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

Mehlika Inanici, Ph.D.

Professor of Architecture, University of Washington, Seattle

inanici@uw.edu

Outline

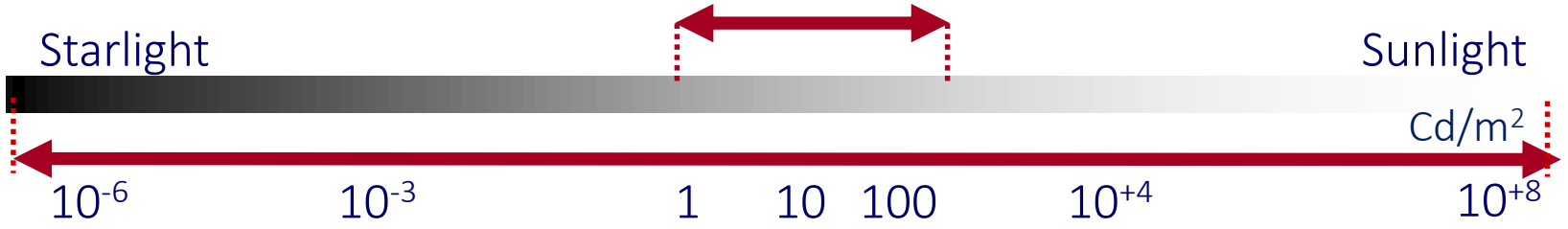
1. HDR photography concepts: Measuring Light with HDR photography
2. HDR photography rules: How is it captured?
3. Generating the HDR image
4. Post-processing: Correcting for aberrations and Accuracy
5. Applications: Visual stimuli
6. Applications: Non-Visual stimuli
7. Concluding remarks

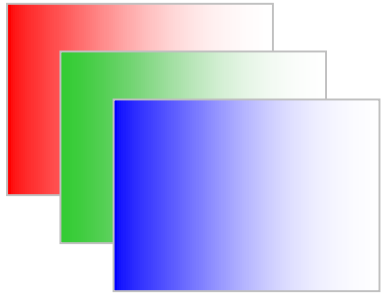
1. Measuring Light with HDR Photography

- 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


Starlight
Sunlight
Cd/m2
10-6
10-3
1
10
100
10+4
10+8

1. Measuring Light with HDR Photography



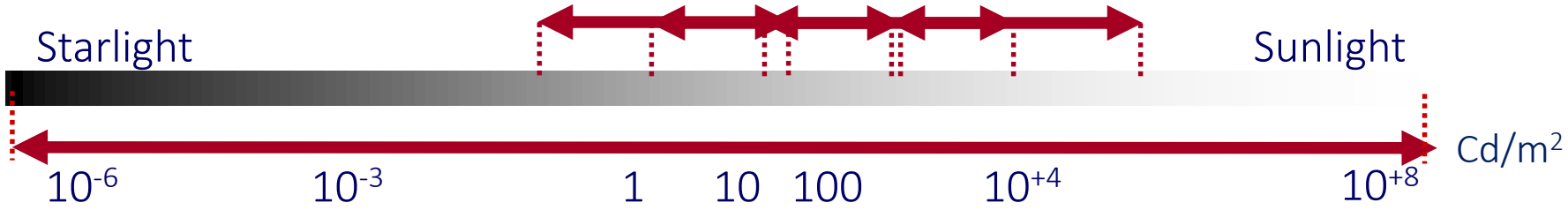


- Digital and chemical photography
- Conventional display devices
- Low Dynamic Range Image formats

RGB [0 - 255]

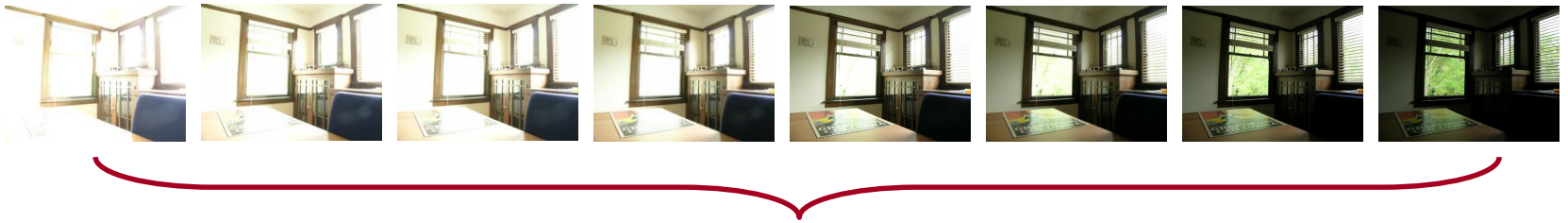
1. Measuring Light with HDR Photography



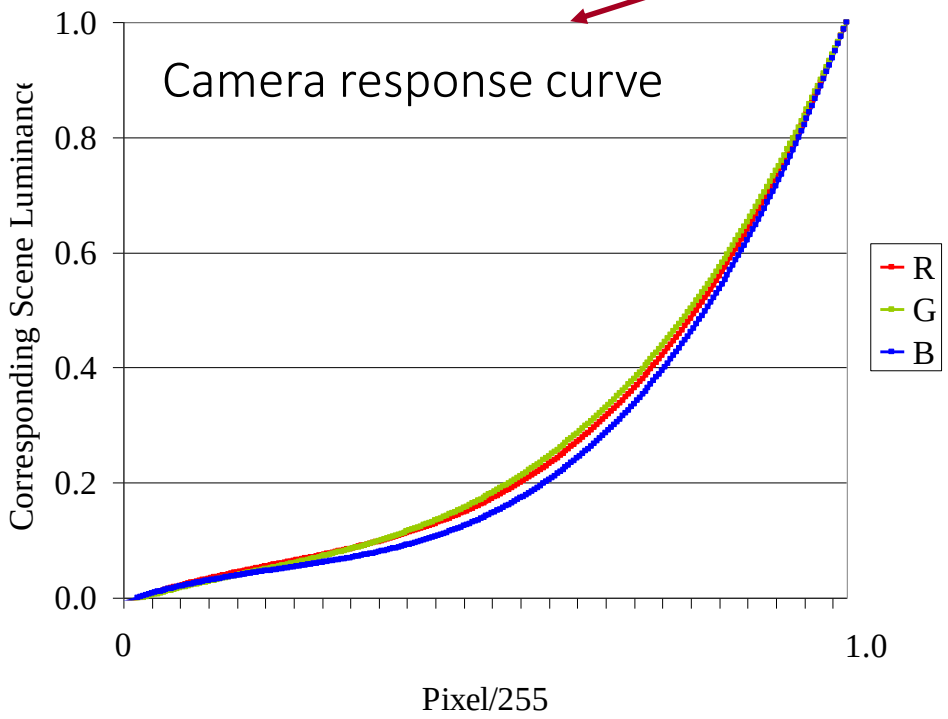



1. Measuring Light with HDR Photography

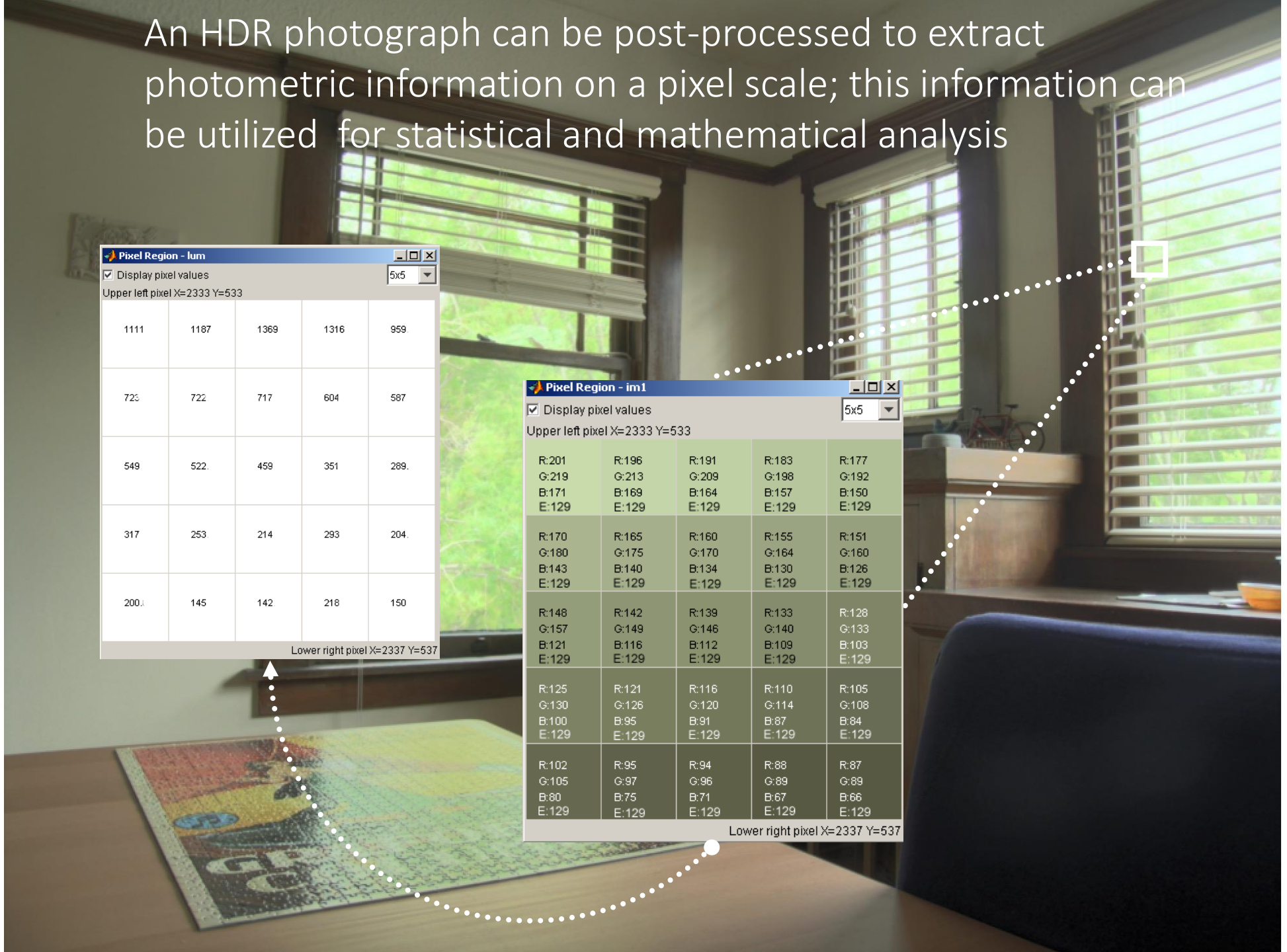


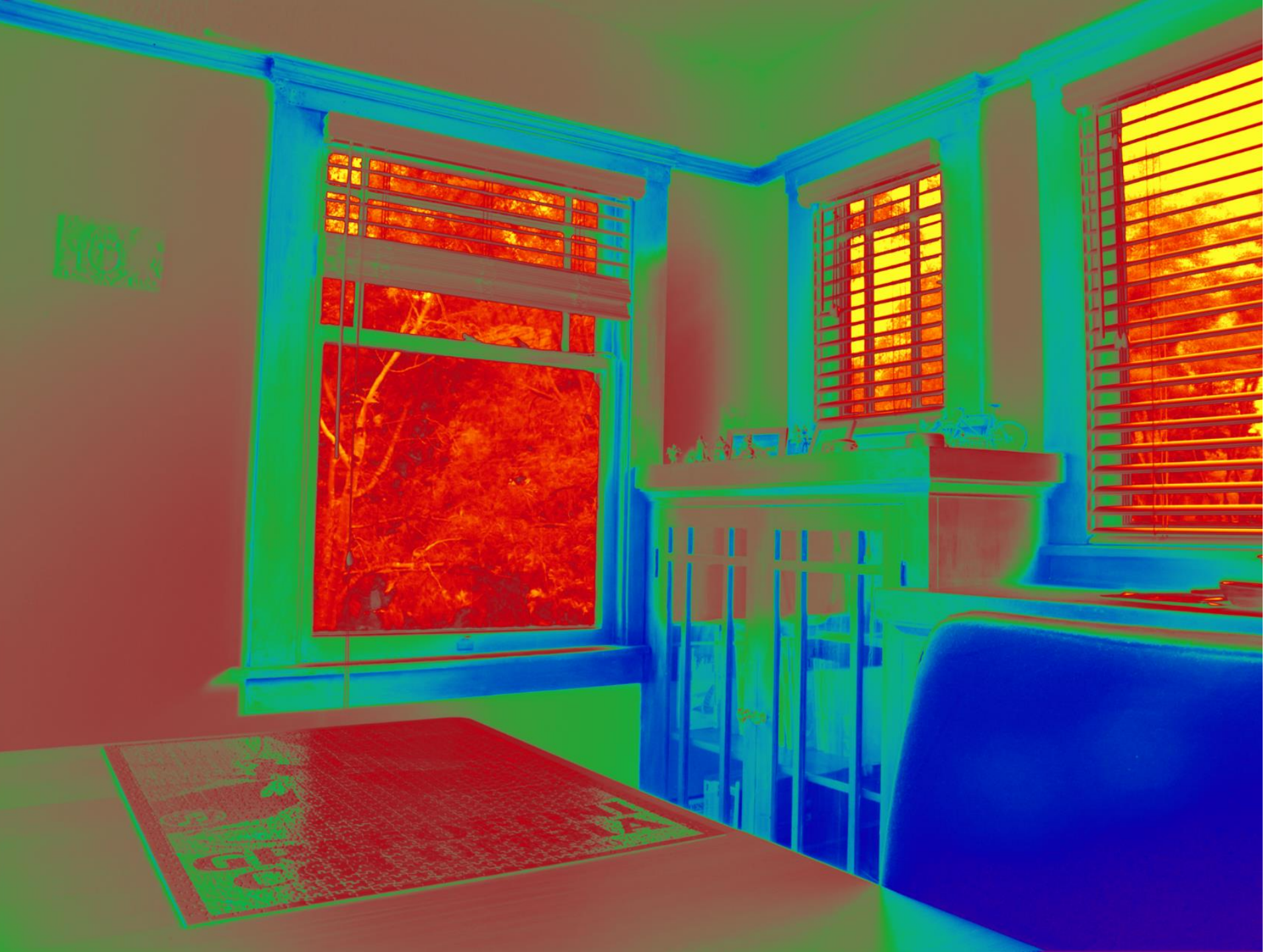
HDRI Software - Photosphere

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



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
Pixel Region - lum
Display pixel values
5x5
Upper left pixel X=2333 Y=533
1111 1187 1369 1316 959
723 722 717 604 587
549 522 459 351 289
317 253 214 293 204
200 145 142 218 150
Lower right pixel X=2337 Y=537
Pixel Region - im1
Display pixel values
5x5
Upper left pixel X=2333 Y=533
R:201 G:219 B:171 E:129
R:196 G:213 B:169 E:129
R:191 G:209 B:164 E:129
R:183 G:198 B:157 E:129
R:177 G:192 B:150 E:129
R:170 G:180 B:143 E:129
R:165 G:175 B:140 E:129
R:160 G:170 B:134 E:129
R:155 G:164 B:130 E:129
R:151 G:160 B:126 E:129
R:148 G:157 B:121 E:129
R:142 G:149 B:116 E:129
R:139 G:146 B:112 E:129
R:133 G:140 B:109 E:129
R:128 G:133 B:103 E:129
R:125 G:130 B:100 E:129
R:121 G:126 B:95 E:129
R:116 G:120 B:91 E:129
R:110 G:114 B:87 E:129
R:105 G:108 B:84 E:129
R:102 G:105 B:80 E:129
R:95 G:97 B:75 E:129
R:94 G:96 B:71 E:129
R:88 G:89 B:67 E:129
R:87 G:89 B:66 E:129
Lower right pixel X=2337 Y=537



Original Method:

Devebec PE and Malik J. “Recovering High Dynamic Range Radiance Maps from Photographs” SIGGRAPH, August 1997.

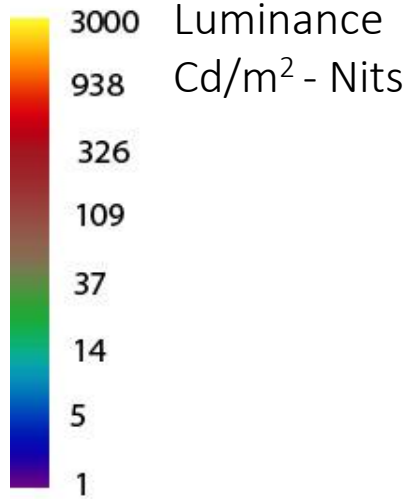
Photosphere

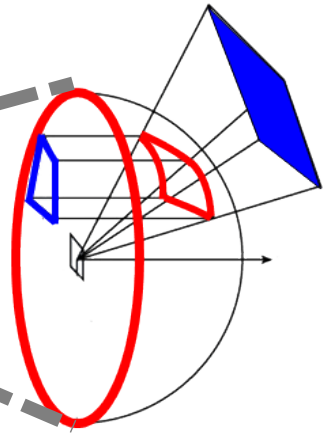
Released by Greg Ward in 2004

Validation:

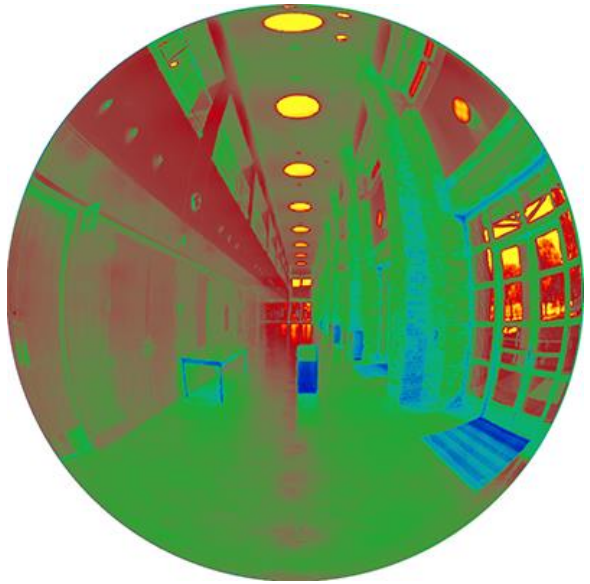
Inanici M. “Evaluation of High Dynamic Range Photography as a Luminance Measurement Technique”, Journal of Lighting Research and Technology, 38(2), 2006, 123-136.

Selected as a “Classic Paper” in LRT.

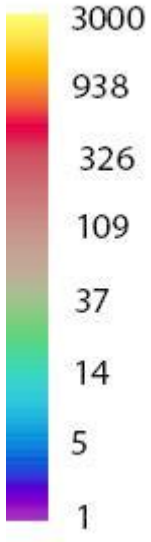




Hemispherical Projection (Cosine corrected)



Pixel Luminance
cd/m^2



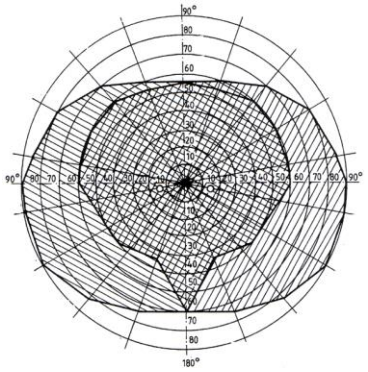
346 Lux @ Eye/Camera

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.

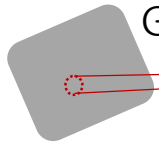
Rule #1: Use a tripod to take multiple-exposure photographs!

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.

Camera mounted on a sturdy tripod

180° fisheye lens



Grey card

Luminance Meter

Illuminance meter

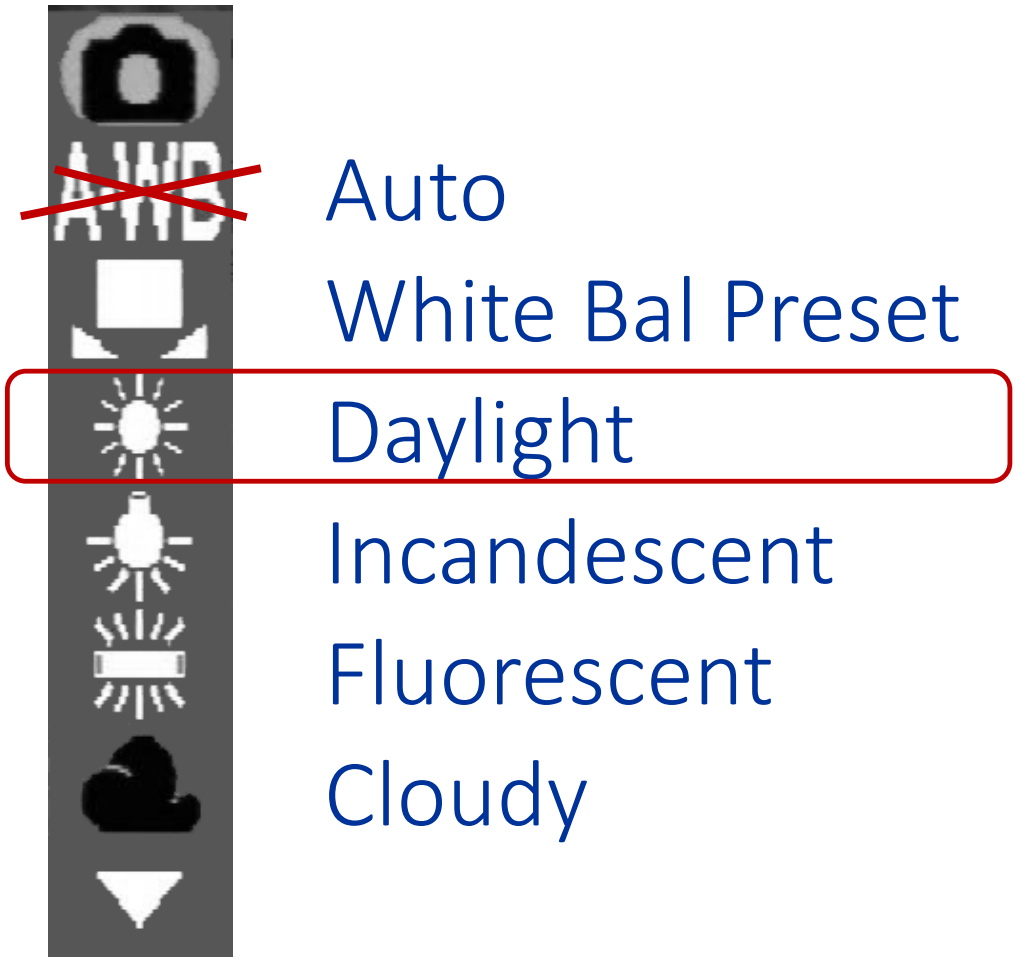
2.2 HDR Photography rules: White balance

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.



2.3 HDR Photography rules: File format

Rule #3: File format

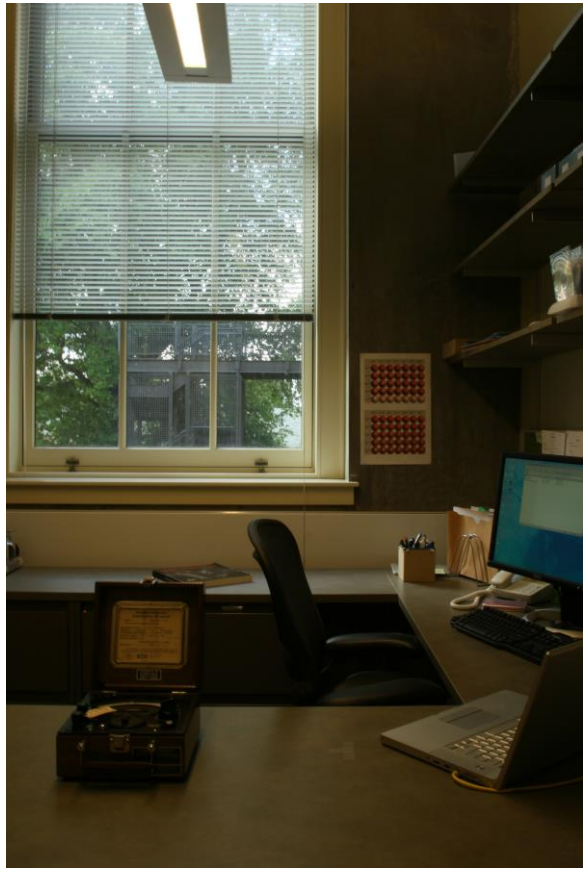
The input format of multiple exposure photographs (low dynamic range images) in Photosphere is jpg.

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.

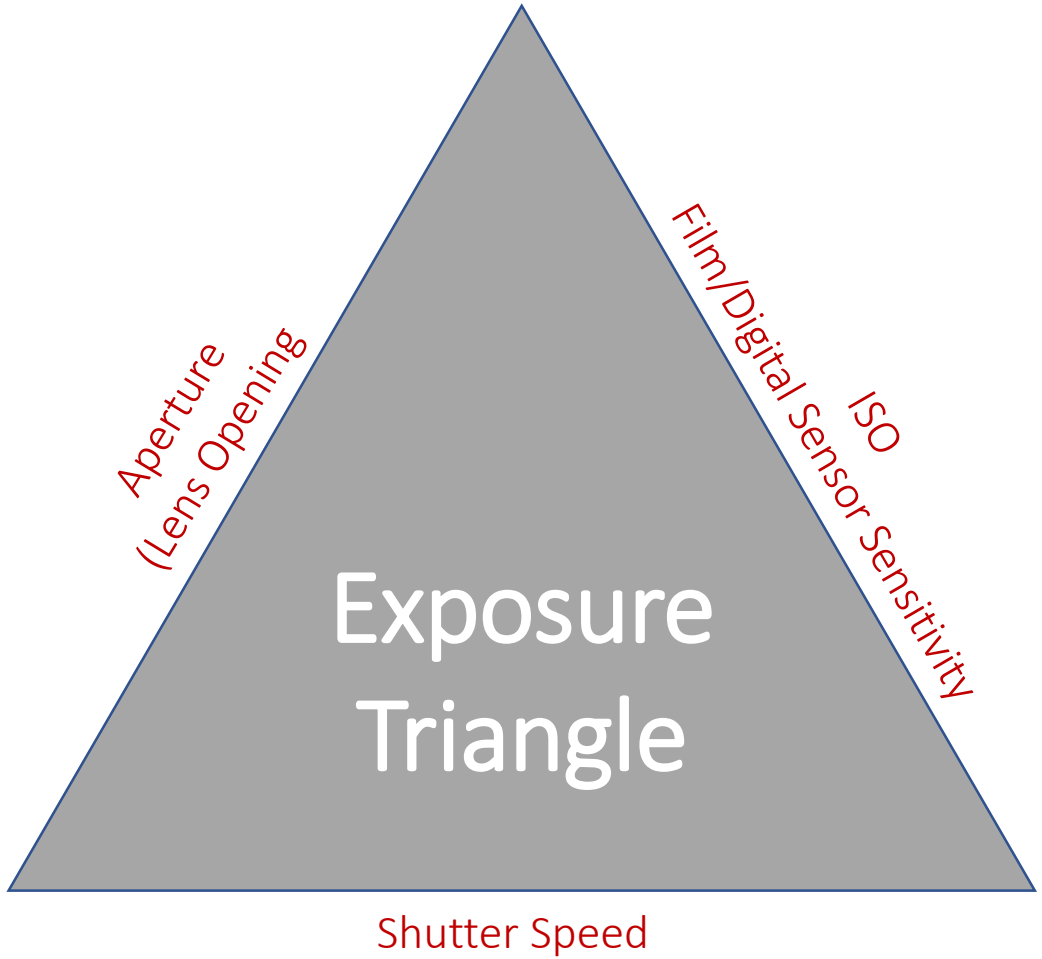


ISO 100

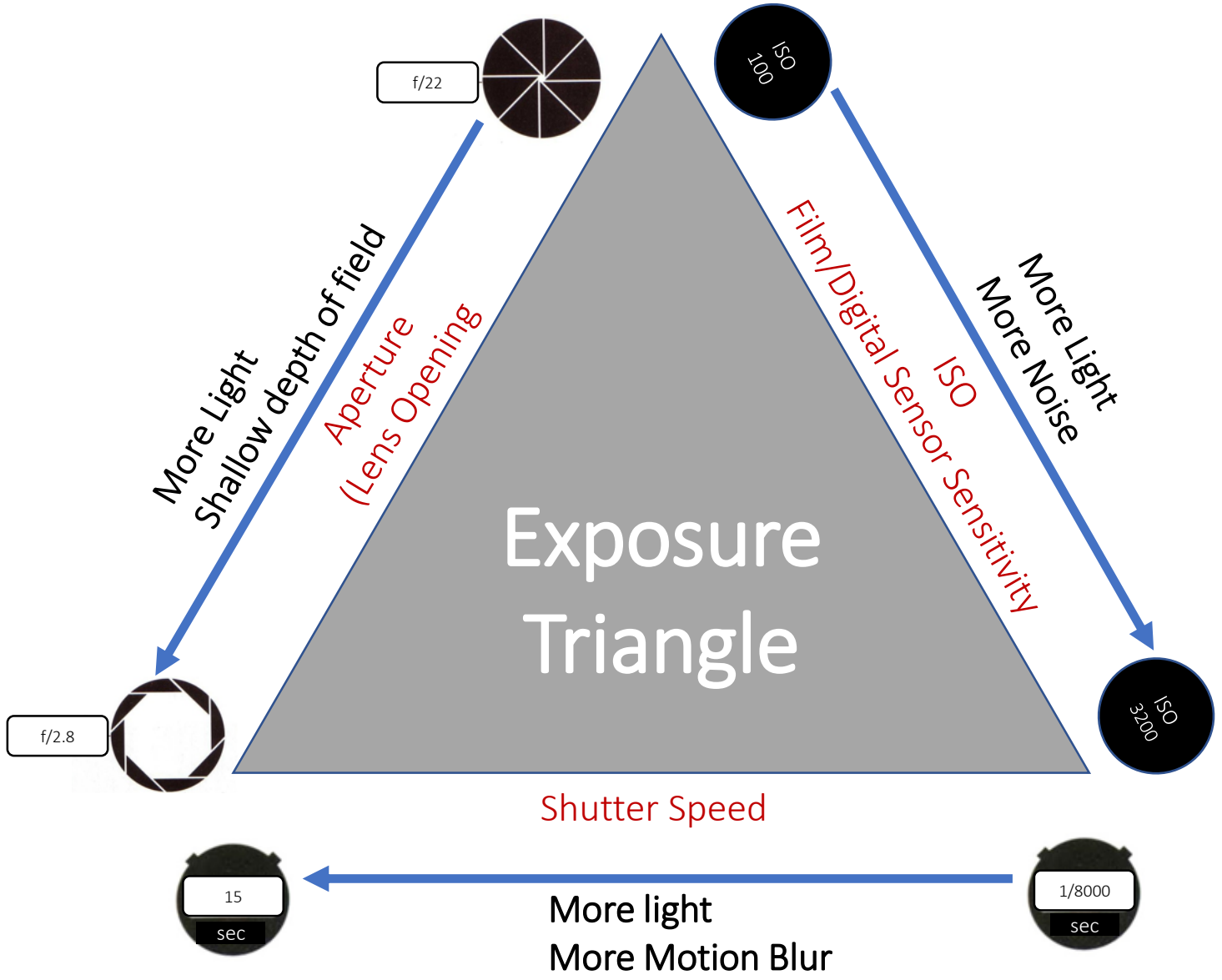
ISO 400

ISO 1000

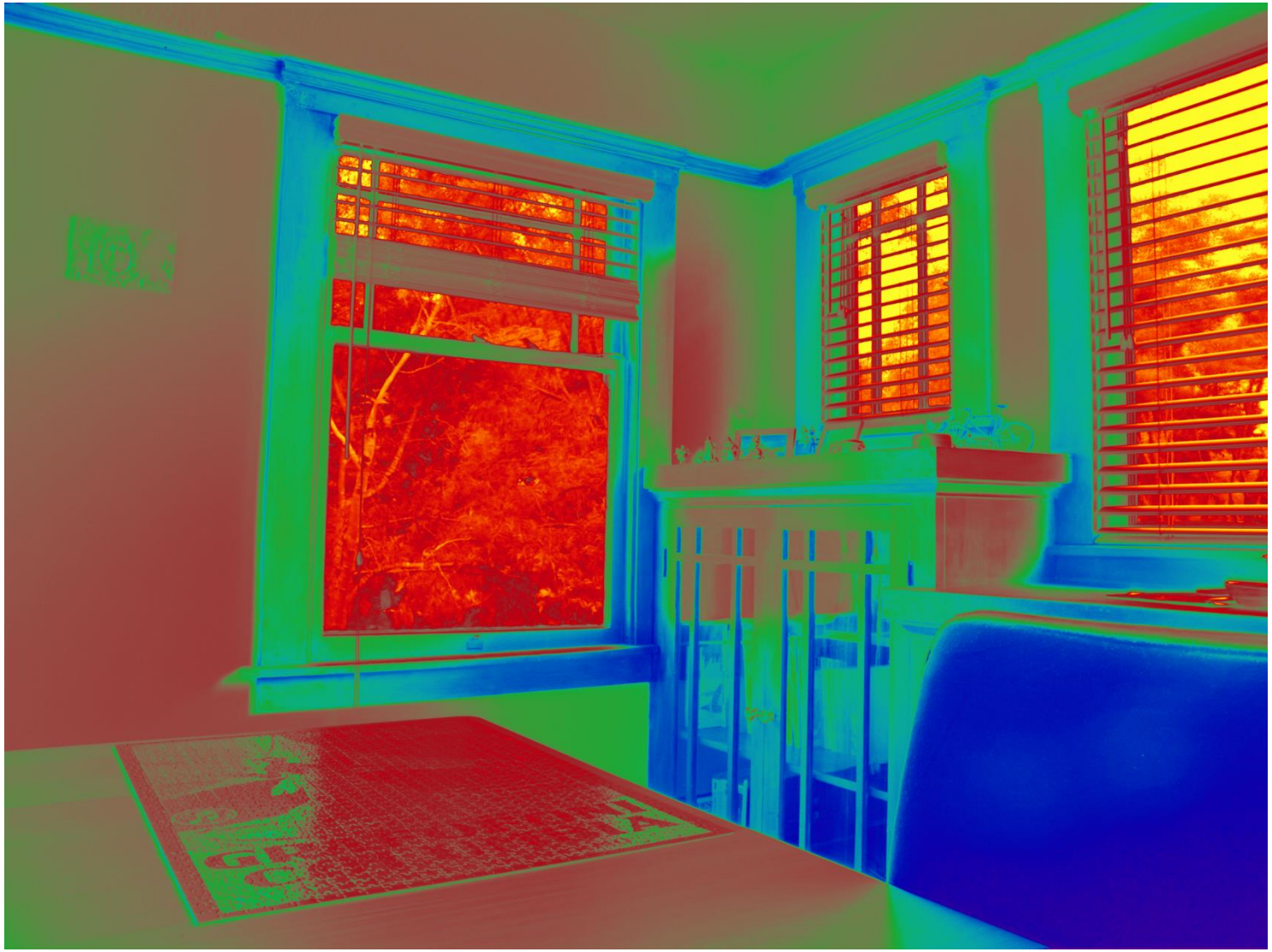
2.5 HDR Photography rules: Multiple exposures



2.5 HDR Photography rules:



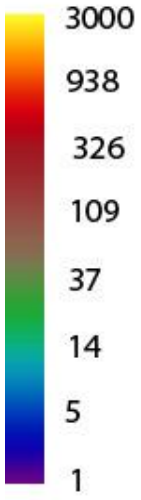
2.5 HDR Photography rules: Aperture Size



Aperture size: f / 4.0

Measured target luminance range between 1 – 16,000 cd/m^2

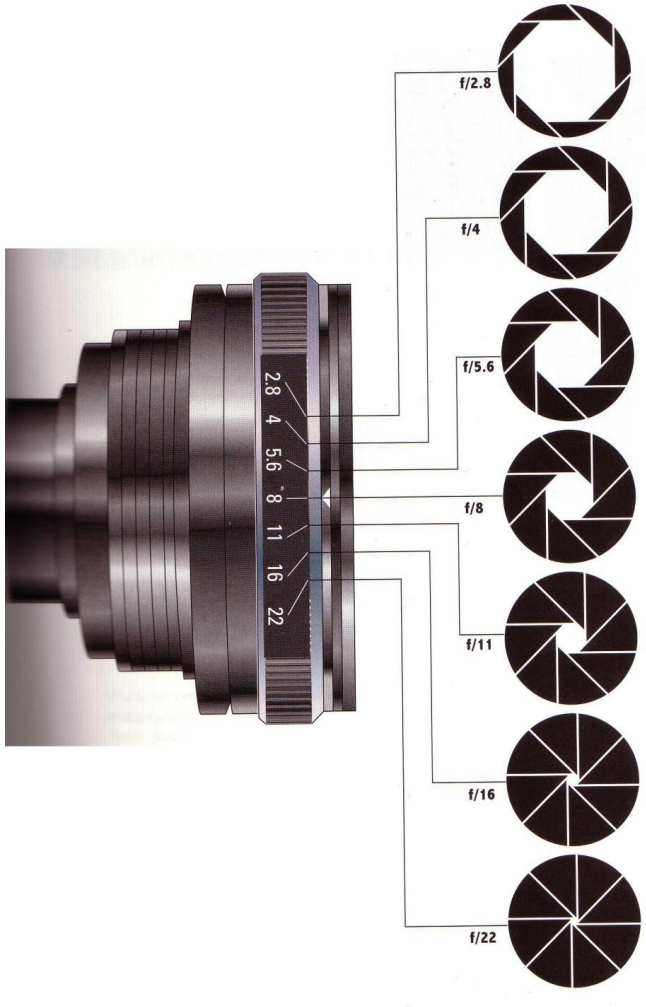
Maximum measurable luminance value with f/4.0 is ~**100,000 cd/m^2**



Luminance
Cd/m^2 - Nits

Inanici M. “Evaluation of High Dynamic Range Photography as a Luminance Measurement Technique”, Journal of Lighting Research and Technology, 38(2), 2006, 123-136.

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/m^2 as max. Luminance
- Multi-exposure sequence with f/11 captures approximately 1,000,000 cd/m^2 as max. Luminance
- Multi-exposure sequence with f/22 captures approximately 3,200,000 cd/m^2
- f/22 causes a significant amount of lens flare, impairing accuracy for the rest of the scene

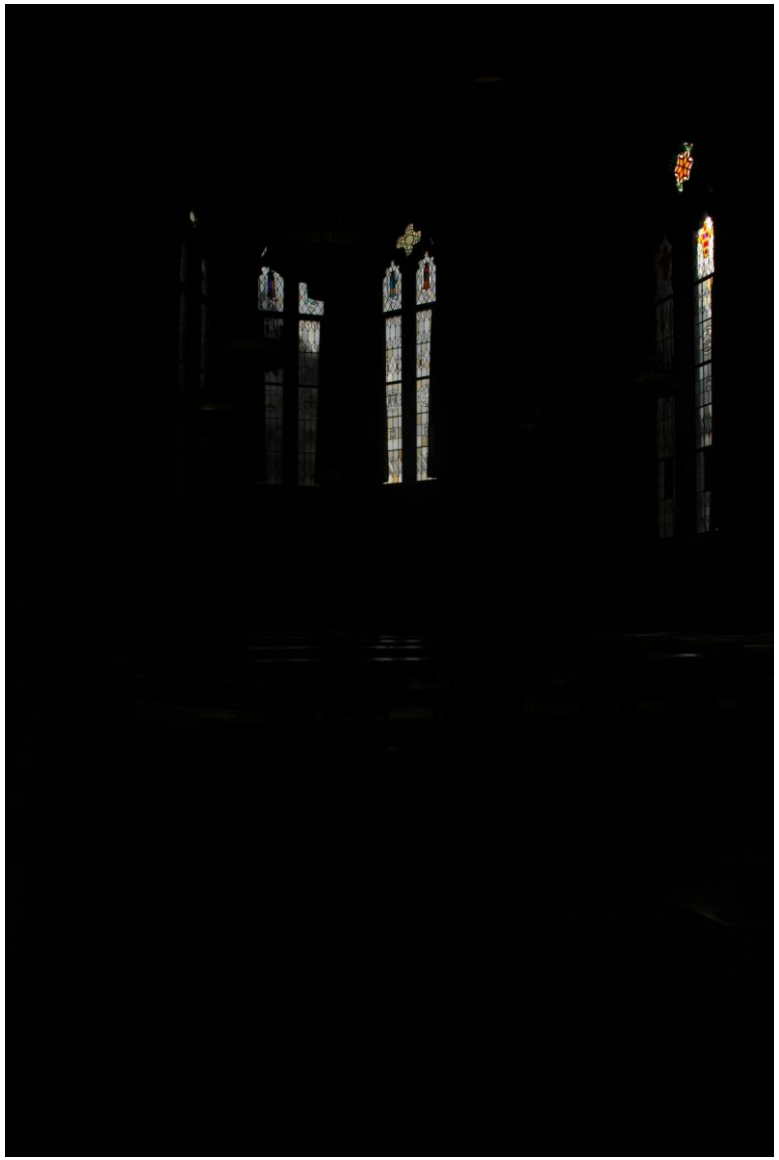
Jakubiec A, Inanici M, van den Wymelenberg K, Mahic A. "Improving the Accuracy of Measurements in Daylit Interior Scenes using High Dynamic Range Photography," *Passive and Low Energy Architecture Conference,* Los Angeles, CA, July 11-13, 2016.
Jakubiec A, van den Wymelenberg K, Inanici M, Mahic A. "Accurate Measurement of Daylit Interior Scenes using High Dynamic Range Photography," CIE Lighting Quality and Energy Efficiency Conference, Melbourne, Australia, March 3-5, 2016.

2.6 HDR Photography rules: Shutter speed

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 under exposed image should not be totally black!

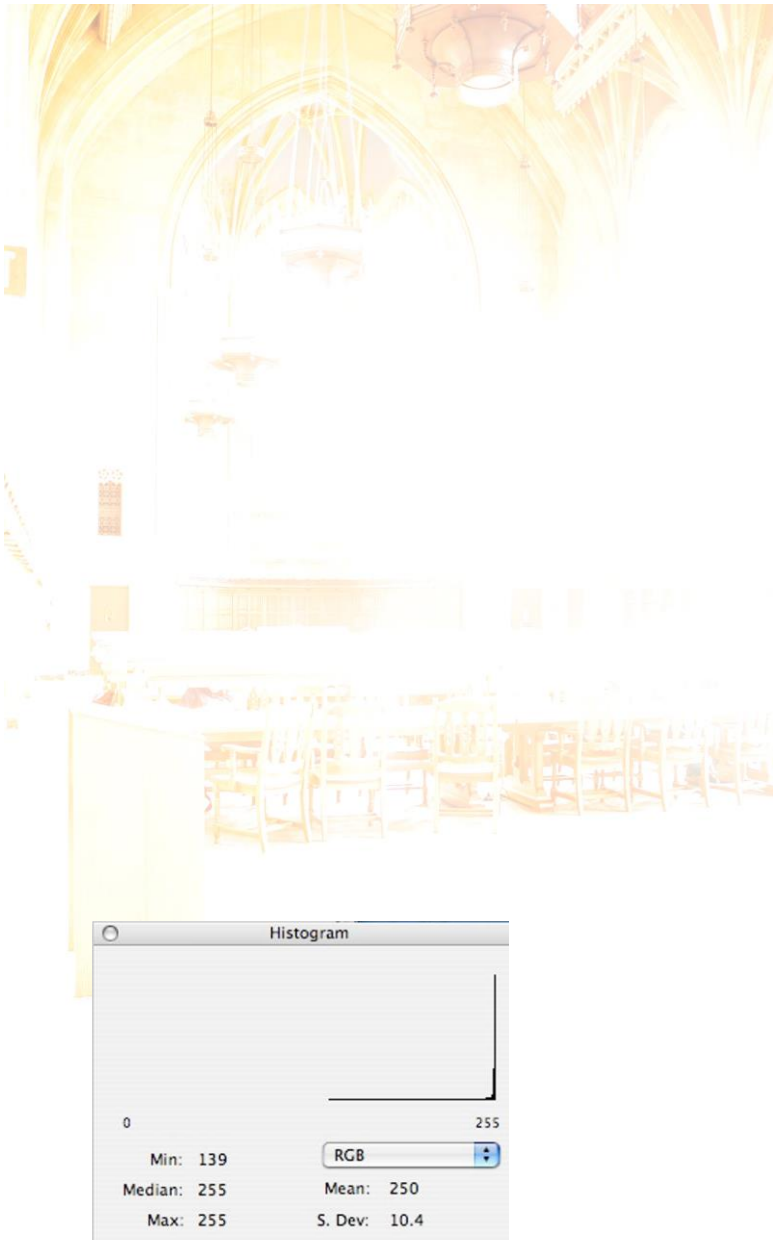


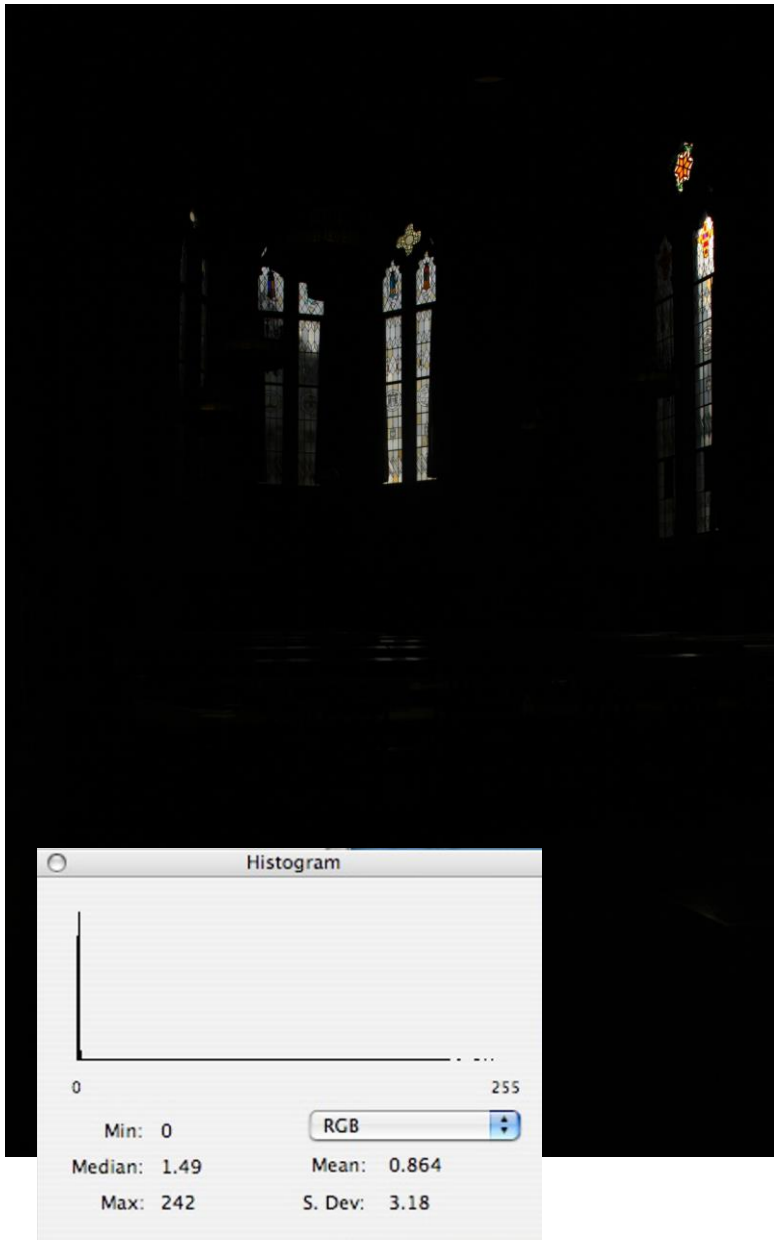
2.6 HDR Photography rules: Shutter speed

Rule #6:

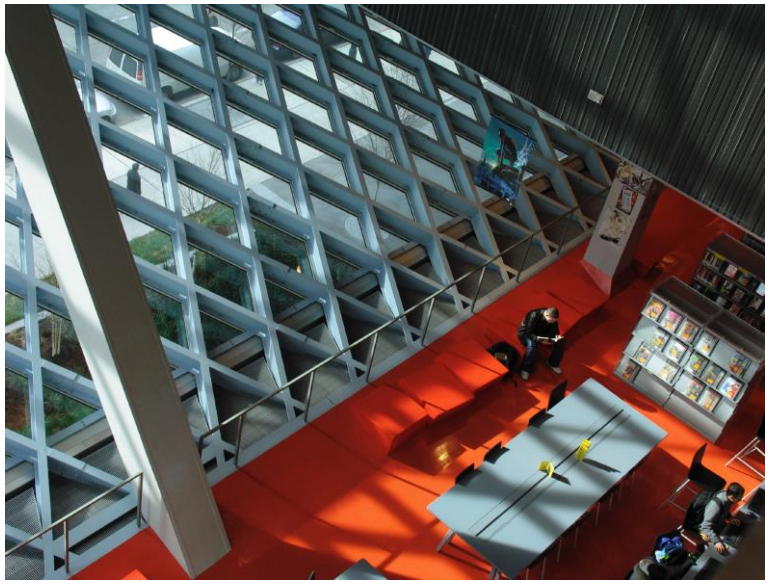
The starting shutter speed depends on the scene (test before you start).

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.





2.7 HDR Photography rules: Capture time



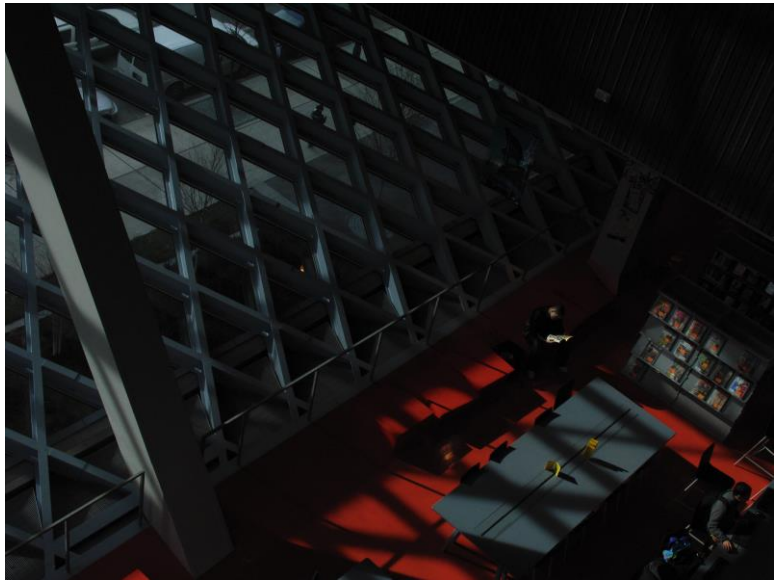
Rule #7:

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.

2.7 HDR Photography rules: Capture time



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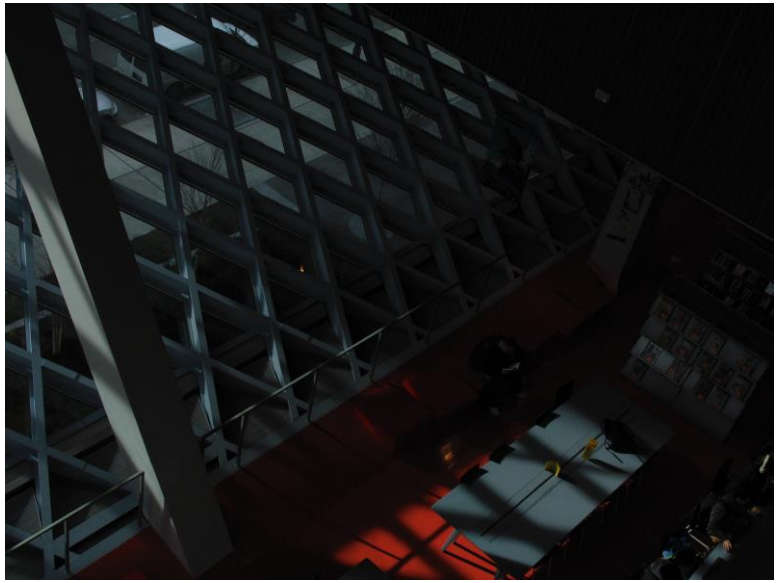
2.7 HDR Photography rules: Capture time



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.

For a regular HDR assembly, take 6 - 8 exposures to cover the range.

2.8 HDR Photography rules: First Capture Determining the camera response curve

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

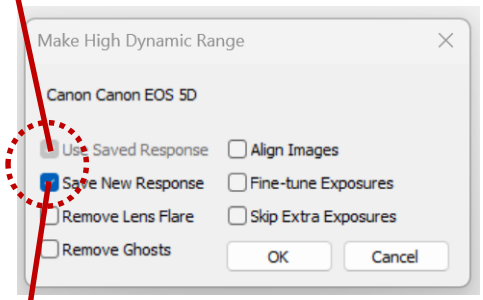
1. Use a tripod with a camera (a fisheye lens is preferred but not required)
2. Fix white balance to daylight
3. Set the file format to jpg
4. Fix the film speed to ISO 100
5. Fix the aperture size to f/11
6. Vary the shutter speed to take 6-8 photographs
7. Take photographs quickly in a stable environment
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.

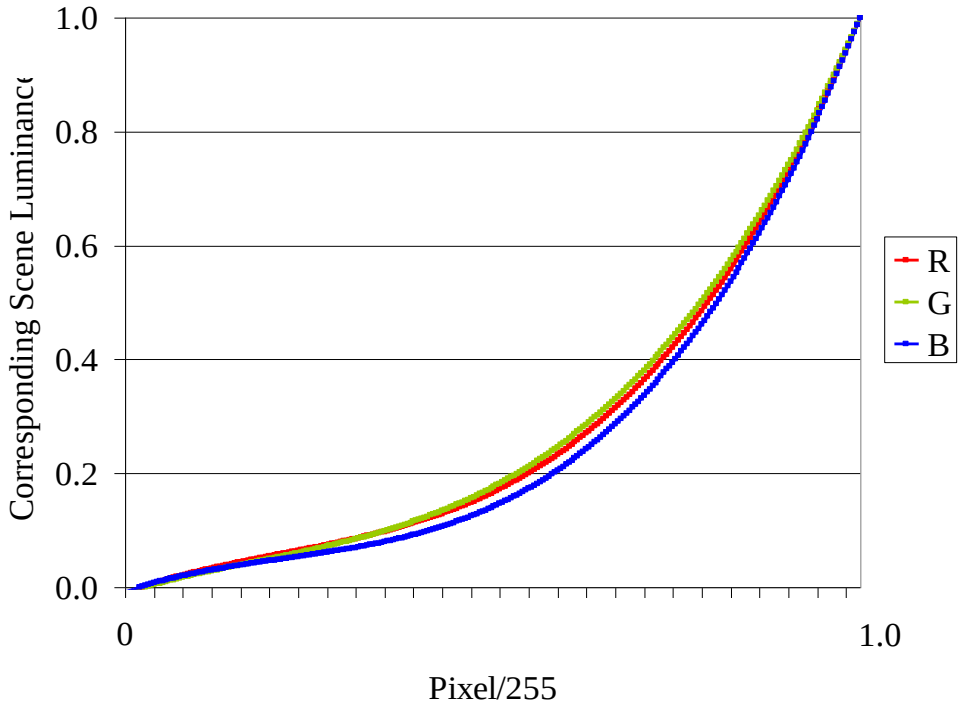
All subsequent HDR image mergings



The first introduction of the camera to the software

3.2 HDR Image Generation: Camera Response Curve

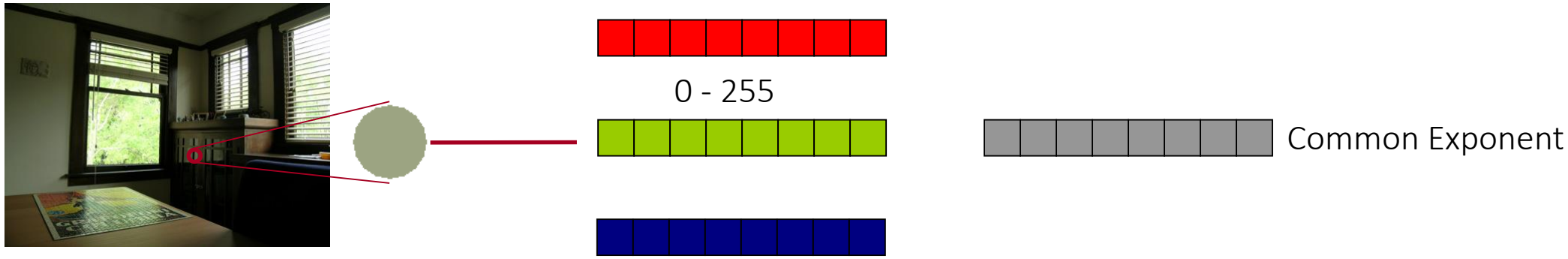
Radiometric self-calibration* is a computationally derived calibration process that is used to relate the pixel values to real-world luminances. The curves (for RGB channels) that model the accumulated radiometric non-linearities of the image acquisition process, without addressing the individual source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

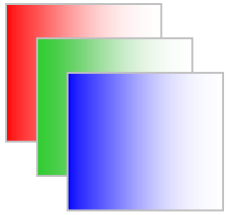


Every camera has a different calibration curve

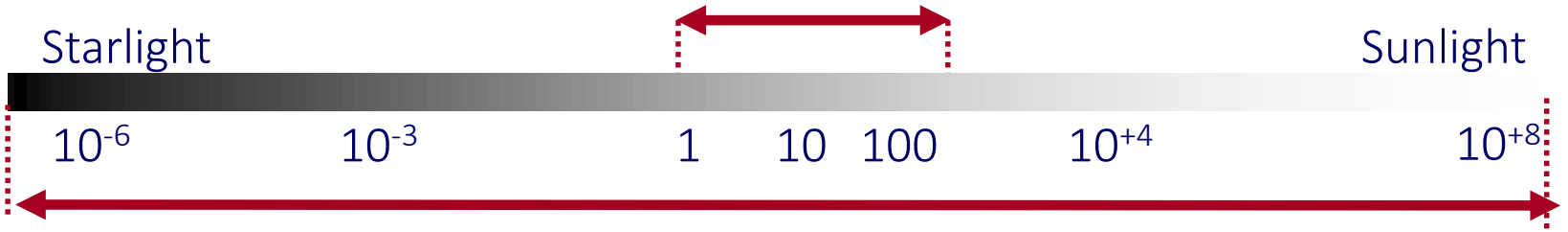
*Mitsunaga T and Nayar S. “Radiaometric Self calibration,” IEEE Computer Society Conference on Computer Vision and Pattern Recognition , 1999.

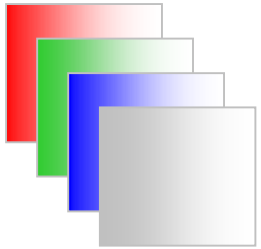
3.3 HDR Image format





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

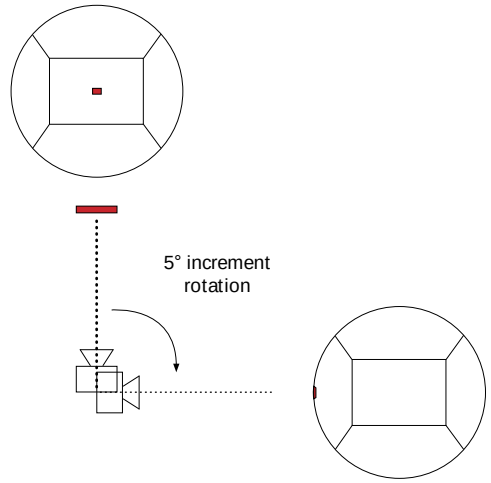
Use a fixed, single target (50% neutral grey card)

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

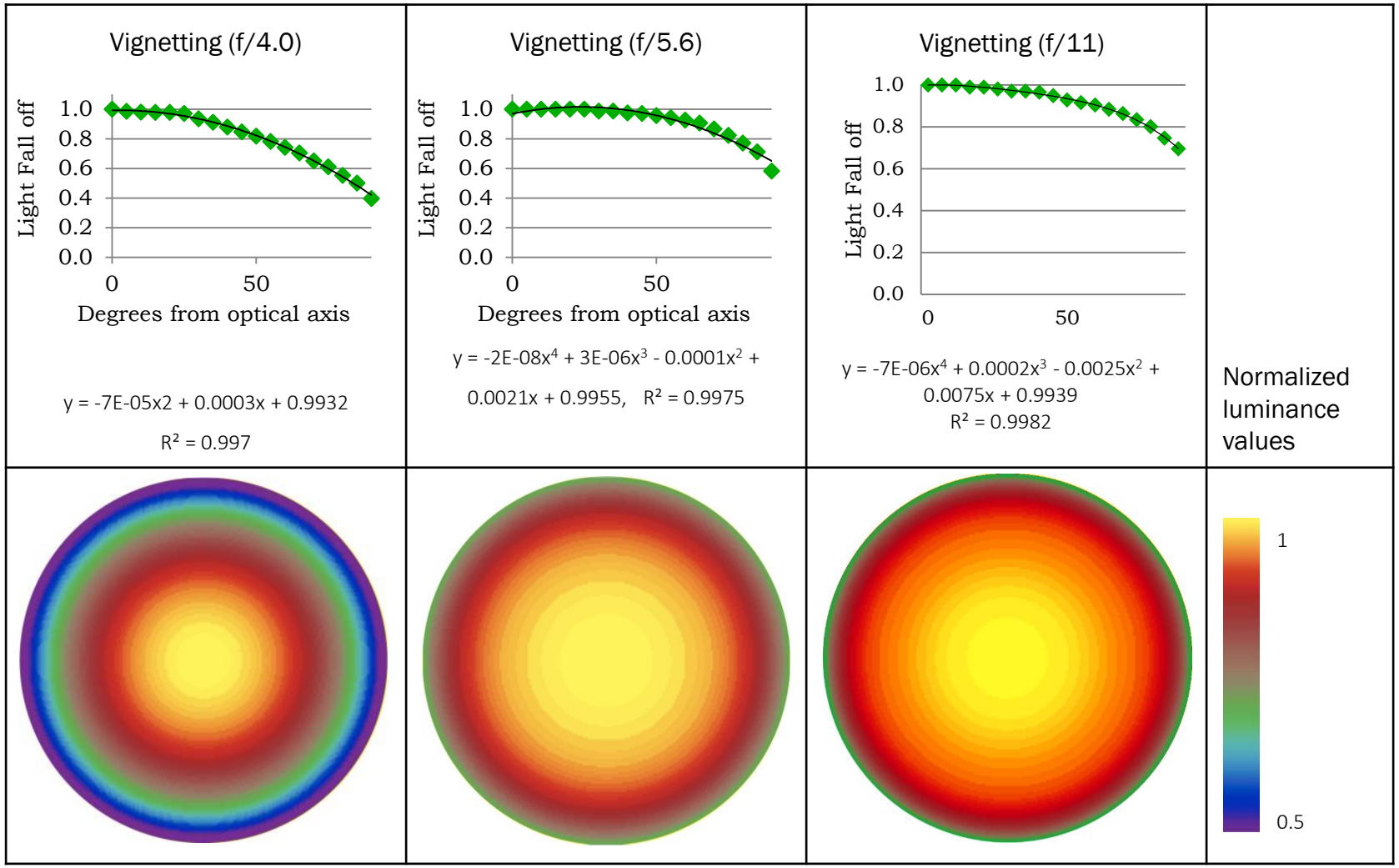
Rotate the camera in 5-degree increments about its nodal point. Each time, a new image is captured.

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

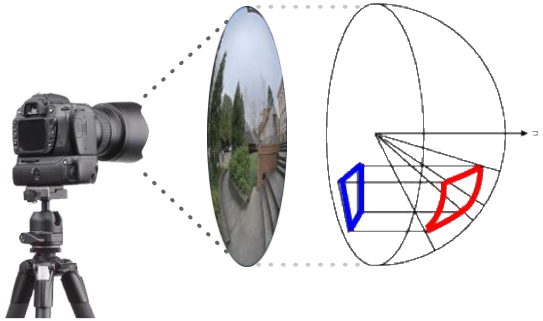
Measure under stable electric lighting conditions.



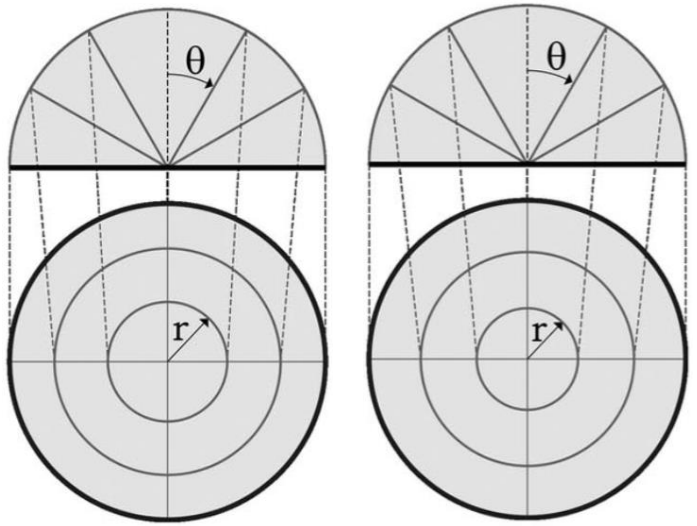
4.1 HDR Post-processing: Vignetting correction for fisheye lenses



4.2 HDR Post-processing: (Optional) Correct for lens geometric aberrations



Equidistant / Equisolid projection



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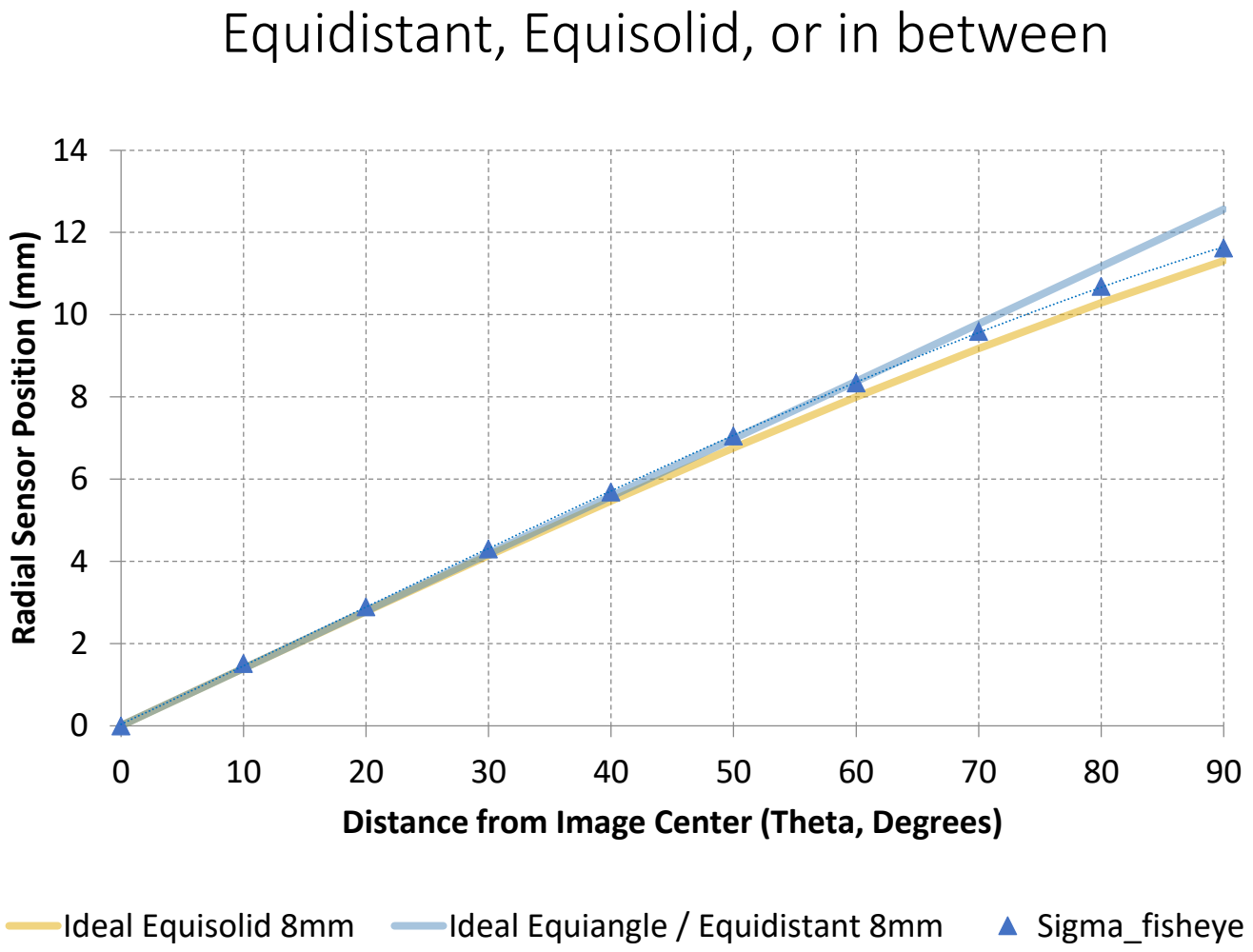
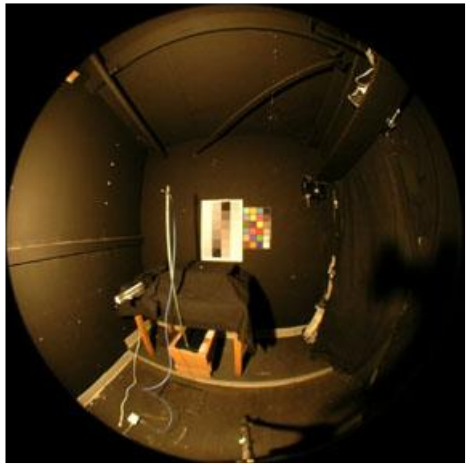


4.3 HDR Post-processing: Luminance Calibration

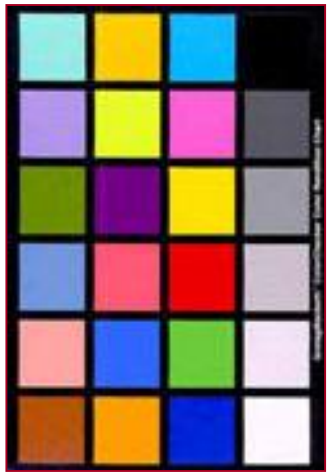
A single luminance measurement of a gray card in the field can be used to calibrate the image.

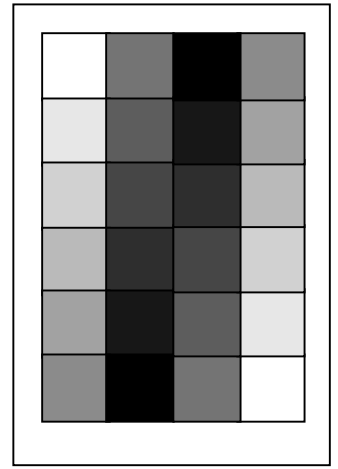
It is recommended to perform one luminance measurement for every scene captured.

4.4. Accuracy of HDR Photography



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

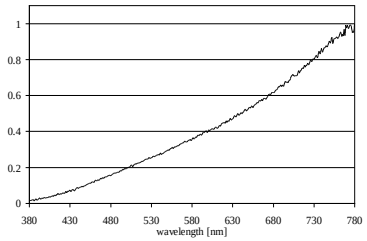




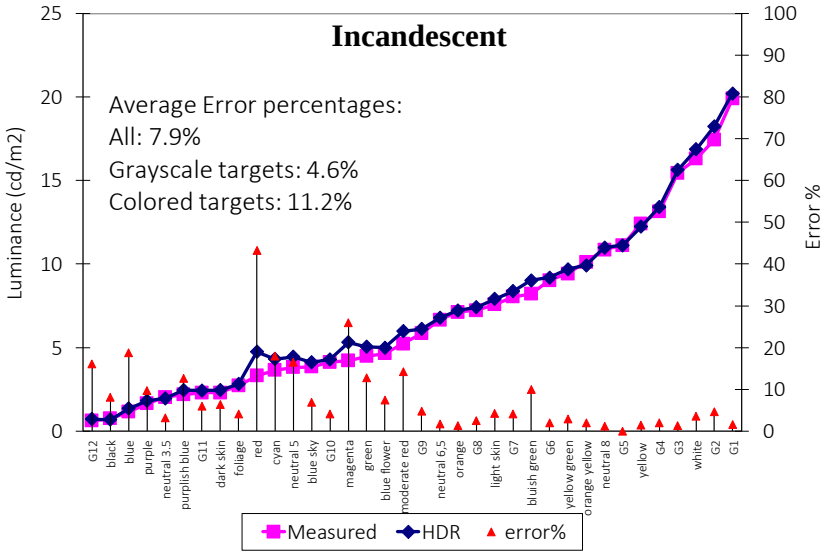
Inanici M. “Evaluation of High Dynamic Range Photography as a Luminance Measurement Technique”, Journal of Lighting Research and Technology, 38(2), 2006, 123-136.

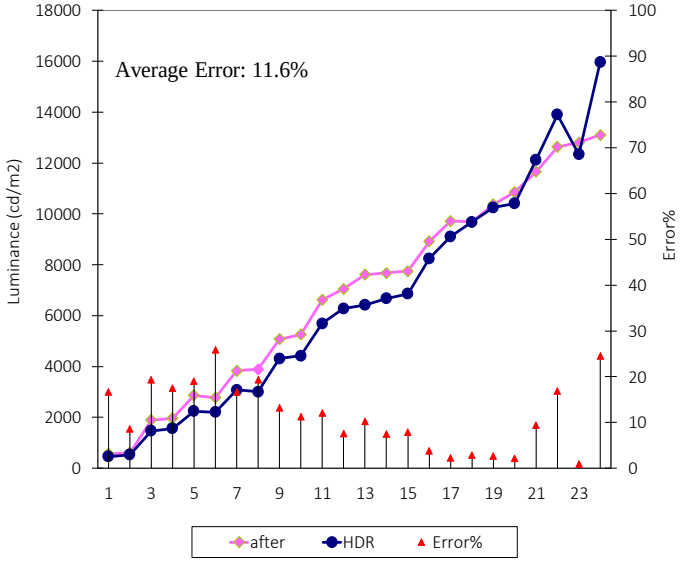
4.4 Accuracy of HDR Photography

Spectral data



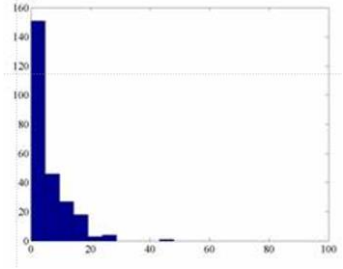
Luminance measurements

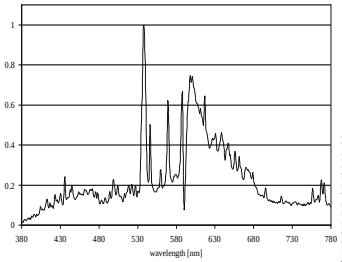


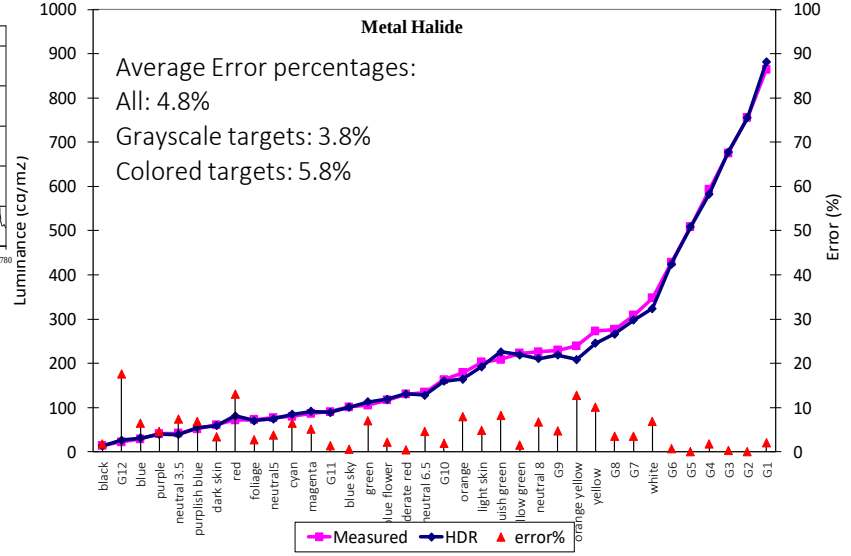


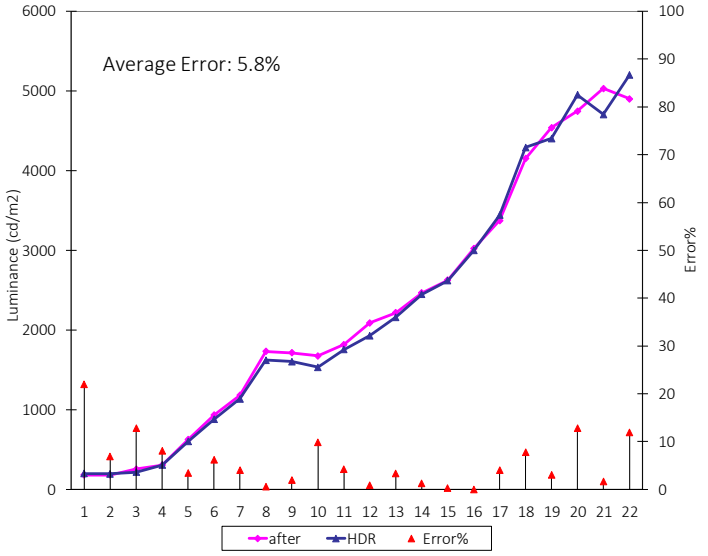
Average Error
for all targets < 10%

Average error for grey scale < 5%

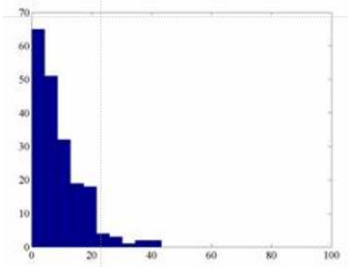








Error % for colored targets (without color corrections)*



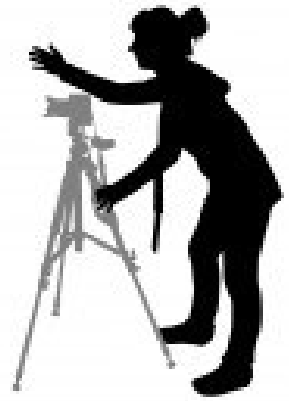
4.5 Post-processing: Illuminance Calibration

(Recommendation) #10:

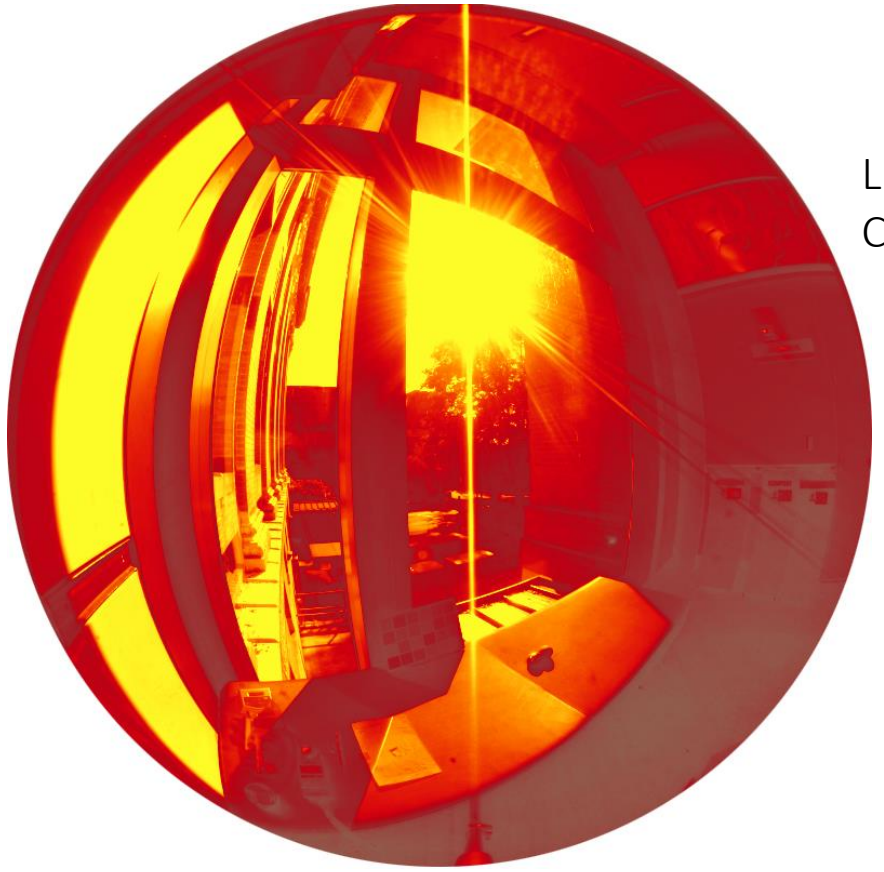
Further calibration for high luminance scenes (sun disc is visible in the scene)

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

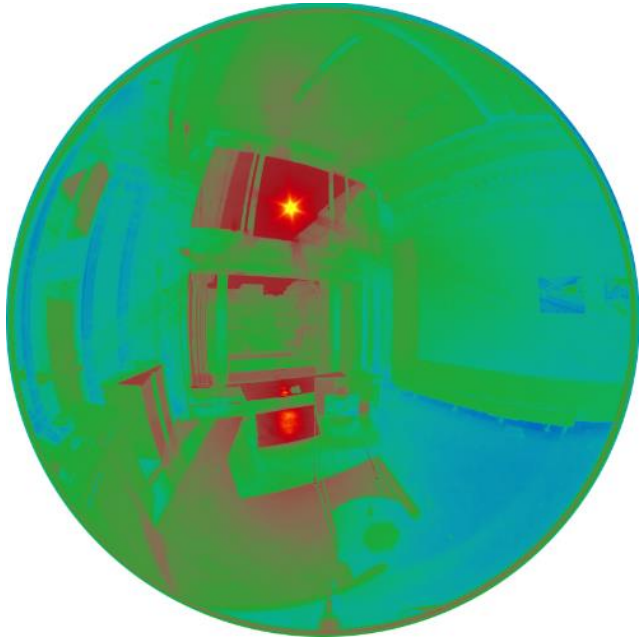
This value can be used for luminous overflow in HDR post-processing.

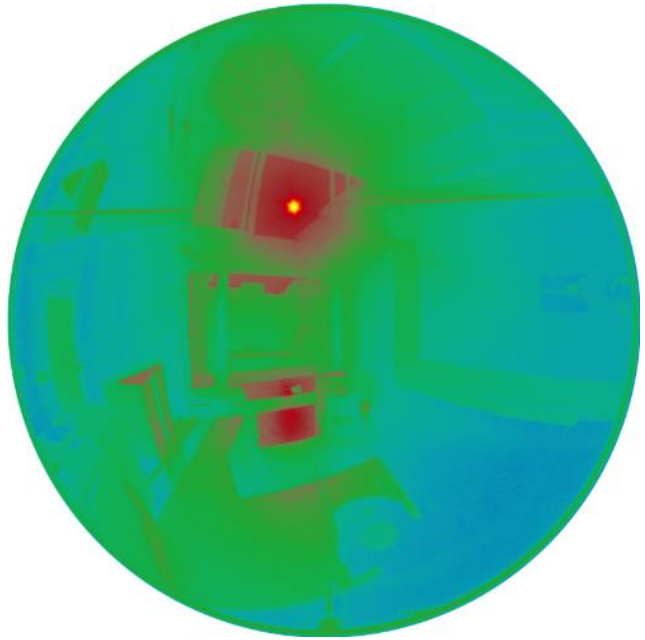


4.5 Post-processing:
Luminous overflow: very high luminances in the field



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





f/11 & No Filter ~1 million cd/m^2

f/11 & ND3 ~272 million cd/m^2

Jakubiec A, Inanici M, van den Wymelenberg K, Mahic A. "Improving the Accuracy of Measurements in Daylit Interior Scenes using High Dynamic Range Photography," *Passive and Low Energy Architecture Conference,* Los Angeles, CA, July 11-13, 2016.
Jakubiec A, van den Wymelenberg K, Inanici M, Mahic A. "Accurate Measurement of Daylit Interior Scenes using High Dynamic Range Photography," CIE Lighting Quality and Energy Efficiency Conference, Melbourne, Australia, March 3-5, 2016.

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: 2.18×10^9 cd/m^2

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

Neutral Density Filter 3

Original method:
Stumpfel J., Jones A., Wenger A., and Debevec P. 2004. “Direct HDR Capture of the Sun and Sky”, 3rd International Conference on Virtual Reality, Computer Graphics, Visualization and Interaction in Africa, Cape Town, South Africa.

Validation:
Inanici M. “Evaluation of High Dynamic Range Image-based Sky Models in Lighting Simulation,” Luekos, Journal of the Illuminating Engineering Society (IES), 7(2), October 2010, 69-84.

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

- 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
- increases 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 overflown pixels.
- The luminances of the brightest pixels (pixels above a threshold) are increased until image illuminance matches the measured illuminance.

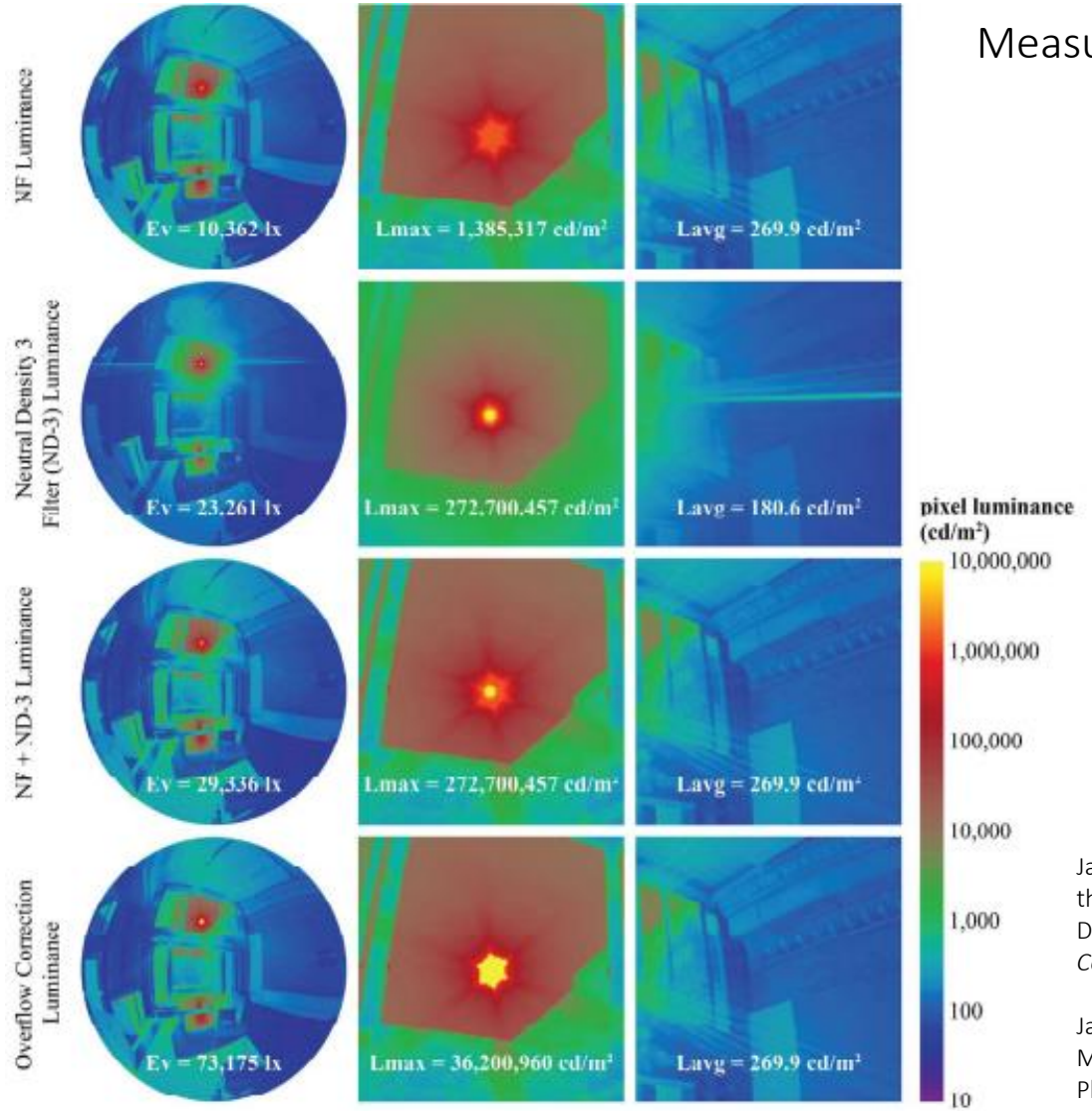
4.5 Post-processing:
Luminous overflow: very high luminances in the field

No filter f/11

ND3 with f/11

Partial combinations of
no filter and ND3 with f/11

Luminous overflow correction



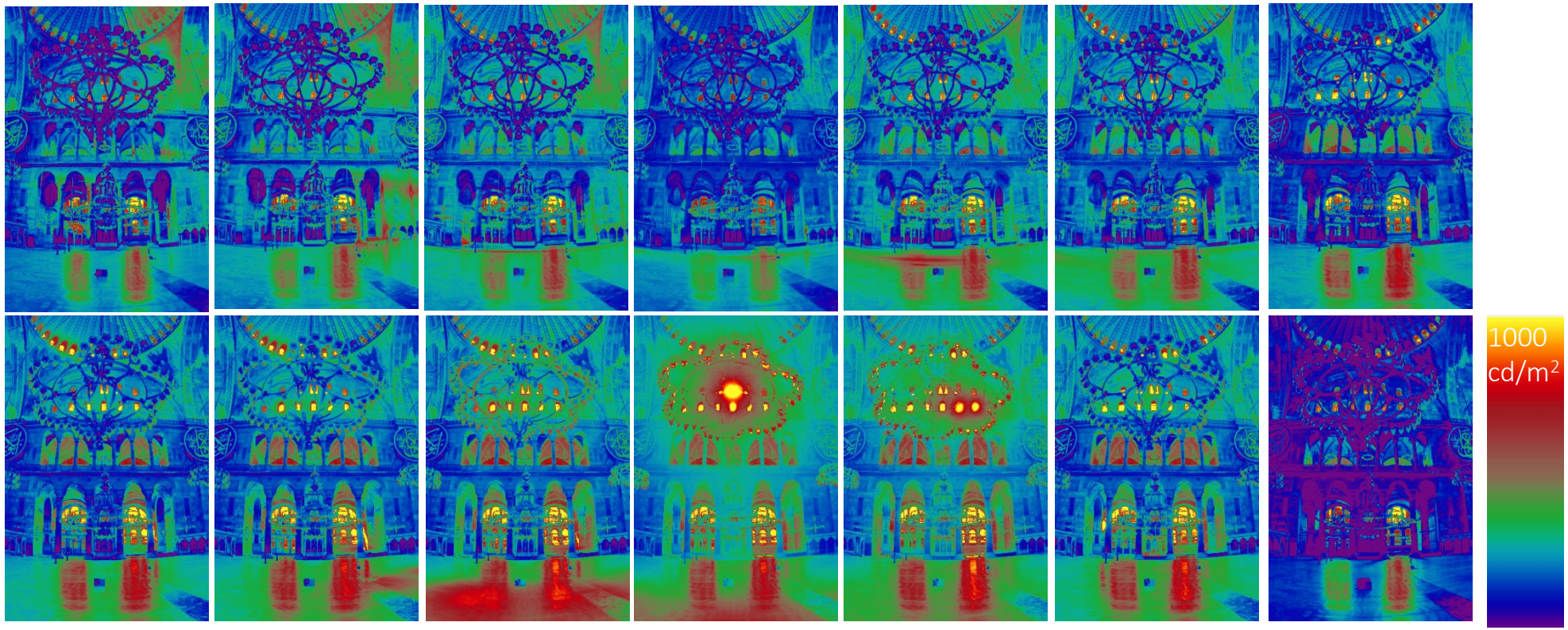
Measured illuminance: 73,175 Lx

Jakubiec A, Inanici M, van den Wymelenberg K, Mahic A. "Improving the Accuracy of Measurements in Daylit Interior Scenes using High Dynamic Range Photography," *Passive and Low Energy Architecture Conference,* Los Angeles, CA, July 11-13, 2016.

Jakubiec A, van den Wymelenberg K, Inanici M, Mahic A. "Accurate Measurement of Daylit Interior Scenes using High Dynamic Range Photography," CIE Lighting Quality and Energy Efficiency Conference, Melbourne, Australia, March 3-5, 2016.

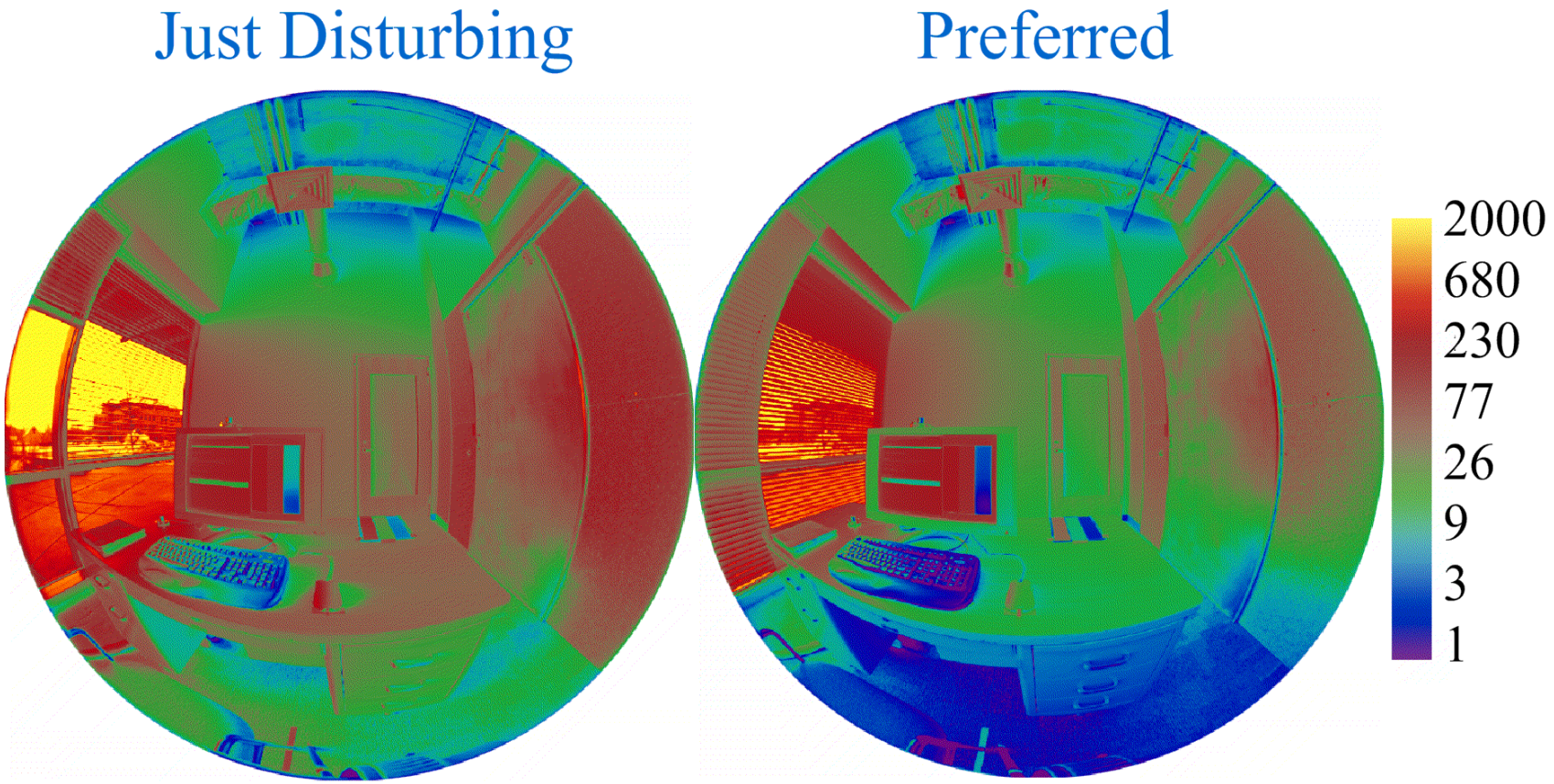
5.1 Applications:
Evaluation of existing environments

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



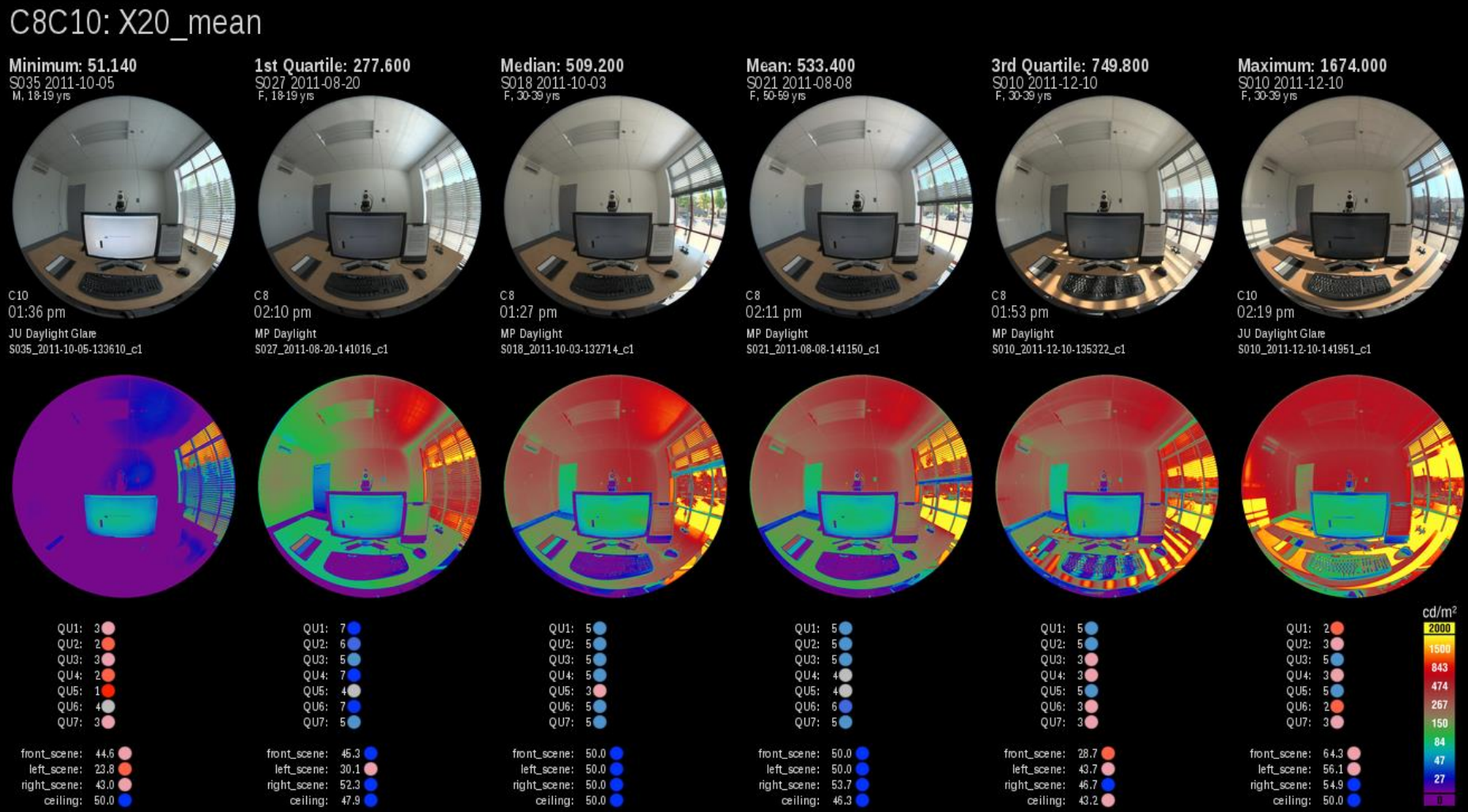
Inanici M. ”Lighting Analysis of Hagia Sophia”. Annuals of Hagia Sophia Museum: No. 17, Istanbul: December 2014, 128-202

5.2 Applications: Human subject studies



van den Wymelenberg K, Inanici M and Johnson P. "The Effect of Luminance Distribution Patterns on Occupant Preference in a Daylit Office Environment," *Luekos*, *Journal of the Illuminating Engineering Society (IES),* 7(2), 103-122, 2010.

5.2 Applications: Human subject studies



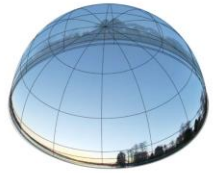
van den Wymelenberg K and Inanici, M. "Evaluating a New Suite of Luminance-Based Design Metrics for Predicting Human Visual Comfort in Offices with Daylight," Leukos: 12(3), 113-138, 2016.
van den Wymelenberg K and Inanici M. “A Critical Investigation of Common Lighting Design Metrics for Predicting Human Visual Comfort in Offices with Daylight,” *Leukos,* 10(3), 145-164, 2014.

5.3 HDR Sky models

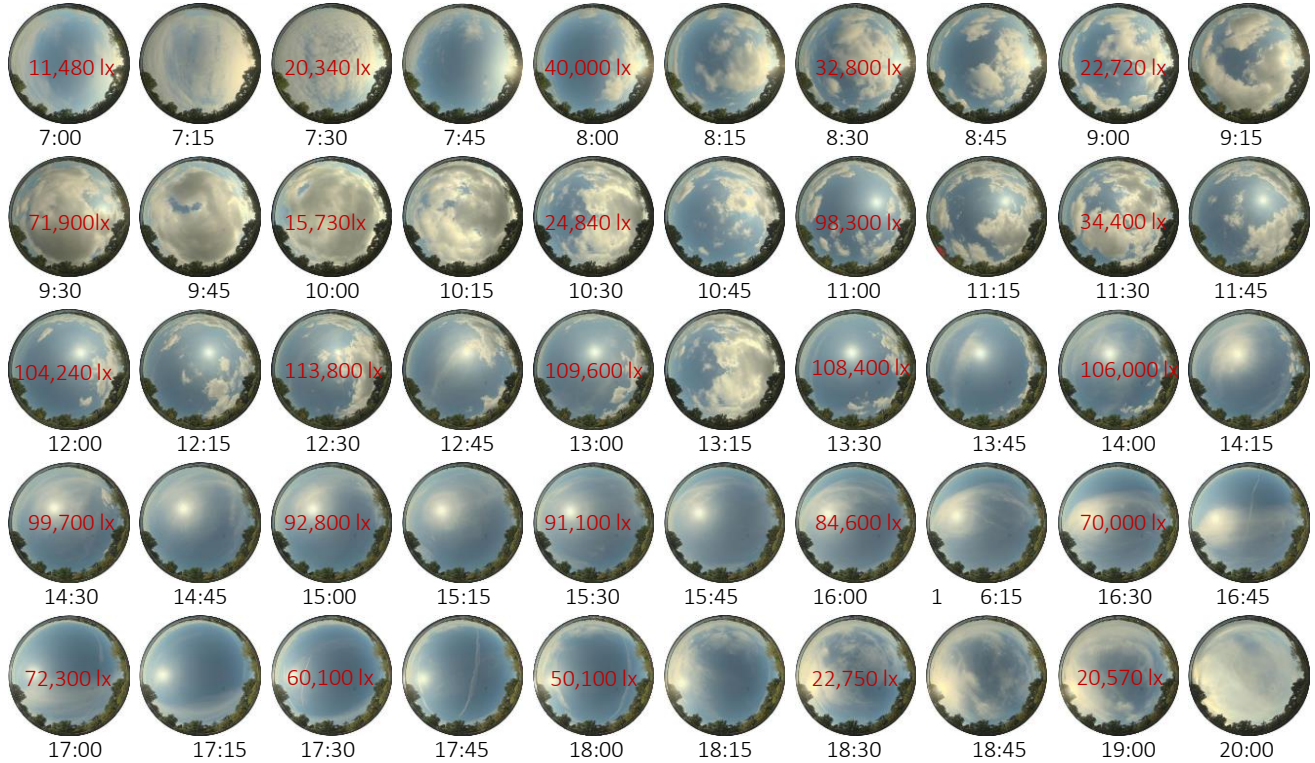
High Dynamic Range image is assembled from multiple exposure photographs;

Post processed to correct for aberrations

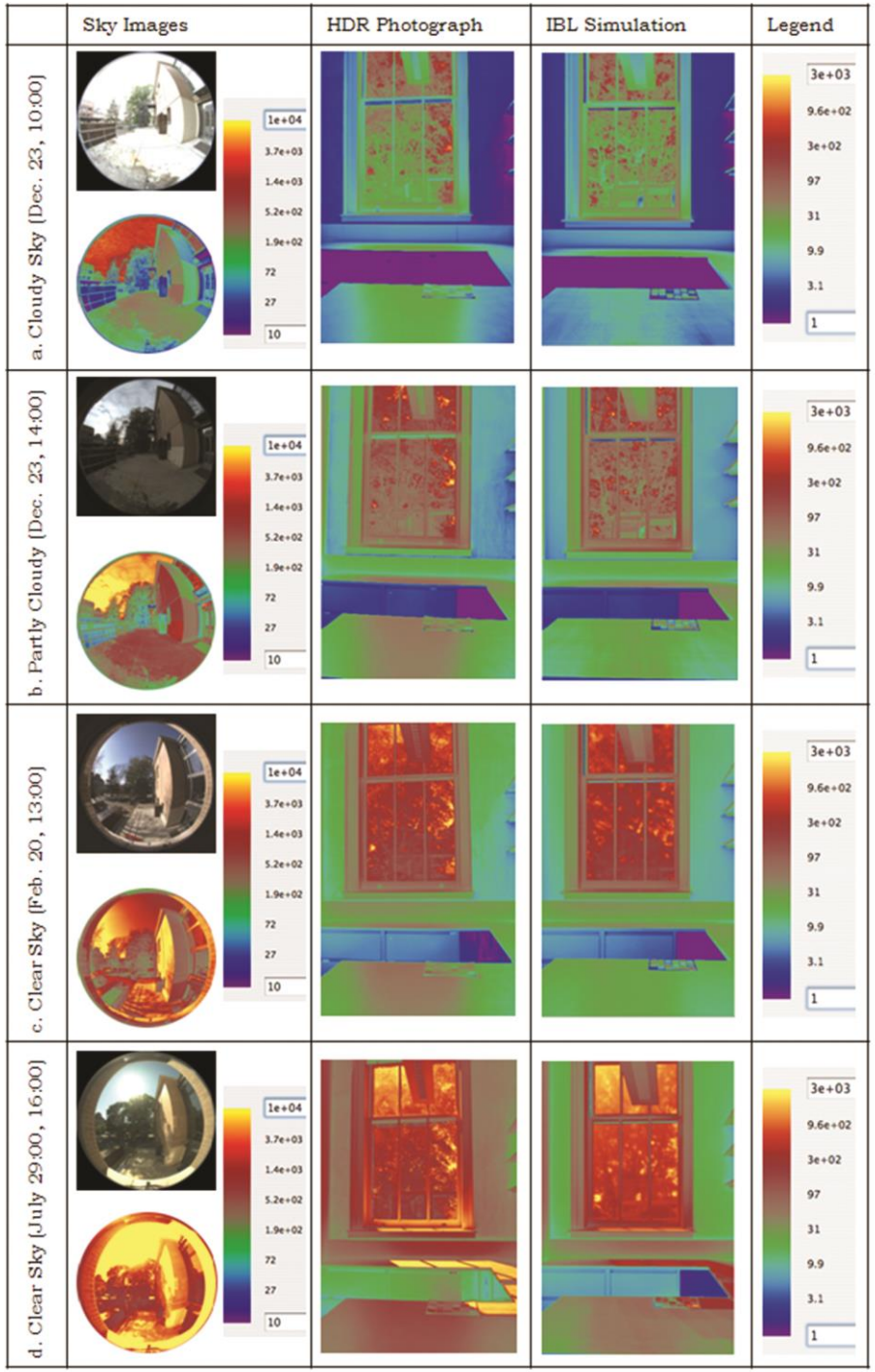
Projected onto an invisible hemisphere;



To model a naturally occurring sky.



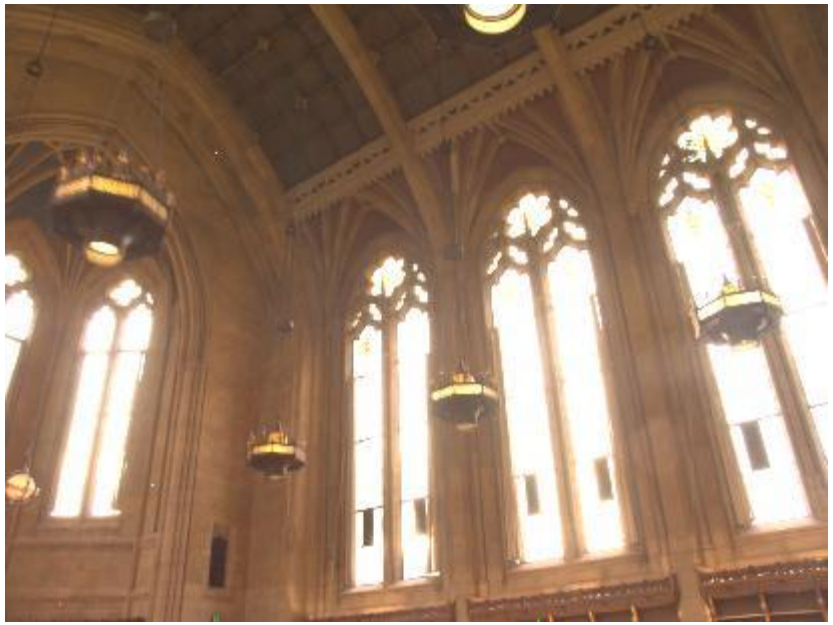
5.4 Applications
Image-based Lighting Simulations



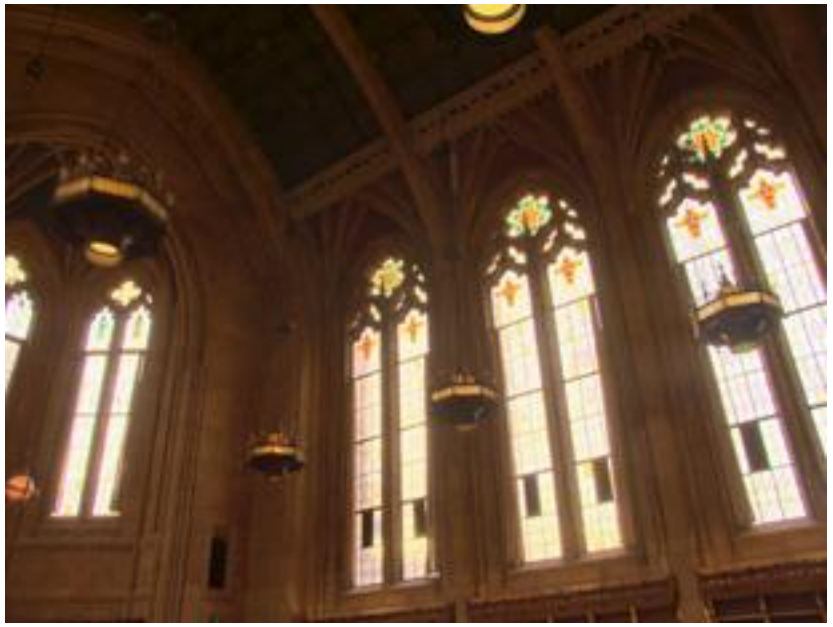
Inanici M and Hashemloo A. "An investigation of the daylighting simulation techniques and sky modeling practices for occupant-centric evaluations", *Building and Environment*, 113: 220-231, 2017.

Inanici M. “Evaluation of High Dynamic Range Image-based Sky Models in Lighting Simulation,” *Luekos*, Journal of the Illuminating Engineering Society (IES), 7(2), October 2010, 69-84.

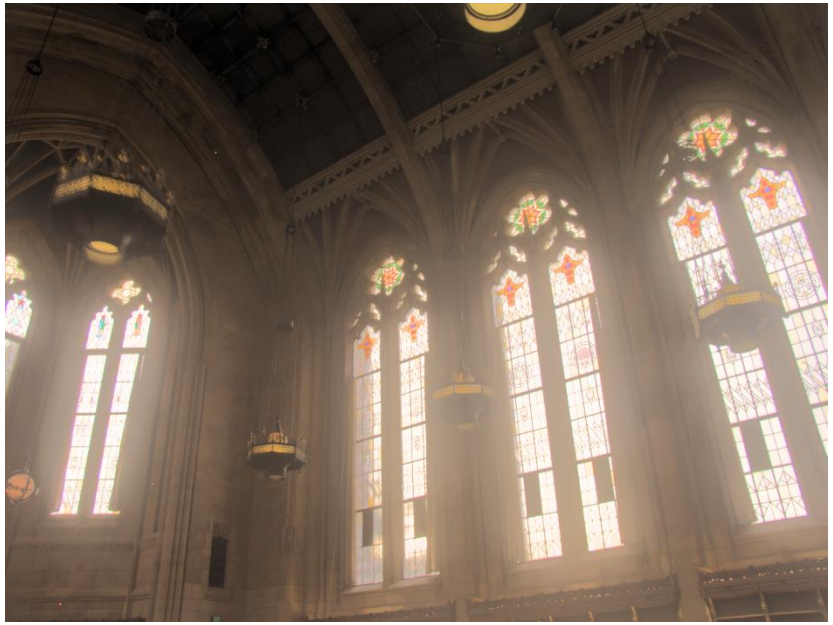
5.6 Applications: Visualization through tone-mapping



Select Exposure



Reinhard Photographic Tone Mapping



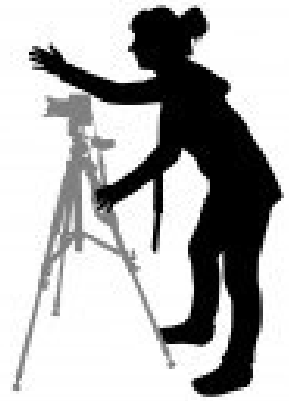
Ward Human sensitivity Tone Mapping
Radiance (pcond –h)

-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)

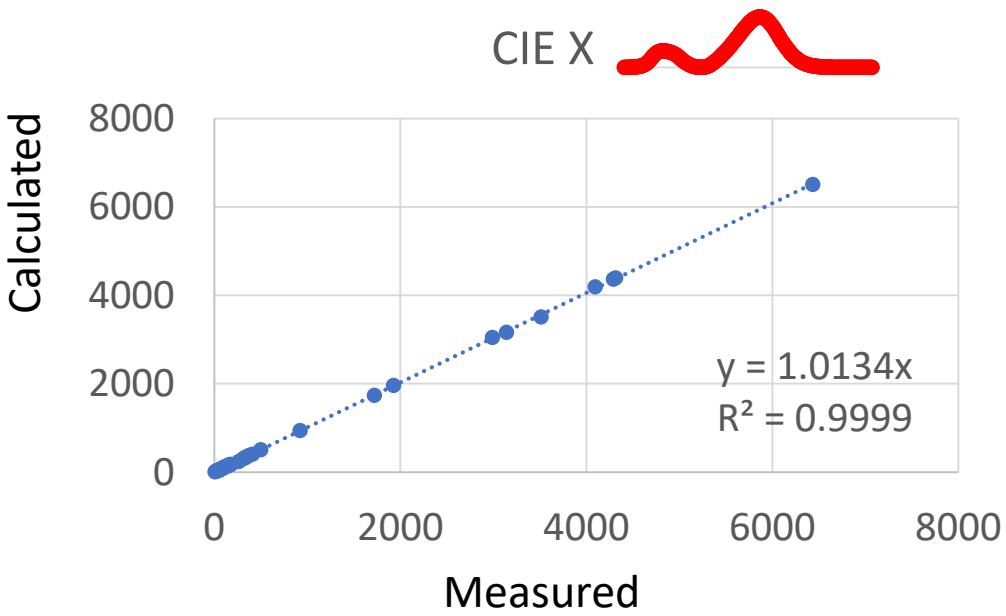
6. Applications: Non-Visual impact of lighting Trichromatic (CIE XYZ) Calibration

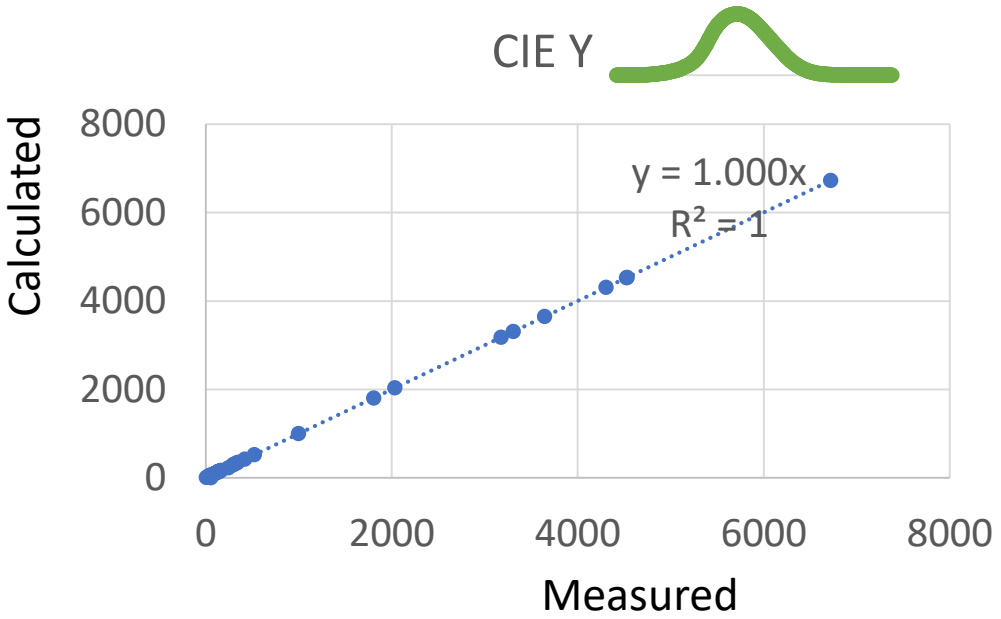
Recommendation #11:

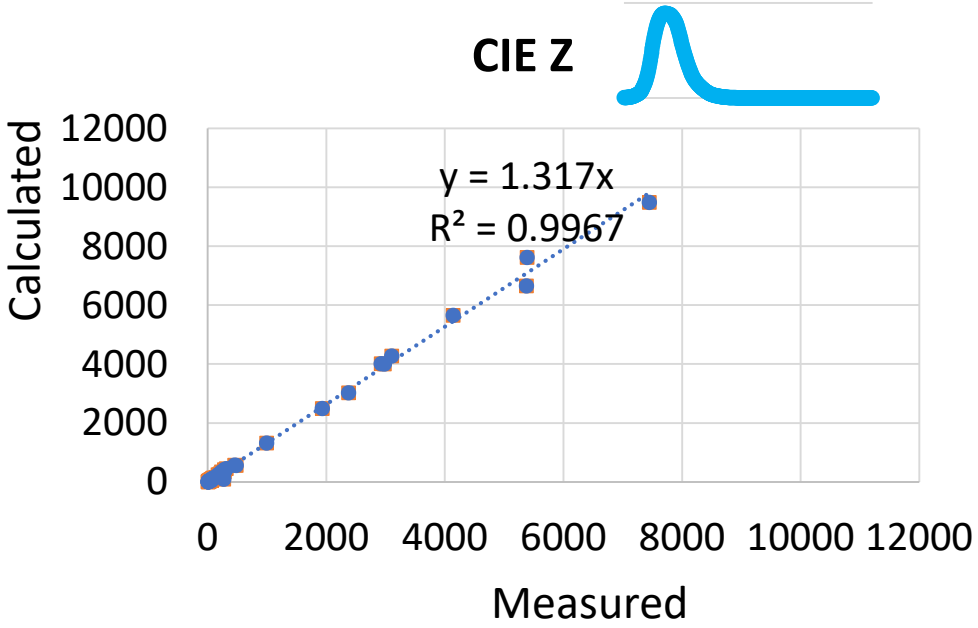
If you would like to use your HDR image for measuring non-visual effects of light (melanopic light), use a hand-held spectrophotometer or colorimeter, instead of an illuminance meter.



6. Applications: Non-Visual impact of lighting





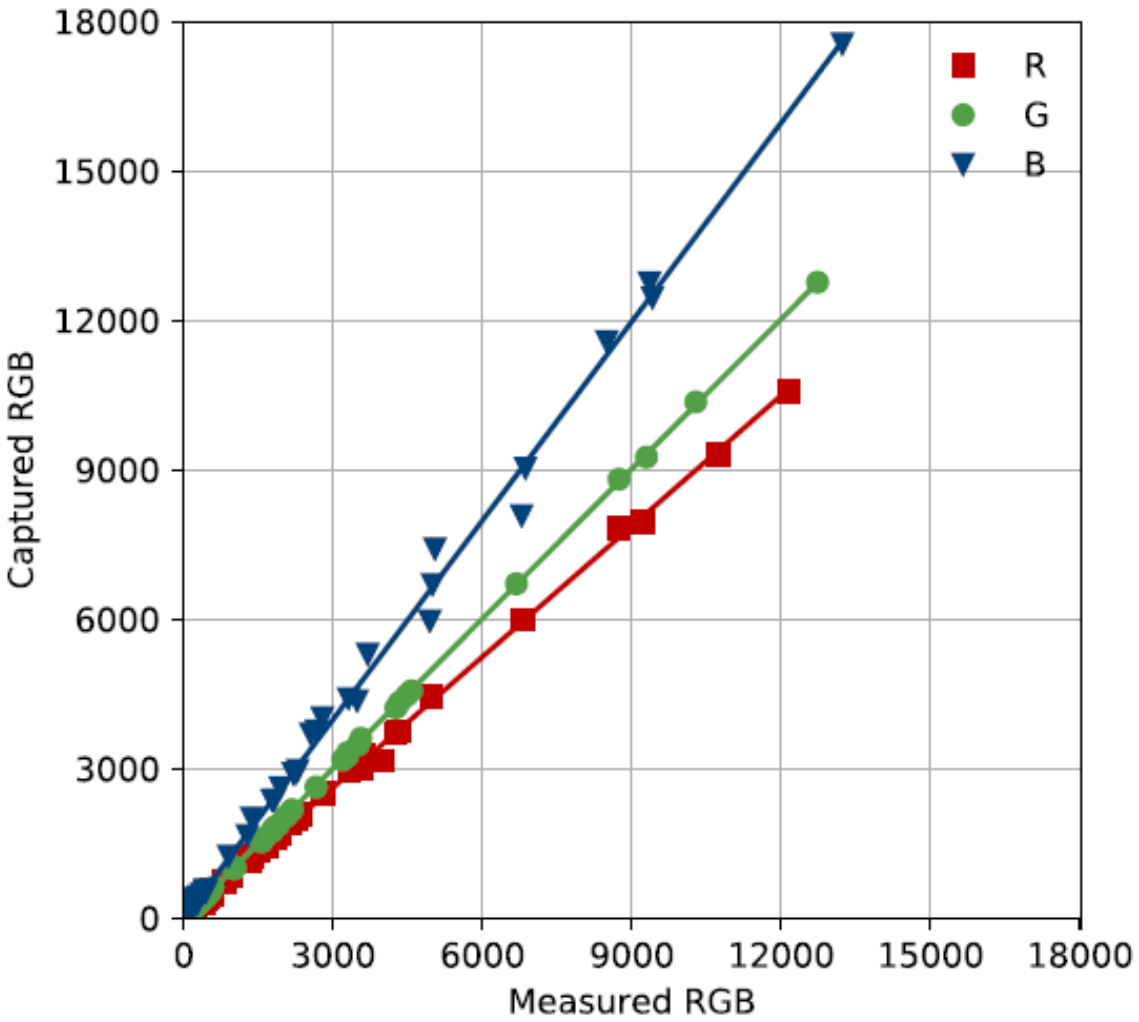


$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.4124 & 0.3576 & 0.1805 \\ 0.2127 & 0.7152 & 0.0722 \\ 0.0193 & 0.1192 & 0.9505 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

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

Jung BY and Inanici M. "Measuring Circadian Lighting through High Dynamic Range Photography," *Lighting Research and Technology*, 51(5): 742-763, 2019.

6. Applications: Non-Visual impact of lighting



original img data

$R = 0.8743\ x$
$R^2 = 0.99721$

$G = 1.0022\ x$
$R^2 = 0.99995$

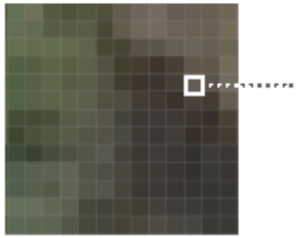
$B = 1.3308\ x$
$R^2 = 0.99922$

calibrated img data

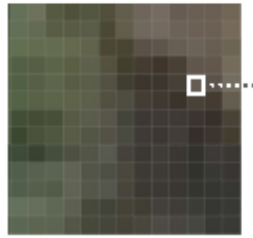
$R = 1\ x$
$R_{cal} = 1.1438 * R$

$G = 1\ x$
$G_{cal} = 0.9978 * G$

$B = 1\ x$
$B_{cal} = 0.7514 * B$



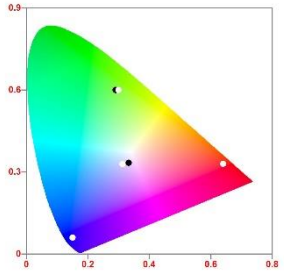
R = 100
G = 91
B = 83

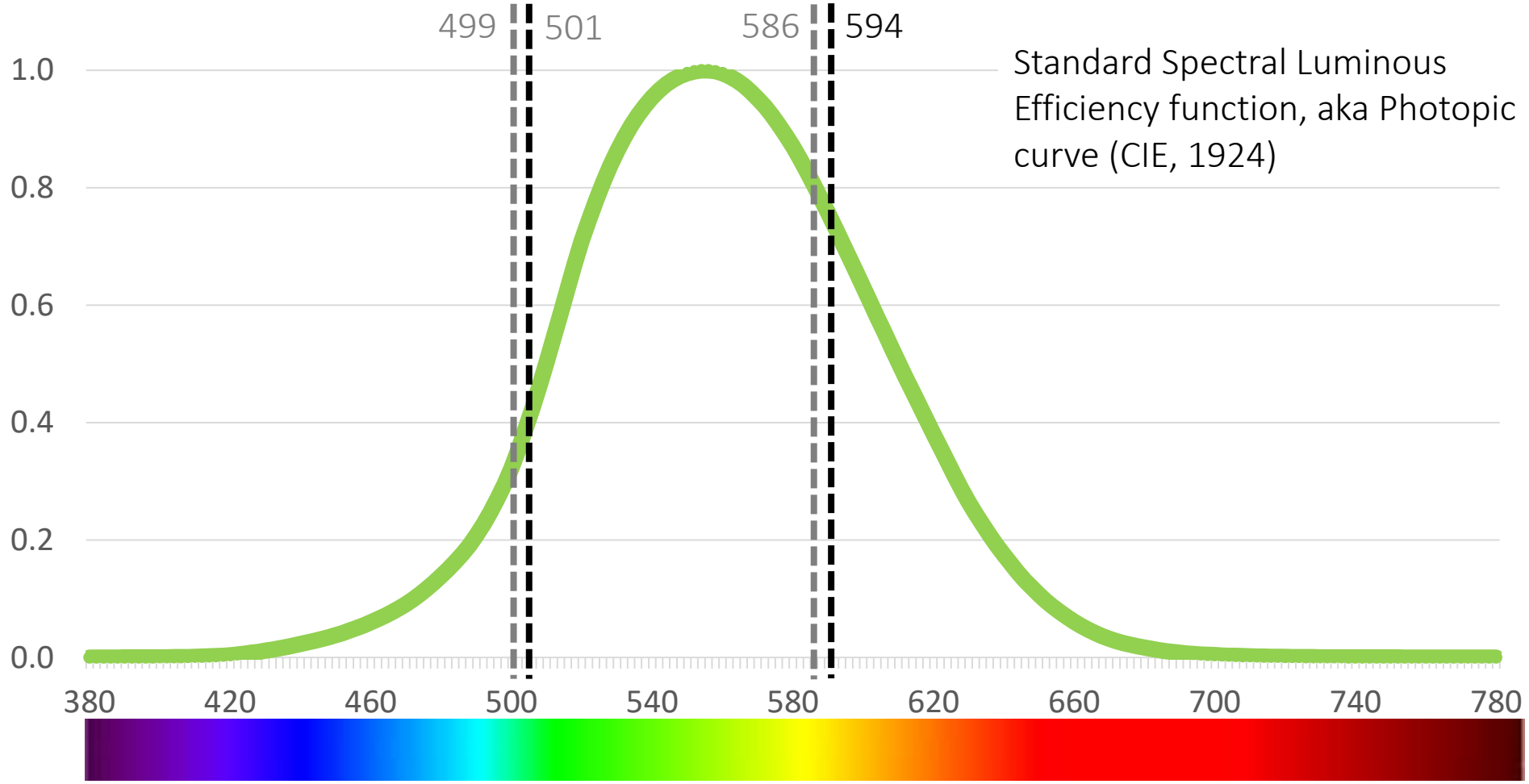


R = 114
G = 91
B = 62

Error % with global calibration of camera < 10%
Error % with every scene < 1%

Photopic Curve V(λ)

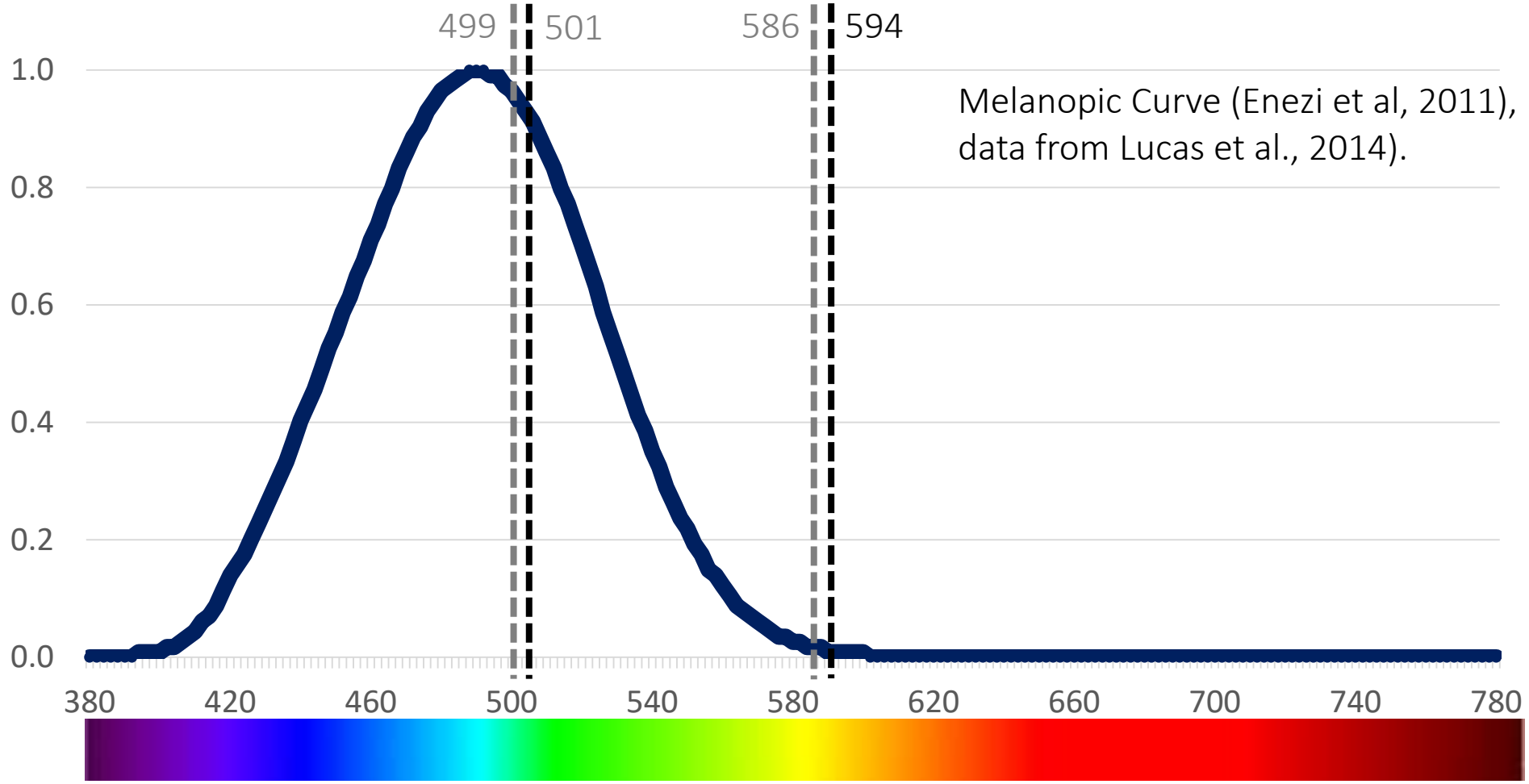




(Radiance primaries) Y= 179 * (0.2651*R + 0.6701*G + 0.0648*B)

(sRGB primaries) Y = 179 * (0.2121*R + 0.7152*G + 0.0722*B)

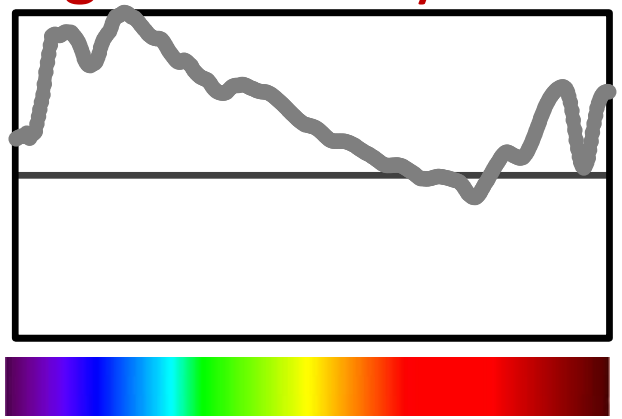
Melanopic Curve



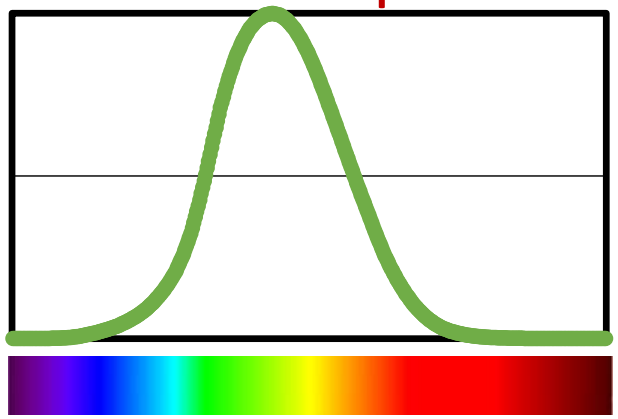
(Radiance primaries) EML = 179 * (0.0023 * R + 0.3911 * G + 0.6066 * B)

(sRGB primaries) EML = 179 * (0.0013 * R + 0.3812 * G + 0.6175 * B)

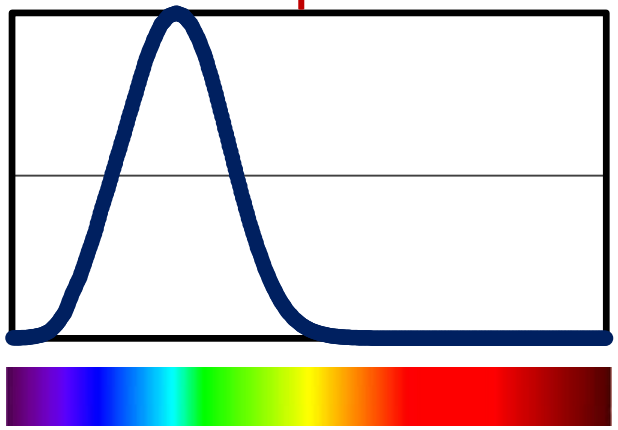
Light at the Eye

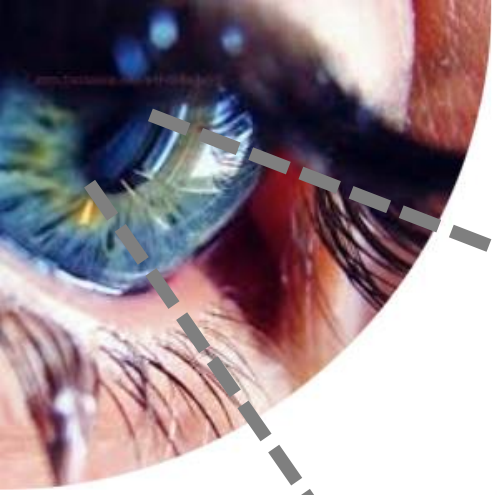


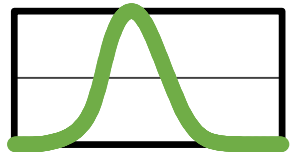
Visual Response

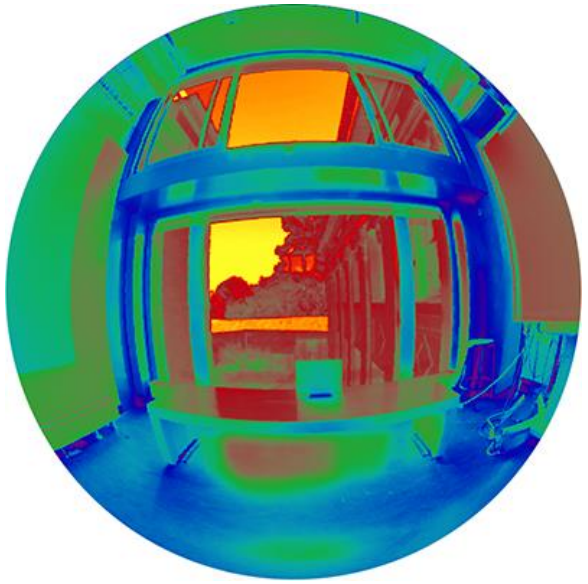


Non-visual (melanopic) response



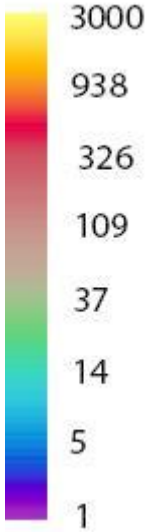




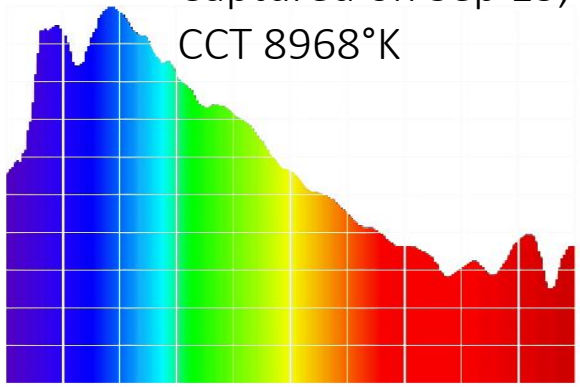


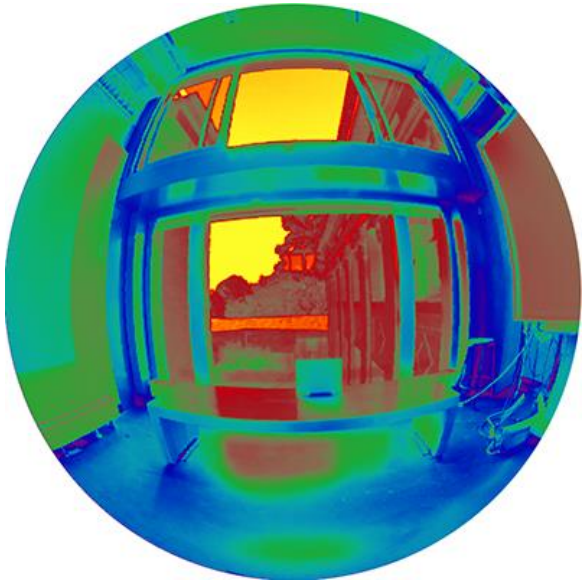
488 Photopic Lux @ Eye/Camera

Pixel Luminance
cd/m^2

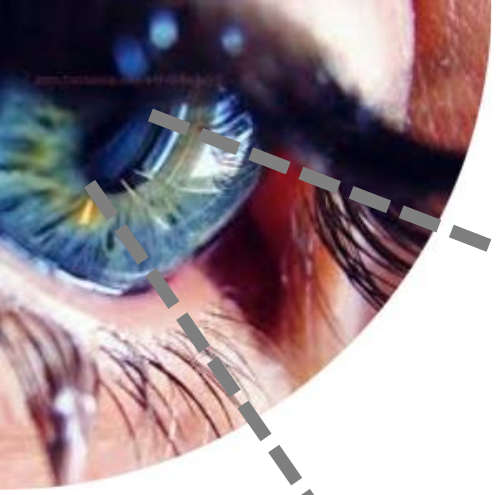


Captured on Sep 15, 8:30 am
CCT 8968°K

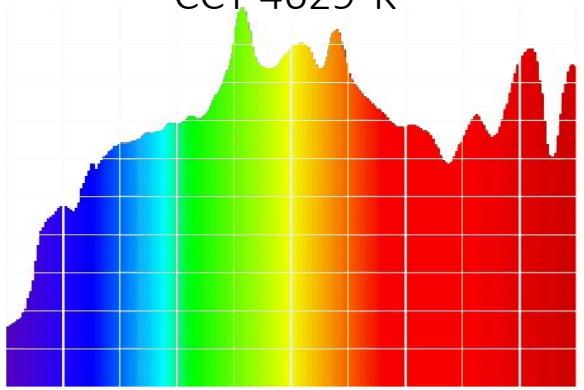


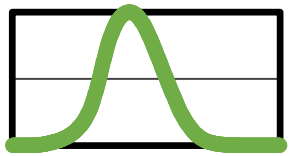


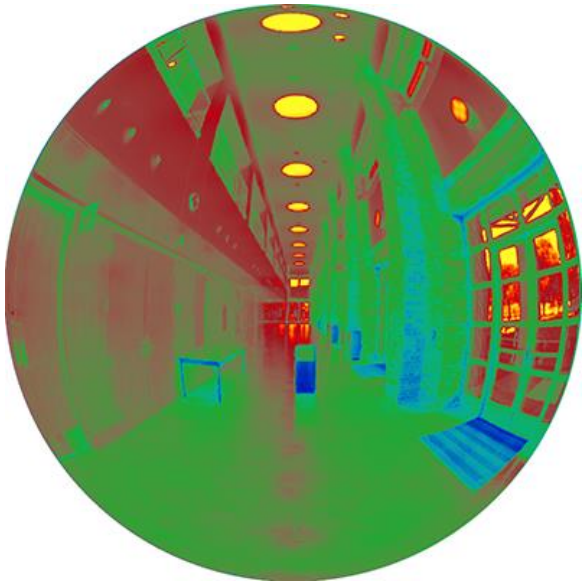
576 Melanopic Lux @ Eye/Camera



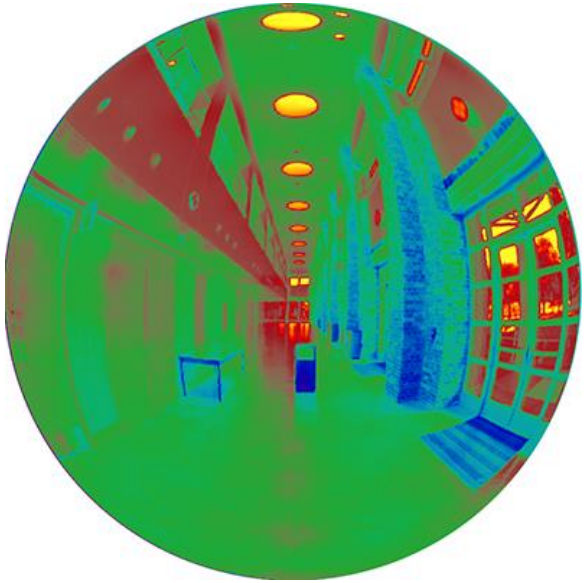
Captured on Sep 15, 9:30 am
CCT 4629°K





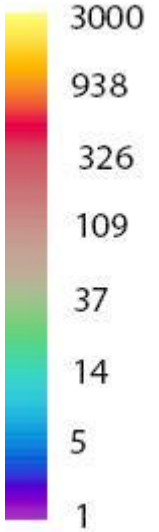


346 Photopic Lux @ Eye/Camera



269 Melanopic Lux @ Eye/Camera

Pixel Luminance
cd/m^2



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.

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

Mehlika Inanici, Ph.D.

Professor of Architecture, University of Washington, Seattle

inanici@uw.edu