

# VALIDATION OF THE VIRTUAL GONIO-SPECTROPHOTOMETER BASED ON THE REAL MEASUREMENTS

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## Abstrakt

Navrhli sme virtuálny gonio-spektrofotometer schopný merať spektrum odrazeného svetla od povrchu materiálu, ktorý je reprezentovaný dvojsmernou distribučnou funkciou (BRDF). Náš virtuálny gonio-spektrofotometer je možné prispôbiť na merania spĺňajúce normy ako sú ISO 2813 alebo ASTM D523. Ukážeme aplikáciu navrhovaného virtuálneho gonio-spektrofotometra na ohodnotenie počítačovej reprezentácie vzhľadom na materiál použitím výsledkov meraní v laboratóriu. Virtuálny gonio-spektrofotometer je overený vzhľadom na merania získané reálnym gonio-spektrofotometrom, kde boli použité reálne vzorky materiálu. Prezentované overovanie je dosiahnuté porovnávaním celkového žiarivého toku odrazeného od reálnej vzorky a výpočtu prevedeného použitím matematickej reprezentácie vzorky ako je BRDF.

**Kľúčové slová:** meranie vzhľadom, lesk, BRDF

## Abstrakt

A virtual gonio-spectrophotometer is proposed to perform measurements of the reflectance spectrum of material surfaces mathematically represented by the bidirectional reflectance functions (BRDF). Our virtual gonio-spectrophotometer can be customized to allow measurements obeying industrial standards such as ISO 2813 or ASTM D523. We demonstrate the application of proposed virtual Gonio-spectrophotometer for the evaluation of digital representation of the material appearance utilizing laboratory measurements. Virtual gonio-spectrophotometer is validated according to measurements obtained with real gonio-spectrophotometer, where real material samples have been used. Presented validation is performed by measuring the total radiant flux reflected from real sample and comparing it to the mathematical representation of sample by BRDF.

**Keywords:** appearance measurements, gloss, BRDF

**Classification:** Rendering, Reflectance modeling

## 1 Introduction

The object appearance is determined by its surface geometry and the light scattering from it. To measure the surface properties, the gonio-spectrophotometers was developed [2]. A gonio-spectrophotometer is an instrument measuring the spectral distribution of reflected radiant power as a function of angles

of illumination and observation. The device consists of a light source aperture and a receptor enabling to orient them in variety of directions to perform comprehensive measurements.

Variety of the empirical models, that describe the reflection off the surface exist. An example is the empirical Wards's model [10], that uses the combination of functions capturing the reflection attributes such as the diffuse reflectance in all directions or the concentration of light scattering in a direction near the specular direction for glossy materials. Besides the empirical models, another sort of BRDF models exist applying the basic principles of physics to the surface microscopic structure, for example the Cook-Torrance's reflection model [3].

Manufacturers in industry often need to characterize the appearance of their products (eg. paint finish). Because of the complexity of full BRDF acquisition, it is more reasonable to rely on simple measurements often used in industry; those are for example, industrial spot measurement devices, such as colorimeters or glossmeters has been developed [4]. Glossmeters are build according to industrial standards such as ISO 2813 [8] or ASTM D523 [1], that define the geometry of specular gloss measurement including the incidence angles of light, and optics [7]. Gloss is the appearance attribute of surfaces that causes them to have appearance from shiny to mat. We can measure it by focusing on the light reflected off the surface and neglecting the material structure. Industrial standards prescribe black glass as a standard for the calibration of the gloss measuring devices. Perception of the gloss is influenced by physiological and psychological aspects of the human vision. Some psychophysically-based models of surface gloss have been found by multi-dimensional scaling algorithms based on the subjective evaluation of the images [12] [6].

Our goal is to design and implement the methodology devoted to the measurement, analysis and simulation of gloss and spectral reflectance from samples represented by BRDF. In practice, these measurements are generated by industrial devices using real material samples. Our task is to define the properties of a virtual surface generally represented by a BRDF and perform the measurements with the virtual device, simulating the real measurement device. Thus the obtained virtual measurements can be compared with actual measurements on real samples and afterwards we can evaluate the precision of virtual representation (model) of a surface scattering.

With the aim to find correspondence between the parameters of designed reflectance model and industrial measurement scales for albedo and gloss used by glossmeters and colorimeters, a concept of virtual gonio-spectrophotometer can be used. Virtual samples in such concept are represented by an analytical reflectance model and their parameters and complexity can be easily varied. Simulations can be further utilized for study of surface reflectance properties in many standardized scenarios.

Analytical model defines the scattering profile at a single point. Unfortunately, the measurement devices are unable to process a single ray or do the measurement at single point of the sample, therefore the virtual device should also do the measurements on a very small area corresponding to the real devices [11].

The remaining of this paper is organized as follows. In Section 2 we introduce definitions needed in our concept, in Section 3 we define the real measurement device measuring the optical characteristics of the material surface. Section 4 introduces the optical properties of a sample and properties of the light source required in our measurement concept. Proposed virtual device is described in Section 5. In Sections 6 and 7 we demonstrate some measurements on real samples and measurements on their respective virtual representations. In Section 8 we conclude our work by discussing the comparison of the virtual and real measurements.

## 2 Theoretical Background

To make physically-based numerical definitions, we need to define various expressions for how incident light energy is distributed by a material with respect to the position, direction, and wavelength.

The power radiated is referred to as the radiant flux  $\Phi$ . To find the flux  $\Phi(t)$  at a particular instant,

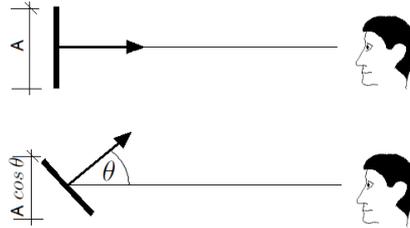


Fig. 1. The apparent size of a surface  $A$  is larger when it is projected in the direction of its surface normal, than when it is projected in a direction at an angle  $\theta$  to the normal.

we consider differential period of time  $dt$ . The differential amount of energy  $dQ$  transferred in  $dt$  is:

$$\Phi(t) = \frac{dQ}{dt}. \quad (1)$$

The average flux leaving per unit area, or radiant exitance  $M$ , is the total flux leaving divided by surface area  $A$ , or

$$M = \frac{\Phi}{A}. \quad (2)$$

To express the radiant exitance from a particular point  $(x, y)$  of the area, consider area around this particular point. By considering the infinitesimally small area  $dA$ , we can define the radiant exitance  $M(x, y)$  at a particular position:

$$M(x, y) = \frac{d\Phi(x, y)}{dA}. \quad (3)$$

This denotes the energy of light emitted from the point at coordinates  $(x, y)$  per second per unit area.

The radiant energy per unit time and area arriving at a surface is called the *irradiance*  $E$ . It is defined in the same manner as  $M$ , with the only difference being whether the radiant energy is approaching or leaving the surface.

To include directional effects, we should consider how the point of view affects perception of an area. When viewing direction is perpendicular to a patch then perceived area of this patch is greater than perceived area of a patch viewed at a more glancing angle, see Figure 1. Since we are dealing with infinitesimally small patches then, we can omit perspective deformation. Therefore the value of reduced area can be computed using orthogonal projection. Such projection is achieved by multiplication of the area by  $\cos \theta$ .

The key quantity radiance in a particular direction  $\Theta$  is defined as the radiant flux per unit solid angle and unit area projected in the direction  $\theta$  (angle between surface normal and direction  $\Theta$ ). The radiance  $L$  is defined as:

$$L(x, y, \Theta) = \frac{d\Phi(x, y, \Theta)}{\cos \theta dA d\omega}, \quad (4)$$

where  $d\omega$  is the solid angle. Solid angle is equal to the area of the segment of unit sphere.

The flux  $d\Phi(x, y, \Theta)$  is a fragment of flux  $d\Phi(x, y)$  emitted from infinitesimally small patch at  $(x, y)$ , which exits unit sphere through the solid angle  $d\omega$  in the direction  $\Theta$ , see Figure 2. Although rays emitted from a patch to an area of the solid angle may have not particular direction, when patch and solid angle become infinitesimally small, only rays from patch with the specific direction reach the area of the solid angle.

The other variable that we want to account for in addition to time, position, and direction, is a wavelength. To express flux, irradiance, radiant exitance, intensity, or radiance as a function of

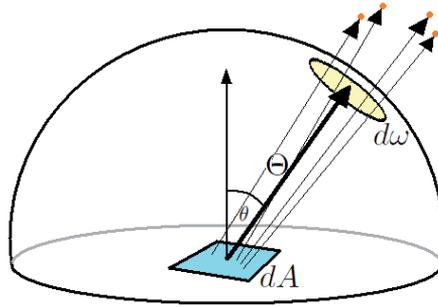


Fig. 2. Flux of the light emitted from the area  $dA$  exiting unit sphere through the solid angle.

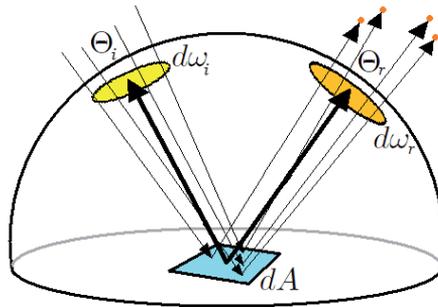


Fig. 3. Flux of the light entered unit sphere through  $d\omega_i$  and reflected from the area  $dA$  through solid angle  $d\omega_r$ .

wavelength, we consider the quantity at a value of  $\lambda$  within a small band of wavelengths between  $\lambda$  and  $\lambda + d\lambda$ . By associating a  $d\lambda$  with each value, we can integrate spectral values over the whole spectrum.

To describe how a surface redirects light, we consider light incident on the surface at  $\mathbf{x} = (x, y)$  with radiance  $L(\lambda, \mathbf{x} \leftarrow \Theta_i)$  (arrows mean that the light is emitted into particular direction from the surface point or is incident at the surface point, respectively) within a differential solid angle  $d\omega_i$ . The irradiance  $dE_i$  on the surface that will be either absorbed or redirected is:

$$dE_i(\lambda, \mathbf{x} \leftarrow \Theta_i) = L(\lambda, \mathbf{x} \leftarrow \Theta_i) \cos \theta_i d\omega_i. \quad (5)$$

The  $\cos \theta_i$  term appears because the radiance  $L$  means energy per unit area  $dA$  in the direction of travel  $\Theta_i$ , and that direction projected into the orientation of the surface we are considering is  $\cos \theta_i dA$ . The  $d\omega_i$  term enters in because we want to know the effect of energy coming from a single direction representing a differential section of all the possible directions above the surface. The light reflected by the surface in each direction can be described by the radiance in each direction. The effect of a material redirecting light is then given by a function that is the ratio of the radiance reflected in a particular direction  $\Theta_r$  as a result of the total incident flux per unit area from another direction  $\Theta_i$  as shown in Figure 3. This ratio is referred to as the BRDF defined by

$$f_r(\lambda, \mathbf{x}, \Theta_i \rightarrow \Theta_r) = \frac{dL_r(\lambda, \mathbf{x} \rightarrow \Theta_r)}{dE_i(\lambda, \mathbf{x} \leftarrow \Theta_i)}. \quad (6)$$

The BRDF is a distribution function, not a reflectance. It describes how the radiance is distributed in different directions, rather than expressing the fraction of energy reflected.

For physically correct BRDF, the fraction of the energy reflected to all directions from light incident in one direction must be between 0 and 1 if the surface is not emitting light

$$0 \leq \int_{\omega_r} f_r(\lambda, \mathbf{x}, \Theta_i \rightarrow \Theta_r) \cos \theta_r \, d\omega_r \leq 1. \quad (7)$$

## 2.1 Fresnel Reflectance

The Fresnel equations describe the amount of light is reflected and refracted at a perfectly smooth surface between two media.

The equations from the wave optics and polarization of light has to be considered. Key components of the Fresnel equations are the reflection coefficient (usually denoted  $F_r$ ), that gives the fraction of incident light that is reflected and the transmission coefficient  $F_t$ , that gives the fraction that is refracted. For parallel polarized light (p-polarized, the electric field oscillates in the plane of incidence) reflection coefficient is defined as:

$$r_{\parallel} = \frac{n_2 \cos \theta_i - n_1 \cos \theta_t}{n_2 \cos \theta_i + n_1 \cos \theta_t}. \quad (8)$$

For perpendicular polarized light (s-polarized, electric field oscillates perpendicular to plane of incident) it is:

$$r_{\perp} = \frac{n_1 \cos \theta_i - n_2 \cos \theta_t}{n_1 \cos \theta_i + n_2 \cos \theta_t}. \quad (9)$$

Here  $\theta_i$  and  $\theta_t$  are the angles between the surface normal and the directions of the incident and transmitted beams, and  $n_1$  and  $n_2$  are the indices of refraction of the media on the incident and transmitted side of the surface.

Note that  $r_{\parallel}$  and  $r_{\perp}$  describe the relationship between the amplitudes of the involved electric fields. For unpolarized light the reflection coefficient is

$$F_r = \frac{r_{\parallel}^2 + r_{\perp}^2}{2}. \quad (10)$$

The transmission coefficient is then

$$F_t = 1 - F_r. \quad (11)$$

Real materials are not perfect insulators. Therefore their index of refraction incorporates extinction coefficient  $k$ , that indicates the amount of absorption loss when the electromagnetic wave propagates through the material. Thus index of refraction can be written in complex form:

$$\hat{n} = n + ik, \quad (12)$$

where  $n$  is the refractive index indicating the phase velocity.

## 2.2 Cook-Torrance Reflectance Model

The Cook-Torrance model is a physically-based microfacet model that is focussed on (glossy) specular reflection [3]. It uses the surface roughness model developed by Torrance & Sparrow in [9]. This model treats surface as a collection of microscopic facets. The macroscopic optical properties of a surface are then analytically derived from properties of individual facets and statistical distributions of such properties.

Although, the surface has a normal  $\mathbf{N}$ , at a microscopic level the surface has height variations that result in many different surface orientations at a detailed level. At the perfectly flat surface a viewer is

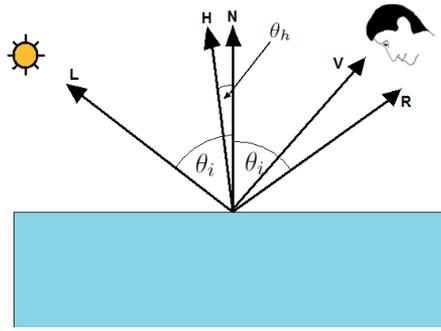


Fig. 4. The geometry of reflection showing the angle  $\theta_i$  between the surface normal  $\mathbf{N}$  and the direction of illumination  $\Theta_i \equiv \mathbf{L}$ .

able to see light source at the point where halfway vector  $\mathbf{H}$  is in the direction of an average surface normal  $\mathbf{N}$ . Halfway vector  $\mathbf{H}$  is a bisector of the angle between the direction of illumination  $\Theta_i \equiv \mathbf{L}$  and the viewer direction  $\Theta_r \equiv \mathbf{V}$ , see Figure 4.

Rather than explicitly model the small geometric features, general reflectance functions use statistical models. Statistical models are used because the variation in surface height is assumed to be irregular and random. A statistical model for surfaces in reflectance models generally takes the form of giving the distribution of facets that have a particular slope. The facet slope distribution function  $D$  represents the facets that are oriented in the direction  $\mathbf{H}$ . Let us consider parameter  $m$ , which is the root mean square slope of microfacets parameterizing the surface's roughness. Smaller values of  $m$  produces more specular appearance.

The commonly used distribution is the Beckmann distribution function. It is based on physical theory on scattering of electromagnetic waves and does not require the introduction of arbitrary constants. The formula is:

$$D = \frac{e^{-\frac{\tan^2 \alpha}{m^2}}}{m^2 \cos^4 \alpha}, \quad (13)$$

where alpha is the angle between the normal vector  $\mathbf{N}$  and the half vector  $\mathbf{H}$ .

If we assume V-grooved surface (Figure 5), then we need to count with self-shadowing and masking. The geometric attenuation factor  $G$  models the geometric effects shadowing and masking between microfacets that occur at larger angles of incidence or reflection. It is defined by the formula:

$$G = \min\left(1, \frac{2(\mathbf{H} \cdot \mathbf{N})(\mathbf{V} \cdot \mathbf{N})}{\mathbf{H} \cdot \mathbf{V}}, \frac{2(\mathbf{H} \cdot \mathbf{N})(\mathbf{L} \cdot \mathbf{N})}{\mathbf{H} \cdot \mathbf{V}}\right). \quad (14)$$

The Cook-Torrance model provides a good reproduction of the appearance of many real materials. Especially, metallic surfaces profit from the increased realism of the specular factor. Effects like the characteristic color shift towards the color of the incident light near grazing angles and the off-specular peak for very rough surfaces greatly improve the perceived realism of renderings. The off-specular peaks are the consequence of shadowing and masking causing asymmetries.

Combination of diffuse and specular component of Cook-Torrance's model can be written as:

$$f_r(\Theta_i \rightarrow \Theta_r) = \frac{k_d}{\pi} + k_s \frac{F_r D G}{\pi \cos \theta_i \cos \theta_r}, \quad (15)$$

where  $k_d + k_s \leq 1$ ,  $\theta_r$  is the angle between  $\mathbf{N}$  and  $\mathbf{V}$ , and  $F_r$  is Fresnel term given by the Equation 10. We assume mirrorlike microfacets which are reflecting the light from a source to the viewers direction just in constellation where  $\mathbf{H}$  is microfacet's normal.

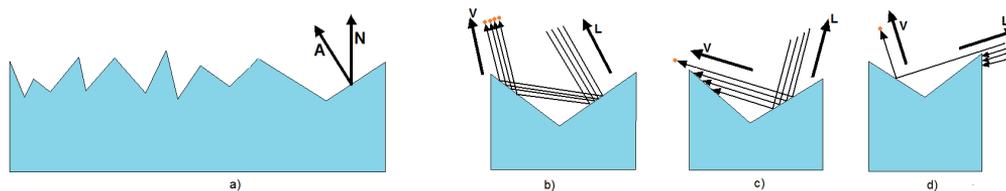


Fig. 5. Microfacet geometry. (a) Surface composed of microfacets with average normal  $N$ . Interaction between microfacets: (b) interreflection, (c) masking, (d) shadowing.

### 3 Definition of the Gonio-spectrophotometer

The measurement of the BRDF requires a system that consists of a light source, positioning system to hold a sample of the material, and a sensor that records the quantity of light scattered from the material. The measurement is performed usually by the measuring device such as gonio-spectrophotometer. A gonio-spectrophotometer is defined as an instrument that measures spectral power as a function of illumination and observation directions. The light flux that is incident on the material sample comes from an emitter. After being reflected by the surface, it is captured by a detector (spectrophotometer). For BRDF measurements the detector is placed on hemisphere above the sample. The device requires to move the receptor aperture and the light source. Both, the direction of illumination  $\Theta_i$  and viewing direction  $\Theta_r$  (see Figure 3) can be varied independently within the hemisphere above the material sample. The reflected flux is recorded for each position of the source and detector aperture. Number of positions depend on the angular accuracy of recorded BRDF. Since BRDF is reciprocal, that means we get the same results when we exchange the source and receptor aperture, the number of positions should be reduced to the half.

### 4 Required inputs

Proposed virtual gonio-spectrophotometer requires two inputs, a description of the spectrum of the illuminant and a description of the reflectance of the virtual surface described by the BRDF.

Illuminant is defined by its *spectral power distribution* (SPD). SPD is a representation of the radiant power emitted by a light source as a function of wavelength.

Although our implementation allows arbitrary SPD of the light source, in our experiments we use standard illuminant  $D_{65}$  sampled at 5nm intervals. Illuminant  $D_{65}$  defined by the International Commission on Illumination (CIE) represents the noon daylight with a correlated color temperature of approximately 6500 K.

To measure radiant flux reflected off the surface we need a description of how surface reflects the light in dependence of the angle of the illumination. Such distribution could be ensured by BRDF such as Cook-Torrance's BRDF.

In our experiments we have used complex refractive index of real materials as a function of the wavelength. This has been used to compute Fresnel term in analytical BRDF used in virtual measurements.

### 5 Virtual Gonio-spectrophotometer

In the simulation of gonio-spectrophotometer, the hemisphere over the sample is subdivided into small patches. Proposed virtual-goniospectrophotometer consists of light source and detector aperture. A patch belongs to the source or detector aperture (see Figure 6) if its position is close (within adjustable

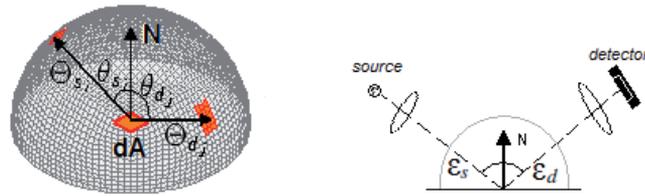


Fig. 6. Subdivided hemisphere and the geometry of the measurement. Angles  $\epsilon_s$  and  $\epsilon_d$  are angles between the surface normal and the direction to the center of source aperture and detector aperture, respectively.

tolerance which represents size of apertures) to direction of the illumination  $\Theta_i$  or observation  $\Theta_r$ , respectively.

Total flux reflected from the sample surface is computed by the sum of incident flux from the source aperture patches (from each source aperture patch in direction  $\Theta_{i_k}$ ) reflected toward the detector aperture patches (to each detector aperture patch in direction  $\Theta_{r_l}$ ). Thus total flux captured by the receptor aperture is computed by the numerical integration over the source and detector patches (adding the energy reflected from each patch  $i_k$  toward each patch  $r_l$ ).

To perform the integration over these apertures, we project them onto unit hemisphere. Then we subdivide hemisphere into the small patches (see Figure 6). Each patch area of the hemisphere serves us as the solid angle fraction. Particular radiant flux is coming through all source patches, that are incident with the surface. For each receptor patch, the contribution of reflected flux to this patch is computed. This leads to double summation, over the source and over the receptor aperture. The amount of energy reflected from the source to the receptor is determined by the BRDF. Total flux at a particular wavelength  $\lambda$ , reflected from patch at the surface area  $d\mathbf{A}$  reaching detector aperture is computed by following formula:

$$\begin{aligned} \Phi = d\mathbf{A} \sum_k L(\mathbf{x} \leftarrow \Theta_{i_k}) \cos(\theta_{i_k}) \Delta\omega_{i_k} \times \\ \times \sum_j f_r(\lambda, \mathbf{x}, \Theta_{i_k} \leftarrow \Theta_{r_l}) \cos(\theta_{r_l}) \Delta\omega_{d_l}, \end{aligned} \quad (16)$$

where  $d\mathbf{A}$  is area of a patch at the surface,  $\Delta\omega$  (index  $i$  refers to the source patches, index  $r$  refers to the detector patches) is area of particular patch on the hemisphere,  $\Theta$  is the direction from surface patch to the particular patch on the hemisphere,  $\theta$  is the angle between the surface normal and that direction, see Figure 6. Function  $f_r$  is BRDF and  $L$  is incident radiance, where fragment of the radiant flux  $\Phi$  is determined by the spectral energy of the light source.

The real measurement devices such as glossmeters can not measure the light reflection at a single point of the sample, but rather they measure reflection in a small region. Inhomogeneous surfaces such as metallic or pearlescent varnishes have varying  $f_r$  at each surface point. This can happen often when there is a drawing on the surface, for example. It is therefore necessary to divide the sample into smaller parts and make a calculation in each of its parts.

## 6 Real Measurements

To validate our virtual gonio-spectrophotometer, firstly, we calibrate our virtual gonio-spectrophotometer using real measured black glass. With calibrated virtual gonio-spectrophotometer we will simulate measurements of the material reflectance and we compare it with results of real reflectance measurements. For that purpose we set up reflectance measurement device, that measure spectral reflectance of the real material samples. This device consists of the light source and the spectrometer, see



Fig. 7. We set up the measuring device containing light source and spectrometer. Device is able to measure spectral reflectance under multiple angles.

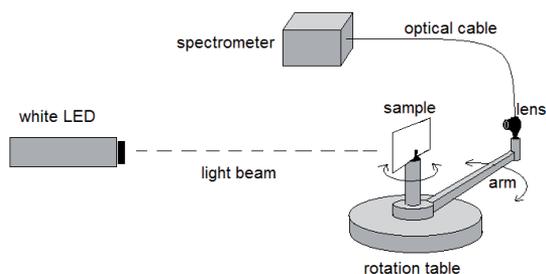


Fig. 8. Scheme of the device for the validation of the virtual gonio-spectrophotometer.

Figure 7. Light source is in the fixed position. It is LED STAR 2,5 WHITE 120LM/120° LAMBERTIAN with power input 2.5W, luminous flux 100-120 lm, radiation angle 120° and color temperature 6500-8000K. The receptor is able to move around the sample. It is connected by the optical cable to the spectrometer Solar S100 (grating 300l/mm, TCD linear image sensor, spectral range 190-1100nm, spectral resolution 1nm, dynamic range 900:1). The distance between the source and the sample is 90cm. The sample itself can be rotated in arbitrary angles.

In the Figure 8 is depicted scheme of the measuring device with two degrees of freedom. On the arm is in the distance of 20cm from the sample mounted lens with optic cable connected to the spectrometer.

We performed measurements of real material samples like polished copper and black glass. To compute relative reflectance, we performed measurements of the perfect mirror. Then we measured car paint samples. We obtained the absolute spectral power function from spectrometer. Then we divide absolute results with those obtained from perfect mirror which represent spectral power of the light source. Example of such result is depicted in the Figure 9.

For the purpose of the calibration we choose black glass with refractive index of 1.567. This

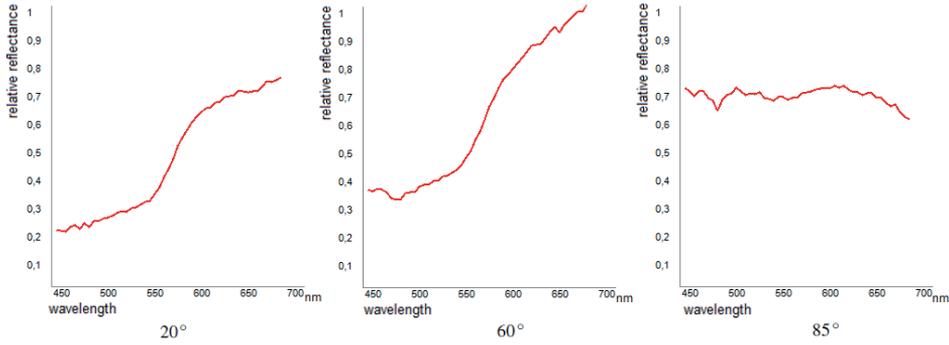


Fig. 9. Relative reflectance of the copper surface sample measured under angles  $20^\circ$ ,  $60^\circ$  and  $85^\circ$ .

material is referred as the standard for device calibration in industrial measurements according to ISO 2813. Also as we will see in the next chapter, we have mathematical expression of the black glass standard. Taking into account this fact, we can perform calibration of our virtual gonio-spectrophotometer following result given by real black glass.

## 7 Virtual Measurements

Industrial gloss measurements satisfy the standards such as ISO 2813 or ASTM D523. Those standards usually prescribe the measurement to be taken at angles  $20^\circ$ ,  $60^\circ$  and  $85^\circ$  to the surface normal (both directions, to the light source and detector are in the same plane with the surface normal;  $\epsilon_s = \epsilon_d = \{20^\circ, 60^\circ, 85^\circ\}$  in the Figure 6), because these degrees of specular gloss measurements offer numerical values which are roughly linearly correlated over a range of values to perceived gloss of high-gloss, medium-gloss and low-gloss surfaces, respectively [5].

### 7.1 Calibration of virtual measurements

The flux reflected off the black glass standard is computed by the following summation:

$$\Phi_{glass} = d\mathbf{A} \sum_k L(\mathbf{x} \leftarrow \Theta_{i_k}) \cos(\theta_{i_k}) \Delta\omega_{i_k} F_r(\cos \theta_{i_k}), \quad (17)$$

where  $F_r$  is Fresnel term (see Equation 10). We use complex refractive index  $\hat{n}$  as a function of the wavelength. Equation 17 is derived from Equation 16 by incorporating  $f_r$  of the black glass standard.

Our virtual measurement of black glass standard was used to find the correspondence with real measurement of black glass. We calibrate virtual gonio-spectrophotometer by setting the parameters that minimize the the root mean square error (RMSE) according to the real black glass measurements. We set the parameters and then we utilized our virtual gonio-spectrophotometer to perform computations of other samples.

Adjustable parameters of our virtual gonio-spectrophotometer are: angles to the detector and source aperture, size of the apertures and the refinement of the subdivided hemisphere. We simulated reflectance of the black glass standard using Equation 17. We performed simulations with variety of parameters setups. We set angles according to the mentioned standards to achieve correspondence with our real measurements of the black glass. Other parameters like aperture sizes and the degree of subdivision were varied. From the variety of setups we got one setup which produces minimal difference to the results acquired from real measurements of the black glass. We evaluated this difference in the terms of RMSE. By the minimization of this error we got virtual gonio-spectrophotometer parameters that we will use to calibrate our virtual gonio-spectrophotometer for the purpose of virtual

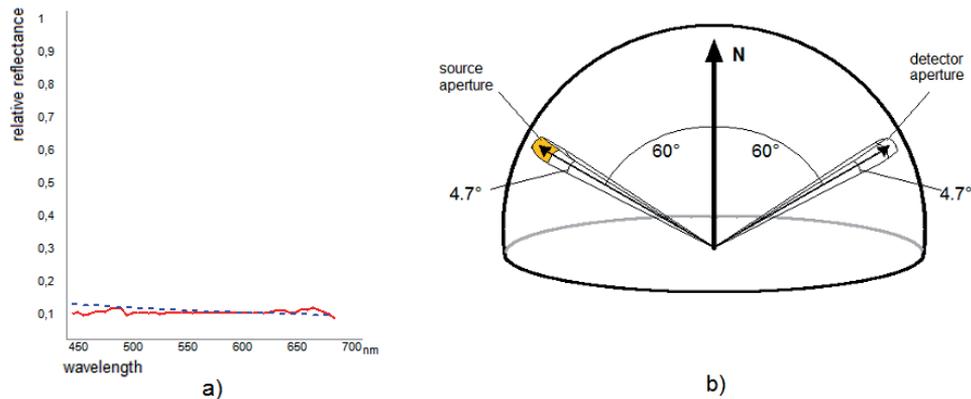


Fig. 10. a) Results of black glass real measurement (solid line) and virtual measurement (dotted line) measured under  $60^\circ$ . b) Geometry of the measurement.

measurements. RMSE describes difference between results of real measured black glass and the simulation. In our experiment, we found RMSE to be 0.0058 using 196608 patches per hemisphere. Further subdivision does not produce smaller error. We found that size of receptor aperture should be at least of the source aperture size. To find this minimal RMSE, we used angular source aperture size of  $4.7^\circ$  (see Figure 10 (b)) and we set detector aperture to the same size. Measurements was taken under  $60^\circ$  and the result of virtual and real measurements is depicted in Figure 10 (a).

## 8 Validation Results

We adjusted parameters of our virtual gonio-spectrophotometer according to the black glass measurements. To validate our virtual gonio-spectrophotometer we evaluate error of measurements based on the Cook-Torrance model. We choose copper as a sample because Cook-Torrance reflectance model proved as suitable approximation of metallic surfaces [3]. For the sake of comprehensiveness we also performed measurements of black glass based on this model.

Our virtual measurements was used to find the correspondence between real samples and analytical Cook-Torrance's  $f_r$  in the terms of RMSE. We empirically found the root mean square slope  $m$  (see Table 1) parameter of the Cook-Torrance model corresponding to the real samples. To evaluate Fresnel term in the Cook-Torrance formula, we used the real measured complex index of refraction, which is the function of the wavelength. Then we evaluated virtual measurements by comparing them with real measurements.

To compute spectral power we first perform computation of radiant flux  $\Phi$  using Equation 16 with  $f_r$  of the measured material, which is represented by the Cook-Torrance formula (see Equation 15). We set the parameters of the virtual gonio-spectrophotometer as we discussed earlier (see Section 7.1).

We performed real measurements of copper and black glass under three proposed angles ( $20^\circ$ ,  $60^\circ$  and  $85^\circ$ ). As a result we got relative spectral reflectance. We have computed reflectance of the virtual materials by our virtual gonio-spectrophotometer. We have compared results for the each sample and angle of measurement and computed relative RMSE. In Table 1 we can see parameter  $m$  of Cook-Torrance model and relative RMSE for each sample. In Figure 11 we can see the resulting relative reflectance from virtual and real measurements of the polished copper. Results of the black glass virtual measurements based on the Cook-Torrance's  $f_r$  are depicted in Figure 12. Virtual gonio-spectrophotometer based on the Cook-Torrance model, proves its robustness with error less then 5% in the case of the polished copper. In the case of the glass, results are affected by error, due to the nature of the Cook-Torrance model which is devoted mainly to the metallic materials.

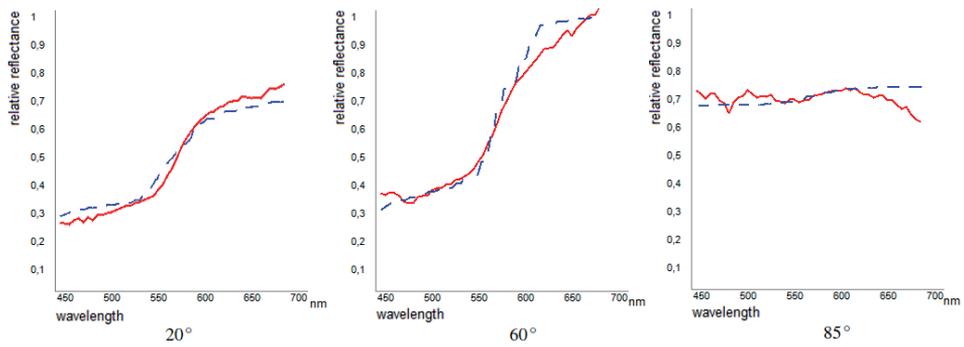


Fig. 11. Relative reflectance of the polished copper under 20°, 60° and 85°. Dotted line represents virtual measurements, solid line represents real measurements.

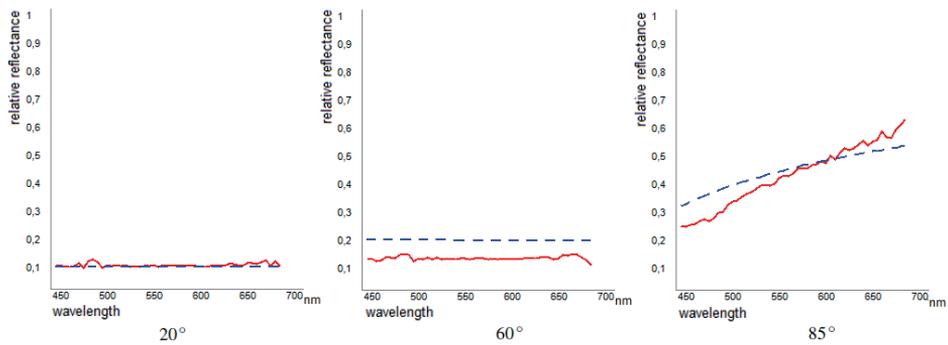


Fig. 12. Relative reflectance of the black glass standard under 20°, 60° and 85°. Dotted line represents virtual measurements, solid line represents real measurements.

## 9 Conclusion

We have developed Virtual Gonio-spectrophotometer, it consists of the simulator of the standard light source and the virtual receptor aperture, that performs measurements on the virtual material samples represented by the BRDF. The Virtual Gonio-spectrophotometer consists of the standard light source and the receptor aperture. Parameters of apertures (eg. position, size) are highly customizable to allow simulations of devices like colorimeter or glossmeter.

We have set up the real measuring device to evaluate our virtual gonio-spectrophotometer and to BRDF acquisition of the real materials. We have experimentally studied simple materials and compared the obtained results to simulations based on the analytical BRDF.

In the future we would like to focus on more complex materials such as metallic car paints. These materials exhibits sparkling effects, therefore their computer representation is more extensive (eg. bidirectional texture function).

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	relative RMSE (%)			$m$
	20°	60°	85°	
polished copper 	2.12	3.53	4.57	0.065
black glass 	0.94	6.44	21.65	0.013

Table 1. The root mean square error of the measurement under specific angle and the root mean square slope  $m$  of microfacets parameterizing the surface's roughness in Cook-Torrance model.

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