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Publication date
2021

Document Version
Accepted author manuscript

Published in
Building Simulation Conference Proceedings

Citation (APA)
Mardaljevic, J., Brembilla, E., Cannon-Brookes, S., & Blades, N. (2021). A hybrid measurement-simulation approach to determine the reflectance map of a historic tapestry. In *Building Simulation Conference Proceedings* International Building Performance Simulation Association.

A hybrid measurement-simulation approach to determine the reflectance map of a historic tapestry

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Abstract

Illumination levels in historic buildings need to be monitored for conservation purposes, especially in daylit spaces which are invariably subject to large spatio-temporal variations in light levels. However, light meters record only at a single point, and numbers are limited. A recently demonstrated image-based technique using digital cameras to measure indirectly the prevailing daylight illumination in spaces is extended. As a prerequisite, the technique requires a reflection map of the 'target' – here, a historic tapestry. Acquiring this without disturbance to the scene required a novel combination of in-situ measurement and lighting simulation. How this was achieved is described in the paper.

Key Innovations

- Hybrid lighting measurement and simulation approach to assess luminous environment in historic buildings.
- Method to derive reflectance of complex patterned surfaces.
- Characterisation of the albedo map of a historic tapestry.
- Derivation of long-term illumination (i.e. light dose) from autonomous HDR capture.

Practical Implications

Quantifying the amount of light exposure on artwork and fabrics in historic properties is essential for their conservation. The method presented here combines simulation and measurement, as well as laboratory and field work, to reduce errors and derive accurate albedo maps of complex patterned surfaces. Historic spaces that are open to public and that showcase fixed, light-sensitive features will benefit from the non-intrusive, non-destructive analysis of long-term light exposure, for which the albedo map is a necessary prerequisite.

Introduction

In historic buildings, curators and conservators are increasingly choosing to display rooms under daylight illumination conditions comparable to how those spaces were originally used. (National Trust (2011)) All predominantly daylit spaces will experience considerable spatio-temporal variation in natural illumination. However, monitoring of light levels to control exposure is only carried out at a limited number of locations, perhaps just one per room (Blades et al. (2017)) Light-sensitive objects such as large tapestries therefore present particular challenges since the daylight dose across the tapestry could vary significantly from that recorded at the periphery of the tapestry. An earlier study in a heritage setting (Ickworth House) employed high dynamic range imaging (HDRI) to measure cumulative daylight exposure by using numerous wallpaper patches as proxy illuminance targets. The Ickworth study sets the background for the evaluation described here – an illustration of the origins of HDR and an overview of the Ickworth study are given in the following sections.

The origin of high dynamic range imaging

The first truly high dynamic range (HDR) images were those created using physically-accurate lighting simulation, e.g. the *Radiance* system described in Ward Larson et al. (1998). The images in Figure 1 show early examples from the *Radiance* system, circa 1992. The upper image shows the appearance of the virtual model – a gallery space with horizontal strip rooflights, below which are horizontal obstructing surfaces. The various surfaces were assigned material properties based on realistic values, e.g. RGB diffuse reflectance values, specularity, roughness and, for the rooflights, glazing transmittance. The virtual model is illuminated only by daylight. The external environment was modelled as a CIE standard overcast sky. Each pixel of the original 'appearance' image contains an RGB radiance value. For display, this is converted to a low dynamic range RGB image, i.e. tone mapped. The image below shows the incident illuminance on the surfaces using false colour.

Ickworth HDR Study

A more recent study used HDR images taken with a digital camera in order to derive the incident day-

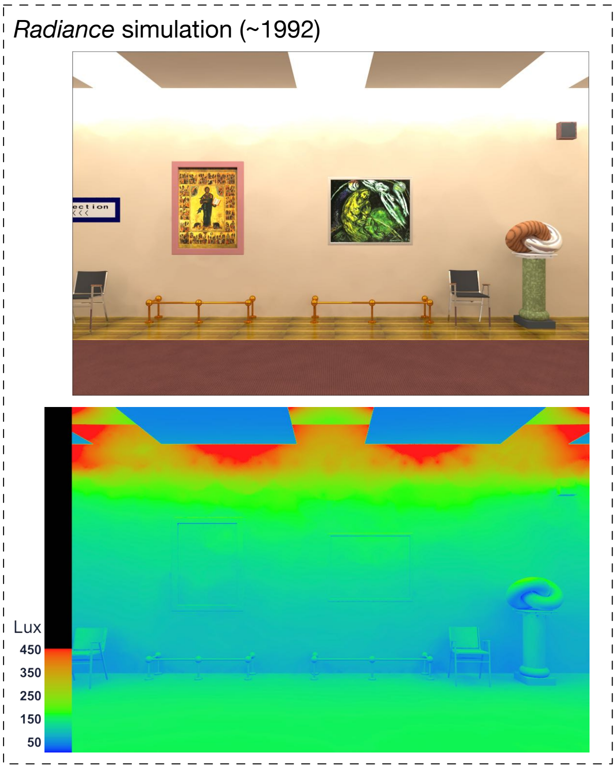

Figure 1: Radiance *simulation of gallery space (∼1992)*

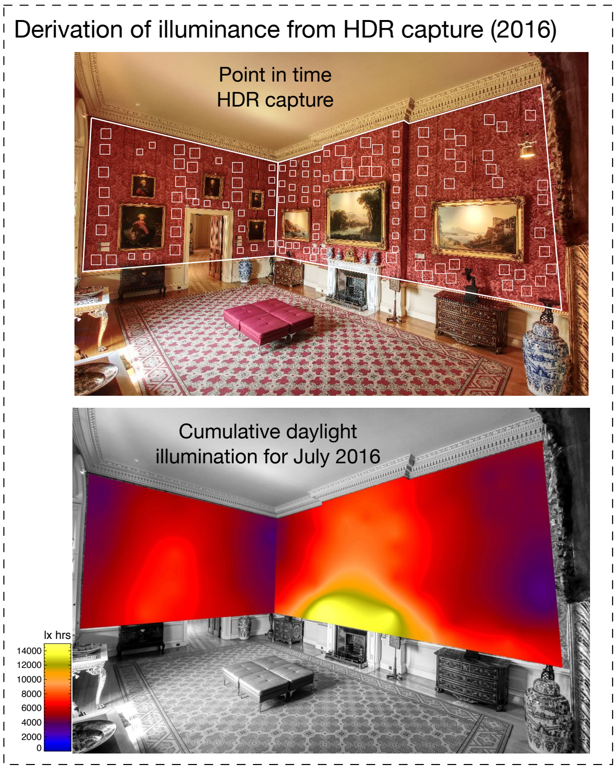

Figure 2: Derivation of illumination field from HDR capture (∼2016)

light illuminance field, Figure 2. In effect, this was an attempt to derive from a single-point measurement (i.e. camera) that which previously could only have been determined by simulation, i.e. the prevailing daylight illumination field across expanses of wall. The setting was the Smoking Room in Ickworth House (Bury St. Edmunds, UK). The technique derives illuminance from the HDR-acquired luminance at numerous patches of the wall surfaces visible in the HDR image. These patches serve as proxy illuminance meters, thereby allowing the prevailing illumination field across the entire visible wall to be derived using a Kriging algorithm. The technique was validated under both controlled and in-situ conditions over periods of several months and shown to have comparable accuracy to the illuminance logging devices commonly used in historic/conservation settings. It is fully described in Mardaljevic et al. (2021).

The Ickworth application depended on having detailed photometric knowledge of the reflective properties of the patterned wallpaper. Preliminary investigations revealed that both the light and dark areas of the wallpaper approximated a diffuse (i.e. Lambertian) reflector fairly well. Although patterned, the wallpaper patches could be considered to act as areas of fixed, constant diffuse reflectance provided they were of sufficient size so that, whatever the random positioning of the patch on the wall, the photometric characteristics (i.e. mix of light and dark areas) varied only negligibly across all the selected areas. The photometric evaluation included also the determination of the minimum size of square patch which, whatever the random positioning, always gave the same, i.e. characteristic reflectance for the paper.

A major consideration was the practicalities of remote monitoring in a heritage setting and ensuring the absolute minimum of disturbance. The 2016 monitoring campaign at Ickworth required that HDR capture in the Smoking Room took place over several months. The capture system had to operate completely autonomously and in the absence of any network connection. The Ickworth House wifi network could not be extended the distance required to include the Smoking Room, and there was not a sufficiently strong 3G/4G signal in the room to attempt an internet connection via telecommunication means. Thus it would not be possible to confirm remotely that the system was functioning, let alone to transfer the huge volumes of data that were expected (of the order of a Tb). So, in addition to autonomous operation, the system had to be resilient and have the capacity to recover from accidental interference (e.g. power loss) and potential system failures (e.g. the stalling of the HDR process due to a communication failure between the camera and the controlling computer).

The HDR capture system – based on a consumer DSLR camera and Mac Mini – proved remarkably resilient. The DSLR (Canon 550D) was tethered to the Mac Mini with a 3 m USB to USB-micro cable, and the camera powered by an AC supply unit. The camera was attached to a custom-made bracket which was affixed to a window frame in the Smoking Room following the necessary approval. HDR capture sequence was controlled by a timed script which was executed every 10 minutes using the UNIX `cron` function, e.g. at 12:00, 12:10, 12:20, and so forth. Each HDR capture comprised a sequence of seven ordinary low dynamic range (LDR) images taken in quick succession using a fixed aperture ($f8$) and varying shutter speed covering the range 1/2000 s to 2 s in two exposure stop increments, i.e. 1/2000, 1/500, 1/125 s, etc. Immediately following each capture, the seven LDR images were compiled into a HDR image using the `hdrgen` program with a predetermined HDR image response calibration file.

The Volury – Ham House

Ham House, completed in 1610, is set in formal gardens on the bank of the River Thames in Ham, south of Richmond in the London Borough of Richmond upon Thames, Figure 3. Acquired by the National Trust in 1948, Ham House is considered to be one of the finest examples of a great 17$^{\text{th}}$ century house in the UK. The Volury Room in Ham House contains a set of Flemish late-seventeenth century tapestries (after Poussin). Given the historical importance of these tapestries, daylight admittance to the Volury endeavours to achieve a balance between sufficient (daylight) illumination so that visitors can view and appreciate the tapestries under natural light (as intended), and the need to minimise exposure for long-term conservation of these precious artefacts.

Figure 3: Ham House

The two main panels of the tapestries in the Volury are shown in Figure 4. Both images are from the same view position – a camera affixed to one of the door frames of the Volury. The purpose of the studio lamp is described in a later section. The goal for the Ham House study was to replicate the end result of the Ickworth study, i.e. the derivation of the cumulative illuminance field from long-term HDR captures using digital cameras. The Ickworth methodology, of course, could not be simply replicated since the object (i.e. the tapestry) occupies the majority of the field of view – there are no in-between surfaces (e.g. wallpaper patches) that can serve as markers of known reflectance. Equally, it would not be possible to remove and relocate the tapestry to some controlled illumination environment where it might be possible to photometrically characterise the tapestry.

Figure 4: Left and right sections of the Volury tapestry illuminated by the studio lamp in positions LED1 LED2, respectively – superposed arrows emphasise the significant room-reflected component of illumination (from the studio lamp) incident on the tapestries

Instead, the necessary photometry had to be carried out in situ without any disturbance of the tapestries and, ideally, without any interference with the viewer experience. The latter condition because the Volury is a 'through room' for visitors to Ham House, i.e. it is not possible to close off the Volury without disturbing the visitor flow to the rest of the House. A somewhat ambitious plan was devised to carry out all of the necessary measurements within a narrow timeframe of ∼3 hrs between the House opening in the morning for staff, and 12:00 noon when the House (and Volury) were open to visitors. How this was achieved is described in the following section.

Method

Given all the unavoidable constraints, it was decided that the most promising approach would be to determine the reflectance (i.e. albedo) map using controlled illumination from a photometrically characterised light source. The most practical option appeared to be a studio LED panel. A suitable model, with claimed stable output, appeared to be the LS Edge 1380ASVL. A number of tests to characterise the LED lamp output were carried out in a blacked out laboratory room. Preliminary tests included the consistency of the luminous intensity over time, the consistency of dimming and colour temperature settings, as well as vertical and horizontal symmetry. Adjusting the settings to a 100% output and a CCT of 5600K was found to deliver a consistent output after an initial 'warming up period' of about 30–60 minutes. Under these controlled conditions, more tests on the lamp photometry were performed. The illuminance at a fixed point was measured while rotating the lamp by regular angle steps, both vertically and horizontally, Figure 5a. The recorded illuminance values were used to create a custom modifier for the *Radiance* `brightdata` light source definition – values taken from the interpolated grey line in Figure 5a. The illuminance values simulated using a virtual model of the lamp and laboratory room reported errors within ±2% (dash-dot 'Simulated' curve in Figure 5a). The lamp photometry was also validated against a new set of illuminance measurements, taken at a further distance than the original ones: 3 m as opposed to the original 2 m. Errors between simulated and measured results were all within the ±4% measuring error of the illuminance meters, Figure 5b.

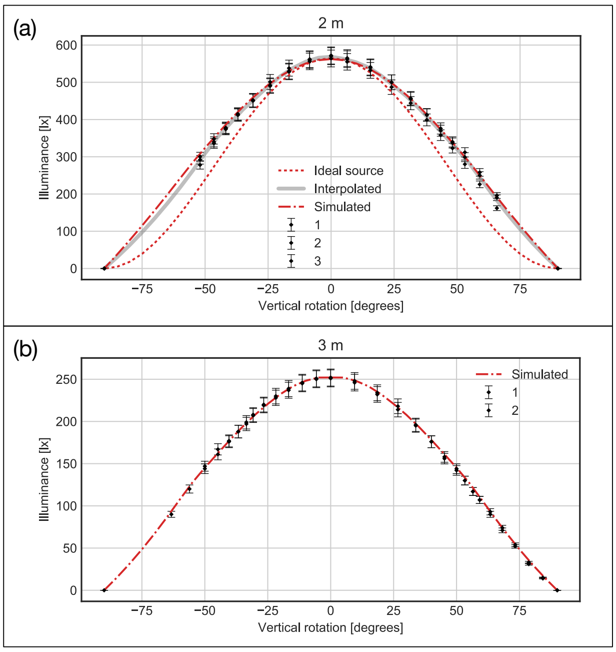

Figure 5: Measurement, characterisation and testing of the LED photometry (vertical rotation)

As is usual with luminaire measurements, the photometry characterises the lamp as if it were a point source, even if it has a large area – which is the case here. Although the lamp has 'barn door' shutters, it would not be reliable to make use of these since any near-field occlusion would invalidate the measured photometry, i.e. the light field would be subject to an indeterminate degree of 'penumbra' occlusion at the periphery. In other words, it was realised in advance that the barns doors could not be used to tightly constrain the illumination from the studio lamp so that *only* the tapestry (on one wall at a time) could be illuminated. Thus, the most reliable means of illuminating the tapestries by a lamp of known photometry meant, unavoidably, illuminating also areas of the Volury around each tapestry, principally, the ceiling, the adjacent walls and the floor. This room-reflected component of illumination from the studio lamp is schematically illustrated in Figure 4.

Although unknowable in advance to any degree of precision, the room-reflected component was estimated to contribute a significant amount of light to the illumination received directly from the studio lamp, perhaps 30% or greater – especially for the regions of tapestry close to the ceiling. Without precise knowledge of the incident illumination field, it is not possible to derive the reflectance map of the tapestry (assuming diffuse reflection). It was decided to attempt a hybrid measurement-simulation approach to account for the room-reflected component of (studio lamp) illumination. This would require first creating a 3D model of the Volury and then converting it to *Radiance* format. Next, the photometric model of the lamp (in *Radiance* format) would be used to simulate the illumination received from the actual lamp (direct and room-reflected light) when the controlled HDR captures were taken. How this was achieved and validated is described in the following section.

Results

A 3D model of the Volury was created from measurements taken by hand in the Volury, Figure 6. Surface reflectances were measured, except for the tapestry itself which was estimated to have an overall reflectance of 0.25 (main part) and 0.15 (border). Uncertainty in the estimation of the tapestry reflectance is, in fact, much less significant than, say, the ceiling since light reflected off the tapestry, back into the room, and then back again onto the tapestry will be a small-order effect compared to light reflected directly off the ceiling onto the tapestry.

The camera for the long-term HDR monitoring in the Volury was installed the evening before the measurements were to be taken. The first task in the morning was to prepare the camera settings, and position it correctly for the monitoring – thereafter it would be left unattended for several months, Figure 7. The camera fixed in this position took the HDR images shown in Figure 4. It was important to make best use of the time available and to obtain measurements that could be used to validate the hybrid measurement-simulation approach.

The procedure was as follows. First, the blinds/shutters in the Volury were closed to ensure that the studio lamp was the sole source of illumination. Next,

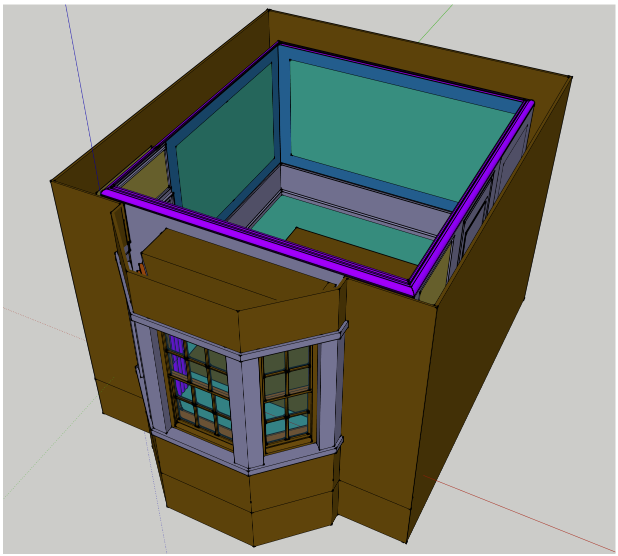

Figure 6: Volury 3D model

the lamp was positioned, in turn, as close as possible to centre-normal to each tapestry (Figure 4). The position of the lamp relative to the room was carefully recorded in each case. With the lamp switched on and stabilised (i.e. warmed up), a number of HDR captures were made using the DSLR now fixed in position above one of the doorways (Figure 7). In between HDR captures, a series of 'opportunistic' measurements of illuminance at accessible points across the tapestry were taken by hand. Accessible points were those that could be reached without disturbing any of the antique furniture positioned in front of the tapestries (Figure 4). Illuminance was measured by hand at 22 points across the left tapestry panel and 29 on the right tapestry panel. Note, the illuminance meter used for these measurements was the same as that used to photometrically calibrate the LED lamp.

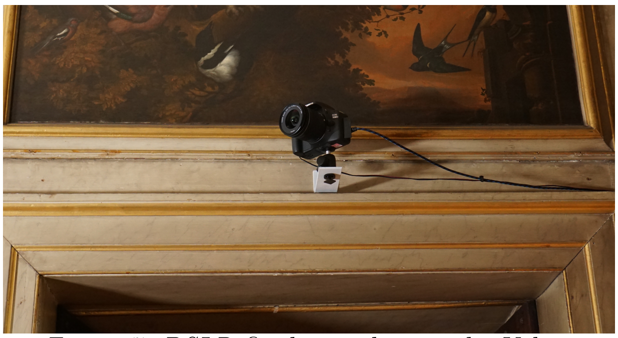

Figure 7: DSLR fixed over door in the Volury

Radiance **simulation of the lamp illuminated tapestries**

The simulations were carried out some weeks after the visit to install the HDR equipment in the Volury and carry out the reflectance map HDR captures (together with the illuminance measurements for validation). For the simulation, the lamp was positioned (in each case) to match the exact location used when the reflectance map HDR captures were taken. The simulation was set to predict the illumination field on the tapestry resulting from the studio lamp. The number of ambient bounces were incremented from 0 (i.e. direct light only) up to 5. The view parameters for the simulation were set to closely match the view of the DSLR camera fixed above the Volury door. However, it was not possible to exactly match views, and so the simulated illumination field was warped slightly to precisely align the simulated tapestry area – on a per pixel basis – with the view of the tapestry 'seen' by the DSLR camera, Figure 8.

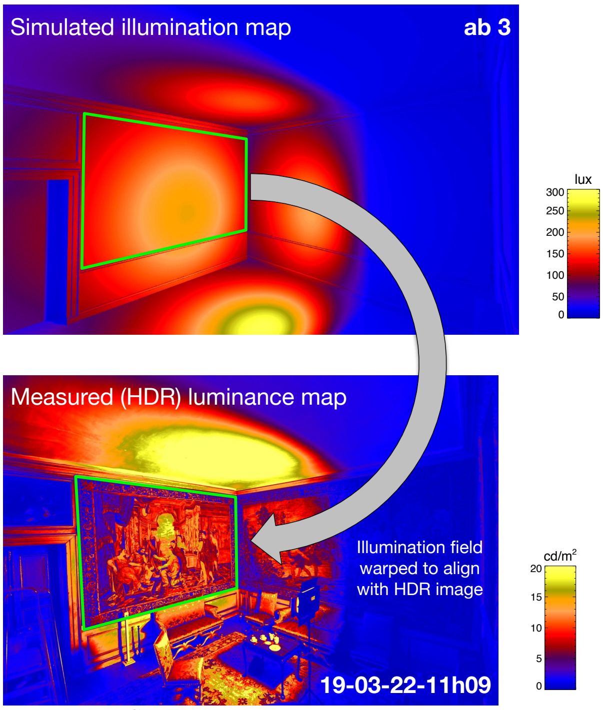

Figure 8: Simulated illumination map and measured (HDR) luminance map

Next, the simulated illuminance values (at the respective points) were compared with the measurements taken by hand on the day on installation. For `ab 0` (i.e. direct light only) simulated illuminances were 20 to 40% less than those measured on the day. Increasing the number of ambient bounces reduced the divergence between simulated and measured illuminances until at `ab 3` no further improvement was deemed significant. At `ab 3` the mean error in predicted illuminance was: 2.5% (left panel) and 1.3% (right panel). The error at each of the measured points is shown in Figure 9. The agreement between simulation and measurement is remarkable, due in part perhaps to using the same (high-quality Hagner) illuminance meter for both the characterisation of the studio lamp and the measurements on the day of installation.

The reflectance map for the tapestries

With confidence from the excellent agreement between simulated and measured illuminance values across the two tapestry panels, the final step was to derive reflectance/albedo maps, in turn, for the left and right panels of the tapestry. With the simulated illuminance field aligned on a per-pixel basis with the

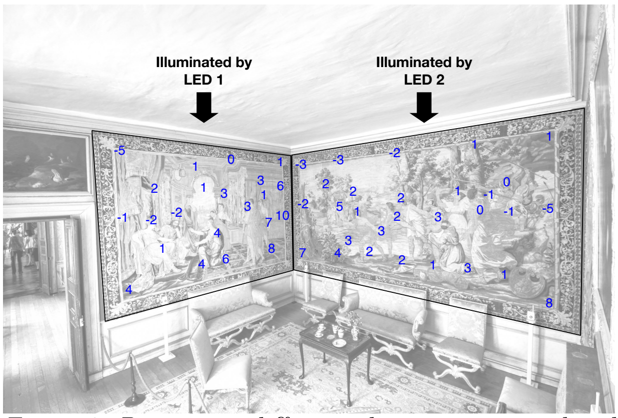

Figure 9: Percentage difference between measured and simulated (ab 3) illuminance across the tapestry at various points when illuminated by LED 1 (left panel) and LED 2 (right panel)

HDR image (Figure 8), it is then a straightforward matter to derive a per-pixel albedo map based on the assumption of diffuse reflectance. The reflectivity $\rho_{(x,y)}$ at each pixel point (x, y) of the tapestry area is:

$$\rho_{(x,y)} = \frac{\pi L_{(x,y)}}{E_{(x,y)}} \tag{1}$$

where $L_{(x,y)}$ is the luminance at that pixel determined from the HDR image and $E_{(x,y)}$ is the incident illuminance at that point determined from the simulation. The composite albedo map derived in this way is shown in Figure 10.

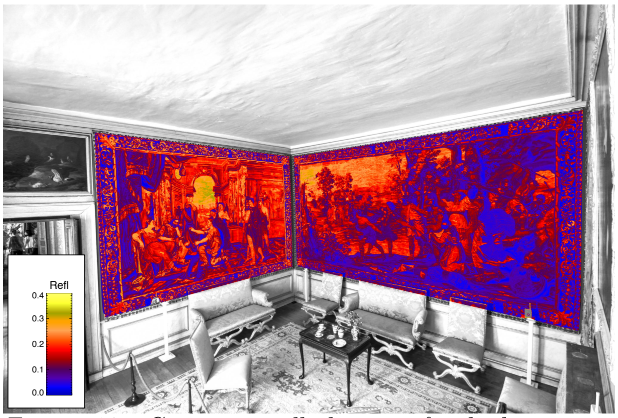

Figure 10: Composite albedo map for both tapestry panels

Preliminary validation

The (unattended) monitoring period for HDR capture began from the day of installation 22nd March 2019 until retrieval of the data 16th December 2019. Useful data during that time covered the period 10th April 2019 until 16th October 2019 when the room was closed off. The tapestry albedo map was used to derive the cumulative daylight dose across the tapestry for the period of useful data coverage. The purpose of this novel technique is, of course, to predict the illumination dose *across* the expanse of the tapestry. However, there were three illuminance logging meters in position at points along the lower border of the tapestry between 10th April 2019 and 16th October 2019. Data from these will be used to validate the daylight dose (i.e. cumulative illuminance) predictions derived from the HDR captures.

The HDR-derived cumulative light dose for one day is shown in Figure 11. The raw illumination map shows some 'print-through' from the albedo map. The cause of this is most likely the combination of several factors:

- The assumption of perfectly diffuse reflectance for the tapestry.
- Employing a single (i.e. monochromatic) luminance response function for a multi-chromatic scene.
- The point spread effect.

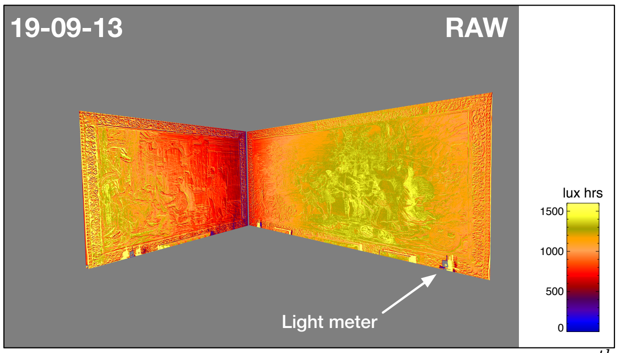

Figure 11: Raw cumulative daily light dose for 13th September 2019 (19-09-13)

Taking each in turn, close visual inspection reveals that the tapestry has some specular (i.e. non-diffuse) component of reflection. Specular reflections are strongly view dependant, and any conspicuous manifestation of their presence will distort the albedo map. From what was observed at the time of measurement, specular reflections from the viewpoint of the camera did not appear to be significant. However it is likely that some low-level component of specular reflections may be recorded in the HDR image. Next, it is known that, for a given HDR calibration using a largely neutral-coloured scene, subsequent application on scenes containing saturated colours will result in errors larger than that expected from the calibration, see Inanici (2006). Lastly, the point spread effect occurs because light is scattered in the optical system of the camera, it is generally referred to as the point spread function (PSF). As a consequence of the scattering, light emanating from a point in the scene which is equivalent to the solid angle of a particular pixel will in fact be smeared across neighbouring pixels also (Inanici (2006)). The PSF will have a noticeable effect on the resulting image wherever there are sharp gradients in either luminance and/or chromaticity at the scale of the pixel resolution of the image. This is evidently the case with the Volury tapestry where there is significant detail at or smaller than the pixel resolution of the HDR image, Figure 12.

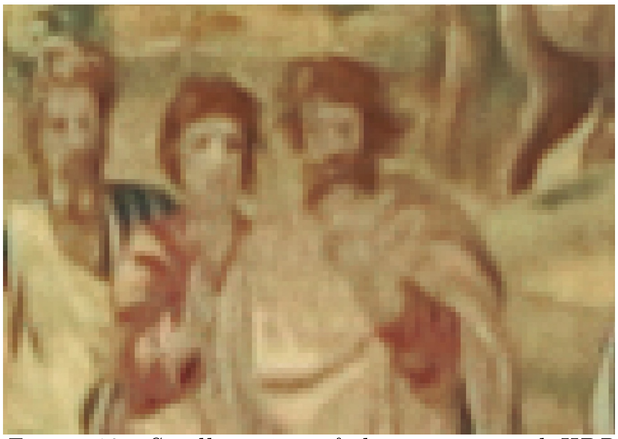

Figure 12: Small section of the tone-mapped HDR image of the tapestry

Any of the three factors described above would be challenging to account for on an individual basis where the other two could be disregarded. Taken together, and where the contribution that each might be making is largely unknown, any attempt to account for these effects would almost certainly require a controlled and highly configurable lighting environment, e.g. something akin to the light stage technology used in the cinema industry for special effects, see Debevec (2012). In other words, in addition to the high costs of such equipment, wholly impractical for the Volury or any other historic setting where disturbance must be kept an absolute minimum. Fortunately, for the purpose described here, the effective 'print through' can be remedied to a large degree with the application of suitable smoothing filters to the raw image. Provided there is no prevailing bias introduced by the combined effect of the factors noted above, filtering the image has the potential to remove the distracting 'print through' whilst revealing the prevailing illumination field.

Various filtering approaches are being investigated, the example below shows application of a median filter to the raw image for day 19-09-13, Figure 13. The image is annotated with the mean lux hours exposure for the two tapestry panels (not including the perimeter and area). Also shown is lux hours exposure measured by the light meter at the indicated position (1008 lx hrs) and that derived from the daily cumulative HDR image of the tapestry using a patch of the tapestry close to and just above the position of the light meter (1120 lx hrs) – a difference of 11%, which is reasonable given the notional ±10% accuracy attributed to these meters.

Using this filtering approach, over the entire period of useful data collection, the measured light exposure was 65,774 lx hrs and that derived from the HDR images was 70,030 lx hrs – a divergence of only 6.5%.

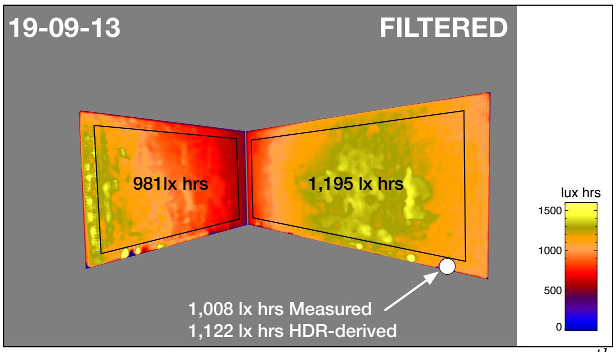

Figure 13: Cumulative daily light dose for 13th September 2019 (19-09-13)

Conclusion

A novel hybrid HDR measurement-simulation approach to determine the reflectance map of a historic tapestry in a real world setting and without any disturbance of the object has been described. The approach requires that the tapestry is illuminated by a suitable light source of known photometry, and that the scene is recorded using a calibrated HDR digital camera. The illumination field at the moment of image capture is reproduced using lighting simulation (i.e. *Radiance*), and the illumination image warped to precisely align with HDR capture. The simulated illumination field was found to have excellent agreement with measurements – the divergence at the majority of the measurement points was typically within the range ±5%. The combination of (simulated) illumination field and (HDR) measured luminance of the tapestry is then used to derive the reflectance (or albedo) map of the tapestry. Factors likely to be the cause of the 'print through' evident in the derived illumination fields have been described and a remedy proposed, i.e. median filtering of the raw image.

The subsequent monitoring campaign produced six months of useful data capture, i.e. a HDR Image recorded every 10 minutes. This was completely autonomous, unattended and without the possibility for remote access. A preliminary validation comparing HDR-derived light doses with measurements recorded by one of the light meters shows good agreement, i.e. within 10%. A more detailed and thorough validation is in progress.

Acknowledgment

The research described in this paper was funded in part by the National Trust (UK). The authors gratefully acknowledge correspondence from Greg Ward (Anyhere Software) regarding filtering of HDR images.

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