FULL 3D BSDF SPECTRORADIOMETER

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ABSTRACT

To expedite colour and gloss measurements, the CIE and ASTM have recommended some basic geometries regarding illumination and viewing angles. There are, however, many surfaces that cannot be adequately measured using such limited conditions. Any gloss and colour measurement can be related to some particular value of the general spectral Bidirectional Scatter Distribution Function (BSDF). In our laboratory, we have built a goniospectroradiometer which allows us to determine the absolute BSDF of an object. Spectral properties can be measured at any spherical angle of illumination and at almost any spherical viewing angle using a detector circulating around the sample with two degrees of freedom. Absolute spectral BSDF values can be calculated from dark current corrected CCD readings (counts) according to ASTM E1392. Spectral and spatial characteristics of the instrument are determined and some measurement results on different kind of samples are reported.

Keywords: Bidirectional Scatter Distribution Function (BSDF), goniospectroradiometer

1. INTRODUCTION

To expedite colour and gloss measurements, the CIE and ASTM have recommended some basic geometries regarding illumination and viewing angles. These specific geometries are usually implemented in colour and gloss measuring instruments respectively.

There are, however, many surfaces that cannot be adequately measured using such limited conditions. Gonio-apparent or special-effect colours (e.g. coloured, metallic finishes, applied to many automobiles) which change in colour according to the angle of illumination and viewing, have rapidly grown in popularity over the last 50 years. Nowadays, dramatic colour effects can be achieved. Furthermore, the gloss values of very matt and black samples are too low to be measured accurately by industrial gloss meters.

Any gloss and colour measurement can be related to some particular value of the general spectral Bidirectional Scatter Distribution Function (BSDF). The use of a multifunctional spectroradiometer to measure this BSDF is an interesting method to study all issues related to colour and gloss characterization.

In addition to the description of the visual appearance of a material, the determination of BSDF is also important in lighting technology. Ray tracing software used for luminaire design requires the BSDF of any material in the luminaire which interacts with the light emitted by the light source.

Our aim was to build a goniospectroradiometer which allows us to determine the absolute Bidirectional Scatter Distribution Function (BSDF) of an object. Spectral properties can be measured at any spherical angle of illumination of the sample and at (almost) any spherical viewing angle using a detector circulating around the sample with two degrees of freedom.

2. OPTICAL LAYOUT

The spectral BSDF $q_{e,\lambda}$ can be defined as the differential spectral radiance $dL_{e,\lambda}$ of a sample observed in a specific observation angle characterized by spherical coordinates (θ_s, φ_s) due to the scattering of incident radiation characterized by the differential spectral irradiance $dE_{e,\lambda}$ received from a specific angle of incidence (θ_i, φ_i) [1]:

$$q_{e,\lambda} = \frac{dL_{e,\lambda}}{dE_{e,\lambda}} \quad (1)$$

According to ASTM E1392 [2], the practical formula used to determine the absolute BSDF under condition that the field of view of the receiver field stop is sufficiently large enough to include the entire illuminated area for all angles of interest, can be written as

$$q_{e,\lambda} = \frac{\Phi_{e,\lambda,s}}{\Phi_{e,\lambda,i}.\Omega_s.\left|\cos\theta_S\right|} \quad (2)$$

where $\Phi_{e,\lambda,i}$ and $\Phi_{e,\lambda,s}$ is the spectral distribution of radiant flux received by the sample and the detector respectively, and Ω_s is the solid angle subtended by the receiver aperture stop from the sample origin. The illuminated area need not be known. Because the incident and scattered flux is measured with the same detector head, the flux ratio is equal to the ratio of the detector responses at each wavelength.

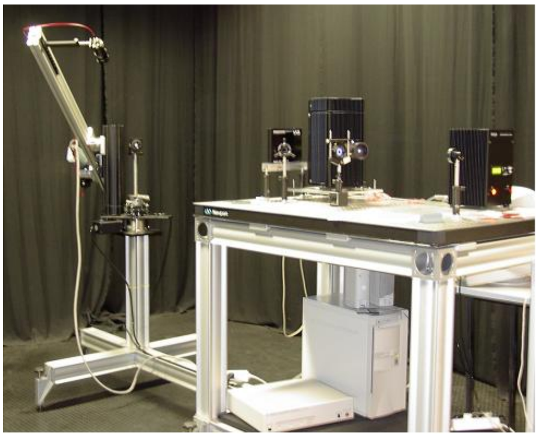

Figure 1. Picture of the BSDF goniospectroradiometer

A picture of the instrument is shown in Figure 1 and the optical layout is presented in Figure 2. A 300W Xe light source (Müller GmbH SVX1530 + XM300-HS) is used for the illumination of the sample [3]. Having large emission intensities in the blue-violet region of the visual spectrum, a better signal-to-noise ratio can be achieved when compared to halogen illumination. A condenser lens images the discharge on to a mirror at a distance of 65 cm. A diaphragm selects the central part of the condenser (5 mm diameter). The radiance of this central spot is uniform to within 5 %. A concave mirror (Newport 20DC1000AL.2 with 500mm focal length) images this diaphragm on to the receiver when the latter is aligned with the incident beam. The image with diameter 2 cm is smaller then the maximum aperture of the detector head (diameter 2.47 cm). Using this set-up, it is possible to measure the power incident on the sample without the need to position the detector head at the sample plane. Furthermore, the reflectance and the transmittance of specular samples can be obtained easily by dividing the received radiant flux by the incident flux, without execution of a spatial scan.

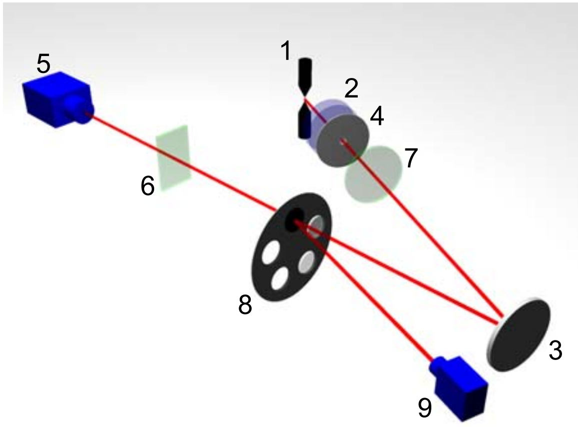

Figure 2. Optical layout of the spectroradiometer: (1) Xenon discharge, (2) condensor, (3) spherical miror, (4) iris diafragm, (5) detector head, (6) sample holder, (7) long-wave pass filter, (8) filter wheel, (9) reference detector.

Before hitting the sample, the incident beam passes through a long-wave pass filter (Schott CG-GG-385) to eliminate second-order wavelengths over the visible spectrum and to absorb the UV-radiation from the light source. Additionally the light beam passes through an automated filter wheel with five positions: blank, opaque and three neutral density (ND) filters. In addition to the variable integration time of the CCD, the three ND-filters extend the dynamic range as will be described later. The spectral transmittance of the filters is determined by measuring the detector response with and without the filter. Read-out of the "dark" signal is performed when the opaque filter obstructs the beam. The reflection of this filter provides a reference beam which is measured by a silicon photodiode. In this way, we are able to monitor and to correct for short-term fluctuations and long-term drift of the Xenon light output.

Measurements using a rotating polarizer show a negligible degree of polarization of the incident radiation. However, it is possible to introduce a (de)polarizer in the optical path.

The sample holder has an aperture in order to measure the incident flux and the bidirectional transmission distribution function BTDF. Incident angles are distributed around the central value with a maximum deviation of 0,5°.

The detector head is located 705 mm from the sample plane and is made up by a 1,5 inch fused silica plano-convex lens (f= 63 mm), coated with an anti-reflective layer, and an iris diaphragm just in front of it. The lens images the illuminated sample area on to an aperture (diameter 2 mm) drilled in the wall of a small integrating cylindrical cavity (internal diameter 5 mm). This aperture determines the field of view, which is larger than the illuminated area on the sample, as required by Eq. (2). The solid angle subtended by the receiver aperture stop from the sample origin is 9,6 10^{-4} sr, corresponding to a plane acceptance angle of 2,0°. This angular resolution can improve when the diaphragm aperture is made smaller, loosing the possibility of absolute measurements (exept when a laser light source is used).

In the base of the cavity, a circular high-grade fused silica fibre bundle is positioned and the incoming radiation is outside of the acceptance cone of the fibre.

The rectangular fibre end termination (200 µm by 6 mm) is coupled to a 1/8 m Oriel spectrometer and is used to replace the input slit of the instrument. The (interchangeable) grating has a line density of 400 lines/mm. At the spectrometer exit plane, a 1 inch Andor open electrode, cooled (-20°C) CCD detector is mounted. With 1024 pixel columns, a spectral resolution of five nm can be obtained and the complete visible spectrum can be measured. Data acquisition with full vertical binning, dark current correction and integration time setting for optimum signal-to-noise ratio is controlled by software.

The spectrograph is mounted on the horizontal rotation axis of the detector head. In this way, the inertia can be kept low and the fibre curvature remains unchanged during measurements.

3. ANGULAR SETUP

The orientation of the incident beam remains fixed in space. The angle of incidence of the light beam can be adjusted using two manual rotation stages shown in Figure 3. By rotating stage 1 and stage 2, any angles θ_i and φ_i can be established. Axis 1 has a resolution of 1', while the resolution of axis 2 is equal to 1°.

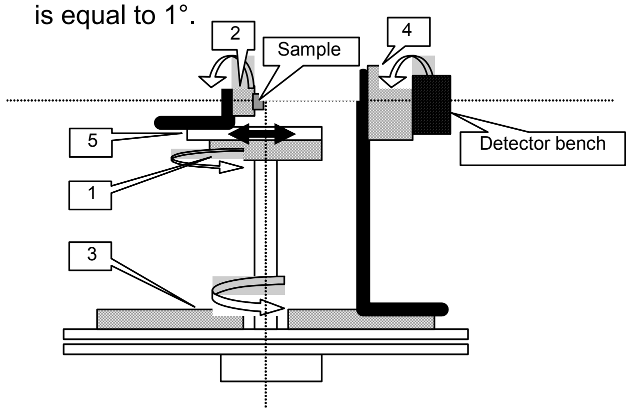

Figure 3. Sample holder with two rotation stages (1 and 2) and a translation stage 5. The detector bench is mounted on a vertical rotation stage 4; this unit is fixed with a bracket on rotation stage 3.

The detector head is mounted on an optical bench of length 1 m. The viewing angle is established by a horizontal and a vertical motorized annular rotation stage (Newport RV 120PE) referenced in Figure 3 as number 3 and 4. Both stages are equipped with an UE41PP stepper motor with an angular resolution of 0,001°. In the lower hemisphere, θ_s is limited by the horizontal mounting table to 85°. The incident beam will be obscured by the detector head over no more than 5°.

The alignment of the four rotation stages, the sample holder and the illumination optics is performed using two perpendicular laser beams. The lasers are fixed on the ceiling (vertical beam) and the wall (horizontal beam) of the laboratory. The intersection of both laser beams determines the rotation center of the sample.

In order to take into consideration the variable thickness of the samples, the sample holder can be horizontally translated using a translation table. The translation travel equals 25 mm, with a resolution of 0,01 mm.

4. RESULTS AND DISCUSSION

4.1 Instrument signature

Measuring the BTDF with no sample in the sample holder provides the instrument signature. The non-interrupted light beam is scanned by the detector head. From this measurement, the minimal angular resolution, the dynamic range and the stray scatter from the instrument components can be obtained. The result is shown in Figure 4. In this plot, $q_{e,\lambda}$ at 400, 550 and 700 nm is plotted from -5° to +5° off-axis with respect to the incident beam in the horizontal direction. Within a small interval of 0,5°, $q_{e,\lambda}$ remains nearly constant because the incident beam is smaller then the aperture of the detector head. For this measurement, the neutral density filter with transmittance of 1 % was switched into the beam and an integration time of 30 ms was required with the CCD output just below saturation (50 000 counts).

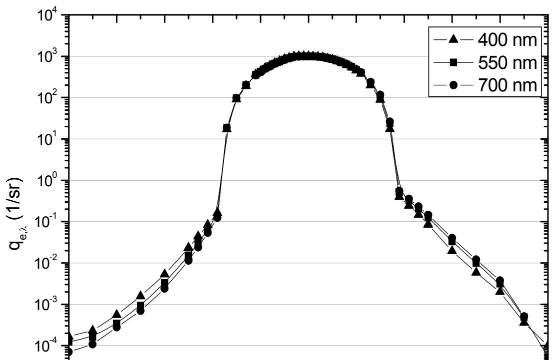

Figure 4. Instrument signature at 3 wavelengths. Notice the angular aperture of the detector head of ±1,5° and the dynamic range of 7 decades.

At 1,5° off axis, the beam is out of the detector aperture and the BTDF decreases dramatically. No neutral density filter is now necessary. With an integration time limited to 100s, a dynamic range of 6 decades is achieved. Instrument stray scatter levels of 10^{-4} sr^{-1} are measured.

4.2 Absolute measurements

The absolute spectral reflectance of a CERAM matt tile with 0:45 geometry is shown in Figure 5. The reflectance is calulated as $(q_{e,\lambda}.\pi)$. For comparison, the measurement of the same CERAM matt tile tool performed at NPL is included. Although we cannot reproduce the measurement of NPL exactly, the deviation is below 3 % except at 380 nm. At 550nm we obtain an absolute reflectance of 88,1%, while NPL predicts 87,8%. Additional test measurements on several other absolute reflectance standards (Spectralon, NIST) also show a good correspondence with the calibration values.

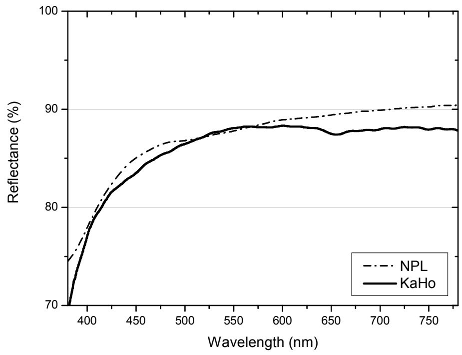

Figure 5. Absolute reflectance with 0:45 geometry of a diffuse CERAM matt tile tool (bold) compared to the NPL calibration (dashed).

For the regular transmittance of a polished glass plate (BK7, n=1,51, thickness 2mm), a value close to 92% was measured, as theoretically expected.

4.3 Spectral Measurements

To illustrate spectral measurement capability of the instrument, the spectral reflectance and transmittance of a red reflective colour filter was measured at 0° and 45° incidence. Since the sample is specular, viewing angles were identical and the ratio of the detector responses at each wavelength with and without the sample were calculated. The results are shown in Figure 6. Typical interference patterns become visible. Because of the change of the optical path length with changing angle of incidence, the cut-off wavelength shifts towards the blue end of the spectrum.

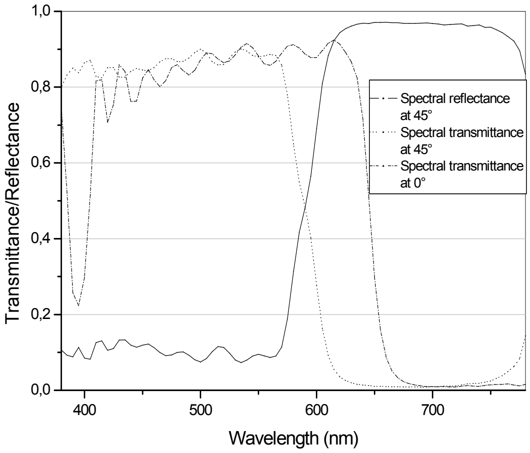

Figure 6. Spectral reflectance at 45° (solid), spectral transmittance at 45° (dotted) and 0° (dashed) of a dichroic filter CP-RR-580.

Measurements of the spectral BRDF of ChromaFlair® samples and more results on spectral issues and colour travels acquired with our BSDF-setup can be found in [4].

4.4 Appearance

We illustrate the possibilities of our BSDF-setup in analysing gloss characteristics and related appearance parameters. A HunterLab colour test chart with two surfaces with the same pigments but with a different texture (shiny and a matt) was studied. The spectral BRDF of both surfaces was measured at an angle of incidence of -8° for different angles of viewing (Figure 7). Naturally, the shiny sample has a higher specular reflection (visible around 8°) than the matt sample. More interesting is the diffuse scattering at viewing angles away from the specular direction. This is shown in detail in Figure 8 for two different wavelengths (500 and 700 nm). The values remain almost constant with viewing angle, pointing to real Lambertian scattering. The value of $q_{e,\lambda}$ for the shiny face is systematically lower than the value for the matt face. This will result in a lower lightness value and a different appearance. It illustrates the influence of the surface texture on the perceived colour even with the same pigmentation.

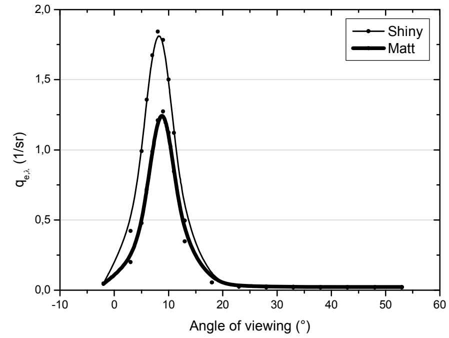

Figure 7. BSD-functions at 500nm of a matt (bold) and a shiny colour test chart (angle of incidence: 8°).

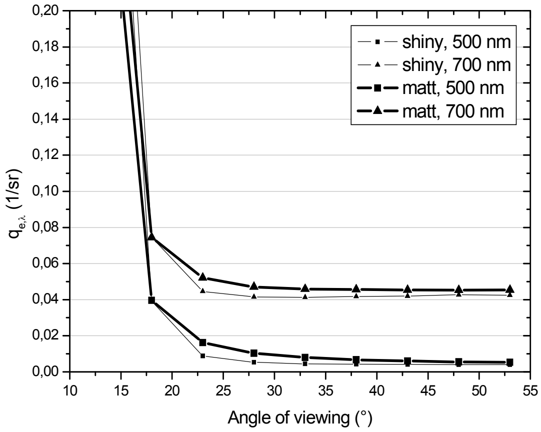

Figure 8. Detail of the off-specular BSDF at two different wavelengths of a matt (bold) and a shiny colour chart (angle of incidence: 8°).

5. CONCLUSIONS

Any gloss and colour measurement can be related to some particular value of the general spectral Bidirectional Scatter Distribution Function (BSDF). The use of a multifunctional spectral gonioradiometer to measure this BSDF is an interesting tool to study all issues related to colour and gloss characterization. Ray tracing software used for luminaire design requires the BSDF of any material in the luminaire which interacts with the light emitted by the light source.

In this paper, we present an instrument capable to determine a full 3D Bidirectional Scatter Distribution Function. Spectral properties can be measured at any spherical angle of illumination and at almost any viewing angle using a detector head circulating around the sample with two degrees of freedom and connected to a spectrograph with CCD detection. Thanks to the special design of the detector head, absolute spectral BSDF-values can be calculated from dark current corrected CCD readings according to ASTM E1392.

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