Daylight Group

HOARE LEA

Daylight Group

01-02-2024

Daylight Exposure in Heritage Buildings

Modelling & Measurement

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PhD

National Trust

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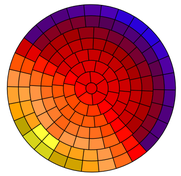
PhD FSLL FIBPSA



Daylight-Experts.com

Expert Witness | Simulation | Measurement | Conservation

Loughborough University

Stephen Cannon-Brookes
PhD

UCL

Cannon-Brookes Lighting & DESIGN

Hardwick Hall

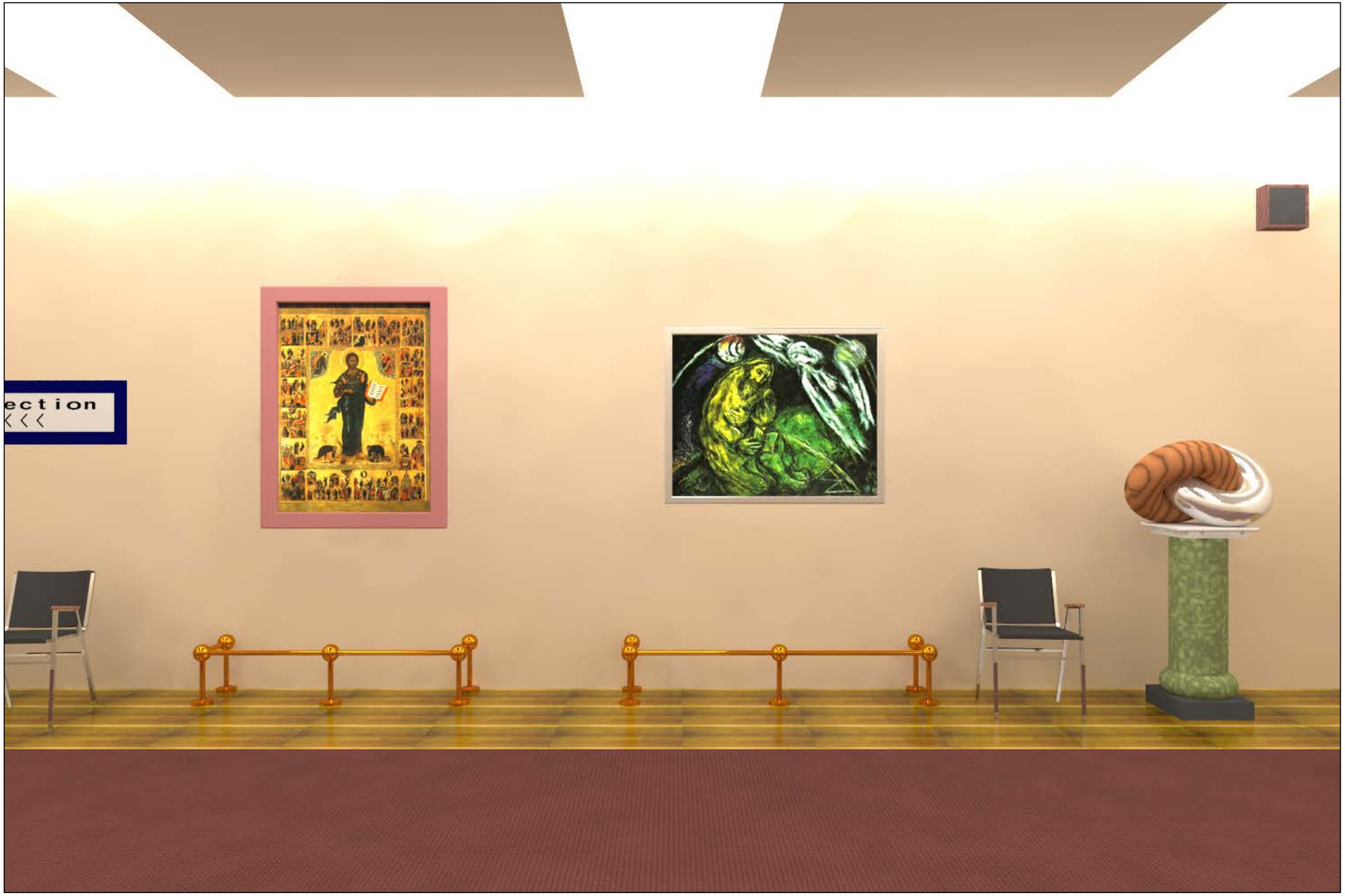

hanwell

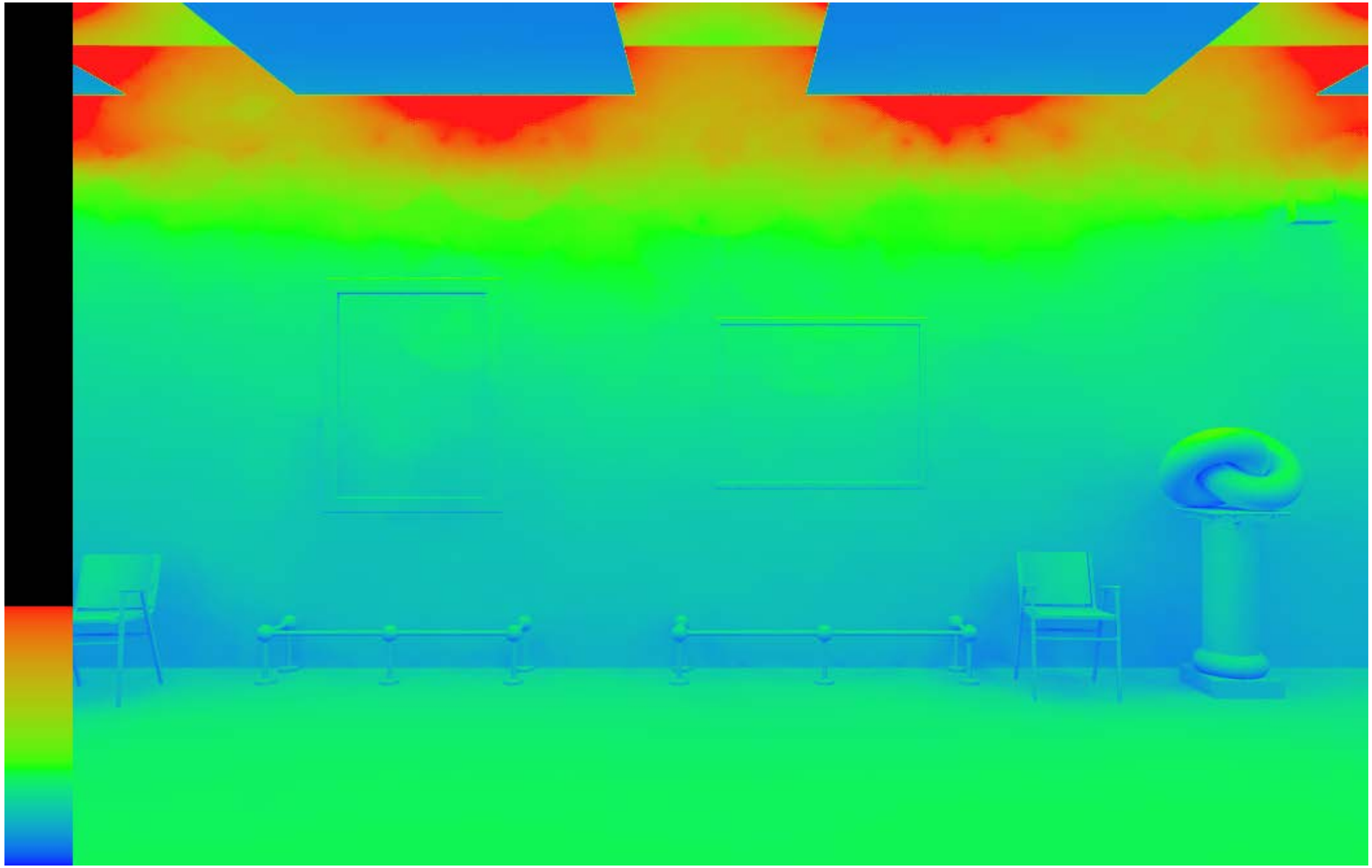
Natural illumination in buildings is characterised by huge **spatial** and **temporal** variation

Simulation of daylight exposure

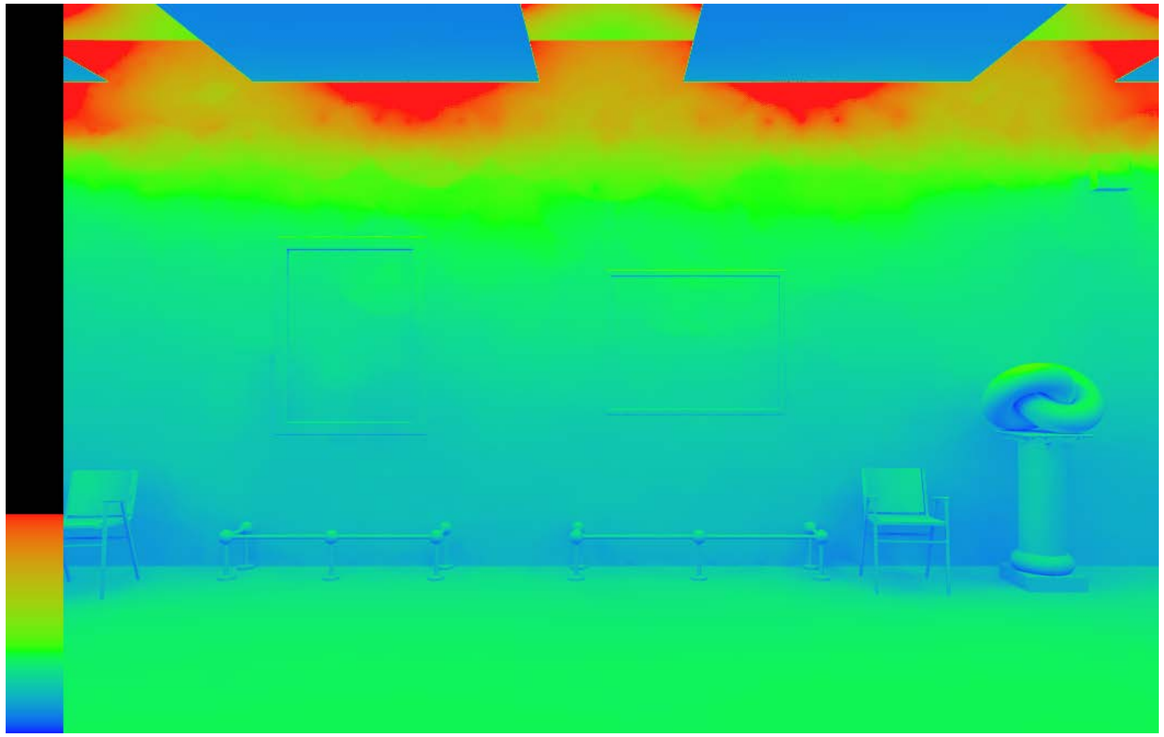
Point in time

Computer simulation of a gallery space with rooflights

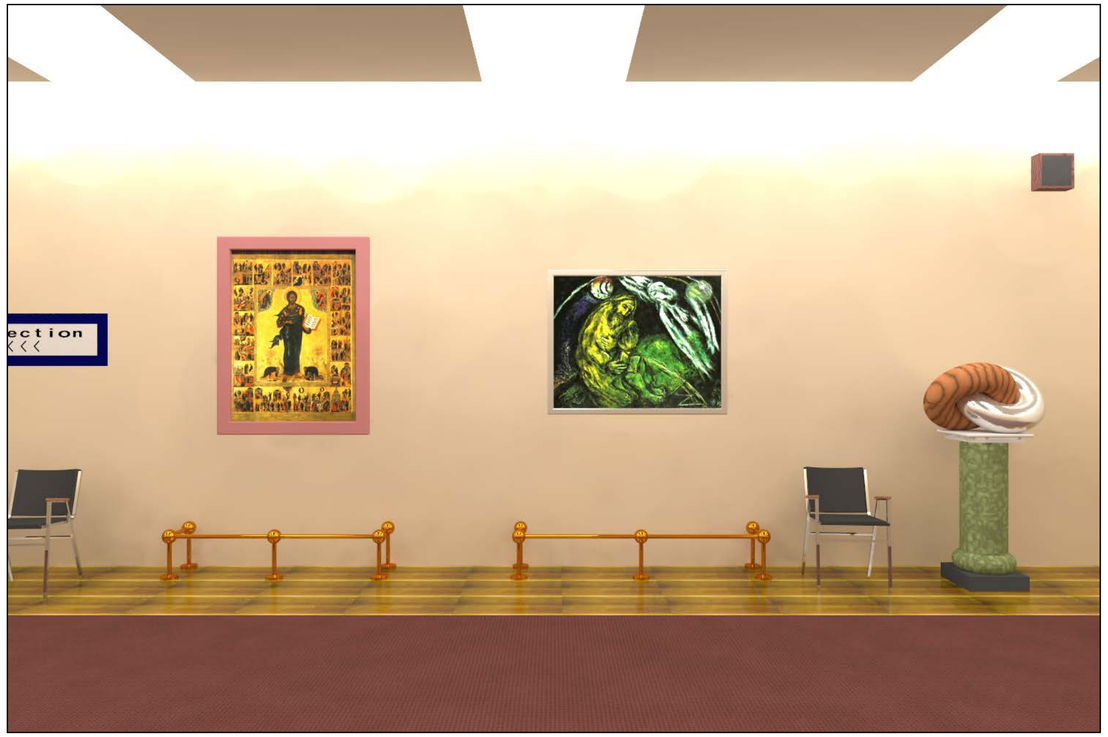



Lux
450
350
250
150
50

Illuminance [lux]



luminance [cd/m^2]



First need to compute the light falling **onto** surfaces before we can compute the brightness of those surfaces

Simulating the long-term exposure of an art work to daylight

Climate-Based Daylight Modelling (CBDM)

CBDM

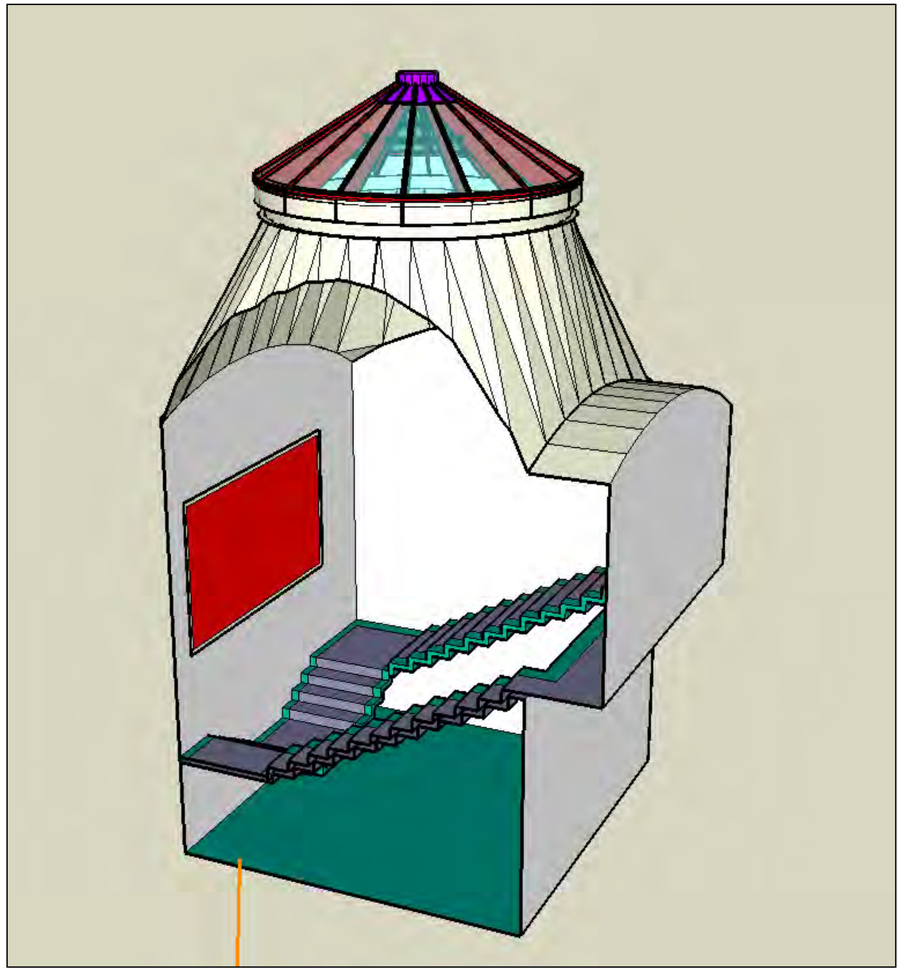
Is the prediction of any luminous quantity (illuminance and/or luminance) using realistic sun and sky conditions derived from standardised (or monitored) climate data, e.g. weather files.

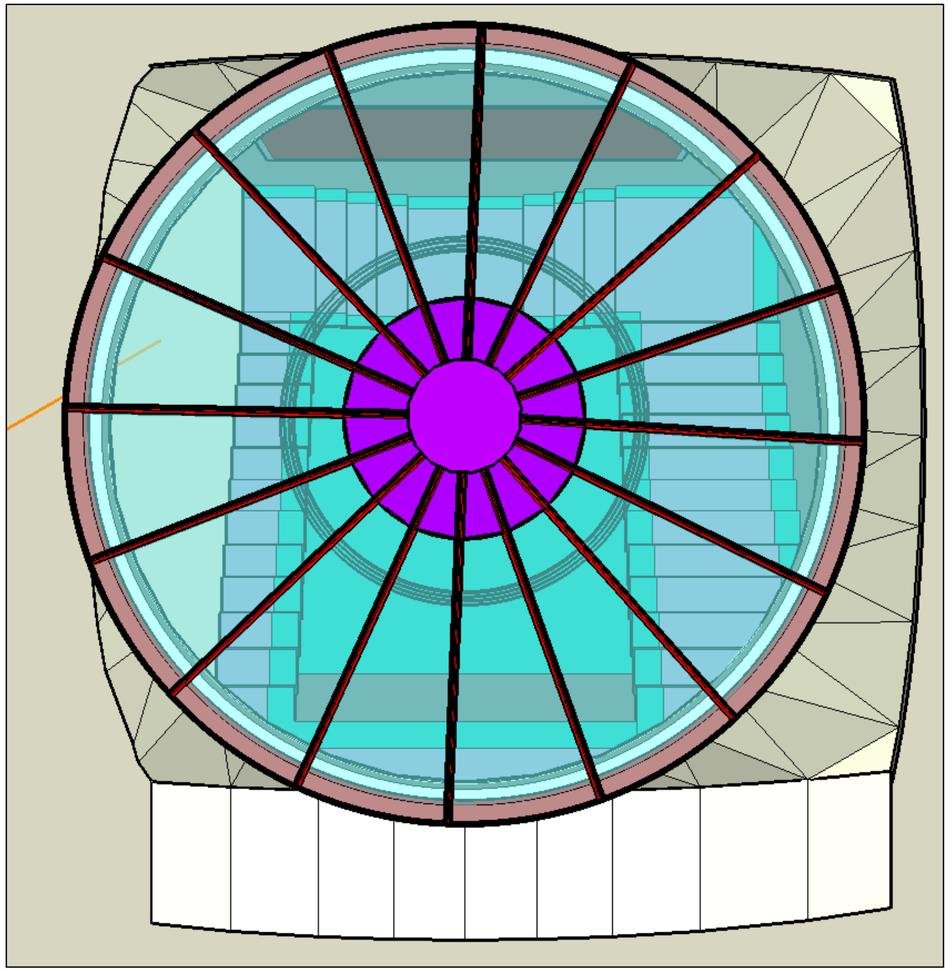
Usually for a full year.

Mount Stewart, Belfast, NI

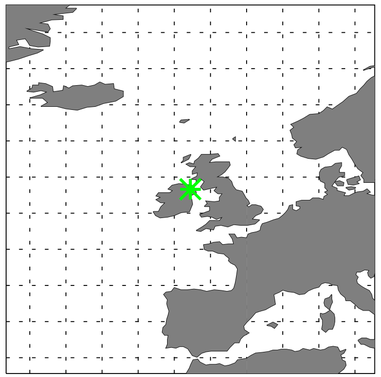
Hambletonian, Rubbing Down

George Stubbs, RA (1724-1806)

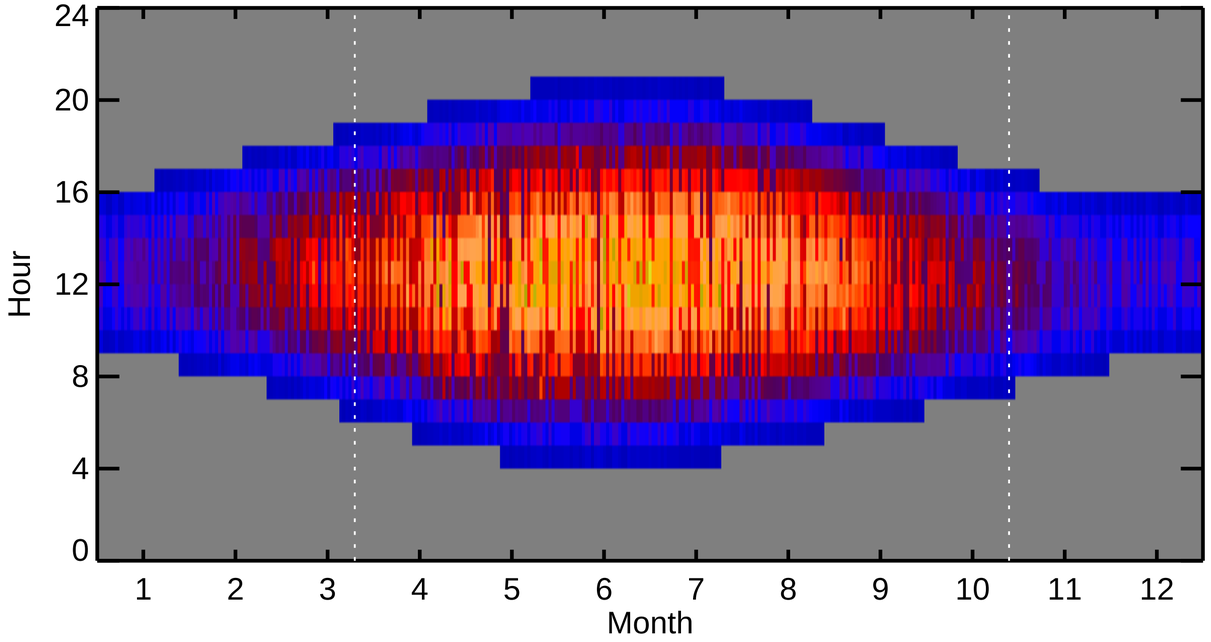




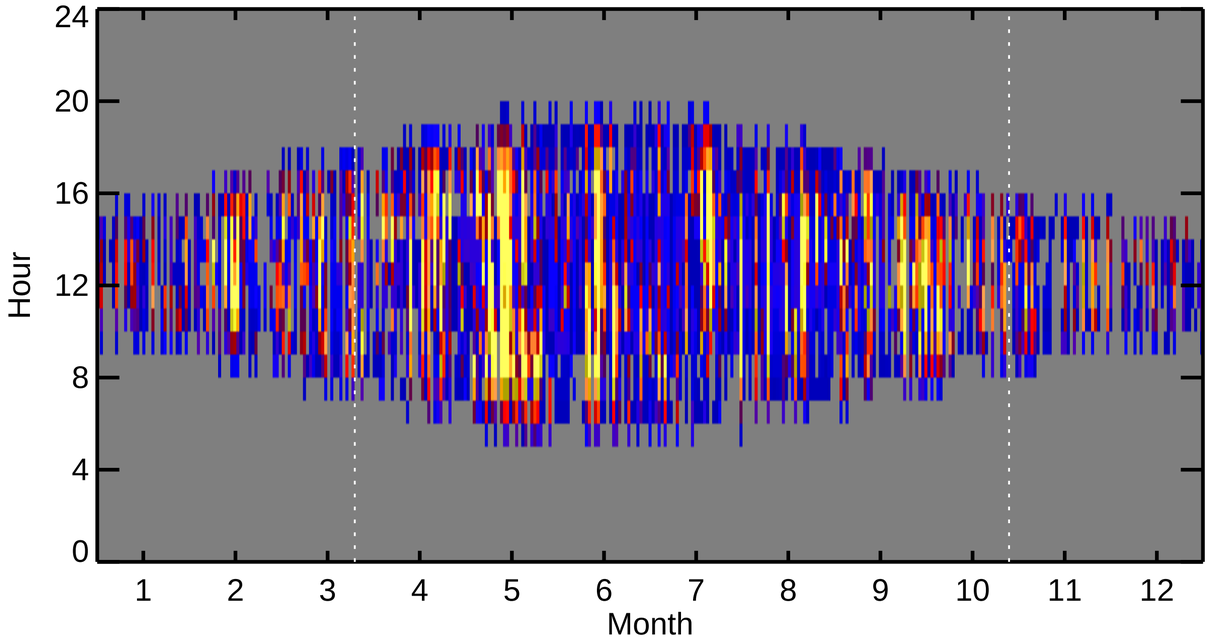
GBR-Belfast

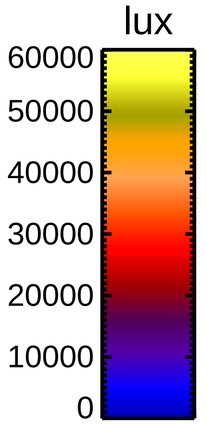


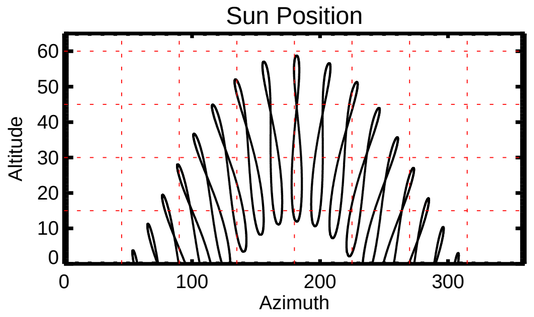
Diffuse Horizontal Illuminance



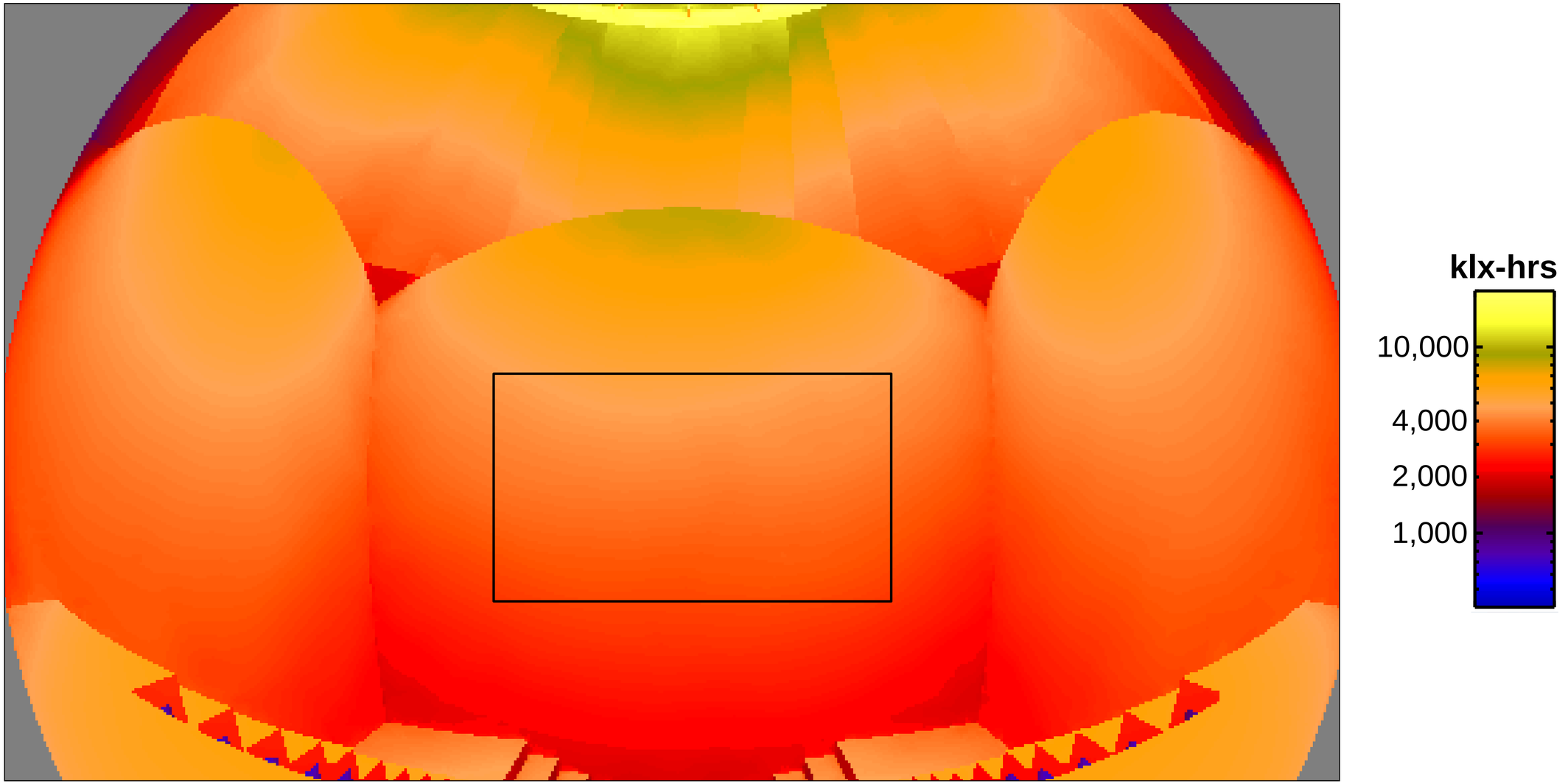
Direct Normal Illuminance

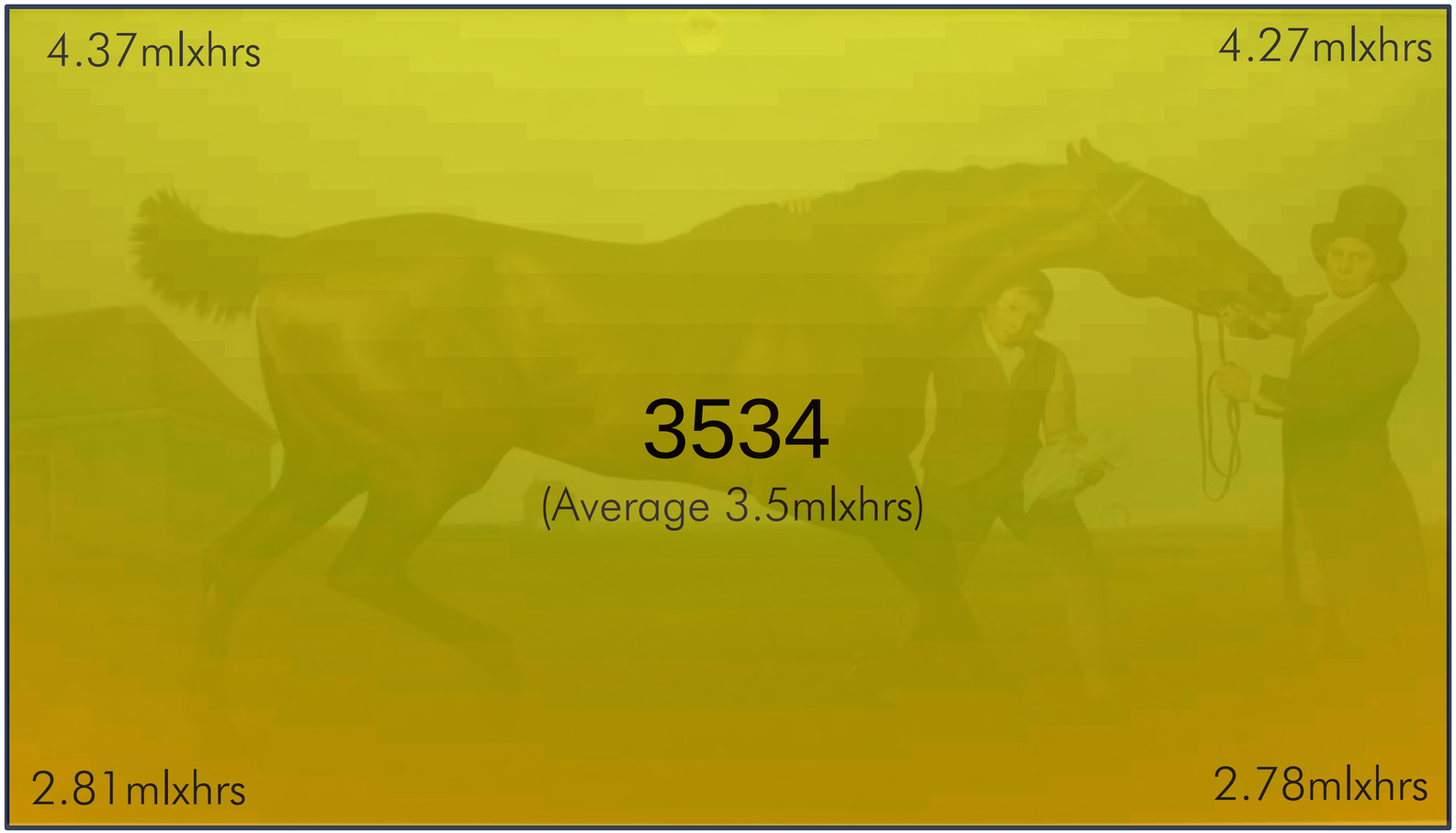


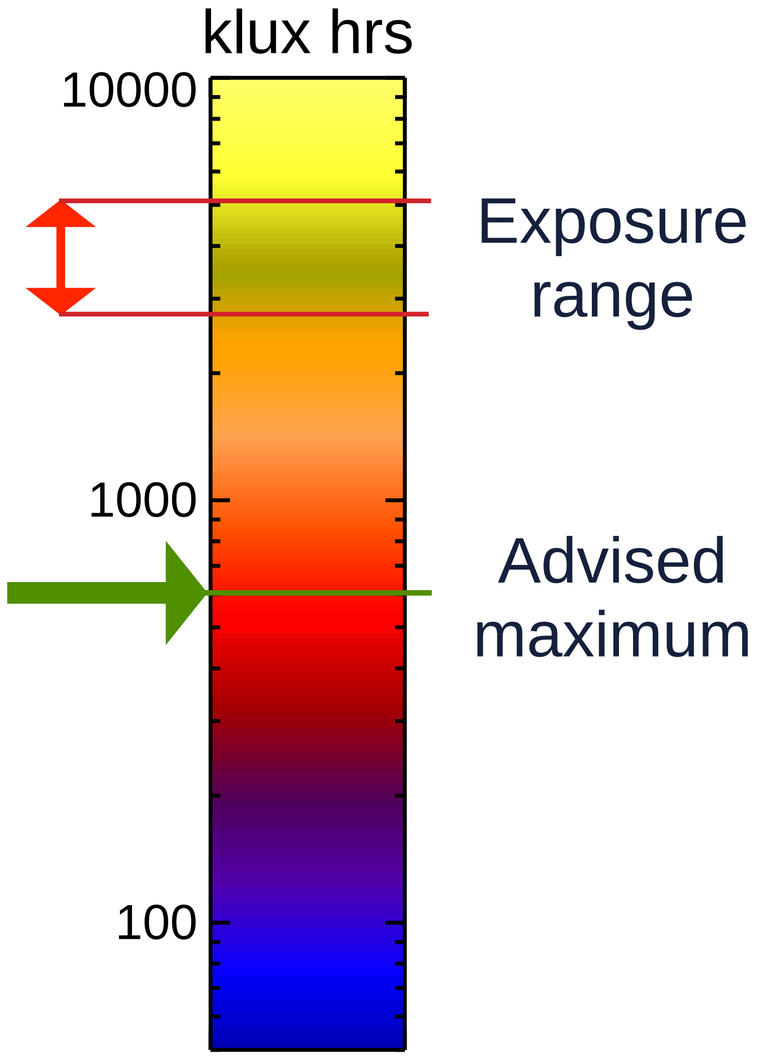




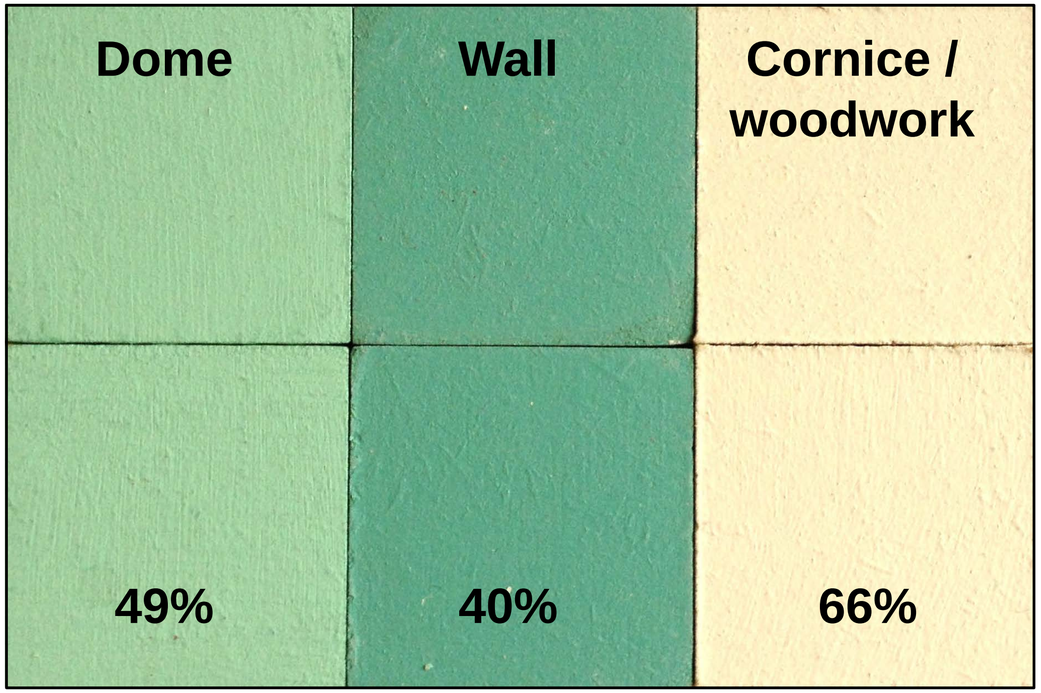
Cumulative annual illumination




4.37mlxhrs
4.27mlxhrs
3534
(Average 3.5mlxhrs)
2.81mlxhrs
2.78mlxhrs

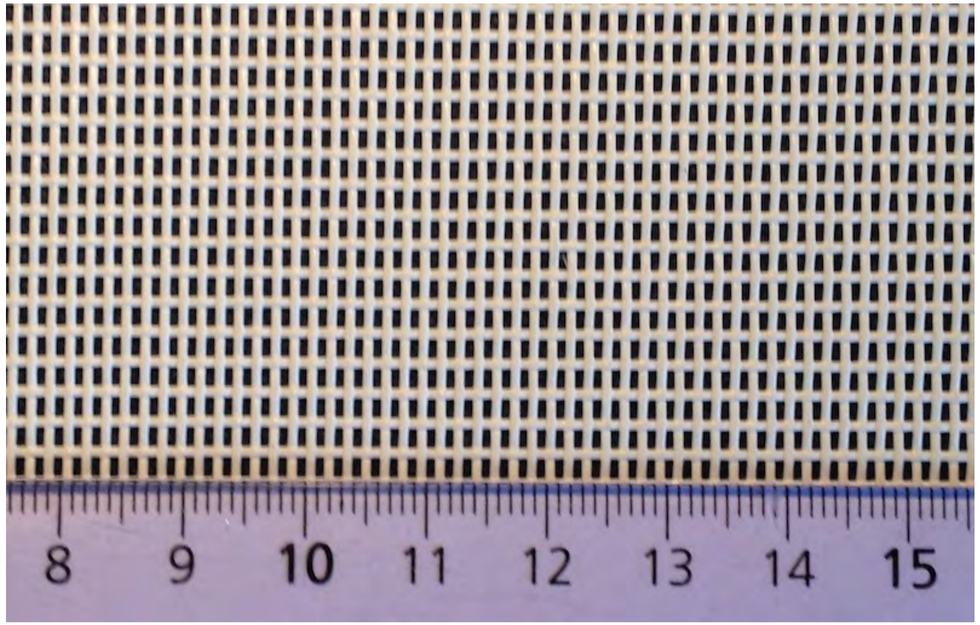

klux hrs
10000
1000
100
Exposure range
Advised maximum

Interventions to reduce annual daylight exposure were first tested using simulation



Reduce reflectivity of key surfaces

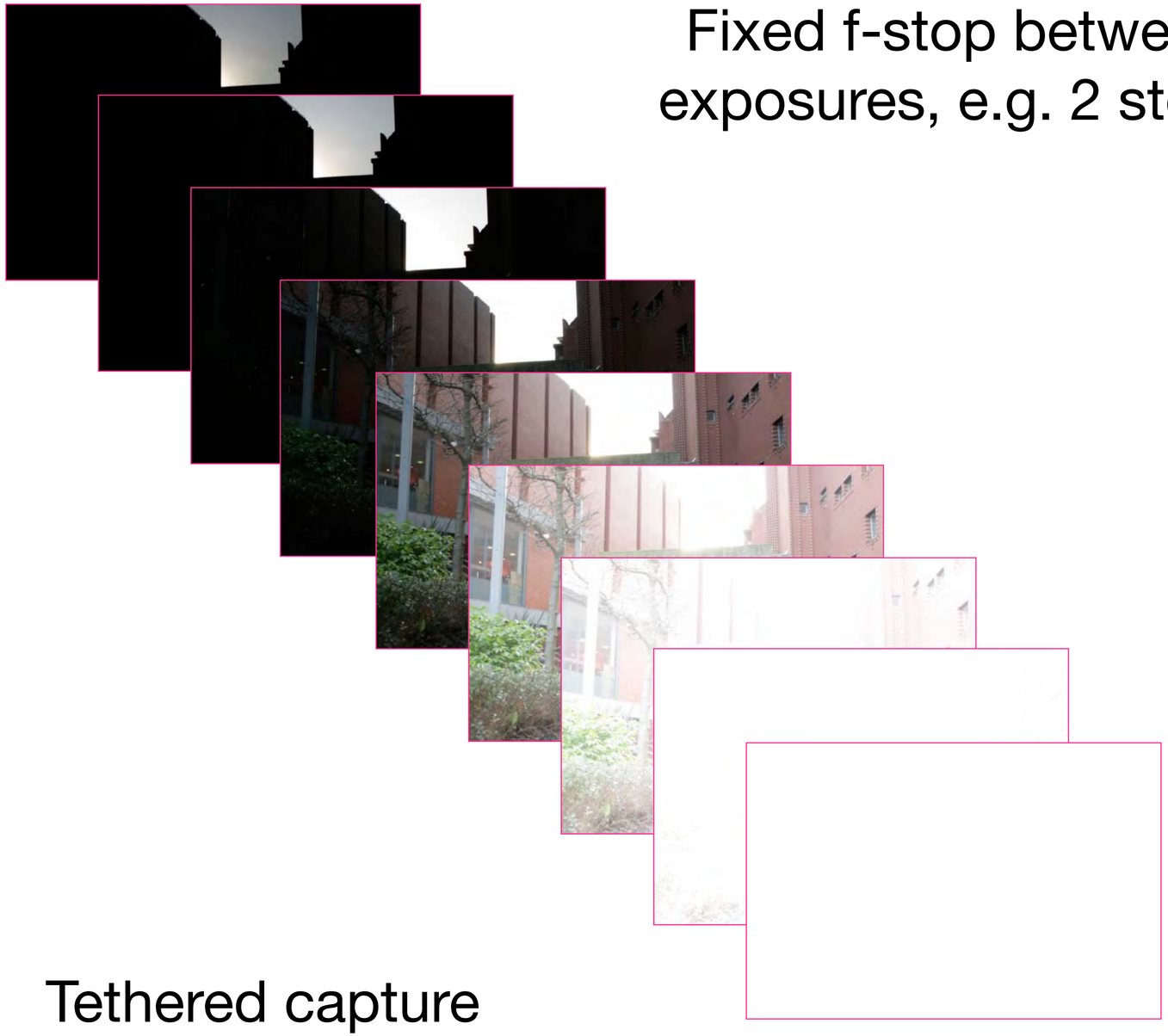
Reduce transmissivity of the skylight



Illuminance measurement using High Dynamic Range (HDR) imaging

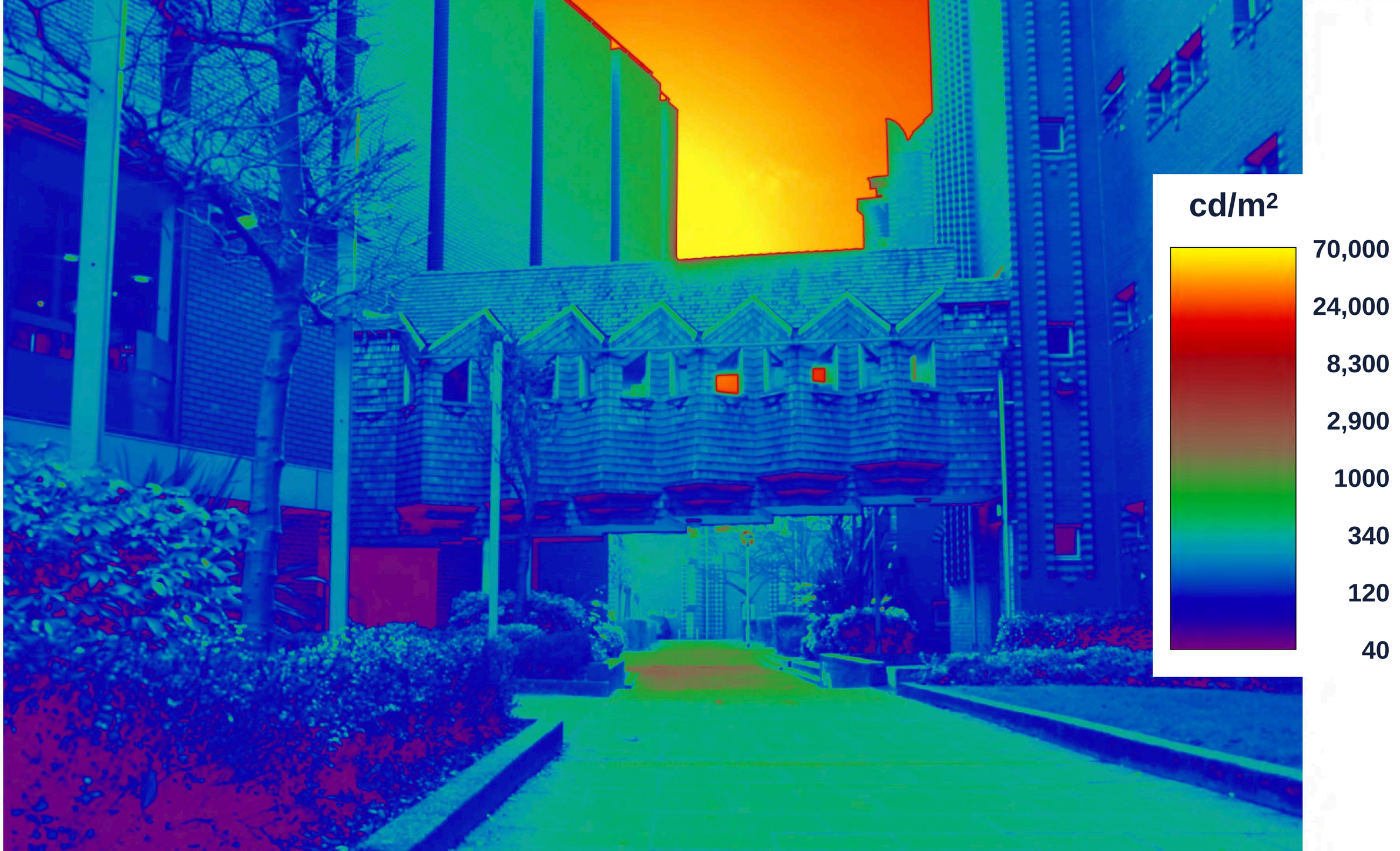
HDR
imaging

Fixed f-stop between exposures, e.g. 2 stops

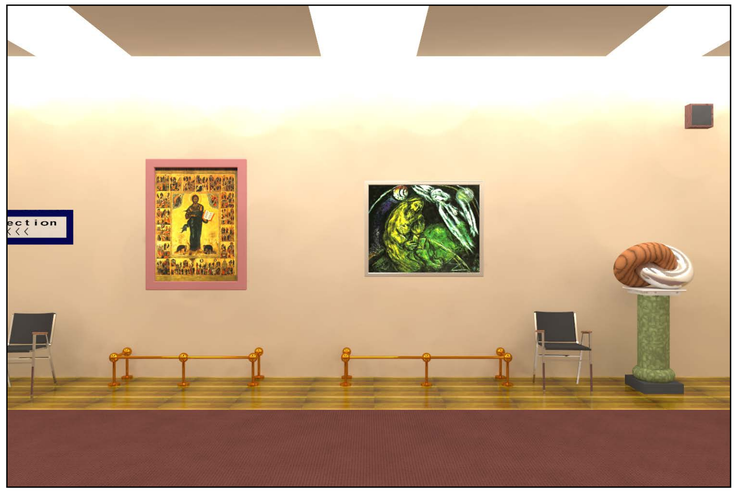


Synthesis of a luminance image from a sequence of ‘ordinary’ image captures

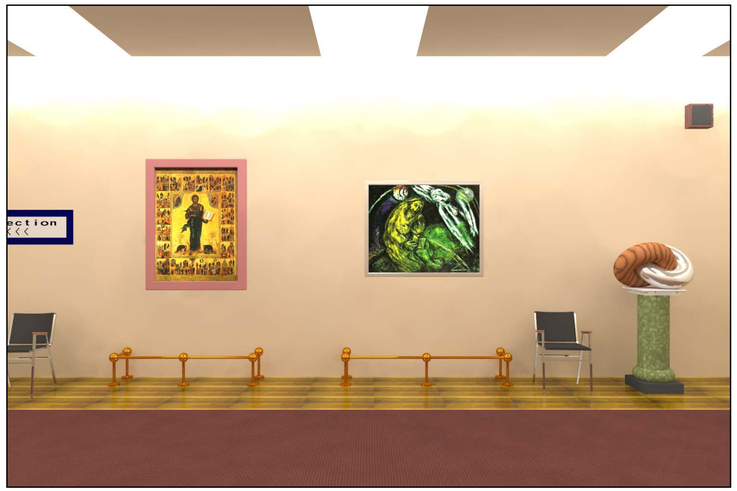
Tethered capture

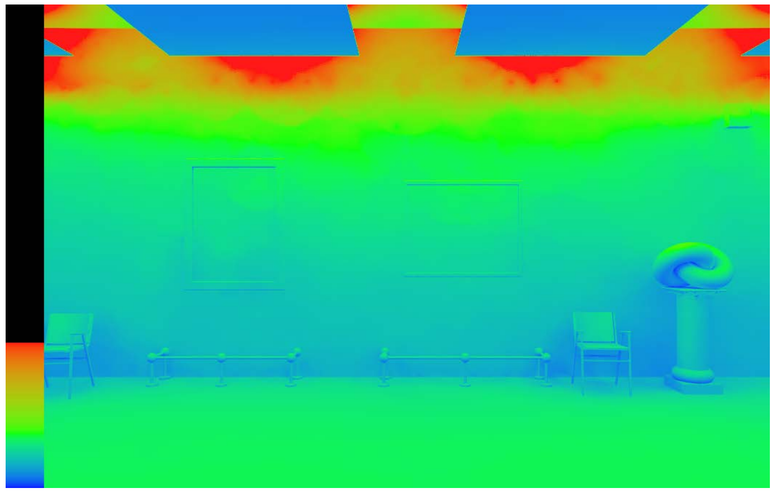

cd/m²
70,000
24,000
8,300
2,900
1000
340
120
40

HDR gives measures of luminance



HDR gives measures of luminance, but what about illuminance?





Illuminance can be derived from the luminance (i.e. HDR) image

Illuminance Proxy HDR imaging

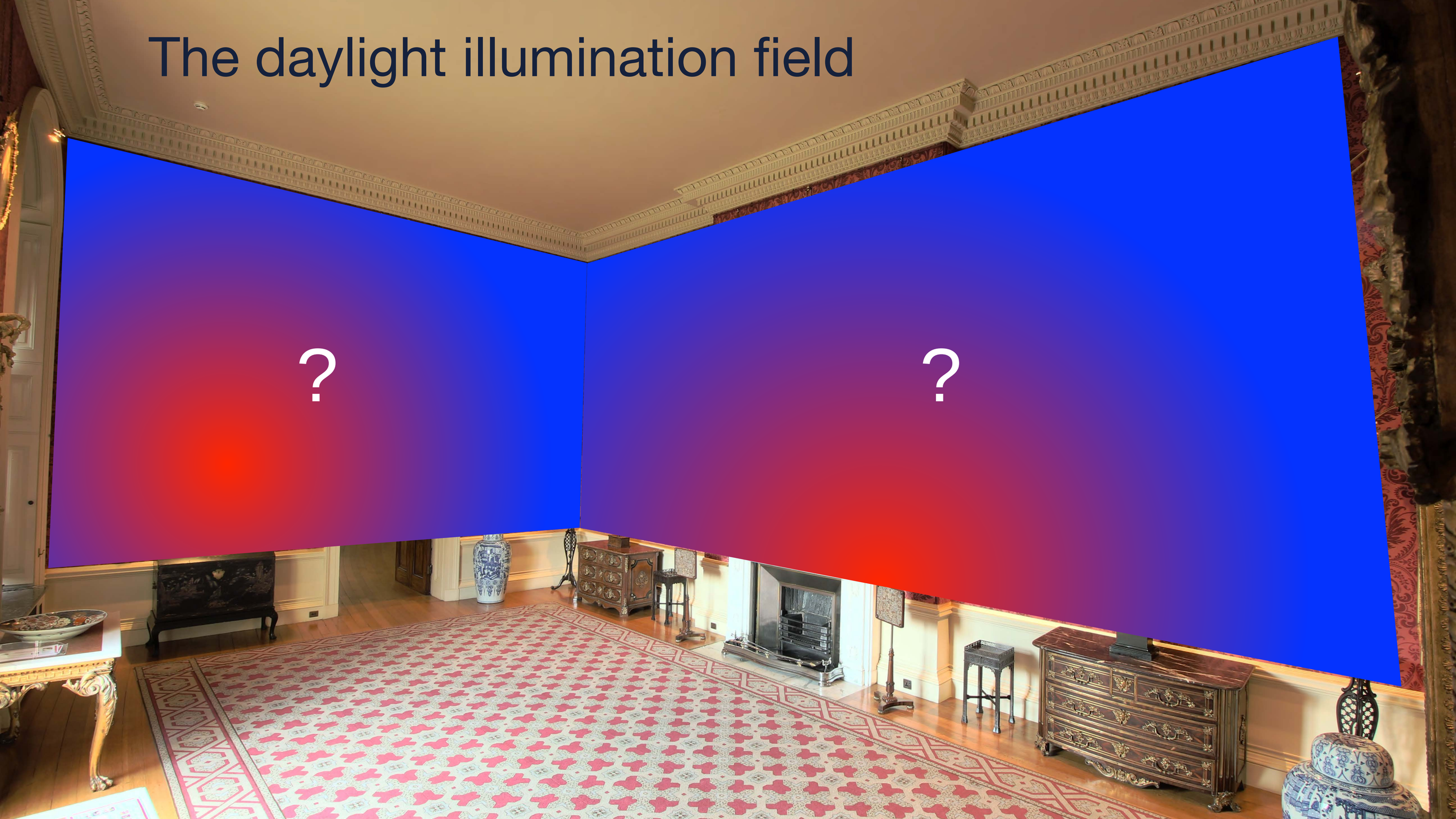
Ickworth House

Bury St. Edmunds

The Smoking Room

Ickworth House

The daylight illumination field

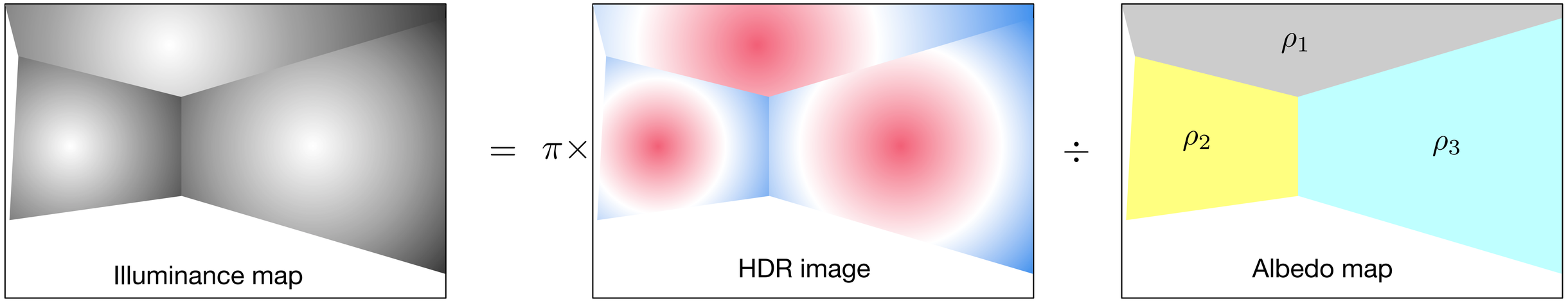


Theory

$$E_r = \frac{\pi L_r}{\rho_r}$$

Assumes that the surface has an ideal diffuse reflectance

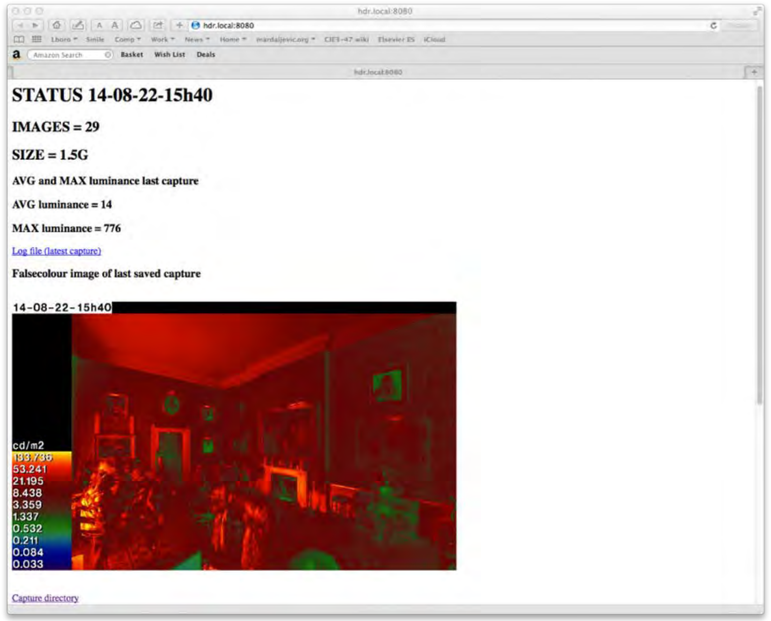
$E_{(x,y)}$ $L_{(x,y)}$ $\rho_{(x,y)}$



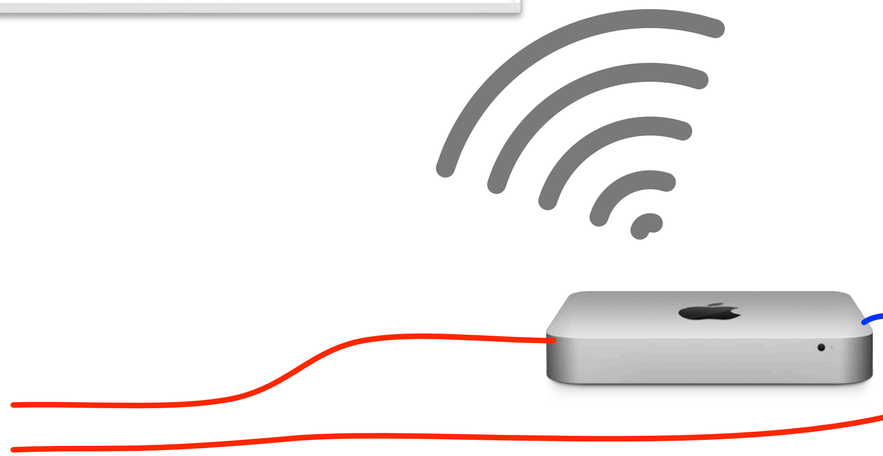
The practicalities

Long-term, autonomous HDR capture

- HDR capture every 10 minutes
- Unattended duration ~6 to 9 months
- On-the-fly deletion of ‘dark’ images
- Automatic backup of images to ‘failsafe’ drive
- Status webpage broadcast on ad-hoc wifi network

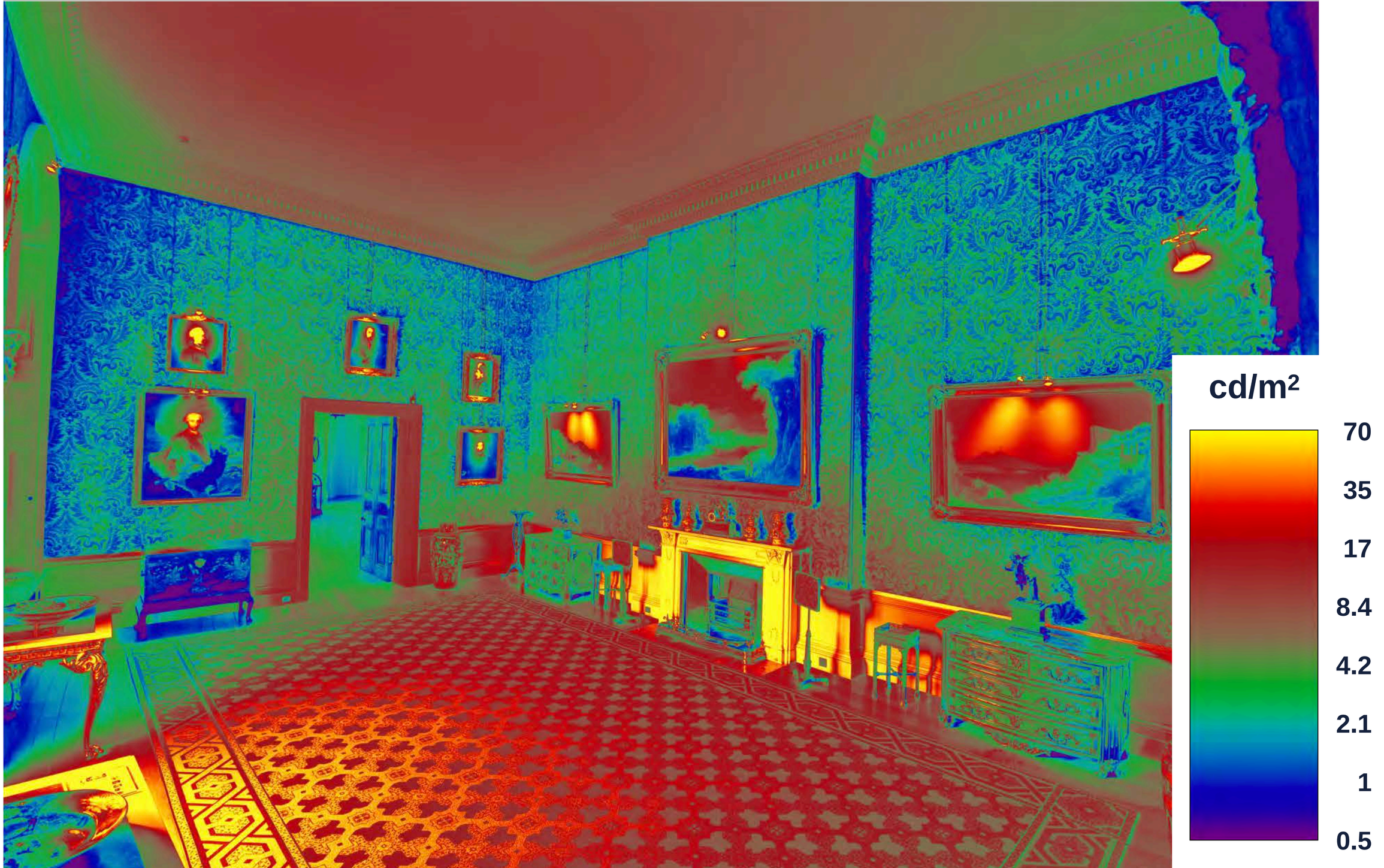


Consumer
DSLR

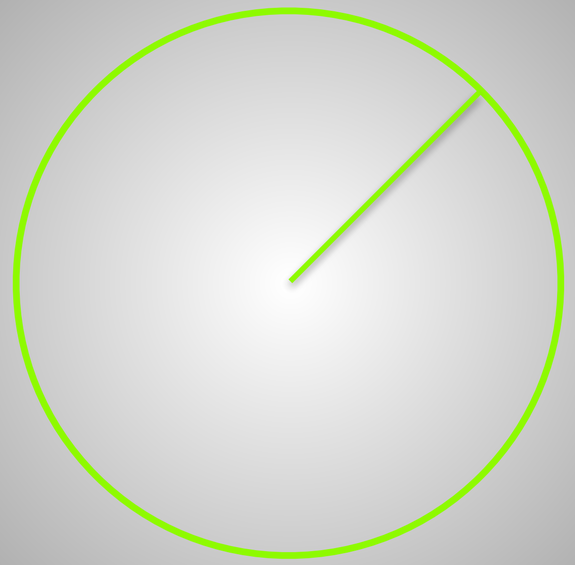


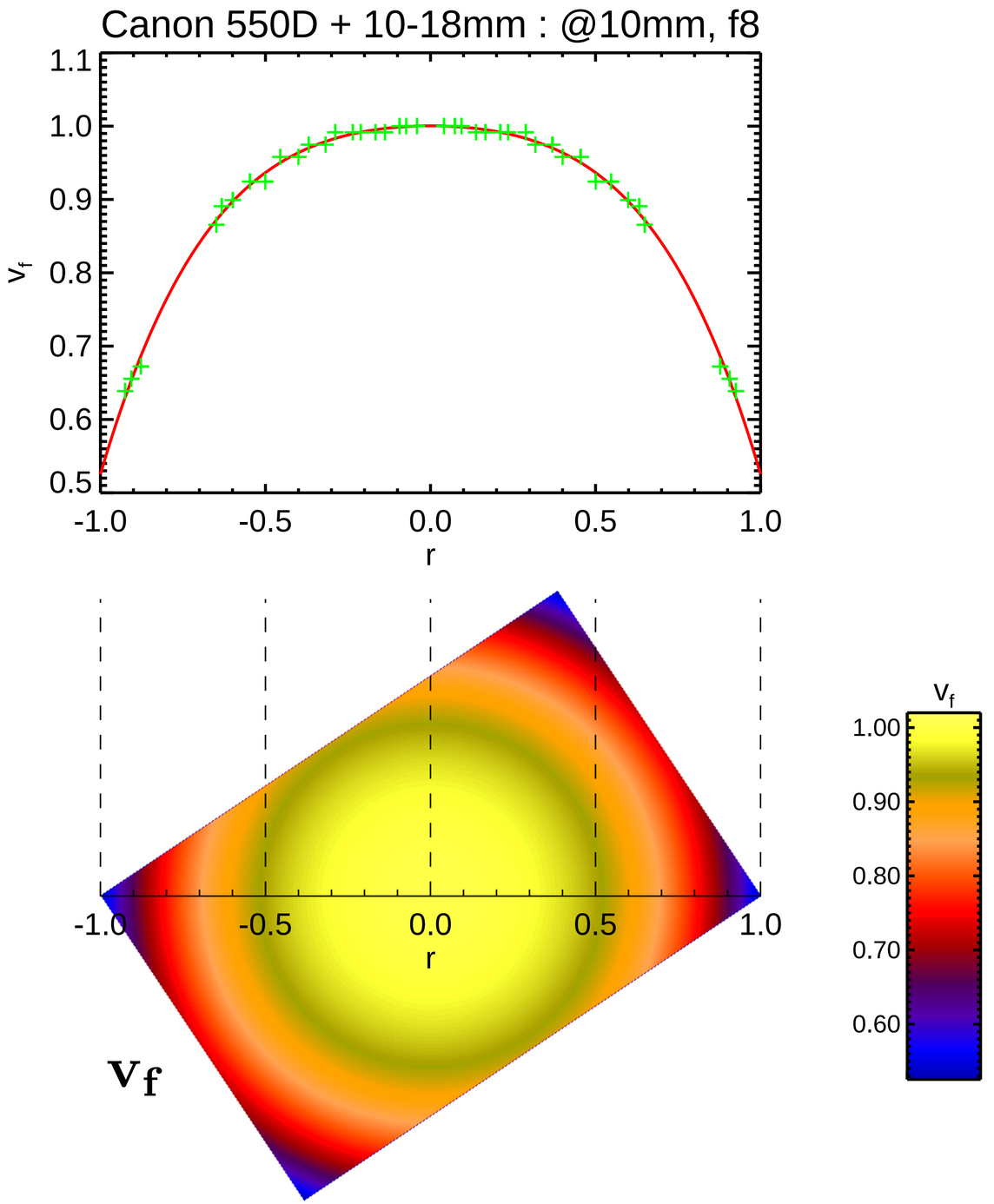
‘Headless’ Mac Mini


Canon
3014


cd/m²
70
35
17
8.4
4.2
2.1
1
0.5

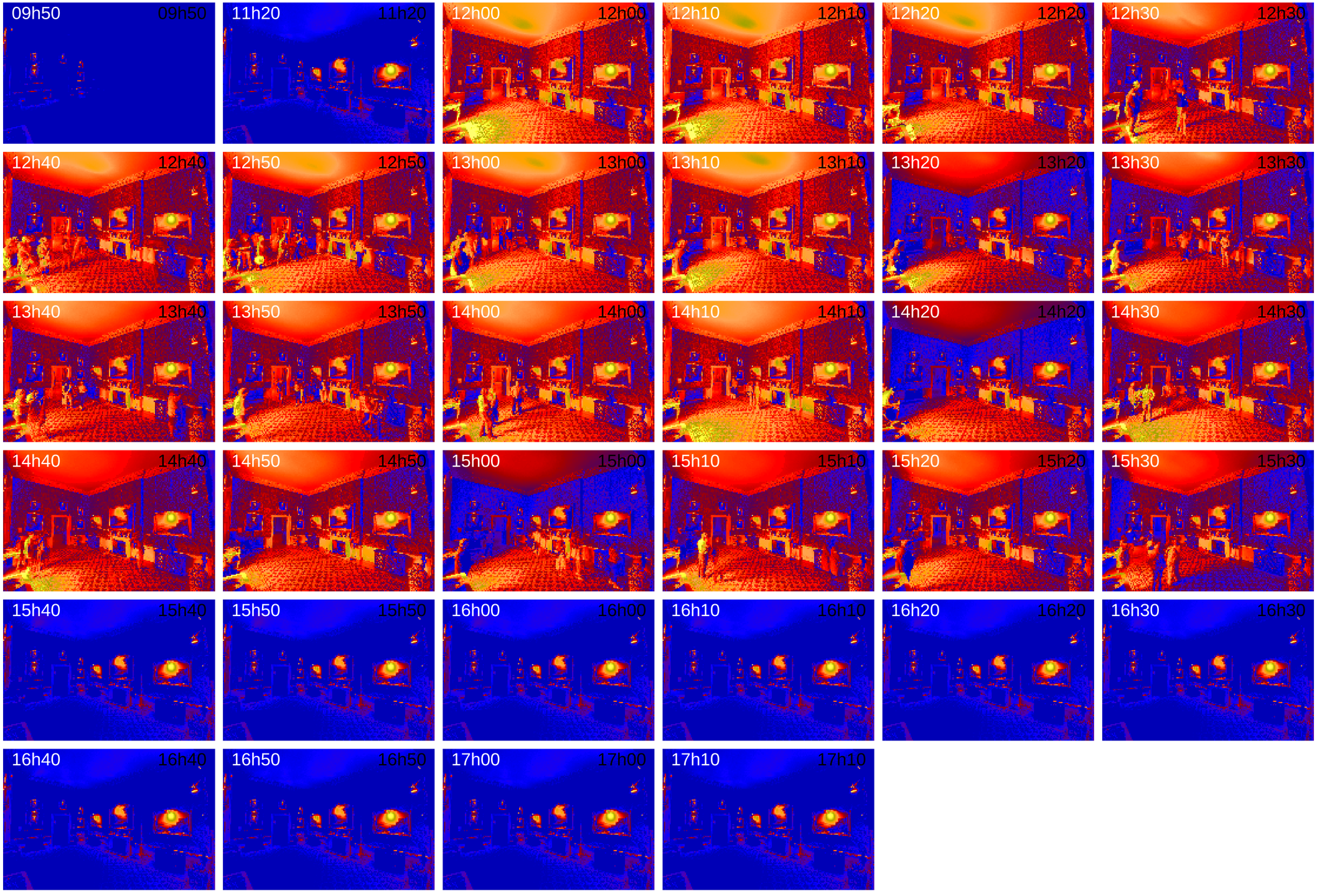
Apply vignetting correction

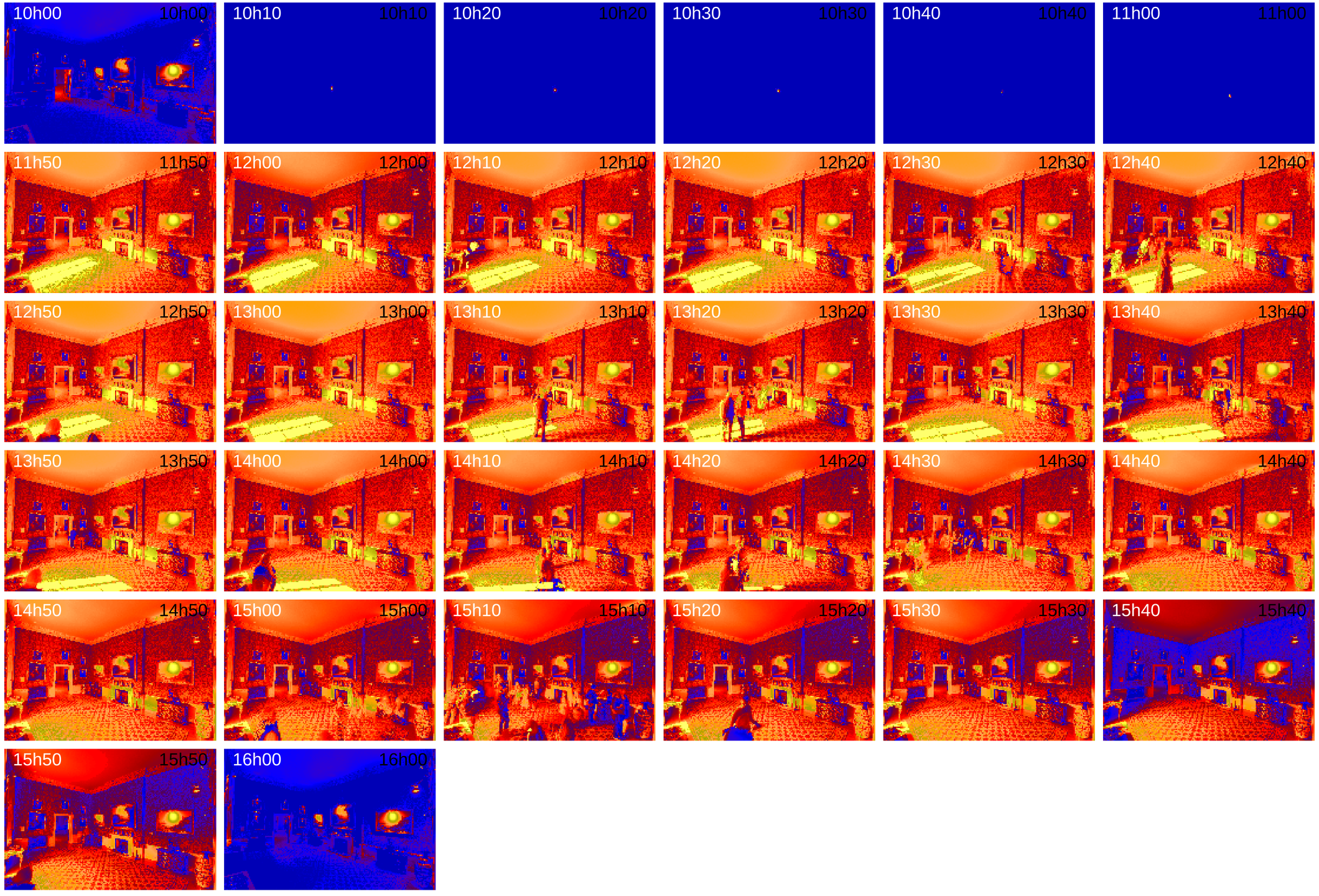



Canon 550D + 10-18mm : @10mm, f8
1.1
1.0
0.9
0.8
0.7
0.6
0.5
v_f
-1.0
-0.5
0.0
0.5
1.0
r
v_f
1.00
0.90
0.80
0.70
0.60

6+ months of unattended monitoring

> Daily ‘visual’ record sheets


09h50
11h20
12h00
12h10
12h20
12h30
12h40
12h50
13h00
13h10
13h20
13h30
13h40
13h50
14h00
14h10
14h20
14h30
14h40
14h50
15h00
15h10
15h20
15h30
15h40
15h50
16h00
16h10
16h20
16h30
16h40
16h50
17h00
17h10


10h00
10h00
10h10
10h10
10h20
10h20
10h30
10h30
10h40
10h40
11h00
11h00
11h50
11h50
12h00
12h00
12h10
12h10
12h20
12h20
12h30
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14h10
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14h40
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14h50
14h50
15h00
15h00
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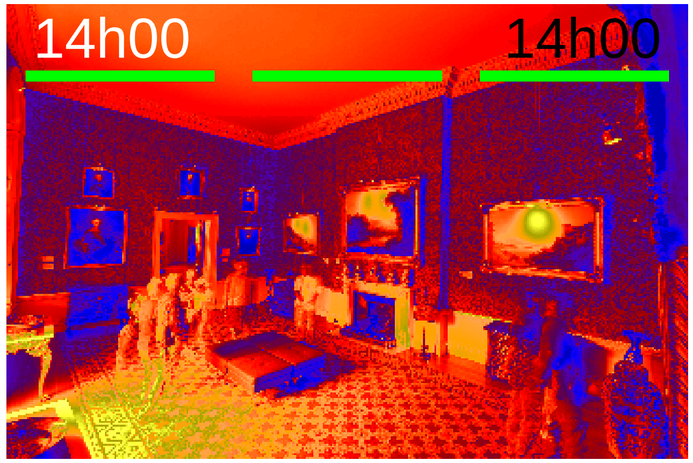
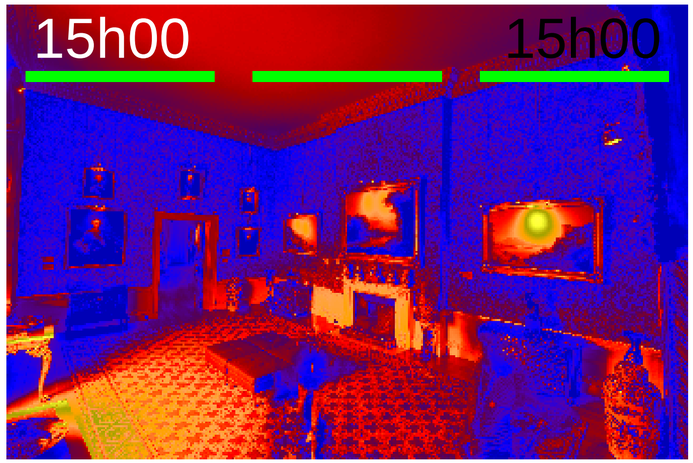
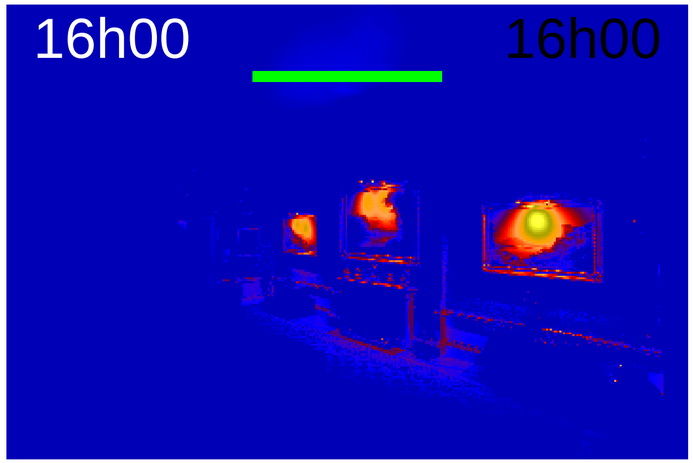
15h40
15h40
15h50
15h50
16h00
16h00


14h00
14h00

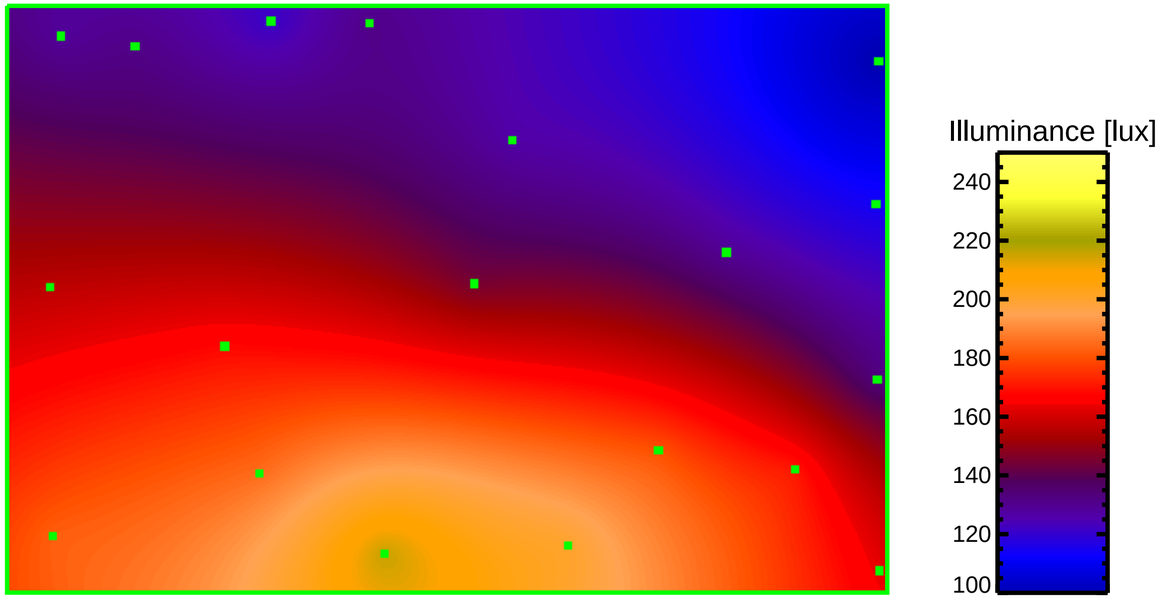

15h00
15h00


16h00
16h00

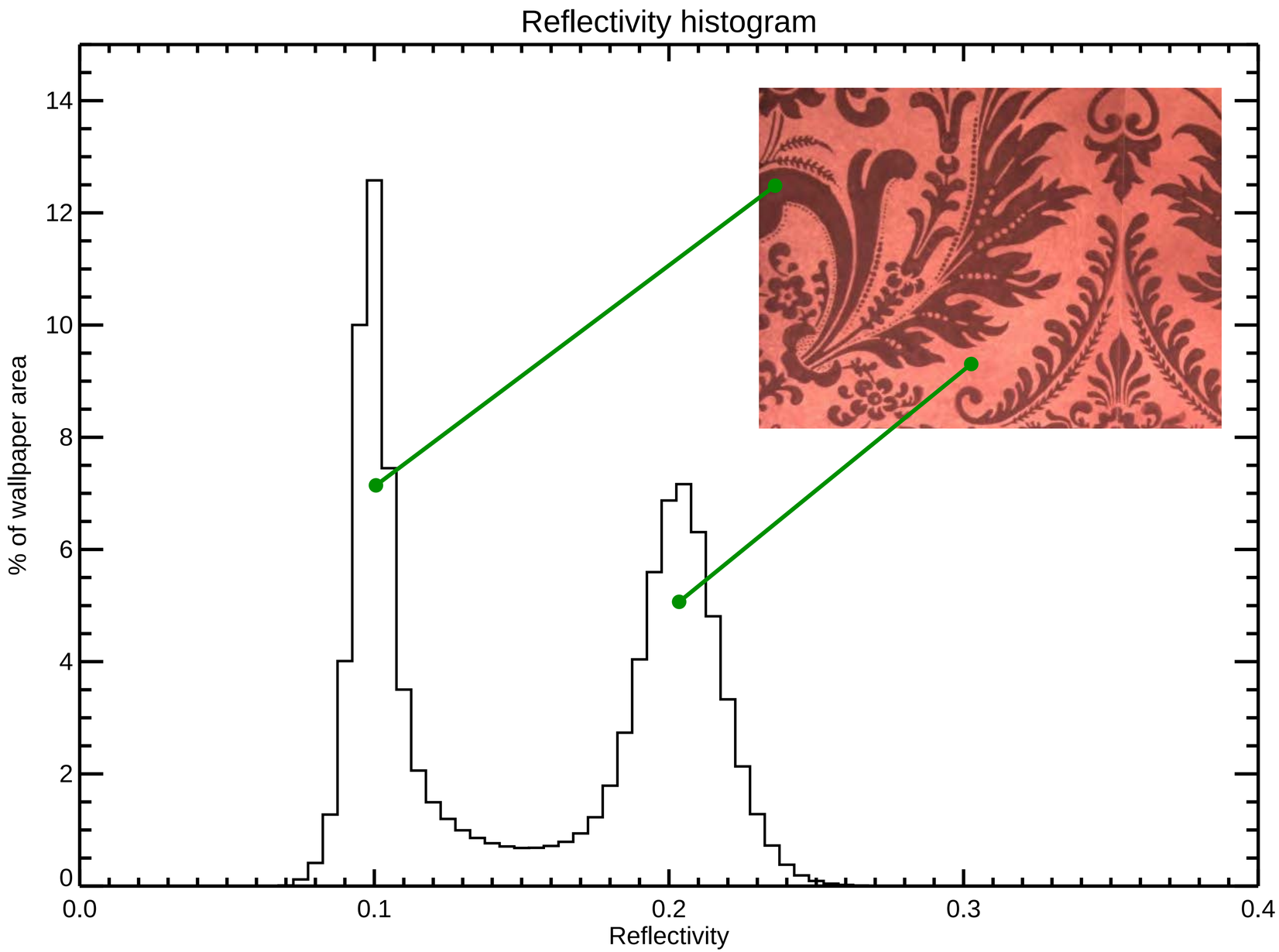
Derive illuminance from HDR luminance

$$E_r = \frac{\pi L_r}{\rho_r}$$

Interpolated illuminance field



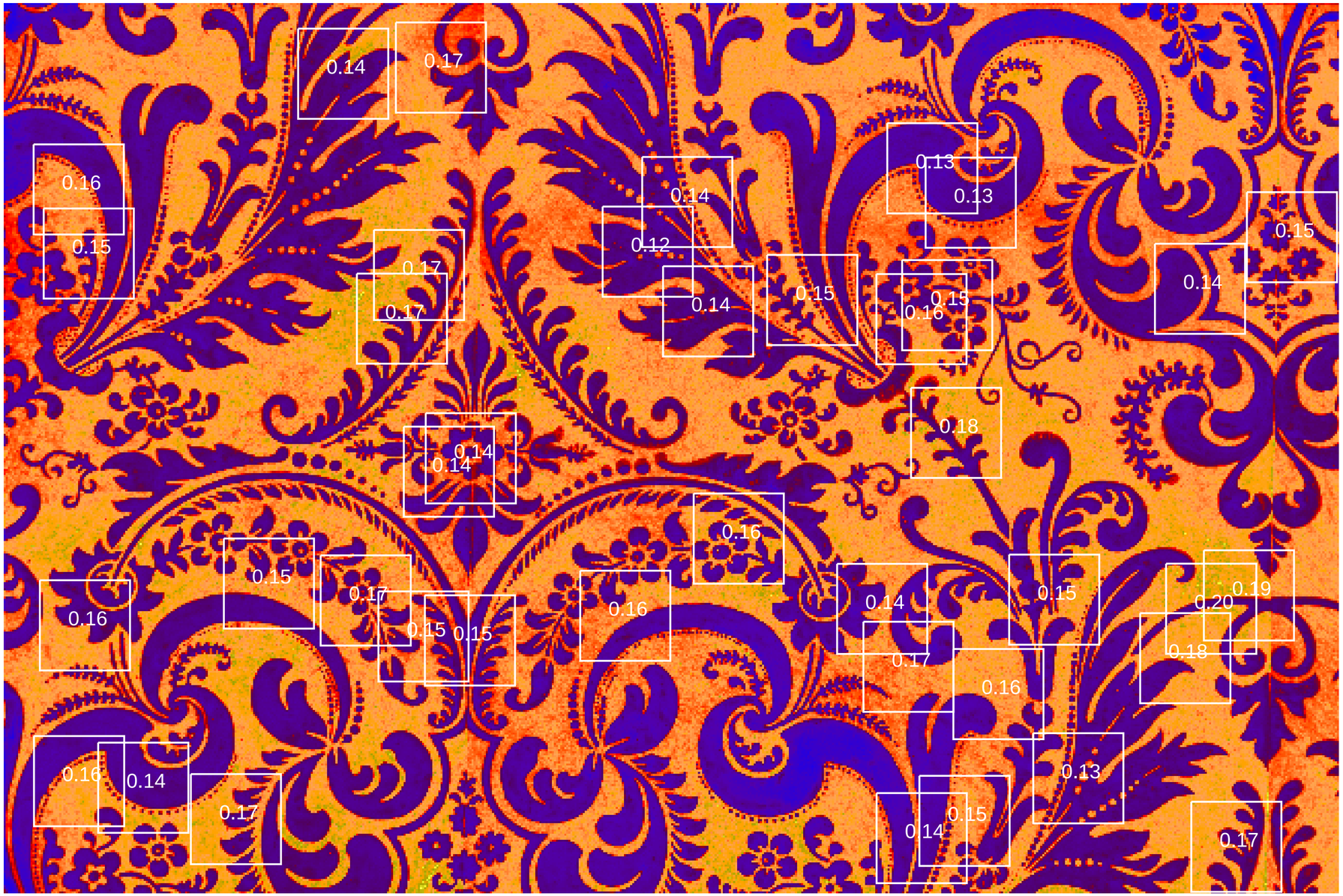
Reflectance map



Average for image = 0.157 or 15.7%

Random 350 pixels

Reflectance - box average

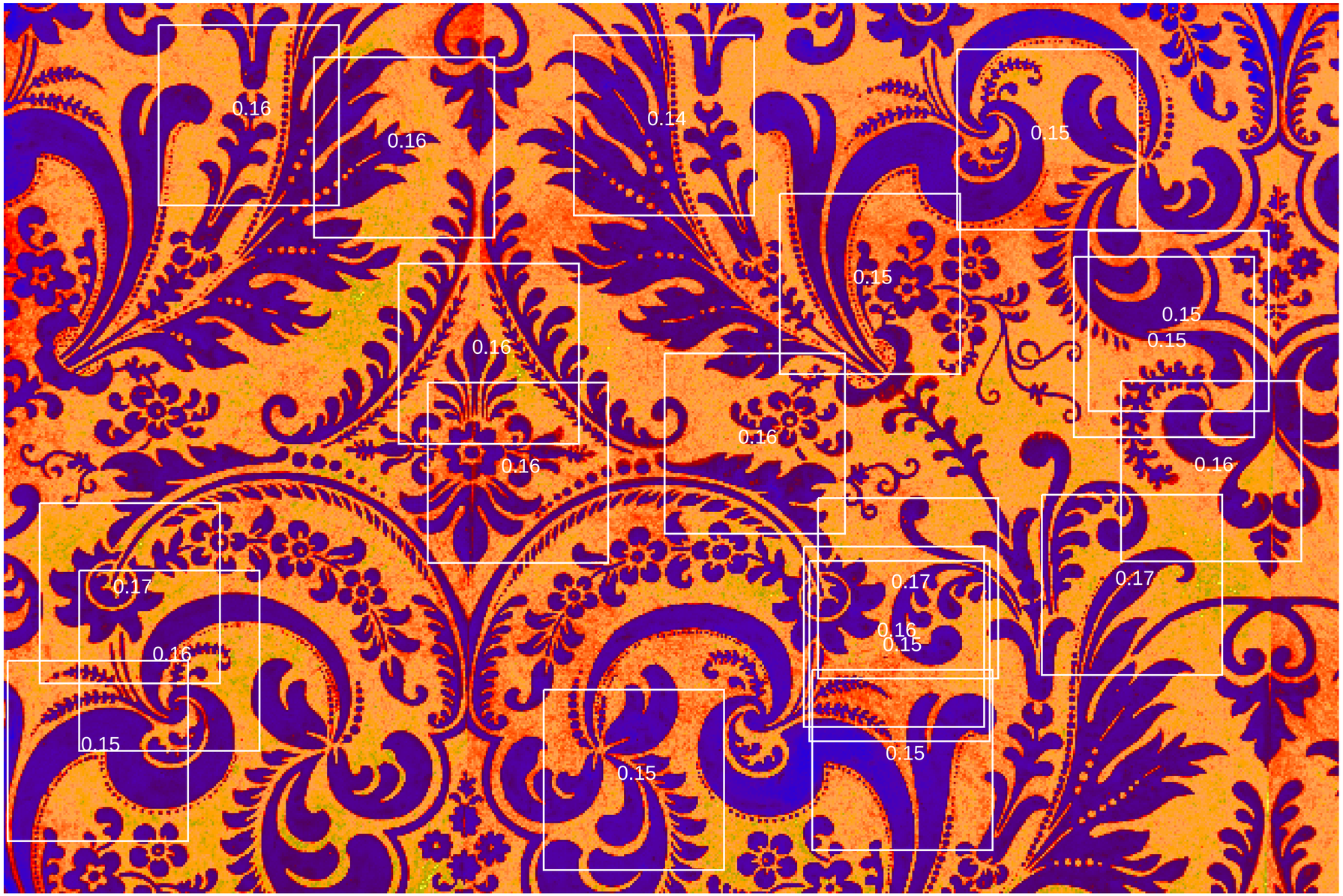


Mean for image = 0.157

Mean [stdev] of box samples = 0.155 [0.017]

Random 700 pixels

Reflectance - box average

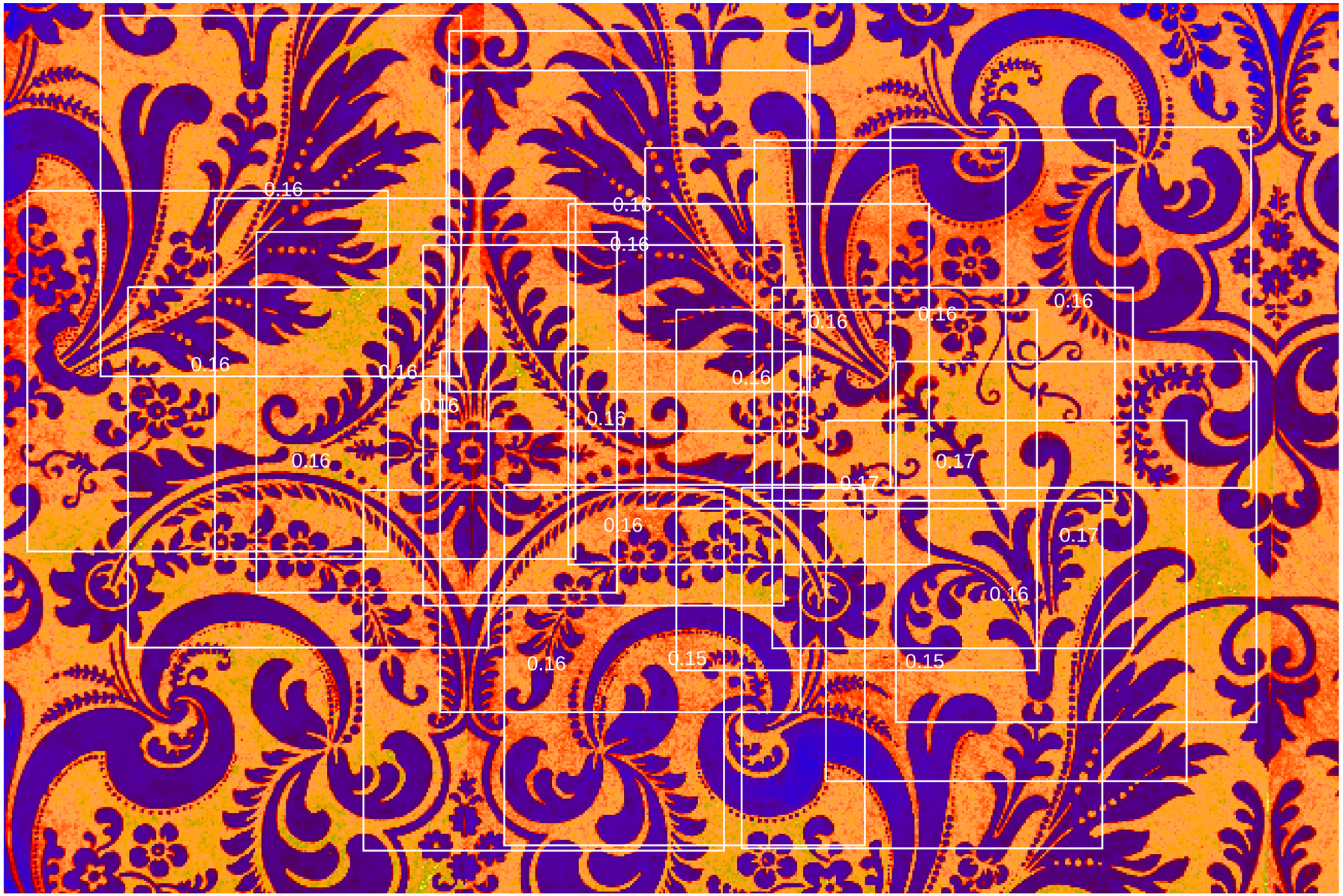


Mean for image = 0.157

Mean [stdev] of box samples = 0.156 [0.007]

Random 1400 pixels

Reflectance - box average



Mean for image = 0.157

Mean [stdev] of box samples = 0.160 [0.004]

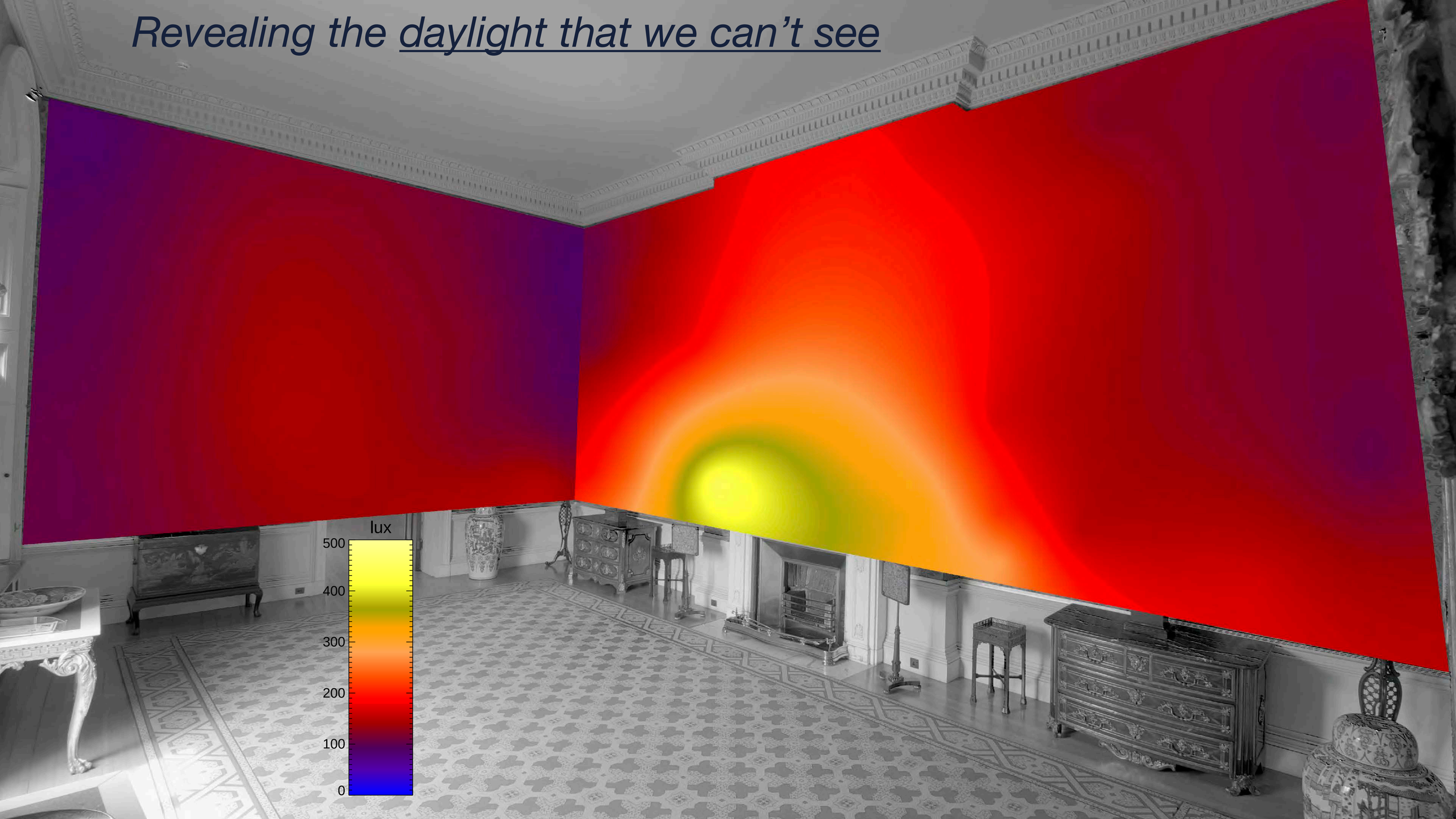

2x the minimum
‘safe’ size

Apply vignetting correction; subtract electric light contribution

Determine mean luminance at the target patches

Interpolate illumination field across target patches

Revealing the daylight that we can't see



But…

Ghostly encounters

Share spine-chilling thrills at some of the most haunted historic houses and castles across England, Wales and Northern Ireland. With ghostly tales from centuries past, there are plenty of ways to get into the spirit of things on a day out with us. Take an eerie walk with your family in a haunted house if you dare. Here's our pick of the most hair-raising haunted locations, and their spooky stories. Are you brave enough to pay them a visit?

Are you ready to hunt for ghosts at Blickling Hall?

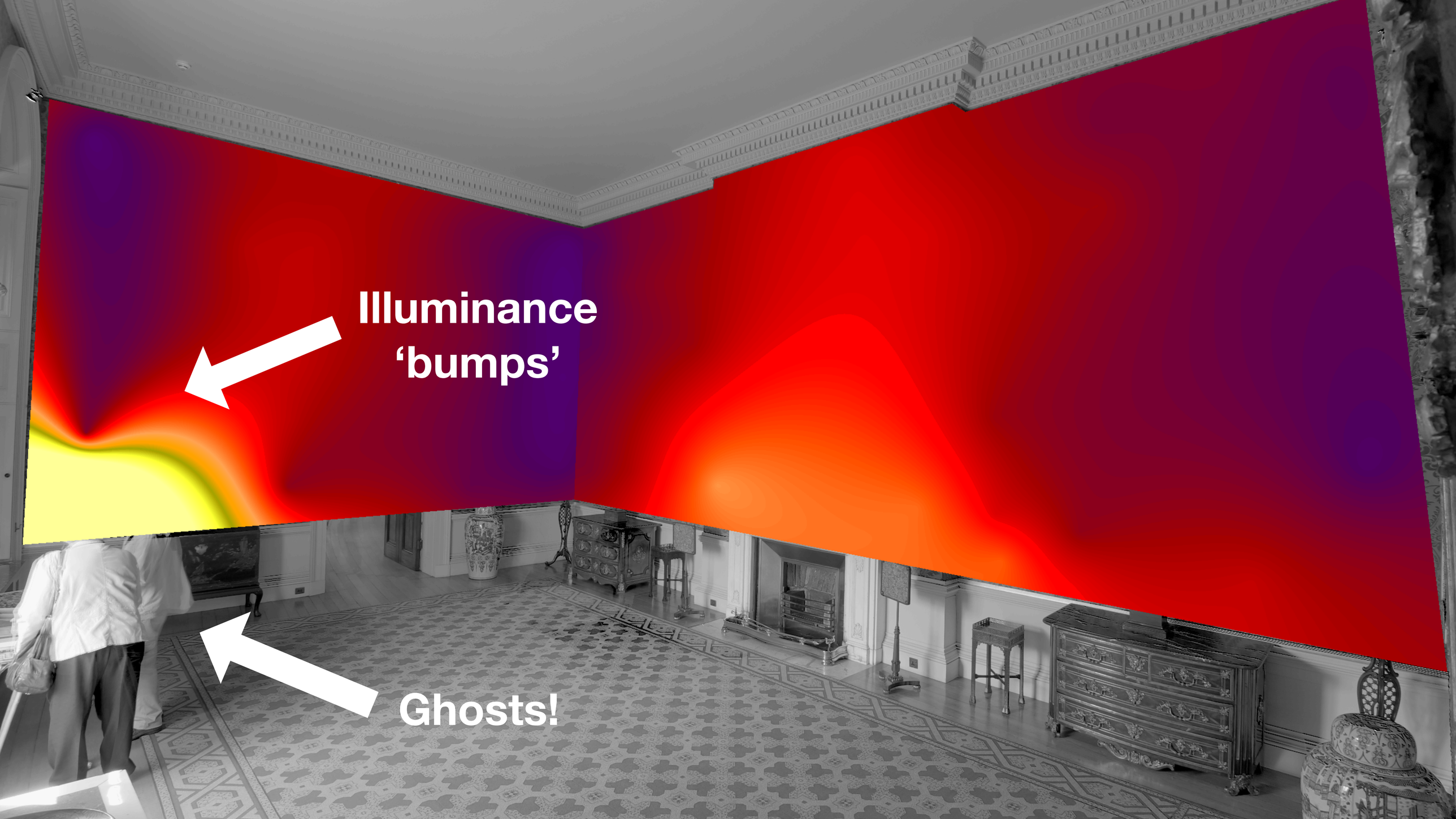
Blickling Estate
Norfolk

Blickling Hall, Norfolk

Thought to be the birthplace of Anne Boleyn, her headless ghost is said to return on the anniversary of her execution.

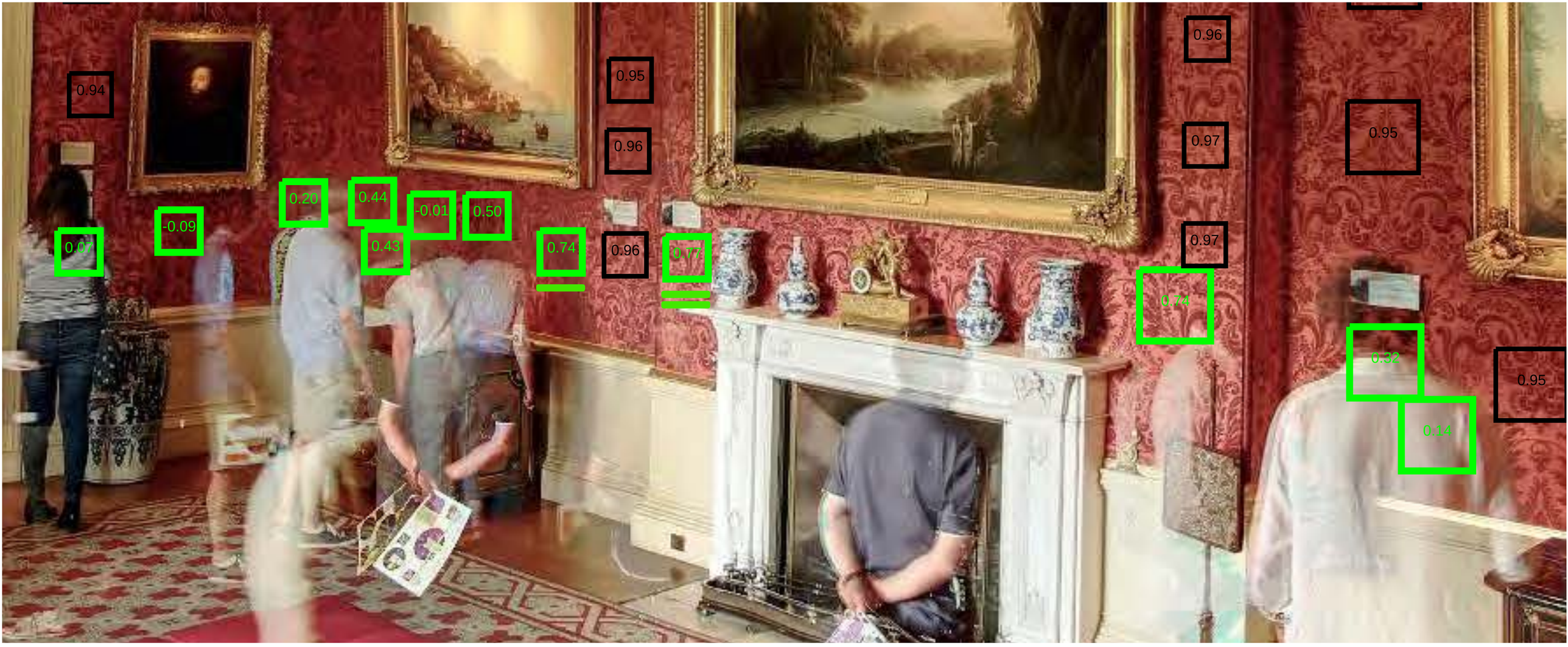
Other ghostly residents allegedly include Sir John Falstofe and Sir Henry Hobart, whose dying groans can be heard emanating from the West Turret Bedroom on the anniversary of his death.

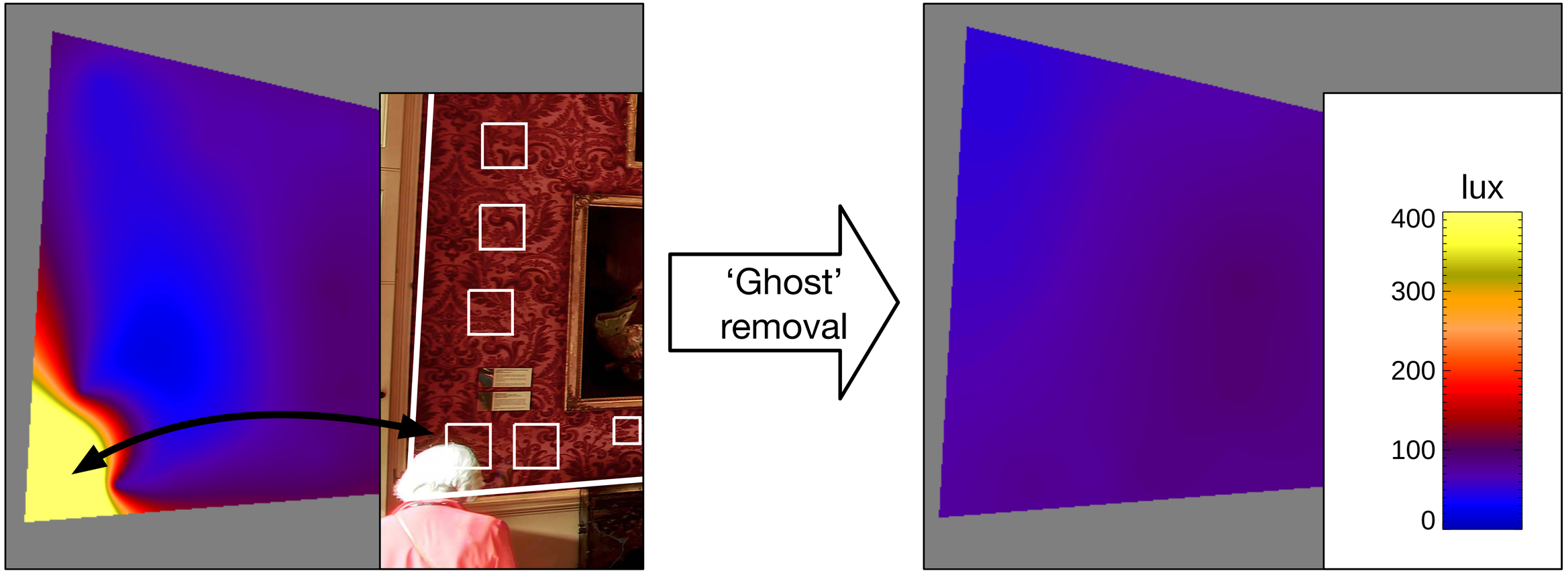
Spot ghosts at Blickling Hall


Illuminance
‘bumps’
Ghosts!

Need a fix…

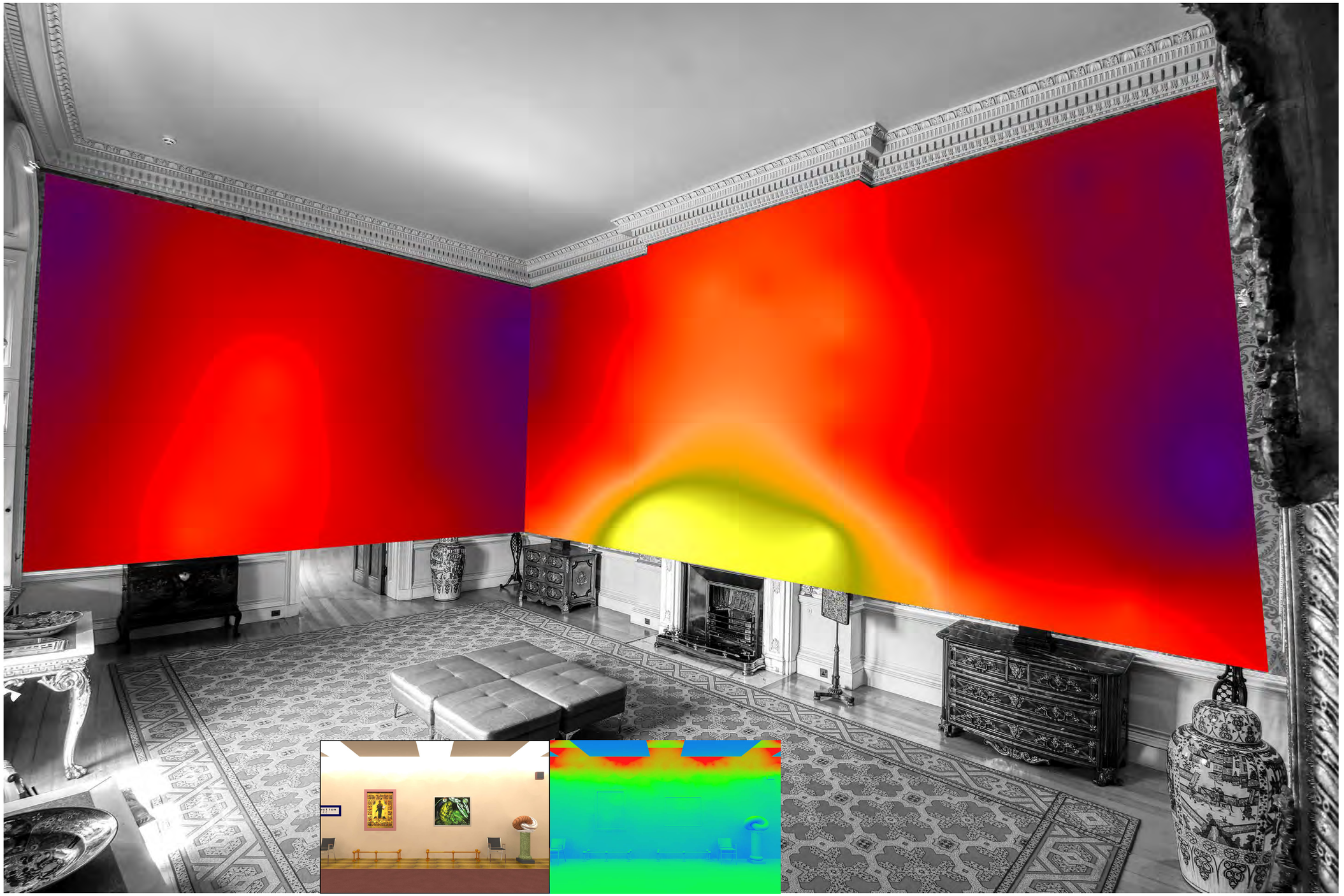
Each wallpaper patch has a distinctive ‘signature’


0.94
0.95
0.96
0.96
0.97
0.97
0.95
0.20
0.44
-0.01
0.50
-0.09
0.07
0.43
0.74
0.96
0.74
0.32
0.95
0.14

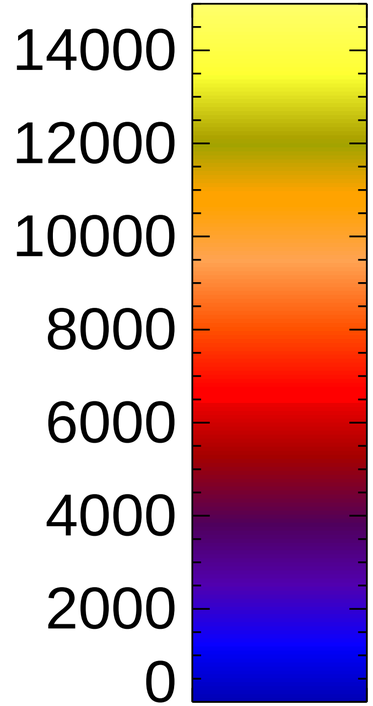

‘Ghost’
removal
lux
400
300
200
100
0

Cumulative daylight exposure

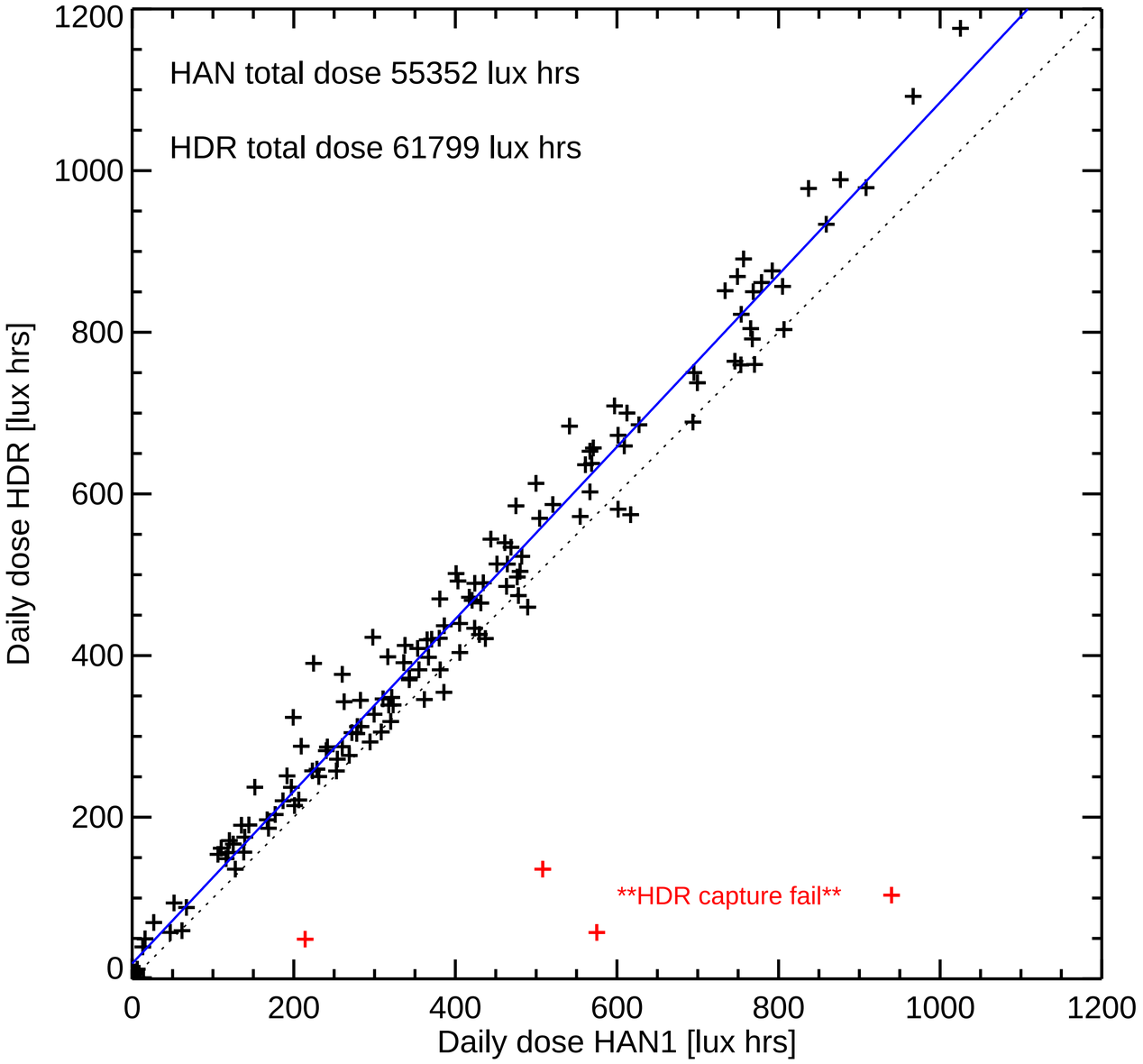
July 2016

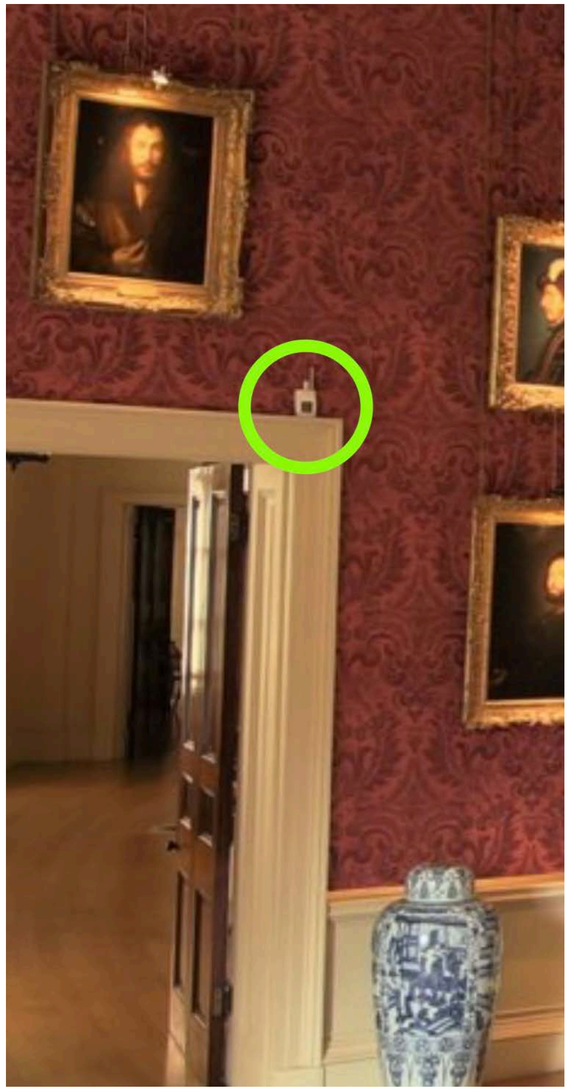


lx hrs



Validation


HAN total dose 55352 lux hrs
HDR total dose 61799 lux hrs
HDR capture fail
Daily dose HDR [lux hrs]
Daily dose HAN1 [lux hrs]
0
200
400
600
800
1000
1200



External monitoring of illuminance

Delta-T BF5 Sunshine Sensor
Measures global and diffuse radiation

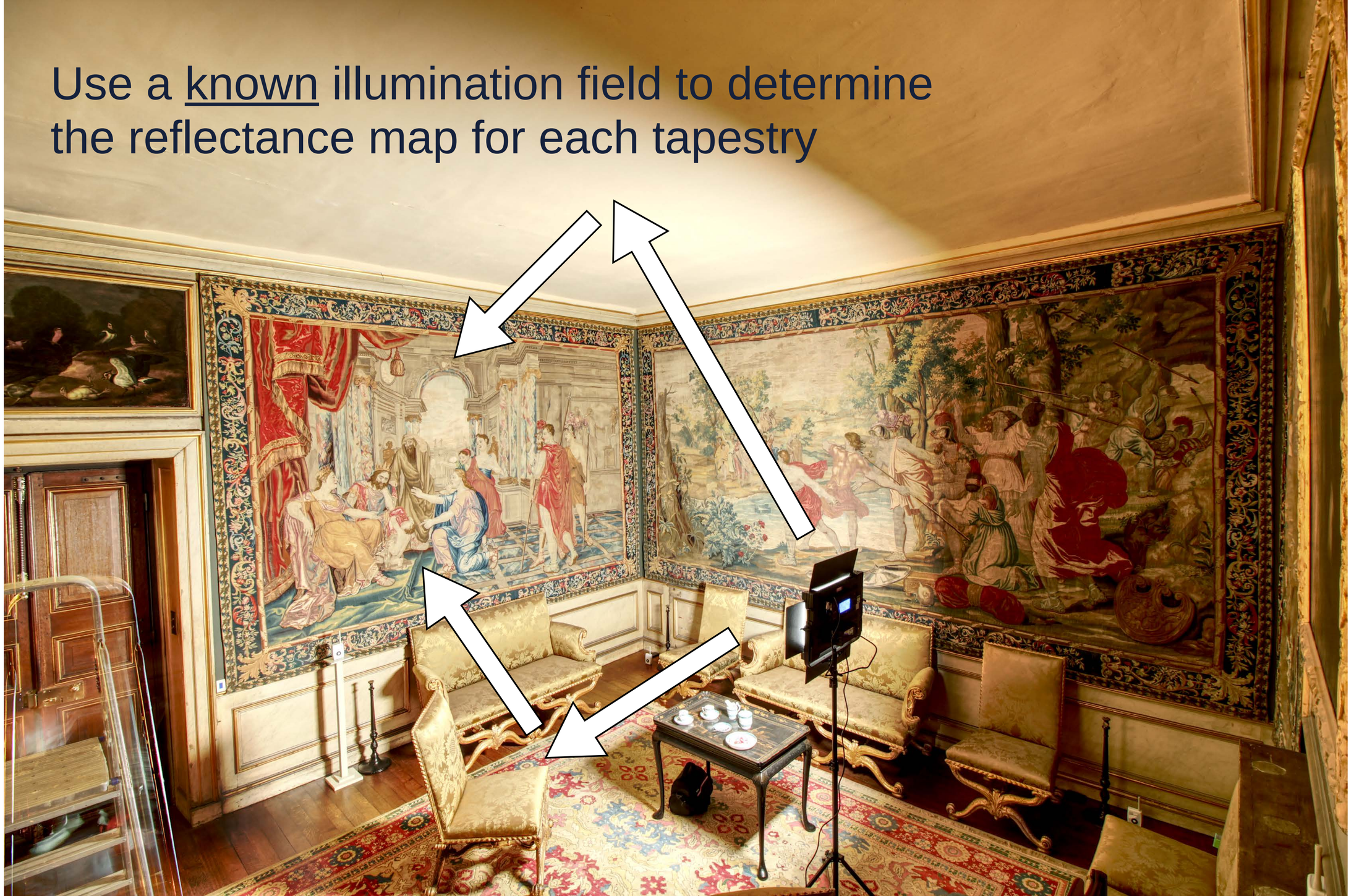
But what if there are no suitable ‘target’ patches of known reflectance?

Ham House, Richmond

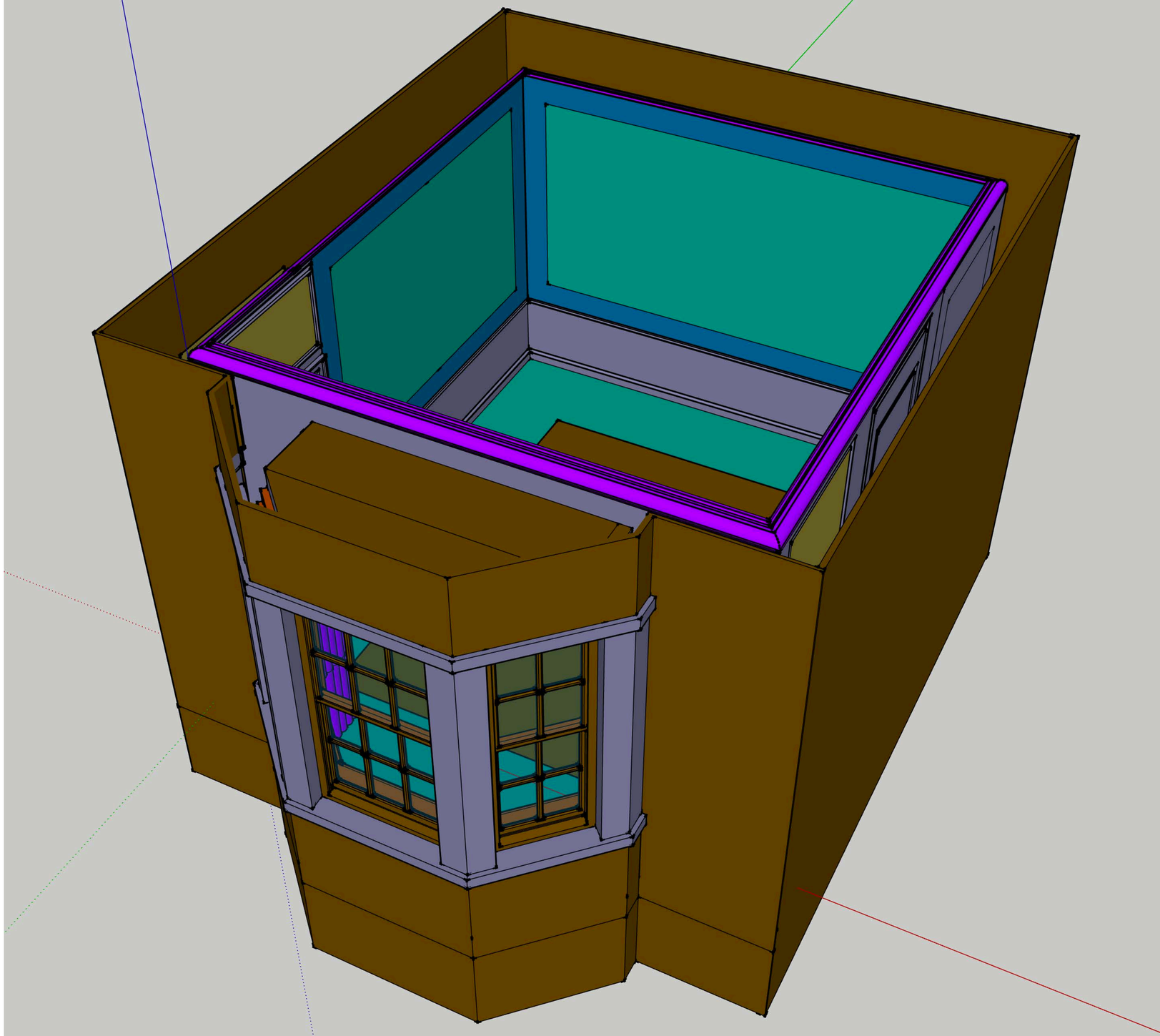
The Volury

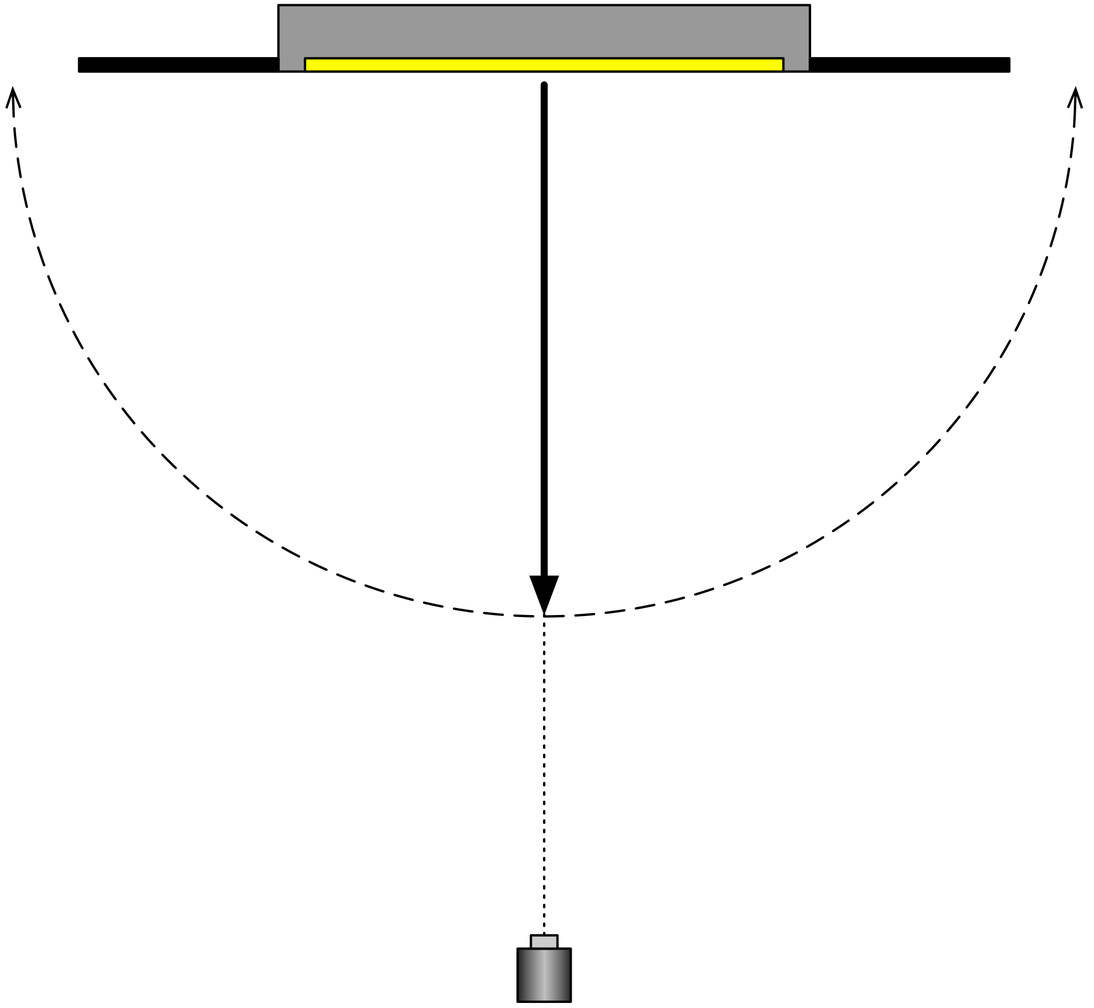
22/03/19

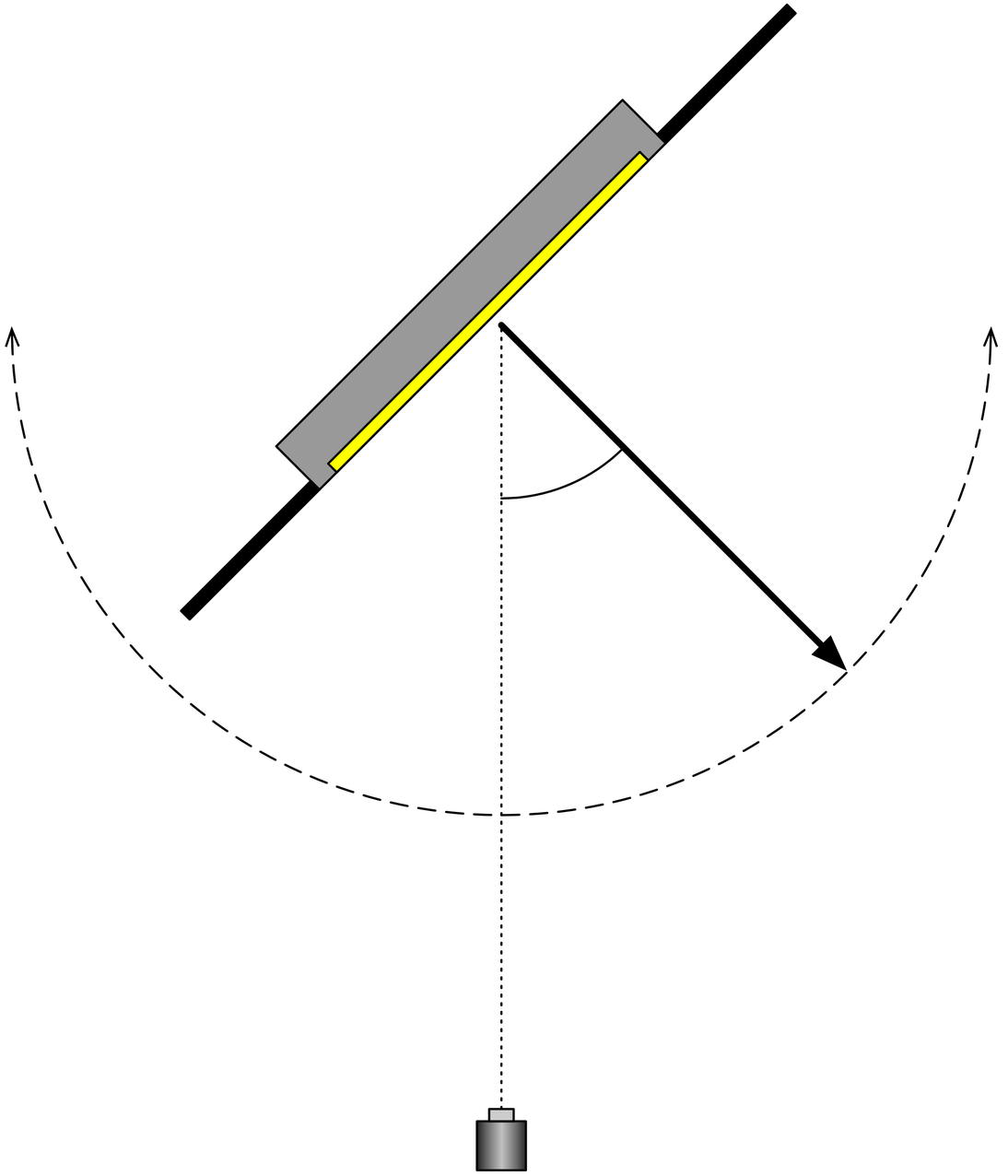
Use a known illumination field to determine the reflectance map for each tapestry

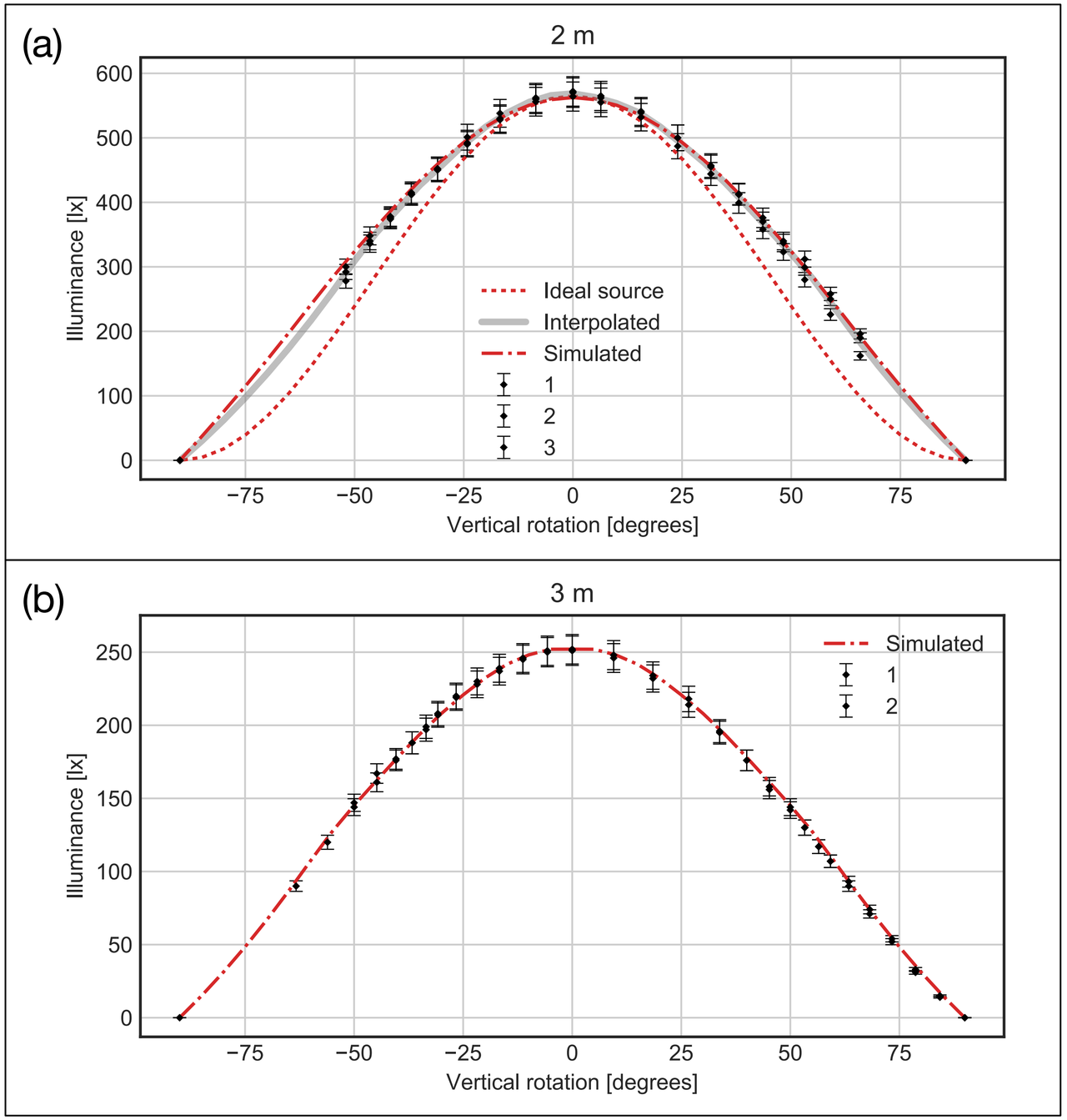


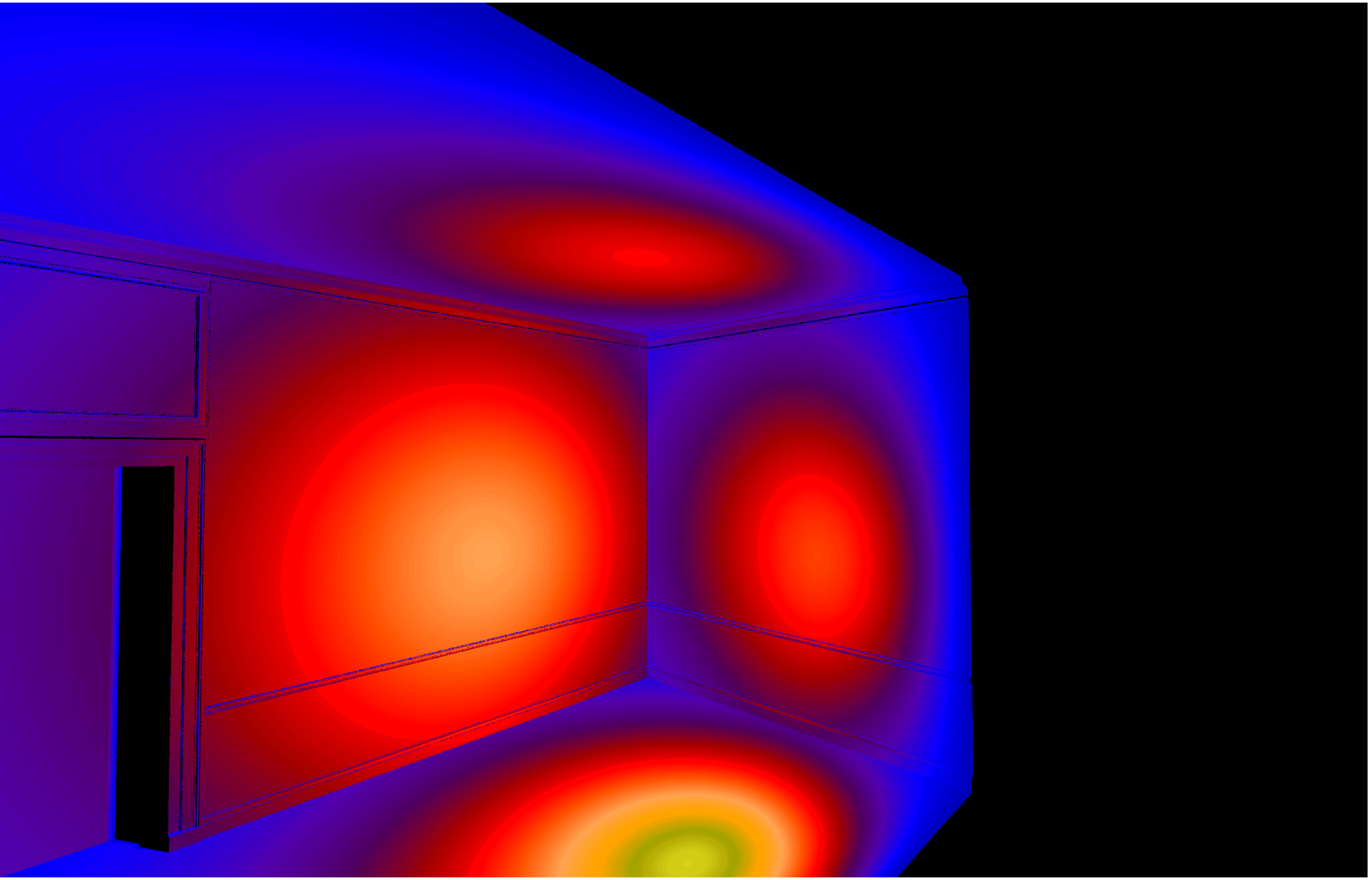
Need to use a *Radiance* simulation to account for both the direct and reflected light from the LED panel arriving at the tapestry



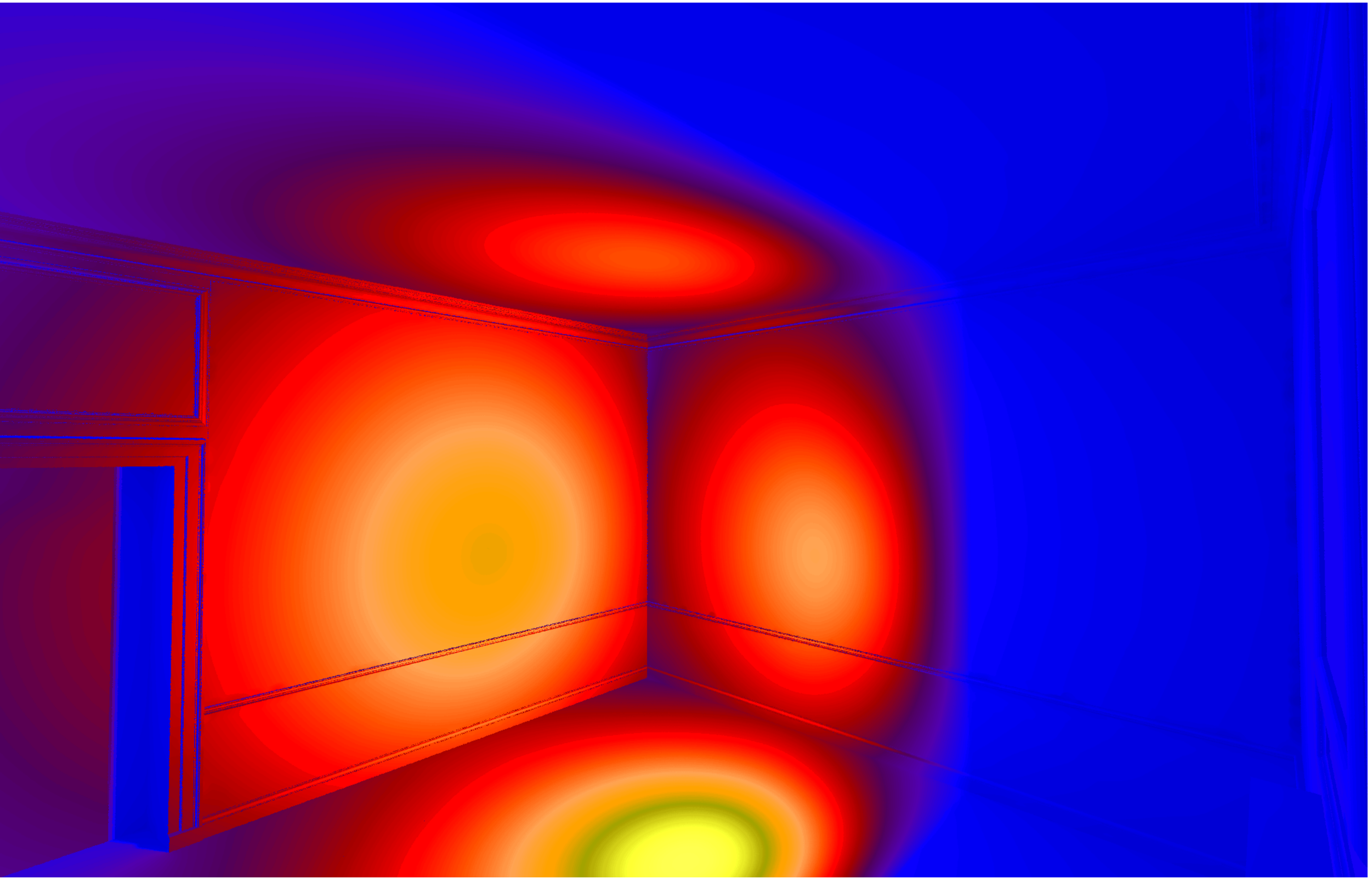


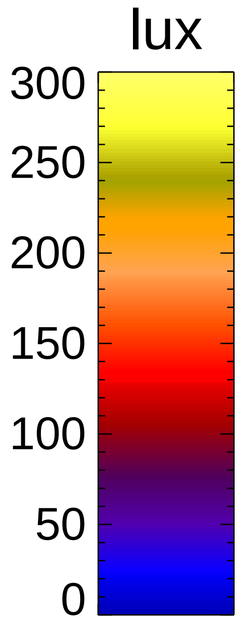



(a)
2 m
Illuminance [lx]
600
500
400
300
200
100
0
Ideal source
Interpolated
Simulated
1
2
3
−75
−50
−25
0
25
50
75
Vertical rotation [degrees]
(b)
3 m
Illuminance [lx]
250
200
150
100
50
0
Simulated
1
2
−75
−50
−25
0
25
50
75
Vertical rotation [degrees]


ab0
lux
300
250
200
150
100
50
0

ab3

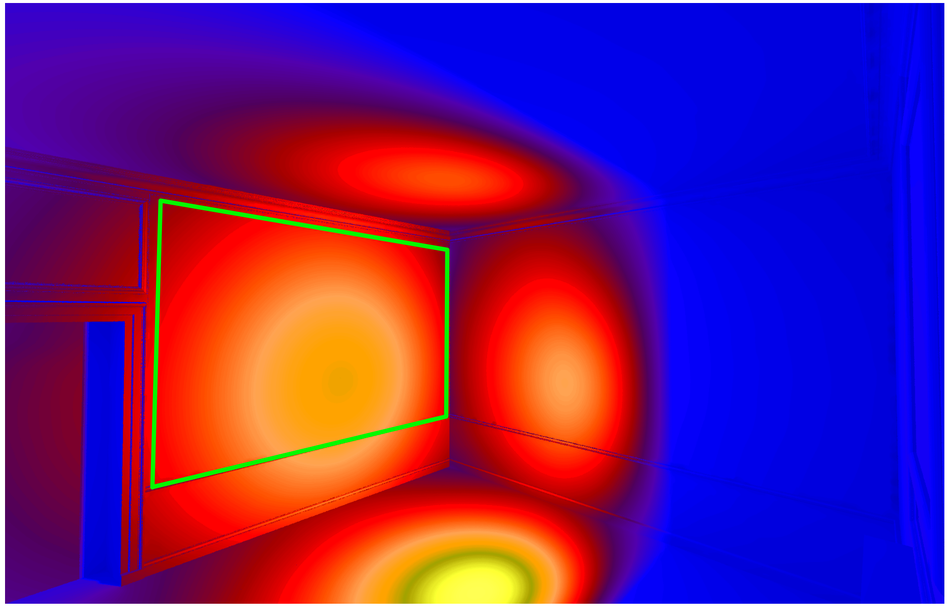


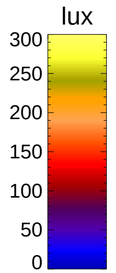



LED 1

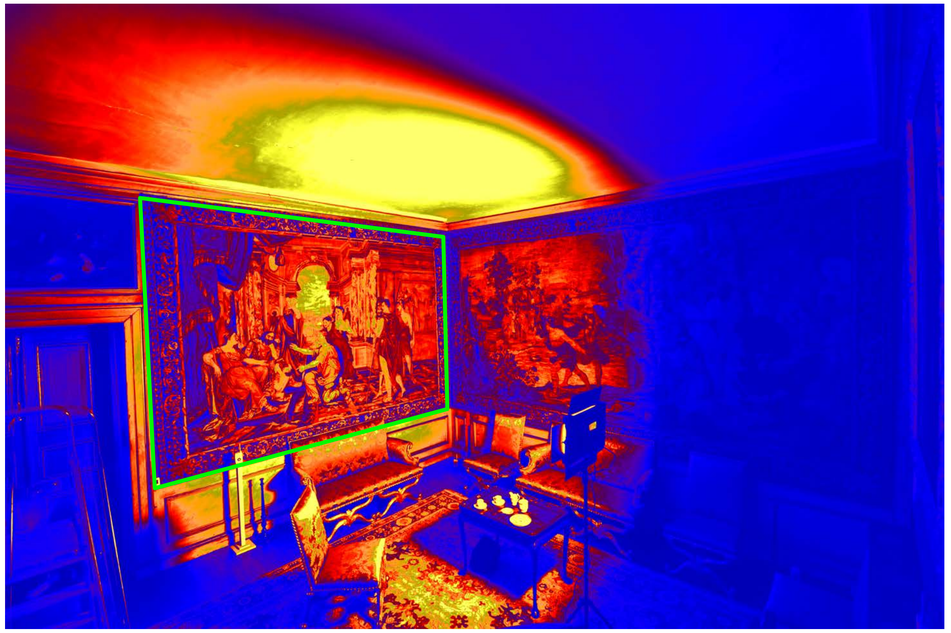

LED 2

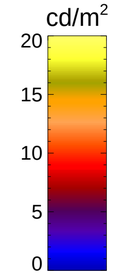
Simulated illumination map





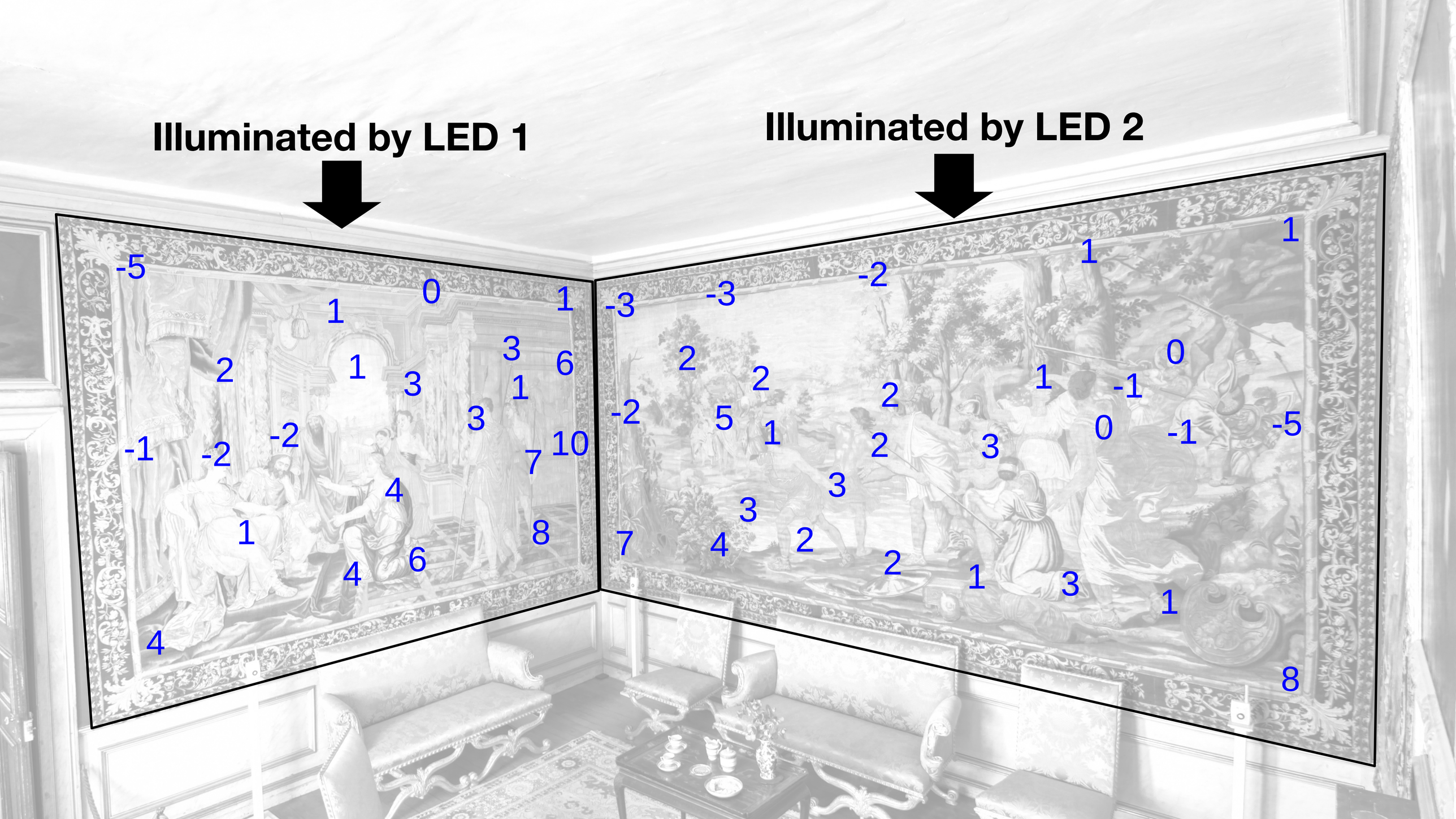
Warp to align precisely





Measured (HDR) luminance map

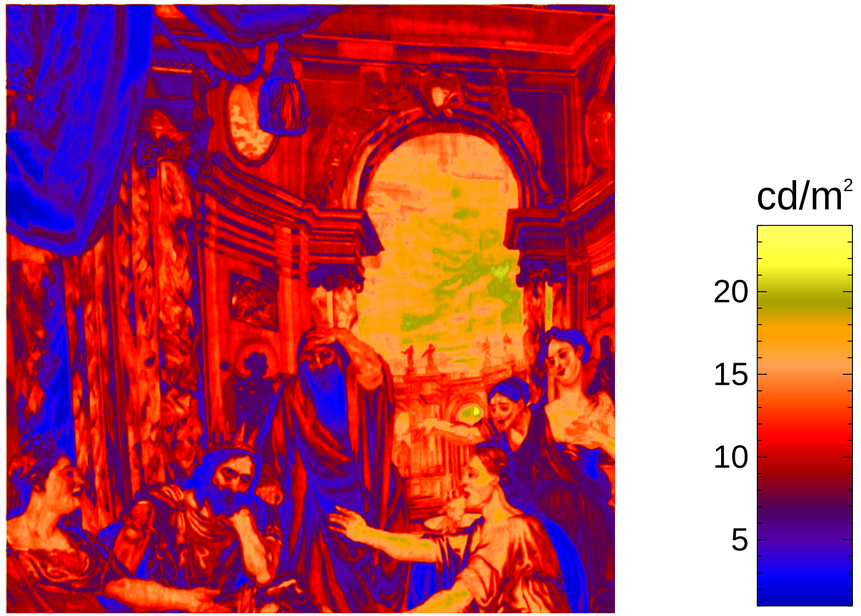
The simulated illuminances were all within 10% of the measured values


Illuminated by LED 1
Illuminated by LED 2
-5 1 0 1
2 1 3 3 6 1
-1 -2 -2 3 7 10
4
1 8
4 6
4
-3 -3 -2 1 1
2 2 2 0
-2 5 1 2 1 0 -1 -5
3 3 -1
7 4 2 2 1 3 1
8

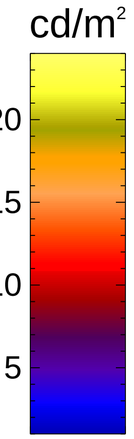
$$\rho = \frac{\pi L}{E}$$

$$\rho_{(x,y)} = \frac{\pi L_{(x,y)}}{E_{(x,y)}}$$

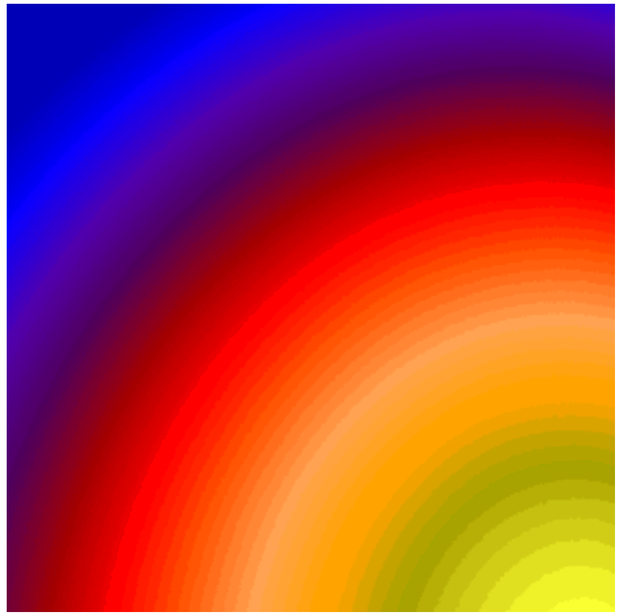
HDR capture

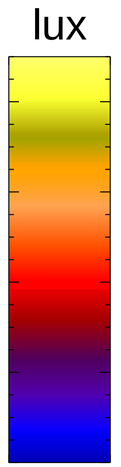


HDR capture

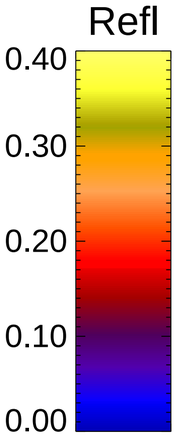


Simulated illuminance



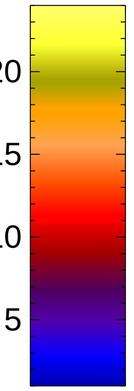


Reflectance map

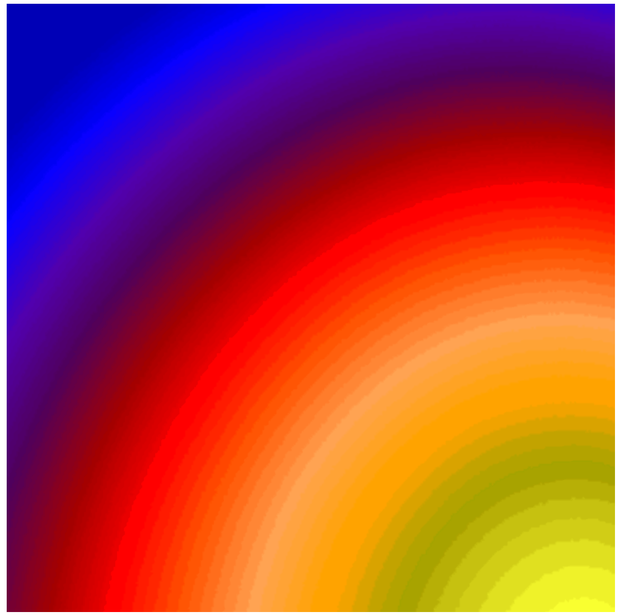


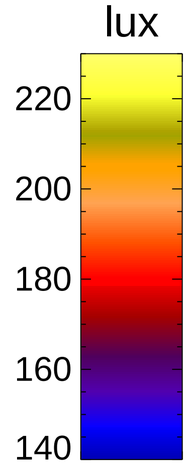
$= \pi$

HDR capture

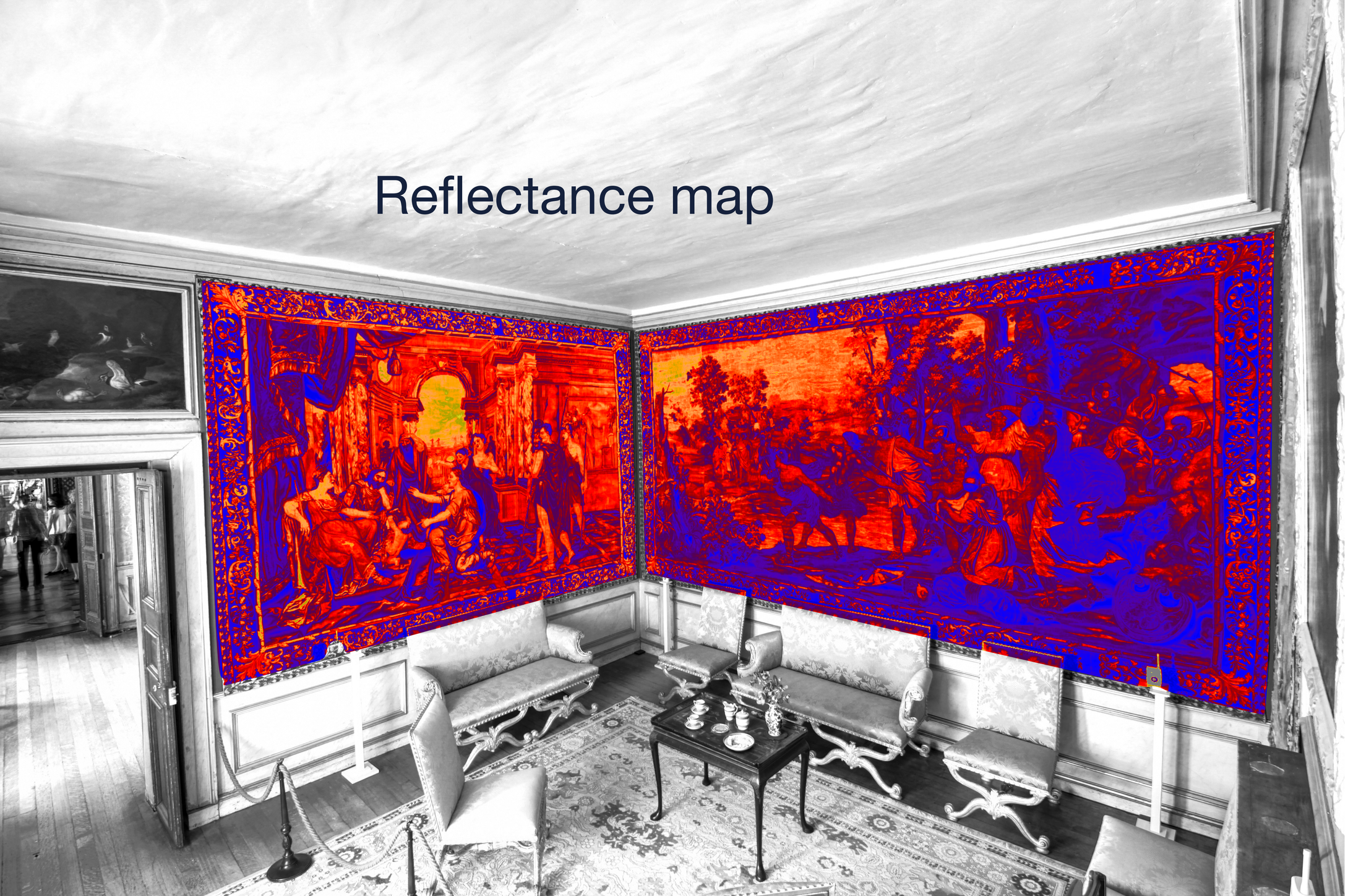


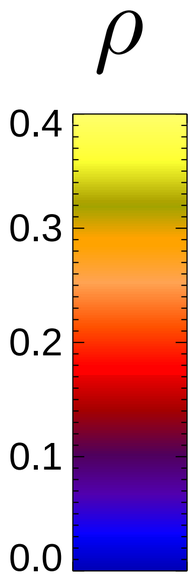
Simulated illuminance





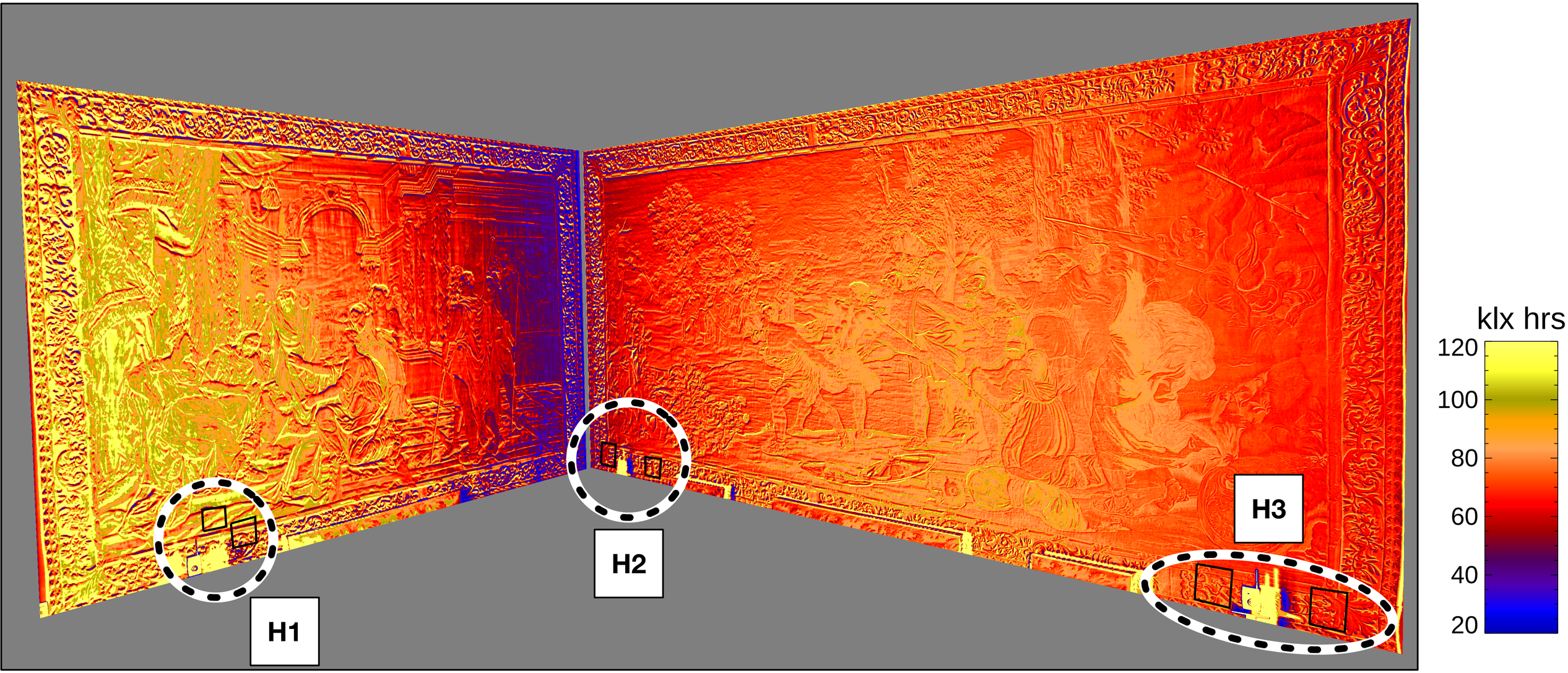
Reflectance map

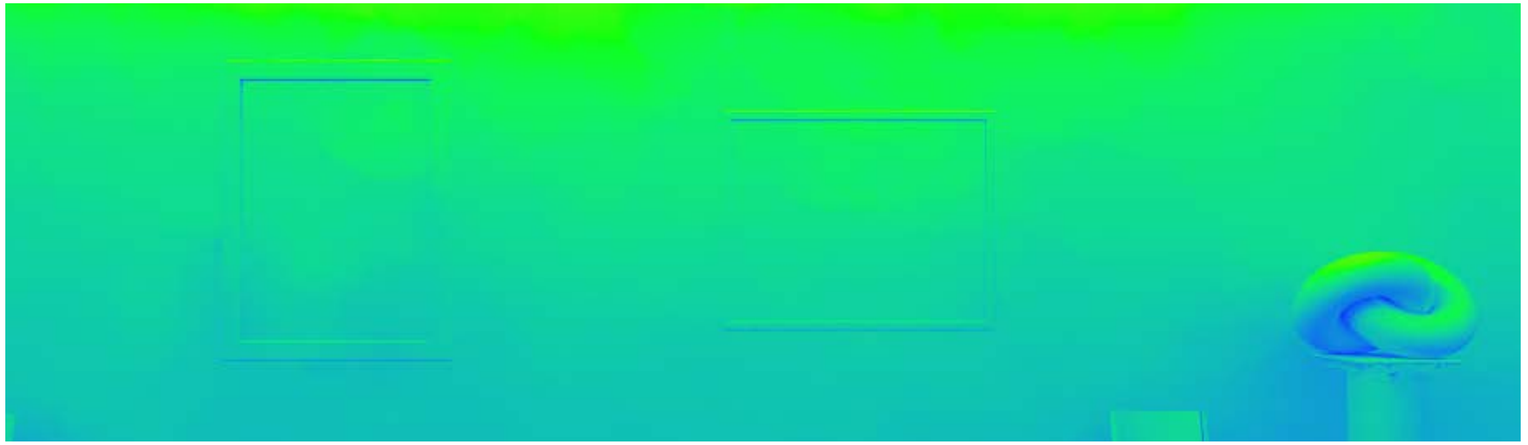




Between 10/04/19 and 16/10/19 there were 159 days of useful data capture — resulting in 4899 ‘non-dark’ HDR captures (~265Gb)

$$D_n = \sum_{i=1}^{4899} \pi \frac{L_i}{6\rho}$$


H1
H2
H3
klx hrs
120
100
80
60
40
20



‘Print Through’

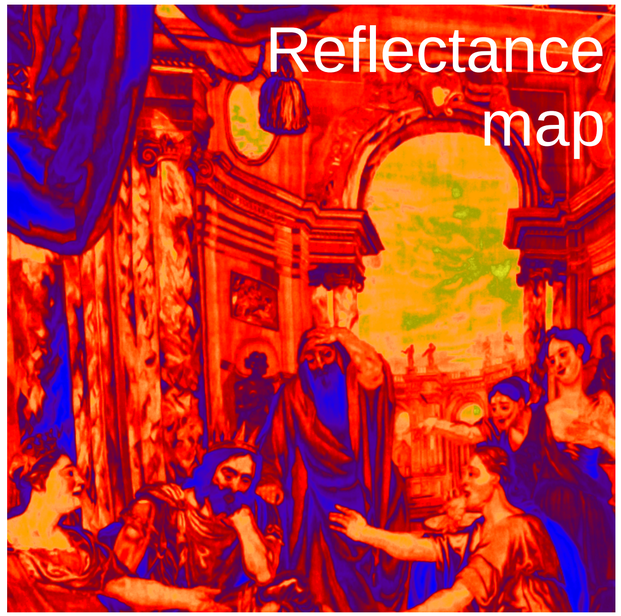
Each reflectance map was based on a single HDR capture taken morning 22/03/19 — useful data capture was from 10/04/19 and 16/10/19

Hypothesis: ‘Print through’ will be apparent if there is anything less than perfect pixel alignment between the reflectance map and the (subsequent) HDR captures

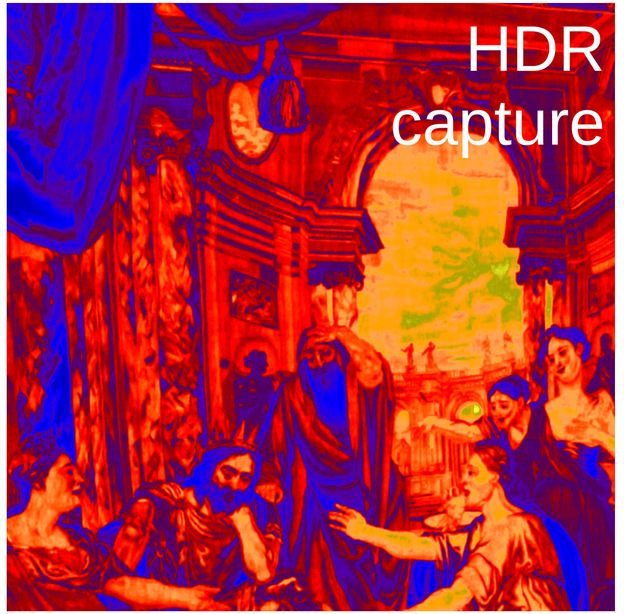
The following is an illustration to test the hypothesis using only the simulated illuminance map and the initial HDR capture taken to derive the reflectance map

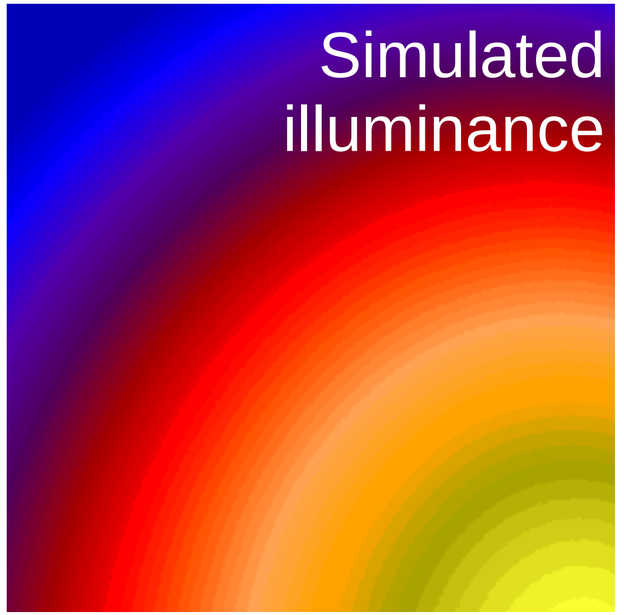
701 x 701 pixels

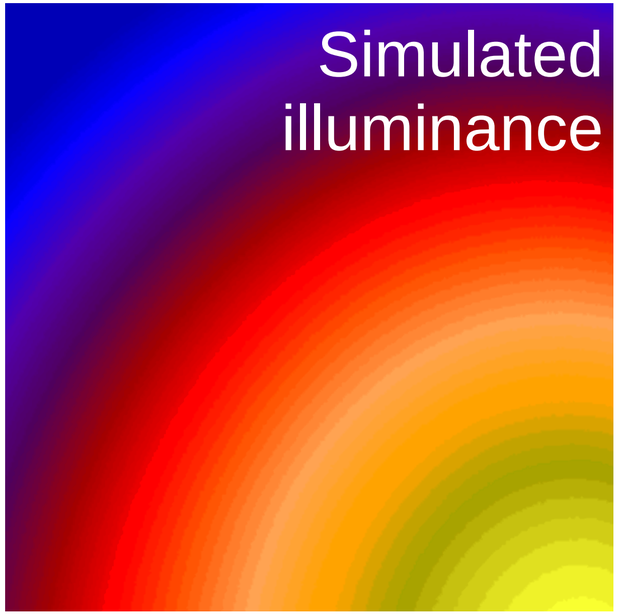
$$E_r = \frac{\pi L_r}{\rho_r}$$



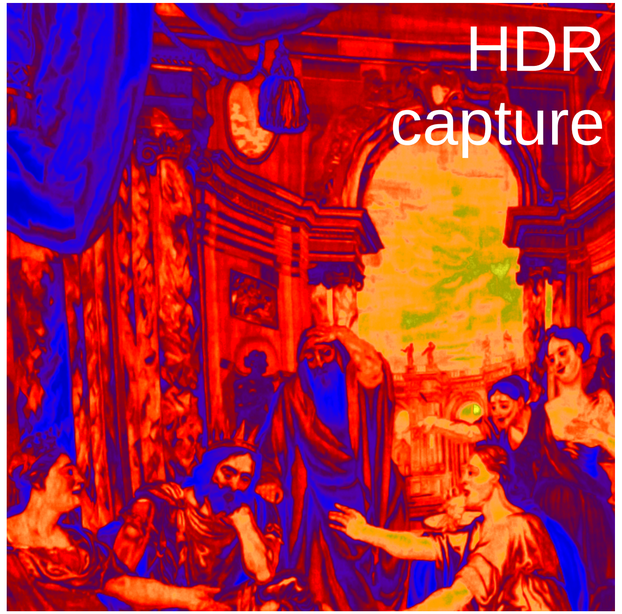
$$= \pi \frac{\text{HDR capture}}{\text{Simulated illuminance}}$$

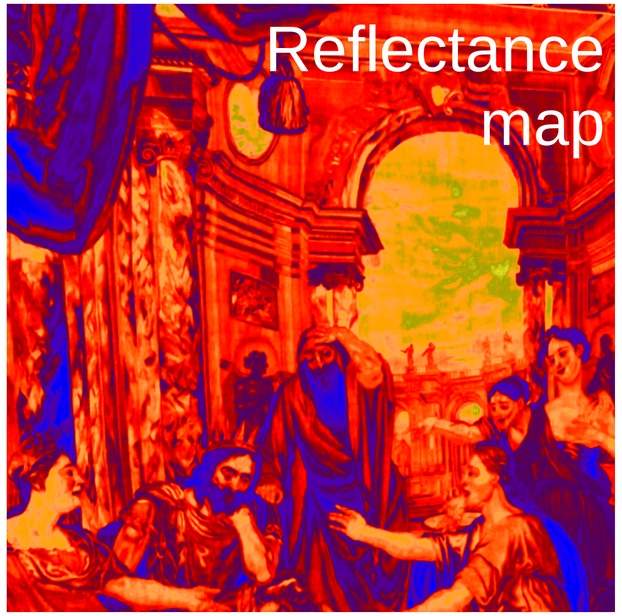


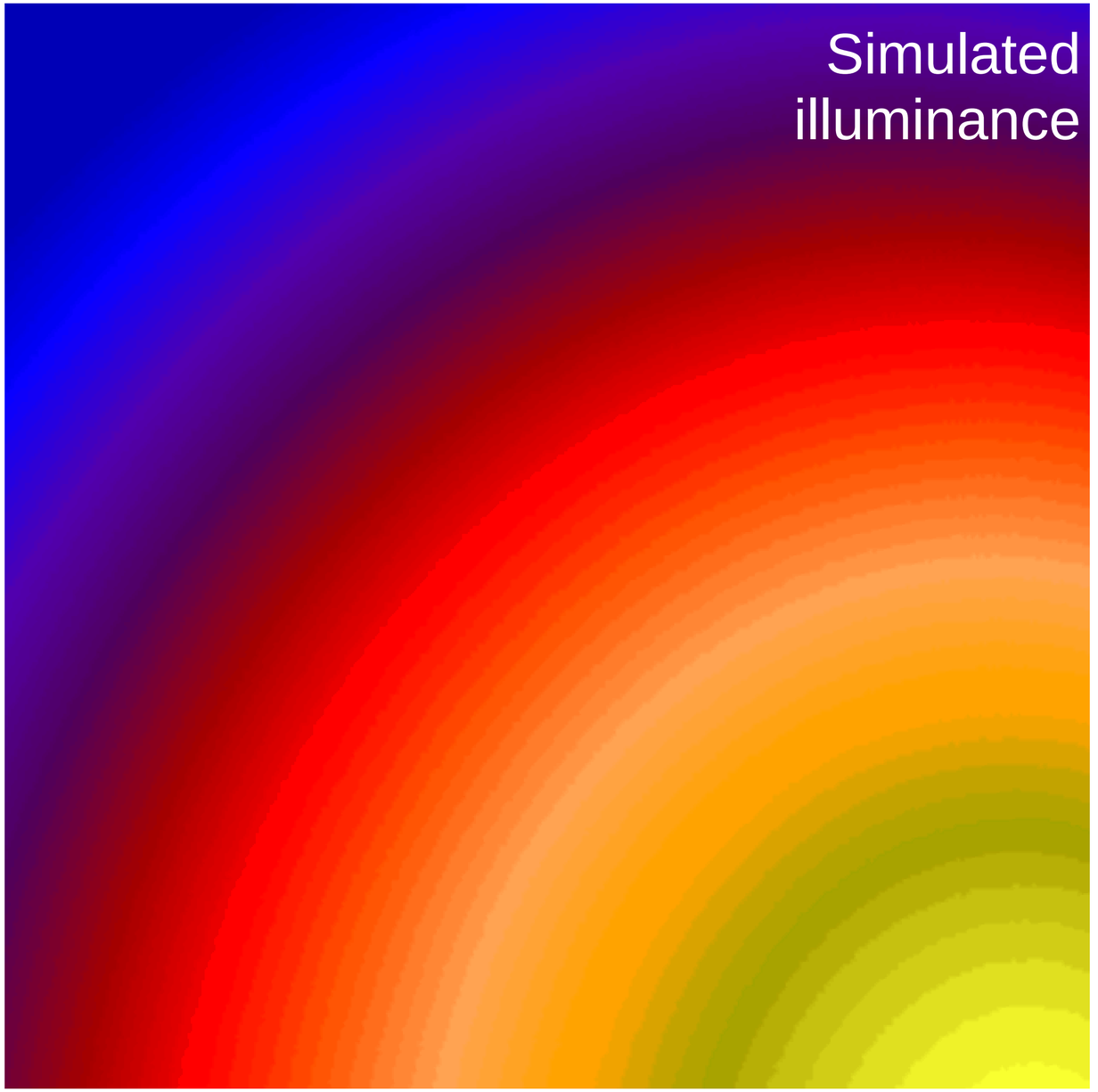


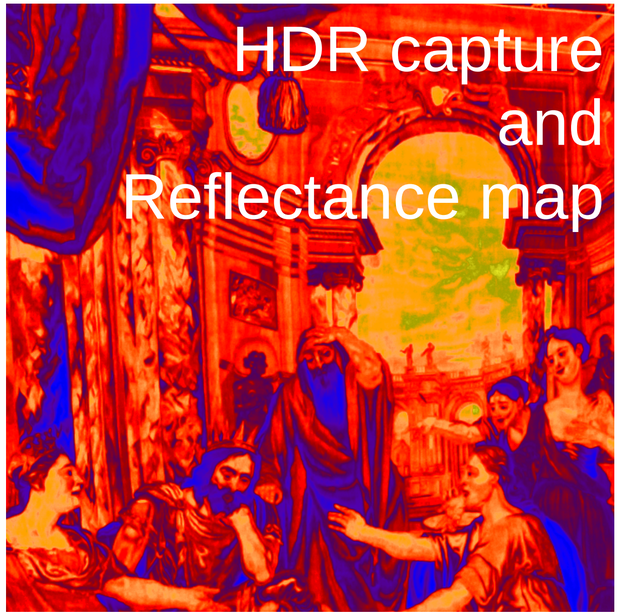


$$= \pi \frac{\text{HDR capture}}{\text{Reflectance map}}$$







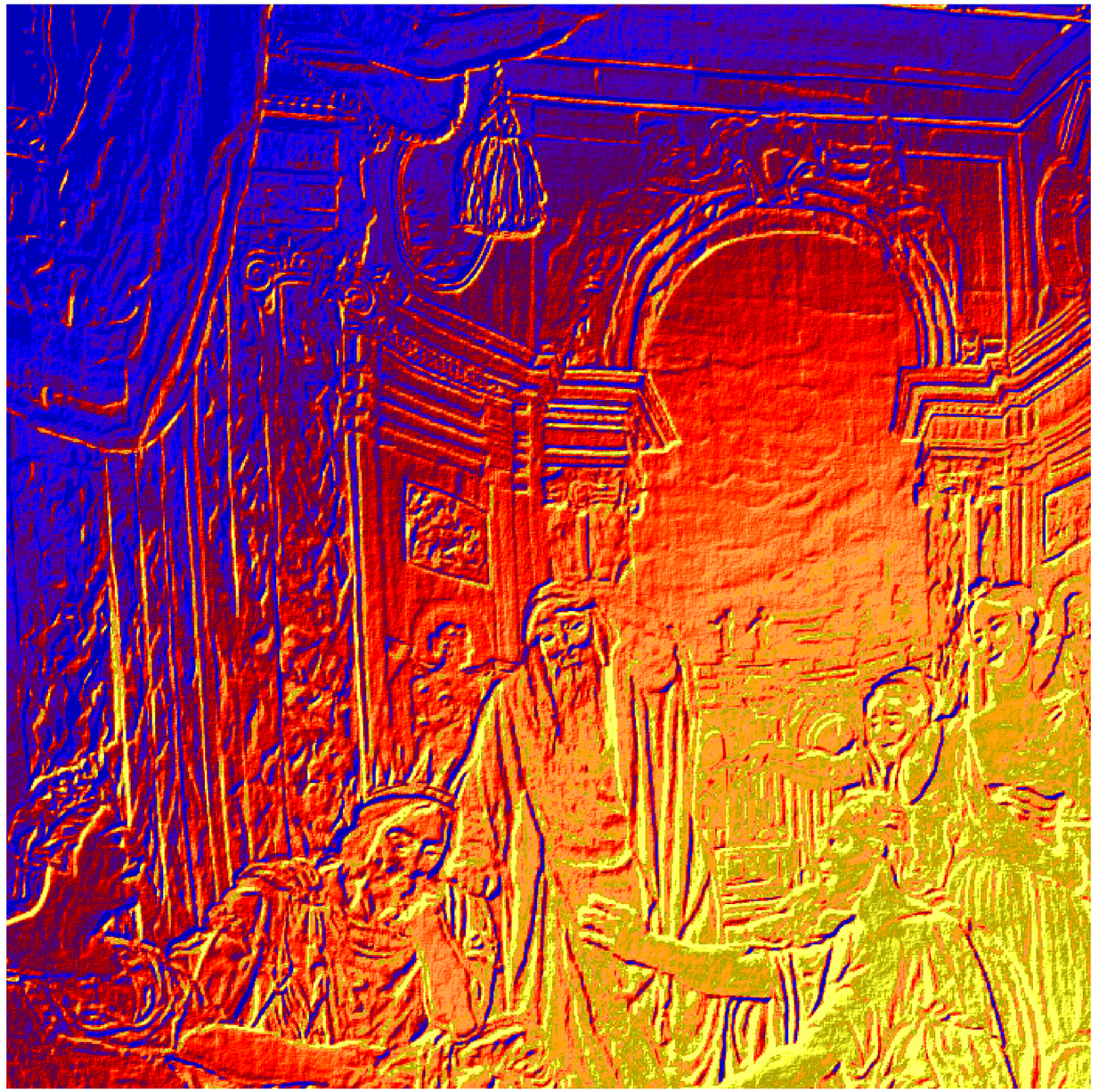


Exact pixel alignment

What happens when we don’t have exact pixel alignment between the reflectance map and the HDR capture?

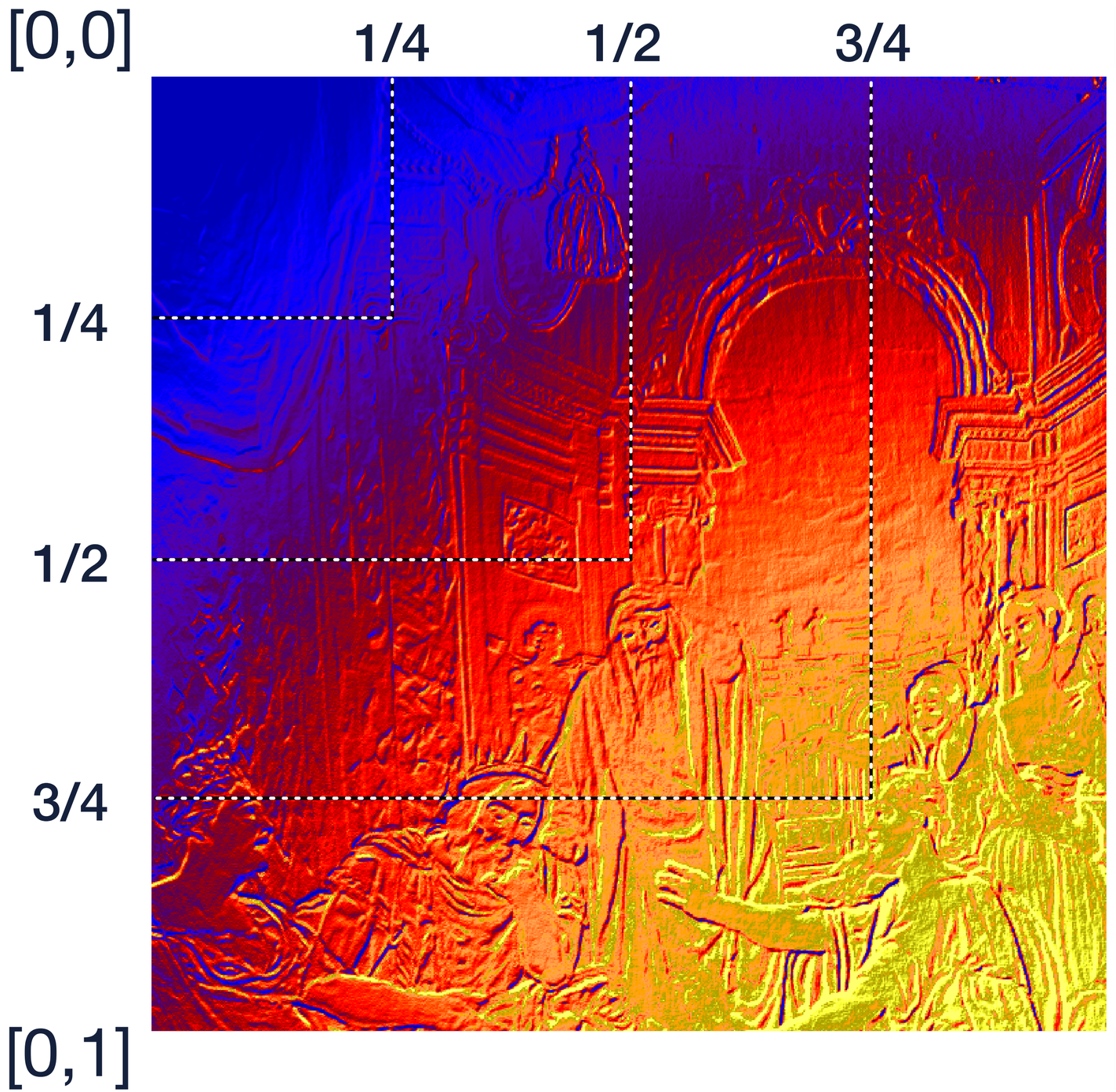
Illuminance with exact pixel alignment between the HDR capture and the reflectance map

[1,1] [1,1]



[1,1] [1,1]

Illuminance with a fixed shift of 1 pixel in x and y between the HDR capture and the reflectance map

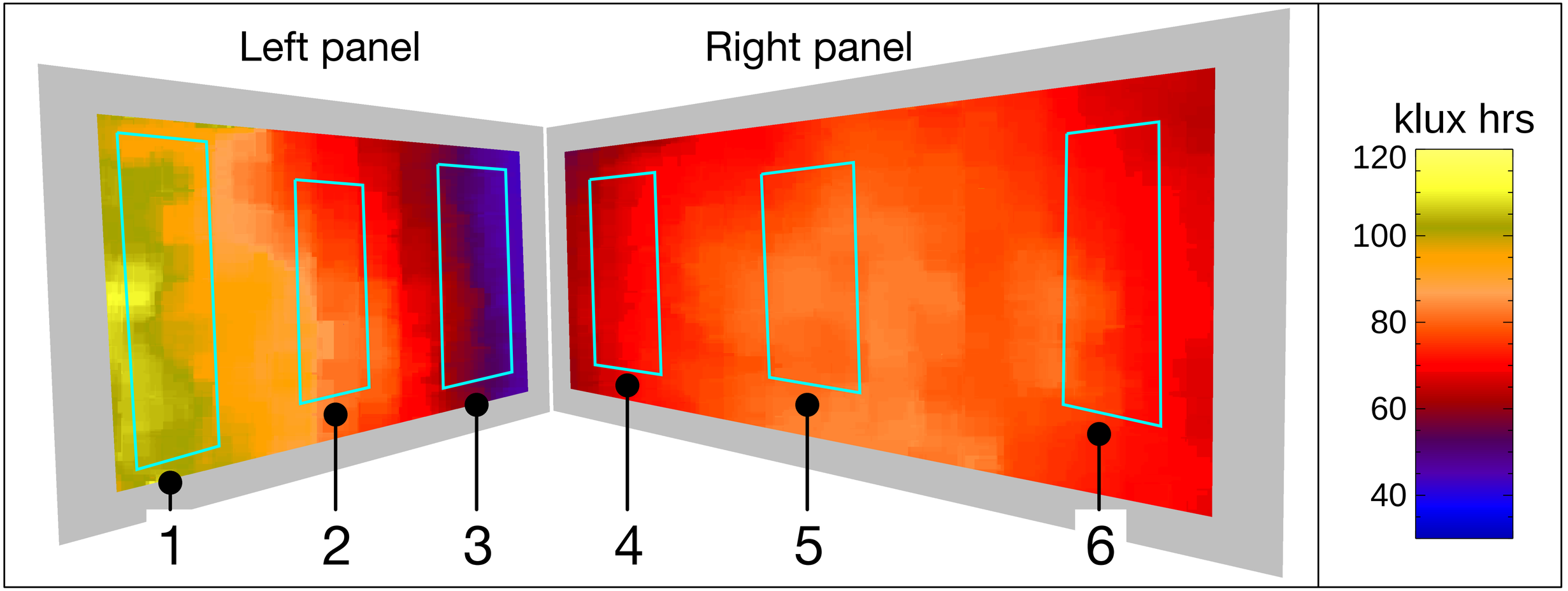


Illuminance with a gradual shift of 1 pixel in x and y between the HDR capture and the reflectance map

Tapestries are known to expand and contract resulting from variations in relative humidity.

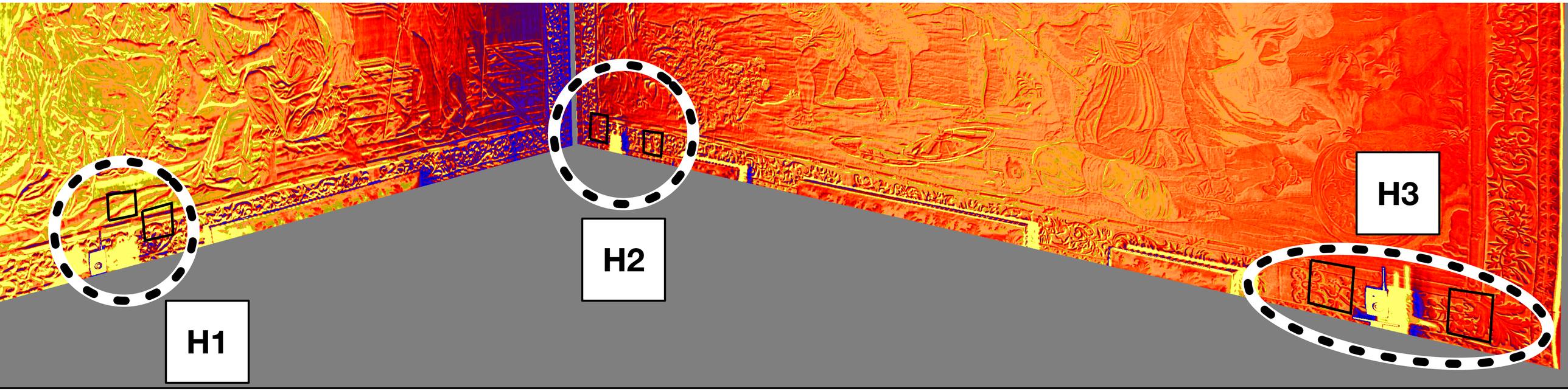
Typical pixel sizes across the tapestries correspond to dimensions in the range 2.2 to 2.6mm.

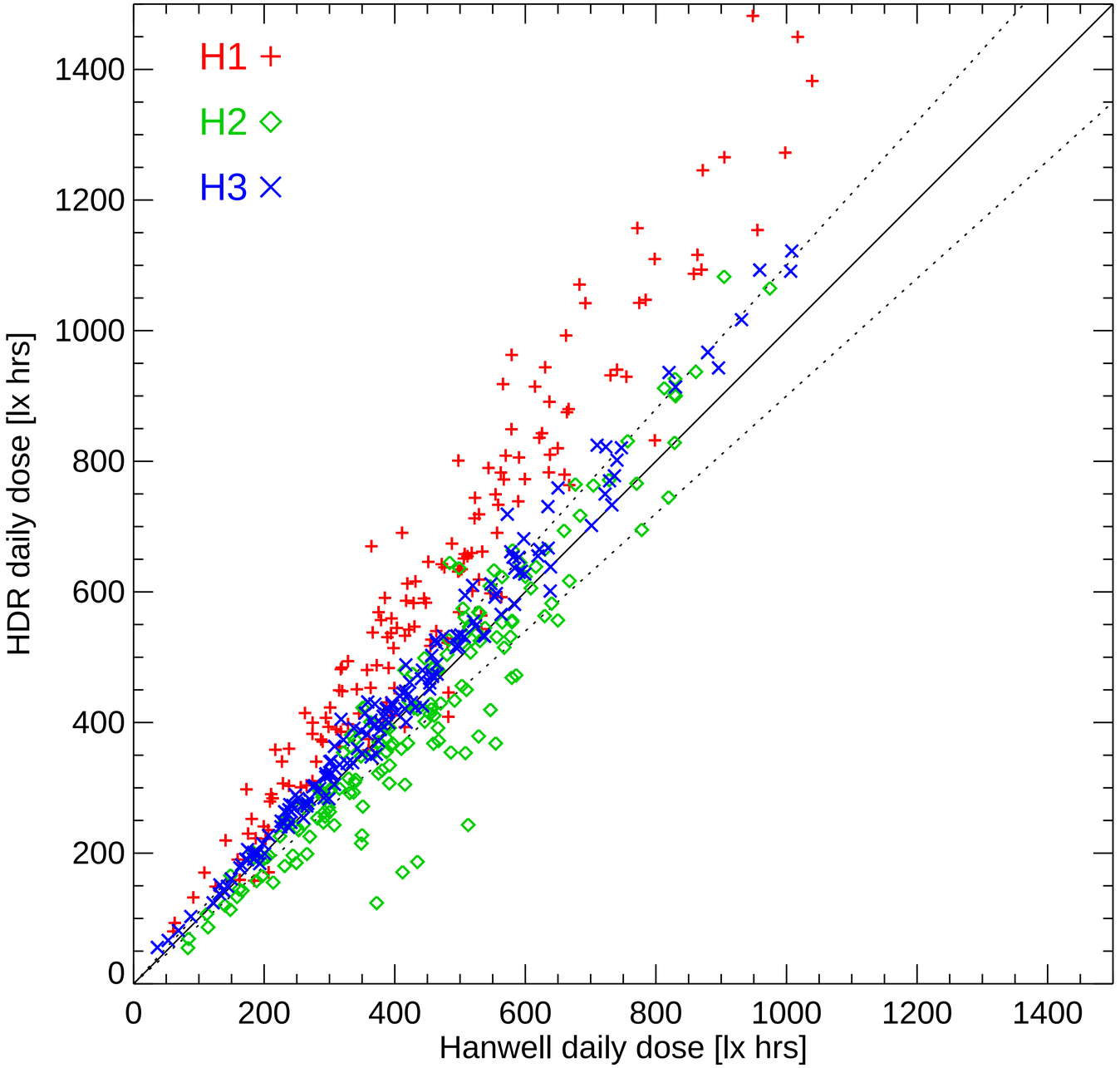
‘Correct’ the illuminance map by applying an energy-preserving filter


Left panel
Right panel
klux hrs
120
100
80
60
40
1
2
3
4
5
6

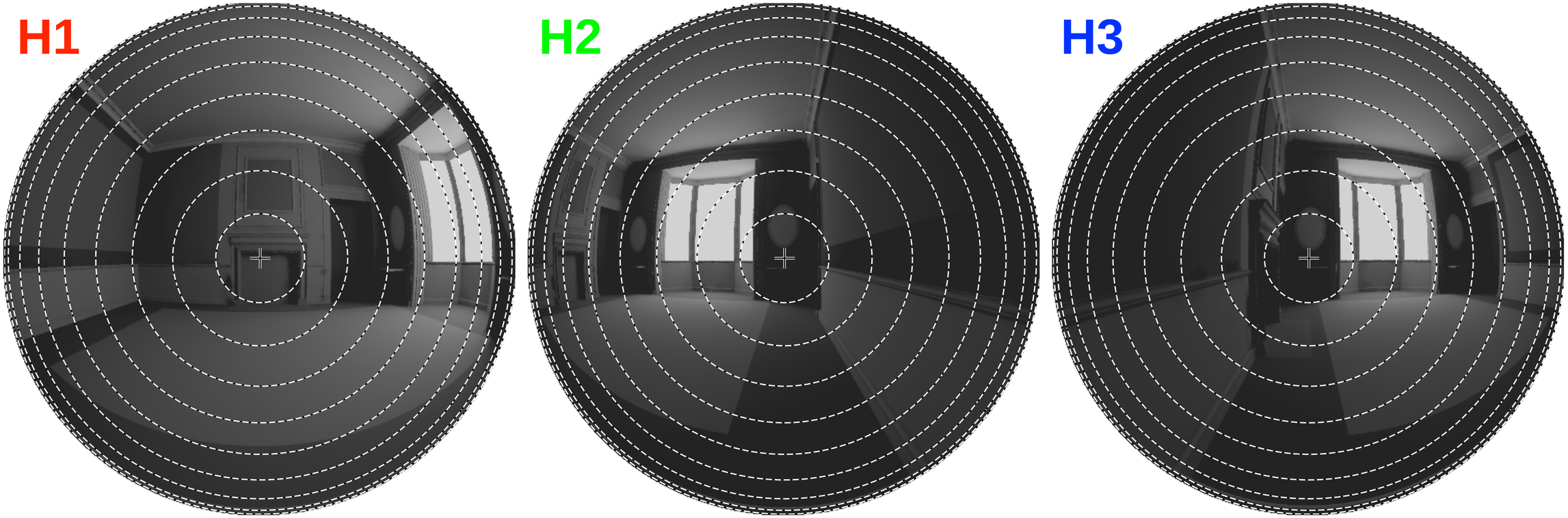
Tapestry area	Unfiltered light dose map [klux hrs]	Filtered light dose map [klux hrs]	Relative difference [%]
Left panel	81.61	81.57	-0.05
Right panel	74.64	74.65	0.01
Section 1	99.54	99.76	0.22
Section 2	80.06	80.17	0.14
Section 3	53.83	53.77	-0.11
Section 4	68.03	67.98	-0.07
Section 5	80.04	80.07	0.04
Section 6	72.53	72.55	0.03

Validation




H1
H2
H3
HDR daily dose [lx hrs]
Hanwell daily dose [lx hrs]
0
200
400
600
800
1000
1200
1400

	Measured light dose [klx hrs]	HDR-derived light dose [klx hrs]	Relative error [%]
H1	74,012	97,510	31.7
H2	69,089	66,571	-3.6
H3	65,772	70,680	7.5



Lessons Learnt

- Mount Stewart
- Ickworth
- Ham House

Selected Publications

J. Mardaljevic, S. Cannon-Brookes, K. Lithgow, and N. Blades. Illumination and conservation: A case study evaluation of daylight exposure for an artwork displayed in an historic building. *CIE 28th Session*, Manchester, UK, 2015.

N. Blades, K. Lithgow, S. Cannon-Brookes, and J. Mardaljevic. New tools for managing daylight exposure of works of art: case study of Hambletonian, Mount Stewart, Northern Ireland. Journal of the Institute of Conservation, 40(1):15–33, 2017.

J. Mardaljevic, S. Cannon-Brookes, N. Blades, and K. Lithgow. Reconstruction of cumulative daylight illumination fields from high dynamic range imaging: Theory, deployment and in-situ validation. Lighting Research and Technology, 53(4):311–331, 2021.

J. Mardaljevic, E. Brembilla, S. Cannon-Brookes, and N. Blades. A hybrid measurement-simulation approach to determine the reflectance map of a historic tapestry. IBPSA - Building Simulation Conference, Bruges, Belgium, 2021.

J. Mardaljevic, E. Brembilla, S. Cannon-Brookes, and N. Blades. A hybrid measurement-simulation approach to determine the daylight exposure of a historic tapestry (Submitted to Lighting Research and Technology)

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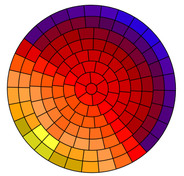
- Katy Lithgow (Perry Lithgow Partnership Ltd).

Loughborough University

UCL

National Trust



Daylight-Experts.com

Cannon-Brookes Lighting & DESIGN