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Study and simulations of speckle effects on BRDF measurements at very high angular resolution

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Abstract

Goniospectrophotometer ConDOR designed by CNAM, France, measures BRDF at very high angular resolution (0.014°), comparable to that of human vision. This is achieved using a very collimated light beam and a dedicated Fourier lens. Interestingly, the BRDF of glossy surfaces measured at this resolution exhibits a granular aspect around the specular direction, like a rapid angular fluctuation, which is not detection noise as it is repeatable between successive measurements on the same sample. Based on our experiments using ConDOR as well as numerical simulations, we claim that this granular aspect comes from an optical effect called speckle, which occurs every time a sufficiently coherent light beam – which is inevitably the case when the incident solid angle is very narrow – strikes a rough surface. First elements of confirmation are given in this paper.

1. Introduction

Quantitative measurement of visual appearance is currently a very popular subject of study because of its value in the industry. Material appearance measurement and simulations indeed have a direct impact on the automobile industry [1], as well as cosmetics, 3D printing [2], high-technology or virtual reality. 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) [3].

Recently, measurement techniques have been improved thanks to the development of goniospectrophotometers and imaging techniques. The LNE-CNAM laboratory has developed an instrument of this kind, ConDOR (Conoscopic Device for Optical Reflectometry) [4], that performs the best angular resolution for BRDF measurements ever achieved so far. It is composed of three main parts, featured in Fig. 1:

- the light source: in this study, a Quartz Tungsten Halogen (QTH) source of white light, filtered by an interference filter centered at 699 nm and with 20 nm bandwidth, going through a circular pinhole of 100 µm placed at the focal point of a collimating lens. This illumination is placed on a 360° rotating platform around the sample.
- the sample, which can be displaced and rotated in space in all directions using a robot arm.
- the detection system, also called the "conoscope". This device is equivalent to a Fourier lens [5] with focal length $f_c' = 344$ mm associated to a low-noise CCD camera (pixel size: 24 µm) that could allow to achieve the exceptional angular resolution of 0.004°. The admission angle of the conoscope is 2° but the BRDF can be explored over larger angular range by changing the relative orientation between the source, the sample, and the conoscope, and by stitching images.

Achieving such a resolution is of course a way to see what the human eye, with its typical resolution of $1' \sim 0.017°$, perceives. It also reveals other effects not perceived visually, namely strong intensity fluctuations superimposed within the specular peak of the BRDF [4,6]. The question we address in this article is the nature of these fluctuations. We show below that they originate in an interference effect, otherwise called speckle, associated to the spatial coherence of the source and the surface randomness of the illuminated sample. This effect was already mentioned in earlier BRDF studies [7]. Here, we compare quantitatively experimental data acquired with ConDOR and numerical data simulated with the same illumination parameters.

This paper is organized as follows: firstly, we report a repeatability study to evaluate the impact of noise of the system on the data, and show that it cannot explain the observed intensity fluctuations. Secondly, we report BRDF measurements performed with ConDOR at various aperture diameters. Finally, we compare these measurements with simulations accounting for speckle under the same aperture conditions.

2. Shot-to-shot intensity fluctuations versus pixel-to-pixel fluctuations in one image.

Access to the BRDF of a test sample implies that one integrates the reflected signal over a sufficient amount of time to average out fluctuations. Indeed, BRDF is defined as the ratio of mean quantities: the reflected radiance in a given direction (θ_i, φ_i) on one hand, and the irradiance incident from a given direction (θ_i, φ_i) on the test sample on the other hand [8,9]. To investigate the nature of the intensity fluctuations in one image of the reflected signal, we thus acquired 100 images with no change in the experimental conditions. The sample is from Natural Color System®, black with a specular gloss 60° assessed with a glossmeter of 95 GU [10]. It is illuminated under incidence angle $\theta_i = 45°$, through an aperture diaphragm with diameter $D = 6$ mm. Figure 2 shows a typical image, where huge pixel-to-pixel intensity fluctuations are observed, with an amplitude almost equal to the signal itself.

Analyzing 100 images acquired in identical conditions on the same sample, we compute for each pixel the standard deviation of the detected signal. Figure 3 shows that the standard deviation of the shot-to-shot relative fluctuations for a given pixel is mostly around 1-2%. This is two orders of magnitude below the pixel-to-pixel fluctuations observed in Fig. 2b, and is therefore a minor effect on the BRDF measurements by ConDOR. Also, the shot-to-shot fluctuations average out after accumulating many images, whereas the pixel-to-pixel fluctuations do not. This clearly hampers access to the BRDF with a good signal-to-noise ratio, and suggests revisiting the definition of the BRDF, as the ratio of both time and ensemble averaged quantities.

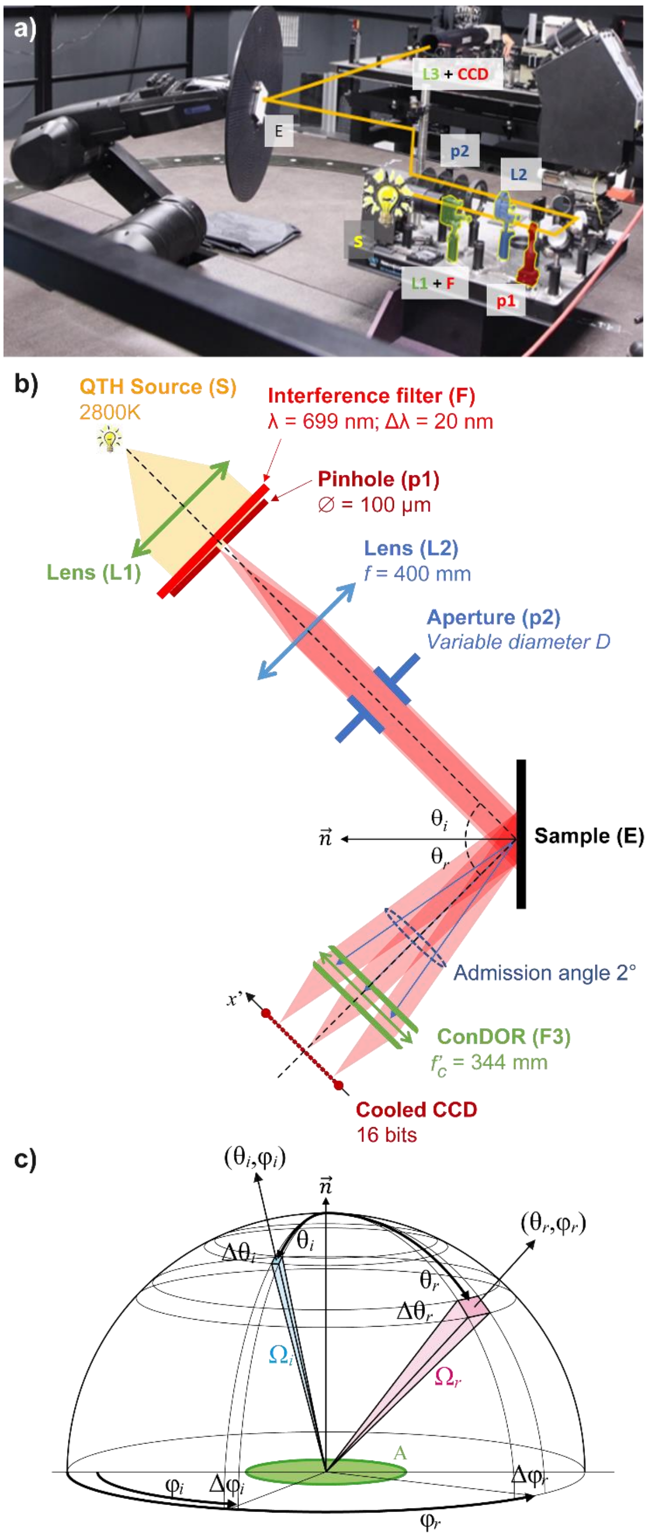

Figure 1. The goniospectrophotometer ConDOR – a) Photography showing the light source (S), the lens (L1) and spectral filter (F), the pinhole (p1), the collimating lens (L2) and the aperture (p2) with diameter D (adjustable in this article), the sample under test (E) with illuminated area A, the Fourier lens of the conoscope (L3) and the CCD camera. b) Schematic of the instrument. c) Definition of the incidence (θ_i, φ_i) and observation (θ_r, φ_r) angles with respect to the sample under test with area A.

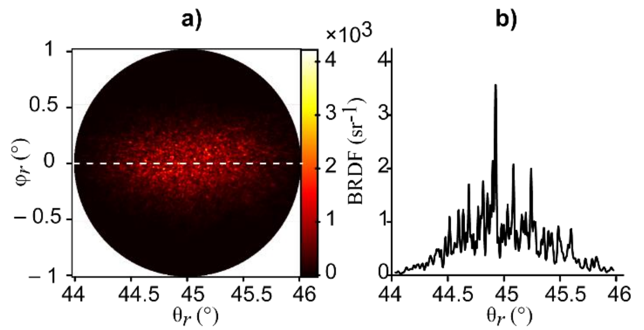

Figure 2. BRDF measurement with ConDOR. Left: single shot image. Right: cross-section along the dashed line shown on the left.

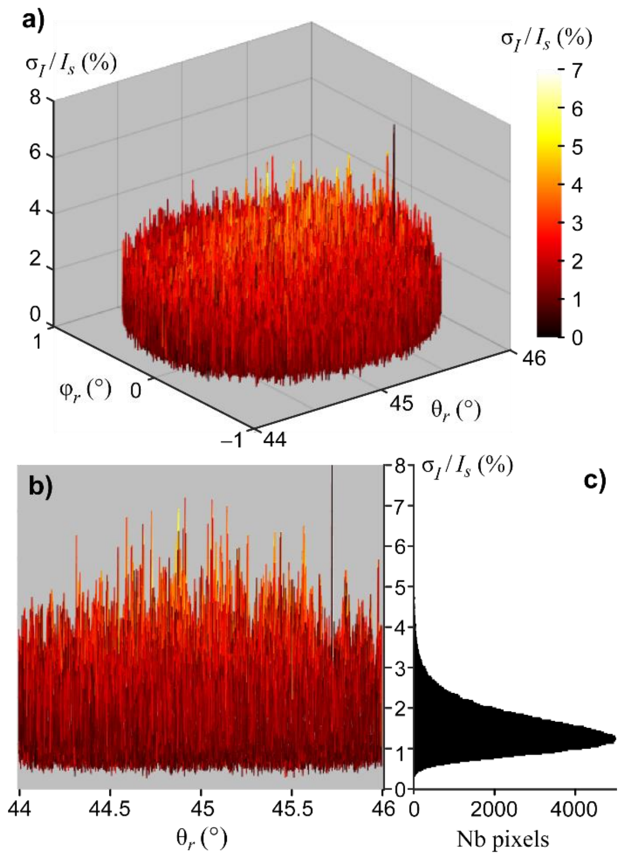

Figure 3. Standard deviation of the relative shot-to-shot fluctuations of the detected signal. a) 3D view and b) side view showing the values of the standard deviation obtained on each pixel of the detector, calculated from 100 images. c) Histogram of the standard deviation values.

3. Speckle and the gamma law

To test the above-mentioned fluctuations against the speckle theory, we now exhibit a few characteristics of the speckle effect. Speckle is a multiple source interference between the many reflecting facets of a rough surface [11]. When the surface is illuminated by a coherent source (by coherent we mean both spatially and temporally), the facet-to-facet height variations associated to the surface roughness translate into a phase roughness, which maps onto the fields scattered by the facets in a given direction. The interference between the scattered fields leads to bright grains in directions where the interference is constructive, separated by dark worm-like areas in directions where the interference is destructive.

Assuming a polarized and coherent point source, the intensity distribution of the granularity that appears in the focal plane of the above-mentioned Fourier lens of the conoscope has the following probability density [11]:

$$p_1(I_s) = \frac{1}{\langle I_s \rangle} \exp\left(-\frac{I_s}{\langle I_s \rangle} \right) \quad (1)$$

where $\langle I_s \rangle$ is the mean intensity, obtained by averaging over many realizations of the surface randomness.

Also, the grain characteristic size is given by:

$$a = \frac{\lambda f'_c}{D} \quad (2)$$

where D is the diameter of the aperture diaphragm limiting the illumination area of the sample (diaphragm (p2), see Fig. 1b), λ is the wavelength of light and f'_c is the focal lens of the conoscope. For λ = 699 nm and D = 8 mm, we obtain a = 30 µm, which is sightly larger than the pixel size (24 µm). The finite size of the light source pinhole [(p1) in Fig. 1b] actually enlarges the size of a grain rather significantly, since its image in the plane of the detector has a diameter of 86 µm. It also contributes to decreasing the contrast of the speckle pattern. Table 1 summarizes the above-mentioned dimensions in angular units and compares them to the resolution of the human eye.

Superimposing on a given pixel the signals associated to N grains with uncorrelated phases leads to a modified probability density of the intensity distribution, given by a gamma distribution with order parameter N [11] (see Fig. 4):

$$p_N(I_s) = \frac{N^N}{\Gamma(N)\langle I_s \rangle^N} I_s^{N-1} \exp\left(-N \frac{I_s}{\langle I_s \rangle} \right) \quad (3)$$

The value of N therefore increases linearly with the incident solid angle. Spectral bandwidth and partial polarization also play some role. Also, a given speckle grain may fall on several pixels simultaneously and, conversely, a given pixel may receive the information of several grains simultaneously.

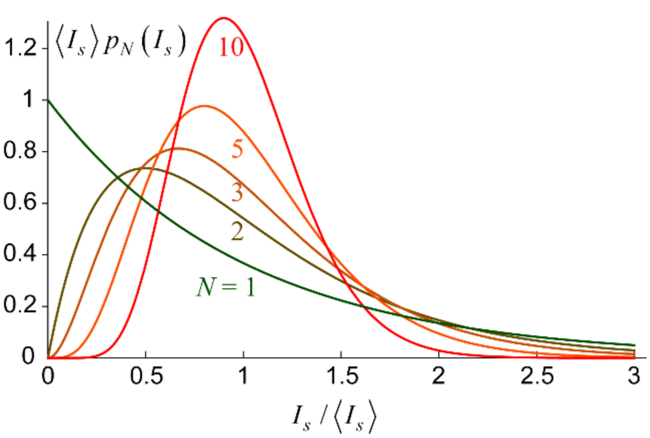

Figure 4. Examples of gamma distributions for different order parameters (N = 1, 2, 3, 5 and 10). As the source size increases, so does the order parameter N, and the probability density function at any point in the plane of the detector gets narrower, approaching a Gaussian for large N values.

Table 1: Parameters contributing to the angular resolution of the ConDOR instrument[a]

Parameter	Angular resolution[b]
CCD Pixel	4
Diffraction by (p2) (D = 8 mm)	5
Pinhole (p1)	14

[a] for the BRDF measurements shown in this article. For comparison, the resolution of the human eye is typically 17×10^{-3} degree.
[b] units of 10^{-3} degree.

4. Dependence of the BRDF measurements with aperture

Figure 5 summarizes the BRDF measurements performed for values of the aperture diameter D = 8 mm, 6 mm, and 4 mm and for a surface sample illuminated at 45° incidence angle. The exposure time of the CCD camera was adjusted for each value of the aperture diameter so as to maintain approximately the same level of illumination on average. The detected intensity pattern shows a granular aspect, with grain sizes and relative intensity fluctuations getting larger as the aperture diameter is reduced. This is further revealed by the histograms of the intensity values detected in the center of the BRDF. Such behaviors are in agreement with the speckle effect: when the aperture diameter is reduced, the grain size increases as shown by equation (2), and each pixel of the detector thus contains less grains in average, leading to a decreasing order parameter and larger relative intensity fluctuations.

5. Comparison to simulated speckle accounting for spatial coherence

In order to test our data quantitatively against the speckle theory, we simulated speckle patterns using the same parameters as ConDOR. As a first step, the sample under test was modelled as a matrix of random phases with uniform distribution between 0 and 2π. Starting with a polarized point-source, the field in the focal plane of the Fourier lens of the conoscope was calculated as the Fourier Transform of the field reflected off the surface sample, i.e. after application of the random phase map. To simulate the BRDF, we empirically took a Gaussian envelope with same root-mean-squared (rms) width as measured by ConDOR:

$$BRDF(\lambda, x', y') = \frac{1}{2\pi\sigma} \exp\left(-\frac{x'^2}{2\sigma^2} - \frac{y'^2}{2(\sigma\cos\theta_i)^2} \right) \quad (4)$$

where θ_i is the incidence angle, x' and y' are the Cartesian coordinates in the image focal plane of the conoscope (see Fig. 1b), referenced to the specular direction, and σ is the rms width of the BRDF Gaussian profile in the incidence plane. The cosine term accounts for the BRDF narrowing in the plane perpendicular to the incidence plane and that contains the specular direction. This narrowing is observed experimentally when the incidence angle increases (see, e.g., Fig. 5) and is explained geometrically by the micro-facet theory [12,13].

To account for the finite size of the light source pinhole (p1) and the fact that any two point-sources in the pinhole are spatially incoherent, we convolved the speckle intensity pattern by the pinhole geometrical image in the detector plane. This is easily done by discretizing the pinhole area. The speckle patterns associated to any two sub-sources are assumed to be exactly identical but for a

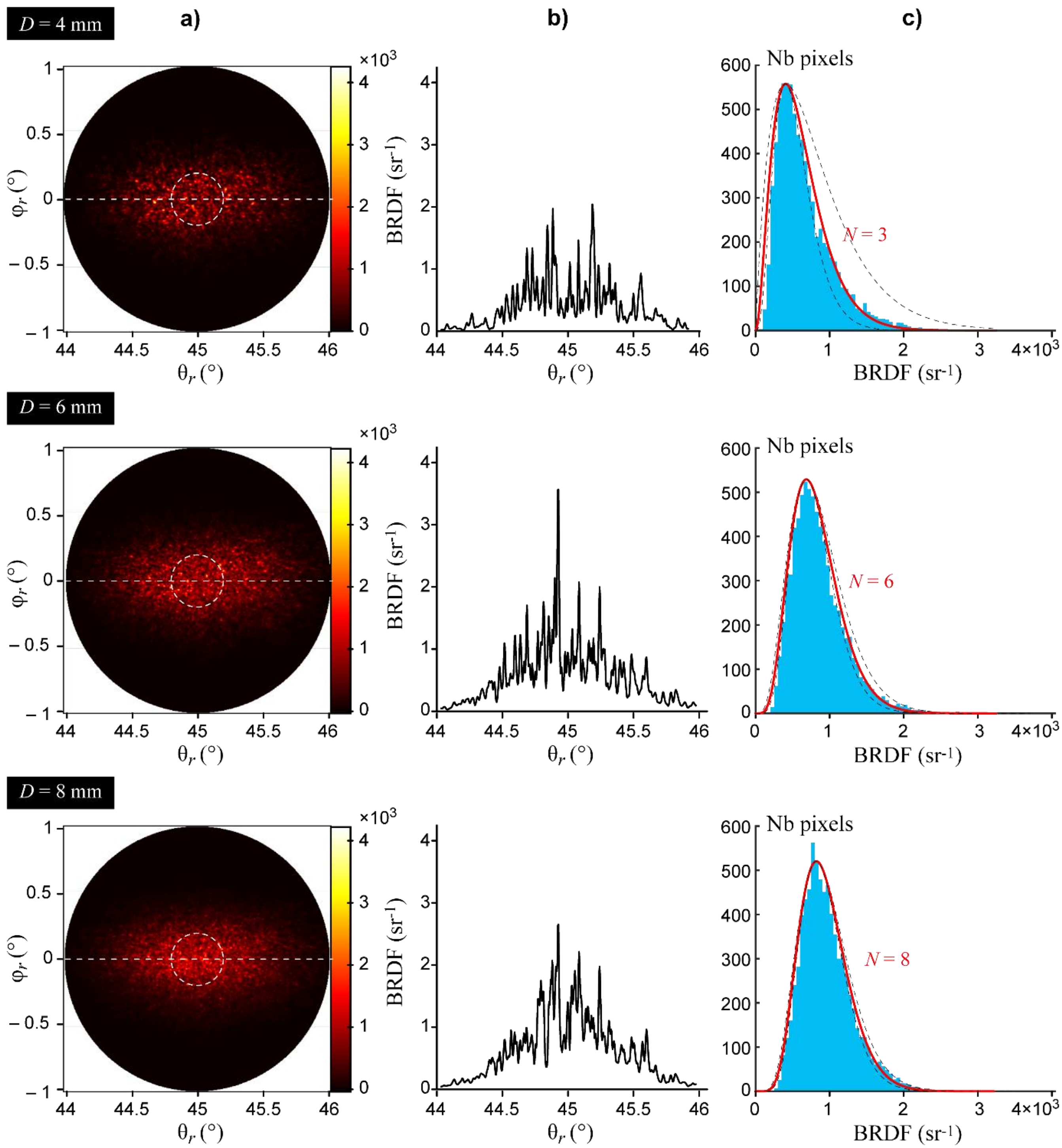

Figure 5. Impact of the aperture diameter on the BRDF measurements performed with Condor. **a)** single shot images of *BRDF measurement,* **b)** *cross-sections (along the dashed white line shown on the images on the left) and* **c)** *histograms of the intensity values recorded in a circular area with 100-pixel diameter in the center of the picture (circular white dashed line). From top to bottom, the aperture diameters are, respectively, 4 mm, 6 mm and 8 mm. The lines on the histograms are gamma distributions (see text): we indicate the best fit and indicate the closest integer order parameter N (red solid line). To appreciate the goodness of fit we also show the distributions with order parameters N + 1 and N – 1 (black dashed lines).*

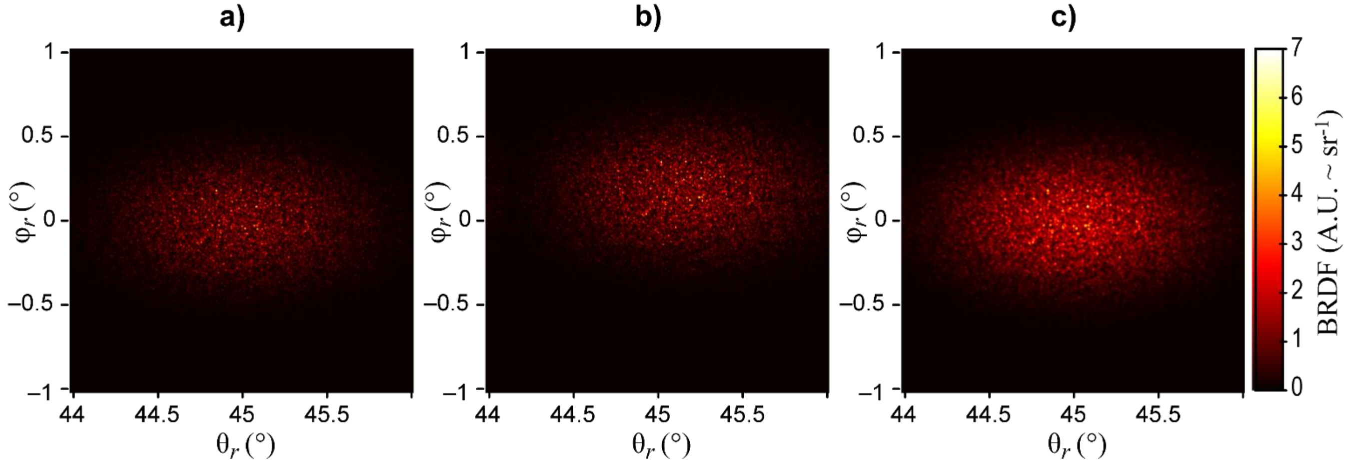

Figure 6 – Speckle patterns simulated under different illumination conditions: (a) the light source is a point on axis, leading to an image centered on the CCD detector; (b) the light source is a point shifted off-axis by 0.17° in both θ_i and φ_i directions, leading to the exact same speckle pattern but tilted by the same angular amount. (c) the light source is a square with uniform illumination and 100μm diagonal size, equivalent to 0.014° in angular size.

displacement in the plane of the detector (see Fig. 6), a realistic assumption given the small pinhole size. The simulated image for a uniformly illuminating pinhole is obtained by summing incoherently all the speckle patterns with equal weights. Also, we modelled the pinhole by a square with diagonal size of 100 µm, for simplicity, i.e. not a circular pinhole. This approximation should have a marginal effect on the simulated image.

Finally, to account for the unpolarized nature of the light, we summed incoherently the identical speckle patterns associated to p and s orthogonal polarizations, with weights equal to 1 and 10.9 respectively, thus accounting for the Fresnel angular reflectance values at 45° incidence angle for the TM and TE polarizations with a refractive index of 1.5 similar to the one of a NCS sample. The results are shown in Fig. 7 for the same values of the aperture diameter D as in the experimental data of Fig. 5. The relative intensity fluctuations clearly decrease with increasing values of the aperture diameter. The quantitative agreement between simulated and experimental data is remarkable. In particular, we recover very similar values for the order parameter N.

6. Conclusions

The exquisite angular resolution of the ConDOR experiment now reveals fine details of the reflected light distribution by a material surface beyond what can be perceived by the human eye. The speckle effect revealed in this article is responsible for strong intensity fluctuations that must clearly be taken into account in BRDF measurement. The race for a better accuracy has reached a turning point. Should the accurate description of a material appearance now require that one should actively degrade the resolution of the instrument so as to blur the speckle effect? Increasing the size of the pinhole further is not an option, as it would degrade the angular resolution of the instrument beyond the eye resolution. Future work should rely on other means to access the BRDF with no concession on the angular resolution.

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Author Biography

Thomas Labardens has received his engineer diploma from Institut d'Optique Graduate School in 2018. He is now a PhD student at the Conservatoire National des Arts et Métiers. His work focusses on speckle effects in high angular resolution BRDF measurement.

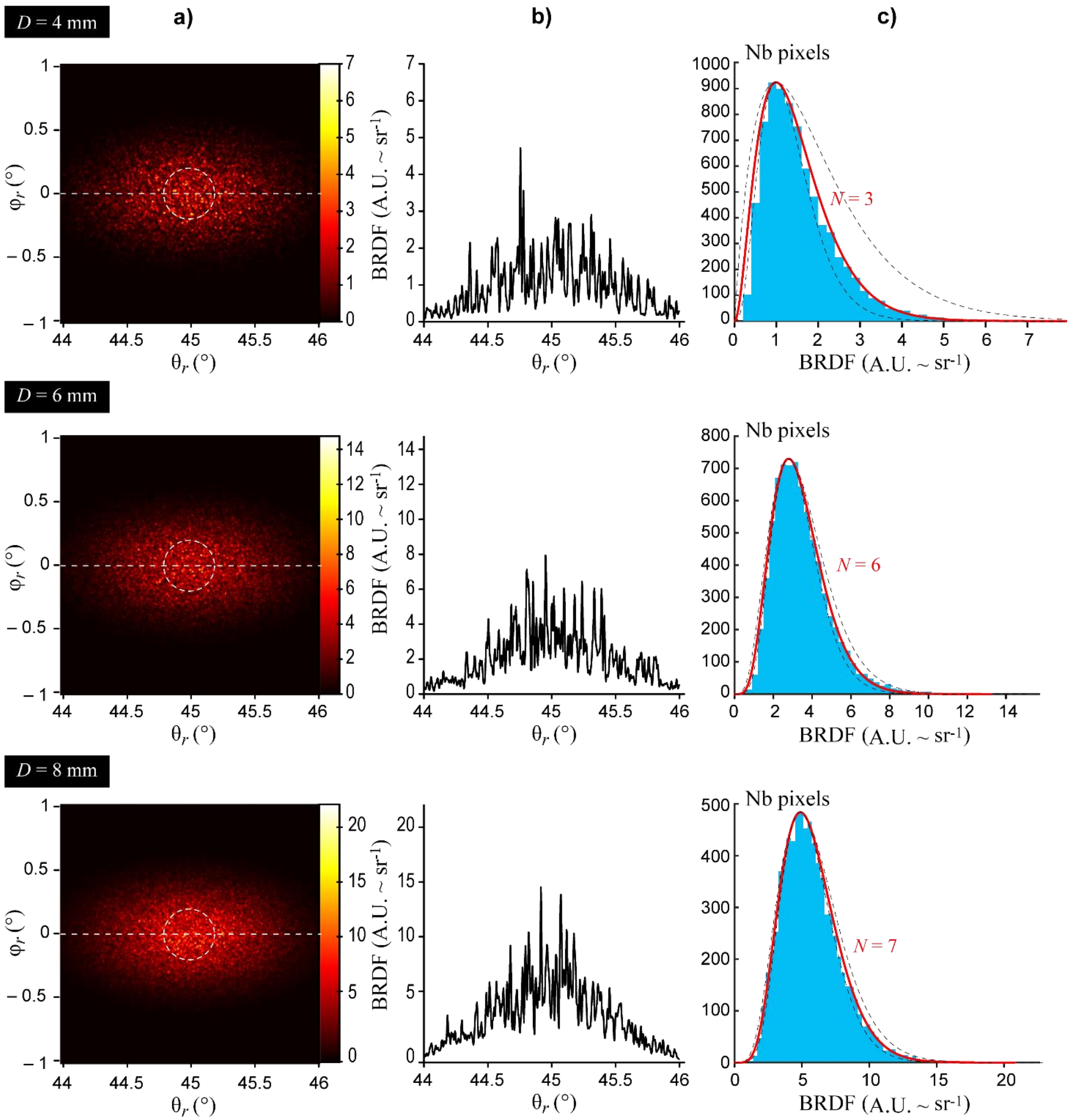

Figure 7. Impact of the aperture diameter on BRDF simulated with similar parameters as Condor. **a)** single shot images of *BRDF measurement,* **b)** *cross-sections (along the dashed white line shown on the images on the left) and* **c)** *histograms of the intensity values recorded in a circular area with 100-pixel diameter in the center of the picture (circular white dashed line). From top to bottom, the aperture diameters are, respectively, 4 mm, 6 mm and 8 mm. The lines on the histograms are gamma distributions (see text): we indicate the best fit and indicate the closest integer order parameter N (red solid line). To appreciate the goodness of fit we also show the distributions with order parameters N* + 1 *and N* – 1 (*black dashed lines)*