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Measurement of bidirectional reflectance distribution function on custom-made gonio-spectrophotometer

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This article presents a new series of measurements of printed samples on custom-made gonio-spectrophotometer and the respective evaluation by bidirectional reflectance distribution function. A set of three different papers (matt, glossy, and metallic) printed with six primary spot colours, together with Spectralon, were measured. Dependence of bidirectional reflectance distribution function on the reflection zenith angle, as well as its spectral representation, is presented. The results obtained are discussed regarding the ability of the custom-made setup to determine glossy and colour components of the studied set of samples. Three methods of calculation of reflectance for a fixed geometry are applied and the CIELAB colorimetric coordinates derived to compare with CIELAB values obtained by a commercially available spectrophotometer.

Keywords: Goniospectrometric measurements; BRDF; Printed samples; Gonio-spectrophotometer

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Introduction

To describe the total appearance of a print material, optical properties are usually measured. For non-diffuse print materials (e.g. highly glossy paper printed with effect inks or varnish coatings) conventional measurements techniques that use a single geometry (for example 45º : 0º) are insufficient to characterize the material of interest. Such a print material should therefore be measured at multiple incident and viewing directions [1,2]. A number of multi-angle instruments (e.g. X-Rite MA98) are commercially available. However, these instruments are able to measure at a fixed incident and viewing directions only, thus limiting the multi-directional measurement possibilities. Gonio-spectrophotometer measures at a broader range of angles as the sensor and/or light source moves around the sample offering more dimensions for performing the multi-directional measurements. The resultant spectral measurement is usually a ratio of the reflected to the incident power. Further, bidirectional reflectance distribution function (BRDF) can also be estimated using these measurements.

BRDF as defined by Nicodemus et al [3] mathematically and physically describes the surface reflectance properties of an opaque surface. It specifies the fraction of the total incident light that is reflected in certain direction. Namely, BRDF is defined as function of zenith (θ) and azimuth (ϕ) angles of incidence light (index *i*) and reflected light (index *r*) as shown in Fig. 1.

$$BRDF(\theta_i,\phi_i;\theta_r,\phi_r) = \frac{dL_r(\theta_i,\phi_i;\theta_r,\phi_r;E_i)}{dE_i(\theta_i,\phi_i)}\ [\mathrm{sr}^{-1}] \tag{1}$$

where E_i is incident irradiance and L_r reflected radiance [3–6].

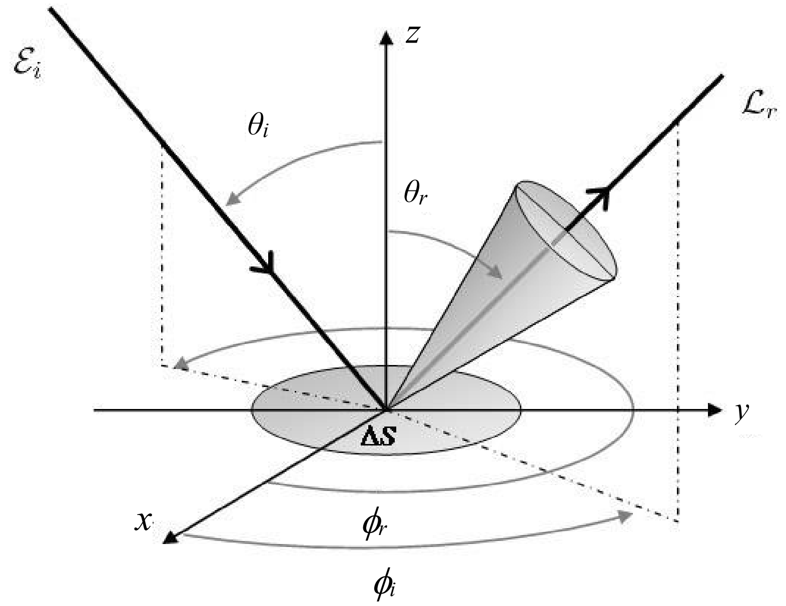

Fig. 1 *Definition of BRDF in the system of x-y-z coordinates* [7]

In order to obtain colorimetric properties of an object, the reflectance R of an object has to be specified. The reflectance of an object is defined as the ratio of reflected radiant flux Φ_r to incident radiant flux Φ_i [8,9]. In practical measurements, the incidence radiant flux is determined indirectly by measuring the reflectance factor $\hat{R}(\lambda)$, where the Φ_r is divided by a flux from a reference standard Φ_D illuminated identically, when assuming that the reference standard is a perfect Lambertian surface (see Eq. 2a). Alternately, the radiance factor can be computed by applying the radiance (L) (eq. 2b) or BRDF (eq. 2c).

$$\hat{R} = \frac{\Phi_r}{\Phi_D} \tag{2a}$$

$$\hat{R} = \frac{L_r}{L_D} \tag{2b}$$

$$\hat{R} = \frac{BRDF_r}{BRDF_D} \tag{2c}$$

L_r is the radiance at the sample surface while L_D radiance at the surface of the reference standard. The reflectance of the reference standard is considered to be equal to 1 [10]. For every combination of θ_i, ϕ_i, θ_r, and ϕ_r, the BRDF is $1/\pi$ and $\Phi_D = \Phi_i/\pi$. Reflectance of an object can therefore be computed using (Eq. 3).

$$R = \frac{\hat{R}}{\pi} \tag{3}$$

The reflectance measurements can further be converted in a colorimetric space, such as CIEXYZ or CIELAB, by using the colorimetric definitions given in CIE15.2 (see [9,11]).

In this paper, we use a custom-built gonio-spectrophotometer to perform bidirectional reflectance measurements of selected print samples with different reflectance properties. The aim was to determine the ability of the setup by obtaining the angle-dependent spectral characteristics of model samples. In order to fulfil this goal, we decided to estimate the spectral representation of BRDF in dependence of the reflection angle as being analysed on three different paper substrates classified as matt, glossy, and metallic, respectively. Moreover, the colour characteristics are to be modified by imprinting these substrates with six spot colours. Finally, spectral dependence and colorimetric representation for the 45/0 geometry is compared with the results obtained by X-rite SpectroEye spectrophotometer.

Materials and methods

Custom made gonio-spectrophotometer built within this study consisted of illumination part, rotary sample holder, and a detector attached to a rotary table (see Fig.2). For the illumination part, a 100W halogen bulb with a day filter was used. The light was guided through an optical fibre and collimated with a set of lenses. The rotary table (from Siemens) and rotary sample holder (Melles Griot) allowed to adjust the zenith angles θ_i and θ_r independently. Azimuth angles ϕ_i and ϕ_r were fixed at 180° relative position. The signal was detected by spectrometer (model "StellarNet BLACK-Comet"; StellarNet) with physical spectral resolution of 3 nm connected to a computer and data were recorded in range from 380 nm to 730 nm with a reporting step of 5 nm in the SpectraWiz software. The spectrometer with collimation lenses was directly attached to the rotary table without using any optical fibre. The detection solid angle of 0.00014 sr was defined by a circular slit.

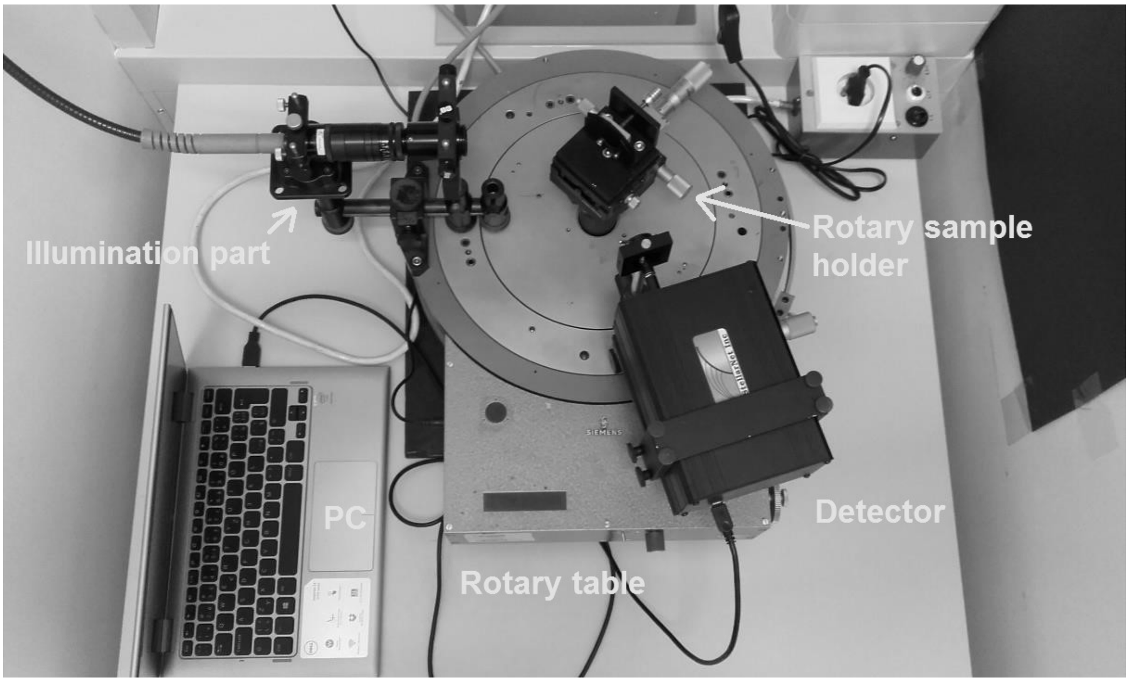

Fig. 2 *Custom made gonio-spectrophotometer – a photo*

In order to stabilize the incident light intensity, measurements were conducted one hour after switching-on the light source. The interpretation and denotation of zenith angles follows the ASTM standard [12].

To evaluate the measurement setup for angle dependent spectral measurements, three paper substrates were used: Matt paper (Luxosatin; Papyrus Group), Glossy paper (Chromolux; M-Real Zanders), and Metallic label paper. Each of these papers were printed with six primary Pantone spot colours by using a printability tester (model "IGT C1"; IGT Testing Systems BV) and Krypto offset inks: Purple (P), Reflex Blue (RB), Process Blue (PB), Green (G), Warm Red

(WR) and Rubine Red (RR). A Spectralon tile (LabSphere) was utilized as the white diffusive reflectance standard. It is a reference material with reflectance properties close to Lambertian ones that is often utilized in gonio-spectrometric measurements [13–15].

The angle dependent measurements of print samples and Spectralon tile were conducted for incidence angles θ_i = 25 deg, θ_i = 35 deg, θ_i = 45 deg, θ_i = 55 deg, and θ_i = 65 deg. A single step in reflection angle was 5 deg and 2.5 deg close to the specular angle, respectively.

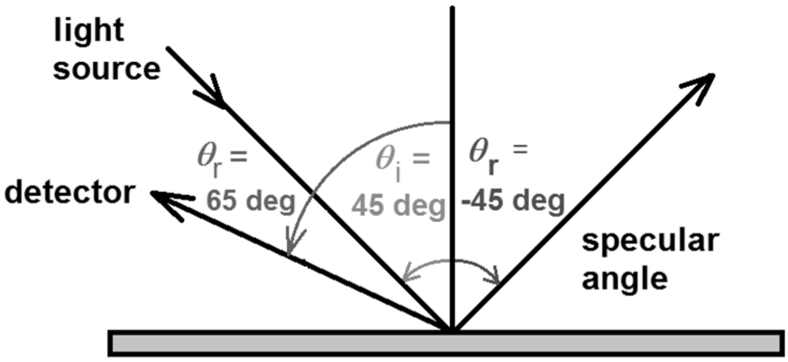

Fig. 3 *Example of representation of the angles for multiangle measurement (θ_i = 45 deg, θ_r = -45 deg and θ_r =65 deg;* after [12])

BRDF from the measurements obtained was calculated according to Matsapey et al. [13] with a modification of incident flux measurement. Because of the limitation of the geometrical setup and maintaining the position of each optical element, it was not possible to measure the incident flux directly. Therefore, the flux was recorded marked as Φ_{45} reflected from a Si-wafer with the known reflectivity in specular reflection (θ_i = 45 deg and θ_r = -45 deg). The indirect measurement of Φ_{45} was done before each analysis of sample or measurement of the Spectralon tile. To achieve the same integration time and sensitivity of the sensor as in case of paper sample measurements, a density filter with known transmittance was placed in the beam path.

Incident irradiance was calculated using Eqn. (4) and radiance exited from the sample surface was estimated using Eqn. (5), where Φ_r is the reflected flux measured from the sample.

$$E_i = \frac{\phi_{45}(\lambda)\Omega_S}{S_0\,\Omega_d\,R_{Si}(\lambda)T_{filter}(\lambda)}\cos(\theta_i) \tag{4}$$

$$L_r = \frac{\phi_r(\lambda,\theta_r)}{S_0\,\Omega_d} \tag{5}$$

Sample BRDF (λ, θ_i, θ_r) was calculated using Eqn. (6).

$$BRDF(\lambda,\theta_i,\theta_r)=\frac{L_r(\lambda,\theta_r)}{E_i(\lambda,\theta_i)} \qquad (6)$$

In equations 4–6: Ω_s is illumination solid angle, Ω_d detection solid angle, S_0 detection area, R_{Si} reflectivity of silicon wafer (for θ_i = 45 deg, and θ_r = -45 deg), T_{filter} is transmission of the filter, θ_i the angle of incidence, and θ_r the angle of reflection.

Spectral characteristics obtained from the gonio-spectrophotometer were evaluated against measurement made using a commercially available spectrophotometer called X-rite SpectroEye. SpectroEye has an θ_i = 45 deg and θ_r = 0 deg geometry and records reflectance data in range from 380 nm to 730 nm at 10 nm steps. Since the device has its own white calibration tile, the reflectance $R_{\mathrm{SpectroEye}}$ was computed as the measured reflectance of the colour sample divided by a reflectance measured on Spectralon tile. The reflectance $R_{\mathrm{SpectroEye}}$ and corresponding CIELAB coordinates served as the reference in the comparison.

The reflectance of printed samples measured by gonio-spectrophotometer was calculated according to three approaches. Only measurements valid for θ_i = 45 deg and θ_r = 0 deg geometry, similar to SpectroEye, were taken into consideration.

First approach considers reflectance equal to normalized $\mathrm{BRDF_N}$ (λ, 45, 0). The normalization is explained in following chapter. Second approach calculates the reflectance R_{BRDF} according to the Eqn. 3, using the radiance factor (Eqn. 2c), where the $\mathrm{BRDF_r}$ (λ, 45, 0) of the sample is related to the $\mathrm{BRDF_D}$ (λ, 45, 0) of Spectralon tile. In third approach, the reflectance R_{Flux} is calculated by Eqn. 3 using the reflectance factor $\hat{R}$ (Eqn. 2a), where the flux reflected from the sample Φ_r (λ, 45, 0) is divided by a flux reflected from a Spectralon tile Φ_D (λ, 45, 0).

Corresponding coordinates in CIELAB space were calculated by standard procedures [8,9,11] by selecting only 400–700 nm wavelength interval of all spectral quantities and using D50 standard light source and 2° standard observer. The colorimetric data obtained from gonio-spectrometric measurements were then compared to the data obtained from SpectroEye measurements by means of the parameter ΔE^*_{ab}.

Results and discussion

Angle dependence

The angle dependent BRDF (550, 45, θ_r) values of Spectralon tile obtained from measurements at custom made gonio-spectrophotometer are shown in Fig. 4, together with the data from the literature [16]. Although the wavelength with the highest intensity of the light source is chosen, it can be seen that BRDF data obtained by custom made gonio-spectrophotometer are lower than those published in the literature and also lower than theoretical value, 0.318 sr^{-1}. However, the angle depended distribution more or less follows the expected tendencies and the magnitude of BRDF had to be increased by constant $K = 2.5$ in order to normalize measured data to the values from the literature. The difference is attributed to some geometrical limitations of the custom built setup, and it is considered as a systematic error. Therefore, all BRDF values measured on printed samples were corrected by the constant K, which will be marked as $BRDF_N$ in the following text.

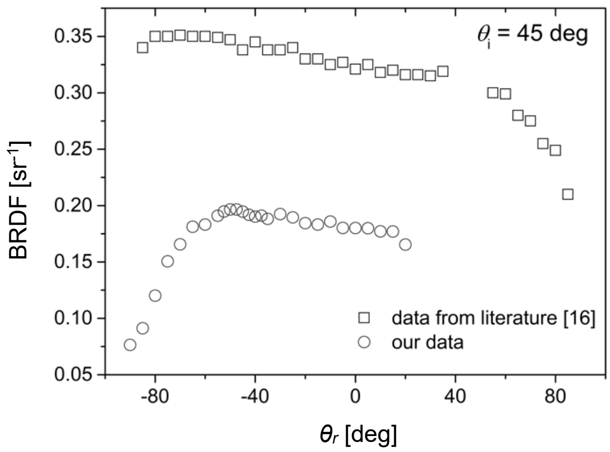

Fig. 4 *Comparison of BRDF (680, 45, θ_r) of the Spectralon tile obtained from the literature* [16] *and measured values of BRDF (550, 45, θ_r)*

Spectral representation of Spectralon tile's $BRDF_N$ (λ, 45, 0) shows a relatively good match with the theoretical value in the wavelength range of 390–670 nm. Out of this interval, the difference becomes larger (see Fig. 5). Disagreement between calculated BRDF data for wavelengths lower than 390 nm and for those larger than 670 nm are very likely due to the error(s) caused by a low intensity of the light source in these regions and possible nonlinearities in the optical system caused by the Si-wafer or density filter. That might influence the calculation of incidence irradiance E_i (eq. 4).

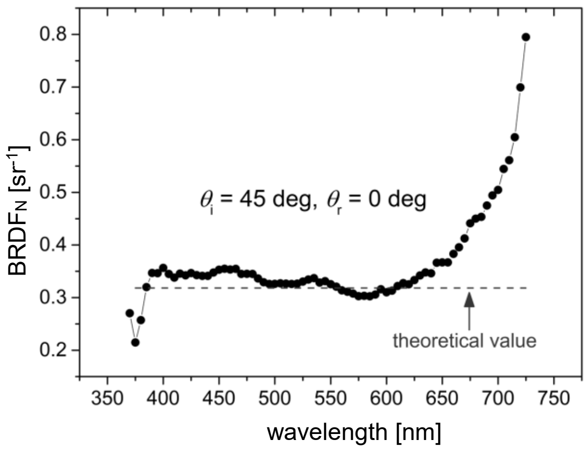

Fig. 5 *The BRDF$_N$ (λ, 45, 0) values of the Spectralon tile after normalization by the constant K together with the theoretical value (dashed)*

Fig. 6 shows the angle dependent representation of BRDF$_N$ (470, 45, θ_r) of matt PB colour sample and of clear matt paper. As can be expected, the values of BRDF$_N$ (470, 45, θ_r) of clear matt paper are almost constant, and the paper substrate can therefore be considered as a very good diffuser. In case of printed paper, the peak close to θ_r = -45 deg represents the specular reflection. The ink layer fills the pores of the matt paper, thus smoothing the surface that then appears glossier that the clear matt substrate. Similar results can be found for all the other print samples.

The angle dependent representation of BRDF$_N$ for glossy paper and glossy PB colour sample is shown in Fig. 7. Differently from the matt paper substrate, the glossy paper is characterized by a distinct specular reflection detected by the custom built setup as a sharp peak close to the specular reflection angle. The peak gets wider, when the ink layer is being applied. The change in the distribution can be attributed to a larger content of light diffusion, the sample appears less glossy than the clear glossy substrate.

Largest values of BRDF$_N$ were obtained for metallic samples in specular reflection. Again, the application of ink layer widens the width of the reflection peak, decreasing the glossy appearance of colour samples (see Fig. 8).

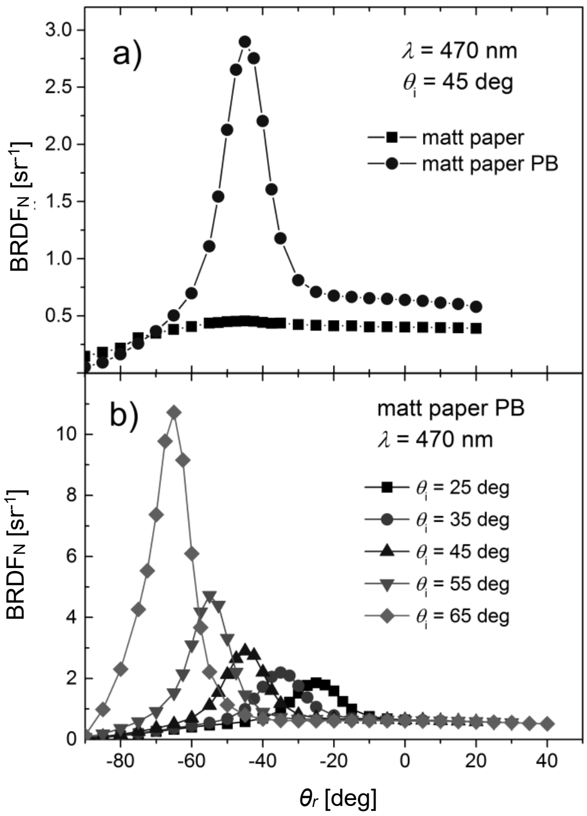

Fig. 6 *The BRDF$_N$ (470, 45, θ_r) as obtained for clear matt paper and for the matt PB colour sample (a) and BRDF$_N$ (470, θ_i, θ_r) of matt PB colour sample (b)*

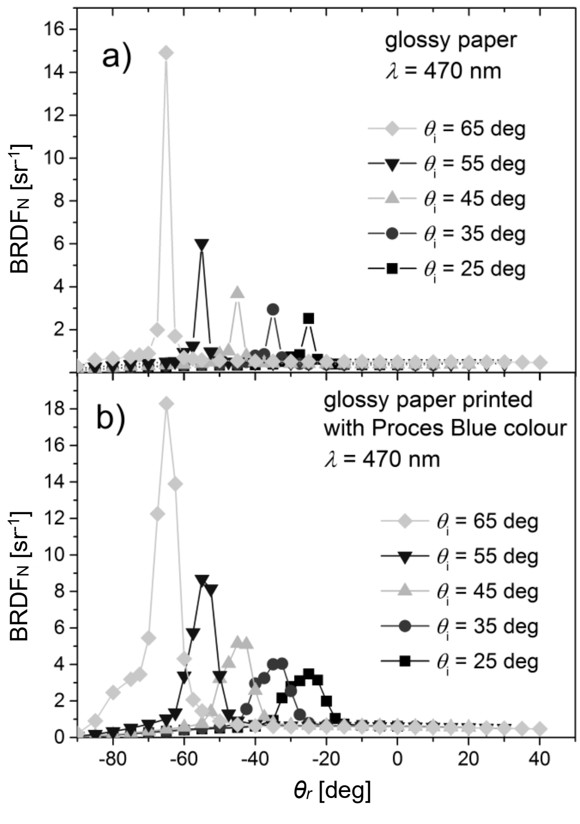

Fig. 7 *The BRDF$_N$ (470, θ_i, θ_r) as obtained for clear glossy paper (a) and glossy PB colour sample (b)*

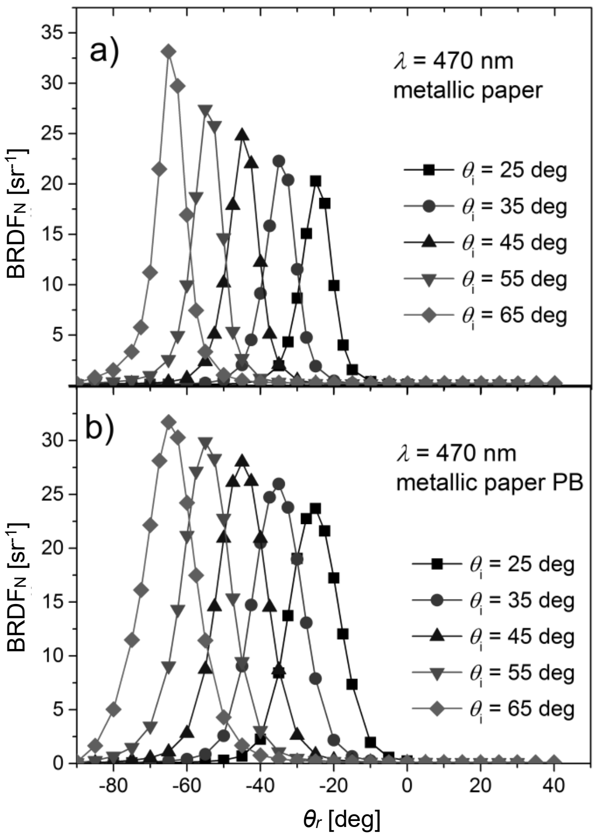

Fig. 8 *The BRDF$_N$ (470, θ_i, θ_r) as obtained for clear metallic paper (a) and metallic PB colour sample (b)*

Spectral dependence of the BRDF$_N$ (λ, $\theta_i = -\theta_r$) of the matt and glossy PB colour sample is illustrated in Fig. 9. By comparing the matt and the glossy substrate, one can notice that absolute values of BRDF$_N$ are higher in the case of glossy paper for the specular reflection. In both cases, this parameter does not have significant spectral dependence. The glossy component prevail the colour component in case of specular reflection regardless of the θ_i. The data for off-specular reflection will be presented in next chapter.

In the case of metallic colour samples, the results are different. Spectral dependence of BRDF$_N$ is well pronounced in the specular reflection, but almost negligible in off-specular reflection (see Fig. 10).

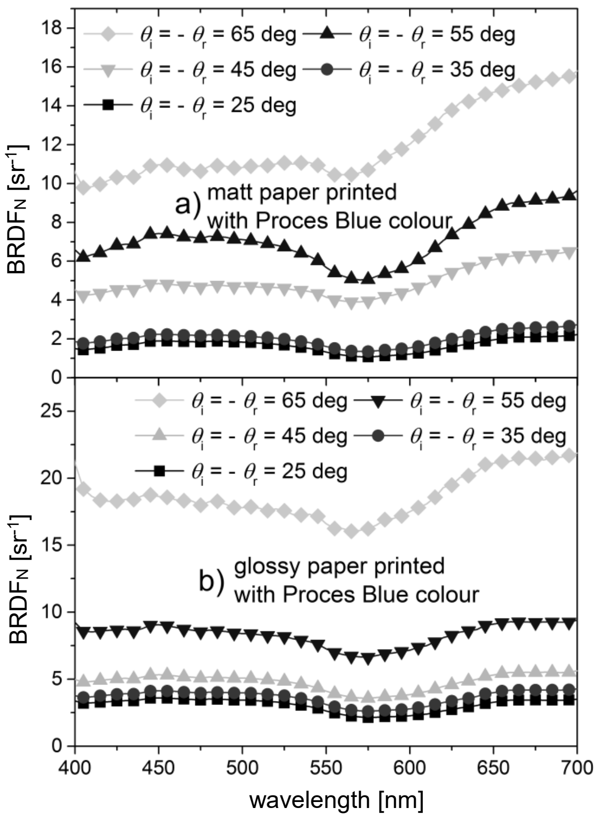

Fig. 9 *The BRDF$_N$ (λ, θ$_i$ =-θ$_r$) as obtained for matt PB print sample (a) and glossy PB print sample (b)*

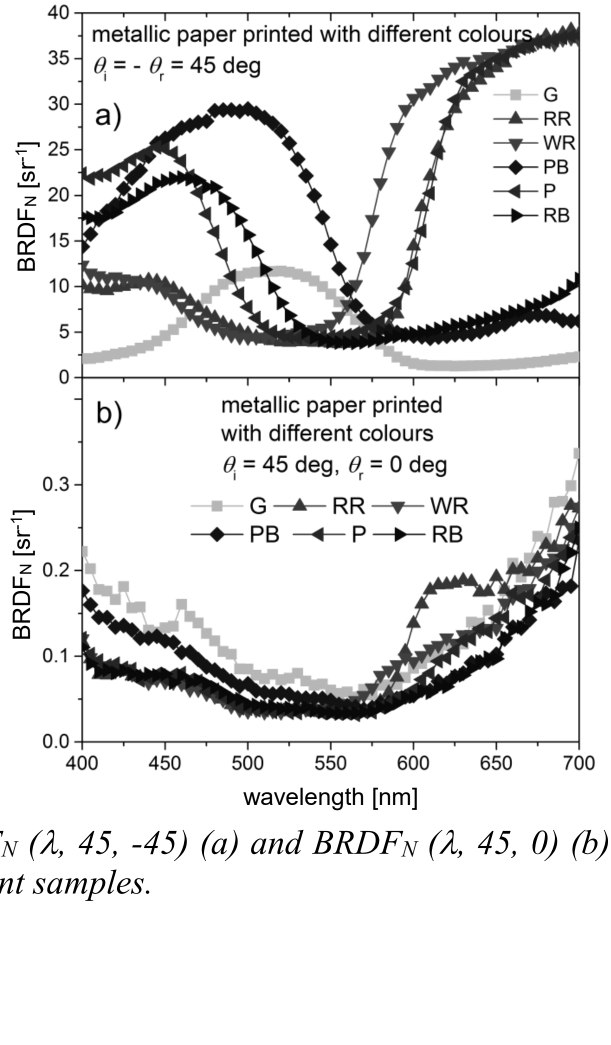

Fig. 10 *The BRDF$_N$ (λ, 45, -45) (a) and BRDF$_N$ (λ, 45, 0) (b) as obtained for al metallic colour print samples.*

The evaluation of the BRDF values obtained indicates that the custom made gonio-spectrophotometer is able to obtain the angle dependent spectral data in accordance with the expectation regarding the determination of the sample glossiness. In case of paper substrates, the information about the colour (absorption) prevails in the off-specular geometries, while for highly glossy metallic substrate, the situation is more complicated. As described by Mikula et al. [17], specular reflection from semi-transparent colour ink layer applied onto mirror-like metallic substrate bears the information from the front boundary reflection of the ink layer and the bottom boundary reflection of the metallic substrate. The colour appearance of printed metallic paper can be observed by our setup in specular reflection (see Fig. 10a) similarly as reported in [17] and it is attributed to the bottom boundary reflection.

Colorimetric evaluation

The reflectance estimation, as specified in "Methods and materials" by means of three approaches, was done in order to compare it with reflectance acquired by measurements using commercially available SpectroEye spectrophotometer. The reflectance valid for θ_i = 45 deg and θ_r = 0 deg is presented in Figs. 11 and 12 for matt and glossy substrate, respectively. As can be seen, the reflectance peaks are identified in the same region; however, the distribution over wavelengths differs from the reference $R_{\mathrm{SpectroEye}}$ in all cases. The $\mathrm{BRDF_N}$ of colour samples exhibits a similar error at long and short wavelength regions as in case of Spectralon tile, which is shown in Fig. 5. Therefore, the R_{BRDF} seems to be a better representation. However, it differs from the reference reflectance $R_{\mathrm{SpectroEye}}$ in blue and green regions more than the $\mathrm{BRDF_N}$. The reflectance calculated from the fluxes R_{Flux} exhibits a better match in blue and green regions, but worse in red regions.

The measured sample reflectance was converted into colorimetric space CIELAB using a standard illuminant D50 and CIE 2° colour matching functions. Colorimetric difference ΔE^*_{ab} was calculated between the measurements performed using the custom-built gonio-spectrophotometer and SpectroEye. Table 1 shows the obtained colorimetric differences for all the spot colours printed on matt and glossy paper samples. Here, one can observe that the minimum differences are obtained for red spot colours printed on both paper substrates when $\mathrm{BRDF_N}$ or R_{BRDF} (Eqn. 2c) is applied in calculations. The difference in the long wavelength region (above 620 nm) of $\mathrm{BRDF_N}$ and R_{BRDF} does not have a large impact on magnitude of calculated colour difference (see Tab. 1). The CIELAB coordinates calculated from R_{Flux} seem to be closer to the reference values for green and blue colour samples even though the difference being still large. In general, the colorimetric match among the analyzed samples is not achieved. This may be due to the different solid angles of both measuring devices, however, the largest impact can be attributed to the insufficient stability and spectral power distribution of the light source applied in the setup.

In general, it appears that the data obtained from the gonio-spectrophotometer contain a more achromatic signal. The differences among computation methods of reflectance are attributed to the insufficient stability and spectral power distribution of the light source applied in the setup. The indirect measurement of incidence flux was done prior to each measurement of the sample. The Spectralon tile was however measured just once within the study. The results show that the sample and the reference Spectralon tile are not illuminated identically and, therefore, the assumption to ensure the same illumination for colorimetric evaluation was not fulfilled.

Yet another point to consider here is that the colorimetric space and the colorimetric difference were developed by the colour science community to evaluate and reproduce the colour on diffuse materials measured at a fixed geometry. In the present study, only fixed geometry of custom built gonio-spectrophotometer (θ_i = 45 deg and θ_r = 0 deg) is considered for colorimetric evaluation. This geometry was assumed to be close to that of SpectroEye spectrophotometer. However, they are not identical and other optical parameters may have impact on the colorimetric differences reported. These measurements therefore need further investigations with a different error metrics.

When calculating the CIELAB values from the measurements it is assumed that the reference white used is diffuse and has a maximum L^* value of 100. The sample being measured bidirectional may have a higher luminance, especially at grazing angles, thus having lightness value above 100**,** which can lead to a false colour representation.

Table 1 *Colour differences between SpectroEye experiments and gonio-spectrometric measurements applying three methods of reflectance calculation*

Sample	G-Matt	P-Matt	PB-Matt	RB-Matt	RR-Matt	WR-Matt
ΔE^*_{ab} (BRDF$_N$)	25.2	14.7	13.9	10.5	6.6	4.3
ΔE^*_{ab} (R_{BRDF})	25.1	17.9	15.1	12.6	7.7	3.2
ΔE^*_{ab} (R_{Flux})	20.6	13.8	8.7	11.9	16.3	13.3
Sample	G-Glossy	P-Glossy	PB-Glossy	RB-Glossy	RR-Glossy	WR-Glossy
ΔE^*_{ab} (BRDF$_N$)	26.4	18.9	16.1	17.9	8.3	8.9
ΔE^*_{ab} (R_{BRDF})	26.4	21.9	16.9	19.8	9.1	7.6
ΔE^*_{ab} (R_{Flux})	21.3	18.5	11.6	12.8	17.5	17.9

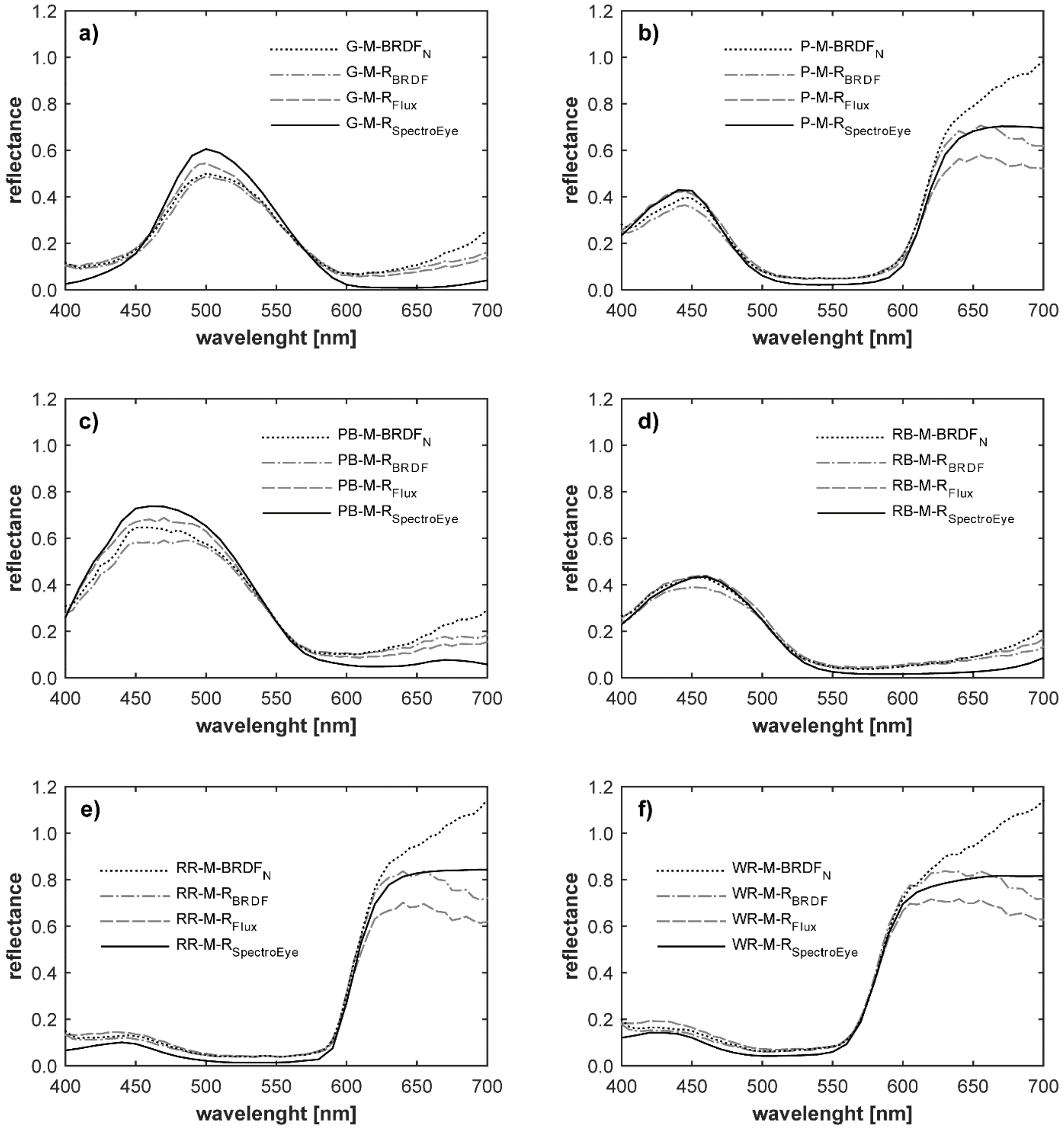

Fig. 11 *Reflectance of colour samples on matt substrate calculated by three approaches as obtained from gonio-spectrophotometric measurements in comparison to reflectance obtained from SpectroEye spectrophotometer for Green (a), Purple (b), Process Blue (c), Reflex Blue (d), Rubine Red (e) and Warm Red (f)*

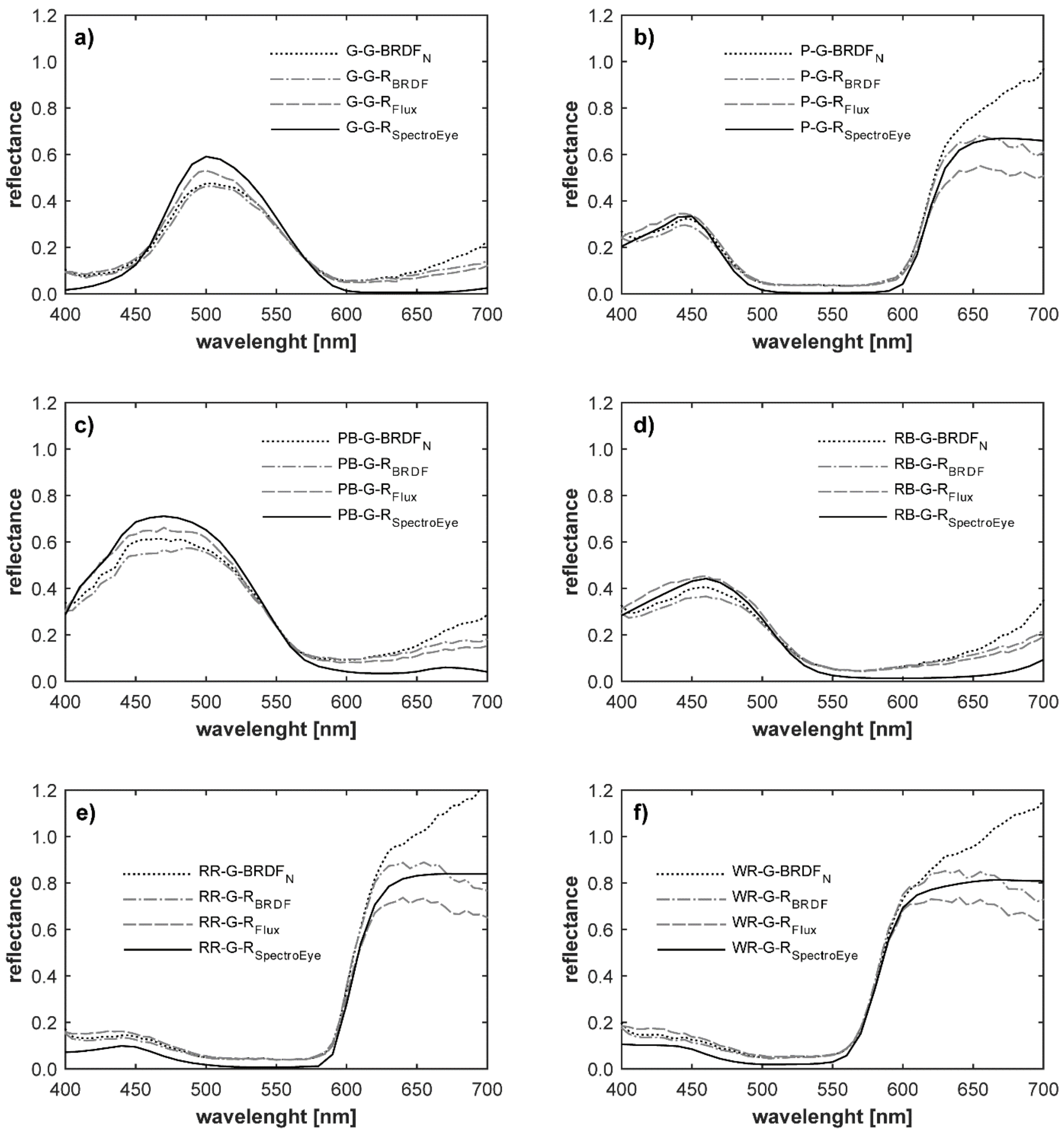

Fig. 12 *Reflectance of colour samples on glossy substrate calculated by three approaches as obtained from gonio-spectrophotometric measurements in comparison to reflectance obtained from SpectroEye spectrophotometer for Green (a), Purple (b), Process Blue (c), Reflex Blue (d), Rubine Red (e) and Warm Red (f).*

Conclusions

A custom made gonio-spectrophotometer was built within this study and its ability to obtain angle dependent spectroscopic measurements was tested. The indirect measurement of the incident flux reflected from Si-wafer and measurement of reflected flux from the sample were applied in order to calculate BRDF of the sample. A Spectralon tile and three substrates, matt, glossy and metallic printed by six spot colours were measured by the gonio-spectrophotometer.

The values obtained for Spectralon tile were lower when compared to the data published in the literature. Therefore, the normalization constant $K = 2.5$ has been introduced. For wavelengths below 390 and above 670 nm, the calculated BRDF contains some systematic error due to a low power of the light source in these regions and, also, due to nonlinearities of the optical system while measuring the reference incidence flux.

The angular dependence shows distinctive differences between clear paper substrates and their corresponding colour prints. The ink layer causes increase of the glossiness in case of matt substrate, but lowers the glossy appearance for glossy and metallic substrate. In case of metallic samples, the colour information is brought in close to specular angles only. For glossy and matt colour samples, the colour information prevails in off-specular angles.

When we compare the measurements obtained at fixed geometry using the custom-made gonio-spectrophotometer with experiments made with comer-cially available spectrophotometer (X-Rite SpectroEye), the spectral reflectance and also the colorimetric values do not match very well. The error is larger in case of blue and green spot colours (approximately $\Delta E^*_{ab} = 20$ on matt paper), but it is relatively less for red spot colour (approximately $\Delta E^*_{ab} = 5$ on matt paper). However, the position of the peaks (of spectral measurements) matches the reference spectral reflectance measurements. The insufficient stability of the light source might play a pivotal role in the reported colour differences. These differences might be also caused by a different optical setup of gonio-spectrophotometer and SpectroEye device, when even the incidence and reflectance angles are expected to be identical.

The results show some potential in development of the measurement setup with respect to obtaining the angle-dependent spectroscopic BRDF data. In future work, it will be important to examine and evaluate the custom built gonio-spectrophotometer using a more stable light source along with a different approach for calculating the incident flux. The calculations to obtain the incident flux by measuring the flux reflected from the reference white standard seems to perform better compared to those using a high glossy Si-wafer. A thorough analysis of the setup would require further investigation related to energy meter calibration, repeatability, light source consistency, and measurement accuracy.

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