Rapid determination of the photometric bidirectional scatter distribution function by use of a near-field goniophotometer

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ABSTRACT

The bidirectional scatter distribution function (BSDF) characterizes the scattering properties of a material for any angle of illumination or viewing, and offers as such a complete description of the spatial optical characteristics of the surface. An accurate determination of the BSDF is important in many scientific domains, such as computer graphics, architectural and lighting design, and the field of material appearance characterization (e.g. the color and gloss properties).

Many BSDF measuring instruments have been reported in the literature. The majority of these instruments are goniometric measurement devices, by use of which the BSDF is determined by scanning all incoming and outgoing light flux directions in sequence. For this, the sample, detector, and/or source perform relative individual movements. In result, the major restriction of this type of instruments constitutes the measurement time, which may run to the order of several hours depending on the accuracy (angular resolution) and the complexity (spectral coverage, absolute measurement capability, etc.) of the reported measurement data.

This paper describes the results of a feasibility study, in which an alternative goniometric measurement system is designed, enabling to acquire the photometric BSDF in a full three-dimensional (3D) space, with a high mechanical angular resolution (0.1°) in a time efficient way (about 30 minutes). A near-field goniophotometer, originally intended to measure luminance intensity distributions and luminous fluxes of light sources and luminaires, was converted for this purpose. Besides a discussion of the design and the measurement procedure, test sample measurements are presented to illustrate the versatility of the device.

Keywords: bidirectional reflectance distribution function, near-field goniophotometry, optical metrology, material appearance characterization

1. INTRODUCTION

The bidirectional reflectance distribution function (BRDF) and bidirectional transmittance distribution function (BTDF) characterize the scattering properties of a material in reflection and transmission mode, respectively, and are therefore the most universal way of describing the optical scattering from a surface. The introduction of the concept and the notation of the BRDF is accredited to Nicodemus et al.[1]. BRDF was defined in radiometric terms as the surface radiance of a sample, in a particular viewing direction, due to the scattering of the radiation incident from a particular direction of irradiation:

$$\rho(\theta_i,\phi_i;\theta_r,\phi_r;\lambda)=\frac{dL_{e,\lambda,r}(\theta_i,\phi_i;\theta_r,\phi_r)}{dE_{e,\lambda,i}(\theta_i,\phi_i)}\ [\mathrm{sr}^{-1}], \quad (1)$$

with ρ the spectral BRDF at wavelength λ, (θ_i,ϕ_i) the spherical co-ordinates of the light incident on the surface, (θ_r,ϕ_r) the spherical co-ordinates of the light scattered from the surface, $dL_{e,\lambda,r}$ the differential spectral radiance, and $dE_{e,\lambda,i}$ the differential spectral irradiance. The spherical co-ordinates are referenced to the surface normal.

An appropriate determination of the BRDF is important for many applications, e.g. computer graphics[2-3], remote sensing[4-5], appearance characterization[6-7] and lighting design[8-9]. In result, many BRDF and BTDF measuring instruments

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have been reported in the literature[10]. The majority of these instruments are goniometric devices, in which incoming and outgoing light flux directions are scanned in sequence. For this, the sample, detector, and/or source perform relative individual movements. With this type of instruments usually a broad angular coverage may be realized both in and out of the plane of incidence, and even both in reflectance as well as in transmittance mode. However, one of the major restrictions constitutes the measurement time, which may run to the order of several hours depending on the accuracy (angular resolution) and complexity (spectral coverage, absolute measurement capability, etc.) of the reported measurement data.

To speed up acquisition without limiting the measurement to a scan of the plane of incidence only, alternative measurement devices have been proposed which detect multiple angles simultaneously. This can e.g. be achieved by use of a camera in combination with optical accessories, such as a mirrored hemisphere which is used as a projection surface[11-12], or by use of a specimen holder with known surface curvature (e.g. a spherical material sample)[13]. The major drawback of these type of devices is however that, due to the fact that they have been optimized to be time efficient, other features become generally more restricted (e.g. just the ability to perform measurements in reflectance or transmittance mode only)[7].

Within the field of lighting research and technology, near-field goniophotometry has recently been introduced - although the measurement principle is known for a longer time - as an alternative to model the luminous intensity distribution (LID) of light sources in far-field conditions (where the photometric distance law is applicable)[14]. For this, the relative luminance distribution of the source is measured from all light-emitting directions by use of an imaging luminance camera. A normalization of the data is obtained from an additional luminous flux determination with a photometer. Both devices (camera and photometer) are installed on the frame of a goniometer, such that they can rotate on an imaginary sphere around the light source. As such, the application of the imaging luminance camera allows for a compact set-up to determine the LID.

Three near-field goniophotometers (Technoteam type RiGO 801) have been installed at the Light&Lighting Laboratory in 2010. A picture of the largest device is presented in Figure 1. The camera and photometer move around the geometrical center located at the intersection of the two rotation axes of the goniometer, at a distance of 1.54 m. In addition to these two detectors, a spectrometer (Ocean Optics QE65000) coupled to an optical fiber is installed on the rotation frame, such that radiometric measurements can also be performed (see inset picture). The commercial combined imaging luminance/color camera (LMK 98-4, manufactured by Technoteam) is equipped with a set of changeable objective lenses, enabling to measure the LID of luminaires with various dimensions of up to 2 m diameter. The photometer consists of an 18 bit illuminance meter, which can also be used for far-field photometric measurements if the dimensions of the device under test (DUT) are negligible in comparison with the distance to the detector. When both detectors are used, an LID measurement (scanning the whole sphere around the DUT with an angular accuracy set to 1° for both rotation angles) can generally be performed in approximately one hour (the exact time also depends on the integration time of the camera). Yet, when only the photometer can be used, the same measurement can be performed in a reduced time of approximately 20 min.

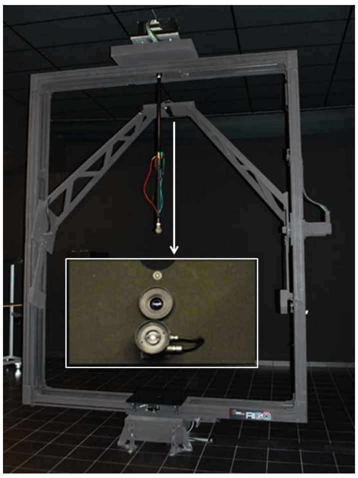

Figure 1. Picture of the near-field goniophotometer. Inset picture: detail of the three detectors installed on the rotation frame of the device; optical fiber/spectrometer, imaging luminance/color camera, and photometer (top – down) .

From this given, the idea has arisen to use the near-field goniophotometer as a photometric BSDF measurement device. Indeed, if an illumination and sample holder system could be developed and integrated into the device, a rapid acquisition of the entire 3D photometric BSDF could be performed with the photometer as detector. This paper reports on a feasibility study, in which the possibility to use a converted near-field goniophotometer for photometric BSDF acquisition has been investigated. Further on in this paper, the design of the system and the measurement procedure are discussed, and finally, some test measurements are presented.

2. INSTRUMENT DESIGN

Our aim was to convert the large near-field goniophotometer device to a full 3D photometric BSDF measurement instrument with the following basic requirements:

- an adjustable (large) sample illumination area,
- a relative determination of the photometric BSDF using a broadband illumination,
- a reasonable acquisition time.

The minimal diameter of the illumination spot was determined based on the surface structure properties of the samples intended to be characterized. Since we wanted to be able to quantify the mean scattering properties of reflectors and filters which are used in luminaires, and which may exhibit a macro-structured surface with a periodicity in the order of mm, an adjustable sample illumination area of at least 10 mm was put forward.

A picture of the constructed illumination system is presented in Figure 2.To achieve the intended illumination spot, a tungsten halogen light source (50W bulb) was used. To realize an acceptable uniformity of the spot at the sample location, a combination of collector and field lenses, and a condenser lens was used, based on the principle of Köhler illumination. The combination of collector and field lenses images the light source on an adjustable diaphragm in front of the condenser lens, acting as the illumination system's aperture stop. This avoids the reimaging of the non-uniform radiance of the filament of the source. A second adjustable diaphragm, positioned behind the field lens, selects the central part and acts as the field stop of the illumination system. In turn, the condenser lens images this second diaphragm onto the system's image plane, located at the sample position. The diameter of the illumination spot can be changed by adjusting the diaphragm acting as the system's field stop, while the intensity can be regulated by adjusting the aperture stop diaphragm. In result, an illumination spot with an adjustable diameter between 8 mm and 50 mm is realized, producing an average illuminance at the sample position of maximally 700 lux. Additional baffles are introduced to reduce stray light. If necessary, a colored glass filter with a dedicated interference coating can be introduced to produce, in combination with the tungsten halogen lamp, a good representation of a D65 illuminant[6]. The total distance of the illumination system is limited to 0.60 m, such that the goniometer is able to freely rotate in space without being obstructed. The entire system is mounted on an optical bench, which in turn is mounted on a frame made of construction profiles (Bosch Rexroth), such that it can be easily installed into, or taken down from the near-field goniophotometer.

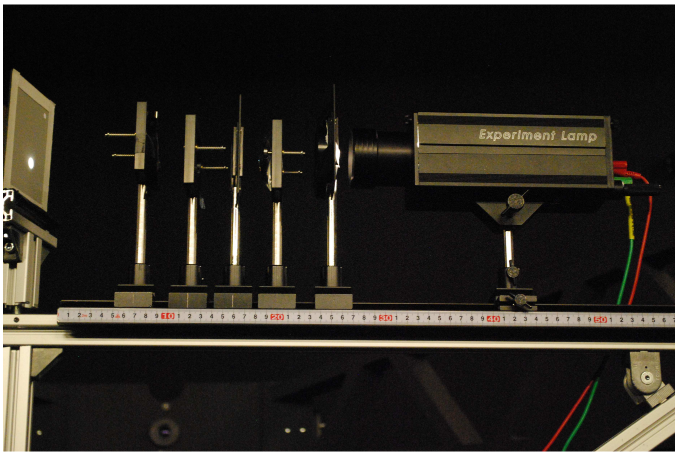

Figure 2. Picture of the illumination system mounted in the near-field goniophotometer setup.

The same frame carries the sample holder, which can be rotated around its horizontal and vertical axis through a rotation stage. In this way, any incident illumination direction can be installed. The sample reference surface can further be adjusted to coincide with the center of the goniometer by a translation of the sample holder over the construction profile, thereby allowing for different sample thicknesses. Exact positioning of the sample can be easily controlled with the imaging luminance camera of the near-field goniophotometer device.

As already mentioned in the introduction section, our idea was to use the photometer of the near-field goniophotometer setup as detector in order to speed up the acquisition of the entire 3D scattering properties of the surface. Since the field of view of the detector is larger than the illumination spot, the sample becomes underfilled. Furthermore, in this configuration (combination of a broad band illumination with a broad band detection) the measurement result is in fact a luminance coefficient q or luminance factor β_V, depending on the fact if measurements are performed in an absolute or relative way, respectively[15].

The luminance factor β_V is defined as the ratio of the luminance of the surface element L, in the given direction (θ_r, ϕ_r), to that of the perfect reflecting or transmitting diffuser, L_{PRD}, identically irradiated and viewed[15]:

$$\beta_V(\theta_i,\phi_i;\theta_r,\phi_r) = \frac{L(\theta_i,\phi_i;\theta_r,\phi_r)}{L_{PRD}(\theta_i,\phi_i;\theta_r,\phi_r)} . \tag{2}$$

The perfect reflecting or transmitting diffuser is in fact a theoretical concept, defined as a diffuser which exhibits an isotropic diffuse reflection, resp. transmission, with a reflectance, resp. transmittance, equal to one. In practice, this theoretical diffuser can be approximated by a matte, neutral white, reference standard with nearly Lambertian direction characteristics.

The relation between the luminance of the practical reference standard, L_{REF}, and the luminance of the theoretical perfect diffuser, L_{PRD}, can be formulated from the definition of the luminance factor β_V (Eq. 2):

$$\beta_{V,REF}(\theta_i,\phi_i;\theta_r,\phi_r) = \frac{L_{REF}(\theta_i,\phi_i;\theta_r,\phi_r)}{L_{PRD}(\theta_i,\phi_i;\theta_r,\phi)} = \frac{q_{REF}}{q_{PRD}} . \tag{3}$$

From the definition of the perfect reflecting diffuser, the luminance coefficient q_{PRD}, in any direction of viewing, is known to be

$$q_{PRD} = \frac{1}{\pi} \, [\mathrm{sr}^{-1}]. \tag{4}$$

In result, Eq. 2 can be rewritten to

$$\beta_V(\theta_i,\phi_i;\theta_r,\phi_r) = \frac{L(\theta_i,\phi_i;\theta_r,\phi_r)}{L_{REF}(\theta_i,\phi_i;\theta_r,\phi_r)} q_{REF}\pi , \tag{5}$$

with q_{REF} being the luminance coefficient of the reference standard in the given direction of viewing, and under the specified conditions of illumination.

3. MEASUREMENT PROCEDURE

From Eq. 5 it can be concluded that the determination of the luminance factor of a surface in a given viewing direction and under specified conditions of illumination, β_V, is reduced to the execution of three measurements, i.e.;

- the measurement of the luminance coefficient of the reference standard, q_{REF},
- the measurement of the luminance of the reference standard, L_{REF}, and
- the measurement of the luminance of the surface under test, L.

While for a complete characterization of the scattering properties of a surface theoretically all three variables have to be determined in every measurement geometry, the quotient of q_{REF} to L_{REF} remains constant if the incident illumination direction is kept invariant (e.g. for a characterization of the scattering properties of a surface under normal incident illumination). As such, only the luminance of the sample surface L has to be determined by scanning the entire reflection or transmission hemisphere. For the determination of q_{REF} and L_{REF}, a predetermined geometry can be put forward; e.g. the 0°:45° geometry in case of normal incident irradiation.

In the further description of the measurement procedure, a normal incident irradiation, and the 0°:45° geometry for determination of q_{REF} and L_{REF}, will be supposed by way of example. The same procedure is however applicable for any other choice of incident illumination direction.

3.1 Determination of q_{REF}

A matte white Ceram tile was used as reference standard. The absolute spectral BRDF ρ_{REF}, determined in a 0°:45° geometry by use of a home-built BSDF measurement device[10], is presented in Figure 3. As can be seen, the spectrum drops down below 530 nm. In result, the luminance coefficient q_{REF} will depend on the relative spectrum of the installed illumination system, $S_{e,\lambda,rel}$, and a correction according to Equation 6 is necessary:

$$q_{REF} = \frac{L_{REF}}{E_{REF}} = \frac{a\int \rho_{REF} S_{e,\lambda,rel} V_\lambda d\lambda}{a\int S_{e,\lambda,rel} V_\lambda d\lambda}, \tag{6}$$

In this equation, a is a constant, V_λ being the photopic eye sensitivity function.

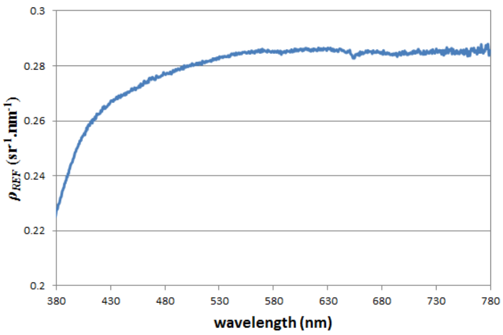

Figure 3. Absolute spectral BRDF ρ_{REF} of the matte white Ceram standard, determined in a 0°:45° geometry.

The spectrometer/optical fiber combination of the near-field goniometer was used to determine the relative spectrum of the applied tungsten halogen illumination system $S_{e,\lambda,rel}$. According to Eq. 6, the luminance coefficient q_{REF} in the 0°:45° geometry was calculated to be 0.2805 sr^{-1}.

3.2 Measurement of L_{REF} and L

In order to determine the luminance of the practical reference standard, L_{REF}, the Ceram tile must be put into the sample holder of the illumination/sample holder system, and positioned in the center of the goniometer. By analogy with q_{REF}, L_{REF} can then be quantified in a 0°:45° geometry. The same procedure can be repeated to determine the luminance L of the sample under test for any viewing angle needed.

In fact, the reported measurement results through the photometer detector are not luminance values but luminous intensities. Yet, since both the reference sample and the sample under test are measured under the same conditions of illumination, the apparent light emitting surface of both samples will be equal for any viewing direction. As such, the exact apparent surface need not to be known.

4. MEASUREMENT EXAMPLES

To illustrate the versatility and utility of the system, three test sample measurements are presented. First, a BRDF measurement of the Ceram reference tile under normal incident irradiation is described. Second, BTDF measurements of two lighting diffusers, again under normal incident irradiation, are considered.

4.1 BRDF of the Ceram reference sample

The measurement results for the Ceram reference tile are presented in Figure 4. Half of the reflection hemisphere was scanned, θ_r ranging from 0° to 90° as seen from the surface normal, with a 2° interval, and ϕ_r ranging from 0° to 180°, also with a 2° interval, respectively. The measurement took less than 9 minutes.

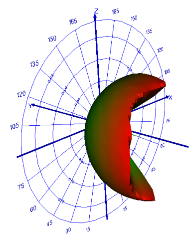

Figure 4. LID of the Ceram reference tile measured in half of the reflection hemisphere.

While the luminous intensity is supposed to be directly proportional to the cosine of the viewing angle as seen from the surface normal due to the expected nearly Lambertian reflection behavior of the matte Ceram tile, a cutout can be observed within a segment of the sphere around the normal direction (for θ_r ranging from 0° to 25°). In this region, the illumination system obstructs the detector from viewing the sample, and the measurement results become invalid. The obstructed solid angle can be diminished by increasing the total distance of the illumination system, making use of another lens combination. Moreover, this restriction becomes less important when larger incident illumination angles are to be applied, for example for the investigation of the surface scattering properties of glossy samples around the specular peak direction.

In order to validate the results, absolute spectral BRDF measurements of the same sample were made in one plane (normal incident irradiation) by use of the home-built BSDF device mentioned earlier. Luminance factors were determined from these measurements, taking into account the relative spectral distribution of the tungsten halogen illumination system. A comparison between the luminance factors derived from the absolute spectral BRDF measurements, and from the measured LID in the near-field goniophotometer, is presented in Figure 5. For all viewing angles, a satisfactory correspondence is observed, validating the measurement results obtained in the near-field goniometer device.

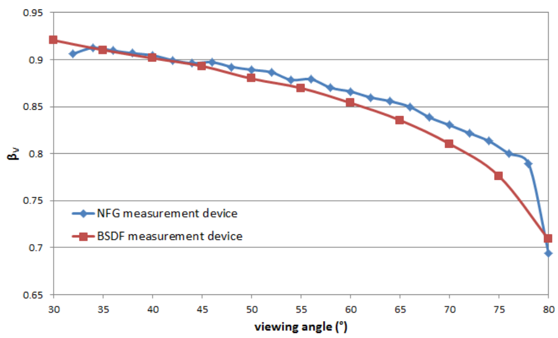

Figure 5. Comparison between the luminance factor β_v as a function of the viewing angle, as determined from the measured LID in the near-field goniophotometer, and derived from absolute spectral BRDF measurements.

4.2 BTDF of a lighting diffuser

Lighting diffusers are used in luminaires to redirect the light coming from the light source(s). They may be a good alternative for lenses, especially in typical applications where a specific light distribution has to be obtained without too much loss of efficiency, and avoiding visual discomfort caused by glare.

A 3D representation of the measured LID, resulting from a normal incident irradiation being transmitted through a linear and a circular MesoOptics diffuser, respectively, is presented in Figure 6 and Figure 7. In both measurements, the entire transmission hemisphere was scanned, θ_r and ϕ_r ranging from 0° to 90° and from 0° to 360°, respectively, with a 2° increment. For both measurements, the measurement time was restricted to 18 minutes. The LIDs clearly show the typical dispersion of the incident irradiation into a narrow plane and a cone, respectively. The restriction of the obstructing illumination system is not present anymore.

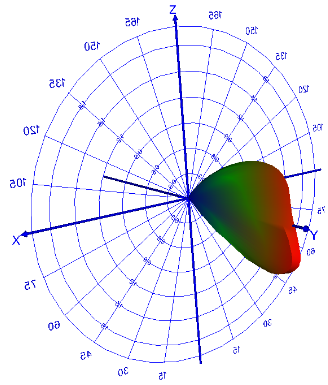

Figure 6. LID of a linear MesoOptics diffuser, measured in the transmission hemisphere.

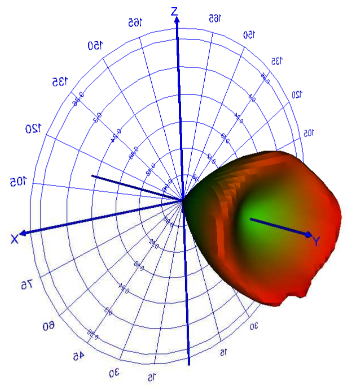

Figure 7. LID of a circular MesoOptics diffuser, measured in the transmission hemisphere.

5. CONCLUSIONS

In this paper the results of a feasibility study have been reported, in which an alternative goniometric measurement system was designed for measuring the photometric BSDF in full 3D space, in a time-efficient way. A near-field goniophotometer, originally intended to measure LIDs and luminous fluxes of light sources and luminaires, was converted for this purpose. Within the near-field goniophotometer, a tungsten halogen illumination source was installed, designed based on the principle of Köhler illumination, and providing a uniform illumination spot of adjustable diameter at the sample position. Photometric measurements are made by use of a photometer which is moved on a spherical surface around the measurement sample. Furthermore, the goniophotometer is equipped with a colorimetric camera, which is used to check the adjustable sample position (variable incident irradiation direction), but which can also be used to acquire colorimetric data if required. Measurements are made relative to a white Ceram reference sample, for which the spectral BRDF has been characterized in another home-built measurement setup, capable of performing absolute spectral BSDF measurements.

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