Low-Cost Photographic Measurement of Colour, Specular Reflectance, and Roughness

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Abstract
Correctly identifying material reflectance characteristics is critical to daylighting simulation. Specular materials can cause visual discomfort for building occupants and jeopardize the safety of pilots, drivers, and pedestrians. Accurate measurement of these characteristics using laboratory tests is generally cost-prohibitive. We have developed a cost-effective “at-home” test to measure RADIANCE material parameters for use in indoor and outdoor visual comfort studies. Our method, which involves a 3D-printed portable enclosure attached to a hobbyist camera, allows in-situ measurements of material reflectance characteristics, either on site or from a collection of material swatches. We use image processing and linear regression to calculate the Ward reflectance model parameters for the best matching RADIANCE material definition. With basic equipment, we can calculate diffuse reflectance within 20% for 90% of cases, and specular reflectance within 10% for 98% of cases, compared to state-of-the-art spectrophotometer readings.

Highlights
- A low-cost portable device to measure reflectance
- Automated RADIANCE material parameter calculation
- Tests on 179 measurements of material samples

Introduction
The reflective characteristics of objects affect the safety and visual perception of people. Bright reflections from solar collector arrays can create glint and glare for pilots and air traffic controllers, causing loss of visual acuity and momentary visual impairment (Ho, et al., 2011; Jakubiec & Reinhart, 2014; Federal Aviation Administration, 2021). In other cases, such as 20 Fenchurch St and the Shard in London, the Vdara Hotel in Las Vegas, and Disney Concert Hall in Los Angeles, concentrated reflected sunlight created excessive temperatures and danger to drivers at focal points. These phenomena can be predicted by simulation if exact specular reflective properties of materials are known. However, daylighting and solar simulations often assume a standardized material palette including only specular glass and diffusely reflective opaque surfaces (Jakubiec, 2022). Jakubiec (2016) shows convincingly that use of measured material reflectance properties in daylighting simulation produces significant quantitative and qualitative differences in simulation results compared to standard assumptions of reflectance.

However, measuring material reflectance is impractical for most architecture firms or specialized consultants who cannot readily justify the cost of maintaining in-house measurement devices or contracting external services. Portable spectrophotometers, like those used by Jakubiec, require annual calibration for a fee and do not account for the scattering effect of material roughness. Laboratory testing meeting ASTM E2387-19 (2019) specifications may cost thousands of dollars per sample for complete bidirectional scattering distribution function (BSDF) measurement. These costs can dissuade architects from using innovative materials (Reinhart & Andersen, 2006) or increase the likelihood of glint and glare when materials with partially unknown properties are specified.

In this paper, we introduce a novel, low-cost, field deployable technique for measuring material reflectance properties. Our device (Figure 1) consists of a hobbyist digital camera, light source, and a 3D-printed enclosure that create a controlled luminous environment, even in outdoor settings. We use a fully automated image processing and regression workflow to calculate RADIANCE (Larson & Shakespeare, 1998) material parameters (diffuse reflectance, specular reflectance, and roughness) that best approximate the actual reflectance distribution of any opaque isotropic material. In the following sections, we describe the construction and image processing steps of our setup, and we assess its accuracy compared to spectrophotometer measurements.

Figure 1: The measurement device includes a 3D printed enclosure, LED light source, and camera.
Background

All materials have some amount of surface irregularity, giving them an appearance that is not perfectly specular (Blushan, 2001). The level of surface irregularity, or roughness, affects object appearance and is important to product inspection and computer graphics applications. Non-optical measurements involve dragging a stylus along the material, which might damage the material (Feidenhansl, et al., 2015). Thus, we prefer optical methods that characterize roughness by observing patterns of light scatter from a material sample.

BSDFs

A BSDF describes the amount of light from an incoming direction \((\theta_i, \varphi_i)\) that is reflected or transmitted in each outgoing direction \((\theta_o, \varphi_o)\) (CIE, 1977). Because we need to describe many possible incoming directions, it is really a four-dimensional function \((\theta_i, \varphi_i, \theta_o, \varphi_o)\) which includes reflected outgoing directions (the bidirectional reflectance distribution function, or BRDF) and transmitted outgoing directions (the bidirectional transmittance distribution function, or BTDF). Nicodemus (1970) developed the BRDF as a dimensionless formula describing light redirection (and later transmission) from a surface and identified it as critical to describing surface appearance. Conceptually, it is:

\[
BSDF(\theta_1, \varphi_1, \theta_2, \varphi_2) = \frac{L_2(\theta_1, \varphi_1, \theta_2, \varphi_2)}{E_1(\theta_1)}
\]

where \(L_2\) describes the emerging light flux in cd/m² and \(E_1\) is the incident illuminance on the sample in lux.

ASTM E2387-19 (2019) describes the procedure for measuring a BSDF using a goniophotometer. Traditional goniophotometers involve a separately movable light source and camera to capture the four-dimensional function (Papamichael, et al., 1988). Marschner, et al. (2000) improved the efficiency of the moving light source method by taking photographs of curved object using two cameras. Though not as useful for architectural materials, which tend to be flat, this has been applied to capture of BRDFs for human skin (Marschner, et al., 1999).

To eliminate the need for moving parts, Ward (1992) introduced a hemispherical mirror allowing the camera to view the material from multiple angles simultaneously to capture anisotropic reflectance characteristics. Andersen (2004) reduced goniophotometer capture time from hours to a few minutes by replacing the single camera with a multi-sensor image processing technique, primarily concerned with light transmission. Using the hemispherical mirror, complex reflectance characteristics can be reduced to a linear combination of basis functions for compact description of BSDFs (Ghosh, et al., 2010). Further cost savings can be achieved using LEDs as both light sources and detectors, eliminating the need for a camera (Ben-Ezra, et al., 2008).

Of particular relevance to our work is a study by Karner, et al. (1996) of anisotropic materials using a sequence of one-dimensional scans of reflectance in a dark test space under a point light source. With this technique, a single scantage is usually sufficient to describe the BSDF of typical isotropic materials.

Simplified BSDF Models

The complexity of a measured BSDF may defy description with a simple mathematical formula, but for many materials, we can achieve a reasonable approximation. A common approach is to split reflected light into a diffuse component, reflected in all directions with cosine weighting, and a specular lobe. Many models assume that the specular lobe follows a Gaussian distribution of normal directions (Blushan, 2001), where the spread is determined by a roughness parameter, for example the root-mean-square of surface deviation from the average orientation (Myers, 1962). This is true of the models by Ward (1992), Dür (2006), and Geisler-Moroder and Dür (2010), each of which takes the form:

\[
BSDF(\theta_1, \varphi_1, \theta_2, \varphi_2) = \frac{\theta_d}{\pi} + \frac{\rho_s \tan^2 \delta / a^2}{\pi a^2} \cdot f
\]

where \(\rho_d\) is the diffuse reflectance, \(\rho_s\) is specular reflectance, \(\alpha\) is the isotropic roughness parameter, \(\delta\) is the angle between the surface normal and the mean of the incident and outgoing vectors, and \(f\) is a function varying between the models, the details of which are unimportant for this discussion. The unified Ward-Geisler-Moroder-Dür (WGMD) model is implemented in RADIANCE plastic and metal materials.

One simplification in the WGMD model is that the same specular lobe characteristics are used for all colour channels, while the diffuse component is allowed to vary by colour channel. Ngan, et al. (2005) note that the Ward model does not perform as well as other models such as Ashikhmin-Shirley (Ashikhmin & Shirley, 2001) against measured data. In fact, RADIANCE makes the Ashikhmin-Shirley model available as an alternative to the WGMD model, though it is not widely used in daylighting practice.

Use of Materials in RADIANCE

RADIANCE is a widely used and extensively validated lighting simulation tool within the daylighting community. While daylighting standards tend to simplify the reflective properties of buildings down to a few standard values (Jakubiec, 2022), RADIANCE is capable of creating visually expressive renderings of architectural materiality (Jakubiec, 2016). Use of accurate material properties improves quantitative daylighting simulation accuracy. Reinhart and Andersen (2006) measured the transmittance properties of a translucent panel using a goniophotometer and fit the data to various Radiance materials, with best performance coming from transdata. Other studies used accurate modeling of material reflectance properties to duplicate glare phenomena in air traffic control tower (Jakubiec & Reinhart, 2014) and office (Jones & Reinhart, 2017) environments. A library of RADIANCE material definitions measured by spectrophotometer (without measured roughness parameters) is available through the SpectralDB online database (Jakubiec, 2016).
Method
During the Covid pandemic, one of us was tasked with analyzing and rendering a set of materials without access to laboratory testing and using only equipment available at home. The difficulty in measuring the WGMD model parameters, especially roughness, of physical material samples led us to develop a novel, low-cost measurement technique. Through successive refinement, we developed this measurement device and image processing workflow.

Enclosure
The purpose of the enclosure is to create a sealed environment that isolates the material sample from outside light sources. It consists of four modular components: the base, box, camera attachment, and LED enclosure (Figure 2). The box is 3D printed from black ABS plastic, which alone is 4% reflective. We lined the inside with a black velvet flock paper to minimize internal reflections. This paper, often used to line jewelry boxes, has a reflectance of less than 0.5%.

![Image of LED enclosure](https://doi.org/10.26868/25222708.2023.1380)

**Figure 2:** The 3D-printed enclosure illuminates a strip of the material sample for the camera under controlled lighting conditions.

The 3D printed enclosure is easily reproducible and deployable. We printed its modular components upside down on their flat surfaces to avoid using printing supports. The camera attachment can be swapped out to fit different cameras; in our case, we sized it for a Canon RF 14-35mm f/4 IS USM lens. The component that attaches to the camera has a thin edge that slides into the outside edge of the camera lens, akin to a screw with threads. This locks the lens into place above the material sample with a consistent orientation.

The base has two perpendicular slit openings forming a cross. The long horizontal slit isolates a section of the material sample underneath so that the images taken can identify the diffuse and specular reflectance of the material in relation to distance from the fixed light source above. The vertical slit sits at the point halfway between the centre of the light source and the camera lens, which is where the specular reflectance peaks. It forms a bright vertical line in the image, which is necessary for the camera’s autofocus feature that searches for sharp edges on horizontal scanlines. In the future, it may allow analysis of anisotropic materials from a single high dynamic range (HDR) image.

The light source is a set of four 5-mm LEDs powered by 3V lithium batteries that can be switched on and off. We use a mixture of cool and warm white LEDs to achieve a neutral colour temperature. The light is located at one end of the enclosure above the visible strip of the sample. It shines into the enclosure through a square aperture that has an area of 400 mm². A sheet of plain white copy paper covering the aperture diffuses the light from the LEDs, which otherwise would create narrow cones of light. The distance from the aperture to the material sample is 150 mm, the same distance as from the camera lens to the sample. In this way, we can observe an isolated strip of material in a reliably fixed orientation with respect to a single light source and camera.

Image Processing
In the WGMD model, the BSDF can be decomposed into diffuse and specular components. Our goal, then, is to find the linear combination of specular and diffuse reflections that best approximates the luminance distribution observed by the camera. We do this in four steps: 1) creation of a reference image, 2) HDR image generation, 3) detection and cropping of the sample region, and 4) linear regression.

**Reference Image:** The reference HDR image is a composite generated from 502 idealized materials with a variety of WGMD reflectance parameters (Figure 3). For each material variant, we generated a RADIANCE simulation with lighting and camera position matching those of the enclosure. The image stores one scanline from each rendering, allowing for efficient disk access. The bottom scanline represents 100% diffuse reflectance, while the remaining scanlines show 100% specular reflectance with increasing roughness. We increase roughness in increments of 0.001 from 0 to 0.5. We chose the upper roughness value arbitrarily; there is no natural limit to roughness, but values beyond 0.5 are difficult to distinguish from purely diffuse materials. Because the enclosure interior has low reflectance (less than 1%), we render the individual material simulations with no ambient bounces, and we include a light source with unitary brightness so that the actual brightness can be applied per colour channel as a factor in post-processing.
Sample Images: We create HDR images of material samples by combining auto-bracketed exposures using hdrgen. Each HDR image is made from seven images with exposures ranging from 1/5000th second to 8 seconds with ISO-100 film speed, f/4 aperture, and 20-mm focal length captured by a Canon EOS R mirrorless camera. Because we can easily take hundreds of photographs in one session, we automate the process of moving the input images into folders labelled with the material sample name according to a spreadsheet logged by the user. Our script moves the input JPEG images into folders, runs hdrgen on the contents of each folder using a calibrated response file, and scales the output HDR images to 512 pixels wide to match the reference image’s width.

Image Processing: Once we have an HDR image of a material sample, we perform rudimentary edge detection to identify the sample using Python. The sample appears as a long strip in the HDR photograph (Figure 4a). We first identify the coordinates of the ends of the strip, and then rotate the image so that the strip is horizontal. The rotation operation may have a smoothing effect on the image, but this is unbiased and therefore not a concern. Next, we identify the top and bottom edges of the horizontal slot and the left and right edges of the vertical slot in the rotated image. Using the vertical slot’s location as a reference, we shift the image left or right to align it with the reference image. We then crop the image to the bounds of the horizontal slot (Figure 4b). Finally, we take the mean of the pixel values in each column of the cropped image, treating red, green, and blue components separately, and calculate the luminance \( L \) of the resulting average scanline (Figure 4c) as follows:

\[
L = 0.213r + 0.715g + 0.072b
\]  

(3)

Note that the coefficients applied to the channels above are based on CCIR-709 primaries and differ slightly from those used for human vision. Vertical lines in Figure 4b and Figure 4c indicate the points directly under the light, directly under the camera, and midway between the two where we expect the specular highlight to occur.

Sample Matching via Linear Regression: In the final step, we perform linear regression to calculate diffuse, specular, and roughness parameters that fit each of the red, green, blue, and luminance channels subject to the following constraints:

\[
L_c(x) = \rho_d L_d(x) + \rho_s L_s(x) \quad (4)
\]

\[
\rho_d \geq 0; \; \rho_s \geq 0; \; \rho_d + \rho_s \leq 1 \quad (5)
\]

where \( L_d(x) \) is the diffuse scanline of the reference image and \( L_{s,a}(x) \) is the scanline of the reference image corresponding to roughness \( a \). Using linear regression, we find the pair of \( \rho_d \) and \( \rho_s \) that minimize mean square error between \( L_d(x) \) and the actual mean pixel values (where \( c \) is either red, green, blue, or luminance). We repeat this for each value of \( \alpha \) and select the combination of \( \rho_d, \rho_s, \alpha \) with the highest coefficient of variation, \( R^2 \) (Figure 5a).

The previous step yields a separate set of results for each colour channel. If we were using the Ashikhmin-Shirley model, we could be done at this point. For the WGMD model, which has separate colour channels for diffuse reflectance only, we use \( \rho_s \) and \( \alpha \) calculated from the luminance channel and recompute \( \rho_d \) by finding a new best fit to equation (4) for each of the red, green, and blue channels \( c \) (Figure 5b).
Figure 5: Best fit curves for FunderMax 0803 NT Tyrol Pine (a) indicate the linear combination of scanlines from the reference image that best approximate each colour channel. For the WGMD model (b), all channels use the same specular reflectance and roughness values, which we render with RADIANCE (c).

Finally, we note that RADIANCE allows the diffuse and specular components each to range from zero to one, rather than constraining valid input according to equation (5). Essentially, it applies the diffuse parameter only to the incoming luminance that does not participate in the specular reflection. Therefore, we modify the diffuse reflectance for use in RADIANCE (Figure 5c) as:

\[ d_c = \frac{\rho_{d,c}}{1 - \rho_s} \]  

Results

We obtained 255 HDR photographs of architectural materials using our device, including metal panels, ceramic tiles, natural and manufactured wood products, woven fabrics, and paper. We discarded some samples from this analysis due to anisotropic properties, small sample dimensions, or inability of our algorithm to detect the sample outline in the photograph, leaving 179 useful samples. We compared the WGMD model parameters to values obtained from a Konica Minolta CM-2500d spectrophotometer as described in Jones and Reinhart (2017), including the conversion in equation (6).

Our device’s predictions of material properties correlate well with the spectrophotometer measurements (Figure 6). Our device tends to measure diffuse reflectance values 1.09 times greater than the spectrophotometer, although there is considerable variation (Table 1). Out of 179 measurements, our total diffuse reflectance measurements (across all colour channels) differ by less than 20% from the spectrophotometer measurements in 90% of cases. Our best fit is for the green channel; this makes sense because the green channel has the largest influence on calculation of the luminance channel, which determines the specular component. The lower \( R^2 \) for the red channel may be an artifact of the warm white LEDs in our device causing the camera to pick up more red light.

Table 1: Our method compared to spectrophotometer.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Trend</th>
<th>( R^2 )</th>
<th>Within 20%</th>
<th>Within 10%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red</td>
<td>( y=0.9246x )</td>
<td>0.8914</td>
<td>89%</td>
<td>64%</td>
</tr>
<tr>
<td>Green</td>
<td>( y=0.9210x )</td>
<td>0.9117</td>
<td>90%</td>
<td>74%</td>
</tr>
<tr>
<td>Blue</td>
<td>( y=0.9128x )</td>
<td>0.8976</td>
<td>93%</td>
<td>69%</td>
</tr>
<tr>
<td>Specular</td>
<td>( y=0.3355x )</td>
<td>0.6133</td>
<td>99%</td>
<td>98%</td>
</tr>
</tbody>
</table>

Figure 6: Our device’s reflectance measurements correlate with those from the spectrophotometer for red diffuse reflectance, green diffuse reflectance, blue diffuse reflectance, and specular reflectance.

We see greater discrepancy in the specular reflectance measured by our method compared to that from the spectrophotometer. However, because the specular component measured by the spectrophotometer considers only a single reflection angle, we are not sure that it corresponds to the specular component in the WGMD model, which is an integral over the entire specular lobe. In fact, our ability to measure the width of the specular lobe by obtaining a roughness parameter may make our method superior to the spectrophotometer in this regard. We lack a validated means of quantifying error in our roughness measurements at this point.
Results for several materials of different types are shown in Figure 7. Some of the samples we measured produced noisy scanlines, either because of texture or variation of material colour. Our regression approach produces a best-fit curve that essentially represents the average surface luminance in any region of the photograph captured by our setup. That means that we can derive a roughness parameter that reasonably approximates the material appearance, even if the scanline does not follow the curvature expected by the WGMD model. Because the total amount of light reflected from a large surface in each direction should follow from that average, this suggests our derived material parameters should be useful for quantitative lighting calculations.

In some cases, our approach does a poor job of characterizing materials. In Figure 8a, the specular highlight of the blue-glazed terracotta picks up a red tint from the warm white LEDs, making the observed specular lobe in the red channel brighter than in blue or green. The WGMD model does not account for this, even when we take light source colour into account. As a result, the best fit curve for the red channel is substantially higher than the green and blue channels outside of the specular lobe, giving the measurement an unexpected beige tint. We observe the reverse for the yellow tile in Figure 8b, where specular reflection of light from the cool white LEDs leads to an unexpected blue tint in the rendering. For some materials, including coated metals (Figure 8c), the assumption that the specular lobe follows a Gaussian shape is not accurate. Compared to the WGMD model, the slope of the measured scanline is steeper near the specular lobe’s peak and more gradual elsewhere. As a result, our method underpredicts the brightness of the specular peak and overpredicts diffuse reflectance. We note a similar shape to the measured BSDFs in Ward (1992), so we understand this to be a shortcoming of the WGMD model and similar models. In general, we cannot guarantee that the total light energy reflected in our best fit model is the same as that for the original material. Our goal, however, is to create a good enough match to the material that we can duplicate its specular highlights in simulations of reflected glare.

Figure 7: Renderings of materials show the correspondence between physical material appearance and our derived WGMD model BSDFs for (a) galvanized metal, (b) ceramic tile, and (c) roofing shingles.
Discussion

We present a method that can be immediately used by lighting and daylighting designers with access to a camera and computer for post processing. STL files for 3D-printing the enclosure and software for the image processing steps described in this paper are available at github.com/MITSustainableDesignLab/reflectometer. In practice, the method can be applied during design as well as in the field, and we recommend that architectural design teams use it to reduce risk of discomfort or disability glare in the built environment.

One of the limitations of publicly available online datasets such as SpectralDB (Jakubiec, 2016) is that potential contributors need access to a spectrophotometer, which has thus far seriously reduced their number. Our new method not only increases the number of potential contributors, but also allows estimation of material roughness, a key optical property that could thus far only be approximated using goniophotometer measurements. The light level produced by the LEDs in our enclosure is quite low. This necessitates long photographic exposures, but it results in images with limited dynamic range. Future investigations could use a single exposure, or even a cell phone camera running an associated app.

At present, we limit our work to isotropic materials and the RADIANCE plastic primitive. By isolating the vertical slot in our images, our device could also measure anisotropic reflectance using the WGMD or Ashikhmin-Shirley model. We see an advantage to the latter because it specifies specular colour. Using Ashikhmin-Shirley would simplify our calculations, reduce the likelihood of the colouration error shown in Figure 8a, and generally improve the realism of RADIANCE renderings. We recommend this as an industry shift going forward.

Conclusion

We presented a portable, low-cost device and automated workflow for obtaining RADIANCE material reflectance parameters for daylighting and glare simulations. Our device consists of a light-blocking enclosure, light source, and camera for taking HDR images of materials. Our workflow identifies the sample region in the HDR image and uses linear regression to obtain the best-fit WGMD model parameters to describe its diffuse and specular reflectance and surface normal deviation, or roughness.

Figure 8: Our method yields inaccurate results for colour when the specular highlight has a tint, as in (a) glazed terracotta and (b) ceramic tile. For some coated metals (c), the measured scanline is not Gaussian at the tails.
Based on measurement of 179 HDR photographs of materials, our device generally produces reasonable correspondence to spectrophotometer measurements of diffuse reflectance. Our device is unique in its ability to capture specular reflectance and roughness without the need for a goniophotometer or other laboratory equipment. As a result, we can now simulate glare phenomena in real buildings using accurate reflectance properties recorded in site visits or from vendor-provided material samples. This is in keeping with our greater goal of making informed decisions affecting visual comfort and safety early in the design process.

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