Advocating a statistical definition for the BRDF

Pierre Chavel[1], Mathieu Hébert[1], Lionel Simonot[2], Thomas Labardens[1,3], Ana-Maria Rabal-Almazor[3], and Gael Obein[3],

[1] Univ Lyon, UJM-Saint-Etienne, CNRS, Institut d Optique Graduate School, Laboratoire Hubert Curien 42023, SAINT-ETIENNE, France, [2]Université de Poitiers, Institut Pprime CNRS, Chasseneuil Futuroscope, France, [3]LNE-CNAM, La Plaine St Denis, France

Corresponding e-mail address: pierre.chavel@univ-st-etienne.fr

The definition of BRDF as ratio of radiance to irradiance assumes that the geometrical optics framework applies, implicitly meaning that spatial coherence and diffraction of light have no significant effect in the reflection process. However, when pushing the measurement to the limit of small solid angles for illumination and collection, these effects manifest themselves in the form of speckle, an optical phenomenon related to the stochastic nature of scattering objects. We suggest that BRDF should be defined as the statistical average of the former.

ABOUT THE CURRENT DEFINITION

From an optical point of view, there is an issue in the current definition of BRDF [1]. This quantity implicitly assumes spatially incoherent light, which prevents any interference. It also assumes that the limit of illumination of the surface from one single direction, therefore by a plane wave with a zero solid angle, can be reached. But that is precisely the case of maximal spatial coherence, prone to interferences that will occur after scattering by the sample. Similarly, geometrical optics is assumed valid on the light collection side, ignoring diffraction by the sample. But a minimal collection solid angle corresponds to the most visible diffraction effects, which are however intrinsic to the phenomenon of scattering by small random fluctuations in the surface shape (roughness) and manifest themselves as speckle. Therefore, speckle effects [2] are ignored by that definition, while they are in fact maximized in the limit of the narrowest possible solid angles on the illumination and/or collection side.

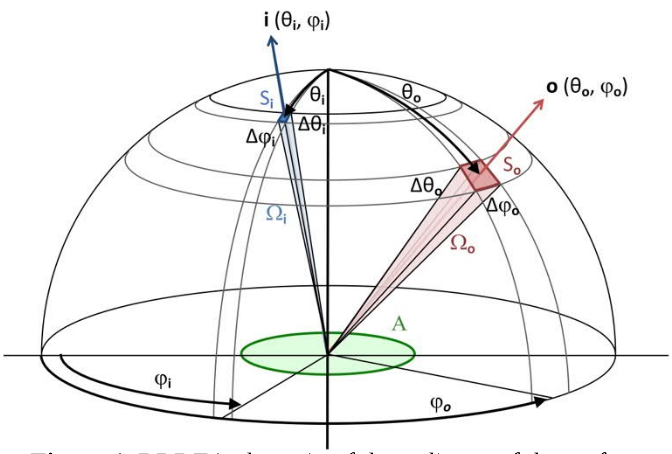

Figure 1. BRDF is the ratio of the radiance of the surface element in a given direction to the irradiance on the sample produced by directional incident radiation. It assumes that the divergence of the incident beam and solid angle of collection both tend to zero.

THE IMPACT OF COHERENCE

Actually, until recently, the question of coherence was not an issue for BRDF measurement since most devices had a solid angle $\Omega_\mathbf{i}$ large enough that coherence effects were not observable. Similarly, the rather large collection solid angle $\Omega_\mathbf{o}$ did not allow to resolve any speckle pattern, but instead averaged the radiance and blurred speckle grains. However, recently, high-resolution BRDF measurement devices have considerably increased the directionality of the incident beam as well as the achievable angular resolution at collection [3]. Consequently, speckle is clearly visible in the measurements (Figure 2).

Notice in addition that speckle patterns depend on wavelength of light. The most contrasted patterns are observed with monochromatic radiations. Some researchers have observed residual speckle in laser-based BRDF measurements [4] and have proposed experimental solutions to reduce it. In case of white light or broad spectral bands, the speckle patterns produced by each wavelength add to each other on an incoherent basis (flux collected). If the detection is not spectrally resolved, the contrast of the speckle patterns decreases or may even disappear, at least far from the specular direction. In the case of ConDOR, however, even though the incident light has V(λ) spectrum, the observed speckle has a rather high contrast due to the small solid angles. Because diffraction patterns scale linearly with wavelength and with deviation angle, the speckle blur due to spectral width increases with the angle between the direction of observation **o** and the specular direction.

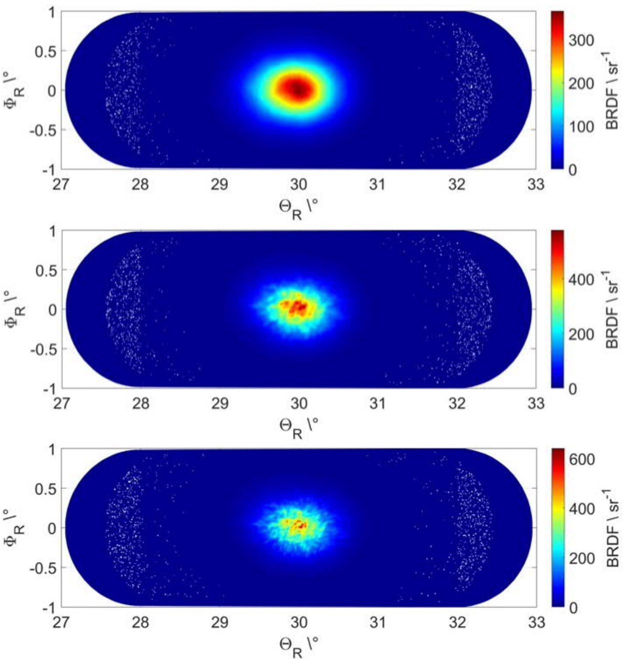

Figure 2. BRDF of a high gloss black sample extracted from NCS gloss scale ($gloss_{60°}$ = 95 GU) around the specular direction. Illumination $\theta_I = 30°$, $\varphi_I = 180°$, V(λ) spectral range. Angular resolution is 0.315° (top), 0.057° (middle), 0.029° (bottom). Speckle appears when resolution decreases.

Conversely, residual speckle is most conspicuous close to the specular direction.

Enforcing a definition for BRDF that assumes incident light source to be perfectly spatially incoherent, i.e., in which coherence of light is not a parameter (in opposition to wavelength and polarization), would entail considering that speckle is not part of the measured BRDF but rather an experimental error (even though, in certain conditions, this error cannot be removed). To be convinced of this, one may consider a perfectly homogeneous scattering material with uniform appearance: Its BRDF should by definition be the same since the microstructure responsible for scattering is statistically uniform, whereas the speckle patterns varies strongly from one area to another due to the variations of local microstructure.

NEW DEFINITION PROPOSED

The purpose of this paper is not to enumerate practical methods to remove speckle effects but rather to propose a new definition for BRDF representative of the scattering properties of the material "as if" the incident beam was spatially incoherent. Following earlier work by Hoover and Gamiz [5], we suggest that that can be achieved by considering, at each wavelength λ and for given polarization states on both sides, the expected value of the radiance scattered by the sample over areas whose random structure is statistically similar but independent from each other, in practice over areas which do not overlap with each other:

$$f(\mathbf{i},\mathbf{o}) = \frac{\langle L(\mathbf{i},\mathbf{o})\rangle}{E(\mathbf{i})}$$

where f is the BRDF, L is the radiance in the direction **o** and E is the irradiance from direction **i**.

The BRDF measurement in each area includes a random fluctuation due to speckle, but the average of all measurements will discard these fluctuations whose expectation is zero. The number of measurements to be averaged depends on the solid angle of illumination: as a smaller solid angle induces a more contrasted speckle, the number of measured areas must be increased, which requires a larger sample. The manufacturers of measuring devices should explicitly state the way to obtain the mathematical expectation of the radiance according to the device's characteristics. If the incident solid angle is large enough to be considered as incoherent, one radiance measurement suffices. The new BRDF definition is then equivalent to the usual one. The user must just be aware of the limitation in terms of angular resolution.

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REFERENCES

[1] F. Nicodemus, J. Richmond, J. Hsia, I. Ginsberg, T. Limperis, Geometrical considerations and nomenclature for reflectance, US Dept. of Commerce, National Bureau of Standards., US Govt. Print. Off. (1977).

[2] J.W. Goodman, Speckle Phenomena in Optics: Theory and Applications, ISBN 0 974 7077-9-1, Roberts and Co, Publishers, Englewood (Co), 2007.

[3] G. Obein, S. Ouarets and G. Ged, “Evaluation of the shape of the specular peak for high glossy surfaces”, in Proceedings of the SPIE Proc. SPIE 9018, Measuring, Modeling, and Reproducing Material Appearance, 901805, SPIE, Bellingham, 2014.

[4] G.T. Georgiev and J.J. Butler "The effect of speckle on BRDF measurements", in Proc. SPIE 5882, Earth Observing Systems X, 588203, SPIE, Bellingham, 2005.

[5] B.G. Hoover and V.L. Gamiz, Coherence solution for bidirectional reflectance distributions of surfaces with wavelength-scale statistics, J. Opt. Soc. Am. A 23, 314-328, 2006.