CHARACTERISATION AND MODELLING OF ADVANCED DAYLIGHT REDIRECTION SYSTEMS WITH DIFFERENT GONIOPHOTOMETERS

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Abstract

In this work we present a characterisation of Daylight Redirecting Components (DRCs) by comparing a scanning with an image based Goniophotometer (GPs). Both GPs can be employed in order to measure Bidirectional Scattering Distribution Function (BSDF). The measurements of the BSDF can be transformed into BSDF data driven model. The latter one can be in turn used to perform light scattering simulations. The aim of this work is to validate the correlation between the measurements from both systems. Three different DRCs (Laser Cut Panel (LCP), Daylight Redirecting Film (RF) and Daylight Redirecting Prisms (DRP)) with dimensions 15 x 30 cm^2, 34 x 34 cm^2 and 30 x 30 cm^2 respectively were measured. The results for each sample for one light incident direction (θ (altitude)=24° and ϕ (azimuth)=60°) from both GPs were analysed and visualised in the software *Mountain V3.0.1*. DRCs LCP and RF correlate to each other relatively well. The only discrepancy is their slightly wider scattered light distribution. However the DRP sample correlates to smaller extent, the scattered peaks are not only much wider but slightly differently positioned. The wider light distribution can be explained by different instrument signature (light beam diameter and resolution of the measurements). In addition to the visual assessment the total light transmission and Full Width at Half Maximum were compared. Similarly to the visual evaluation DRCs RF and LCP samples showed more coherent results (79.8% vs 88.4% for RF and 89.8% vs 78.0% for LCP) whereas transmission values for DRP vary significantly more (76.9% vs 44.0%). The difference in RF sample can be explained by the instrument signature, however DRP sample requires further investigation in the future work.

Keywords: BSDF, Goniophotometry, Daylight Redirecting Components.

INTRODUCTION

DRCs attract more and more attention nowadays thanks to their possibility to bring high quality illumination to offices (lack of flicker, friendly colour temperature and uniformity) The others benefits brought by DRCs is low daylight glare probability, wellbeing and increased productivity both delivered by having the spectrum of natural daylight in the offices [1]. All of the above mentioned profits make the DRCs attractive candidates to replace the regular glazing systems in office buildings. However, a few factors like for instance position (latitude, longitude), shape and orientation of the buildings might require usage of different types or special adjustments of DRCs [3]. Therefore the planners often abandon the idea of incorporating the DRCs while planning. Thus, in order to foster the usage of the DRCs functional model for fast and accurate simulation have to be developed. A few approaches have been studied in order to conduct proper simulations of DRCs. For instance analytical models with estimated parameters or models fitted to measurements. However more complex behaviours are not addressed by analytical models, for instance with retro-reflection or multiple peaks. In such a case most accurate simulations can be performed by Bidirectional Scattering Distribution Function (BSDF) data driven models. BSDF is defined as a fraction of light intensity scattered in a given direction divided by incident light intensity[2]. Nevertheless, a generation of these models require a large number of accurate measurements of the light scattering by the DRCs. The light scattering properties can be measured by means of goniophotometers. The results provided by two goniophotometery laboratories were chosen for the comparison, one placed in Luzern University of Applied Sciences and Arts in the Competence Centre Envelopes and Solar Energy (HSLU CCEASE) and one in Ecole Polytechnique Fédérale de Lausanne in the Solar Energy and Building Physics Laboratory (EPFL LESO-PB). Although both systems can characterise DRCs, to our best knowledge, a comparison between their measurements has never been done. Such a comparison is crucial for coherent modelling and simulation of DRCs.

MATERIALS AND METHODS

Selection of DRCs

A set of three DRCs (LCP, RF and DRP) was decided to be characterised by the GPs[3]. LCP sample was produced from a 7 mm thick plate of polymethylmethacrylate (PMMA) in which an array of cavities was produced by a laser cutter. These cavities were redirecting the light due to the internal reflecting interfaces. The light redirection in RF sample is based on micro structured prisms. This prismatic foil with thickness of 300 µm was mounted on window glass in order to prevent bending. Last sample - DRP was manufactured form PMMA material and its light redirection relies on light refraction by micro lenses on sun-façade side and micro prisms on inwards side.

Goniophotometers setups

The HSLU set-up comprises a dark room housing the scanning goniophotometer (GP-S) and separate control room. The GP-S setup with the description of the main parts is presented in Figure 1 [4]. The measurements are conducted as follows: Collimated light from the optical bench illuminates a vertically mounted sample. A detector spherically rotates around the sample and reports light levels reflected off and transmitted through the sample for every angle. Thus, the full spatial range of reflection and transmission scattering values can be measured. The post for sample mount is equipped with motor which allows automatic rotation of the sample, therefore incident angle can be varied automatically.

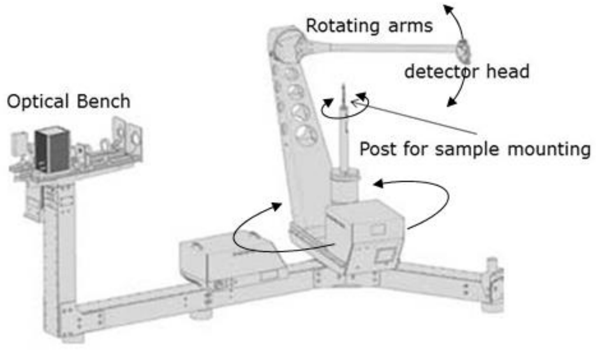

Figure 1: Sketch of the goniophotometer installed in the laboratory at HSLU with description of its main components [5].

The GP-S measures angularly resolved scattering values which results in BSDF values [5]. The resolution of measurement is independent on direction. Additionally, it features high resolution measurement in areas of interest by means of automatic peak scanning or manual configuration of fine scanning. The example of resolution of measurements is presented in the Figure 2 where each of the grey lines in the polar plot corresponds to the acquired data. Furthermore, refined peak scanning was performed in position θ=25° ϕ=210°.

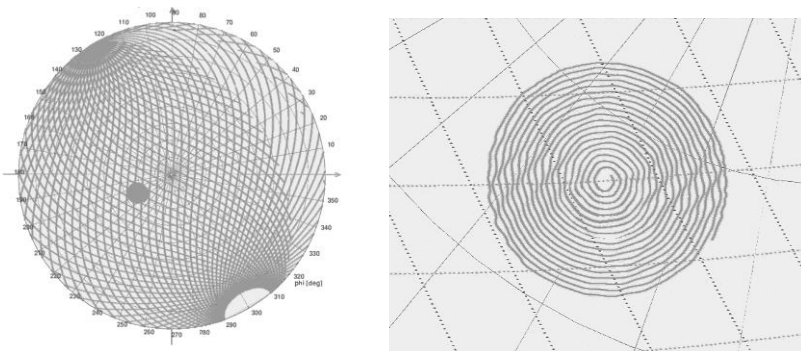

Figure 2: Dynamic resolution of GP-S. Left: whole hemisphere showing the measurement paints along the measurement path, right magnified local high resolution scanning.

The silicon detector working in the multistage amplification mode with V-lambda filter was used as a detector. Halogen lamp with hot mirror 700 nm was employed as a light source. Light was collimated by means of optical setup resulting in beam diameter of 6 cm.

The image based goniophotometer (GP-I) available at the LESO-PB uses advanced digital imaging techniques (CCD video camera) and is based on light incident directions following the 145 sky subdivisions of Tregenza. In Figure 3 schematic of transmitted light detection is presented.

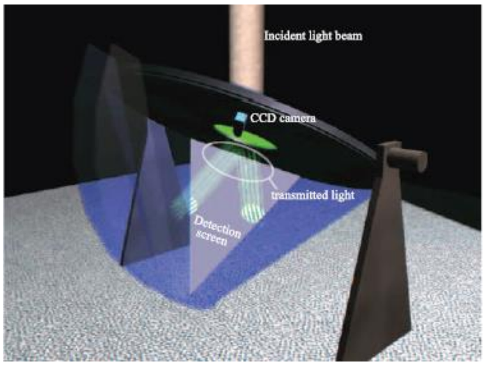

Figure 3: GP Detection of the transmitted light flux in the GP-I setup [6].

The output resolution of the outgoing light directions is fixed every 5° in azimuth and elevation, leading to a subdivision of the hemisphere in 1297 patches. The resolution of the measurements is presented in Figure 4, where one point of data acquisition can be seen in every 5° in azimuth and elevation.

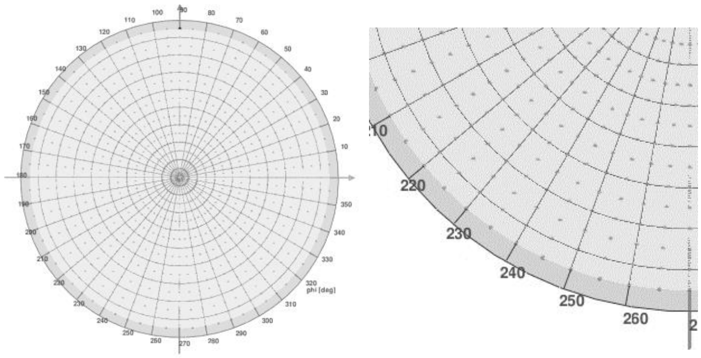

Figure 4: Fixed resolution of GP-I. Left: whole hemisphere, showing the measurement points in every 5° patch. Right: magnified part of the hemispherical projection.

The projector with a collimated light beam was used as a light source and was placed 10 m away from the samples. Hence, resulting in a strongly collimated light [3]. In Table 1 a main features of GP-I and GP-S are compared.

Features	GP-S	GP-I
Maximum sample size	90 x 100 cm^2	40 x 40 cm^2
Light beam diameter	Variable 1 – 7 cm	10 cm
Resolution	>100’000 points/hemisphere	1297 points/hemisphere
Resulting hemisphere	Transmission and reflection in one measurement	Transmission and reflection in separate measurement
Time of measurement for one incident direction	Approx. 10 min	Few seconds

Table 1 Comparison of the main features of both GP-S and GP-I [6].

Data post processing

Mountain software was applied for data visualisation and post processing. Post processing of the data includes: integration of transmission values and transformation from Differential Scattering Function (DSF) to BSDF. The standard import data format consists of ASCI text file with columns corresponding to θ, φ, and BSDF values. The angles θ and φ are according to standard spherical coordinate system. Post processed data are exported in the same format. Data from both GPs were analysed and exported by *Mountain*.

RESULTS

Scatter visualization

Each of the samples was measured for transmission with the following incident direction: θ=24° and ϕ=60°. In Figure 5 all the measured data are presented.

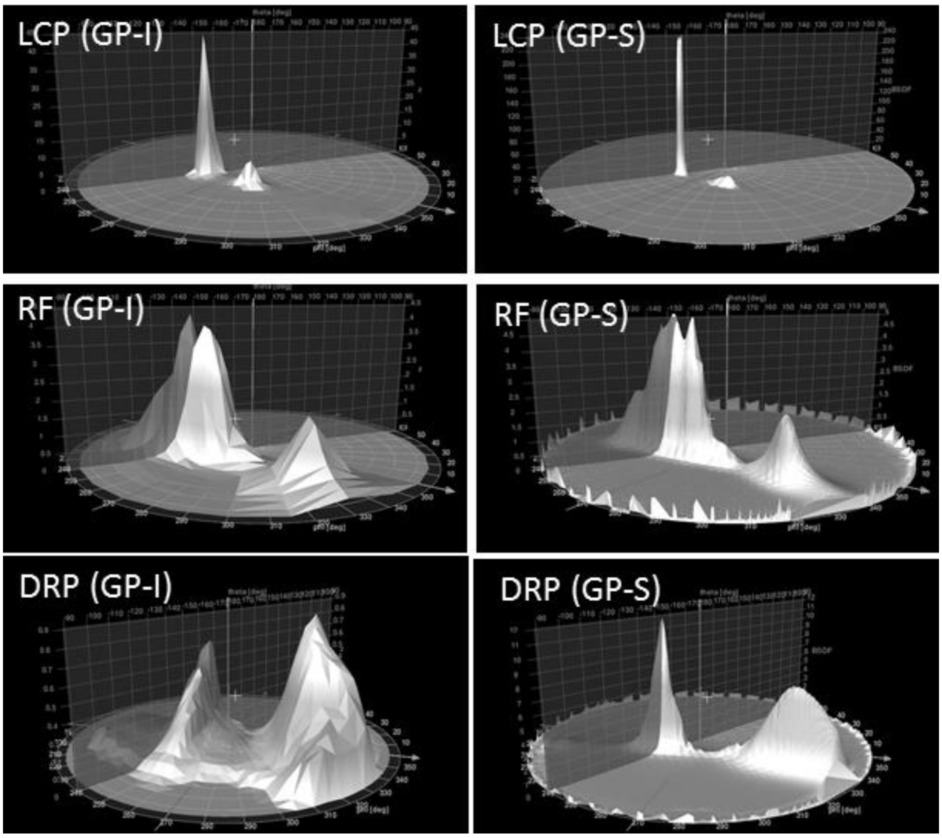

Figure 5: Light transmission characteristics through DRCs.

Transmission and FWHM values

In Table 2, a summary of FWHM values are listed. In the second and third column data post processed by *Mountain* are presented. Fourth column shows raw data from GP-I.

Sample acronym	GP-I		GP-S		GP-I raw
	Int. trans. [%]	FWHM [°]	Int. trans. [%]	FWHM [°]	Int. trans. [%]
LCP	77.9	4	89.8	3	78.0
RF	83.4	10	79.8	8.5	88.4
DRP	65.8	-*	76.9	-*	44.0

Table 2: Summary of light transmission and FWHM values from both system as post processed Mountain (expect last column with raw values from GP-I).

**-FWHM could not be reliably compered due to significant differences in the light scattering characteristics.*

DISCUSSION

LCP (most specular redirecting sample) appears quite similar across both GP. The visualization shows that both peaks are well refined and are placed in the same positions (θ=157° ϕ= 240° and θ=155° ϕ=240°). The only difference that can be noticed is slightly more scattered light distribution. However their FWHM are still at similar levels (4° vs 3°). Sample RF shows similar behaviour. Scattered light is distributed in a wider manner and the peaks are not as well defined. The FWHM values for both systems are comparable (10° vs 8.5°). Besides the above described discrepancies, it can be observed that the characteristics of the light scattering properties are maintained in the measurements from both systems. A source of the discrepancies found in measurements in samples LCP and RF can be explained by the instrument signature [7]. As described in the former chapter the light beam employed in goniophotometer at GP-I laboratory is larger in diameter, thus the resolution of the measurements is decreased. Furthermore, the resolution of acquired data is lower in GP-I laboratory which introduces additional differences. Both of those factors significantly lower the acquired resolution resulting in more spread light scattering properties. The measurements of the last sample, DRP, exhibit the largest dissimilarities. The main peaks can be still noticed, however, their spread is much wider. Main underling reason of these discrepancies is the same as for sample LCP and RF. However, the DRP sample is the most diffusive one, thus the deviations are the biggest. Additionally, the DRP exhibits different behaviour depending on where it was illuminated. Thus, these larger differences can be explained by different light beam diameter.

As for the transmission values, significant (close to 10 % for LCP and RF and more than 30% for DRP) differences can be observed in values calculated by software *Mountain* and the raw values from GP-I. In order to validate whether these discrepancies appeared due to the different calculation methods the raw BSDF from GP-I were evaluated by the same software. These values are presented in the second and third column and it can be noticed that the transmission values through the LCP are similar from both laboratories (77.9% for GP-I vs 89.8% for GP-S). This could be expected as the light scattering characteristics were very similar for both GPs. Values for sample RF also exhibit high correlation (83.4% for GP-I vs 79.8% for GP-S). Analogously, to the measurements of the LCP the light scattering characteristics remains in lower coherence. Transmission values of sample DRP did not show any similarity (up to 50 % relative differences), it can be explained by relatively big difference in measured scattering properties and requires further investigation.

CONCLUSION

A comparison of the analysis from two goniophotometers of three daylight redirecting components (LCP, RF and DRP) was achieved in this document for one light incident direction (θ=24°and ϕ=60°). Their light transmission distribution functions (BTDF) were compared together with their integrated transmission values to assess the differences between the goniophotometers. It was found that qualitatively they are similar, featuring the same topology but quantitatively they differ. The light scattering characteristics remains the same for more specular redirecting samples: the Laser Cut Panel shows the highest coherence followed by the RF sample. The more diffusing sample inhibited less similarity: the DRP acting as an example of sample without coherence between measurements. The reasons for the observed discrepancies for the diffusing sample must be further investigated and will be part of future work, together with using the monitored data in daylight simulations.

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REFERENCES

[1] L. Mohanty, X. Yang, and S. K. Wittkopf, "Optical scatter measurement and analysis of innovative daylight scattering materials," *Sol. Energy*, vol. 86, no. 1, pp. 505–519, 2012.

[2] F. O. Bartell, E. L. Dereniak, and W. L. Wolfe, "The Theory And Measurement Of Bidirectional Reflectance Distribution Function (Brdf) And Bidirectional Transmittance Distribution Function (BTDF)," *Proc. SPIE 0257, Radiat. Scatt. Opt. Syst.*, 1981.

[3] C. Basurto, "On advanced daylighting simulations and integrated performance assessment of complex fenestration systems for sunny climates," EPFL, PhD thesis No. 6425, 2014.

[4] P. Apian-Bennewitz, "New scanning gonio-photometer for extended BRTF measurements," *Proc. SPIE*, vol. 7792, pp. 77920O–1–20, 2010.

[5] L. O. Grobe and S. K. Wittkopf, "Optical characterization of materials and structures for daylighting and PV applications," 2010.

[6] M. Andersen, C. Roecker, and J. L. Scartezzini, "Design of a time-efficient video-goniophotometer combining bidirectional functions assessment for transmission and reflection," *Sol. Energy Mater. Sol. Cells*, vol. 88, no. 1, pp. 97–118, 2005.

[7] J. C. Stover, *Optical scattering: measurement and analysis*, vol. 2. SPIE optical engineering press Bellingham, WA, 1995.