Multi-angle spectroscopic measurements at University of Pardubice

Petr Janicek

Eliska Schutzova

Ondrej Panak

E-mail: petr.janicek@upce.cz

The aim of this work was:

- to conduct the measurement of samples printed on three different types of paper substrates on custom made gonio - spectrophotometer.
- to calculate BRDF as a function of wavelength, angle of incidence and reflection angle.

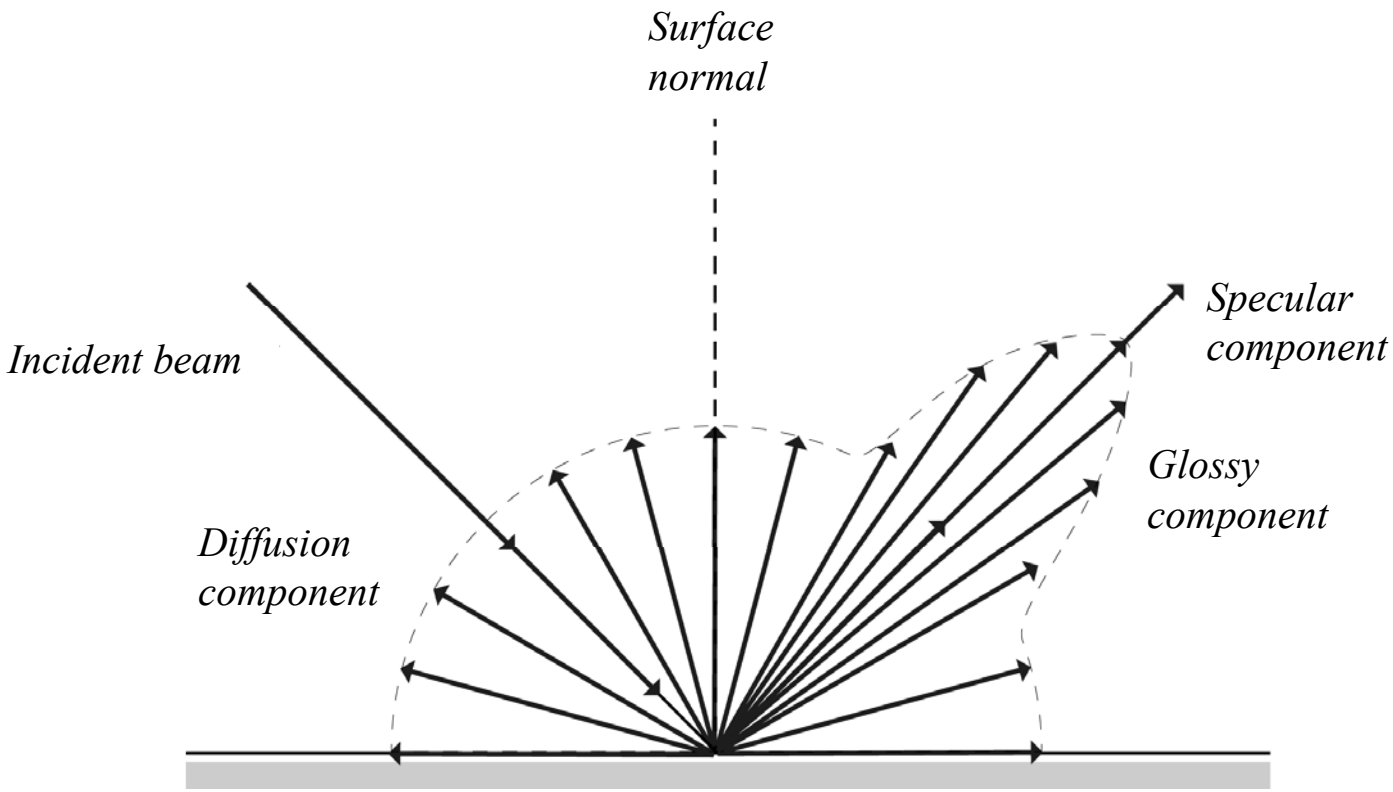
Bidirectional reflectance distribution function (BRDF)

Mathematically and physically describes local properties of the surface.

Indicates how much from the incidence light is reflected to certain direction.

Input information for material appearance.

BRDF is a combination of specular, diffusion and glossy component



Model BRDF

$$f_r(\theta_i, \phi_i; \theta_r, \phi_r) = \frac{dL_r(\theta_i, \phi_i; \theta_r, \phi_r; \mathcal{E}_i)}{d\mathcal{E}_i(\theta_i, \phi_i)} \left[\frac{1}{sr}\right]$$

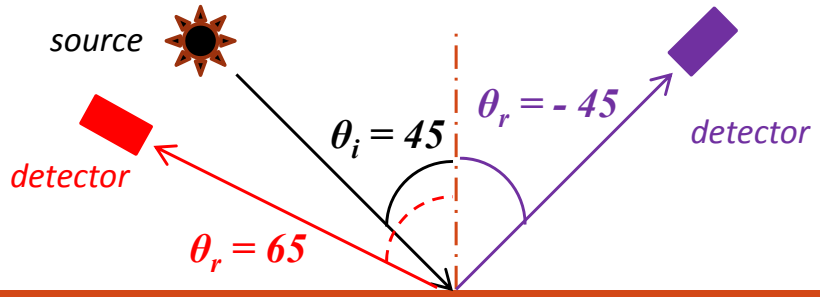
θ and ϕ determine direction

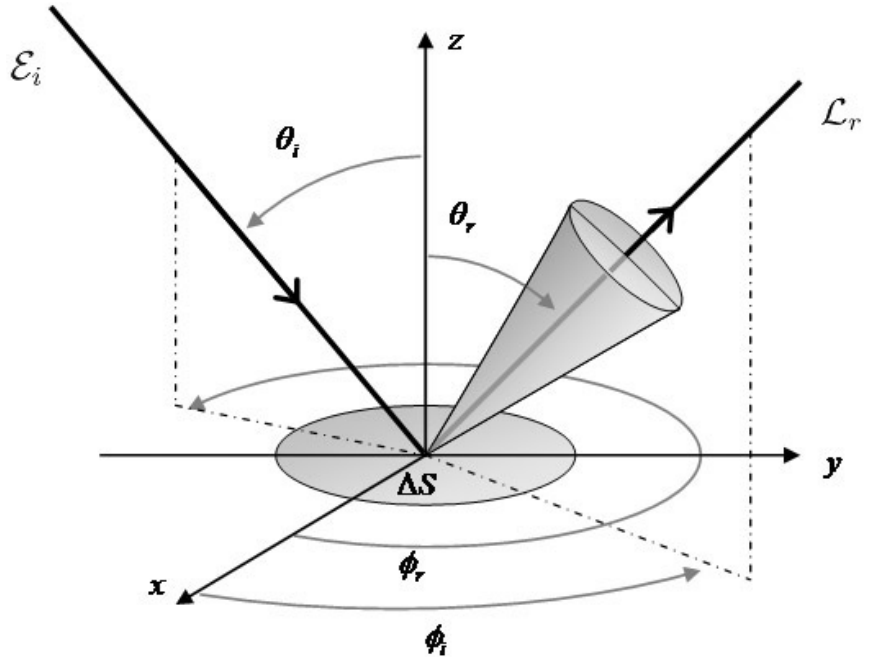
index *i* denotes element connected with *incident* spectral irradiance

index *r* denotes element connected with *reflected* spectral radiance

$\mathcal{E}_i$ is incident irradiance

L_r is reflected radiance





BRDF in the coordinate system

(Sensing & Measurement. Probing Optical Properties of Nanomaterials. © 2016 SPIE, n.d. Web. 25 Apr. 2016.)

Angles sign convention (ASTM)

Gonio-spectrophotometer

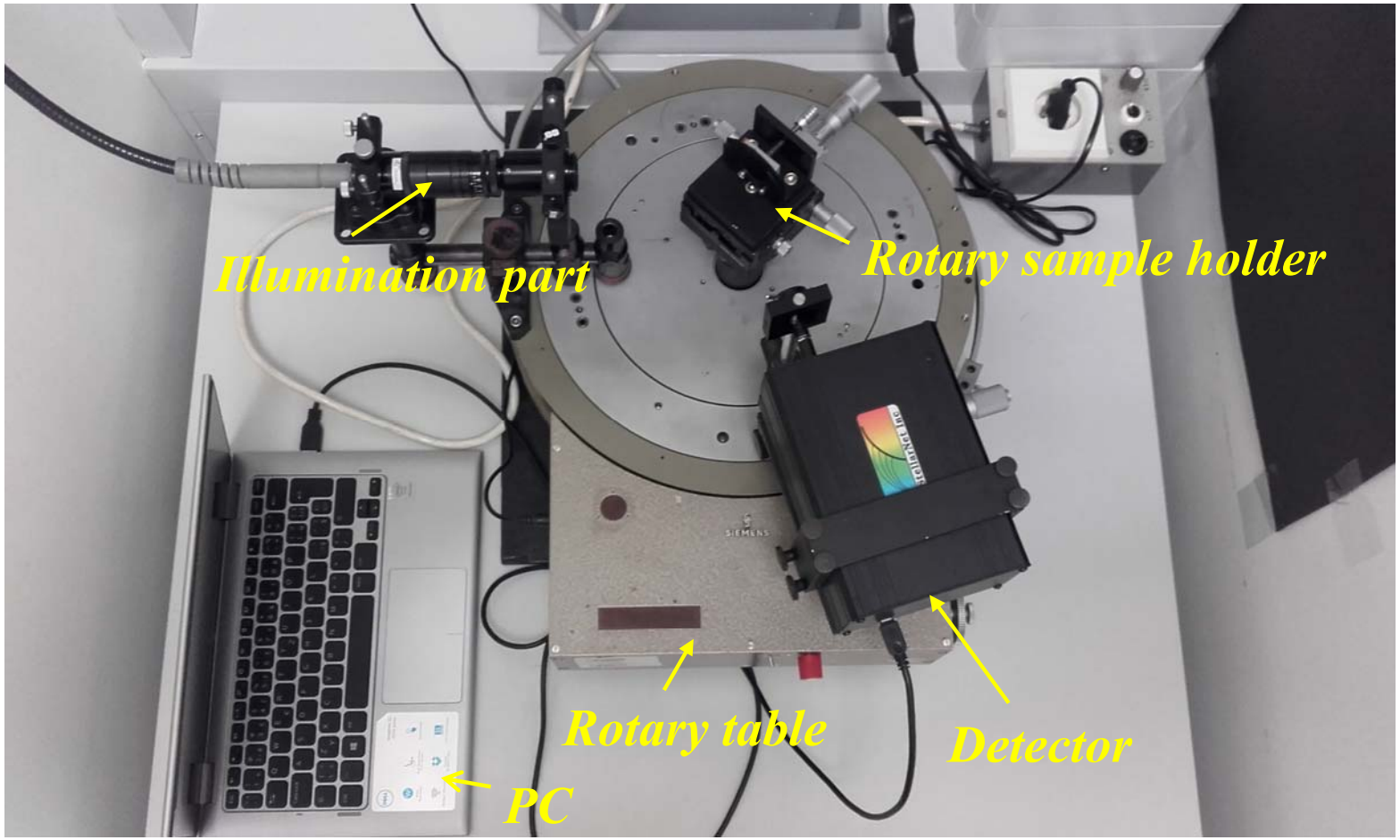
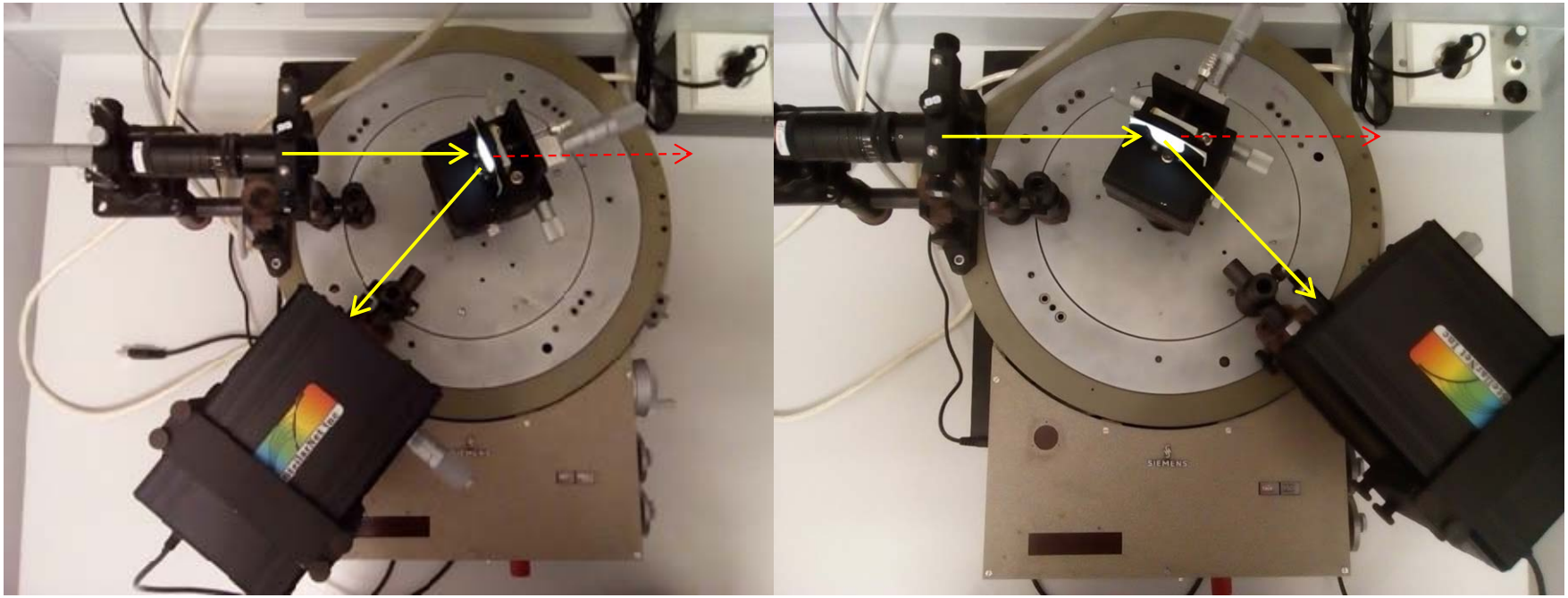


Illustration of two different incident and reflection angles for specular reflection



$\theta_i = 25\ deg, \theta_r = -25\ deg$

$\theta_i = 65\ deg, \theta_r = -65\ deg$

Parameters of gonio-spectrophotometer

Mechanical calibration

Settings of parameters in SpectraWiz program

- Detector integration time
- Number of Scans to Average
- XTiming resolution control

Calibration process is not easy (dependent on the user experience)

For us this work was entry to gonio-spectrophotometric measurements.

More sophisticated devices are commercially available (e.g. X-Rite MA9X).

Image source: www.xrite.com

Calculation of BRDF

Based on paper by Matsapey et al.

- Instead of „Direct flux“ the F_{45} for θ_i = 45 deg and θ_r = - 45 deg with Si wafer (with known reflectivity) and filter (to have the same integration time) was measured
- Incident irradiance

$$E_i = \frac{F_{45}(\lambda)\cdot\Omega_s}{S_0\cdot\Omega_d\cdot R_{Si}(\lambda)\cdot T_{filter}(\lambda)}\cdot cos(\theta_i)$$

- Reflected radiance

$$L_r = \frac{F_r(\lambda,\theta_r)}{S_0\cdot\Omega_d}$$

- BRDF

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

Ω_s – illumination solid angle, Ω_d – detection solid angle
S_0 – detection area, R_{Si} – reflectivity of silicon wafer
T_{filter} – transmission of the filter
θ_i – angle of incidence, θ_r – angle of reflection

Literature source: Matsapey N. et al., *Meas. Sci. Technol.* **24** (2013) 065901

Measured samples

Prepared on the print facility IGT

Three paper substrates

- Matt paper Luxosatin from Papyrus Group
- Glossy paper Chromolux from M-real Zanders
- Metallic paper with silver metallic paint

Seven printed colors Pantone Krypto

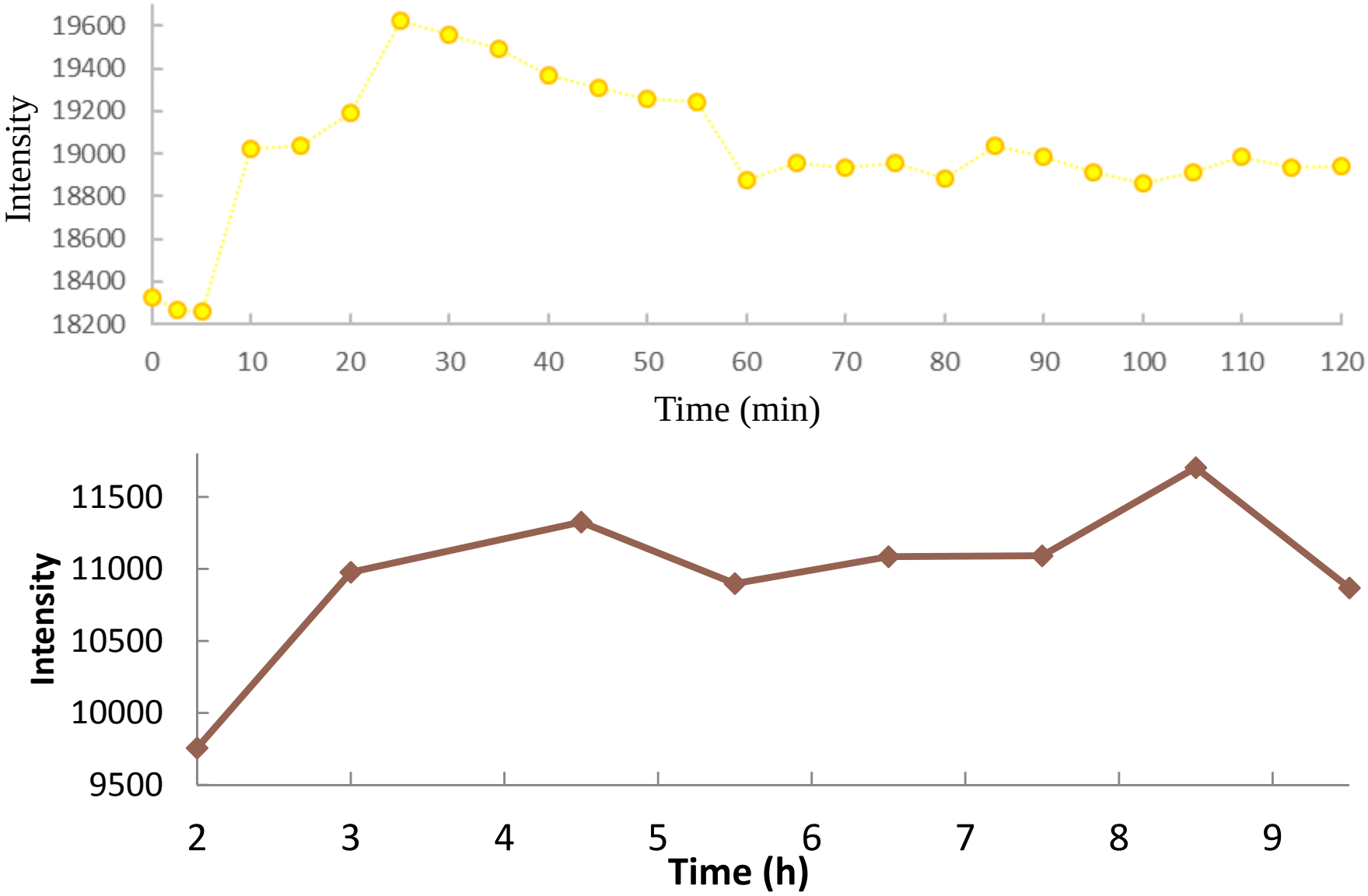
- Purple (P), Reflex Blue (RB), Proces Blue (PB), Green (G), Yellow (Y), Warm Red (WR) and Rubine Red (RR)

Measured incidence angles

- θ_i = 25 deg, θ_i = 35 deg, θ_i = 45 deg, θ_i = 55 deg, θ_i = 65 deg

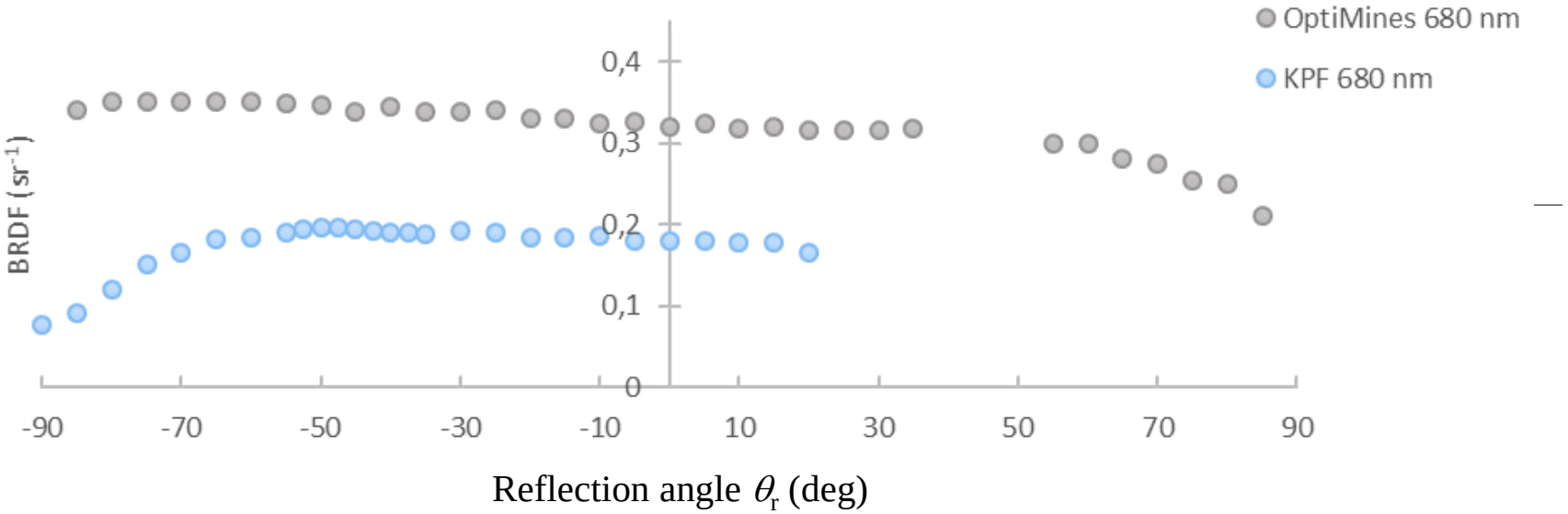
Step in measurement for reflection angle 5 deg, close to specular angle 2.5 deg

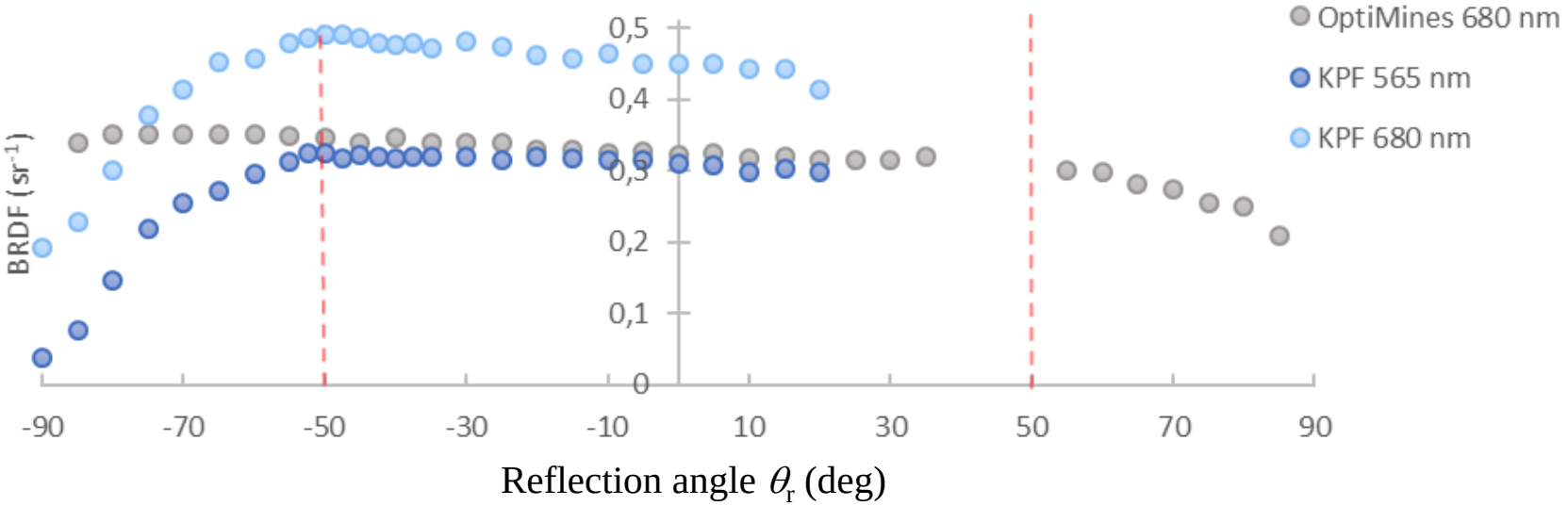
Stability of the gonio-spectrophotometer illumination source



Dependence of intensity of the gonio-spectrophotometer source on time after turning on. Measurement every 5 minutes (up). Measurement during whole day (down).

Measurement of Spectralon

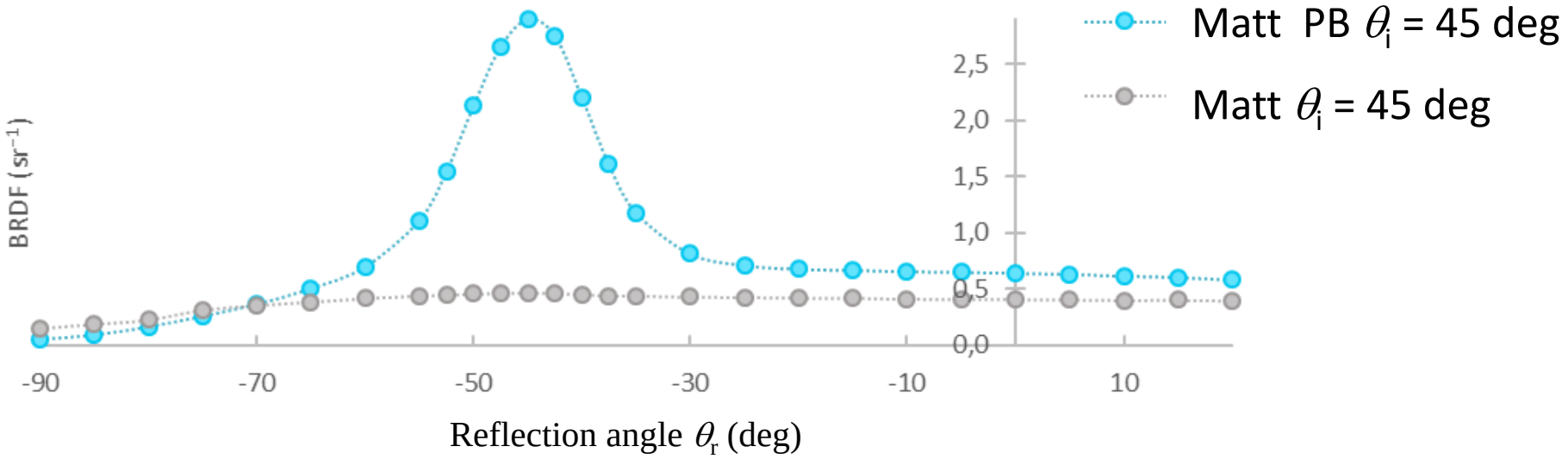




Comparison of BRDF of the Spectralon obtained from the literature and measured values (up). Comparison of the values after adjustment by the constant K (down).

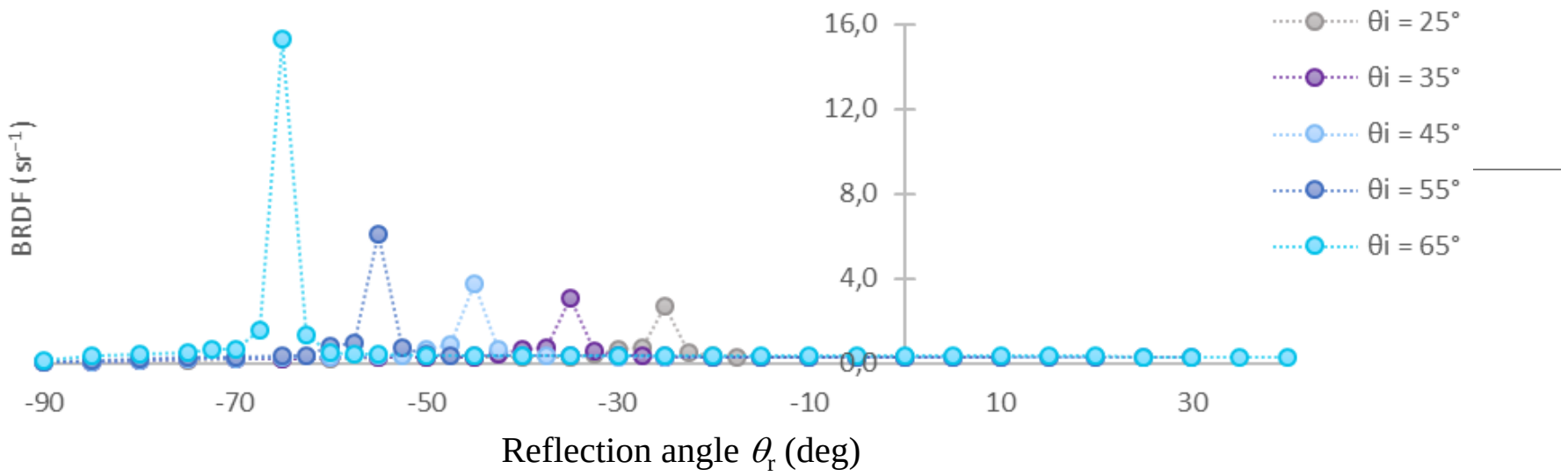
Literature source: OptiMines 680 nm = Bhandari A. et al., *Appl. Opt.* **50** (2011) 2431-42

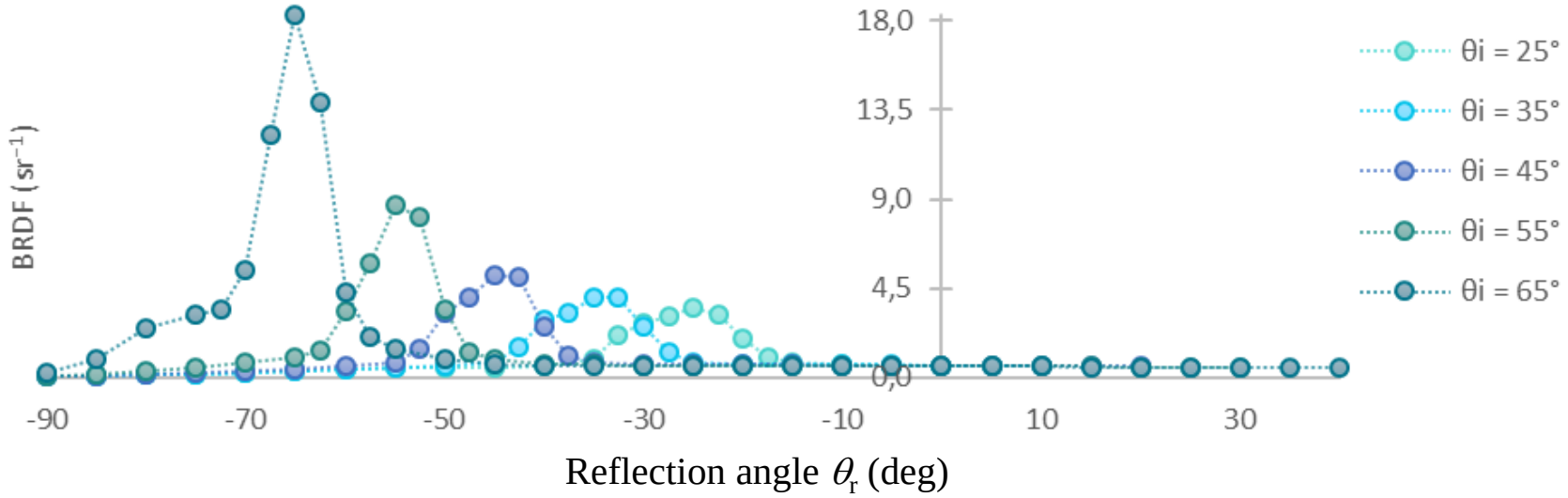
Comparison of matt substrate with the matt paper printed with the Proces Blue color



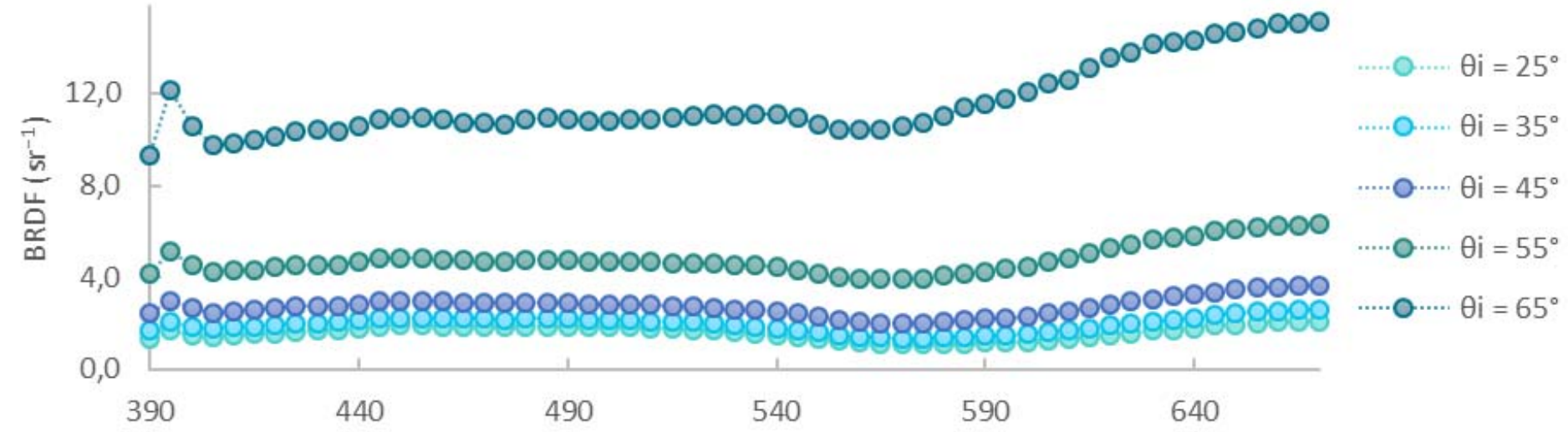
Dependence of BRDF on reflection angle (θ_i = 45 deg and wavelength 470 nm).

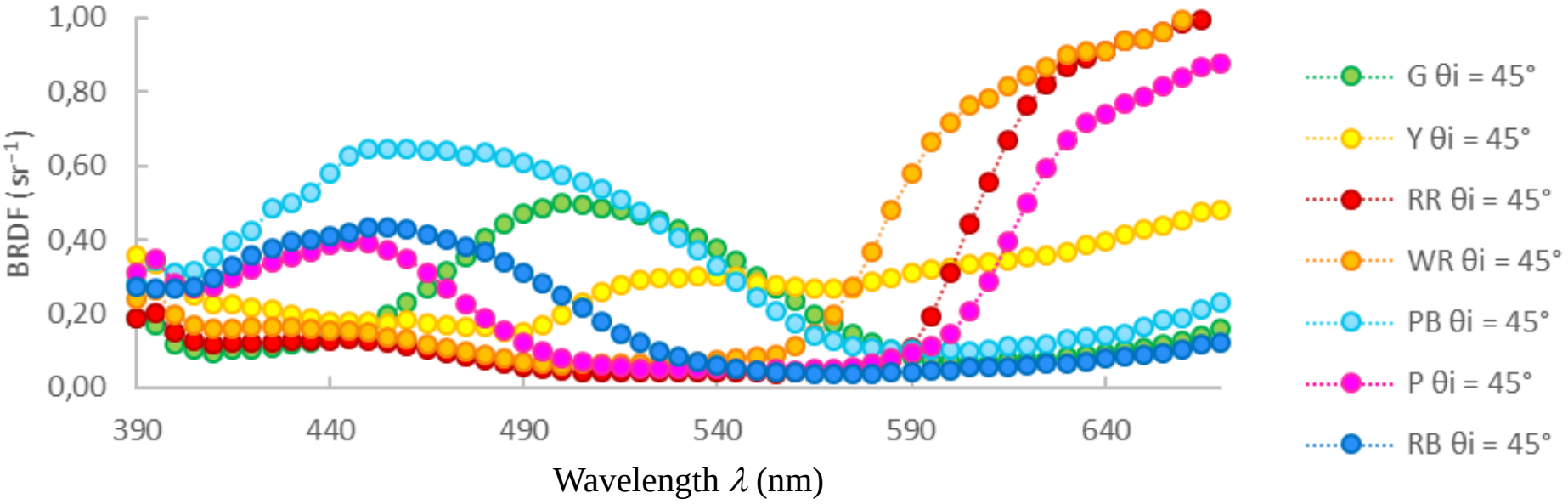
Comparison of dependence of BRDF on the reflection angle for glossy paper





Glossy paper substrate for wavelength 565 nm (up).
Glossy paper with Proces Blue color for wavelength 470 nm (down).

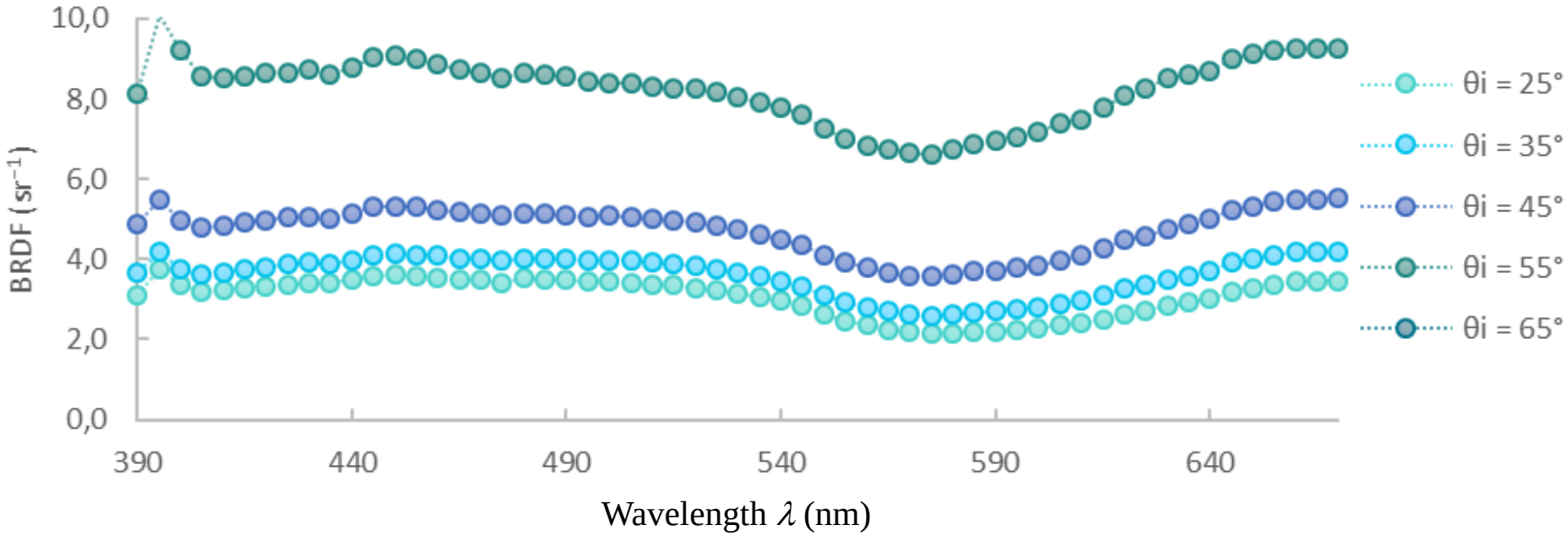


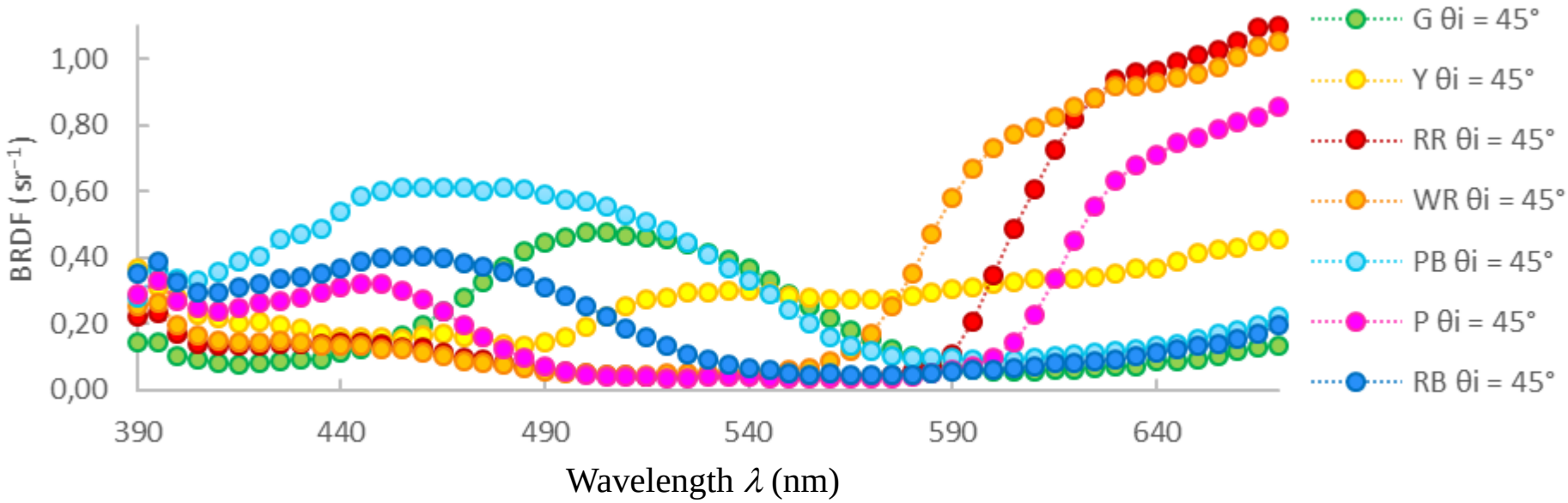


Mat paper substrate - comparison

For specular reflection, Proces Blue color (up).

For θ_i = 45 deg and θ_r = 0 deg for all colors (down).

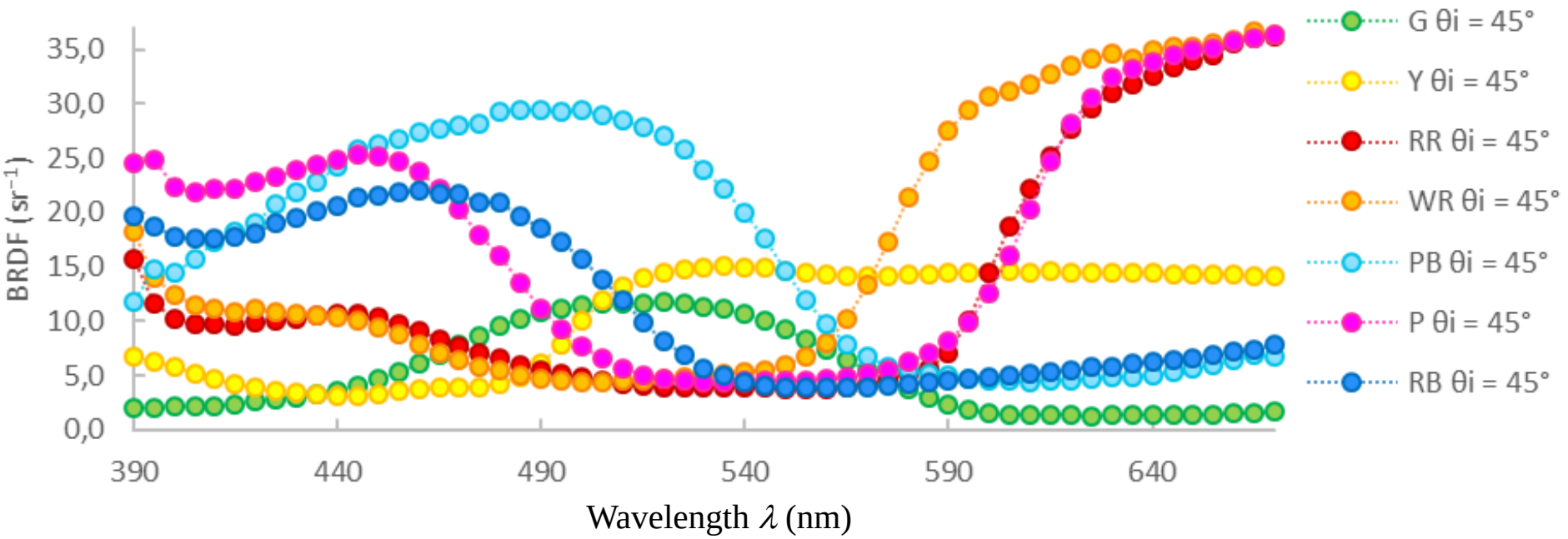


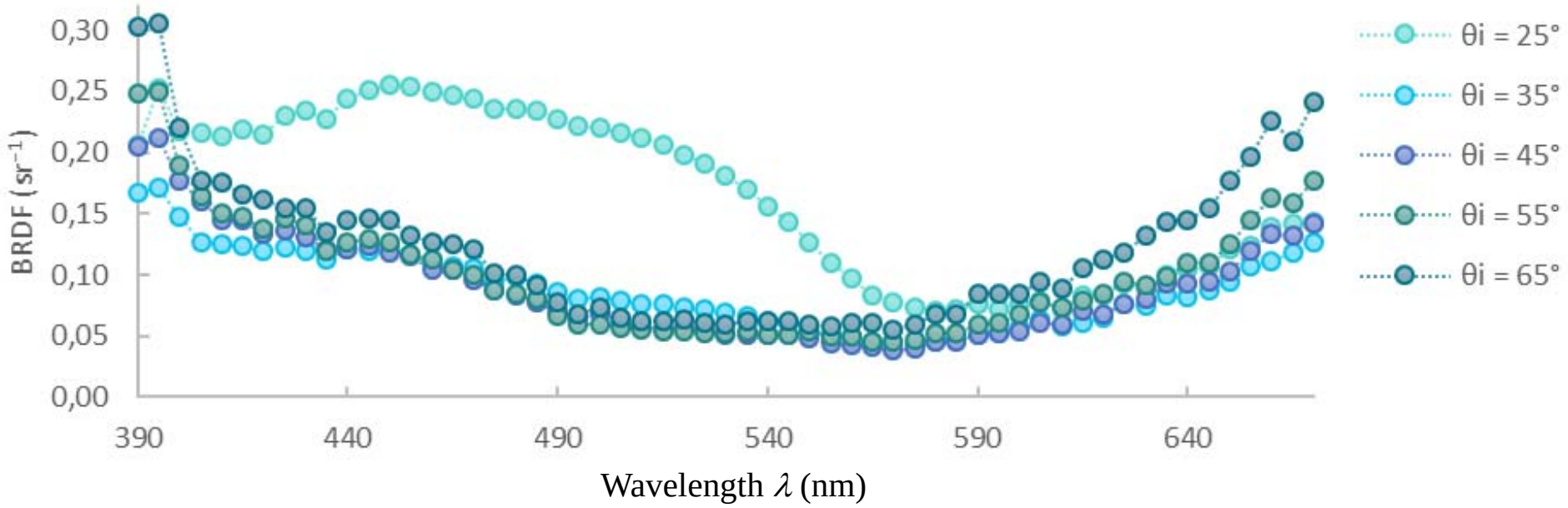


Glossy paper substrate - comparison

For specular reflection, Proces Blue color (up).

For θ_i = 45 deg and θ_r = 0 deg for all colors (down).





Metallic paper substrate - comparison

For specular reflection for all colors (up).

For θ_i = 45 deg and θ_r = 0 deg for Proces Blue color (down).

Calculated and measured *L**, *a**, *b**

	G	P	PB	RB	RR	WR	Y
	Method X_w,Y_w,Z_w/ Method $\hat{R}$						
ΔE^*_{ab}	**1,40**	**2,80**	**1,47**	**2,25**	**2,05**	**1,04**	**0,18**
	Method X_w,Y_w,Z_w/X-Rite						
ΔE^*_{ab}	**33,36**	**39,58**	**35,18**	**32,66**	**44,23**	**49,74**	**43,12**
ΔL	32,85	32,79	34,89	28,33	34,00	38,31	8,43
ΔC	2,09	18,97	4,44	15,10	28,29	31,71	40,97
ΔH	5,43	11,22	0,66	6,00	0,25	0,69	10,44
	Method $\hat{R}$ /X-Rite						
ΔE^*_{ab}	**32,88**	**37,48**	**34,87**	**31,98**	**42,54**	**49,31**	**43,20**
ΔL	32,54	31,96	34,40	27,91	33,25	38,40	8,45
ΔC	1,03	17,21	5,72	15,09	26,54	30,95	40,99
ΔH	4,57	9,32	0,15	4,00	0,40	0,11	10,70

For matt paper substrate

Conclusion

Custom made gonio - spectrophotometer can be used for measurement of BRDF of printed samples.

All data have to be multiplied by constant value to have the absolute values agreement (compared to theoretical/ literature Spectralon values).

In the spectral range from 390 nm to 670 nm the results match theoretical assumptions.

Pioneer work with promising results and open questions (stability of the light source, wavelength range, necessity of using constant *K* in calculations).