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Investigation of white standards by means of bidirectional reflection distribution function and integrating sphere methods

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The paper deals with investigation of the white Lambertian standards by means of optical methods, *i.e.*, the bidirectional reflection distribution function (BRDF) method and the reflectance study with an integrating sphere. All measurements have been made using the $L^*a^*b^*$ color system. The effect of the choice of a standard on values of trichromatic parameters and the effect of aging of standards is discussed.

Keywords: optical scattering, white standards, color measurements.

1. Introduction

The aim of our investigation was to determine the angular distribution of reflected light from most often used white standards and to examine their usability in the color measurements. White standards, applied in color systems, have to comply with several conditions, *i.e.*, the total reflectance should exhibit nearly a 100% reflection coefficient over the wavelength range 380–780 nm, the standards cannot show fluorescence in the UV–VIS–NIR spectral range, they should not exhibit electrization (in order to avoid attracting dust and impurities) and they are to be the proof of mechanical damage. A standard recommended by International Commission on Illumination (CIE) should be a perfectly reflecting diffuser which exhibits no absorbance over the range of use [1]. An ideal white standard has to fulfil the Lambert law, *i.e.*, the lighting power per solid angle I, diffused under angle θ_s to the normal to the reflected surface is

$I = I_0 \cos\theta_s$, where I_0 is the lighting power at 0°. White or gray diffusers which fulfil the Lambert law are called the Lambertian diffusers. The scattered light investigations rely on methods which allow one to choose the best standards for the most reliable measurements.

For the color measurements, standards made from magnesium oxide (MgO), barium sulfate ($BaSO_4$) and polytetrafluoroethylene (PTFE, commercially known as spectralon) are used. Some standards are made in the form of powder and some as packed pastilles. Presently, it is hard to find materials which exert the diffuse reflectance only. Most of them show more or less specular reflectance. This kind of reflectance is a source of significant errors in color or BRDF measurements. According to the Rayleigh criterion, even very good real diffusers become glossy when the incident beam is close to π/2. The best way to eliminate completely the specular reflectance is to use standards in the powder form. But they are often inconvenient to prepare and, moreover, they may cause trouble in certain experimental setups. Spectralon, as a new type of white standard, appears now to be most versatile because no preparation process is needed [2].

2. Experimental results and discussion

For optical measurements of real diffusers applied in our laboratory, two basic experimental methods have been used. The first utilizes an integrating sphere for determination of total and diffuse reflectance. The second measures the angular dependence of reflected radiation from the sample (BRDF). Both methods allow one to estimate deviation of real white standards from the ideal Lambertian diffuser.

The best way of estimating diffusers is to use biredirectional reflection distribution function (BRDF) method [3]. BRDF (in sr^{-1}) is the ratio of the incident radiance L_e to the sample irradiance E_e

$$\mathrm{BRDF} = \frac{L_e}{E_e} = \frac{P_s}{P_i\,\Omega \cos\theta_s} \tag{1}$$

where P_s is the scattered power, P_i is the power of incident beam, Ω is a solid angle and θ_s is a scattered angle. The parameters used in the BRDF measurements are shown in Fig. 1.

For standards in the form of powder, the radiation striking the surface penetrates into the volume and thus it does not represent an ideal (Lambertian) surface. In the first approximation, the solution for determining the angular dependence of the reflected radiation is found by using the Seelinger law [2, 4]

$$P_s = K \frac{\cos\theta_s \cos\phi}{\cos\theta_s + \cos\phi} \tag{2}$$

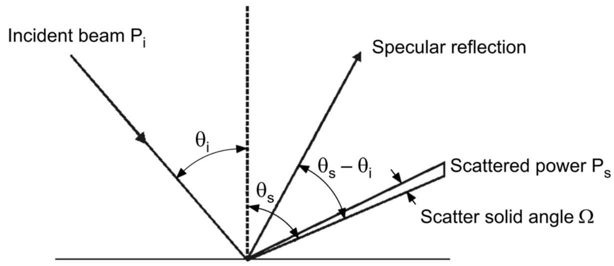

Fig. 1. Parameters used in the BRDF method.

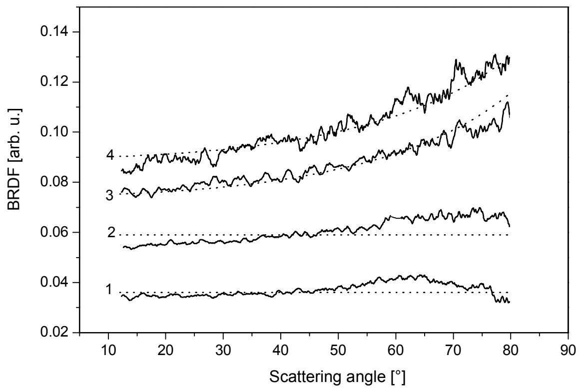

Fig. 2. BRDF plot for four white standards: spectralon (1), packed $BaSO_4$ (2), powdered MgO (3), and powdered $BaSO_4$ (4). Dotted straight lines 1 and 2 represent the ideal Lambertian diffusers, while dotted curves 3 and 4 represent the Seelinger diffusers.

where K is a constant dependent on the absorption coefficient k and ϕ is the incidence angle. According to this formula, the intensity of scattered light increases with an increase of scattered angle θ_s.

Two processes occur when the incident energy interacts with the reflecting surface: i) the specular reflection at the sample surface, and the larger the absorption, the larger the specular reflectance, and ii) selective absorption in the volume of sample. Deviations from the Lambert law increase with increasing angles θ_s and ϕ.

For BRDF measurements, the goniometric table with a 0.01° resolution has been adapted. A 650 nm laser diode as a light source and Si diode as a detector have been used. Figure 2 shows the intensity of diffused light *vs*. scattered angle for four white standards, measured at the incidence angle equal to 60°. The Lambertian ideal diffusers are represented by dotted constant straight lines. The larger the deviation from the plateau line, the lower the class of diffuser. As can be seen from Fig. 2, two packed standards, *i.e.*, spectralon (1) and $BaSO_4$ (2), resemble the Lambertian diffusers, while the other two powdered standards, *i.e.*, MgO (3) and $BaSO_4$ (4), show rather the Seelinger diffuser behavior represented by dotted curves fitted to the experimental data.

The main factor influencing the Lambertian properties of standards is adsorption of impurities on the surface. Even if reflectance is relatively high (more than 95%), an impure standard cannot be considered as the Lambertian diffuser.

The BRDF measurements allow one to estimate the quality of standards and control their refurbishing process. Figure 3 shows the same spectralon sample before (**a**),

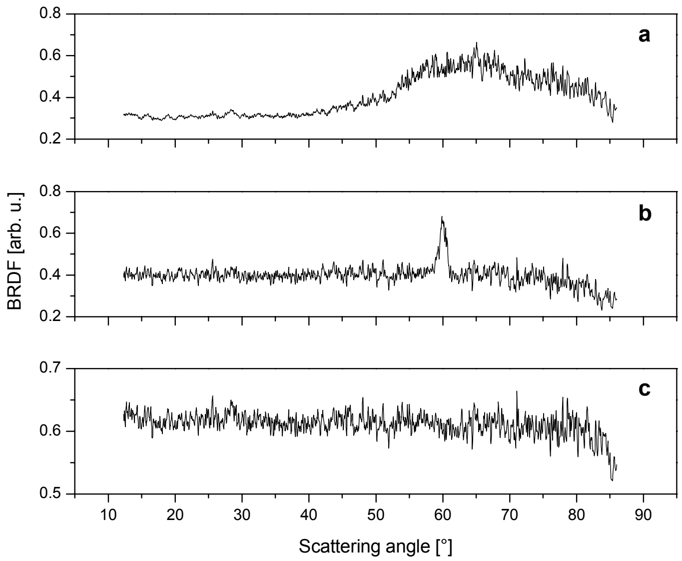

Fig. 3. BRDF plot of the same spectralon sample before (**a**), during (**b**) and after (**c**) the cleaning process (the incidence angle is 60°).

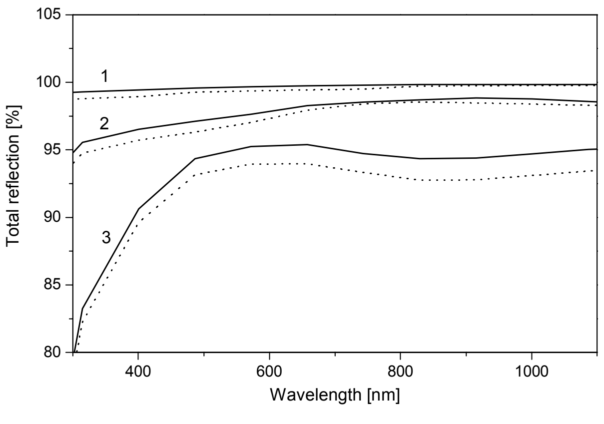

Fig. 4. Wavelength dependence of total reflectance for three white standards: spectralon (1), packed $BaSO_4$ (2), and powdered MgO (3). Solid and dashed lines represent new factory-made standards and the same standards after three-year exploitation, respectively.

during (**b**) and after (**c**) the cleaning process. The use of nitrogen bath and deionizated water in an ultrasound chamber causes the flattening of the BRDF curve and improves diffusive properties of the spectralon standard (*cf.* Figs. 3**a** and 3**b**). A small specular reflection peak visible in Fig. 3**b** has been easily removed by a slight sanding (Fig. 3**c**).

For photometric measurements of standards, the Perkin–Elmer double-beam integrating sphere over the range 300–1200 nm has been used [5]. We have studied white standards approved by NIST (National Institute of Standards and Technology, USA). Figure 4 shows the total reflectance spectra of three standards. The same investigation has been repeated for the standards after the three-year exploitation. As can be seen from Fig. 4, a decrease of reflectivity with time is the smallest for spectralon.

3. Color measurements

Measurements of color glass DARK GREEN (Volkswagen windscreens) by means of the ISP-REF integrating sphere (Avantes Co.) have been performed (Fig. 5). The sphere is a single-beam Ulbricht ball of 60 mm in diameter with a built-in tungsten-halogen lamp as a light source and sample is illuminated with the diffuse light. The reflected light signal is collected at 8° angle from the normal (so-called *d*/0° geometry). A light trap switch has made it possible to include the specular reflectance (switch on) or only the diffuse reflection (switch off). The light collected from the output port is transmitted through an optical fiber and dispersed via fixed grating across a CCD linear detector which is responsive in the range 300–1100 nm. Color parameters have been determined using the $L^*a^*b^*$ system for the D65 illuminant. In this system, color is represented by a point with three-dimensional coordinates, *i.e.*, luminance L ranging from 0 to 100, and hue coordinates a and b ranging from –120 to +120. The nominal values of color parameters of the investigated glass have been established by the producer as $L = 34.4$, $a = -2.3$ and $b = 0.2$.

Justification of the experimental setup requires the reference measurements by using a white standard. The results, of course, depend on the choice of reference and their accordance with the ideal Lambertian diffuser for which $L = 100$, $a = 0$ and $b = 0$. For analysis of variability of color parameters, we have used the formulae listed below

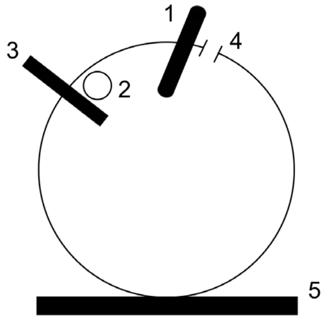

Fig. 5. Scheme of integrating sphere of *d*/0°-type: 1, 3 – apertures for total reflectance measurements, 2 – light source, 4 – output port for collected light, 5 – examined or reference sample.

which, in a quantitative way, show differences between parameters characterizing two colors (1 and 2), and are defined in various spaces, according to CIE [6], as follows:

– luminance space

$$\Delta L = L_1 - L_2$$

– hue space

$$\Delta a = a_1 - a_2, \quad \Delta b = b_1 - b_2$$

– total color space

$$\Delta E = \sqrt{(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2}$$

– chromaticity space

$$\Delta C = \sqrt{a_1^2 + b_1^2} - \sqrt{a_2^2 + b_2^2}$$

The Table shows the results for the DARK GREEN glass. The setup has been subsequently calibrated by means of spectralon, $BaSO_4$ and MgO, and the same standards after the three-year exploitation. The results are presented in the growing order of the values of ΔC and ΔE.

T a b l e. Color spaces for the DARK GREEN glass.

Standards	Color spaces				
	ΔL	Δa	Δb	ΔC	ΔE
Spectralon (2004)	–0.60	0.3	–0.1	1.13	0.56
$BaSO_4$ (powder)	0.72	0.4	–0.5	1.73	1.13
Spectralon (2001)	0.91	0.3	–0.4	1.51	1.21
$BaSO_4$ (packed 2001)	1.22	0.4	0.7	1.92	2.33
MgO (powder)	2.30	1.1	–0.6	3.11	3.70

In most color measurements, differences $\Delta a < 0.5$, $\Delta b < 0.5$ and $\Delta L < 1$ are acceptable for industrial applications [7]. Thus, if the standards are kept in good conditions, results of color measurements may be reliable, even for older standards.

4. Conclusions

The BRDF and spectral reflectance measurements appear to be a very convenient tool for evaluating the quality of white standards. As follows from these studies, packed standards are more Lambertian, while powdered standards exhibit the Sellinger diffuser properties. Both kinds of standards can be used in color measurements as a reference. The effect of aging is observed in packed standards but it does not influence the results of color measurements (according to the norms approved in industrial applications). The BRDF measurements are also very useful when estimating the refurbishing process of packed white standards.

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