# M5.1, 5.2 Report on measurements for the visual characterization of facade systems

WP5. Measurements, T5.1

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# 1 Introduction

Within the FACEcamp task 5.1, the existing measurement methods for visual characterization of shading and daylight systems have been analysed as well as new concepts investigated via testing setups. The outcomes enrich the knowledge basis for further investigations and to derive measurement methods towards a standardized characterization scheme for complex façade systems.

# 2 Objectives

This report aims at describing the physical fundamentals as well as the established methods for the visual measurement characterization of complex façade systems through determination of Bidirectional Scattering Distribution Function (BSDF) datasets.

# 3 Methodology

The following steps were addressed within this report towards a visual system characterisation and described in detail:

- Definition and characteristic of a BSDF
- Provided resolutions and data formats
- Generation of BSDFs via simulation and measurement methods
- New design approaches for a BSDF measuring system: Instrumental Investigations and current possibilities at Bartenbach

# 4 Results

The work, presented in detail in the technical annex, has achieved the mapping of existing methods for the determination of the BSDF as well as the scouting of possible new approaches.

With BSDFs (Bidirectional Scattering Distribution Functions) it is possible to efficiently represent diffuse shading blinds as well as specular redirecting components with their transmitting and reflecting characteristics of visible and solar radiation (see Technical Annex chapter 1).

Although the Klems-resolution based BSDF has been established as a standard for daylight simulations as well as energy calculations of complex facades, for specific tasks like glare detection, higher resolution BSDFs are highly recommended and a highly relevant topic in research at the moment (see Technical Annex chapter 2).

Most sophisticated software tools in this field (e.g. Radiance, EnergyPlus, TRNSYS…) have implemented those models. International Databases (e.g. LBNL's Complex Glazing Database) or Tools (e.g. LBNL's WINDOW7, Radiance' genBSDF) enable meanwhile to freely create such BSDF data based on a geometrical model (see Technical Annex chapter 3).

Due to the different standards and resolution, a harmonization work has been started within IEA SHC Task 61, while FACEcamp focused on screening workflows on suitable daylighting- and energy simulation software especially applicable for complex façade systems and towards standardizing model input formats (see Technical Annex chapter 3).

Worldwide, different methods have been established to elaborate BSDFs directly from measurements. While BSDF-generation via simulation allows higher flexibility, less time and costs, several approximations or idealisations are made in the modelling process, which might lead to significant differences compared to reality. Measurement might close these gaps, that's why a combination of measurement and simulation can optimize this process (see Technical Annex chapter 5).

Therefore, Bartenbach has established a combined simulation and measurement method, which allows to use the flexibility and efficiency of simulations, while incorporating methods for reliability-checks of the gained results using the Mini-Diff V5 (see Technical Annex chapter 6).

# 5 Conclusions

The screening and evaluation of methods in FACEcamp WP5 to characterize complex façade systems from different aspects (daylighting, glare, energy demand) have shown the BSDF as a highly valuable method to provide the necessary data. Nevertheless, in the branches of the façade, shading and cladding industry, BSDFs are still known by a minority. Furthermore, the methods to derive reliable BSDF data requires significant details in material and geometry description. Furthermore, planners are mostly not aware about those capabilities or do not have the expertise and tools to deal with those aspects in detail.

The Technical Annex of this report might give advice in this direction by address all those aspects. It gives a summarized overview on the state of research as well as existing standards and methods to characterize complex façade systems with higher reliability and efficiency.

# Technical Annex

# 1 Visual characterization of facade systems with BSDFs – Basics

## 1.1 Definition

Even though, standardized methods for characterizing angle-dependent solar-optical properties of transparent glazing surfaces based on their physical principles (i.e. visible and solar transmittance, reflectance and absorptance, solar heat gain coefficient) are well established, for optically complex structures (like light scattering or daylight redirecting systems) only methodical concepts exists, which are not standardized.

The BSDF is a fundamental radiometric concept, and accordingly the BSDF has established itself as a physically measurable quantity in different applications. In optics it is used for the characterization of surfaces or model development for optical simulation, in computer graphics for realistic modelling of materials and surface properties. Surface technology uses BSDF for the characterization of surface qualities, and increasingly BSDF find a way into the building industry, for the description and modelling of highly complex facades in building energy simulation as well as daylight simulations.

Depending on the system to be described (Clear glass/films, venetian blinds, fabrics…) and the investigated ratings (interior illuminance evaluation, glare evaluation, luminance, energy balancing…), different requirements on the BSDF dataset in terms of resolution (Klems/ Tregenza/ Shirley-Chiu) are given.

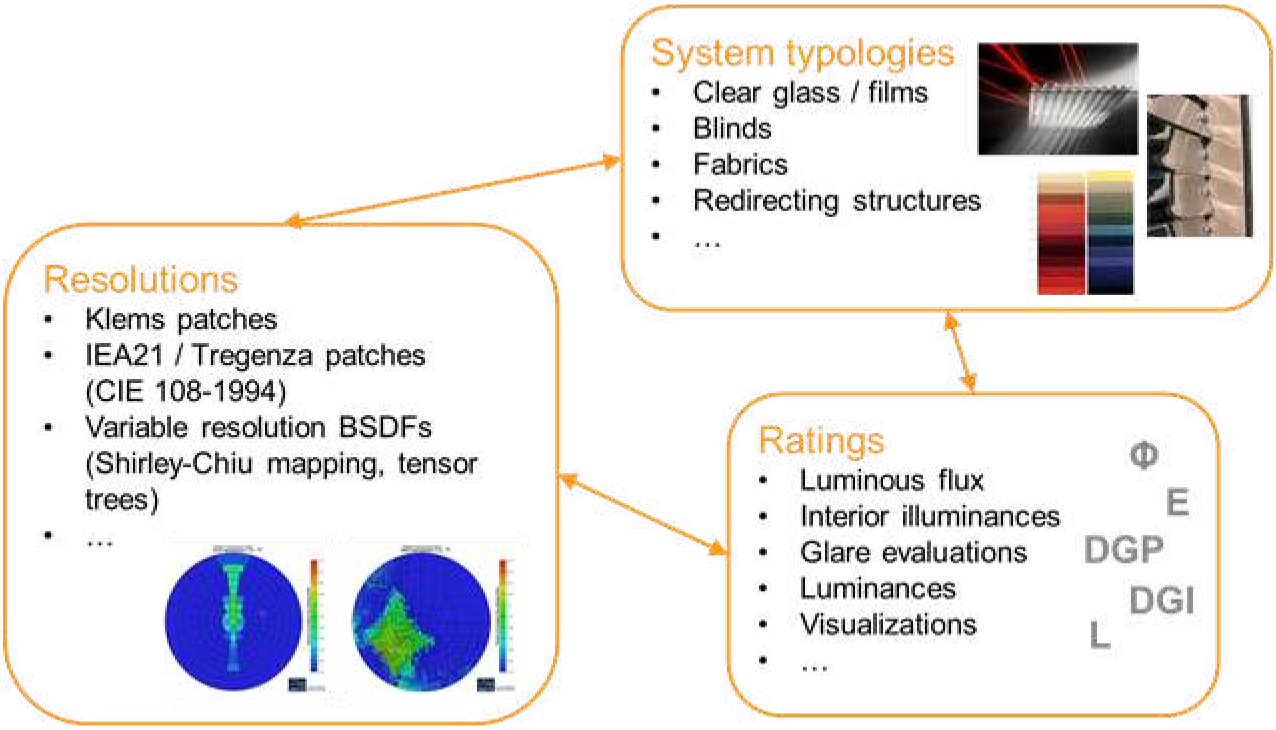


*Figure 1: BSDF requirements.*

The bidirectional scattering distribution function (BSDF) is the general mathematical function which describes the scattering of optical radiation from a surface as a function of the angular positions of the incident and scattered beams. It is the ratio of radiance on the exiting side to incident irradiance. In practice the term bidirectional reflection distribution function (BRDF) is used when it is specifically about reflected scattering. Likewise, the bidirectional transmission distribution function (BTDF) refers to scattering transmitted through a material.

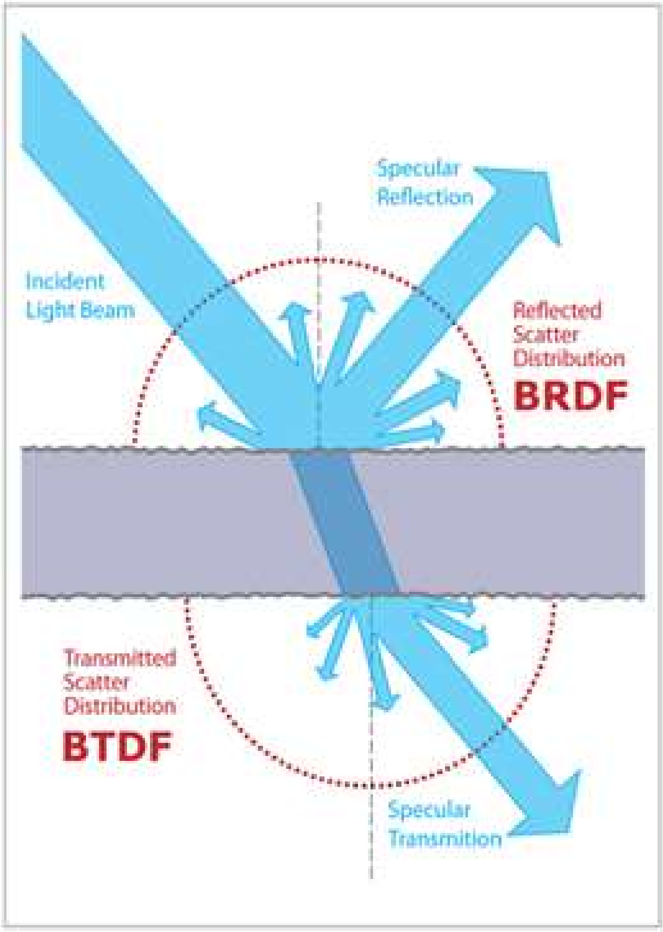


***Figure 2: The composition of a BSDF. BSDF = (BTDF + BRDF), BSDF – bidirectional scattering distribution function, BRDF – bidirectional reflection distribution function, BTDF – bidirectional transmission distribution function. (Source: [https://en.wikipedia.org/wiki/Bidirectional_scattering_distribution_function](https://en.wikipedia.org/wiki/Bidirectional_scattering_distribution_function))***

Using BSDFs, it is possible to efficiently integrate shading and daylighting systems in building energy simulations of thermal performance (i.e., solar heat gains through a window with a shade attachment) even without detailed information of the system's geometric or material properties. However, the Klems subdivision of the hemisphere where every patch corresponds to an average solid angle of 0.043 sr (which corresponds to a cone with a 2x6.7° apex angle) must be handled with care when used to compute other performance parameters that require accurate spatial distribution of illuminance / irradiance or luminance / radiance in the indoor space (such as annual sunlight exposure (ASE), discomfort glare, thermal comfort).

Therefore, beside the initial Klems resolution, different resolutions for BSDF datasets have been established in recent years, which will be introduced in the following chapter.

## 1.2 The rendering equation

$$L_v(\theta_v, \phi_v) = \int_0^{2\pi} \int_0^{\pi/2} L_l(\theta_l, \phi_l) f(\theta_l, \phi_l; \theta_v, \phi_v) \cos\theta_l \sin\theta_l \, d\theta_l \, d\phi_l$$

| | |
|---|---|
| **($\theta_l$,$\phi_l$)** | light source direction |
| **($\theta_v$,$\phi_v$)** | viewpoint direction |
| **f($\theta_l$,$\phi_l$; $\theta_v$,$\phi_v$)** | BRDF |
| **$L_l$ ($\theta_l$,$\phi_l$)** | radiance from the light source direction |
| **$L_v$ ($\theta_v$,$\phi_v$)** | radiance to viewpoint direction |

*(Kajiya J. T. 1986; Nicodemus et al. 1977)*

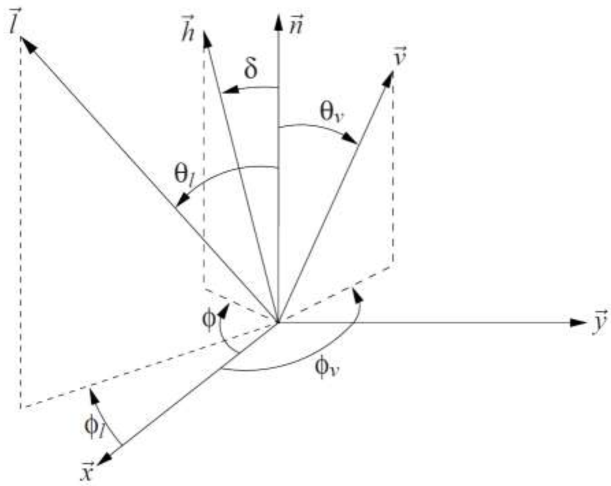


***Figure 3: : Diagram showing vectors used to define the BSDF***

## 1.3 Physical plausibility

**Positivity**

$$f(\theta_l,\varphi_l\ ;\theta_V,\varphi_V) \geq 0$$

**Helmholtz reciprocity:**

$$f(\theta_l,\varphi_l\ ;\theta_V,\varphi_V) = f(\theta_V,\varphi_V\ ;\theta_l,\varphi_l)$$

**Energy balance:**

Albedo

$$a(\theta_l,\phi_l) = \int_0^{2\pi}\int_0^{\pi/2} f(\theta_l,\phi_l;\theta_v,\phi_v)\cos\theta_v \sin\theta_v d\theta_v d\phi_v$$

bounded by 1

BSDFs need to have additional properties, including positivity, obeying Helmholtz reciprocity and conserving energy. In this way they can represent physically plausible materials in the rendering equation (Kajiya J. T. 1986; Nicodemus et al. 1977).

# 2 BSDF formats

## 2.1 Klems patches

In 1994, Klems proposed that the solar heat gain coefficient (SHGC) of optically complex fenestration systems be calculated based on a 145x145 discretization of incident and exiting hemispheres. This hemispherical basis subdivision scheme, which yields approximately equal irradiances for each patch at constant radiance, is used in simulation tools such WINDOW7 or RADIANCE to describe a system's bidirectional scattering distribution function (BSDF i.e., the angle-dependent, solar-optical properties of the system).

Key facts of the Klems scheme:

- subdivision of hemisphere into 145 patches
- approx. equal illuminance from each patch if luminance is constant in hemisphere
- 9 θ ranges {0°-5°, 5°-15°, 15°-25°, 25°-35°, 35°-45°, 45°-55°, 55°-65°, 65°-75°, 75°-90°}
- Φ subdivisions per θ range {1, 8, 16, 20, 24, 24, 24, 16, 12}
- average solid angle 2π/145 = 0.0433 sr, i.e. cone with 2 x 6.73° apex angle [2π*(1-cos(α/2)) = 2π/145]

## 2.2 Tregenza patches

In 2000, the IEA SHC Task 21 "Daylight in Buildings: Design Tools and Performance Analysis" proposed a hemispherical basis for BSDF characterization of shading and daylighting materials that better meets the requirements for daylight performance analysis . For incident directions, Tregenza's sky hemispherical subdivision is used . In contrast to Klems' basis, the 145 directions are distributed to cover approximately equal solid angles. However, as for the Klems basis, they only coarsely discretize the hemisphere of incident directions.

Key facts of the Tregenza scheme:

- subdivision of hemisphere into 145 patches
- approx. equal solid angles for each patch
- 8 θ ranges {0°-6°, 6°-18°, 18°-30°, 30°-42°, 42°-54°, 54°-66°, 66°-78°, 78°-90°}
- Φ subdivisions per θ range {1, 6, 12, 18, 24, 24, 30, 30}
- average solid angle 2π/145 = 0.0433 sr, i.e. cone with 2 x 6.73° apex angle [2π*(1-cos(α/2)) = 2π/145]

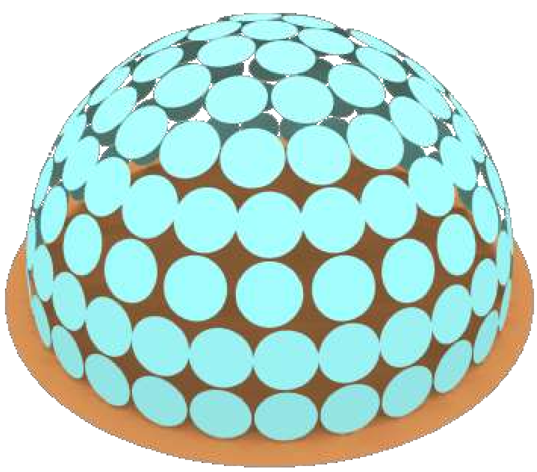

***Figure 4: Tregenza patches.***

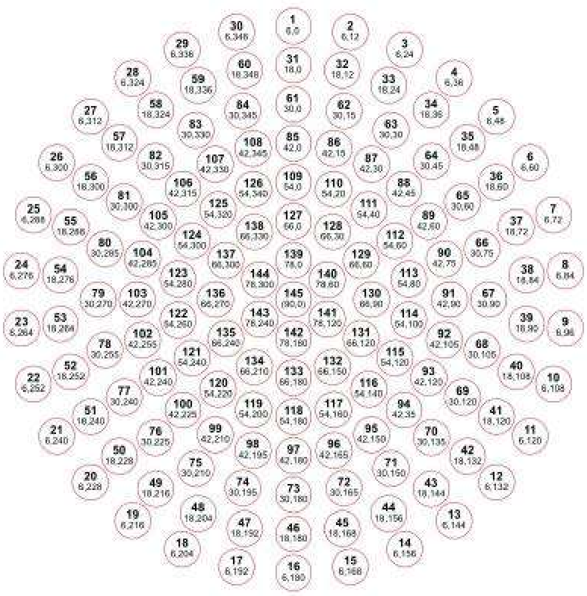

***Figure 5: Klems patches.***

## 2.3 Variable resolution BSDFs

For specular and scattering systems, the coarse representations Klems and Tregenza may lead to significant errors. To overcome this, a variable resolution BSDF approach was introduced by Ward et al. , that enables high accuracy via fine angular resolution for steep gradients of the BSDF while providing a coarse structure in areas with flat gradients.

- high resolution for spikey regions
- low resolution for smooth regions
- based on Shirley-Chiu-mapping (preserves fractional area, i.e. projected solid angle)
- maximum dimensions in 4D 22n x 22n (n = 4 / 5 / 6: 2562 / 10242 / 40962)

This enables a highly efficient data structure (ideal diffuse reflector needs a single value {1/π}). On the other side, the BSDF data leaves the fixed matrix structure, which brings restrictions in flexibility using the established “phase-methods” for efficient daylight simulations of CFS. Either the daylight coefficient approach (DC) is used or the extended 5-phase method, which uses variable resolution BSDFs for high resolution required calculations (e.g. glare evaluation).

## 2.4 BSDF data and file formats

***Table 1: Established data formats:***

| Name | Input resolution | Output resolution | Currently used by software |
|---|---|---|---|
| WINDOW7 | Klems (145) | Klems (145) | WINDOW7, Relux, Radiance |
| IEA 21 | Tregenza (145) | 5deg full, i.e. 5°x5° (1297) | Relux, Dialux, Radiance |
| Shirley-Chiu | variable (limitation through data size) | variable (limitation through data size) | Radiance |

```xml
<?xml version="1.0" encoding="UTF-8"?>
<WindowElement xmlns="http://windows.lbl.gov" xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
        <WindowElementType>System</WindowElementType>
        <Optical>
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                <Material>
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                        </Material>
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                                <ThetaBounds>
                                        <LowerTheta>5</LowerTheta>
                                        <UpperTheta>15</UpperTheta>
                                </ThetaBounds>
                                </AngleBasisBlock>
```

***Figure 6: XML file format. Definition of data discretization in header → data blocks interpreted by software accordingly***

# 3 Generating BSDFs by simulations

## 3.1 Simulation

Lucid Shape
Computer Aided Ligthing

- genBSDF: part of the RADIANCE software package
  http://radiance-online.org/cgi-bin/viewcvs.cgi/ray/src/util/genBSDF.pl
- WINDOW7: LBNL software for calculation of total window thermal performance indices
  http://windows.lbl.gov/software/window/window.html
- commercial software (e.g. LucidShape, ASAP, LightTools, TracePro, …):
  calculation of illumination and conversion from ray file to patches

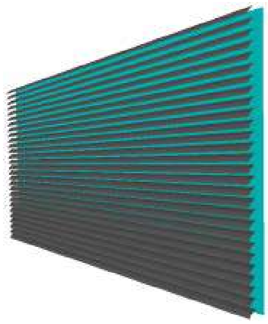


*Fig. 1: Geometrical model used by genBSDF*

## 3.2 RADIANCE – genBSDF

- Simulation via backward raytracing
- Klems patches + variable resolution (3D/4D) +
- possibility for user-defined resolution
- Geometry & material:
  BSDF for the whole subsystem (including geometry) or only the material description

## 3.3 LBNL WINDOW7

- Calculation with Radiosity
- Klems patches resolution (fixed)
- Visual and thermal characterisation
- Limited in geometry & material definition
- BSDF only for subsystem (shading)
- Combination of layers using comprehensive databases (IGDB and CGDB)
- Creation of system BSDFs in Klems resolution

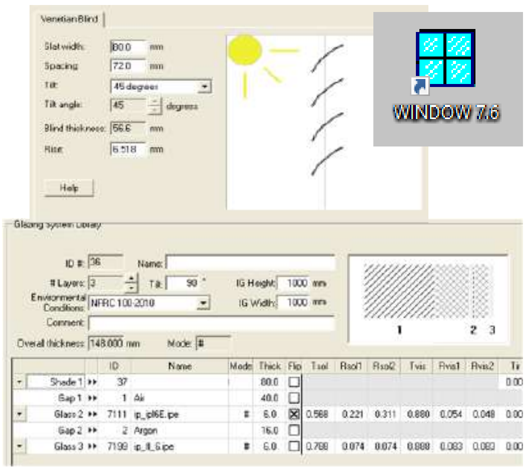



*Fig. 2: Glazing + shading system setup in WINDOW7*

# 4 BSDF standardization

## 4.1 Ongoing work

Standard products for use in the transparent part of facades (clear glazing, diffusing shades) can be characterized sufficiently with the algorithms and methods included in nowadays simulation software. However, when it comes to more complex systems as needed for proper glare protection and daylight redirection, established standards are missing. Therefore, within IEA SHC Task 61[1], investigations

[1] IEA SHC Task 61 / EBC Annex 77: Integrated Solutions for Daylighting and Electric Lighting: From component to user centered system efficiency, http://task61.iea-shc.org/

on procedures of BSDFs are made towards a standardized representation of complex facade systems. Research activities within FACEcamp focused on screening workflows on suitable daylighting- and energy simulation software especially applicable for complex façade systems (FACEcamp toolchain). Also, in FACEcamp different BSDF measurement methods have been investigated and were contributed to the international Task 61 activities.

# 5 Generating BSDFs by measurements

## 5.1 Overview on measurement approaches

There are different approaches to the practical measurement of BSDFs. A BSDF measurement setup usually consists of a light source, a sample mount and a detector. In a simple setup, all components are mounted “in plane” on an optical table, resulting in data along the scattering plane only. However, for the majority of samples, this is not sufficient. Out-of-plane setups come in two varieties: Scanning goniophotometers move a detector mechanically around the sample, while imaging goniophotometers capture images of the resulting luminance distribution on a receiver surface and calculate the BSDF from this.

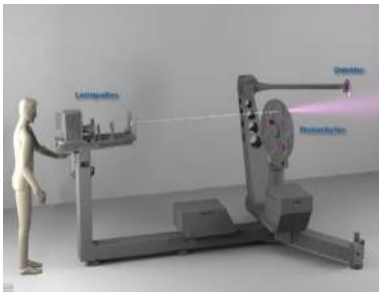
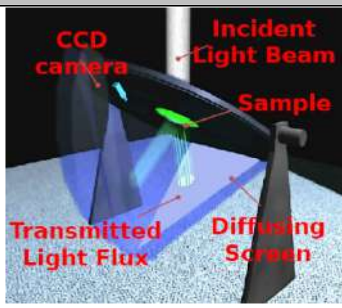
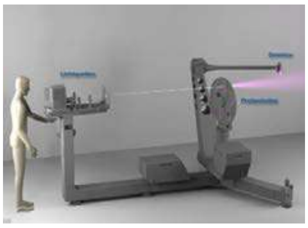
| ***In-plane measurements*** | ***Scanning goniophotometer*** | ***CCD based goniophotomter*** |
|---|---|---|
|  | <br>Image: www.pab-opto.de | <br>Image: J. Kämpf, 2011 |
| | <br>Source: www.lighttec.fr | <br>Source: www.lighttec.fr |

***Fig. 3: Methods of BSDF determination by measurements***

## 5.2 Comparison of the different measurement approaches

**Scanning goniophotometer**

| **pab goniometer**<br>[www.pab.eu/gonio-photometer/](www.pab.eu/gonio-photometer/) | **Key features** | **Data format provided by device software** | **Laboratories** |
|---|---|---|---|
|  | versatile BSDF equipment with high signal range and high angular resolution | Tabular ASCII | Fraunhofer ISE Freiburg<br>HSLU Lucerne<br>LBNL Berkeley<br>Pab |

**Description:**

- Manufactured by pab advanced technologies Ltd.
- Mechanical scanning of a detector head with multiple sensors over a virtual sphere surface that is centred on the intersection between the incident beam and the sample.
- The sample can be rotated around vertical and horizontal axes to allow a broad range of incidence angles.
- Diameter of virtual sphere scanned by detector: 1 m
- Light sources: halogen and xenon lamps
- Detectors: silicon diode, optionally filtered, InGaAs (IR up to 2.5um), SiC (UV)
- Modular design, multiple lamp systems and sample mounts are available
- Unscattered beam measurement as reference
- Adaptive BSDF scanning

Further information:

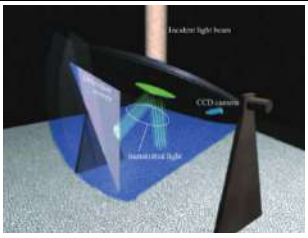
- http://www.pab.eu/pg2-advantages.pdf
- http://www.pab.eu/pg-flyer-en.pdf

| **Reflet 180**<br>[www.lighttec.fr/scattering-measurements/](www.lighttec.fr/scattering-measurements/) | **Key features** | **Data format provided by device software** | **Laboratories** |
|---|---|---|---|
|  | Compact equipment with high dynamic range and high precision | Text files<br>LightTools (opr) | LightTec |

**Description:**

- Angle of incidence: tunable from 0° to 90° (BRDF and BTDF)
- Angular range: 2D and 3D spherical measurements
- Light source: Halogen White Lamp + Passband Filter
- Spot Size (diameter): 1 to 13 mm continuous

- Wavelength detector sensitivity: 400 to 1700 nm
- Detector Acceptance Angle: +/-0,04°/ 1,1°/ 2°
- Minimum BRDF: 10e-4
- Dynamic range: 10e9 for visible and 10e6 for IR range

<table>
<tr><th colspan="4">Image based goniophotometer</th></tr>
<tr><td>IBP / EPFL<br>www.ibp.fraunhofer.de<br>www.epfl.ch</td><td>Key features</td><td>Data format provided by device software</td><td>Laboratories</td></tr>
<tr><td></td><td>Comprehensive BTDF monitoring</td><td>IEA 21, Text files</td><td>EPFL Lausanne<br>Fraunhofer IBP Stuttgart</td></tr>
<tr><td colspan="4">Description:<br>- Angle of incidence from 0° to 90°<br>- Light source: Hydrargyrum Medium-arc Iodide lamp (5600 K colour temperature)<br>- Spot size (diameter): 6 to 15 cm<br>- Wavelength detector sensitivity: visual range, fitted with the photopic luminosity function<br>- Minimum BTDF: 10e-3<br>- Maximum resolution in exiting hemisphere: 1297 (5°)<br>- Duration: 12 hrs for 145 incident directions</td></tr>
<tr><td colspan="4"></td></tr>
<tr><td>Mini Diff v2<br>www.lighttec.fr</td><td>Key features</td><td>Data format provided by device software</td><td>Laboratories</td></tr>
<tr><td></td><td>Portable equipment, easy to use and fast</td><td>Text files (ASTM, mesh, slice), Light Tools, Radiant Zemax, Speos, Trace Pro; ABg (Harvey Shack) and Gaussian fits</td><td>LightTec<br>Bartenbach</td></tr>
<tr><td colspan="4">Description[2]:<br>- Angle of incidence: fixed at 0°, 20°, 40°, 60° (BRDF and BTDF)<br>- Angular aperture: -75° to +75° (hemispherical measurement)<br>- Light source: 3 colour collimated sources (RGB) at 465nm, 525nm and 630nm<br>- Spot Size (diameter): 1mm<br>- Wavelength detector sensitivity: 3 channels red, green and blue (RGB)<br>- Dynamic range: 10e5<br>- BSDF Accuracy < 5% (for Lambertian sample)</td></tr>
</table>

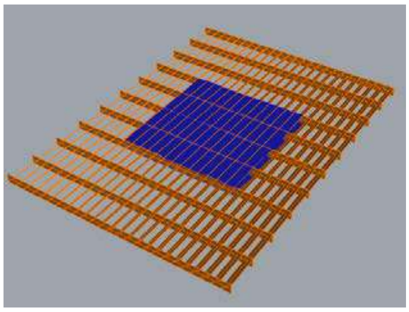
[2] LIGHT TEC: MINI-DIFF V2, for 2D/3D scattered light measurements, Preliminary datasheet. http://www.lighttec.fr/wp-content/uploads/2017/10/Flyer-Mini-Diff-V2.pdf (accessed 11 February 2020).

- BSDF Repeatability < 2% (for Lambertian sample)
- Colour Accuracy Duv < 0.1
- Angular Aperture -75° to +75°

| **Integrating sphere** | | | |
|---|---|---|---|
| **Ulbricht sphere** | **Key features** | **Data format provided by device software** | **Laboratories** |
|  | Measurement of integrated flux, i.e. integrated transmission or reflection for daylight systems | Varies<br>(depending on manufacturer) | Fraunhofer IBP LBNL Berkeley<br>HSLU Lucerne<br>Fraunhofer ISE<br>Bartenbach |
| **Description:**<br>- Standard instrument in photometry and radiometry<br>- Single measurement gives integrated value<br>- Lambertian coating of inner surface with high reflectance<br>- Available in different sizes<br>- Specific to measurement of daylighting systems:<br>o Direct-hemispherical transmission can be measured with a single measurement for each incidence direction<br>o Separate beam light source necessary for illumination of sample<br>o Can be used as cross-check to validate integrated values obtained from goniophotometer measurements | | | |

# 6 Current BSDF measurement possibilities at Bartenbach

## 6.1 Used methods for visual characterization



1. **Simulation of BSDFs based on material and geometry models**

- Radiance genBSDF
- ASAP / LucidShape + in-house tools

2. **Measurement direct-hemispherical transmission**

- Beam radiation and integrating sphere

- Diffuse measurement luminaire
- Derivation of BSDF for non-scattering systems possible

3. **Measurement of surface characteristics**

- new measurement device Mini-Diff
- V2 for BRDF and BTDF (full hemispherical)
- for any incident angle BRDF in the irradiation plane (only one cross section, time-consuming)

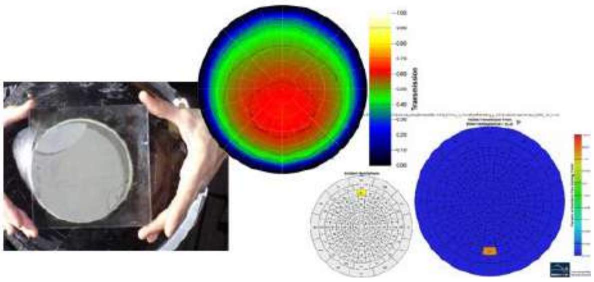


*Fig. 4: Visual characterization via simulations*

## 6.2 New measurement device: Mini-Diff V2

Mini-Diff V2 is a compact and portable optical system for 2D/3D scattering characterization: it can measure the BRDF & BTDF of different kind of materials and objects:

- Measurements of BSDF in red, green, and blue (RGB)
- TIS measurements for RGB
- Dynamic range is 1:$10^5$
- Colorimetric data: Lab or u'v'

*Figure 7: Light Tec Mini-Diff V2*

*Table 2: Datasheet of the measuring device Mini-Diff V2*

| Mini-Diff V2: Preliminary Datasheet | |
|---|---|
| **Description** | Handheld device for characterizing surface scattering (BSDF) and surface color.<br>   |
| **Light Sources** | 3 color collimated sources: Red, Green and Blue for RGB measurements.<br>• Red: 630nm [Δλ1/2=25nm]<br>• Green: 525nm [Δλ1/2=35nm]<br>• Blue: 465nm [Δλ1/2=25nm] |
| **Angle of Incidence** | • For reflection measurements: 0°, 20°, 40° and 60°<br>• [Optional] For transmission measurements: 0°, 20°, 40° and 60° |
| **Dynamic Range** | $10^5$ |
| **BSDF Accuracy** | < 5% (For Lambertian sample) |
| **BSDF Repeatability** | < 2% (For Lambertian sample) |
| **Color Accuracy** | Duv < 0.1 |
| **Angular Aperture** | -75° to +75° - Hemispherical measurement |
| **Effective Measured Area** | Φ1 mm |
| **Angular Resolution** | 1° |
| **Output Data** | 3D BSDF, 3D Angular Resolved Scatter (ARS) |
| **Exportation File Format** | Exportation to optical simulation software (list available upon request) |
| **Package** | • Mini-Diff V2 measurement device<br>• Standard reference materials (white and black)<br>• Measurement and post processing software + factory calibration<br>• USB cable<br>• Storage box<br>• User manual<br>• [Optional]: BTDF module + Standard BTDF Reference + RJ11 Cable |
| **Dimensions** | • Storage box: 355*130*441 mm<br>• Mini-Diff V2 device: 100*100*300 mm<br>• [Optional] BTDF Module: 100*100*100 mm |
| **Weight** | • Mini-Diff V2 device: 2 kg<br>• [Optional] BTDF Module: 0,5 kg |

The measurement procedure and their application is mentioned in Deliverable 5.2.

# 7 References

Kajiya J. T.: The rendering equation. SIGGRAPH Comput. Graph. 20, 4 (1986), 143–150.

Nicodemus et al.: Geometrical Considerations and Nomenclature for Reflectance. NBS Monograph 160, U. S. Dept. of Commerce, 1977.

Klems J.H.: A new method for predicting the solar heat gain of complex fenestration systems; Overview and derivation of the matrix layer calculation. ASHRAE Transactions 100 (1), 1994

CIE 108-1994: Guide to Recommended Practice of Daylight Measurement, 1994

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