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What is This?
Using digital cameras as quasi-spectral radiometers to study complex fenestration systems

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This work discusses the use of digital cameras fitted with absorption filters as quasi-spectral radiometers. By filtering incident light into selected wavelength intervals, accurate estimates of radiances can be made for unknown spectra. This approach is being employed as part of a new video-projection goniophotometer to study the properties of angularly and spectrally selective complex fenestration systems. Complex fenestration systems are increasingly being used to distribute solar radiation purposefully in buildings. They can be utilized to optimize energy performance and enhance daylighting. Radiance estimates from calibrated digital cameras enable the assessment of quasi-spectral, bi-directional scattering distribution functions of total radiance transmitted or reflected by a fenestration system over desired wavelength intervals. A silicon and an indium gallium arsenide digital camera are used to enable measurements across a 380 to 1700 nm wavelength interval.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>experimentally determined constant ($-0.13254$)</td>
</tr>
<tr>
<td>$a_{\Delta \lambda, \text{filterset}}$</td>
<td>fraction of total radiance in a wavelength interval $\Delta \lambda$, assumed for each filter set based on a neutral sample</td>
</tr>
<tr>
<td>$b$</td>
<td>experimentally determined constant (363.51)</td>
</tr>
<tr>
<td>$ASR$</td>
<td>Absolute spectral responsivity</td>
</tr>
<tr>
<td>$E_e$</td>
<td>spectral exitance of the light source ($\mu W/cm^2$)</td>
</tr>
<tr>
<td>$E_{e, \text{source}} (\lambda)$</td>
<td>spectral exitance of the light source ($\mu W/cm^2$)</td>
</tr>
<tr>
<td>$E_{e, \Delta \lambda}(\theta_i)$</td>
<td>directional radiance incident on a sample spanning wavelength interval $\Delta \lambda$</td>
</tr>
<tr>
<td>$f$</td>
<td>$f$-number of the camera</td>
</tr>
<tr>
<td>$H(\lambda)$</td>
<td>spectral exposure of sensor array measured spectral exposure given by scene radiance multiplied by integration time ($\mu J/cm^2$)</td>
</tr>
<tr>
<td>$h(\lambda)$</td>
<td>$h(\lambda)$ resulting in $NDL = 0.3$ for the red, green, or blue channel ($\mu J/cm^2$ sr)</td>
</tr>
<tr>
<td>$h_{R,G,B}^{0.3}(\lambda)$</td>
<td></td>
</tr>
<tr>
<td>$c$</td>
<td>experimentally determined constant ($1.4468e7$)</td>
</tr>
<tr>
<td>$CCD$</td>
<td>Charge-coupled device</td>
</tr>
<tr>
<td>$CFS$</td>
<td>Complex fenestration system</td>
</tr>
<tr>
<td>$D$</td>
<td>experimentally determined constant ($-0.40717$)</td>
</tr>
<tr>
<td>$DL_{R,G,B}$</td>
<td>digital level in the red, green, or blue channel</td>
</tr>
<tr>
<td>$e$ (subscript)</td>
<td>radiometric units</td>
</tr>
<tr>
<td>$h(\lambda)$</td>
<td>measured spectral exposure given by scene radiance multiplied by integration time ($\mu J/cm^2$ sr)</td>
</tr>
</tbody>
</table>

Address for correspondence: M Andersen, MIT Building 5-418, 77 Massachusetts Ave, Cambridge MA 02139, USA. E-mail: mand@mit.edu

Figures 1–6, 8, 12 and 19 appear in colour online: http://lrt.sagepub.com

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[1/\rho^{2}_{R,G,B,filterset}] assumed total responsivity of CCD camera for a given filter set based on a neutral sample

HMI Hydrargyrum medium-arc iodide

InGaAs Indium gallium arsenide

k camera spectral exposure constant

$L_{c,beam,380-945}$ total radiance in a polychromatic beam for the wavelength interval between 380 nm and 945 nm ($\mu W/cm^2 sr$)

$L_{c}(\lambda)$ spectral radiance ($\mu W/cm^2 sr$)

$L_{c,j}(\theta_i, \phi_i, \theta_r, \phi_r)$ bidirectional spectral radiance for filter combination j. ($\mu W/cm^2 sr$)

$L_{c,\Delta \lambda}(\theta_i, \phi_i, \theta_{t(r)}, \phi_{t(r)})$ bi-directional radiance across a wavelength interval $\Delta \lambda$

N aperture number

NDL-R,G,B normalized digital level (digital level divided by $2^8$) in the red, green, or blue channel

NIR Near infrared radiation

$p_{\Delta \lambda}$ fraction of total radiance in a wavelength interval $\Delta \lambda$

$r_{RGB}(\lambda)$ absolute spectral responsivity of CCD camera in the red, green, and blue channel (NDL/($\mu J/cm^2 sr$))

$r_{RGB,\Delta \lambda}$ discretized absolute spectral responsivity of CCD camera in the red, green, and blue channel (NDL/($\mu J/cm^2 sr$))

$t_{int}$ integration time

VC($x,y$) vignetting correction factor as a function of pixel coordinates ($x,y$)

$\theta_i$ incident altitude angle (radians)

$\phi_i$ incident azimuth angle (radians)

$\theta_{t(r)}$ transmitted or reflected altitude angle (radians)

$\phi_{t(r)}$ transmitted or reflected azimuth angle (radians)

1. Introduction

In 2004, building energy consumption accounted for 39% of total U.S. energy consumption.\textsuperscript{1} According to one study, energy use due to fenestration systems through impacts on heating, cooling and lighting demand accounted for about 7 quadrillion BTUS of energy consumption, or about 7% of annual U.S. energy consumption.\textsuperscript{2} If one existing fenestration technology, low-emissivity glazings, were deployed throughout the residential building market it was estimated that residential heating and cooling energy consumption attributable to windows would drop by about 41%.\textsuperscript{3}

Daylighting systems designed to enhance lighting conditions within spaces have potential impacts on occupant comfort, electrical energy savings and aesthetics. Loftness and Harktopf estimate that 30 to 60% of annual lighting energy could be saved through effective daylighting strategies.\textsuperscript{4} Daylighting may also improve comfort, human health, productivity, the performance of tasks, and have financial implications, but if implemented poorly may have opposite effects, such as causing glare or overheating.\textsuperscript{5}

Angularly and spectrally selective fenestrations are one type of complex fenestration system (CFS). These systems can transmit or reflect different parts of the solar spectrum in different directions for different angles of incidence of solar radiation. The potential of this kind of system, for example, is to transmit visible light deeply into spaces throughout the year while reflecting near infrared radiation (NIR) during the summer and transmitting it during the winter. One study showed that angularly selective glazings tuned theoretically for optimal optical properties could reduce annual cooling energy loads by 18% and annual electricity use by 15% relative to spectrally selective windows, already an improvement over conventional windows.\textsuperscript{6} At the same time, they would provide a better daylight distribution.

Accounting for both daylighting and thermal issues in the development of angularly and spectrally selective glazings requires the study of angularly and wavelength dependent optical properties of fenestration systems across the entire spectrum of solar radiation.

\textit{Lighting Res. Technol.} 2009; 41: 7–25
The ability to study these properties will help in characterizing, modeling and analyzing their performance in the built environment as well as in designing new systems. A new spectral video-goniophotometer is under development at the Massachusetts Institute of Technology (MIT) to meet this need.

The methods developed here for using digital cameras as quasi-spectral radiometers enable video-projection goniophotometers to measure quasi-spectral, bi-directional scattering distribution functions (BSDF). A growing library of BSDFs is useful for daylighting and energy simulations involving complex materials and CFS. The calibrated cameras could also be used separately to conduct thermal and visual assessments of rooms. This is similar to the use of digital cameras for studying luminance or radiance distributions in rooms, except that the use of filters could expand the assessment to include quasi-spectral transmission and reflection properties of surfaces.

2. A spectral video-goniophotometer

Goniophotometers have been widely used to study the optical properties of lamps and luminaires, ground surfaces and ground textures and natural materials such as wood. They are increasingly being used for assessing the bi-directional optical properties of fenestration system materials and components. Only very recently have goniophotometers for fenestration systems been developed that measure spectral as well as bi-directional dependence.

However, existing goniophotometers that provide spectral information utilize detectors to scan the hemisphere of radiation emerging from a sample. The development of quasi-spectral radiance measurement using digital cameras will enable video-projection goniophotometers to measure spectral properties using a video-projection method. This has advantages over scanning goniophotometers because a full hemi-sphere of data can be collected at once, saving time, and spatial averaging prevents missing parts of the distribution due to poor sampling resolution.

The goniophotometer under development at MIT will measure quasi-spectral BSDFs of materials and components used in fenestration systems. The basic components are a 400 W Dedolight hydrargyrum medium arc iodide (HMI) source, a rotating sample holder, a projecting device, and a charge coupled device (CCD) and Indium Gallium Arsenide (InGaAs) digital camera. Filters are used to sample the spectrum of the source, isolating wavelength intervals over which radiance estimation can be performed accurately. A schematic of the device is shown in Figure 1. A more complete description of the video-goniophotometer can be found in other sources.

Filtered radiation impinges on a fenestration sample at the center of the rotating table, coincident with one focal point of the hemi-ellipsoid. After irradiating the sample, radiation is transmitted or reflected into a full hemisphere, reflected off of the hemi-ellipsoid and directed towards its other focal point where it is recorded by a digital camera equipped with a fish eye lens.

The quasi-spectral radiance estimated by the digital camera combined with absorption filters provides the numerator for a quasi-spectral BSDF while the denominator,

![Figure 1 The MIT video-goniophotometer](image-url)
the irradiance of the sample, is known. An average BSDF across a wavelength interval $\Delta \lambda$ for the radiation source can then be calculated as follows:

$$BSDF_{e, \Delta \lambda}(\theta_{(r)}, \varphi_{(r)}, \theta_i, \varphi_i) = \frac{L_{e, \Delta \lambda}(\theta_{(r)}, \varphi_{(r)}, \theta_i, \varphi_i)}{E_{e, \Delta \lambda}(\theta_i)}$$  \hspace{1cm} (1)$$

The full spectral BSDF is entirely independent of the source of radiation, and is a property of the material or system being studied, whereas the quasi-spectral BSDF defined above depends on the radiation source spectrum, chosen to simulate solar radiation.

3. Camera calibrations

A critical step in the measurement of quasi-spectral BSDFs is the spectroradiometric calibration of the CCD camera and InGaAs NIR digital camera. These calibrations enable the measurement of radiance for unknown spectra reflected or transmitted from spectrally and angularly selective fenestration samples.

The CCD camera is a Kappa DX20 color CCD camera. The InGaAs camera is a Sensors Unlimited SU320 1.7RT camera. A Fujinon FE185C057HA high resolution fisheye lens is used with both cameras. The NIR filter has been removed from the CCD camera to capture wavelengths between 780 and 945 nm. A non-linear gamma of 0.5 was chosen for the CCD camera to enable better differentiation of low luminance features in a single image. Ultimately, the pixels will be averaged over user selected solid units of angle. The integration time, which can range from minutes to microseconds, is varied to capture images of less or more radiance or luminance.

For both cameras a vignetting correction will be applied, in terms of a function $VC(x, y)$ dependent on the $x, y$ image coordinates to correct for light drop-off near the end of the image. An angular resolution of 0.0017 steradians for the CCD camera and 0.25 steradians for the InGaAs camera limits the BSDF features distinguishable by each camera. Spatial calibrations for each camera have also been performed relating pixel location to zenithal angle of incidence on the camera. Due to the fish eye lens, the relationship between pixel distance from principal point and zenithal angle is linear and passes through the origin, by definition of the principal point. A coefficient of 0.1886° per pixel relates zenith angle to the pixel location relative to the principal point for the CCD camera, whereas the coefficient is 0.7995° per pixel for the NIR camera.

3.1 Spectroradiometric calibration

Spectroradiometric calibration of the digital cameras was performed to relate digital output to the radiance viewed by the camera. The output of a digital camera for a given pixel at a given wavelength is related to the spectral exposure, in units of energy, of the sensor area correlating to that pixel. The spectral exposure is dependent on the number of photons of a given wavelength impinging on the detector area, which are in turn related to the radiance of the scene viewed by the camera. In its most simple form, the spectral exposure, $H(\lambda)$ is related to scene spectral radiance by:

$$H(\lambda) = k \frac{L_e(\lambda)}{N^2} t_{\text{int}}$$  \hspace{1cm} (2)$$

where $k$ is a constant depending on the optical and geometric properties of the imaging system, $N$ is the aperture number, $t_{\text{int}}$ is the integration time and $L_e(\lambda)$ is spectral radiance. In this application, the $f$-number of the lens is fixed at $f/4$, and thus $N$ in the equation can be absorbed into the constant $k$. Furthermore, the digital output for a pixel is physically related to its spectral exposure and can be thought of as a function of the scene radiance, such that:

$$NDL_{R,G,B}(\lambda) = \frac{DL_{R,G,B}}{28} = f(H(\lambda))$$  \hspace{1cm} (3)$$
where NDL_{R,G,B} and DL_{R,G,B} are the Normalized Digital Level and Digital Level of the R, G, or B channel.

To study the relationship between spectral exposure and the NDL response of the camera, the camera output was measured against known monochromatic radiances and integration times. The constant of proportionality relating radiance to spectral exposure, \( k \), was not measured. Instead, the relationship between NDL and the product of \( L_e(\lambda) \) and \( t_{\text{int}} \) was measured directly.

A Labsphere KI-120 Illuminator tungsten-halogen lamp, a Spectral Products CM110 monochromator, and a \( \sim 99\% \) reflective Labsphere Spectralon coated diffusing, reflectance standard were used to create monochromatic radiances for viewing by the camera as shown in Figure 2.

Pictures were taken at many integration times, from about one millisecond to many seconds to cover a full range of exposures from below the camera’s threshold to above saturation for each wavelength. Spectral radiances of about 0.1 to 1 \( \mu \text{W/cm}^2\text{-sr-nm} \) were used for the relative spectral sensitivity calibration.

An Ocean Optics USB2000 spectrometer was used to measure the irradiance of the reflectance standard, from which the radiance seen by the camera was calculated using known properties of the standard. These experiments were conducted with monochromatic beams at every 50 nm from 450 nm to 950 nm of about 1 to 50 \( \mu \text{W/cm}^2\text{-sr} \). The shape of these response curves was observed to be the same for each channel and all wavelengths.

This measured camera response is best approximated by a logistic dose response function, selected from a set of functions that best model the response of digital cameras.\(^{20}\) This function is the solid line in Figure 3 plotted against all data points.

The logistic dose response curve for the camera was found to be:

\[
\text{NDL}_{R,G,B} = a + \frac{b}{1 + (h(\lambda)/h_{R,G,B}^{0.3}(\lambda))/c)^d}
\]  

with \( a = -0.13254, \ b = 363.51, \ c = 1.4468e7 \) and \( d = -0.40717 \). Equation (4) can be inverted and solved for the monochromatic radiance viewed by the camera to give the equation:

\[
L_e(\lambda) = \frac{h_{R,G,B}^{0.3}(\lambda)}{t_{\text{int}}} \times c \left( \frac{b}{(\text{NDL}_{R,G,B} - a) - 1} \right)^{1/d}
\]  

\[(5)\]
3.2 Spectral sensitivity

The spectral sensitivity properties of the camera are contained in the wavelength dependent normalization factor, $h_{0}^{0.3}(\lambda)$, for each channel. A 5 nm wavelength resolution in the spectral sensitivity is desired to achieve accurate measurements of spectra as explained in (ASTM 2001).21

The normalization spectral exposures $h_{0}^{0.3}(\lambda)$ were determined as follows. Images of monochromatic radiances were taken at the same integration time for each wavelength. The Ocean Optics spectrometer was used to measure the spectral irradiance of the reflectance standard. The monochromatic radiance viewed by the camera was calculated based on the measured irradiance and the reflectance standard’s spectral reflection coefficients.

Through the inverted logistic dose response function given by Equation (5), the normalized spectral exposures, $h_{0}^{0.3}(\lambda)$, were calculated from the real digital output of the camera, the normalization digital level, NDL = 0.3, and the measured spectral exposure, or radiance multiplied by integration time. This relation is given by:

$$\frac{h_{0}^{0.3}(\lambda)}{h_{\text{Measured}}(\lambda)} = \frac{c((b/(0.3 - a)) - 1)^{1/d}}{c(b/((\text{NDL}_{R,G,B,\text{Measured}}) - a) - 1)^{1/d}}$$

(6)

where all quantities are known except $h_{0}^{0.3}(\lambda)$. The inverse of these normalized spectral exposures gives the absolute spectral responsivity (ASR) of each channel.22 The ASR can be written $r_{R,G,B}(\lambda) = 1/h_{R,G,B}^{0.3}(\lambda)$, where the subscripts denote a different ASR for each channel. It has the units of digital output per unit energy per unit area per solid unit of angle, or NDL/(μJ/cm²–sr).

An integrating sphere was used to more accurately measure irradiance, as shown in Figure 2, from which radiance was calculated to scale the relative sensitivity of each channel to the correct magnitude. The relative sensitivity of each channel was positioned relative to the integrating sphere measurements such that the sum of the square of the differences between the scaled ASRs and the integrating sphere data points was minimized.

The result of this spectral sensitivity calibration is an ASR curve for the R, G and B channels given by $r_{R,G,B}(\lambda) = 1/h_{R,G,B}^{0.3}(\lambda)$ over 5 nm wavelength intervals, rewritten in discrete form as $r_{R,G,B,\Delta \lambda} = 1/h_{R,G,B,\Delta \lambda}^{0.3}$, spanning 380 to 945 nm as shown in Figure 4. A similar characteristic response and spectral sensitivity was also measured for the InGaAs camera, as shown in Figure 5, and the same analytical methods apply although they are not discussed in detail here.

3.3 Response to polychromatic radiation

Theoretically, the digital output of the camera stimulated by polychromatic radiation
should be related to the total, not spectral, exposure of its sensor array as explained in (Brown et al). The total exposure of a pixel is given by the integral of its spectral exposures weighted by that channel’s ASR, \( r_{R,G,B,\Delta\lambda} = 1/h^{0.3}_{R,G,B,\Delta\lambda} \). The digital output of the channel is a function of this total exposure, given by:

\[
NDL_{R,G,B} = f\left( \sum_{380-945} r_{R,G,B,\Delta\lambda} L_{e,\Delta\lambda} t_{\text{int}} \right) \quad (7)
\]

where the exposure has been written in terms of radiance and integration time and the result is in discrete form. \( L_{e,\Delta\lambda} \) is the total radiance over a wavelength interval \( \Delta\lambda \) and the sum occurs over all wavelength intervals to which the camera is sensitive. If the total radiance of the beam across the range to which the camera is sensitive is given by:

\[
L_{e,\text{beam},380-945} = \sum_{380-945} p_{\Delta\lambda} L_{e,\text{beam},380-945} \quad (8)
\]

where \( p_{\Delta\lambda} \) is the fraction of the total radiance from 380 to 945 nm in a wavelength

Figure 4 Absolute spectral responsivity curves for R, G and B channels scaled to integrating sphere calibration points

Figure 5 Absolute spectral responsivity of the InGaAs camera
interval $\Delta \lambda$, then Equation (8) can be re-written in as:

$$\text{NDL}_{R,G,B} = f\left( \frac{L_e, \text{beam}, 380-945 t_{\text{int}}}{\sum_{380-945} r_{R,G,B, \Delta \lambda} \Delta \lambda} \right)$$

(9)

Thus, the absolute responsivity of the camera to a polychromatic beam is simply a weighted sum of the ASRs where the weights are determined by the relative spectra of the beam, given by $p_{\Delta \lambda}$, across the wavelength interval over which the camera is sensitive. Because the non-linear response of the camera has the same shape for all channels and all wavelengths, the function relating NDL and radiance for a polychromatic beam is the same as that for a monochromatic beam, shown in Equation (4). This suggests that the functional form of Equation (9) is given by:

$$\text{NDL}_{R,G,B} = a + \frac{b}{1 + \left( \frac{L_e, \text{beam}, 380-945 t_{\text{int}}}{h_{R,G,B, \text{beam}} / c} \right)^d}$$

(10)

which has the same form as Equation (4) except that the absolute spectral responsivity has been replaced by a polychromatic responsivity given by the weighted sum of absolute spectral responsivities, or:

$$\frac{1}{h_{R,G,B, \text{beam}}^{0.3}} = \sum_{380-945} \frac{p_{\Delta \lambda}}{h_{R,G,B, \Delta \lambda}^{0.3}}$$

(11)

This can be thought of as the total (not spectral) absolute responsivity of each channel to a polychromatic beam with the relative spectrum given by $p_{\Delta \lambda}$.

The final equation relating the camera’s digital output for polychromatic radiation to the total radiance in that beam is given by:

$$L_e, \text{beam}, 380-945 = \frac{h_{R,G,B, \text{beam}}^{0.3}}{t_{\text{int}}} \times c \left( \frac{b}{(\text{NDL}_{R,G,B} - a)} - 1 \right)^{1/d}$$

(12)

where the absolute responsivity of R, G and B to the beam, $1/h_{R,G,B, \text{beam}}^{0.3}$, is given by Equation (11).

Experiments confirm that this relation holds. The digital response of the camera to polychromatic beams with known radiances was measured using the experimental setup shown in Figure 6. First, a polychromatic beam made up of two monochromatic beams...
was imaged. Two monochromatic sources irradiated the Labsphere reflectance standard simultaneously and separately. The spectral irradiance of the standard was measured for each scenario, from which radiance was calculated. The result for the B channel, mixing a 500 and 550 nm beam, is shown in Figure 7. The measured points and predicted response curves are shown to match closely, typically better than 5% across the range of the camera’s response. The polychromatic response function also holds for more typical polychromatic beams, such as a tungsten halogen lamp filtered with a 695 nm longpass filter, as shown in Figure 8.

3.4 Measuring radiance of spectra altered by spectrally selective fenestrations

In order to use the known polychromatic response of the camera to assess the radiance distribution emerging from spectrally selective fenestration samples it is necessary to filter radiation into sub-intervals over

![Figure 7](image-url)  
**Figure 7** Two beam polychromatic experiment: predicted exposures (Pred) from B channel compared to measured exposures (Meas) for two separate beams (500, 550 nm) and a polychromatic beam (Comb)

![Figure 8](image-url)  
**Figure 8** General polychromatic response: camera response to tungsten-halogen lamp with 695 nm long pass filter
which accuracy can be maintained in radiance estimation. Ignoring speed and operability issues, the simple solution is to filter the spectrum into near monochromatic beams for which the relationship between digital response and radiance is well known. However, this is impractical.

A different method has been developed to accurately measure the net radiometric or photometric transmission or reflection across wavelength intervals of interest, divided into segments of the visible and NIR. This is done by choosing filters which span wavelengths over which the camera’s sensitivity is reasonably constant, and alterations in observed spectra result in acceptable radiance estimation errors.

Simulations of the camera’s predicted radiance for unknown spectra filtered to span finite wavelength intervals were performed using a wide variety of color filters. The total radiance across each wavelength interval calculated from the simulated digital output was compared to the true radiance across the interval. Simulations were performed with all possible combinations of Schott short, long and band pass filters listed in the Schott Glass Filter Catalog. Schott Color Glass Filters were chosen because they provided affordable filters with reasonably sharp transitions from absorption to transmission over appropriate intervals.

The filter combinations that led to the best predicted radiance and luminance from the camera across each interval for a range of expected fenestration samples was chosen for use with the CCD camera. The optimal filters are shown in Table 1. The filtered spectrum of the HMI lamp used to simulate solar radiation is shown in Figure 9. These filters span larger wavelength intervals where either the R, G, or B channel have gradually changing ASR and span smaller wavelength intervals where the channel ASR have greater slopes. There are also more filters for wavelengths at which the photopic response curve has the greatest slope to achieve greater accuracy in luminance measurements.

To quantify the accuracy of radiance measurement, the spectrum viewed by the camera for each filter set was altered systematically by assuming a fenestration sample with linearly increasing or decreasing spectral transmission or reflection coefficients. As shown in Figure 10 for filter set 3, the method was tested using spectral coefficients that systematically varied by a defined percentage over a defined wavelength interval.

The errors introduced by using the camera to estimate the radiance of unknown spectra for each filter set were calculated. Note that some knowledge of the spectrum is assumed, that is, the spectrum viewed by the camera is assumed to be altered from an expected spectrum (the filtered HMI spectrum). Each channel’s responsivity to the expected spectrum, given by Equations (11) and (12), is used to calculate radiance. The error between the radiance calculated using this responsivity was compared to the true radiance of the altered spectrum.

The error analysis provides limits on how much a spectrum can be altered from the expected spectrum within each wavelength interval such that the camera can still measure radiance or luminance accurately. As shown in Table 2, alterations to the spectrum were defined that introduce errors in radiance estimation by no more than about 13%. Errors in luminance estimation were introduced to maintain accuracy of 10% in the

<table>
<thead>
<tr>
<th>Table 1 Filter Specifications</th>
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</thead>
<tbody>
<tr>
<td>Wavelength interval</td>
</tr>
<tr>
<td>1) 380–500 nm</td>
</tr>
<tr>
<td>2) 450–590 nm</td>
</tr>
<tr>
<td>3) 480–590 nm</td>
</tr>
<tr>
<td>4) 500–650 nm</td>
</tr>
<tr>
<td>5) 550–640 nm</td>
</tr>
<tr>
<td>6) 570–690 nm</td>
</tr>
<tr>
<td>7) 650–850 nm</td>
</tr>
<tr>
<td>8) 800–945 nm</td>
</tr>
</tbody>
</table>

Lighting Res. Technol. 2009; 41: 7–25
dominant regions of the photopic curve, and no more than 25% for less sensitive regions, such as the deep blue and red.

Table 2 shows the maximum allowable HMI spectrum alterations, and thus constraints on fenestration sample spectral transmission or reflection properties, by the magnitude of the change in spectral properties (Percent change in R or T) over a wavelength interval (Variation interval). These are the worst errors introduced by such a variation, meaning that the slope of the alteration and the position of the change are those which cause the most error. Any variations over larger intervals, for smaller changes to the spectrum, for the same change positioned across any other wavelengths within the interval, or for a change that slopes in the other direction, will lead to less error.

3.5 Camera calibration error

The errors due to the spectroradiometric calibration of the camera and its ability to measure filtered spectra accurately were measured experimentally. First, the ASR curves of the R, G and B channels were shifted slightly

![Figure 9](image-url) Unfiltered HMI lamp spectrum and the filtered HMI lamp spectra for each of the eight filter combinations listed in Table 1.

**Table 2** Constraints on spectral transmission and reflection coefficients within filter wavelength intervals

<table>
<thead>
<tr>
<th>Parameter/filter set</th>
<th>F1</th>
<th>F2</th>
<th>F3</th>
<th>F4</th>
<th>F5</th>
<th>F6</th>
<th>F7</th>
<th>F8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filter start wavelength (nm)</td>
<td>380</td>
<td>450</td>
<td>480</td>
<td>500</td>
<td>550</td>
<td>570</td>
<td>650</td>
<td>800</td>
</tr>
<tr>
<td>Filter end wavelength (nm)</td>
<td>500</td>
<td>590</td>
<td>590</td>
<td>650</td>
<td>640</td>
<td>690</td>
<td>850</td>
<td>945</td>
</tr>
<tr>
<td>Variation interval (nm)</td>
<td>50</td>
<td>100</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Percent change in R or T</td>
<td>35</td>
<td>30</td>
<td>50</td>
<td>35</td>
<td>30</td>
<td>50</td>
<td>30</td>
<td>50</td>
</tr>
<tr>
<td>Max rad. error</td>
<td>10</td>
<td>9</td>
<td>9</td>
<td>13</td>
<td>13</td>
<td>6</td>
<td>5.5</td>
<td>13</td>
</tr>
<tr>
<td>Max lum. error</td>
<td>19</td>
<td>24</td>
<td>9</td>
<td>9</td>
<td>7</td>
<td>21</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>
from Figure 4 to minimize the error in the predicted radiance for the eight filter sets shown in Table 1. This small adjustment to the ASR curves is appropriate, as it enables absolute positioning of the ASR curves measured against known polychromatic spectra. This supplemented the initial method using monochromatic beams to position the ASR curves. The corrected ASR curves are shown in Figure 11.

The resulting errors in radiance estimation are shown in Figure 12. These are the average error over a set of validation experiments for the preferred channel within each filter set. That is, the R, G or B channel is selected as the preferred channel for radiance estimation for each filter set depending on the sensitivity of the channel in that interval. B is the preferred channel in filter sets one through three, G is the preferred channel in sets four, five and eight, and R is the preferred channel for sets six and seven. The average error due to the camera calibration for known spectra within each filter set is less than 5%.

4. Estimating BSDFs using radiance estimates of filtered radiation

The ultimate goal of the video-goniophotometer is to measure quasi-spectral BSDFs of

\[ \text{Relative spectrum and R/T coefficients} \]

\[
\begin{array}{llllllll}
\text{Wavelength (nm)} & 400 & 600 & 400 & 600 & 800 & 400 & 600 & 800 \\
\end{array}
\]

\[
\begin{array}{llllllll}
\text{Relative spectrum and R/T coefficients} & 0 & 0.2 & 0.4 & 0.6 & 0.8 & 0.2 & 0.4 & 0.6 \\
\end{array}
\]

\[
\begin{array}{llllllll}
\text{Wavelength (nm)} & 0 & 0.2 & 0.4 & 0.6 & 0.8 & 0 & 0.2 & 0.4 \\
\end{array}
\]

\[
\begin{array}{llllllll}
\text{Relative spectrum and R/T coefficients} & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
\end{array}
\]

\[
\begin{array}{llllllll}
\text{Wavelength (nm)} & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
\end{array}
\]

\[
\begin{array}{llllllll}
\text{Relative spectrum and R/T coefficients} & 0 & 0.2 & 0.4 & 0.6 & 0.8 & 0.2 & 0.4 & 0.6 \\
\end{array}
\]

\[
\begin{array}{llllllll}
\text{Wavelength (nm)} & 0 & 0.2 & 0.4 & 0.6 & 0.8 & 0 & 0.2 & 0.4 \\
\end{array}
\]

\[
\begin{array}{llllllll}
\text{Relative spectrum and R/T coefficients} & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
\end{array}
\]

\[
\begin{array}{llllllll}
\text{Wavelength (nm)} & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
\end{array}
\]

Figure 10 The effect of linearly varying hypothetical transmission coefficients, shifted across the filtered spectra, were studied to calculate the theoretical accuracy of using each filter set to estimate radiance and luminance across a given band.
fenestration samples. The camera calibrations described above, enable radiance estimation for light altered by spectrally selective fenestration samples to a reasonable level of accuracy. These radiance estimates can be achieved at every pixel location in the image, which correspond to angles of emergence from a fenestration system sample. Knowing the irradiance of the sample and the angle of incidence, quasi-spectral BSDFs can be calculated as defined in Equation (1) for each filter set. These quasi-spectral BSDFs represent the average reflection or transmission coefficient of the sample for all directions across a wavelength interval.

The spectral and total irradiation of the sample and the expected, relative spectral and total radiance emerging from a neutral sample can be calculated from measured properties of the hemi-ellipsoid and the spectrum of the HMI lamp. These are used to calculate an assumed absolute responsivity of the camera for each filter set, given by:

$$\frac{1}{\frac{1}{\lambda^3} R, G, B, \text{filterset}} \left( \frac{\phi_i, \theta_i, \phi_{(r)}, \theta_{(r)}}{\lambda^3} \right)$$

$$= \sum_{\text{filter interval}} \frac{a_{\Delta \lambda, \text{filterset}}(\theta_i, \phi_i, \theta_{(r)}, \phi_{(r)})}{\frac{1}{\lambda^3} R, G, B, \Delta \lambda} \quad (13)$$

**Figure 11** Corrected absolute spectral responsivity curves

**Figure 12** Average radiance estimation error for best channel among R, G and B
Where $a_{\Delta \lambda, \text{filterset}}(\theta_i, \phi_i, \theta_{i(r)}, \phi_{i(r)})$ is the relative spectrum of the light viewed by the camera for a given filter set. In general, $a_{\Delta \lambda, \text{filterset}}(\theta_i, \phi_i, \theta_{i(r)}, \phi_{i(r)})$, depends on the spectral transmission or reflection coefficients of the sample. As previously shown in Table 2, however, ignoring this dependence and assuming a neutral sample across the selected wavelength interval introduces acceptable errors in radiance estimation. This responsibility can then be used in Equation (12) to calculate the radiance in each direction emerging from the sample for each filter set.

Combining the BSDFs for each filter set across the 380 to 945 nm interval leads to step-like, or quasi-spectral transmission or reflection coefficients for each direction. A sample of these quasi-spectral BSDFs, in only one direction, for four different fenestration samples is shown in Figure 13. These are simulated results which include only errors caused by the radiance estimation method, but not camera calibration errors.

The total, radiometric BSDF across the 380 to 1700 nm interval, including the estimate from the NIR camera, can be calculated for a given light source from the quasi-spectral BSDF as follows:

$$
\text{BSDF}_{e, 380-1700}(\theta_i, \phi_i, \theta_{i(r)}, \phi_{i(r)}) = \sum_{\text{band}=1}^{9} \left[ \int_{\text{band}} E_{e, \text{source}}(\lambda) \cos(\theta_i) \, d\lambda \right] \times \int_{380}^{700} E_{e, \text{source}}(\lambda) \cos(\theta_i) \, d\lambda
$$

- $\text{BSDF}_{e, 380-1700}(\theta_i, \phi_i, \theta_{i(r)}, \phi_{i(r)})$ is the total radiometric BSDF of the sample across the 380 to 1700 nm interval,
- $E_{e, \text{source}}(\lambda)$ is the spectral exitance of the source,
- $\int_{380}^{700} E_{e, \text{source}}(\lambda) \cos(\theta_i) \, d\lambda$ is the total irradiance of the sample across the 380 to 1700 nm interval,
- $\text{BSDF}_{e, \Delta \lambda}(\theta_i, \phi_i, \theta_{i(r)}, \phi_{i(r)})$ is the radiometric BSDF across an interval $\Delta \lambda$ of the sample as given by Equation (1), and
- $\Sigma_{\text{band}=1}^{9} \left[ \int_{\text{band}} E_{e, \text{source}}(\theta_i, \phi_i, \lambda) \, d\lambda \right] \times \text{BSDF}_{e, \text{band}}(\theta_i, \phi_i, \theta_{i(r)}, \phi_{i(r)}) = L_e(\theta_i, \phi_i, \theta_{i(r)}, \phi_{i(r)})$ is the total radiance transmitted or reflected by the sample in direction $(\theta_{i(r)}, \phi_{i(r)})$ for angles of incidence $(\theta_i, \phi_i)$.

A total photometric BSDF can also be calculated similarly with the inclusion of the photopic response curve in Equation (14).

A variety of real fenestration materials from the Optics 5 database were simulated to verify the quasi-spectral BSDF estimation method over a range of spectral properties. They included coatings, applied films, monolithic substrates, and laminate combinations on clear and tinted glazings. Simulations were only performed across a 380 to 945 nm interval because the HMI spectrum in the NIR region is not yet known.

For each simulation, the errors in estimated radiance for each filter set, the estimated radiance across the 380 to 945 nm wavelength interval for unfiltered radiation, and estimated luminance for unfiltered radiation were calculated. The resulting quasi-spectral BSDF for four of the simulations, for only one direction, are shown in Figure 13. The calculated errors in estimated total radiance and luminance reflected or transmitted by the sample are shown in Table 3.

The errors in total radiance or luminance are typically less than 3% for most of the samples. The samples that show higher errors, such as the Heat Mirror Twin Coat and Solargard Royal Blue are special cases. The 7% error in estimated reflected luminance and 5% error in reflected radiance for the Heat Mirror Twin Coat arise mainly because the reflected luminance and radiance are so low. The 5% error in estimated reflected luminance
for the Solargard Royal Blue sample arises mainly because of the drastically changing spectral transmission coefficients across photometrically significant wavelength intervals.

5. Conclusions

This work presents new methods for measuring radiance, luminance, and quasi-spectral, bi-directional transmission and reflection properties of fenestration systems using digital cameras. The calibrated cameras combined with color filters create a novel way for measuring the radiance and luminance of radiation with unknown spectra. The camera calibration errors introduce on average 5% error to the radiance estimation when the preferred channel is used. The assumed responsivity of the camera when measuring unknown spectra introduces at most 13% error, in the worst case, for samples with spectral properties that vary significantly over the filter intervals.

The quasi-spectral BSDFs developed using these radiance and luminance estimates

Using digital cameras as quasi-spectral radiometers

Figure 13 Real and predicted spectral or quasi-spectral BSDF in one direction for simulated samples from Optics 5

Table 3 Total radiance (380–945 nm) and luminance errors for simulated samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>Total radiance error (%)</th>
<th>Total luminance error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SolarGard@SILVERAG25 LOW E</td>
<td>0.19</td>
<td>0.39</td>
</tr>
<tr>
<td>Panorama autumn bronze 30</td>
<td>1.52</td>
<td>0.31</td>
</tr>
<tr>
<td>Solis clear on clear</td>
<td>2.21</td>
<td>1.69</td>
</tr>
<tr>
<td>Pewter on clear</td>
<td>0.20</td>
<td>0.08</td>
</tr>
<tr>
<td>Heat mirror twin coat</td>
<td>4.98</td>
<td>6.94</td>
</tr>
<tr>
<td>Sea storm</td>
<td>2.06</td>
<td>0.18</td>
</tr>
<tr>
<td>Solargard royal blue</td>
<td>2.65</td>
<td>5.30</td>
</tr>
<tr>
<td>Armourglass greylight</td>
<td>0.78</td>
<td>2.52</td>
</tr>
<tr>
<td>Vanceva</td>
<td>1.10</td>
<td>0.11</td>
</tr>
<tr>
<td>Azurelite</td>
<td>2.52</td>
<td>0.31</td>
</tr>
</tbody>
</table>
recreate the gross spectral properties of fenestration samples, providing the average transmission or reflection coefficients over specified wavebands for each direction. The total radiometric or photometric BSDFs calculated from these quasi-spectral BSDFs have been shown to be accurate to within 5% for most typical samples, and often much lower, neglecting camera calibration errors.

Further work has shown that these methods can be used to estimate much more accurate spectral transmission and reflection coefficients of fenestration samples. This is achieved by creating a linear system, $Ax = b$, where the radiance measured by the camera for each filter set and channel make up the vector $b$, $A$ is a matrix determined by the source spectral exitance and spectral transmission and reflection coefficients of the hemi-ellipsoid, and $x$ is a vector of the unknown transmission or reflection coefficients of the fenestration sample. A set of solutions can be found for $x$ to estimate the spectral properties of the fenestration sample.

The quasi-spectral radiance estimation method using digital cameras could also be used to measure scene radiance or luminance. Spectral transmission or reflection coefficients of surfaces in a room or differences in relative spectra of sources viewed by the camera could be deduced from the digital output of the cameras.

**Acknowledgements**

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**References**


Discussion

Comment: A Laouadi (National Research Council of Canada, 1200 Montreal Road, Building M-24, Ottawa, Ontario, Canada, K1A 0R6)

The bi-directional spectral distribution functions (BSDF) of complex fenestration systems (CFS) are particularly needed for daylighting calculations, where surface point illuminance and visual detail of objects are of great importance, for thermal calculations to control solar heat gains, and for fenestration product ratings. However, measurement of CFS spectral characteristics using conventional scanning goniophotometers is a laborious and expensive process. A substantial amount of data (in the order of a million points) need to be measured to cover the incident and emerging hemispheres, spectral data points (300 nm to 2500 nm), and the number of the optical properties to be measured (front/back reflectance and transmittance). Therefore, any new measurement approach to minimise the conventional data collection process with sufficient accuracy is highly encouraged. The approach of this paper using video-projection and digital cameras as quasi-spectral radiometers is one step towards achieving this goal. Cameras can collect data from the full emerging hemisphere in one measurement shot. However, the proposed quasi-spectral measurement using colour filters is still limited to a certain wavelength range, covering only the visible and a small part of the NIR.
Finding filters and cameras to cover the remaining spectral ranges is also challenging. In addition, it would be beneficial if the authors could provide an indication of the overall uncertainty of the proposed approach, including camera errors and effect of the inter-reflected stray light in the dome, particularly for real spectrally/angularly-selective CFS products.

Another approach to reduce the conventional data collection process of CFS that I would like to propose for future research consideration stems from the fact that the BSDF may be decomposed into purely geometrical and optical functions, particularly for CFS products where their micro or macro-sopic geometries do not interfere with the source wavelengths. In other words, the monochromatic BSDF at different wavelengths have similar distributions, but are different only in magnitudes. In this regard, the BSDF may be scaled so that the resulting functions are independent, or weakly dependent of wavelength. By denoting $s_{BDF}$ for the scaled bi-directional distribution functions of a given optical property, the BSDF may be obtained using the following proposed relation:

$$BSDF(\theta, \varphi, \theta_i, \varphi_i, \lambda) = P(\theta_i, \varphi_i, \lambda) \cdot s_{BDF}(\theta, \varphi, \theta_i, \varphi_i)$$

where $P(\theta_i, \varphi_i, \lambda) = \sum_k BSDF_k \cdot \cos \theta \cdot \omega_k$, stands for a given spectral directional-hemispherical optical property to be measured (transmittance or reflectance), and $\Omega_k$ is an elemental solid angle subtended by the sample surface along the scattering direction $k$. The spectral optical property ($P$) can be obtained using the standard measurement approach of integrating spheres, and the scaled functions ($s_{BDF}$) can be obtained using a monochromatic or a non-spectral (broadband) measurement approach, without resorting to any colour filter.

**Reply to comment:**

N Gayeski, E Stokes and M Andersen

First, the authors would like to thank Dr Laouadi for his support of this research on spectral video-goniophotometers and for his insightful comments which present a clear and compelling description of the needs and the challenges in measuring spectral, bi-directional scattering distribution functions (BSDF). We agree with him that there is a need to extend the range of spectral BSDF measurement into the near infrared (NIR), and this has already been undertaken in this research. An Indium Gallium Arsenide (InGaAs) camera sensitive over the 900–1700 nm region has been calibrated using the same methods described in this article. The absolute spectral responsivity of the InGaAs camera turned out to be relatively constant, as shown in Figure 5. As a result, the camera can be used accurately without filters for samples that do not change significantly over the regions where the sensitivity varies. For improved accuracy, filters over the 900–1000 and 1600–1700 nm regions could be used.

The errors presented in this article include only errors in the spectro-radiometric calibration of the CCD camera (Figure 12) and methodological errors in estimating quasi-spectral BSDF (Table 3). A refined, spectral BSDF can also be estimated from the camera measurements using a method described in Stokes et al., resulting in greater accuracy. A characterisation of the total error for the device, including, for example, inter-reflections inside the dome has not yet been completed. This will be performed once all aspects of the video-goniophotometer are operational and tests can be performed using real fenestration samples and base cases, such as a perfectly diffusing sample or empty space.

Dr Laouadi’s recommendation to perform a separation of variables for wavelength $\lambda$ and emerging angles $\theta, \varphi$ to enable a faster measurement method is intriguing. However, it is
unclear how, a priori, it can be known whether a given fenestration system will have a spatial distribution of emerging light that is independent of wavelength. For prismatic panels for example, the magnitude and direction of transmitted radiation varies with wavelength and incident direction, which makes it impossible to simply use a scaling factor that is a function of wavelength. For glazings with a metallic coating this effect may be more pronounced. Before pursuing this direction of research, it would be useful to know the subset of fenestration systems to which this method might apply.

Reference