Measurement uncertainty for BRDF

Alejandro FERRERO
Instituto de Óptica, Consejo Superior de Investigaciones Científicas (CSIC), Spain
alejandro.ferrero@csic.es

Measurement uncertainty for BRDF

Realization of the BRDF scale

Procedure

A diffuse reflectance specimen is used to realize the 0º:45º reflectance standard.

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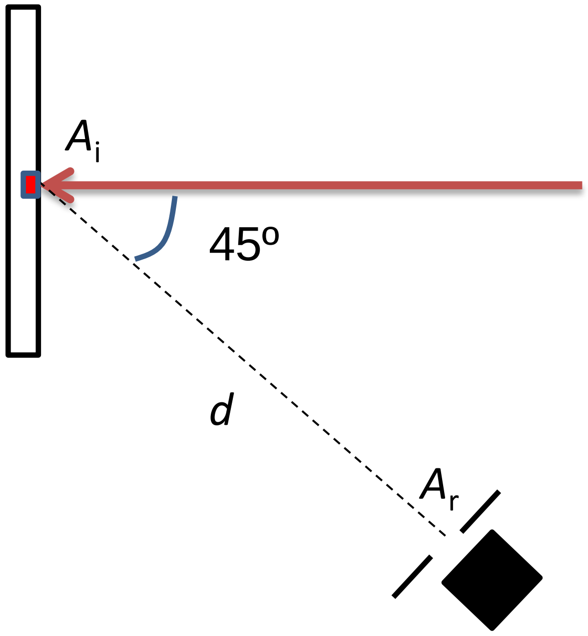

Evaluation of the reflected radiant flux:

The sample is irradiated with a directional beam at normal incidence (θ_i = 0º), and the reflected optical radiation is collected at 45º (θ_r = 45º), by a photodiode at a known distance, *d*, from the irradiated position on the surface, and with a precision aperture of area A_r, that needs to be larger than the irradiated area on the surface.

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Evaluation of the incident radiant flux:

At exactly the same illumination conditions, the sample is replaced by the photometer, and it is irradiated, with the incident flux under-illuminating the precision aperture.

A dark photodiode reading, $r_{i,0}$, is subtracted to the signal photodiode reading, $r_{i,s}$.

This procedure is repeated for the different wavelengths.

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Measurement equation

$$f_{\mathrm{r}}(\theta_{\mathrm{i}},\varphi_{\mathrm{i}};\theta_{\mathrm{r}},\varphi_{\mathrm{r}}) = \frac{\mathrm{d}L_{\mathrm{r}}(\theta_{\mathrm{i}},\varphi_{\mathrm{i}};\ \theta_{\mathrm{r}},\varphi_{\mathrm{r}};E_{\mathrm{i}})}{\mathrm{d}E_{\mathrm{i}}(\theta_{\mathrm{i}},\varphi_{\mathrm{i}})}$$

$$f_{\mathrm{r}}(\theta_{\mathrm{i}},\varphi_{\mathrm{i}};\theta_{\mathrm{r}},\varphi_{\mathrm{r}}) = \frac{\mathrm{d}\Phi_{\mathrm{r}}(\theta_{\mathrm{r}},\varphi_{\mathrm{r}})}{\mathrm{d}\Phi_{\mathrm{i}}(\theta_{\mathrm{i}},\varphi_{\mathrm{i}})\omega_{\mathrm{r}}\cos\theta_{\mathrm{r}}}$$

$$f_{0:45} = \frac{\left(r_{\mathrm{r,s}} - r_{\mathrm{r,0}} - \delta_{\mathrm{r,st}}\right)d^2}{\left(r_{\mathrm{i,s}} - r_{\mathrm{i,0}} - \delta_{\mathrm{i,st}}\right)A_{\mathrm{r}}\cos 45} \times C_{\Phi} \times C_{\mathrm{U}} \times C_{\mathrm{NL}} \times C_{\lambda} \times C_{\mathrm{P}} \times C_{\omega}$$

where the C-factors represent potential correction factors for the instability of the light source (C_{Φ}), the non-uniformity of the photodiode (C_{U}), the non-linearity of the photodiode (C_{NL}), the non-monochromaticity of the light source (C_{λ}), the polarization of the light source (C_{P}), and the non-directionality of the incident radiant flux (C_{ω}). The δ terms represent the part of stray light not included in the dark reading.

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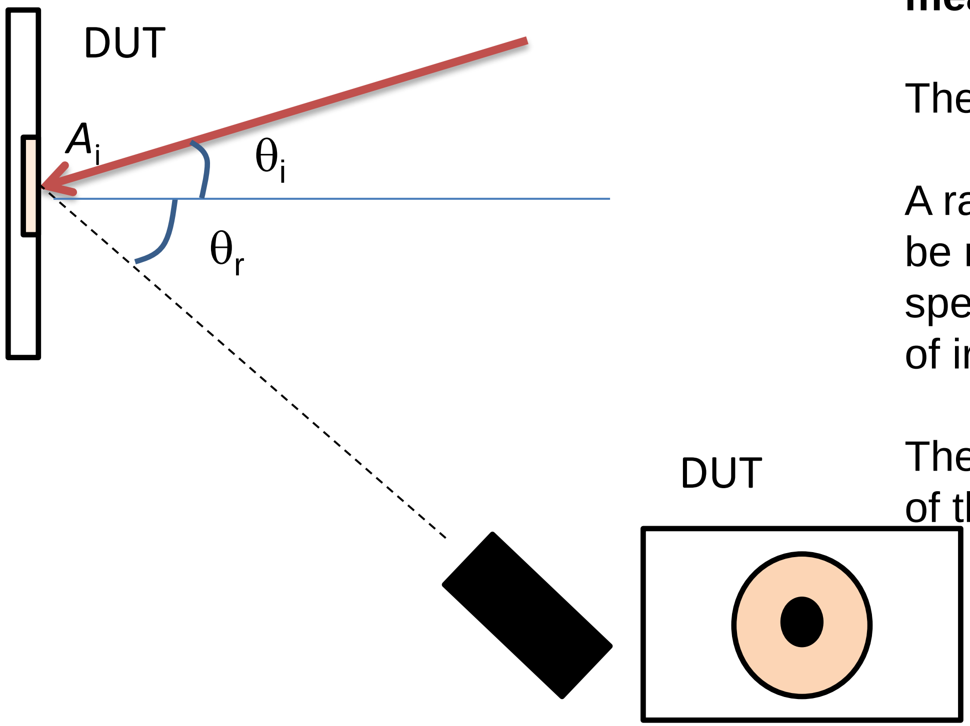
Procedure

The previously realized 0º:45º reflectance standard is used to provide traceability of the bidirectional reflectance at any other geometry, according to the following procedure.

Measurement uncertainty for BRDF

Full-BRDF measurement

Procedure



Evaluation of the radiance at different geometries on the sample to be measured:

The sample is irradiated with white light.

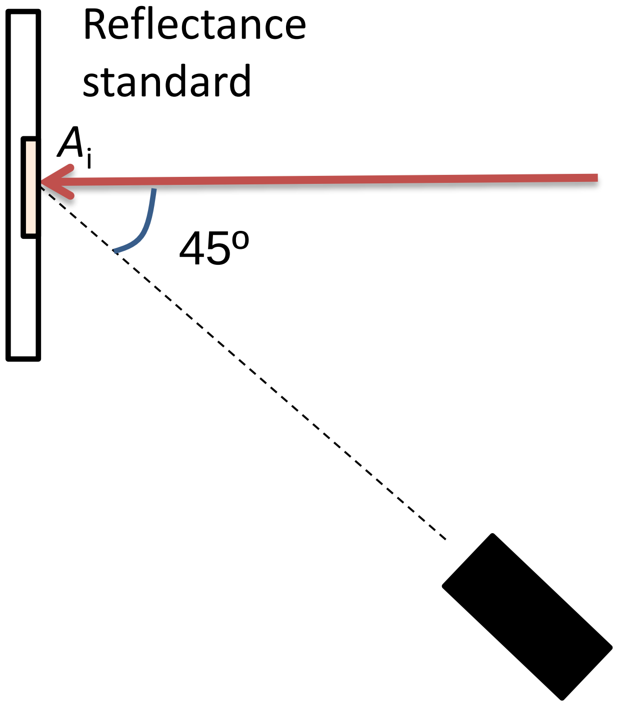
A radiance reading, L_{DUT} , from the sample to be measured is obtained by spectroradiometer at the different geometries of irradiation and collection.

The irradiated area overfills the field-of-view of the spectroradiometer.

Measurement uncertainty for BRDF

Full-BRDF measurement

Procedure



Evaluation of the radiance at 0º:45º on the 0º:45º reflectance standard:

A radiance reading, $L_{0:45,S}$, from the standard is obtained by a spectroradiometer at 0º:45º.

Measurement uncertainty for BRDF

Full-BRDF measurement

Measurement equation

$$f_{\mathrm{r}}(\theta_{\mathrm{i}},\varphi_{\mathrm{i}};\theta_{\mathrm{r}},\varphi_{\mathrm{r}})=\frac{\mathrm{d}L_{\mathrm{r}}(\theta_{\mathrm{i}},\varphi_{\mathrm{i}};\ \theta_{\mathrm{r}},\varphi_{\mathrm{r}};E_{\mathrm{i}})}{\mathrm{d}E_{\mathrm{i}}(\theta_{\mathrm{i}},\varphi_{\mathrm{i}})}$$

$$f_{\mathrm{r}}(\theta_{\mathrm{i}},\varphi_{\mathrm{i}};\theta_{\mathrm{r}},\varphi_{\mathrm{r}})=\frac{L_{\mathrm{r}}(\theta_{\mathrm{i}},\varphi_{\mathrm{i}};\ \theta_{\mathrm{r}},\varphi_{\mathrm{r}};E_{\mathrm{i}})}{L_{\mathrm{i}}(\theta_{\mathrm{i}},\varphi_{\mathrm{i}})\omega_{\mathrm{i}}\cos\theta_{\mathrm{i}}}$$

$$f_{0:45,\mathrm{S}}=\frac{L_{0:45,\mathrm{S}}}{\boxed{L_{\mathrm{i}}(\theta_{\mathrm{i}},\varphi_{\mathrm{i}})\omega_{\mathrm{i}}}}$$

$$\boxed{f_{\mathrm{r}}(\theta_{\mathrm{i}},\varphi_{\mathrm{i}};\theta_{\mathrm{r}},\varphi_{\mathrm{r}})=\frac{L_{\mathrm{DUT,rel}}(\theta_{\mathrm{r}},\varphi_{\mathrm{r}})f_{0:45,\mathrm{S}}}{L_{0,45,\mathrm{S,rel}}\cos\theta_{\mathrm{i}}}\times C_{\Phi}\times C_{\mathrm{U}}\times C_{\mathrm{NL}}\times C_{\lambda}\times C_{\mathrm{P}}\times C_{\omega}}$$

Measurement uncertainty for BRDF

Sources of uncertainty

Name of the quantity	**Symbol of the quantity / X_i**	**Better estimation of the quantity / x_i**	**Standard uncertainty / u(x_i)**	**Estimation type**	**Degrees of freedom**	**Sensitivity coefficient / c_i**
Reading of signal in reflection	$r_{r,s}$	Average	$\frac{s(r_{r,s})}{\sqrt{n}}$	A	n-1	$\frac{f_{0:45}}{r_{r,s} - r_{r,0} - \delta_{r,st}}$
Reading of dark in reflection	$r_{r,0}$	Average	$\frac{s(r_{r,0})}{\sqrt{n}}$	A	n-1	$\frac{-f_{0:45}}{r_{r,s} - r_{r,0} - \delta_{r,st}}$
Reading of signal in direct incidence	$r_{i,s}$	Average	$\frac{s(r_{i,s})}{\sqrt{n}}$	A	n-1	$\frac{-f_{0:45}}{r_{i,s} - r_{i,0} - \delta_{i,st}}$
Reading of dark in direct incidence	$r_{i,0}$	Average	$\frac{s(r_{i,0})}{\sqrt{n}}$	A	n-1	$\frac{f_{0:45}}{r_{i,s} - r_{i,0} - \delta_{i,st}}$

Measurement uncertainty for BRDF

Sources of uncertainty

Name of the quantity	Symbol of the quantity / X_i	Better estimation of the quantity / x_i	Standard uncertainty / u(x_i)	Estimation type	Degrees of freedom	Sensitivity coefficient / c_i
Stray light in reflection	$\delta_{r,st}$	Upper limit is estimated	$< 0.001\times r_{r,s}$	B	∞	$\frac{-f_{0:45}}{r_{i,s} - r_{i,0} - \delta_{i,st}}$
Stray light in direct incidence	$\delta_{i,st}$	Upper limit is estimated	$< 0.001\times r_{i,s}$	B	∞	$\frac{f_{0:45}}{r_{i,s} - r_{i,0} - \delta_{i,st}}$
Distance	d	Certificated value of end-to-end bar length standard, $d \pm U_d$	$U_d / 2$	B	∞	$\frac{2f_{0:45}}{d}$
Size of the precision aperture	A_r	Certificated value, $A_r \pm U_A$	$U_A / 2$	B	∞	$\frac{f_{0:45}}{A_r}$

Measurement uncertainty for BRDF

Sources of uncertainty

Name of the quantity	**Symbol of the quantity / X_i**	**Better estimation of the quantity / x_i**	**Standard uncertainty / u(x_i)**	**Estimation type**	**Degrees of freedom**	**Sensitivity coefficient / c_i**
Cosine of 45º	$cos\ 45$	Calculated from d and the size of the alignment spot, Δε	$\frac{\Delta\varepsilon}{2\sqrt{2}d}$	B	∞	$\frac{\sqrt{2}f_{0:45}}{2}$
Instability of the light source	C_{Φ}	Unity	Estimation OR Correction	B OR A	∞ OR n-1	$\frac{f_{0:45}}{C_{\Phi}}$

Measurement uncertainty for BRDF

Sources of uncertainty

Name of the magnitude	Symbol of the magnitude / X_i	Better estimation of the magnitude / x_i	Standard uncertainty / u(x_i)	Estimation type	Degrees of freedom	Sensitivity coefficient / c_i
Non-uniformity of the photodiode	C_U	Unity	$< 0.001 \times r_{i,s}$	B	∞	$\frac{f_{0:45}}{C_U}$

Measurement uncertainty for BRDF

Sources of uncertainty

Name of the quantity	Symbol of the quantity / X_i	Better estimation of the quantity / x_i	Standard uncertainty / $u(x_i)$	Estimation type	Degrees of freedom	Sensitivity coefficient / c_i
Non-linearity of the photodiode	C_{NL}	Ratio of the certificated values at the different scales of the picoammeter, U(s1) and U(s2)	$\frac{\sqrt{U^2(s1)+U^2(s2)}}{2}$	B	∞	$\frac{f_{0:45}}{C_{NL}}$

Measurement uncertainty for BRDF

Sources of uncertainty

Name of the quantity	**Symbol of the quantity /** X_i	**Better estimation of the quantity /** x_i	**Standard uncertainty /** $u(x_i)$	**Estimation type**	**Degrees of freedom**	**Sensitivity coefficient /** c_i
Non-monochromaticity of the light source	C_λ	Unity	$< 0.001\, f_{0:45}$	B	∞	$\frac{f_{0:45}}{C_\lambda}$

Measurement uncertainty for BRDF

Sources of uncertainty

Name of the quantity	**Symbol of the quantity / X_i**	**Better estimation of the quantity / x_i**	**Standard uncertainty / u(x_i)**	**Estimation type**	**Degrees of freedom**	**Sensitivity coefficient / c_i**
Polarization of the light source	C_P	Unity	$< 0.001\ f_{0:45}$	B	∞	$\frac{f_{0:45}}{C_p}$

Clarke F, Garforth F and Parry D 1983 Lighting Research & Technology 15 133–149.

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Sources of uncertainty

Name of the quantity	**Symbol of the quantity / X_i**	**Better estimation of the quantity / x_i**	**Standard uncertainty / u(x_i)**	**Estimation type**	**Degrees of freedom**	**Sensitivity coefficient / c_i**
Non-directionality of the incident radiant flux	C_ω	Unity	$< 0.001\, f_{0:45}$	B	∞	$\frac{f_{0:45}}{C_\omega}$

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Uncertainty in numbers

Name of the quantity	Symbol of the quantity / X_i	Estimation type	Degrees of freedom	Relative standard uncertainty
Net reading of signal in reflection	$r_{r,s} - r_{r,0}$	A	n-1	$\sim 3 \times 10^{-3}$
Net reading of signal in direct incidence	$r_{i,s} - r_{i,0}$	A	n-1	$\sim 1 \times 10^{-4}$
Stray light in reflection	$\delta_{r,st}$	B	∞	$\sim 4 \times 10^{-5}$
Stray light in direct incidence	$\delta_{i,st}$	B	∞	negligible
Distance	D	B	∞	$\sim 4 \times 10^{-4}$
Size of the precision aperture	A_r	B	∞	$\sim 5 \times 10^{-5}$
Cosine of 45º	cos 45	B	∞	$\sim 2 \times 10^{-3}$
Instability of the light source	C_{Φ}	A	n-1	$\sim 3 \times 10^{-3}$
Non-uniformity of the photodiode	C_U	B	∞	negligible
Non-linearity of the photodiode	C_{NL}	B	∞	$\sim 3 \times 10^{-4}$
Non-monochromaticity of the light source	C_{λ}	B	∞	$\sim 1 \times 10^{-5}$
Polarization of the light source	C_P	B	∞	$\sim 8 \times 10^{-4}$
Non-directionality of the incident radiant flux	C_{ω}	B	∞	negligible

Thanks for your attention