High Dynamic Range Imaging as a Means to Quantify Luminous Flux

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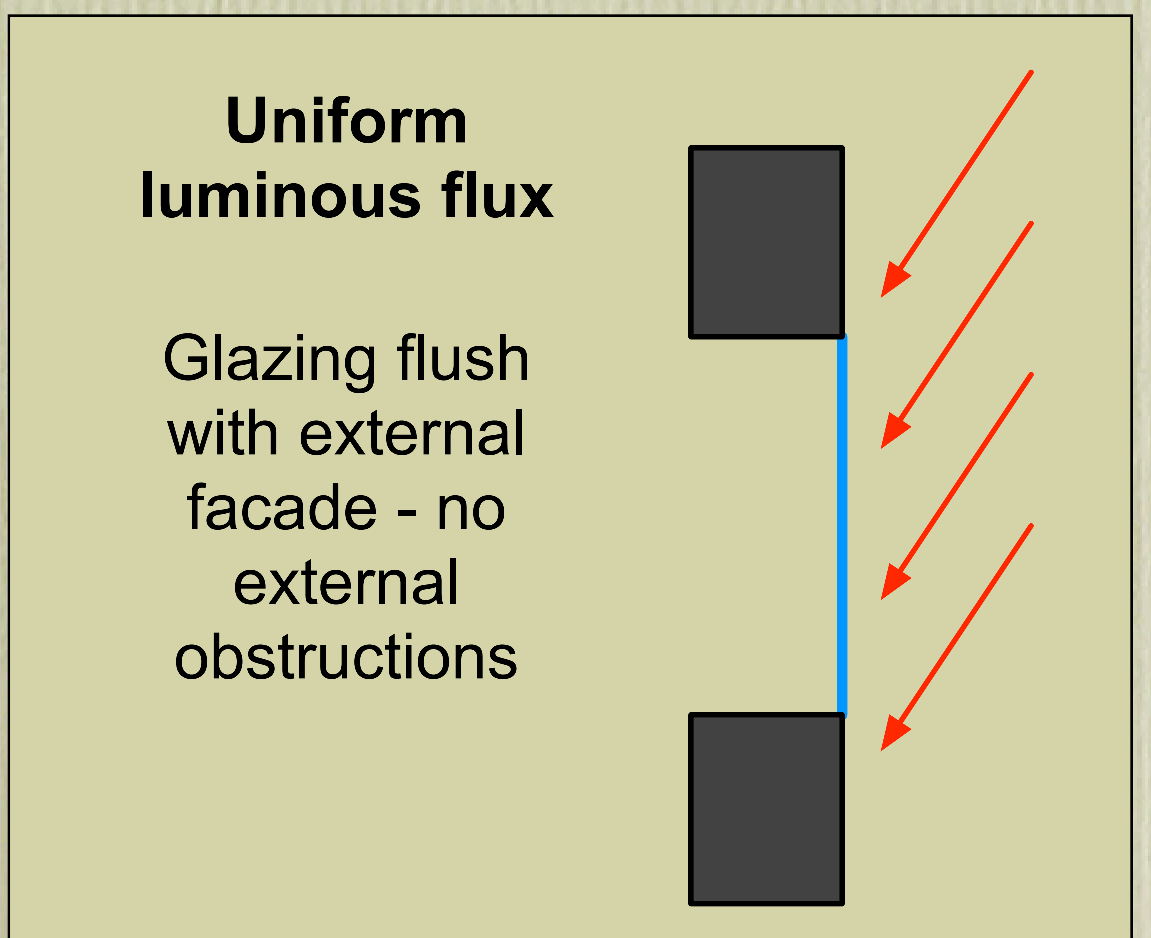
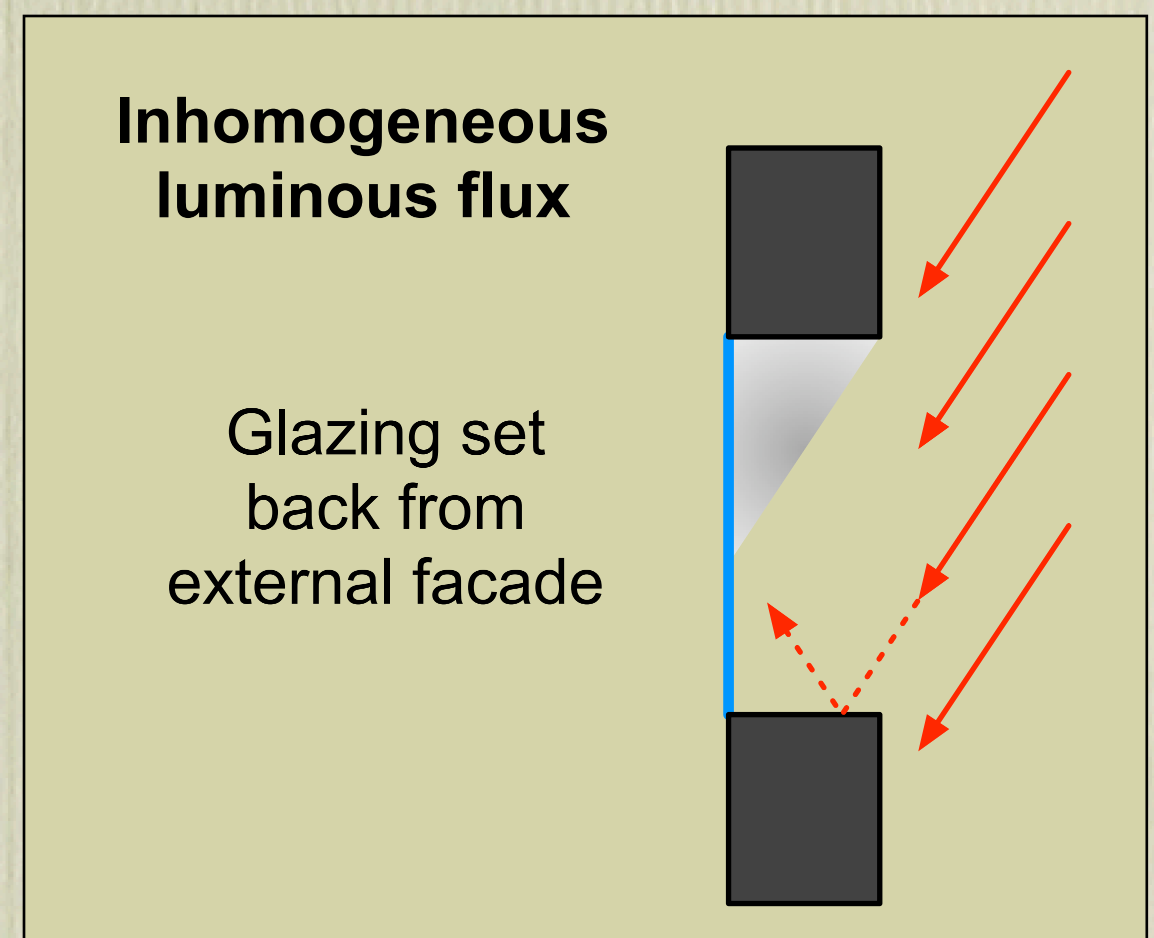
Light through windows

The luminous flux through a glazing aperture is rarely uniform - the presence of any reveal or nearby obstructing element will produce an inhomogeneous flux.





How can one measure the luminous flux through a window?

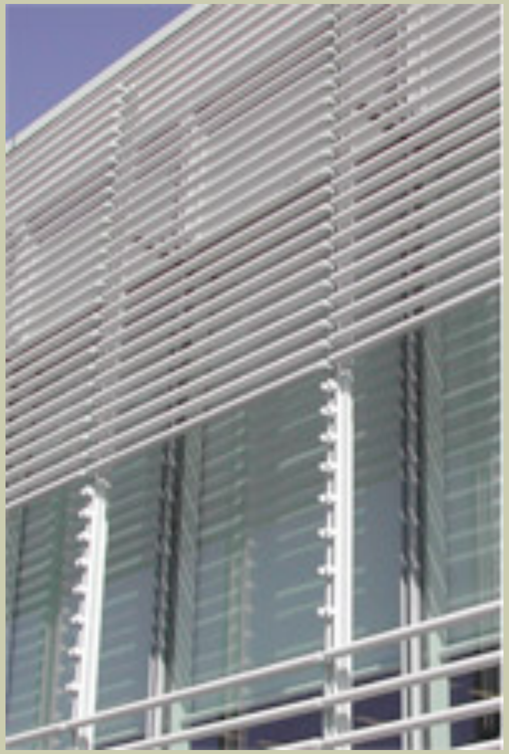
Commonly achieved by taking spot measurements at the inside window surface using a standard illuminance meter.

If the illumination is inhomogeneous but varying gradually (i.e. no direct component), then the flux may be estimated from a number of spot measurements across the window (the illumination conditions must remain steady).

Almost impossible to measure reliably if the illumination field is complex (i.e. direct sun).

The complex shadow patterns cast by shading devices make flux estimation from spot measurements under direct illumination highly impracticable.

Images of the New York Times building mockup



One possible solution turns out to be remarkably simple

The technique is based on determining the relation between the luminance of a diffusing surface viewed from the “back” and the illuminance incident on the “front” side.

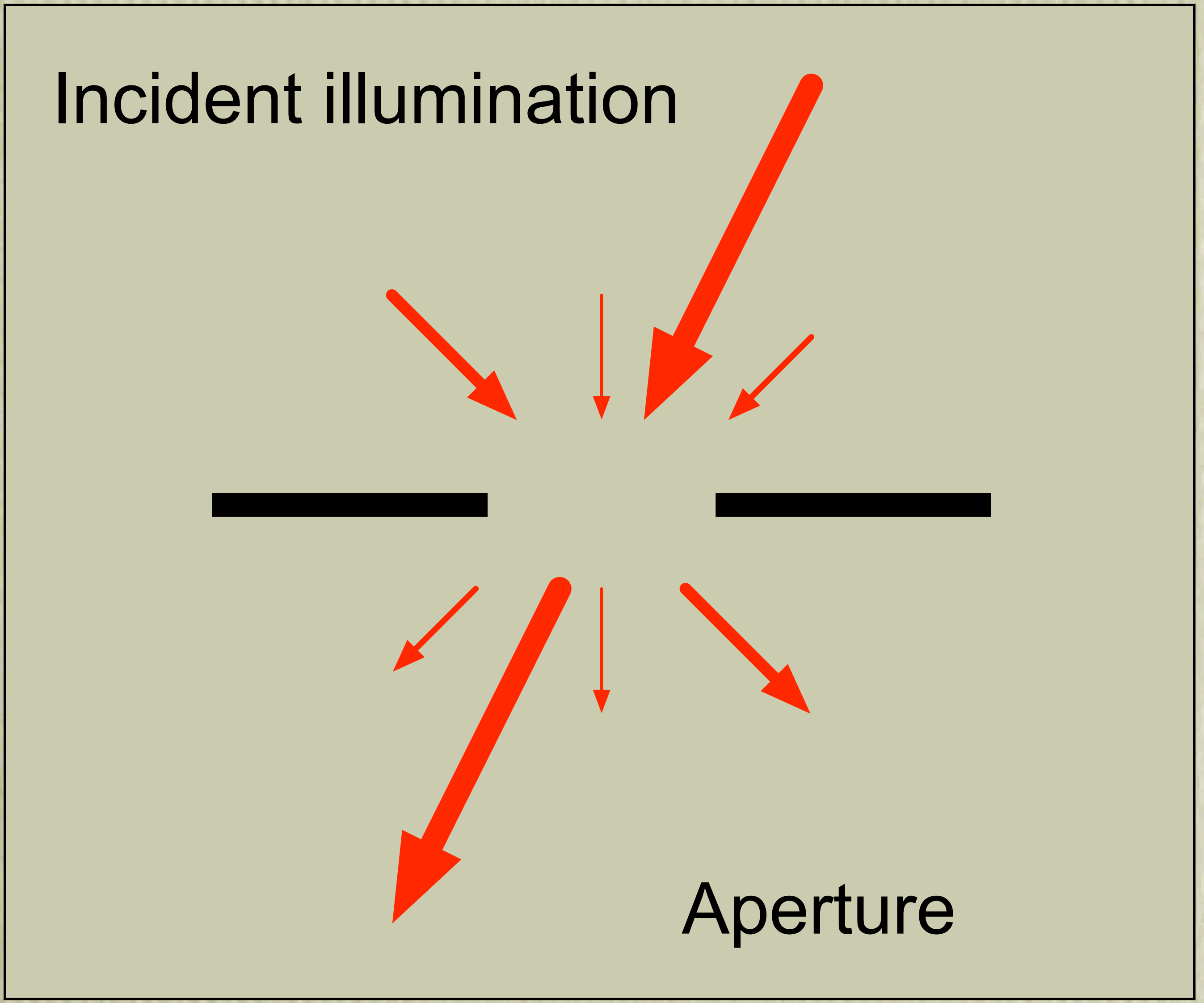
When this relation is known, the incident flux on the front-side of the diffusing surface can be derived from an HDR (i.e. luminance) image taken of the rear-side

The technique is called:

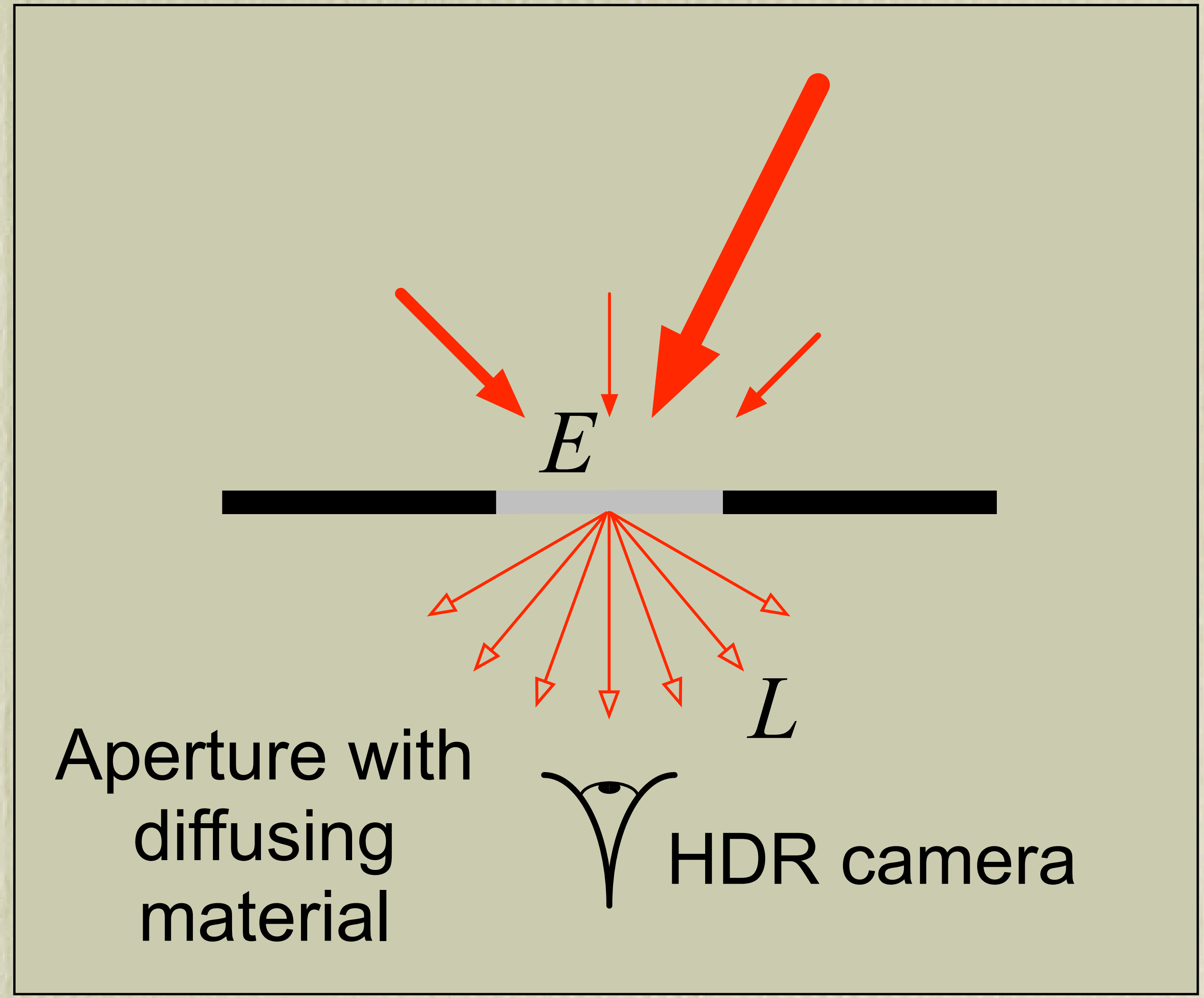
Illuminance Proxy - High Dynamic Range Imaging

or

IP-HDRI



Incident illumination
Aperture



E
L
Aperture with diffusing material
HDR camera

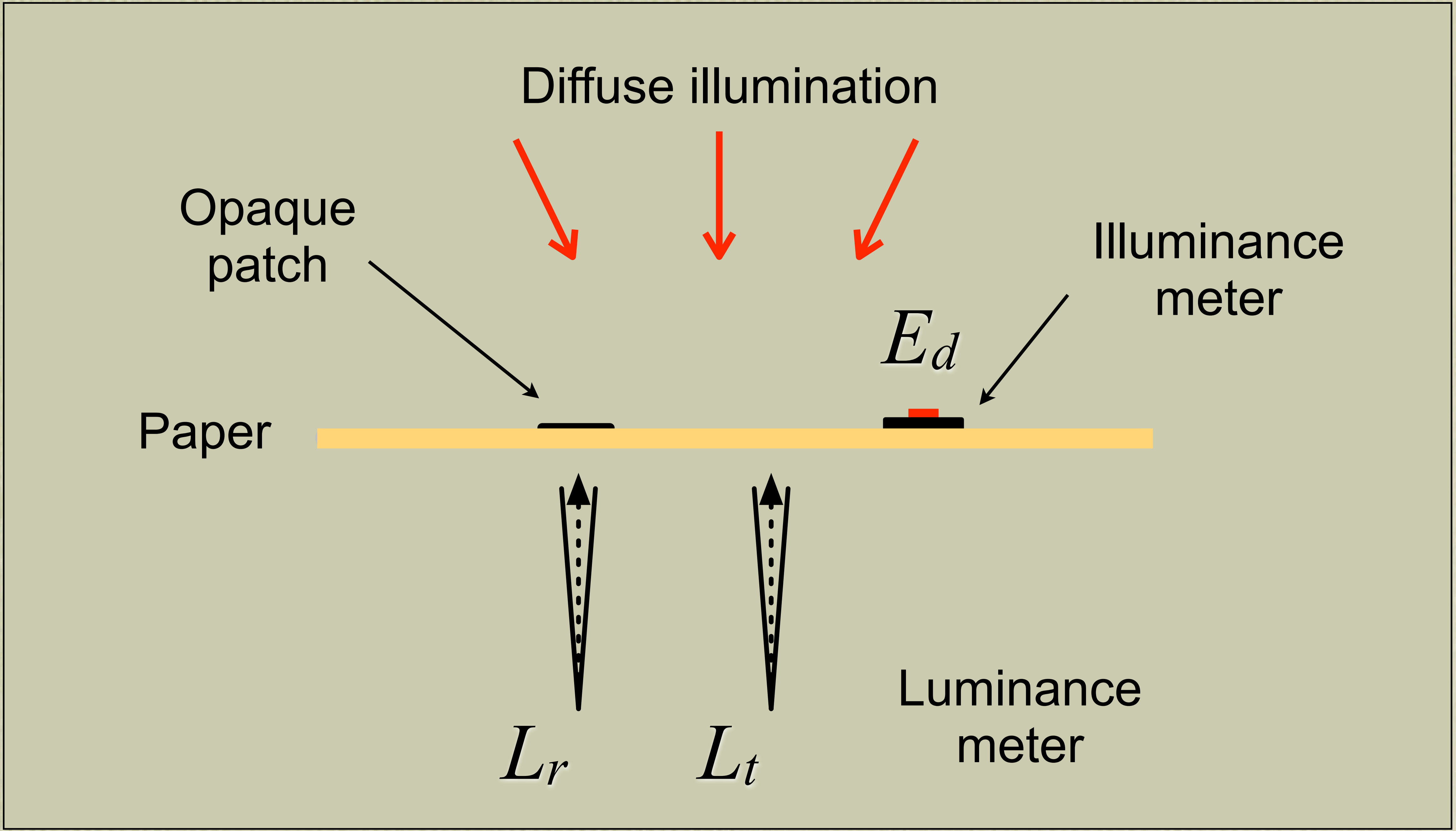
The luminance coefficient

A first approximation is to assume a proportional relation between the front-side incident illuminance E and the rear-side visible luminance L:

$$L = qE$$

where q is the luminance coefficient for the transmission of visible radiation through the diffusing material.

[We consider the angle dependance of q with direct illumination later]



Under steady conditions, record the:

- illuminance incident on the paper E_d
- luminance of the rear-side of the paper L_t
- luminance behind the patch L_r

Determine q from measurements

Equipment: Illuminance meter, luminance spot photometer and some paper.

Source of illumination was diffuse daylight under clear sky conditions (which are much more stable than overcast skies).

Note that we need to subtract L_r from L_t to remove the component of luminance due to reflected light on the rear-side of the paper.

A value for *q*

For convenience, and since we wish to derive illuminance from luminance, we present values of q^{-1}.

For standard large-format ink-jet paper, we determined $q^{-1} = 22.3$sr.

We use this value to measure the lumen output of a window set in a deep reveal. Greg Ward's Photosphere HDR browser was used to display/analyse the images.

Example I: Lumen output of a window

Cut out paper to size. Stick a number of small opaque patches to the outward facing side of the paper. Affix the paper to the inside of the window.

Create an HDR image of the window. Ideally, the camera should be positioned horizontally with a view normal to the centre of the glazing, and distant from the window to minimise vignetting effects.

Diffuse illumination

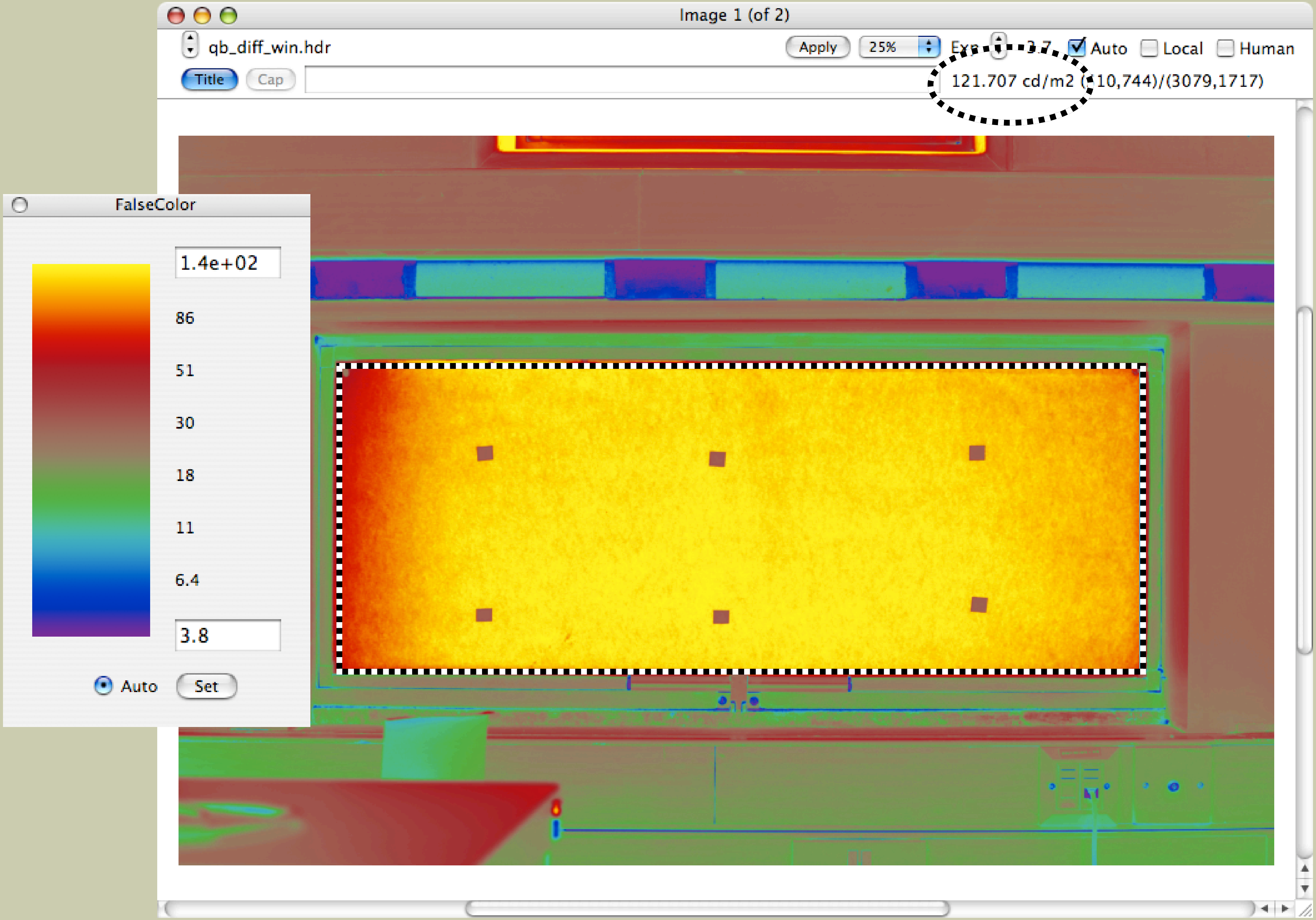


Image 1 (of 2)
qb_diff_win.hdr
Apply
25%
Auto
Local
Human
Title
Cap
121.707 cd/m2
FalseColor
1.4e+02
86
51
30
18
11
6.4
3.8
Auto
Set

Calculation

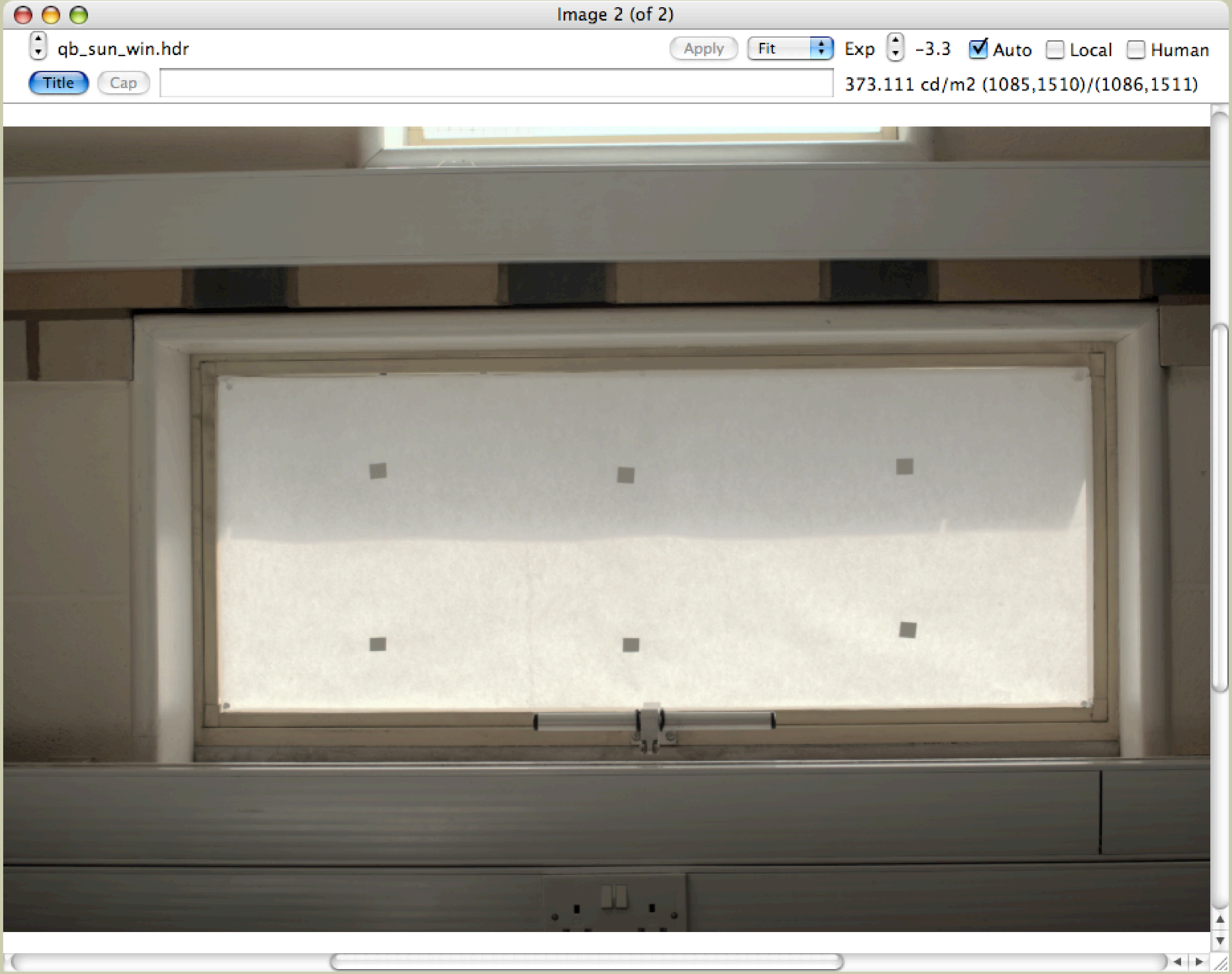
Mean luminance (L_r) of the six opaque patches was 30.3 cdm^{-2}. Mean luminance (L_t) across the entire glazing area was 121.7 cdm^{-2}. Glazing area A = 0.374 m^2.

Lumen output (F) of the window:

$$F = EA = q^{-1}(L_t - L_r)A$$

$$F = 22.3 * (121.7 - 30.3) * 0.374$$

$$F = 762 \text{ lumens}$$



Direct illumination

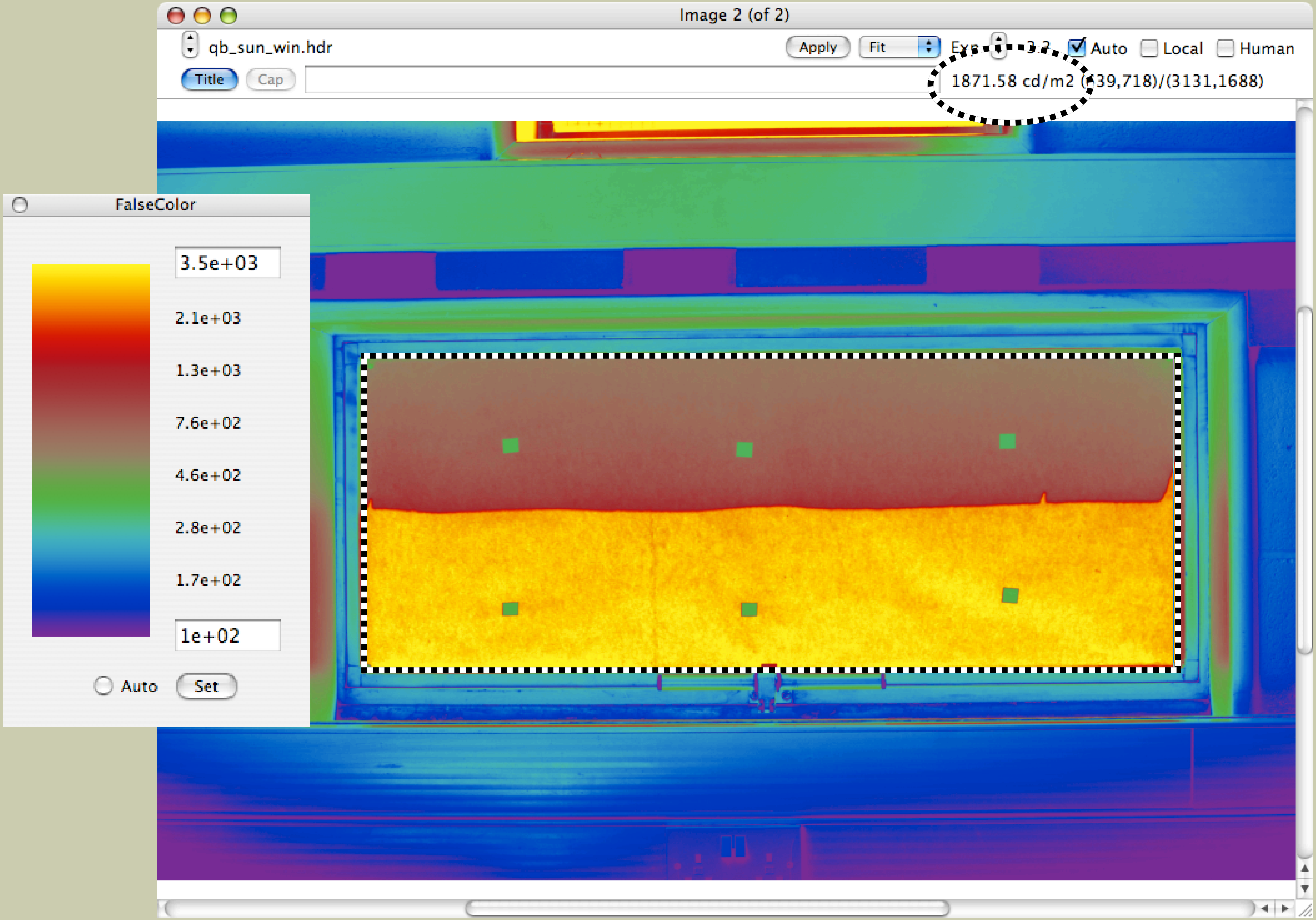


Image 2 (of 2)
qb_sun_win.hdr
Apply
Fit
Auto
Local
Human
Title
Cap
1871.58 cd/m2 (539,718)/(3131,1688)
FalseColor
3.5e+03
2.1e+03
1.3e+03
7.6e+02
4.6e+02
2.8e+02
1.7e+02
1e+02
Auto
Set

Repeat for sunlit window

Mean luminance (L_r) of the six opaque patches was 352 cdm^{-2}. Mean luminance (L_t) across the entire glazing area was 1871 cdm^{-2}. Same glazing area.

$$F = 22.3 * (1871 - 352) * 0.374$$

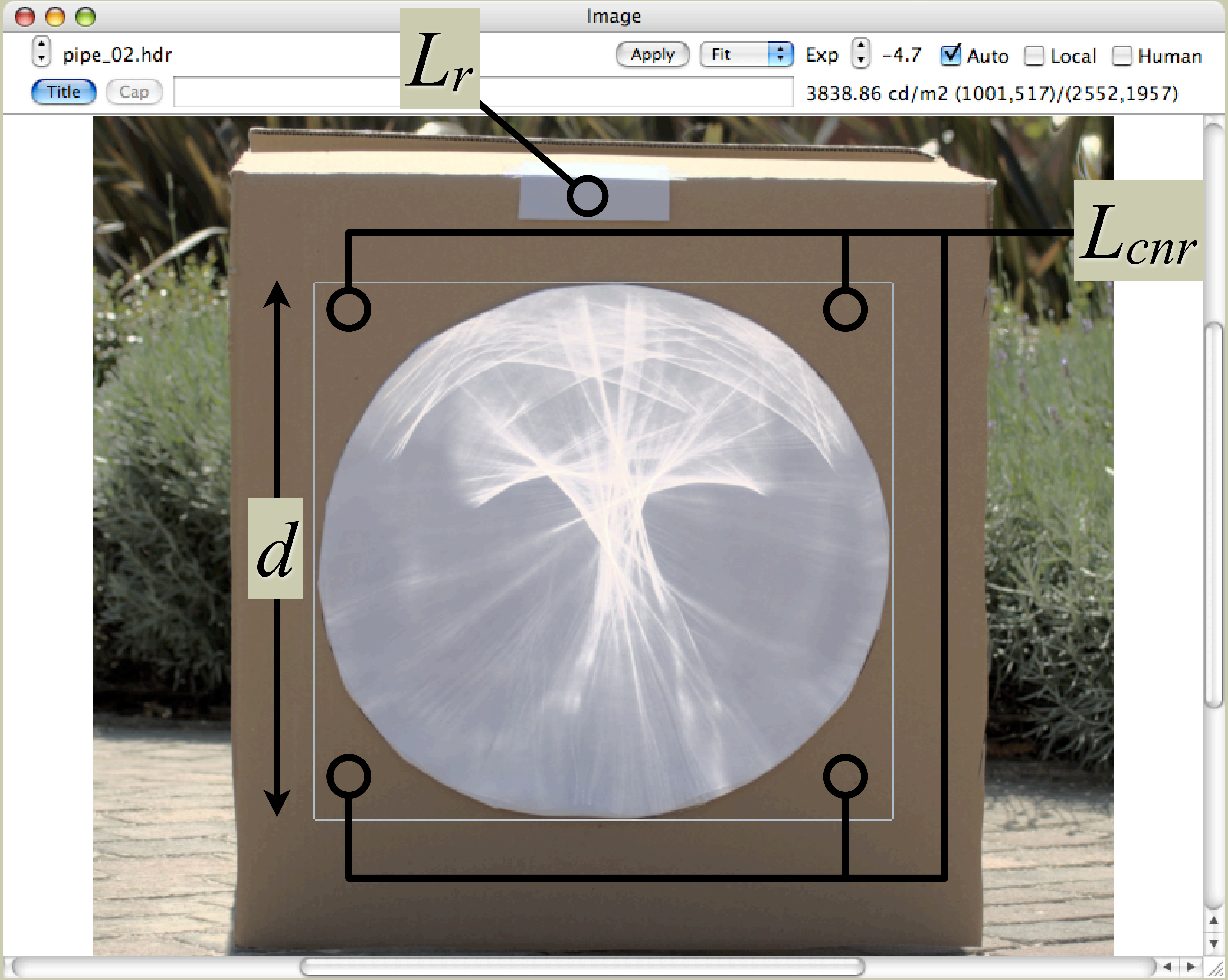
$$F = 12{,}700 \text{ lumens}$$

Compare with 762 lm for diffusely lit window and ~1700 lm for 100W bulb.

Example II: Lumen output of a light pipe

Cover one end of the pipe with paper. Determine the reflected component of illuminance from a paper patch fixed to the supporting frame (cardboard).

Non-rectangular geometry complicates matters a little, but it is still possible to get a reasonably accurate value for luminous output with minimal extra effort.



Assume circular cross-section

The mean luminance (L_t) of the (circular) paper is:

$$L_t = L_{sqr}\frac{4}{\pi} - L_{cnr}\left(\frac{4}{\pi} - 1\right)$$

The mean luminance (L_{sqr}) of the square region that just bounds the circular pipe was 3840 cdm^{-2}.

The mean luminance (L_{cnr}) of the four corner sections of cardboard was 711 cdm^{-2}.

This gives L_t = 4695 cdm^{-2}.

L_t includes the reflected component of luminance (L_r = 2510 cdm^{-2}) which must be subtracted to give the luminance due to transmitted light only.

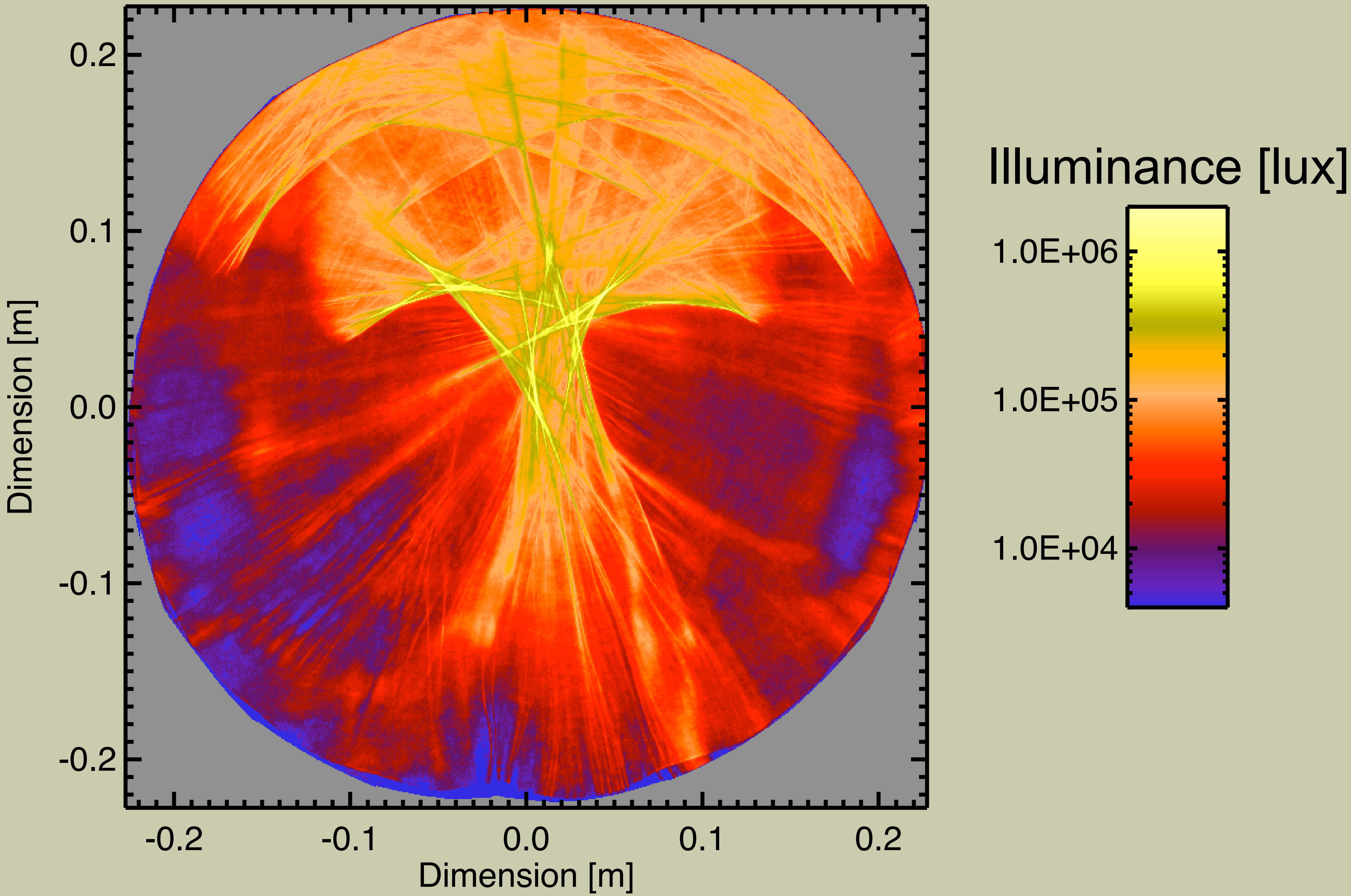
The lumen output (F) of the light pipe was:

$$F = EA = q^{-1}(L_t - L_r)A$$

$$F = 22.3 * (4695 - 2510) * 0.163$$

$$F = 8{,}250 \text{ lumens}$$

HDR images created by Photosphere can be exported for analysis/display by other software



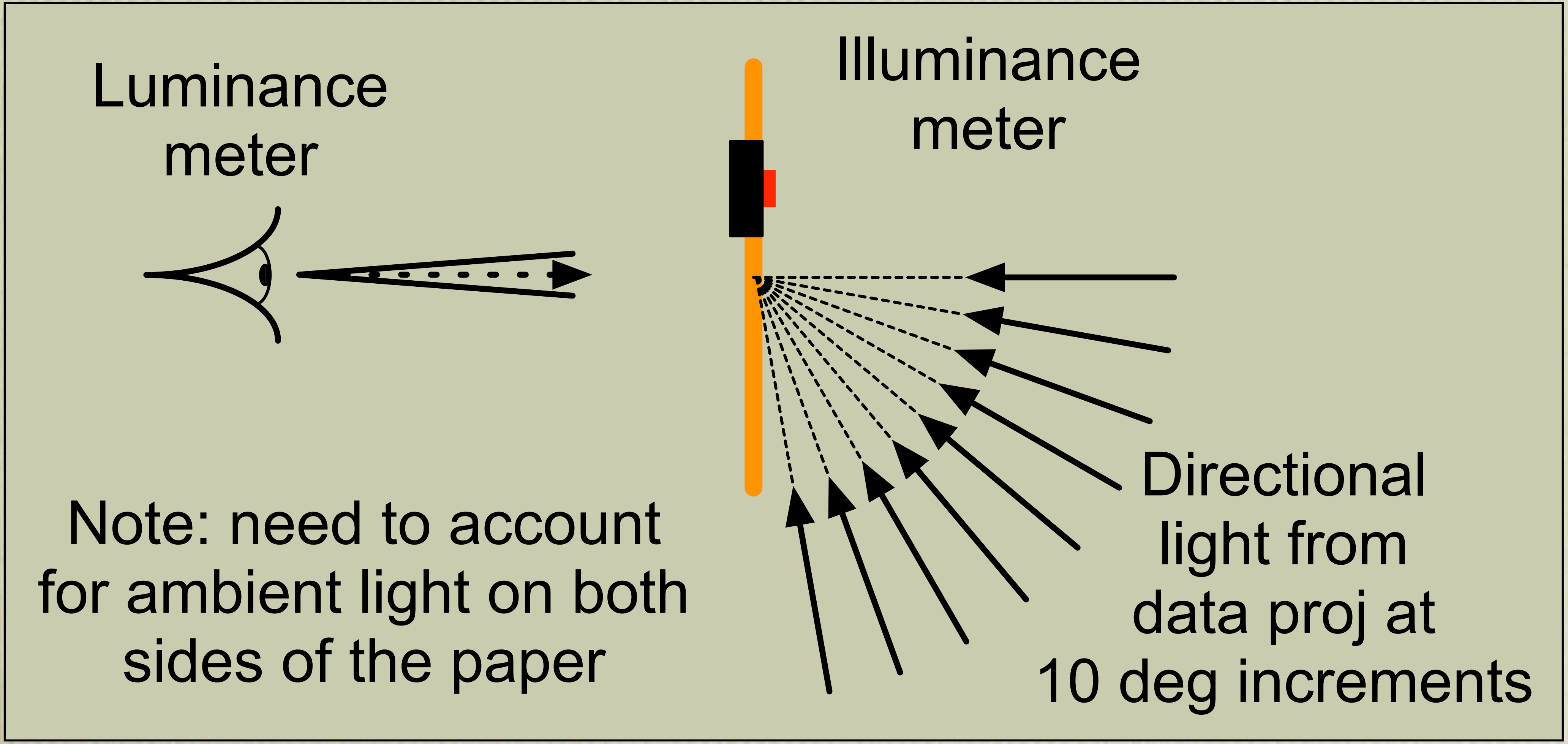
Accounting for the angular dependance of q

For more exacting work, the angular dependance of q with direct illumination can be determined and used in the derivation of illuminance from HDR images. Two sets of measurements were carried out:

- A “rough and ready” set taken at DMU using everyday instruments.
- A “smooth and considered” set taken at MIT using specialised equipment.

The "rough and ready" set

Equipment: Data projector, illuminance meter, luminance spot photometer and a protractor.

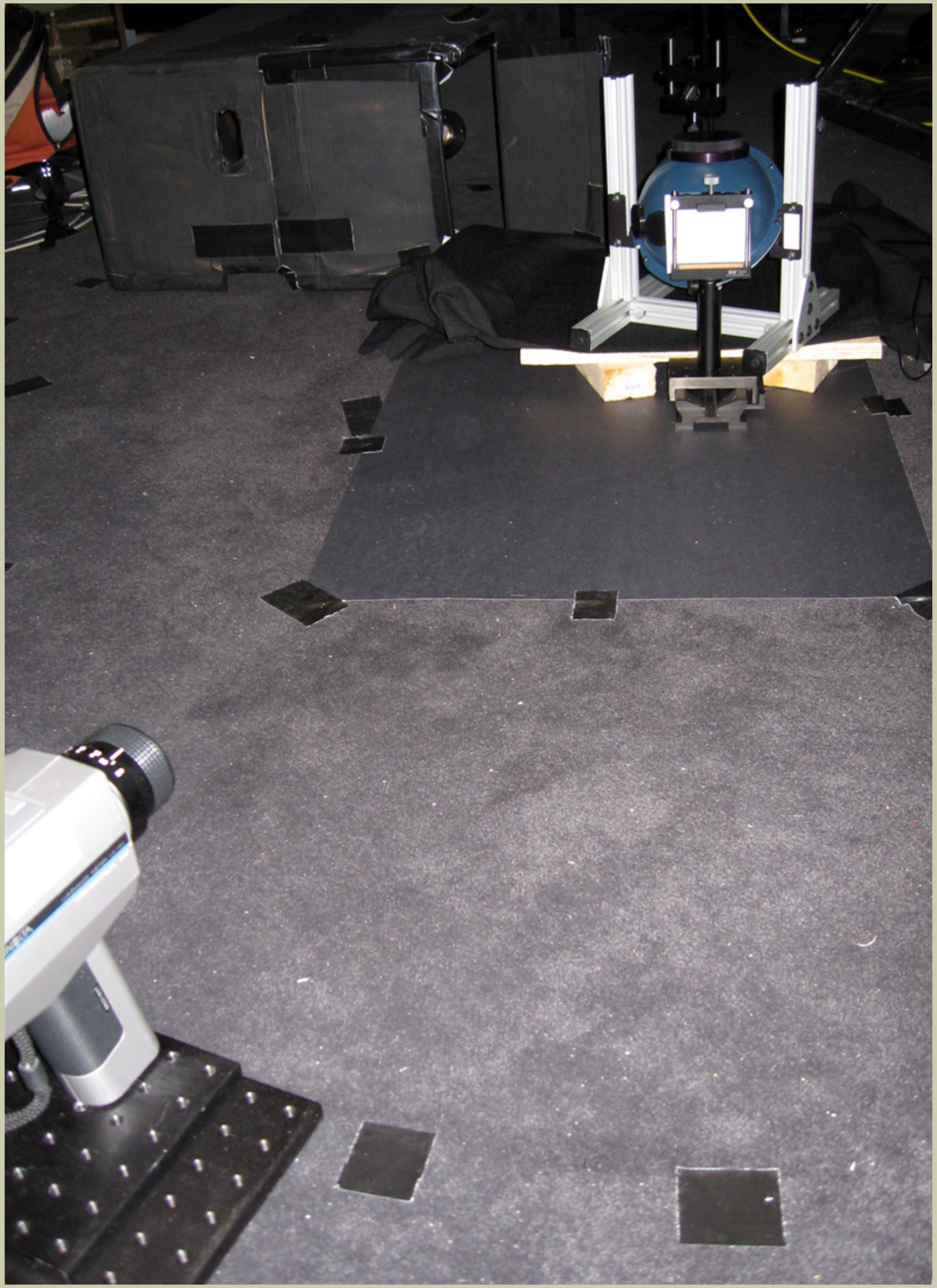


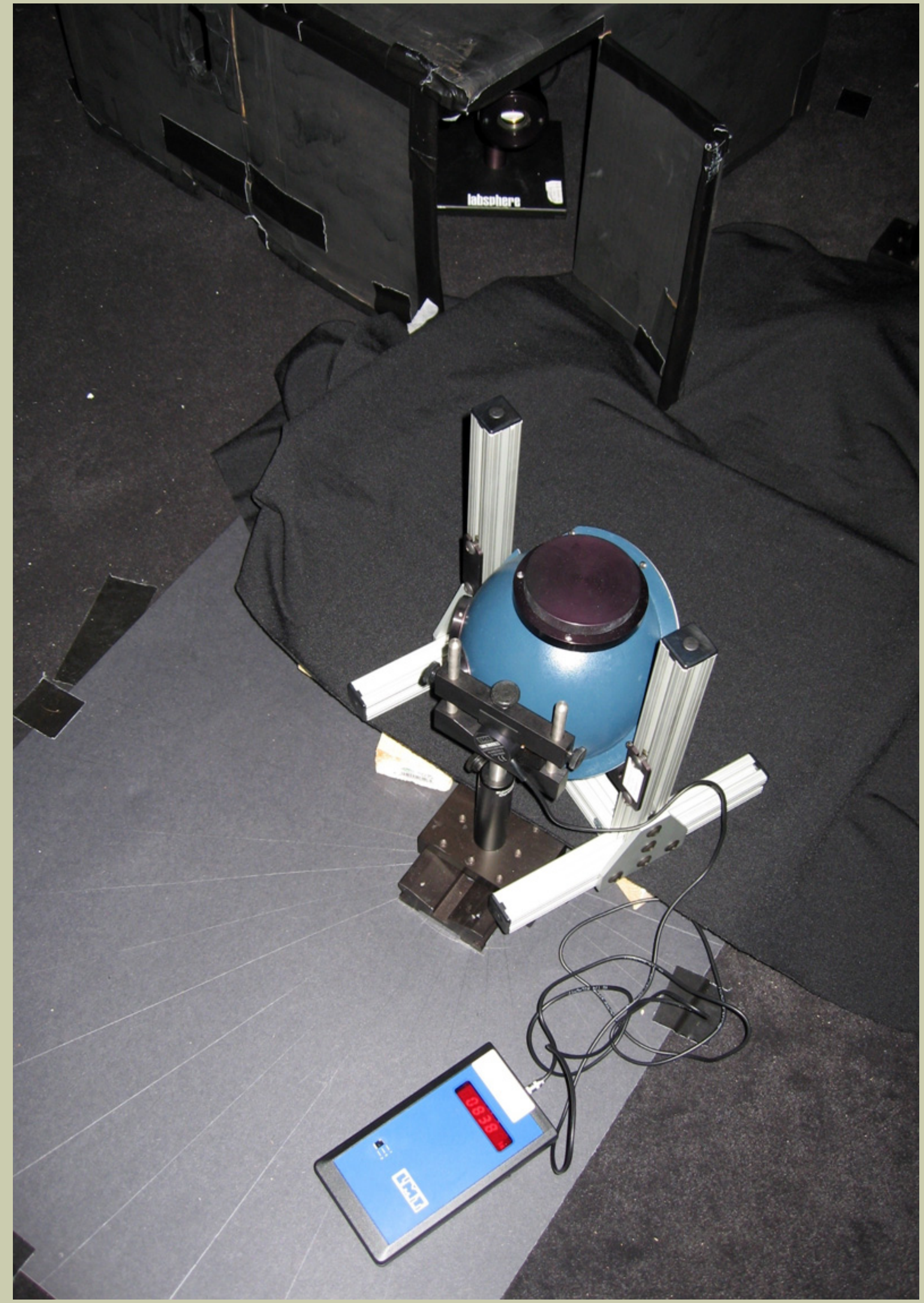
The “smooth and considered” set

Equipment: Specialist light sources (KI-120 Kohler Illuminator), illuminance meter, integrating spheres, luminance spot photometer, optical rail, posts, carriers, etc.

The measurements were conducted in a 4m × 4.5m black chamber.

A value for q under controlled diffuse illumination was also determined for comparison with DMU’s measurements.



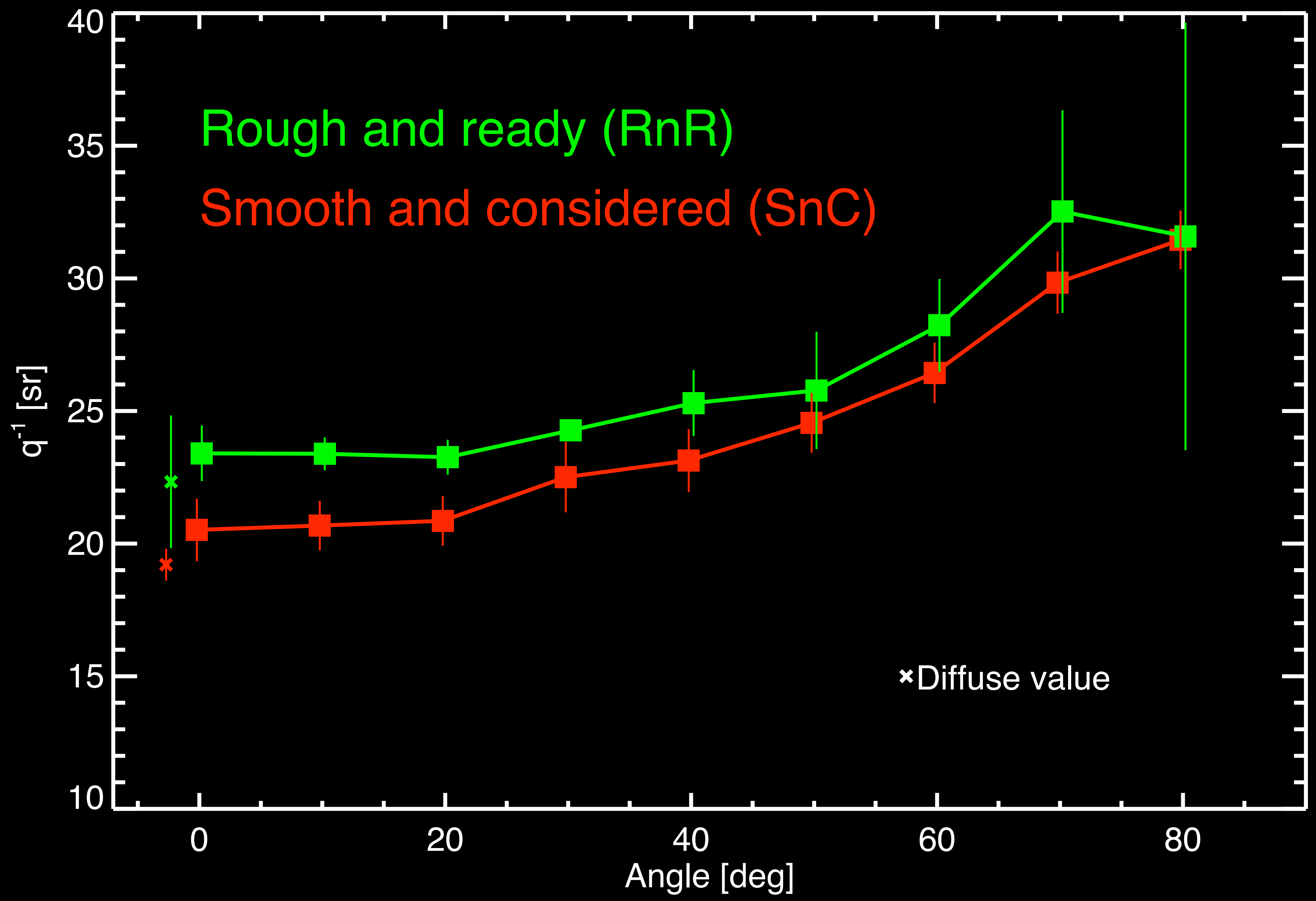


Inside the black chamber at MIT

Diffusing properties of the paper

The measurements at MIT included determining the angular dependence of luminance with the view direction.

These measurements proved that the paper was sufficiently diffusing so that results were largely insensitive to camera position for the majority of likely scenarios.



Rough and ready (RnR)
Smooth and considered (SnC)
×Diffuse value
q^{-1} [sr]
Angle [deg]
40
35
30
25
20
15
10
0
20
40
60
80

Findings and comparison

Both curves are fairly flat up to ~40 deg.

The RnR values are consistently greater than the SnC, but only by ~10 to 15%.

Thus, reasonable accuracy can be achieved using the RnR method - modest demands for time and equipment.

Surprisingly, the diffuse value for both sets is less than the respective zero degree incidence direct values. Why?

When to use the angle dependant value for q?

When IP-HDRI is employed to measure direct and diffuse illumination separately (example follows).

When direct illumination is the dominant source - more accurate to use a single value for q taken from the curve.

Note: Less straightforward manipulations of HDR image data may need to be done using dedicated programs/scripts.

Example III: Measuring direct and diffuse illuminance

Equipment: Suitable camera, laptop, calibrated paper, box, coin, stick and rock (if windy).

Large box preferred and avoid use of wide angle settings to minimise vignetting.

Separate q_{dif} and q_{dir} values used (RnR curve).

IP-HDRI values were within 10% of those measured by an illuminance meter.

Mk II version
(Mk I was cardboard)

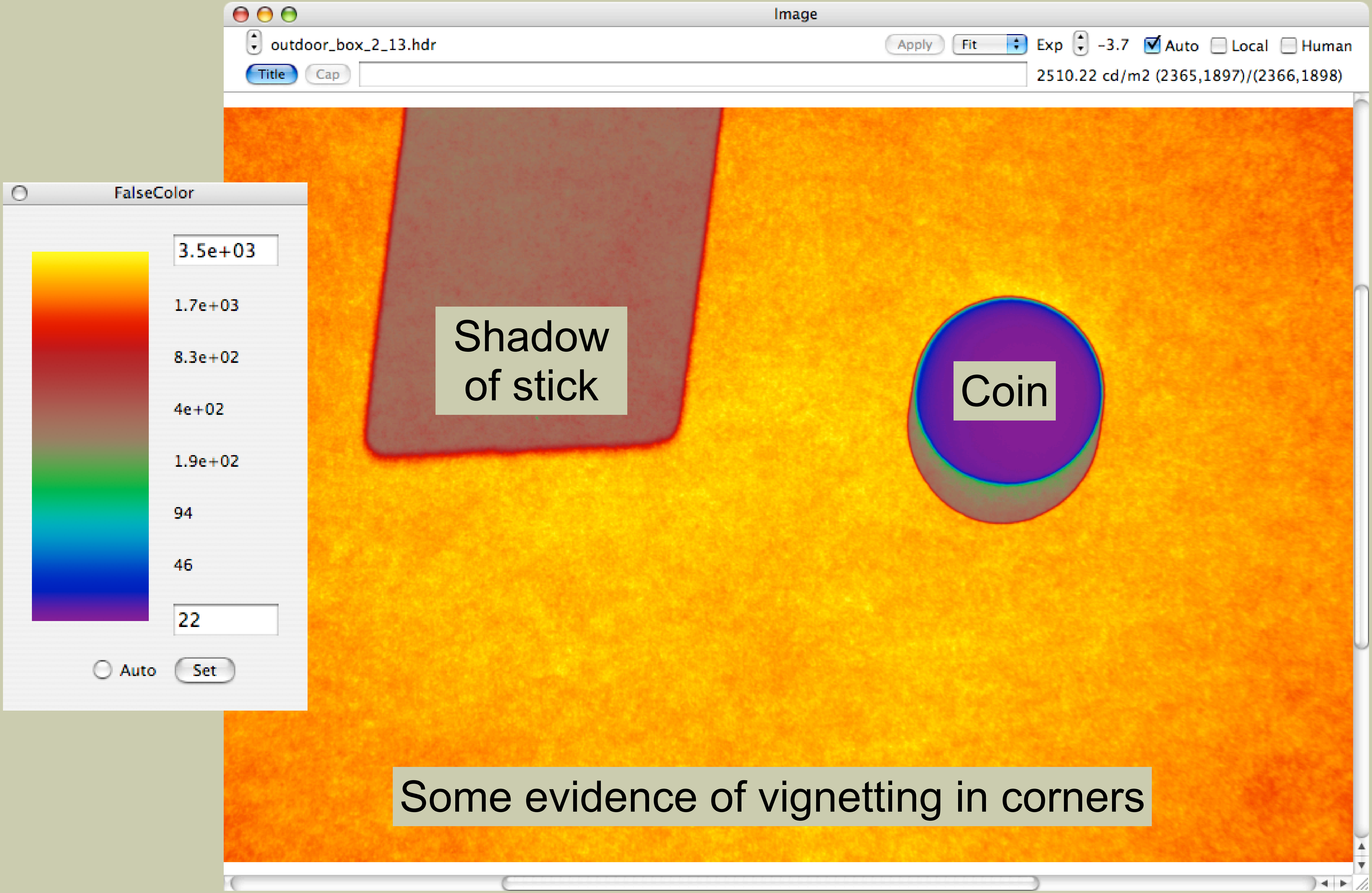


Image
outdoor_box_2_13.hdr
Apply
Fit
Exp -3.7
Auto
Local
Human
Title
Cap
2510.22 cd/m2 (2365,1897)/(2366,1898)
FalseColor
3.5e+03
1.7e+03
8.3e+02
4e+02
1.9e+02
94
46
22
Auto
Set
Shadow of stick
Coin
Some evidence of vignetting in corners

Diffuse light [lux] (obstructed)		Direct light [lux]	
Measured IP-HDRI	Error %	Measured IP-HDRI	Error %
9400 8976	-4.5%	66100 69448	+5.1%
8360 9178	+9.8%	66040 63827	-3.5%
10100 10271	+1.7%	83200 82306	-1.1%
8200 8016	-2.2%	56800 58064	+2.2%

IP-HDRI opens up a whole new range of possibilities

- Quantify the effectiveness of arbitrarily complex shading devices under real-world conditions e.g. brise soleil, fritted glass, blinds, nets, fabrics etc.

- Light-pipe design and evaluation e.g. effectiveness of reflective coatings.

- Illumination effect of external/internal finishes e.g. reflective window reveals.

Quantify the lumen output of a light-well using a “flux-net”

A “flux-net” is a sparse mesh of small rectangles of paper strung across a building aperture. Half of each rectangle has an opaque patch on the upper side.

QA of transmission properties for *Radiance* modelling

Characterisation of the transmission properties for non-standard materials is notoriously difficult.

Where suitable *Radiance* descriptions do exist, IP-HDRI could be used to support QA testing that the materials in the simulation are behaving as expected - in terms of both overall transmitted flux and (at a pinch) output distribution.

IP-HDRI: Advantages over standard methods

The standard method is to use either an integrating sphere (IS) or a goniophotometer (GP).

Both of these methods require a **time**, **cost** and **expertise** investment orders of magnitude greater than that for IP-HDRI.

Although IS and GP may offer greater accuracy under lab conditions (for small samples), real-world measurement with these may prove to be impossible due to scale and stability of illumination considerations.

Further work

A paper describing this work is in preparation (same title and authors as this presentation).

In addition to expanding on the work presented here, the paper addresses issues not raised in this presentation and considers further applications of the technique.

Acknowledgements

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