical photography
- Conventional display devices
- Low Dynamic Range Image formats

RGB [0 - 255]
1. Measuring Light with HDR Photography

- Starlight
- Sunlight

Light levels:
- $10^{-6}$
- $10^{-3}$
- $1$
- $10$
- $100$
- $10^4$
- $10^8$
- $\text{Cd/m}^2$
1. Measuring Light with HDR Photography

HDRI Software - Photosphere
Developed by Greg Ward
Free, available from www.anyhere.com
Mac, Windows, Linux, and Raspberry Pi

Camera response curve

HDR Image
An HDR photograph can be post-processed to extract photometric information on a pixel scale; this information can be utilized for statistical and mathematical analysis.
Original Method:
Devebec PE and Malik J. “Recovering High Dynamic Range Radiance Maps from Photographs” SIGGRAPH, August 1997.

Photosphere
Released by Greg Ward in 2004

Validation:

Selected as a “Classic Paper” in LRT.
346 Lux @ Eye/Camera

Hemispherical Projection (Cosine corrected)
High Resolution

Starlight

Sunlight

10^{-6} cd/m^2 10^8

High Dynamic Range

Large field of view
2.1 HDR Photography rules: How is it captured?

Any **camera** with manual settings would work.

**Rule #1:** Use a **tripod** to take multiple-exposure photographs!

If you are going to use HDR images for human subjects research, a **fisheye lens** with a full-frame camera is highly recommended.

(If you have access) A **luminance meter**, a **grey card**, and an **illuminance meter** can be used for the calibration and fine-tuning of images, which improves accuracy.
Rule #2:

Fix the white balance in your camera to daylight (D65) (even when the light source is different).

Do not leave the camera in Auto mode! Auto white balance takes the brightest value as white and adjusts all other colors in the image accordingly.

White is defined in Photosphere as the daylight with a Correlated Color Temperature of 6500K.
Rule #3: File format

The input format of multiple exposure photographs (low dynamic range images) in Photosphere is jpg.

JPG saves the images in the standard RGB space with d65 light source (sRGB).
2.4 HDR Photography rules: ISO setting

Rule #4: ISO setting

Set the film speed to ISO 100.
2.5 HDR Photography rules: Multiple exposures

Exposure Triangle

- Shutter Speed
- Aperture (Lens Opening)
- ISO/Digital Sensor Sensitivity
2.5 HDR Photography rules:

Exposure Triangle

- **Shutter Speed**
  - 1/8000 sec

- **Aperture/Lens Opening**
  - f/22

- **ISO**
  - 100

- **More Light**
- **Shallow depth of field**
- **More Motion Blur**
- **More Light**
- **Film/Digital sensor sensitivity**
- **More Noise**
Aperture size: \( f / 4.0 \)

Measured target luminance range between 1 – 16,000 \( \text{cd/m}^2 \)

Maximum measurable luminance value with \( f/4.0 \) is \( \sim 100,000 \text{ cd/m}^2 \)

2.5 HDR Photography rules: Aperture size

Accuracy of common interior surfaces vs the sun

- Rule #5: Set the aperture size to f/11.

- Multi-exposure sequence with f/4 captures approximately 100,000 cd/m² as max. Luminance

- Multi-exposure sequence with f/11 captures approximately 1,000,000 cd/m² as max. Luminance

- Multi-exposure sequence with f/22 captures approximately 3,200,000 cd/m²

- f/22 causes a significant amount of lens flare, impairing accuracy for the rest of the scene


Rule #6:

Vary the shutter speed starting with long exposure and work your way to short exposures.

The overexposed image should not be totally washed with light and the underexposed image should not be totally black!
Rule #6:

The starting shutter speed depends on the scene (test before you start).

I recommend using the shortest shutter speed in your camera to capture high luminances such as the sky and sun in a well daylit scene.
Rule #7:

Take photographs in a stable environment.

Capture multiple exposures as quickly as possible! (under ~2 minutes)

The earth rotates 1° every 4 minutes to complete its daily cycle.
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For a regular HDR assembly, take 6 - 8 exposures to cover the range.
Rule #8:

For determining the camera response curve, select a scene that has both low and high luminance values and gradual changes within the scene.

Take at least 12 exposures.

Use the same camera response curve for all subsequent captures.
2.9 HDR Photography rules: Luminance Calibration

Rule #: 9

If you have access to a luminance meter and a mid-level gray card, measure a target on the gray card with the luminance meter (right before and/or after taking multiple exposure photographs.

This value can be used as a calibration value during HDR generation.
2.10 HDR Photography rules: Recap

1. Use a tripod with a camera (a fisheye lens is preferred but not required)
2. Fix white balance to daylight
3. Set the file format to jpg
4. Fix the film speed to ISO 100
5. Fix the aperture size to f/11
6. Vary the shutter speed to take 6-8 photographs
7. Take photographs quickly in a stable environment
8. For your first capture, take 12+ photographs
9. Take a luminance reading of a grey card in every capture (preferred)
3.1 HDR Image Generation

Rule #10

Do not process images in Photoshop or any image generation software other than Photosphere.

All subsequent HDR image mergings

The first introduction of the camera to the software
3.2 HDR Image Generation: Camera Response Curve

Radiometric self-calibration* is a computationally derived calibration process that is used to relate the pixel values to real-world luminances. The curves (for RGB channels) that model the accumulated radiometric non-linearities of the image acquisition process, without addressing the individual source of each non-linearity.

3.3 HDR Image format

Traditional image formats (Low Dynamic Range Imagery)
24-bit image formats e.g. TIFF, JPEG, GIF...
[0 - 255]

High Dynamic Range Imagery
32-bit image formats e.g. HDR (RGBE, Radiance pic)
4.1 HDR Post-processing: Vignetting correction for fisheye lenses

Fisheye lenses exhibit noticeable light falloff (vignetting) for the pixels far from the optical axis.

The smaller the aperture opening, the smaller the vignette effect.
4.1 HDR Post-processing: Vignetting correction for fisheye lenses

Use a fixed, single target (50% neutral grey card)

Mount the camera on a tripod head that centers the lens about its nodal point to avoid parallax errors.

Rotate the camera in 5-degree increments about its nodal point. Each time, a new image is captured.

19 photographs are taken for a single vignetting measurement, assuming symmetry.

Measure under stable electric lighting conditions.
### 4.1 HDR Post-processing: Vignetting correction for fisheye lenses

<table>
<thead>
<tr>
<th>Vignetting (f/4.0)</th>
<th>Vignetting (f/5.6)</th>
<th>Vignetting (f/11)</th>
</tr>
</thead>
</table>
| $y = -7E^{-05}x^2 + 0.0003x + 0.9932$  
$R^2 = 0.997$ | $y = -2E^{-08}x^4 + 3E^{-06}x^3 - 0.0001x^2 + 0.0021x + 0.9955$  
$R^2 = 0.9975$ | $y = -7E^{-06}x^4 + 0.0002x^3 - 0.0025x^2 + 0.0075x + 0.9939$  
$R^2 = 0.9982$ |

<table>
<thead>
<tr>
<th>Normalized luminance values</th>
</tr>
</thead>
</table>

[Graphs showing light fall-off from optical axis for different f-stops, with equations and $R^2$ values provided.]

4.1 HDR Post-processing: Vignetting correction for fisheye lenses
4.2 HDR Post-processing: (Optional)
Correct for lens geometric aberrations
4.2 HDR Post-processing: (Optional) Correct for lens geometric aberrations

Equidistant, Equisolid, or in between

![Graph showing equidistant, equisolid, or in between post-processing options.

- Ideal Equisolid 8mm
- Ideal Equiangle / Equidistant 8mm
- Sigma_fisheye

Distance from Image Center (Theta, Degrees) vs. Radial Sensor Position (mm)
4.3 HDR Post-processing: Luminance Calibration

A single luminance measurement of a gray card in the field can be used to calibrate the image.

It is recommended to perform one luminance measurement for every scene captured.
4.4. Accuracy of HDR Photography

- Incandescent lamp
- Fluorescent Lamp (T5, T8, T12 w/ CCT 3000-6500°K)
- High Pressure Sodium
- Metal Halide
- LED

4.4 Accuracy of HDR Photography

Spectral data

Luminance measurements

Incandescent

Metal Halide

Average Error percentages:
All: 7.9%
Grayscale targets: 4.6%
Colored targets: 11.2%

Average Error percentages:
All: 4.8%
Grayscale targets: 3.8%
Colored targets: 5.8%

Average Error: 11.6%

Average Error: 5.8%

Error % for colored targets (without color corrections)*
4.5 Post-processing: Illuminance Calibration

(Recommendation) #10:

Further calibration for high luminance scenes (sun disc is visible in the scene)

If you are using a fisheye lens, measure the illuminance on the **camera lens** in the field.

This value can be used for luminous overflow in HDR post-processing.
4.5 Post-processing:
Luminous overflow: very high luminances in the field
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Luminous overflow: very high luminances in the field

f/11 & No Filter ~1 million cd/m²
f/11 & ND3 ~272 million cd/m²


4.5 Post-processing:
Luminous overflow: very high luminances in the field

Apr 25, Mostly clear day, Global hor illuminance: 100,965 lux, Max L: $2.18 \times 10^9$ cd/m$^2$

Two apertures with f / 4.0 and f/16 to increase the dynamic range

Neutral Density Filter 3

Original method:

Validation:
Neutral density filters could be utilized to increase the dynamic range.

Neutral density filters have a negative impact on mid-range luminances:
- Introduce noise to the image
- Cause color shifts
- Increase the complexity of fieldwork

Best to correct for overflow digitally by comparing illuminance measured at the camera lens and illuminance derived from the HDRI:
- The differences between measured and image-derived illuminances are attributed to luminous overflow pixels.
- The luminances of the brightest pixels (pixels above a threshold) are increased until image illuminance matches the measured illuminance.
4.5 Post-processing:
Luminous overflow: very high luminances in the field

No filter f/11

ND3 with f/11

Partial combinations of no filter and ND3 with f/11

Luminous overflow correction

Measured illuminance: 73,175 Lx


5.1 Applications:  
Evaluation of existing environments

Recorded interior lighting conditions  
from sunrise to sunset (Sep. 24, 7:00 – 19:00) every 15 m. in Hagia Sophia

5.2 Applications: Human subject studies

5.2 Applications: Human subject studies


5.3 HDR Sky models

High Dynamic Range image is assembled from multiple exposure photographs;

Post processed to correct for aberrations

Projected onto an invisible hemisphere;

To model a naturally occurring sky.
5.4 Applications
Image-based Lighting Simulations


5.6 Applications: Visualization through tone-mapping

Select Exposure

Reinhard Photographic Tone Mapping

Ward Human sensitivity Tone Mapping
Radiance (pcond –h)

- a acuity loss (defocus darker regions of image)
- v add veiling glare due to very bright regions
- s human contrast sensitivity function
- c color visibility loss (scotopic vision)
6. Applications: Non-Visual impact of lighting
Trichromatic (CIE XYZ) Calibration

Recommendation #11:

If you would like to use your HDR image for measuring non-visual effects of light (melanopic light), use a hand-held spectrophotometer or colorimeter, instead of an illuminance meter.
6. Applications: Non-Visual impact of lighting

Calculated

y = 1.0134x
R² = 0.9999

CIE X

Measured

y = 1.000x
R² = 1

CIE Y

Calculated

y = 1.317x
R² = 0.9967

CIE Z

Measured

[\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}

[\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}

6. Applications: Non-Visual impact of lighting

Error % with global calibration of camera < 10%
Error % with every scene < 1%
Photopic Curve $V(\lambda)$

Standard Spectral Luminous Efficiency function, aka Photopic curve (CIE, 1924)

(Radiance primaries)  $Y = 179 \times (0.2651R + 0.6701G + 0.0648B)$

(sRGB primaries)      $Y = 179 \times (0.2121R + 0.7152G + 0.0722B)$
**Melanopic Curve**

EML = 179 \times (0.0023 \times R + 0.3911 \times G + 0.6066 \times B)

EML = 179 \times (0.0013 \times R + 0.3812 \times G + 0.6175 \times B)

Melanopic Curve (Enezi et al, 2011), data from Lucas et al., 2014).
Light at the Eye

Visual Response

Non-visual (melanopic) response
Captured on Sep 15, 9:30 am
CCT 4629°K
346 Photopic Lux @ Eye/Camera
269 Melanopic Lux @ Eye/Camera
7. Conclusions

- HDR Photography is a validated method of measuring lighting at a given time

- Its accuracy is dependent on the capturing and post-processing procedures

- Its applications range from the evaluation of existing spaces to human factors research, post-occupancy analysis, and relighting digital spaces and objects with captured lighting conditions.
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