



**HAL**  
open science

## Advocating a statistical definition for the BRDF

Pierre Chavel, Yvan R. P. Sortais, Thomas Labardens, Lionel Simonot, M Hébert, Gaël Obein

► **To cite this version:**

Pierre Chavel, Yvan R. P. Sortais, Thomas Labardens, Lionel Simonot, M Hébert, et al.. Advocating a statistical definition for the BRDF. *Journal of Physics: Conference Series*, 2022, 2149 (1), pp.012013. 10.1088/1742-6596/2149/1/012013 . hal-03620283v2

**HAL Id: hal-03620283**

**<https://hal.science/hal-03620283v2>**

Submitted on 28 Mar 2022

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License

PAPER • OPEN ACCESS

## Advocating a statistical definition for the BRDF

To cite this article: P Chavel *et al* 2022 *J. Phys.: Conf. Ser.* **2149** 012013

View the [article online](#) for updates and enhancements.

### You may also like

- [Initial studies of the directional reflectance changes in pressed and sintered PTFE diffusers following exposure to contamination and ionizing radiation](#)  
G T Georgiev, J J Butler, K J Thome et al.
- [Influence of BRDF on NDVI and biomass estimations of Alaska Arctic tundra](#)  
Marcel Buchhorn, Martha K Reynolds and Donald A Walker
- [Goniorefectometric properties of metal surfaces](#)  
P Jaanson, F Manoocheri, H Mäntynen et al.



The Electrochemical Society  
Advancing solid state & electrochemical science & technology

242nd ECS Meeting

Oct 9 – 13, 2022 • Atlanta, GA, US

Abstract submission deadline: **April 8, 2022**

Connect. Engage. Champion. Empower. Accelerate.

**MOVE SCIENCE FORWARD**



Submit your abstract



# Advocating a statistical definition for the BRDF

P Chavel<sup>1</sup>, Y Sortais<sup>2</sup>, T Labardens<sup>3</sup>, L Simonot<sup>4</sup>, M Hébert<sup>1</sup> and G. Obein<sup>3</sup>

<sup>1</sup> Univ Lyon, UJM-Saint-Etienne, CNRS, Institut d'Optique Graduate School, Laboratoire Hubert Curien UMR 5516, F-42023, SAINT-ETIENNE, France

<sup>2</sup> Université Paris-Saclay, Institut d'Optique Graduate School, CNRS, Laboratoire Charles Fabry, 91127 Palaiseau, France

<sup>3</sup> Conservatoire National des Arts et Métiers, EA 2367, La Plaine St Denis, France

<sup>4</sup> Université de Poitiers, Institut Pprime UPR CNRS 3346, Futuroscope Chasseneuil, France.

pierre.chavel@institutoptique.fr

**Abstract.** The definition of BRDF as a 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, recent applications of BRDF push at increasing the angular resolution and thus at reducing the solid angles for illumination and collection. Therefore speckle, an optical effect inherent to the stochastic nature of scattering objects, becomes apparent. We suggest that BRDF should be redefined as the statistical average over that effect.

## 1. Introduction

Quantitative measurement of visual appearance is an important subject of study because of its application in quality control of industrial products (paper [1], varnishes [2], metals [3]), in development of new visual effects (automotive [4], cosmetics [5], packaging [6]) and in rendering models for virtual reality (computer graphics[7], virtual prototyping [8]). One way to assess the appearance of a material is to measure the way it reflects and scatters light when illuminated from a given direction. This implies measuring the so-called Bidirectional Reflectance Distribution Function (BRDF), defined in 1977 as the ratio of a radiance by an irradiance [9].

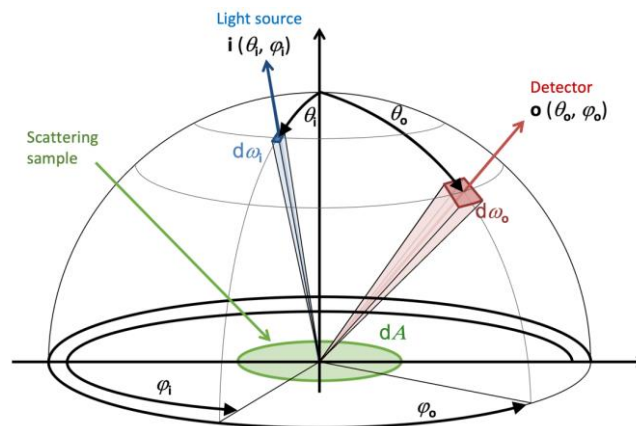
When a surface element  $dA$  of a scattering sample is illuminated with an irradiance  $dE_i$  by an input beam with an elementary solid angle  $d\omega_i$  around an incidence direction of unit vector  $\mathbf{i}$ , it scatters light in the hemisphere (see Fig. 1). Its radiance  $dL_{io}$  is measured in an elementary solid angle  $d\omega_o$  around an outgoing direction of unit vector  $\mathbf{o}$ . Following [9], and for specified wavelength and polarization, the BRDF of surface element  $dA$  is currently defined as

$$BRDF(\mathbf{i}, \mathbf{o}) = dL_{io}/dE_i. \quad (1)$$

In order to support industry in its quality control on visual effects, manufacturers are developing a new generation of instruments capable to assess the BRDF. To characterize pearlescent or goniochromatic coatings, fine spectral resolution is required [10]. To characterize gloss [11] or sparkle [12], high angular resolution is required.

To appropriately answer the demand for calibration of these new instruments, national metrological institutes have developed new reference goniospectrophotometers with either high spectral resolution [13][14][15] or high angular resolution [16], all equipped with detection systems allowing to accurately assess reliable and traceable BRDF values.





**Figure 1.** Notation used for the description of the BRDF: illumination is done along direction  $\mathbf{i}$ , observation along direction  $\mathbf{o}$ . The measured area is called  $dA$ .

But reducing the spectral bandwidth or the angular resolution to extremely low values leads at some point to facing coherence effects with the apparition of speckle, which modulates the BRDF with a random graininess [17][18][19]. In this manuscript, we address spatial coherence issues, and therefore high angular resolution. Spectral effects play a similar but different role when high spectral resolution is sought, an issue that will not be considered here.

One can then ask the following question: “what is being measured here?” As a matter of fact, the BRDF is supposed to be a radiometric quantity that is a characteristic of the material. But in these extreme measurement situations, coherence induces additional physical effects in the BRDF measurement process, which are not due to the material as such but come from the nature of light propagation in the presence of the randomness of the specific sample being measured. From a radiometric point of view, that last part should not be part of the BRDF and should be removed.

Following earlier work [19] [20], we propose in this article to recover the BRDF by averaging out the speckle effect with no compromise on the angular resolution. This leads us to propose a new definition of the BRDF, representative of the scattering properties of the material without perturbation by the specific sample area currently being illuminated, as is the case in the standard situation of spatially incoherent illumination.

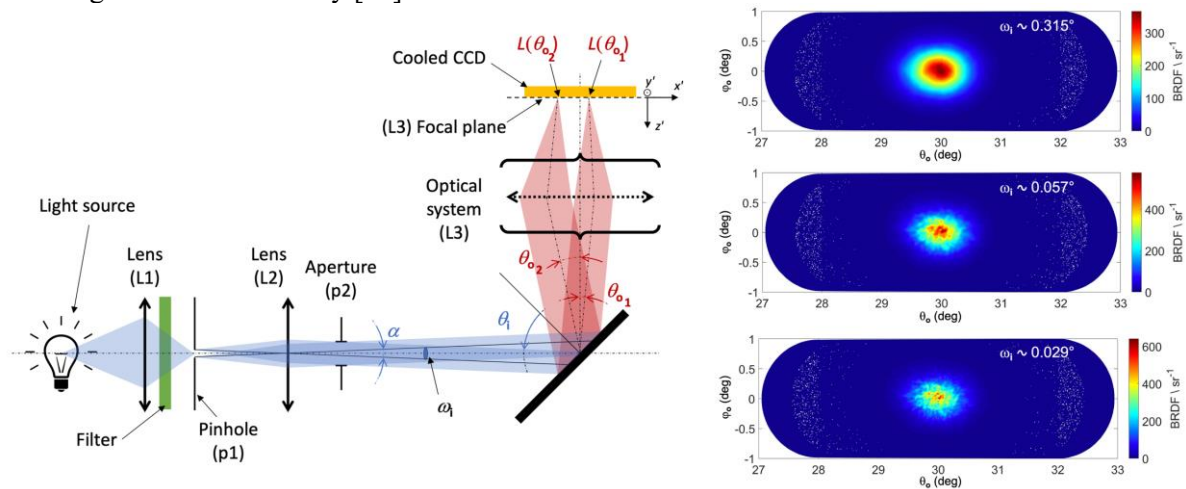
The paper is organized as follows: firstly, we recall the origin of speckle and show experimental evidence of its appearance when the light source becomes spatially coherent. Secondly, we show how speckle averages out when accumulating BRDF measurements performed on uncorrelated areas of the same sample, as is also illustrated by simulations. We conclude by proposing a new definition for the BRDF.

## 2. Speckle and coherence

Speckle appears as the result of a multiple source interference between the many wavelets scattered by a rough surface [21]. When the surface is illuminated by a polarized, spatially, and temporally coherent source, the height variations associated with surface roughness translate into a phase roughness, which maps onto the fields scattered in a given direction. The interference between the scattered fields leads to bright grains in directions where the interference is (at least in part) constructive, separated by dark worm-like areas in directions where the interference is destructive.

Until recently, the question of spatial coherence was not an issue for BRDF measurement since most devices had a solid angle  $d\omega_i$  large enough that coherence effects were not observable because speckle grains were smeared out by the accumulation of contributions from the different, mutually incoherent, source points. Similarly, the rather large collection solid angle  $d\omega_o$  did not resolve any speckle pattern, but instead averaged the radiance and blurred speckle grains. In high-resolution BRDF measurement devices such as ConDOR [16], the high directionality of the incident beam as well as the solid angle at

collection make speckle clearly visible in the measurements. Figure 2 shows the optical design of ConDOR and results obtained when measuring the BRDF of a glossy sample [23] illuminated under incidence  $\theta_i = 30^\circ$ : speckle appears as the input solid angle  $\omega_i$  is reduced [24]. This, of course, is possible because the solid angle on the collection side  $\omega_o$  is smaller than  $\omega_i$ . Here, it is the pixel size of the camera that defines  $\omega_o$ . It has an aperture angle of  $0.004^\circ$  that is about the angular size  $\lambda/\mathcal{D}_{p2}$  of a speckle grain with  $\lambda = 700$  nm and  $\mathcal{D}_{p2} = 10$  mm (see Fig. 2) for the diameter of aperture p2. Shorter wavelengths would lead to less contrasted granularity, as a given pixel would receive the information of several grains simultaneously [20].



**Figure 2.** Left: Optical design of ConDOR, a goniospectrophotometer with ultra-high angular resolution. The resolution is imposed by the divergence of the illumination beam, that is controlled by the diameter of the pinhole (p1) and can be adjusted from  $0,017^\circ$  to  $1^\circ$  [17]. Aperture (p2) defines the illumination beam diameter. The radiance along observations directions is measured with a Fourier optics based optical system combined with a cooled CCD [22]. Right: ConDOR BRDF measurements on a sample of NCS black gloss scale with the highest glossiness [23] for decreasing values of the angular resolution. Illumination with  $V(\lambda)$  photometrical spectrum.

### 3. Averaging out speckle

#### 3.1. Experiments

The speckle effect originates from the interplay between the coherence of the light source and the stochastic nature of the surface roughness. Assume a collimated wave with a given wavelength and polarization state impinges on a perfectly homogeneous scattering surface, i.e. the roughness of which is described by a stationary random process. Assume furthermore that the speckle grain size in the scattered light is well resolved. The observed speckle pattern is then maximally contrasted. Also, two non overlapping areas of the sample create statistically independent speckle fluctuations, while the global shape of the intensity distribution, which is the statistical average of the radiance, remains unchanged.

To illustrate this phenomenon, we operated ConDOR with a fully spatially coherent source. We replaced aperture (p1) with the exit face of a single-mode fibered laser at about  $\lambda = 635$  nm (Thorlabs item LPS-635-FC). The bandwidth  $\Delta\lambda$  is negligible in the present conditions. Also,  $\mathcal{D}_{p2}$  was set to 5 mm to ensure that the speckle grains are well resolved by the pixels of the CCD camera, whilst allowing enough flux to be detected in few ten seconds exposure time. With these settings, the angular resolution of the BRDF measurement is limited by the aperture diameter, i.e., neither the pixel size nor the pinhole. Table 1 summarizes the above-mentioned dimensions in angular units.

**Table 1.** Parameters contributing to the angular resolution of the ConDOR instrument.

Parameter	Angular resolution
CCD Pixel (24 $\mu$ m)	0.004 $^\circ$
Diffraction by (p2) ( $\mathcal{O}_{p2} = 5$ mm)	0.009 $^\circ$

<sup>a</sup> for BRDF measurements using a fully spatially coherent laser source at  $\lambda = 635$  nm. For comparison, the resolution of the human eye is on the order of 0.025 $^\circ$ .

The BRDF measurements reported here were done on the glossiest black sample of NCS gloss scale [23]. Illumination is along  $\mathbf{i}$  ( $\theta_i = 45^\circ$ ,  $\varphi_i = 180^\circ$ ). Results collected in and around the specular direction ( $\theta_o = 45^\circ$ ,  $\varphi_o = 0^\circ$ ) are presented on Figure 3 and confirm the theory. Illuminating a unique area of the sample leads to a BRDF measurement showing a well contrasted speckle pattern (see Fig3. (a) & (c)): large intensity fluctuations are observed, with peaks several times higher than the local average amplitude. Indeed, interference occurs between wavelets diffracted by many locations on the sample, creating multiple interferences with a random character. Also, the associated bright grains are separated from each other by areas where the intensity nearly vanishes. Shot-to-shot relative intensity fluctuations have been measured to about 4%, and are therefore negligible with respect to the observed pixel-to-pixel fluctuations: the latter are robust with respect to time-averaging by the detector [25]. We have studied elsewhere [20] the intensity statistics in one image and shown that they indeed correspond to the expected statistics of the speckle effect.

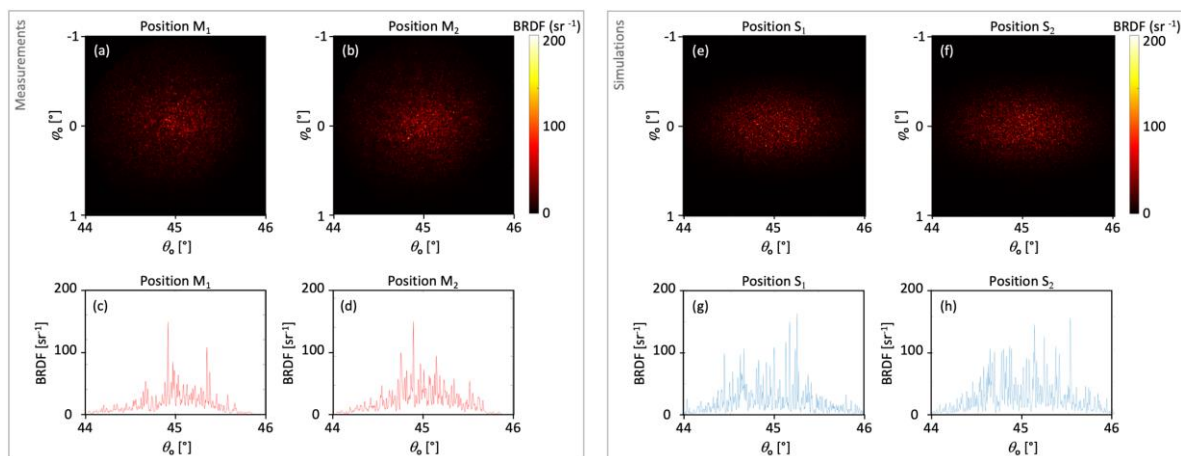


Figure 3. (a) & (b) BRDF measurements performed with ConDOR on two different non-overlapping areas of the same sample. (c) & (d) Cross-sections of the BRDF measurements shown in (a) and (b) along the plane of incidence ( $\varphi_o = 0^\circ$ ). (e) & (f) BRDF simulated with parameters similar to those of ConDOR. (g) & (h) Cross-sections of the BRDF simulated shown in (e) and (f) along the plane of incidence ( $\varphi_o = 0^\circ$ )

Illuminating a different, non overlapping area of the same sample (see Fig 3 (b) & (d)), yields globally to the same BRDF but the spatial distribution of the grains differs. The conservation of the general shape reflects the stationarity of the sample roughness. The variations of the grains reflect the roughness details from each particular illuminated area.

Following earlier work by Hoover and Gamiz [19], we repeated the experiment for 25 uncorrelated areas of the same sample. The data are shown on Fig 4 (a). Statistical average of the data, on each pixel, efficiently averages out the speckle-induced fluctuations, revealing the BRDF of the surface. Fluctuations remain, however, due to the limited number of non overlapping areas available on the sample. Illuminating smaller areas of the sample by decreasing the aperture (p2) diameter would of



course allow averaging over more areas, but at the expense of the angular resolution of the BRDF measurement due to the diffraction by (p2) which increases the speckle grain size.

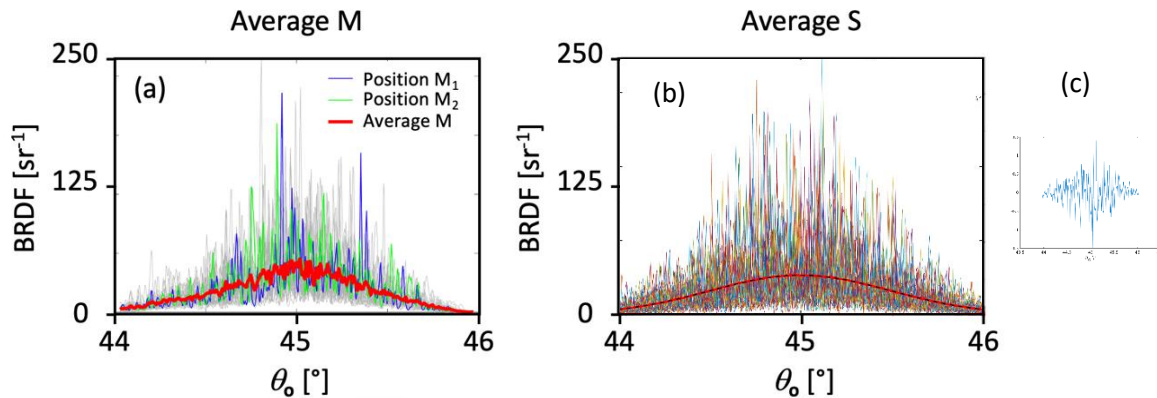


Figure 4. (a) Cross-section of BRDF measurements in the plane of incidence for 25 non-overlapping areas of NCS95 sample (only the region around the specular direction is shown). The average (red curve) exhibits reduced intensity fluctuations (b) Impact of statistical averaging on BRDF simulated with parameters like those of (a) The statistical average over 15 000 different realizations (red curve) is quite close to the mathematical expectation, here a Gaussian profile (dashed line, see Eqn (2)), as shown by the small residuals in (c), which is the difference between the red curve and the dashed line of (b).

### 3.2. Simulations

To further study the effect of statistical averaging whilst not compromising on the angular resolution, we performed simulations of the BRDF measurements as described in [20], using the same parameters as those used for the measurements by ConDOR (see section 3a). As in [20], the BRDF was empirically simulated as a Gaussian profile with the same root-mean-squared (rms) width as that measured by ConDOR:

$$BRDF(\theta_0, \theta_i, \varphi_0, \varphi_i, \lambda) \propto \exp\left(-\frac{x'^2}{2\sigma^2} - \frac{y'^2}{2(\sigma \cos \theta_i)^2}\right) \quad (2)$$

where  $\theta$  is the incidence angle,  $x'$  and  $y'$  are the Cartesian coordinates on the CCD sensor (see Fig. 2), referenced to the specular direction, and  $\sigma$  is the rms width of the BRDF Gaussian profile in the incidence plane.

The results are shown in Fig. 3 (e) – (h) at  $\lambda = 635$  nm and for  $\mathcal{D}p2 = 5$  mm. We have simulated 15000 BRDF measurements over uncorrelated areas of the sample. Speckle fluctuations observed on single realizations agree with experimental data. Statistical averaging of the 15 000 simulated images now reveals the BRDF accurately, as shown by the small residuals with respect to the expected Gaussian profile shown in Fig. 4(c). Fairly straightforwardly, when those 15 000 simulated images are grouped by sets of 25, resulting in 600 such sets, the signal to noise ratio is improved by a factor 5. The same cannot be done straightforwardly on the experimental data because the “real” shape of the BRDF is not known accurately. In the simulation, speckle is generated by Fourier filtering computer generated white noise with a prescribed spectral density obeying Eqn (2), therefore the BRDF is known [26].

## 4. Proposal for a new definition of the BRDF

The results presented above demonstrate that there is an issue in the current definition of the BRDF. Specifically, the current definition is self-contradictory if pushed to the limit of angular resolution on both input and output sides: on one hand, it implicitly assumes that the sample under test is illuminated by spatially incoherent light, which precludes any interference; on the other hand, 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, on the collection side, the current definition assumes geometrical optics to be valid, ignoring diffraction by the sample. But a minimal collection solid angle corresponds to the most visible diffraction effects, which are intrinsic to the phenomenon of scattering by small random fluctuations in the surface roughness and manifest themselves as speckle. Therefore, speckle effects are ignored by that definition, while they are in fact maximized in the limit of the narrowest possible solid angles on both the illumination and the collection sides.

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

We therefore propose a new definition for the BRDF that informs about the scattering properties of the surface "as if" the incident beam was spatially incoherent. Following the work reported in the previous section, we suggest defining the BRDF, for specified spectrum and polarization, as the expected value of the radiance scattered by the independent scattering samples from the same statistical ensemble:

$$\text{BRDF}(\mathbf{i}, \mathbf{o}) = \langle dL_{io} \rangle / dE_i, \quad (3)$$

where  $\langle \cdot \rangle$  stands for the mathematical expectation. In this way, the BRDF measurement in each area includes a random fluctuation due to speckle, but the average of all measurements will smooth those fluctuations away.

In practice, that may mean measuring non overlapping areas of the same sample, but always keeping the illuminated area large enough that diffraction by the illuminated aperture does not degrade resolution below the specific needs. The number of measurements to be averaged depends both on the incident solid angle and on the sensor angular resolution: as smaller solid angles induce a more contrasted speckle, with the special case of laser illumination corresponding to the minimal theoretical solid angle, 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 characteristics. If the incident solid angle is large enough to be considered as incoherent and nevertheless reach the desired resolution, one radiance measurement suffices. A similar comment applies to the resolution on the collection side. In such a case, the new BRDF definition is then equivalent to the usual one. The user must be aware of the limitation in terms of angular resolution on both sides and of the diffraction limit resulting from the sample size.

To summarize, the required angular resolution in BRDF acquisition sets upper limits to the illumination and collection solid angles. If high resolution is required, the coherent effects inherent to the stochastic character of scattering samples create speckle. Statistical averaging appears to be the only way to reach high accuracy in BRDF acquisition without compromising angular resolution on either side. The definition of the BRDF should reflect those physical facts.

### Acknowledgement

Initial results on speckle in the ConDOR instrument were obtained by Guillaume Ged. This research was partially funded by the EMPIR project 18SIB03 (BxDiff). The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States.



## References

- [1] Béland M C and Bennett J 2000 *Appl. Opt.* **39** 2719
- [2] Elias M de la Rie R Delaney J Charron E and Morales K 2006 *Optics Communications* **266** 586
- [3] Pitard G Le Goïc GMansouri A Favrelière H Pillet M George S and Hardeberg J 2017 *Lecture Notes in Computer Science* 10269
- [4] Đurikovič R and Mihálik A 2014 *Applied Surface Science* **312** 87
- [5] Boher P Leroux TCavé L Blain L Boulrier V 2014 *Proceedings of Pigment and color science forum (Montréal)*
- [6] Sole A Guarnera G Farup I and Nussbaum P 2021 *The Visual Computer* **37** 2207
- [7] Marschner S WWestin S Arbree A and Moon J 2005 *AM Trans. Graph* **24** 727
- [8] Rouiller OBickel BKautz JMatusik W and Alexa M 2013 *IEEE Comput. Graph. and Appl.* **33** 48
- [9] Nicodemus F ERichmond J CHsia J JGinsberg I W and Limperis T 1977 *Geometrical Considerations and Nomenclature for Reflectance* NBS Monogr No. 160, U.S. Department of Commerce, National Bureau of Standards
- [10] Strothkämper C Hauer K O and Höpe A 2016 *J. Opt. Soc. Am. A* **33** 2016
- [11] Obein G Audenaert J Ged G and Leloup F 2015 *Proc. SPIE* **9398** 0D
- [12] Ferrero A and Bayon S 2015 *Metrologia*, **52** 317
- [13] Höpe A Atamas T Hünerhoff D Teichert S and Hauer K O 2012 *Review of Scientific Instruments* **83** 045102
- [14] Rabal A M Ferrero A Campos J Fontecha J L Pons A Rubiño A M and Corróns A 2012 *Metrologia* **49** 213
- [15] Patrick H Zarobila C and Germer T 2013 *Proc. SPIE* **8866** 01
- [16] Obein G Ouarets S and Ged G 2014 *Proc. SPIE* **9018** 05
- [17] Ged G 2017 PhD dissertation, Conservatoire National des Arts et Métiers
- [18] Georgiev G Tand Butler JJ 2005 *Proc. SPIE* **5882** 03
- [19] Hoover B G and Gamiz V L 2006 *J. Opt. Soc. Am. A* **23**, 314
- [20] Labardens T Chavel P Sortais Y Hébert M Simonot L Rabal A and Obein G 2021 *IS&T Electronic Imaging Symposium, Material Appearance Conference (San Francisco)* 140
- [21] Goodman J W 2020 *Speckle Phenomena in Optics: Theory and Applications*, 2<sup>nd</sup> Ed SPIE Press
- [22] Leroux T 1999 *Proc. SPIE* **3636** 191
- [23] The sample used throughout this article is from Natural Color System®, black with a specular gloss at 60° of 95 GU assessed with a glossmeter; <https://ncscolour.com/product/ncs-gloss-scale/>
- [24] Rabal A M Ged G and Obein G 2019 *Proceedings of the 29th Quadriennial Session of CIE*, CIE x046
- [25] The measurement reported in Fig. 3a actually results from the average of 5 shots of the same illuminated area. The same is true for Fig. 3c, but for another area of the sample.
- [26] Duncan D and Kirkpatrick S J 2008 *Proc. SPIE* **6855** 05