A REVIEW AND ANALYSIS OF PARALLEL GONIOPHOTOMETRY

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ABSTRACT

A reliable computer simulation of natural and artificial lighting of an indoor environment requires the thorough knowledge of the angular intensity distribution of light scattered or emitted by the various objects involved such as the illuminated surfaces, the trans-illuminated windows or fenestration systems, as well as the luminaires. The angular intensity distribution of light flux reflected, transmitted or emitted as a function of the illumination angle can be measured with an instrument called goniophotometer. Fast measurement, essential in most practical applications, requires the simultaneous detection of all scattering directions with a so-called parallel goniophotometer.
In this paper we define and explain the three working principles on which a parallel goniophotometer can rest, namely (i) screen imaging, (ii) dioptric angular mapping, and (iii) catadioptric angular mapping. We provide a state-of-the-art of these instruments and compare their performance and limitations based on a few key parameters.

Keywords: Scatterometer, Parallel goniophotometer, Imaging goniophotometer, BSDF.

1. INRODUCTION

A reliable computer simulation of natural and artificial lighting of an indoor environment requires the thorough knowledge of the angular intensity distribution of light scattered or emitted by the various objects involved [1,2]. These can be the illuminated surfaces [3], the trans-illuminated windows or fenestration systems [4], as well as the luminaires [5]. For light reflected or transmitted by a surface, these scattering properties are generally described by the Bidirectional Scattering Distribution Function (BSDF) [6].

The angular intensity distribution of light flux reflected, transmitted or emitted as a function of the illumination angle can be measured with an instrument called goniophotometer (or scatterometer). A traditional goniophotometer generally consists of a two-axis mechanical scanner moving a photodetector around the sample in small angular steps across the hemisperical space [7]. The major drawback of such a scanning goniophotometer is its impractically long acquistion time [4]. Numerous applications, in particular computer lighting simulations, generally require a multitude of BSDF measurements to account for the large variety of surfaces, illumination angles and wavelengths that are usually encountered [1-5].

In practice, the collection of a large amount of BSDFs requires orders of magnitude faster measurements that can be only achieved by simultaneously measuring the light flux scattered in all directions. This requires a parallel goniophotometer, i.e. a device capable of measuring in a snapshot the far-field angular distribution of light scattered by a sample onto a relatively small two-dimensional sensor array. There exist different methods to realize such an angular-to-spatial mapping function of a parallel goniophotometer.

Despite the fierce need for fast angular-resolved scattering measurements, the scientific literature on parallel goniophotometry is relatively sparse and its dissemination throughout the scientific community is insufficient. On the one hand, given the commercial interests, the best designs are usually proprietary so that thorough technical and scientific information is not accessible. On the other hand, promising designs are often developed for specific applications and remain in its silo.

In this paper, we would like to provide a brief overview of parallel goniophotometry. We explain the different working principles of parallel goniophotometers (2) and provide a state-of-the-art (3) and comparison (4) of these instruments.

2. WORKING PRINCIPLES

A parallel goniophotometer must be able to dispatch the light scattered by a sample in a given direction onto a specific position of a two-dimensional array. To our knowledge, the methods that have so far been used to perform such an angular-to-spatial mapping function can be classified into three main categories based on their working principles. The latters are shown in figure 2 and briefly explained here below.

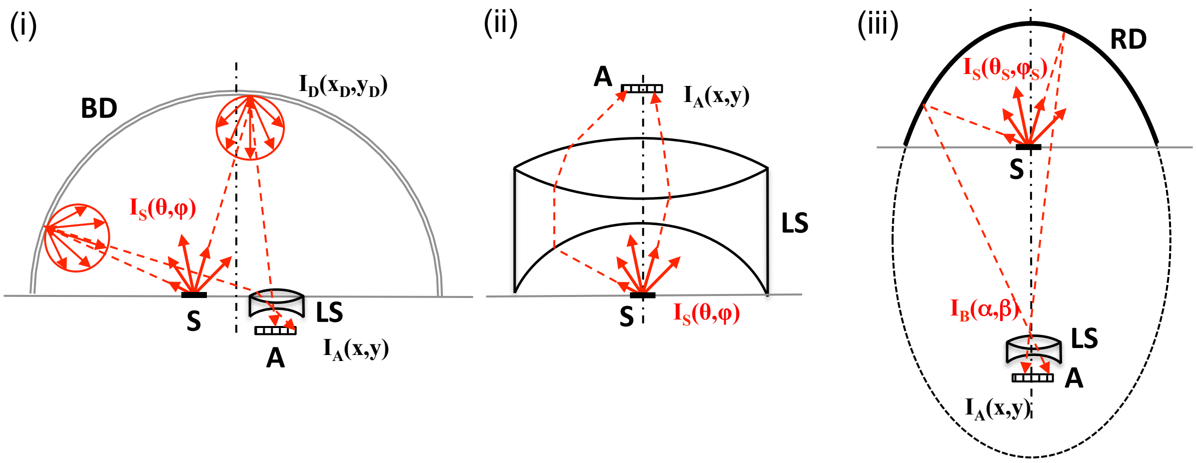

Fig. 1. Three working principles of a parallel goniophotometer: (i) screen imaging, (ii) dioptric angular mapping, (iii) catadioptric angular mapping.

In the screen imaging method (figure 1-i), the sample (S) is surrounded by a dome made of back-scattering material (BD) that intercepts light scattered by the sample over 2π steradian. Light scattered by the sample with the angular intensity distribution $I_S(\theta,\varphi)$ creates a spatial light intensity pattern $I_D(x_D,y_D)$ on the dome surface, which is then imaged by a lens system (LS), here a fish-eye camera. The light intensity pattern $I_D(x,y)$ obtained on the two-dimensional detector array (A) allows reconstructing the angular scattering distribution at the sample $I_S(\theta,\varphi)$. As suggested in Figure 1-i, in the screen imaging method, the angular-to-spatial mapping function is performed as follows: $I_S(\theta,\varphi) \Rightarrow I_D(x_D,y_D) \Rightarrow I_A(x,y)$.

The dioptric mapping method (figure 1-ii) relies, as its name suggests (dioptrics denotes the optics of refractive elements), on a fully refractive optical system directly providing the desired angular-to-spatial mapping function: $I_S(\theta,\varphi) \Rightarrow I_A(x,y)$. This function corresponds to an optical Fourier transform that is performed by a simple lens provided the sample and the detector are located in its first and second focal plane, respectively. Indeed, the second focal plane, also called the Fourier plane, corresponds to the Fourier components of the spatial frequencies of the light intensity distribution in the first focal plane that are directly related to the scattering directions [8]. To perform the angular-to-spatial mapping accurately over large scattering angles, a complex compound lens assembly surrounding the sample must be designed.

In the catadioptric (combination of catoptric and dioptric elements) mapping method (figure 1-iii), a reflecting dome (RD) with specific geometrical properties (catoptric part), is used to transform diverging light scattered by the sample $I_S(\theta,\varphi)$ into a beam of known angular intensity distribution $I_B(\alpha,\beta)$ converging towards a unique focal point. As suggested in Figure 1, this allows using a conventional lens system (dioptric part) to perform the angular-to-spatial mapping function: $I_S(\theta,\varphi) \Rightarrow I_B(\alpha,\beta) \Rightarrow I_A(x,y)$. A catadioptric parallel goniophotometer can be realized in four main types of configurations based either on a parabolic or on an ellipsoidal reflector (see 3.2.3 Figure 1-iii depicts an ellipsoidal configuration in which the sample (S) and the entrance pupil of the lens system (LS) are positioned at the first and second focal points, respectively.

Note that the terminology " mapping" is used for the dioptric and catdioptric methods in order to emphasize that, unlike in the first method (screen imaging), there is no image formation in the angular-to-spatial mapping operation. All these methods require some signal post-processing and a careful calibration that is generally not trivial.

3. STATE-OF-THE-ART

3.1. Instruments based on screen imaging

To date, only a few parallel goniophotometers (PG) based on the screen imaging method have apparently been devised. The oldest reference that we found is a patent by McNeil and Wilson deposited in 1993 describing various configurations of a PG based on a curved screen [9]. More recently, in his PhD dissertation completed in 2002, Deniel used a basic structure consisting of a backscattering screen of cubical shape and a fisheye lens [5]. This work mainly provides a proof of concept and an algorithm to cope with stray light inherent to this method. Another limitation comes from the edges of the cubical screen that prevents measuring some scattering directions.

In the meantime, a thorough work on the same method was carried on at Philips Applied Technolgies by Sipke, who developed a device named "parousiameter" ("parousia" means appearance in Greek) based on a spherical screen [10]. Originally developed to quantify the appearance of TV frames, this device is based on a slightly different configuration than shown in figure 1-i. In this design the fisheye lens is replaced by a convex mirror redirecting light via a hole towards a lens system lying outside of the spherical screen. To cope with stray light issues, the backscattering material of the sphere was optimized. A special grey coating (20% reflectance) with higher directionality than non-Lambertian profile was developed (proprietary) so as to minimize multiple inner-reflections. The software was also optimized to cancel out the offset brought by the stray light background signal. In 2005 Radiant Imaging further developed and commercialised this invention under the name of "Imaging sphere". In one instance, this device features a diameter of 50 cm and provides measurements over a full hemisphere with an angular resolution better than 0.5° for a sample with a diameter of 2 mm.

Apparently not aware of Sipke's work, Boulangez also developed a PG based on a spherical screen within the frame of his PhD completed in 2010 [11].

3.2. Instruments based on dioptric angular mapping

As mentioned in section 2, a simple lens already provides a crude optical Fourier transform required for dioptric angular mapping. Several lens systems have been optimized to perform this function for specific applications.

The first dioptric angular mapping system that was realized consists of a microscope combined with an intermediate custom lens called Bertrand lens. This method, named conoscopy, was reported more than a century ago for the observation of the optical properties of liquid crystalline phase [12]. Since then, conoscopy has been extensively used for the characterization of the optical properties of semi-transparent crystals and liquid cristal displays (LCDs) [13]. A conoscopic measurement is generally realized with a converging light beam (multi-angle trans-illumination) and polarizing optics in the detection path. Given these features, and the limited angular range and sample size, this method is generally not suitable - or needs important modifications - to be exploited in other PG applications.

In the last decade, apparatus with improved performance and scope of measurement have been developed and commercialized. For instance the company ELDIM proposes several instruments optimized for different parameters such as the angular resolution, the angular range and the sample size. Measurements over two π steradians can typically be obtained with an angular resolution of 0.1° with samples of 3 millimeters in diameter. Numerous conference proceedings such as for instance [14] and patents, can be found on instruments designed by ELDIM and their related applications. Other commercial products designed by Autronics-Melchers (ConoScope 88) have similar performance.

3.3. Instruments based on catadioptric angular mapping

Many instruments exploiting the catadioptric angular mapping method have been devised over the last decade. There exists four main configurations, one based on a parabolic mirror and the other three on an ellipsoidal mirror. Two configurations that are based on an ellipsoidal reflector incorporate a lens system with moderate acceptance angle. These configurations allow measuring light scattered over half a hemisphere (including nearly grazing angles). The remaining ellipsoidal configuration relies on a fisheye lens (180° acceptance angle) and allows measuring light scattered over the full hemisphere.

Instruments based on a parabolic design configuration were developed for instance by Dana and Wang [15] as well as by Ren and Zhao [16]. This type of design allows measuring samples of relatively small sizes due to the limitations imposed by the size of the lens system. The illumination of the sample under various angles is realized with a beam-splitter and a collimated source moved in a plane. The first authors used an incoherent light source and a XY-scanner while the second ones used a laser fixed on a rotating head for faster scanning.

Several instruments have been devised in the configuration incorporating an ellipsoidal mirror and a lens system with moderate acceptance angle. Rosete-Aguilar et al. made a theoretical study regarding early design considerations [17] while extensive theoretical and experimental work was carried on by Hahlweg and Rothe [18]. These last authors investigated and built a prototype with inclined geometry to facilitate the illumination of the sample. They also propose a design methodology for this type of PGs. A portable PG was developed by Mattison et al. in a joint program commissioned by Air Force Research Laboratory [19]. This hand-held instrument was designed to allow measuring BRDFs while varying the illumination angle between normal to grazing angles. A laboratory instrument was developed by Stavenga et al. for characterizing the scattering properties of butterfly wings illuminated under a normal incidence angle [20]. In this configuration, some directions of measurement are missing due to a hole in the reflector used for illumination, as well as due to sample obstruction by the sample itself and its fixture.

An instrument incorporating an ellipsoidal mirror and a fisheye lens, initially proposed by Ward [21] for the measurement of BSDF to be exploited in computer simulations, was further developed and realized by Andersen and al. to extend its measurement capabilities, among others, to spectral measurements of complex fenestration systems [22]. Recently, we have been able to show that this category of PGs does not function due to severely biased measurements caused by the spatio-angular-filtering properties of the fisheye lens [23]. We also provide design rules for PGs based on an ellipsoidal mirror and a lens system with moderate acceptance angle. In particular, we show that, to avoid biased measurement, the acceptance must be lower than 40° [24].

4. COMPARISON OF THE METHODS

We briefly describe the key features of the three categories of PGs and provide a crude comparative rating based on a few parameters that are provided in table 1.

Compared to screen imaging systems, the key advantages inherent to dioptric and catadioptric mapping systems are a high throughput and low stray light. The unavoidable stray light contribution in screen imaging systems (despite algorithms for background signal suppression) reduces the dynamical range for the measured signal.

A dioptric mapping system allows fully controlling of the light scattered by the sample. This allows reaching a very high angular resolution for a relatively large sample and small instrument. However, such a system requires the design and fabrication of a complex lens system. This requires a high level of expertise and lengthy developments that are associated with prohibitive costs compared to the other types of PGs.

A catadioptric PG, which can be made of a standard lens system and an off-the-shelf ellipsoidal reflector, generally offers more design flexibility. In practice, a customized design is often necessary for complying with specific requirements, for instance on the spectral range, the angular resolution, the sample size or the dimensions of the instrument.

Table 1 – Comparison of methods for parallel goniophotometry.

	(i) Screen imaging	(ii) Catadioptric angular mapping	(iii) Dioptric angular mapping
Optical throughput	--	++	++
Stray light	-	+	++
Dynamical range	-	o	o
Angular resolution	+	o	++
Spectral range	o	o	--
Illumination	-	+	++
Sample size	-	-	-
Calibration	-	-	+
Design and fabrication	+	o	--

Rating symbols:
++ : Substantial advantage inherent to the method
\+ : Advantage inherent to the method
o : No major advantage or disadvantage inherent to the method
\- : Disadvantage inherent to the method
-- : Considerable disadvantage inherent to the method

With a screen imaging or a catadioptric mapping system, the measurement of a broad spectral range (e.g visible and NIR) can be achieved with different lens systems and detectors optimized for specific wavelength ranges, whereas a dioptric mapping a requires a new design from scratch.

The measurement of large samples (a few centimeters) is necessary in some applications such as the characterization of complex fenestration systems [4,22]. Independent of the category of PG, the practically limited size of the instrument restricts the largest measurement sample size to a few millimetres [24].

Given the practical importance of reflectance measurements (BRDF), a versatile - and ideally fast - sample illumination is crucial. With the screen or reflector inherent to a PG, these features for the illumination are less trivial than in a scanning instrument. Since a hole is necessary in a screen imaging PG, the loss of some scattering directions is unavoidable. To vary the illumination angle, a complex setup to move the sample or the reflector with the illumination hole is required. Sample illumination in a catadioptric PG can be realized either by incorporating a beam splitter [15,16] or using a semi-reflective coating to illuminate the sample through the reflector surface [22]. A dioptric imaging design combined with a beam-splitter allows sample illumination under different angles by laterally scanning the source.

The ease and complexity of the calibration, as well as the amount of post-processing, depends on the type of PG. The calibration of a dioptric mapping instrument, which is implicitly realized in the design phase, is more reliable.

5. CONCLUSION

We have provided a state-of-the-art of parallel goniophotometers and explained their working principles. The latters, which can be classified into three categories, are briefly analysed and compared. Hopefully, this work will be helpful for choosing the best design in view of a new development or for selecting a commercial instrument.

REFERENCES

[1] REINHART, C. F., HERKEL, S. The simulation of annual daylight illuminance distributions - A state of the art comparison of six RADIANCE-based methods. *Energy & Buildings* 2000, 32(2), 167 – 187.

[2] WARD, L. G., SHAKESPEARE, R. Rendering with Radiance: The Art and Science of Lighting Visualization, San Francisco, 1997: Morgan Kaufmann Publishers

[3] DANA, K. J., VAN GINNEKEN, B., NAYAR, S. K., KOENDRIK, J. Reflectance and texture of the real-world surfaces. *ACM Transactions on Graphics* 1999, 18, 1 – 34.

[4] ANDERSEN, M., DE BOER, J. Goniophotometry and assessment of bidirectional photometric properties of complex fenestration systems. *Energy and Buildings* 2006, 38(7), 836 – 848.

[5] DENIEL, J.-M. Modélisation des luminaires et des BRDF: réalisation, mesure et compression. *PhD Thesis, Université de Rennes IFSIC/IRISA* 2002.

[6] CIE. Commission Internationale de l'Eclairage. Radiometric characteristics of material and their measurements. CIE 38 (TC-2.3) 1977.

[7] WHITE, D.R., SAUNDERS, P., BONSEY, S.J., VAN DE VEN, J., EDGAR, H. Reflectometer for measuring the bidirectional reflectance of rough surfaces. *Applied Optics* 1998, 37, 3450 – 3454.

[8] GOODMAN J.W., *Introduction to Fourier Optics, 2nd edition*, New-York 1996: McGraw-Hill Companies Inc.

[9] MCNEIL, J. R., WILSON, S. R., Two-dimensional optical scatterometer apparatus and process, *U.S. patent 5241369*, August 1999.

[10] SIPKE, W., BAUMER, S., Appearance characterization by a scatterometer employing a hemispherical screen. *Surface scattering and diffraction III* 2003, Proc. SPIE 5189, 163 – 173.

[11] BOULANGUEZ, P., Caractérisation multispectrale imageante du champ de lumière de sources et de matériaux pour la photosimulation, *PhD Thesis* 2010, Université Paris-Est.

[12] MAUGIN, C., Sur les cristaux liquides de Lehmann", *Bull. Soc. Min* 34 1911, pp. 71.

[13] YEH, P., GU, C. Optics of Liquid Cristal Displays, 4.4. Conoscopy (p. 139), 1999: John Wiley & sons.

[14] BOHER, P., LUET, M., LEROUX, T. Light scattered measurements using Fourier optics: A new tool for surface characterization. *Optical Metrology in Production Engineering* 2004, Proc. SPIE 5457, 344 – 354.

[15] DANA, K. J., WANG, J. Device for convenient measurement of spatially varying bidirectional reflectance. *JOSA A* 2004, 21(1), 1 – 12.

[16] REN, J., ZHAO, J., Measurement of a bidirectional reflectance distribution and system achievement based on a hemi-parabolic mirror, *Optics letters* 2010, 35(9), 1458 – 1460.

[17] ROSETE-AGUILAR, M., RODRIGUEZ-HERRERA, O. G., BRUCE N., Optical design of a scatterometer with an ellipsoidal mirror, *Opt. Eng.* 2003 42(6), 1772 – 1777.

[18] HAHLWEG, C., ROTHE, H. Design of a full-hemispherical spectro-radiometer with high dynamic range for characterization of surface properties using multi-spectral BRDF data from VIS to NIR. *Optical Fabrication, Testing and Metrology II* 2005, Proc. SPIE 5965.

[19] MATTISON, P. R., DOMBROWSKI, M. S., LORENZ, J., DAVIS, K., MANN, H., JOHNSON, P., FOOS, B. Hand-held directional reflectometer: an angular imaging device to measure BRDF and HDR in real-time. *Scattering and Surface Roughness II, GU Z.-H., MARADUDIN A. A., Editors,* 1998. Proc. SPIE 3426, 240 – 251.

[20] STAVENGA, D. G., LEERTOUWER, H. L., PIRIH, P., WEHLING, M. F. Imaging scatterometry of butterfly wing scales. *Optics Express* 2009, **17**(1), 193 – 202.

[21] WARD, G. Measuring and modeling anisotropic reflection. *Computer Graphics* 1992, 26, 265 – 272.

[22] ANDERSEN, M., STOKES, E., GAYESKI, N., BROWNE, C., Using digital imaging to assess spectral solar-optical properties of complex fenestration materials: A new approach in video–goniophotometry. *Solar Energy* 2009, 84, 549 – 562.

[23] KARAMATA B., ANDERSEN, M. Fundamental design limitations in catadioptric mapping goniophotometers. *Optics Express* 2013, *in preparation*.

[24] KARAMATA B., ANDERSEN, M. Design rules for catadioptric mapping goniophotometers. *Optics Express* 2013, *in preparation*.