Goniophotometry and assessment of bidirectional photometric properties of complex fenestration systems

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Goniophotometry and assessment of bidirectional photometric properties of complex fenestration systems

International Energy Agency (IEA)
Solar Heating and Cooling Programme Task 31

DAYLIGHTING BUILDINGS IN THE 21ST CENTURY

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PREFACE
The main objective of IEA Solar Heating and Cooling Programme (SHC) Task 31 "Daylighting Buildings in the 21st century” is to make daylighting the typical and preferred design solution for lighting buildings in the 21st century by integrating human response with the application of daylighting systems and shading and electric light control strategies. Two key issues, which require research to accomplish energy savings, have been identified as:

- The determination of occupant response towards the luminous and thermal environments in buildings using daylighting systems and daylight responsive controls.
- The integration of daylighting systems, electric lighting, and shading controls taking into account occupant response in order to optimise energy savings.

A third objective is to ensure transference of the results to building design professionals, building owners, and manufacturers. The Task will focus on commercial buildings, both new and existing, including office, retail, and institutional buildings such as schools. The participants in this task are Australia, Belgium, Canada, Denmark, Finland, France, Germany, Italy, Japan, Netherlands, New Zealand, Norway, Sweden, Switzerland, United Kingdom and the United States. Australia is the Operating Agent.

The objective of this Subtask C "Daylighting Design Tools” is to improve the knowledge and quality of lighting tools to enable building designers to predict the energy performance and visual comfort conditions of complex fenestration systems in their daily working process. This Subtask will make a link between industry, designers and software developers and promote the tools to the practitioners. Subtask C is comprised of the following projects:

C1: User Interactions
C2: Algorithms and Plug-Ins
C3: Promotion of Tools & Engines
C4: Validation
EXECUTIVE SUMMARY
This report seeks to provide an overview of the currently available assessment tools for Bidirectional Transmission or Reflection Distribution Functions (BTDFs, BRDFs) of complex fenestration systems (CFS). In the first part of the report, the various existing experimental devices, called goniophotometers, are described, all but one being based on a scanning process to investigate the emerging light flux distribution, the different approach being based on digital imaging techniques. The available BT(R)DF data are listed for each one of them, and their expected accuracy is given whenever explicit in publications. The second part presents an alternative to physical measurements, made possible by using computer simulations based on ray-tracing techniques, as long as every component of the investigated system shows geometric and material properties that are well-known. Different virtual goniophotometer models are described together with the corresponding validation methods and list of available BT(R)DF datasets. Finally, a new database with a graphical user-interface is presented, that aims at providing the relevant features about CFS with a special focus on flexibility and graphical information, in a similar way as for for luminaires selection in electric lighting design.
## Contents

1 Introduction  
2 The Bidirectional Distribution Function  
3 Review of experimental devices for goniophotometric assessment  
3.1 Characterization based on a scanning process  
3.2 Characterization using digital video techniques for a flux-based approach  
3.3 Available experimental devices for façade components at a glance  
4 Assessment of bidirectional distribution functions using numeric methods  
4.1 LESO-PB/EPFL virtual goniophotometer using TracePro®  
4.2 FHG-IBP Numerical Goniophotometer Environment using OptiCad®  
4.3 ENTPE simulation method using Genelux  
5 Conducted comparisons for validating BT(R)DF data  
6 Database of CFS bidirectional measurements  
6.1 Available Datasets  
6.2 Management of CFS database by a graphical interface  
7 Conclusion  
8 Acknowledgements  
9 References  
10 List of Contact Persons  
11 IEA Information  
A Datafile format for BT(R)DFs
1 Introduction

To allow an efficient integration of complex fenestration systems (CFS) in buildings, a detailed knowledge of their directional optical properties is necessary. The latter are described by Bidirectional Transmission (or Reflection) Distribution Functions, abbreviated BT(or R)DF, that express the emerging light distribution for a given incident direction [1]. Having access to such detailed transmission or reflection functions will help manufacturers to develop and optimize their products and architects in selecting the latter judiciously already at the project’s level [2, 3]. It will also help daylighting simulation tool designers to improve their programs’ performances [4, 5, 6, 7, 8] and achieve a reliable modelling of light propagation into rooms using CFS.

A serious effort has been made in developing accurate and efficient bidirectional goniophotometric devices for detailed studies of such systems, capable of measuring BTDFs and/or BRDFs in an appropriate way. The existing instruments are described in this paper, almost all based on a scanning process (except for one), i.e. on relative individual movements of the detector and of the sample and/or the source to monitor all incoming and outgoing light flux directions for which BT(R)DF data are needed. For each of these experimental devices, the characterized systems and available bidirectional data are listed, to provide a complete overview of the accessible information today in this field. Whenever published, their respective validation methods are also given, together with the achieved accuracy estimations on the BT(R)DF data and/or on the directional-hemispherical transmittance or reflectance values calculated from an integration of the latter over the emerging hemisphere.

The second part of this paper focuses on virtual goniophotometers that have been developed, mainly based on commercial forward ray-tracing simulation tools and allowing to complement experimental assessment in a very efficient way. Indeed, such techniques allow more flexibility in parametric studies, and the performances expected for variants (in geometry, material) of a same system can be more easily tested as long as all the parameters are known. The different existing simulation models are described, together with the validation methods or comparisons that were used. A list of available bidirectional datasets based on ray-tracing techniques is also provided.

The angular dependent light transmittance through complex fenestration systems (CFS) and the interaction with outside illuminance conditions provides spatial and time variant indoor light penetration schemes. These dependencies have to be easily handled by the designer to help him find appropriate solutions to a given problem. For this purpose, a flexible database user-interface is being introduced in the third part of the paper. This software aims at comparable software support for CFS as for luminaire selection in artificial lighting
design [9, 10].

2 The Bidirectional Distribution Function

The Bidirectional Transmission (or Reflection) Distribution Function, abbreviated BT(R)DF, is defined by the Commission Internationale de l’Eclairage [1] as “quotient of the luminance of the medium by the illuminance on the medium”. It is therefore angle-dependent at both the incidence and the emergence levels and expresses the emerging light flux distribution for a given incident direction. To represent bidirectional functions graphically, so-called photometric solids are often used, that consist of plotting the BT(R)DF data in spherical coordinates [11], as illustrated in Figures 1(a) and 1(b) for transmission and reflection figures respectively.

From a complete BT(R)DF dataset, it is possible to determine the directional-hemispherical visible transmittance $\tau_{\text{vis}}$ or reflectance $\rho_{\text{vis}}$ by approximating the integral over the whole emerging hemisphere with a sum over all individual BT(R)DF data [5, 12]. This parameter is of great importance in the validation of bidirectional measurements, by comparing it to measurements performed on the same material with an integrating (Ulbricht) sphere [13], but also in the assessment of the global photometric behaviour of a fenestration material.

![BTDF and BRDF representations as photometric solids for the sun-directing glass “Lumitop™” and a Holographic Optical Element [12].](image)

Fig. 1. BTDF, incidence (12°, 60°) (b) BRDF, incidence (0°, 0°)

The achieved BTDF or BRDF dataset is generally saved in ASCII format on an electronic file denominated after the sample name and including the institute’s designation as well as the considered incident direction. This leads to BTDF files named after InstituteNameT_SampleName_IncidentAltitude_IncidentAzimuth.txt and BRDF files named after InstituteNameR_SampleName_IncidentAltitude_IncidentAzimuth.txt.
These files contain the following data, in agreement with the common format for bidirectional measurements defined within the Task 21 of the International Energy Agency [5], based on the subdivision of the sky hemisphere into 145 sectors for luminance measurements defined by Tregenza [14] (see Figure 2):

![Subdivision of the incident hemisphere (sky dome) into 145 sectors of 10° opening: view from normal direction.](image)

- the sample characteristics: name, manufacturer, measurement type (transmission or reflection), symmetry indicator, area, thickness, additional comments, date of measurement and institute denomination;
- the incident direction and, if relevant, additional measurement parameters (resolution, obstruction);
- the directional-hemispherical light transmittance or reflectance $\tau_{1h}$ or $\rho_{1h}$;
- the BTDF or BRDF values, expressed in Cd·m$^{-2}$·lux$^{-1}$ and associated to the regular set of emerging directions given in polar angles (they are displayed in three columns separated by a tab character of ASCII code 9).

An example of file contents is given in Appendix A. Recently, the Berlin University of Technology (TUB) proposed a revision of this default incident directions set [15], that suggests to use sun co-ordinates and to rotate both top and bottom halves of Figure 2 by 84°, respectively downwards and upwards around a horizontal axis. The Lawrence Berkeley National Laboratory (LBNL)
is also currently working on a new angular basis for bidirectional data [16], that would sample the weighted unit hemisphere approximately uniformly and be invariant under a $90^\circ$ rotation in azimuth.

3 Review of experimental devices for goniophotometric assessment

The range of applications for bidirectional goniophotometers has broadened increasingly since the early nineties, especially with the strong progress made in computer graphics rendering. These applications include the characterization of ground surfaces as well as microscopic interactions between layers of different components, of luminaires and lamps or of details about surface texture. A serious effort has been made as well in developing accurate and efficient bidirectional goniophotometric devices for detailed studies of fenestration systems, capable of measuring BTDFs and/or BRDFs in an appropriate way for such materials.

They are almost all based on a scanning process (Section 3.1), i.e. on relative individual movements of the sample, detector, and/or source to monitor all incoming and outgoing light flux directions for which BT(R)DF data are needed. Some propose a way to reduce this onerous scanning process by adopting a flux-based approach (Section 3.2) and relying on digital video capture for light detection.

3.1 Characterization based on a scanning process

3.1.1 Pros and cons of a scanning-based assessment

The two main draw-backs of the scanning approach are the considerable measurement time needed for a BT(R)DF assessment, which is further increased when a finer angular resolution is required due to rapidly varying luminances typically, and more importantly the fact that the investigation is discrete. A preliminary scanning is often required to locate the luminous “peaks” while the risk of missing some significant feature can never be avoided completely.

Irregular resolutions also make it more difficult for simulation programs to implement the BT(R)DF data and the estimation of the global (directional-hemispherical) transmittance or reflectance becomes delicate as a weighting of data is then necessary, based on the areas associated to each point [17].

On the other hand, when using specific detection techniques, an optimal accuracy can be achieved with this approach when assessing the light distribution’s
directionality. Indeed, focusing the emitted light rays onto a detector showing an opening angle as close as possible to their accepted divergence (typically ±0.5°), a very accurate spatial characterization can be ensured, as for the Cardiff goniospectrometer [18], its technique having recently been adopted at TNO as well [19].

When the measured luminance and the emerging direction are on the other hand average values obtained over the whole sample area, as for the device developed at LBNL e.g. [20], the detection surface must be able to encompass the possible divergence of the rays that reach it, either choosing a sensor element of appropriate dimensions, or compensating a too small or too close detector by averaging data obtained at different positions within the target space portion.

3.1.2 Goniophotometers for façade components systems

The first bidirectional goniophotometer designed for BT(R)DF measurements of fenestration materials, shown on Figure 3(a), was developed at the Lawrence Berkeley National Laboratory (LBNL), USA, in the late eighties [20]. Not in use anymore, it consisted of a fixed light source, a sample holder with two rotational degrees of freedom (see Figure 3(b)) to determine the incident direction and of a photopically corrected silicon sensor moving on a semicircular track, pointing at the illuminated sample from the different outgoing directions. It was able to handle samples of about 40 × 40 cm².

At the Fraunhofer Institute for Solar Energy Systems (ISE), Freiburg, Germany, a goniophotometer allowing flexible sample dimensions was designed [21], which was an innovation in regard to LBNL’s device. It included two fixed light sources: a halogen lamp with parabolic mirror, intended for large samples characterization (up to 40 × 40 cm²), and a 1 kW Xenon lamp with collimating lens and varying diaphragms, for small samples (down to about 4x4 cm²). An automated solar cell (2 × 2 cm²) with green V(λ) filter was used as the detector, and moved on a linear rail; it viewed the complete 40 × 40 cm² sample, fixed on an adjustable holder presenting two degrees of freedom. From a relative point of view, the detector was quite close to the sample (only at about twice its dimensions), and it therefore becomes difficult to assess BT(R)DF values without assumptions on emission, especially as the restrictions on detection areas, mentioned above, remain applicable. An important innovation was the adaptive refinement in angular resolution, developed to concentrate detection positions inside interesting areas (typically presenting high luminance gradients). A two-steps investigation was unfortunately required to locate these areas.
In 1998, the device was upgraded [22] by replacing the linear detector rail with a semi-circular rail of 1 m radius, so that its distance to the sample remained constant (see Figure 4(a)); a silicon photodiode was chosen as the detector, with a green $V(\lambda)$ filter to correct the sensitivity in the IR range to a photometric response; interchangeable diaphragms could be placed in front of the detector (for the standard diameter 5 mm, the opening angle was $0.28^\circ$). The signal range was $1:10^7$, allowing the detection of both specular and low scattering components, and an angular resolution as fine as $0.1^\circ$ could be achieved for the detector if necessary. A reference solar-cell had to be added to account for Xenon source fluctuations, which made the assessment process heavier; on the other hand, the light source being of diameter often smaller than the sample itself, it could be viewed through the latter by the detector.

Currently, a further upgrade of this device is under way, with an improved light source and, more importantly, a calibrated and movable Charge-Coupled Device (CCD) camera as the detector, that will thus also be used to identify details on the surface of façade elements, like localized peaks possibly responsible for glare effects [22].

A new goniophotometer has been designed recently by the consultancy company $pab^{\text{®-opto}}$ [23], primarily designed for in-house use and consulting. It will allow both transmission and reflection measurements, as well as a flexibility...
Fig. 4. Mechanical components and movements of the bidirectional goniophotometers developed at ISE and pab\textsuperscript{®}-opto in Freiburg, Germany.

in the sample size (up to 30 $\times$ 30 cm$^2$). Either a Xenon lamp or a laser will be used as the incident light source, and a jointed arm will ensure the automated movements of the detector over the emerging hemisphere (see Figure 4(b)), according to an angular resolution up to 0.1$^\circ$ for both sample and detector, where the latter can be chosen amongst different types and spectral ranges depending on the application (IR, visible, multi channel), optionally adaptable to far infrared measurements.

At the \textit{TNO Building and Construction Research}, Delft, The Netherlands, a goniophotometric design very similar to the former concept at ISE [21] has been developed [24], also combining transmission and reflection measurements, a flexibility to the sample size and positioning the detector by the way of adjustable arms. More specifically, a wide bundle light source is combined to a small opening angle ($\sim$1$^\circ$) sensor (silicon photodiode with green $V(\lambda)$ filter) that can be positioned every 0.1$^\circ$ if necessary. The chosen small light source (2 cm, Xenon 2.5 kW stage light, 100 Hz frequency), placed at 5 m, requires a hundred measurements at frequency 10,000 Hz to be realized and averaged for each incident or emerging direction. The distance from sensor to sample is of 1.2 m, with a maximal sample area of 80 $\times$ 80 cm$^2$, and the sample holder turns around two perpendicular axes. This device was at first developed to characterize transparent-insulating (TI) materials; in 2000, it was adjusted to measure other systems as well [19], like simple and complex glazing, plastics and shading fabrics.
The characteristics of the goniophotometer developed at the Berlin University of Technology (TUB), Germany [25] are the following: capable of measuring transmitted light distribution only, it is based on a spiral scanning, achieved by manual movements of a 100 W incandescent light source on a semi-circular arc, that are combined to a manual rotation of the sample to determine the incident direction. This source and sample system is in turn rotated as a whole to determine the transmitted direction thanks to an automated rotation of the detector. Typical sample diameters stay around 7 cm, but a certain flexibility is allowed.

It is currently upgraded as well, and will be based on a different mechanical principle, close to the one currently used at ISE [22], with a rotating arc on which the detector is moved; however, the latter will not be unique anymore, but will consist of several sensors distributed on the arc, undergoing small movements within the gap to their neighbor. This principle guarantees a complete arc investigation with a number of scanning positions reduced by a factor equal to the number of sensors; the reduction of the measurement time is of course significant but does unfortunately not prevent the scanning process to be laborious for a full BT(R)DF characterization. The light source will be a halogen lamp with reflector, and the sample diameter will be freely chosen amongst 5, 10 or 15 cm.

The Institute for Light and Building technique (ILB), Cologne, Germany, also documents two different concepts. A former design, described in [26], allowed transmission measurements only, and consisted of a fixed 50 W halogen lamp - thus of non-optimal spectrum -, placed at the focal point of a Fresnel lens. The beam was reflected by two redirecting planar mirrors before reaching the mobile detector, a 5 mm² photodiode with a green $V(\lambda)$ filter placed at 0.5m from sample. The incident, respectively transmitted, angular range could be chosen inside a 60°, respectively 80°, half-angle cone from the sample center; only small samples ($5 \times 5$ cm²) could be characterized. Some measurements were performed on pressed glass, a 3M film and a diffusing material, although the obtained results were very poor for the latter, the transmission being too low for the signal to be properly detected.

Upgraded into a new concept two years later [27], it was then capable of handling transmission as well as reflection characterizations; as the addition of a photomultiplier to the photodiode did not prove successful, a Zeiss® spectrometer for adaptable spectral analysis was used instead, moved on a semi-circular rail (80° half-angle movement) in a vertical plane, itself rotating around a vertical axis. A halogen lamp with photopic filter remained at a constant distance of 1 m from the sample by being moved on a second semi-circular rail (80° half-angle movement), in a plane rotating around a horizontal axis. The same positioning accuracy of 0.1° as for the previous devices could be reached, but
only small samples were allowed still ($\leq 7.5 \times 7.5$ cm$^2$). An interesting new feature was the use of a non-calibrated monochrome CCD camera, that was added as a receiver option for qualitative analyzes of surface inhomogeneities; integration times could be varied from 10 ms to 10 $\mu$s.

At Cardiff University, UK, a very innovative goniophotometer was developed [18], now owned by the Technical University of Denmark (DTU) and illustrated in Figure 5. Designed for transmission measurements only, it is capable of collecting angle- as well as wavelength-dependent optical properties, thanks to a detector comprising a light collection system and an optical spectrum analyzer. This detector is placed at 2 m from the sample on a rotating arc (goniometer) and moved with a precision of 1$^\circ$. The light collection system consists of an off axis parabolic mirror that focuses the transmitted light onto the end of an optical fiber bundle; the spectrum analyzer is either a silicon detector (from 300 to 1100 nm) or a InGaAs detector (900 to 2100 nm), with respective resolutions of 5 and 10 nm. Having access to the spectral properties of transmitted light is not only useful for describing visual properties in more details, but is also necessary for the data to be relevant for solar heat gain performances assessment.

The sample is rotated to determine the incident direction with a precision of 0.1$^\circ$; a tungsten halogen lamp (250 W) with parabolic aluminium reflector is fixed on a tripod at 2 m from the sample. This makes the alignment with the latter quite laborious, especially as a high precision is needed in the adjustment because of the detection method. A good uniformity of the incident beam is achieved (<1% below 60$^\circ$ from the beam axis); sample sizes can range from 2 to 9 cm in diameter, which remains restrictive for fenestration systems applications.

Finally, another goniophotometer based on a scanning process was realized at the University of Technology Sydney (UTS), Australia [28, 29]. Of mechanical concept close to the upgraded facility at ISE [22], and also allowing transmission and reflection measurements, it differentiates itself by the two chosen light sources, one of which being a laser, used for detailed studies. This represents the only occurrence of lasers for fenestration systems assessment, apart from the not yet completed pab$^\text{R}$-opto device [23]; these sources are indeed suitable for specular light analysis and offer an almost perfect collimation, but they also present the significant draw-backs of proposing only pulsed and monochromatic signals, that are too low for diffuse materials, and too narrow for large samples. The other source is an arc lamp, used for larger sample areas, with a beam splitter and a collimator. The sample rotates around a vertical axis, and the detector is moved on a quarter-circular arc turning around both horizontal and vertical axes; its distance to the sample is 60 cm at most, but...
can be varied according to the signal level: when scattering occurs, it needs to be brought closer, which also implies that the angular resolution will be coarser (a 0.002° resolution in altitude or azimuth is the finest reachable, but is rarely necessary).

3.1.3 Other goniophotometric applications using a scanning-based analysis

Many other applications are found for goniophotometric measurements. An overview of the broad range of existing devices is here given according to three main categories: instruments for assessing BTDFs or BRDFs of surfaces smaller than a few cm, directional goniophotometers for luminaires, and devices developed for the detailed analysis of surface texture or local variations in luminance, often aiming at image rendering applications.

Several instruments have been designed for analyzing samples of a few cm only.

In Boulder, Colorado, such a device was developed for luminaire modeling applications [30]; it uses an incandescent light source and silicon photodiodes to detect the emerging radiation, and allows sample sizes of 6.5 cm diameter. It was used for reflection measurements, although the principle remains viable in transmission as well. Another apparatus based on the LBNL goniophotometer principle [20] was designed to measure the transmittance properties of small fabric composite samples [31].

At Cornell University, NY, a bidirectional gonioreflectometer for surface texture characterization was developed [32]; the sample size is limited to about
5 cm. A rotating Quartz-halogen source is combined to an opal glass diffuser for depolarization; the incident beam then passes through a condenser lens, an adjustable iris and a Nikon camera lens. The sample can be rotated around two perpendicular axes to determine the incident and reflected directions; a fixed commercial spectroradiometer manufactured by Kodak is used as the detector, where light scattered from the sample is focused after passing through a dichroic polarizer and being reflected on a folding mirror.

A tunable laser source is used in [33], whose beam goes through a large set of optical components (beamsplitter, mirrors, filters, monochromator, polarizer) before reaching the photodiode detector. In [34], an instrument designed to assess BT(R)DFs of silica wool samples is described, using a bolometer mounted on a goniometer as detector.

The Belgian Building Research Institute (BBRI) owns a commercial double beam spectrophotometer (Perkin-Elmer model Lambda 900) with angular accessory (PELA 130) [35], very similar to the customized Perkin-Elmer goniometric spectroradiometers at LBNL [36]: it allows transmission and reflection measurements from 175 to 3300 nm, and creates two symmetric mirror paths (reference and measurement beams), that are each collected in a small integrating sphere. Likewise, a measurement device for BT(R)DFs with a fixed 2 cm light source, a rotating sample, and an integrating sphere mounted on a goniometer for detection is found in [37, 38], combined to a polarizer to measure s- and p- polarizations separately. Other commercially available spectro-radiometers with goniometric accessory are marketed and use a laser source for BT(R)DF assessment [39, 40].

For lighting fixtures, the principle remains the same as for bidirectional measurements, but the aim is to determine how the light emitted from lamps or luminaires is distributed in space, so there is no incident direction to account for.

Several assessment methods rely on a scanning along section views [41, 42], or on the positioning of the detector by robots and a similar adjustment of the analyzed incandescent lamp [43]. More recently, methods allowing to investigate the whole luminaire have been developed, that can differ whether they aim at investigating detailed properties over the luminaire’s surface or only the globally emitted light flux in each direction. In [44], it was chosen to collect the light emitted from the whole luminaire with a mirror, and to redirect it towards a notional sphere that maps the luminous intensity distribution; the same option was taken in [45], yet with a photodetector as the final target.

The preferred technique for luminance field goniophotometry remains however the use of a calibrated CCD camera as the detector, to avoid a scanning over
the luminaire [46, 47, 48, 49, 50, 51, 52, 53]; both CCD camera and photosensor can also be placed on a ring moving around the luminaire [54]; finally, to analyze very small light sources (LED’s), a resort to fiber optics is proposed [55], that are connected to a spectroheliograph in addition to the CCD camera system.

To investigate a texture or local luminance variations on the surface of an object, a BRDF cannot provide a sufficient level of details, as it typically integrates a sample area over a period of heterogeneity. For such detailed analyzes, an investigation of the characterized surface becomes necessary. The use of a CCD camera to perform this investigation in an efficient way appears as the most commonly used option, as it allows to reduce the number of scanned dimensions greatly, without any loss of accuracy if appropriately calibrated. Formally, such a function was defined in [56] as the “Bidirectional Texture Function (BTF)”, which is a six dimensional function, extending the BRDF concept by allowing reflectance to vary spatially along the surface.

At macroscopic levels, gonioradiometers were developed to describe the reflectance properties of ground or vegetation, as in [57] for roads, [58] on boreal forests and fen, [59] on test sites in Nevada and New Mexico, [60], [61] and [62] on fields and land surfaces, and [63] on planet Mars. On the other side, surface texture scattering patterns are investigated at microscopic levels to characterize tapered roller bearings [64], ink-paper interactions [65], or the scattering properties of velvet and shot fabrics wrapped around a right-circular cylinder for a more convenient collecting of radiances by the digital camera [66, 67].

Bidirectional reflectance functions of visual display screens were also studied to assess the parasitic reflections of the ambient light sources in a room [68]: it must be noted that this approach presented an interesting 2-D BRDF concept using a conoscopic receiver and a specific illumination technique (‘Focal Plane Illumination®’). The IEN Istituto Elettrotecnico Nazionale in Turin, Italy [69] developed a bidirectional assessment method for transmission and reflection, where small samples (5 cm diameter) are analyzed by a rotating, spectrally corrected CCD camera, with a resolution up to 40 \( \mu \)m.

At a larger scale, a photogoniometer designed primarily for traffic lights and variable message signs [70], including a large rotating sample holder, chose a detection technique based on a radianceprobe combined to a CCD-spectroheliograph.

Amongst the different instruments developed for a detailed characterization of objects texture for image rendering applications [71, 56, 72, 73, 74, 75, 76, 77, 78], almost all of which use an imaging detector (CCD camera), two approaches can be distinguished for their much better time-efficiency [73, 74]
and [77]: curved test samples are considered, like in [66], and thus capture light reflected from many differently oriented parts of the surface at the same time; this method significantly accelerates the investigation process by eliminating the mechanisms of detector and source positioning, the latter being determined by automated photogrammetry. A tapered kaleidoscope is used in [78]; it allows, on one hand, a camera to view the same surface from many directions simultaneously; on the other hand, the surface can be illuminated from many different directions using a structured light source.

3.2 Characterization using digital video techniques for a flux-based approach

The use of Charge-Coupled Device (CCD) cameras allows a fine investigation of the materials and an appreciable flexibility in the luminance dynamics if different integration intervals are used. One of its greatest advantages is to allow the visualisation of many directions or locations at the same time. Its use to investigate luminance distributions on surfaces and reflectance properties of objects can be extended by projecting the light emerging from the sample on a surface that could be more easily viewed by the camera, preventing the latter from having to move from one acquisition position to the next one.

3.2.1 Pros and cons of a flux-based assessment

Choosing to point an imaging detector towards a projection surface to assess BT(R)DFs allows to combine time-efficiency with continuity of information, as a single digital image gathers thousands of emerging directions without any gap between them. This ensures that no feature can be missed, as each pixel represents an average of the light distribution detected within its area and is adjacent to its neighbor. The only parameter that limits the angular resolution is the pixels size, which nowadays has stopped to be a limitation.

From the luminance mappings offered by the once calibrated digital images, the light flux distribution can be subdivided according to an angular grid of freely chosen intervals in altitude and azimuth, defining contiguous sectors where the BT(R)DF can be averaged without any loss of precision as each mean value will truly represent the angular interval it is associated to, and will not correspond to an infinitesimal solid angle around a given emerging direction. Such BT(R)DF data will then be different from goniophotometric measurements based on a scanning process, unless the investigated material presents perfectly diffusing properties (or unless the averaging sectors become of size comparable to the divergence of detected rays for a given position of the scanning sensor).

By capturing several images of the same luminous situation at different inte-
gration intervals, large dynamics in luminance can be assessed with constant accuracy, and saturation or under-exposure effects can be prevented.

However, as there are many procedures necessary to extract the desired output from raw digital images, these advantages are only accessible at the expense of numerous calibration procedures as well as heavy image and data processing [12], and the reliability of the data assessment and its related accuracy depend on their careful execution. Of course, once all the intermediate conversions have been implemented successfully, the measurement facility becomes again as easy to use as any instrument of the kind.

On the other hand, such an assessment method prevents from being able to achieve a spatial accuracy as optimal as for the instrument developed at Cardiff University [18], as the measured luminances and emerging directions are average values for the sampled region. As mentioned in Section 3.1, it is therefore important to subdivide the emerging hemisphere according to an averaging grid in agreement with the possible divergence of rays reaching a given point on the screen.

### 3.2.2 Review of goniophotometric instruments based on video detection

Several examples of instruments using digital imaging combined to a projection of the emerging light were developed, all of them allowing to lower the processing time for a full BT(R)DF measurement in a remarkable way.

Two of them were designed for photo-realistic rendering of lighting in interior spaces. One is more specifically aiming at characterizing whole advanced glazing and shading systems. Another device is currently under development, based on the assessment principle of one of the photo-rendering instruments but meant to be used for materials and coatings characterization of daylighting systems.

An original and extremely time-efficient approach was developed at the Lawrence Berkeley National Laboratory [79], designed for photo-realistic rendering of lighting in interior spaces. It is schematized in Figure 6(a): the sample and a CCD camera equipped with a fish-eye lens are each positioned at the two focal points of a hemi-ellipsoidal, semi-transparent mirror. Due to practical and mechanical constraints, it was actually not possible to build an ellipsoid, and a half-silvered hemispherical mirror was designed instead, which induces that the two focal points become one, although sample and camera of course cannot be placed at exactly the same position.
The light source (3 W quartz-halogen lamp with parabolic reflector), always pointing towards the sample, is moved automatically. The light rays emerging from the sample are reflected on the interior face of the mirror, and redirected towards the camera. Thus, basically only one image is needed to investigate the whole reflected light distribution; as a consequence, only a few minutes are required to achieve a complete sample characterization, e.g. for about a hundred incident angles. What is more, even reflected directions coincident with the illumination direction are permitted. However, the measurement of polished surfaces presenting sharp specular peaks proved to be unreliable as well as reflectance near grazing angles, the hemisphere being of imperfect shape and the incident beam being not parallel enough.

Based on Ward’s work, a similar measurement device was developed recently at the Université de Rennes 1, in France [52], together with a more conventional approach using of a jointed device and a mobile spectrophotometer. It consists of a digital camera equipped with a fish-eye lens as well, that is placed at the bottom of a cube coated with a diffuse grey painting (see Figure 6(b)), replacing Ward’s hemispherical mirror. This allows to avoid problematic polarization effects due to specular reflections, but induces many parasitic inter-reflections that are difficult to assess and control.

![Diagram](image)

(a) Original concept, designed by Ward (LBNL, 1992) (b) Similar approach, developed by Deniel (Université de Rennes, 2002)

Fig. 6. Time-efficient video-reflectometers developed for photo-realistic rendering of interior spaces.

At the Solar Energy and Building Physics Laboratory (LESO-PB) of the Swiss federal Institute of Technology (EPFL), a different design was realized, shown on Figure 7(a), using a CCD camera and a flat and diffusing projection screen in order to avoid inter-reflections and polarization of the emerging light. The measurement principle is illustrated by Figure 7(b) [80, 12]: the light emerging from the sample is reflected by a diffusing triangular panel towards the CCD camera, which provides a picture of the screen in its entirety; the camera is used as a multiple-points luminance-meter and calibrated accordingly. Within
six positions of the screen and camera around the sample (each separated by a 60° rotation from the next one), a complete and continuous investigation of the transmitted or reflected light is achieved within a few minutes per incident direction, the corresponding BT(R)DF values being calculated at the pixel level and gathered according to a suitable averaging grid [81].

The measurements are performed in a 15 × 7 × 8 m dark chamber made of black velvet curtains and carpet showing reflection factors inferior to 1%. The light source remaining fixed, the incident direction is determined by inclining the sample plane around a horizontal axis, and by rotating the sample around its normal. A light-proof cap protects the measurement space against stray light, and all internal elements are covered with highly absorbing material.

Fig. 7. The LESO-PB / EPFL bidirectional goniophotometer using a CCD camera combined to a flat and diffuse projection screen.

This device was designed for the assessment of advanced daylighting systems such as solar blinds, complex glazing and sunlight redirecting devices. For BRDF assessment (reflection measurements), some additional constraints appeared due to the conflict of the incident and emerging light flux. For five out of the six screen positions (unless incidence is normal), the detection principle could be kept identical as in transmission mode, except that light flux must penetrate the measurement space in a way that the beam is restricted to the sample area only. As there is one position (all six for normal incidence) where the screen obstructs the incoming light flux, a special opening in the latter was required to let the beam reach the sample, producing a blind spot at that specific screen position (and only in reflection mode).

At the Massachusetts Institute of Technology (MIT), a new goniophotometric
instrument based on Ward’s concept is under development. This instrument will be more specifically designed for assessing the bidirectional properties of innovative materials and coatings used either for advanced daylighting systems or for optimized luminaires, whole systems being then modelled in computer simulations (see Section 4). This instrument is expected to be able to provide both the bidirectional transmission (BTDF) and reflection (BRDF) functions of the considered materials, and to allow a wavelength-dependent investigation over the solar spectrum.

3.3 Available experimental devices for façade components at a glance

Table 1 summarizes the main features of the different instruments developed for advanced fenestration systems: research institute, detection device, measurement type, sample size and date (based on the associated documentation’s publishing year(s)) are provided.

4 Assessment of bidirectional distribution functions using numeric methods

Ray-tracing simulations provide a useful tool for evaluating complex systems in full detail. Many assessment methods for the optical performances of glazing or shading systems resorted to comparisons with ray-tracing simulations:

- to establish a set of quantity and quality criteria for advanced daylight systems and determine their performances with Radiance simulations [82];
- to test a new ray-tracing approach for thermal radiation [83] or prismatic panel performances [84];
- to develop an angle-dependent evaluation procedure of solar heat gain coefficient (g-value) and compare measurements to ray-tracing simulations carried out with the software OptiCAD® 1 [85, 86];
- to determine the daylight distribution in a room and compare Radiance simulations with office room monitoring [87].

Based on these methods, three virtual goniophotometers have been realized, that are described below. All of them adopted a flux-based method, splitting the detection surface into adjacent angular sectors, as mentioned for the video-based experimental approaches of Section 3.2.

1 Opticad Corporation.
<table>
<thead>
<tr>
<th>Institute</th>
<th>Sensor</th>
<th>BTDF</th>
<th>BRDF</th>
<th>Sample (cm²)</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>LBNL, USA</td>
<td>silicon photodiode</td>
<td>✓</td>
<td>-</td>
<td>40 × 40</td>
<td>1988/94/95/97</td>
</tr>
<tr>
<td>ISE, Germany</td>
<td>silicon photodiode</td>
<td>✓</td>
<td>✓</td>
<td>≤ 40 × 40</td>
<td>1994/98</td>
</tr>
<tr>
<td>TNO, The Netherlands</td>
<td>silicon photodiode</td>
<td>✓</td>
<td>✓</td>
<td>≤ 80 × 80</td>
<td>1995/2001</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(only ≈ 1 cm observed)</td>
<td></td>
</tr>
<tr>
<td>TUB, Germany</td>
<td>photoelement</td>
<td>✓</td>
<td>-</td>
<td>∈ [5 × 5 ; 15 × 15]</td>
<td>1996/98</td>
</tr>
<tr>
<td>ILB, Germany</td>
<td>spectrometer</td>
<td>✓</td>
<td>✓</td>
<td>≤ 7.5 × 7.5</td>
<td>1996/98</td>
</tr>
<tr>
<td>Cardiff, United Kingdom</td>
<td>optical fiber + silicon / InGaAs</td>
<td>✓</td>
<td>-</td>
<td>≤ 9 × 9</td>
<td>1996/98</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2000/01</td>
<td></td>
</tr>
<tr>
<td>UTS, Australia</td>
<td>radiometer</td>
<td>✓</td>
<td>✓</td>
<td>≤ 40 × 40</td>
<td>1999/2001</td>
</tr>
<tr>
<td>LESO, Switzerland</td>
<td>CCD camera</td>
<td>✓</td>
<td>✓</td>
<td>≤ 40 × 40</td>
<td>1999</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2000/01/02/03/04</td>
<td></td>
</tr>
<tr>
<td>Pab®-opto, Germany</td>
<td>multiple</td>
<td>✓</td>
<td>✓</td>
<td>≤ 30 × 30</td>
<td>under devlpmt</td>
</tr>
<tr>
<td></td>
<td>(IR,visible,multichannel)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MIT, USA</td>
<td>CCD camera</td>
<td>✓</td>
<td>✓</td>
<td>≤ 15 × 15</td>
<td>under devlpmt</td>
</tr>
</tbody>
</table>

Table 1
Main features of developed bidirectional goniophotometers for the experimental assessment of fenestration systems.

4.1 LESO-PB/EPFL virtual goniophotometer using TracePro®

The experimental conditions described in Section 3.2.2 for the LESO-PB/EPFL instrument were reproduced virtually [88, 89] with the commercial forward ray-tracer TracePro® 2 that is based on Monte Carlo calculations. Computer simulation results were then compared to BTDF data assessed with the experimental goniophotometer.

Both the light source and detection device were simulated with characteristics

2 Lambda Research Corporation, Inc.
as close as possible to the reality, although by essence, the model will not take
the inevitable imperfections proper to any physical component into account.
These differences are therefore to be included in the model error estimation.

The major constraints for the simulation model are:

- the virtual light source must be of same angular spread as the real one: a
  set of wavelengths representative of its spectrum were determined and the
  source positioned in order to reproduce the same incident directions as for
  the experimental assessment of BTDFs;
- the model of the sample must present identical geometrical and physical
  properties, and the area exposed to light must fit the experimental illuminated
  surface;
- a detection screen model of same geometry as the one used for the measure-
  ment facility is needed, separated into the same pattern of “averaging”
  sectors.

Instead of either moving the sample and detector according to the incidence
angles, or the source itself, a virtual source was placed against the outside
sample interface. Its dimensions were determined to fit the experimental di-
aphragm aperture (illuminated area), a varying direction vector being associ-
ated to the emitted rays depending on the incident direction. The total pho-
tometric flux received by each detection sector was determined and converted
into the corresponding BTDF value. There was therefore no need to model the
reflection on a diffusing screen and the detection by a virtual CCD camera,
the simulation results being already comparable to experimental data.

In order to have only one tracing session (and not six), all the six screen
positions were simulated at once by the way of six virtual screens. To avoid
inter-reflections between the different detection surfaces, they were defined
as perfect absorbers. Each screen is split into sectors using cones for altitude
splitting and planes for azimuths (Figure 8(a)); the resulting simulation model
for a $5^\circ$ by $5^\circ$ grid is shown on Figure 8(b) with a laser cut panel as the in-
vestigated sample.

The rays were emitted from an annular grid, composed of 45 rings and send-
ing about 200,000 rays ($\sim$6,000 rays at each wavelength). The flux threshold
(fractional value of starting flux for which a ray will be terminated) is usually
set to 0.05 for specular samples and lowered to 0.001 when diffusing surfaces
are considered.

It was checked that a larger number of rays (e.g. 15,000 per wavelength) or
a lower cut-off value (e.g. 0.001 for specular samples or 0.0005 for diffusing
components) did not significantly affect the results: both induced differences
lower than 1% whereas computer simulation time was considerably increased.
Fig. 8. Simulation model composed of an opaque diaphragm, the analyzed sample, a non-interacting incident flux detection surface and six absorbing detection screens split into angular sectors.

It must be noted that the source does not appear as a separate model object: it sends rays according to particular grid and beam specifications, but has no physical (optical) properties.

Ray-tracing plot examples are displayed on Figure 9 for a Serraglaze\textsuperscript{TM} panel and for a Baumann-Hüppe AG venetian blind prototype with curved slats presenting a mirror coating on the upper side and a diffuse coating on the lower side. Only a few (about a thousand) of the 200,000 traced rays are shown on these plots, to get a readable transmitted light distribution.

To complement this study, an additional analysis made possible by the flexibility of virtual models was carried out: an ideal set-up was modeled with a virtual sun as the light source and a hemispherical detector [88].

The parameterisation of a virtual sun was realized by approximating its continuous spectrum with a discrete set of values, of weights proportional to the corresponding radiance of the sun spectrum. As far as the detection surface is concerned, even though a flat projection screen is preferable experimentally to avoid inter-reflections, a virtual hemisphere subdivided in the same way makes up a more ideal detection surface, the light being collected at a constant distance from the sample and with normal rays.
(a) Focus on refraction effects inside the Serraglaze™
(b) Traced rays for a venetian blind in horizontal slats configuration

Fig. 9. Ray-tracing plots examples; towards the left appears the reflected part of the incident beam, not considered in this study.

The resulting hemispherical detector is shown on Figure 2 with a ray-tracing plot for an asymmetric prismatic panel manufactured by Siemens AG. As the transmitted light is only distributed on a small number of angular sectors, only some of them were isolated on the hemisphere to facilitate their assignment to the corresponding angular couples and reduce the processing time.

4.2 FHG-IBP Numerical Goniophotometer Environment using OptiCad®

The FHG-IBP numerical goniophotometer has been developed as an alternative method of including CFS into the process of daylight design and simulation [90, 91]. As illustrated in Figure 11, it represents an automated environment allowing to:

- configure the virtual test set up,
- parameterize and combine CFS samples,
- postprocess data for further use in daylight simulation.

The environment is based on the commercial forward raytracing tool OptiCad® [92] and generally follows the flux based method described earlier. The proce-
Fig. 10. Ideal set-up model configuration: hemispherical absorbing detector and virtual sun.

dure has been validated against analytical and measured reference cases.

4.2.1 Virtual Test-stand

The virtual test-stand does not directly model a specific existing goniophotometer. As depicted in Figure 12, sensor planes that record the flux coming from the sample are arranged as a hemicube. The virtual test-stand can be operated to either determine BTDF or BRTF datasets. The set-up parameters can be user-defined. This allows to influence the angular resolution of the B(R)TDF datasets. In addition to this, the accuracy due to near field photometric aspects can be controlled. Figure 12(a) illustrates the flux received from venetian blinds inclined $0^\circ$ and $40^\circ$ which are illuminated by a virtual light source at an angle of $60^\circ$. The slats have a mirror coating on the concave side. In Figure 12(b), the obtained normalized BTDFs at slat inclinations $0^\circ$ for 10,000 and 1,000,000 traced rays are depicted.

The angular resolution is determined by the subdivision of the hemicube’s sensor planes into patches. Angular resolutions of about $4^\circ$ can be obtained with the hemicubal arrangement of sensor planes with roughly 5,000 patches, $2^\circ$ with 20,000 patches. As for the determination of candle power distributions of luminaires, the recording of BTDF data has to meet photometric far field conditions. In order to approximate the probe in the hemicube as a point source, the minimum inverse-square distance between the sample and the sensor detecting the emitted flux must be kept. [93]. For a perfect diffusing
(lambertian) source, a ratio of 1:10 between the circumpassing disk around the aperture holding the sample and the distance to the sensor results in an error inferior to 1%. The candle power distribution $I$ typically can be described by $I = I_0 \cos(\vartheta)^n$, with $\vartheta$ the zenith angle under which the sample is examined, $I_0$ the candle power at normal observation. A perfect diffusor is parametrized by $n = 1$. With stronger specular (i.e. directional) characteristics of the candle power distribution, the error increases; on the other hand, in order to obtain the a same constant error, the distance of the sensor plane to the aperture has to be increased. Since in numerical goniophotometry the distance is not physically restricted, it can be chosen large. For a square shaped aperture with an edge length of 20 units and a minimum distance to the sensor planes of 1,000 units, the error falls below 0.02%. On the other hand, specular distributions with a maximum of $n = 47$ can still be recorded at a maximum error of 1%.

Fig. 11. Flowchart illustrating the program interaction and dataflow of the FHG-IBP numerical goniophotometer environment.
(a) Flux detection on hemicube  

(b) Normalized BTDF at slat inclination 0° (upper figure: 10,000 traced rays, lower figure 1,000,000 traced rays.

Fig. 12. Illustration of FHG-IBP numerical goniophotometer. The flux detected on the sensor planes of the hemicube is converted into luminance coefficients (BTDF values).

4.2.2 CFS-Sample Generator

The software allows to automatically generate different CFS samples without having to directly provide OptiCad® code. Different combinations of CFS components can be arranged in layer structures. Table 2 gives a selection of the samples currently available with a listing of the key configuration parameters. Figure 13 illustrates the generated layer structure of a compound system of a laser cut panel placed in the gap between two glazing panes.
4.2.3 Postprocessing

In [7], a method is offered to calculate the systems’ candle power distributions from the outside luminance distribution and the systems’ BTDF; these distributions can then be integrated into radiosity or ray-tracing based lighting calculation engines. Figure 14 shows a photo-realistic visualization of a daylit room using a light redirecting glass in the upper area of the façade. Integration into the lighting calculation engines allows the calculation of illuminance conditions due to complex facade systems on arbitrary work surfaces, as depicted in Figure 15. To use BTDFs in daylighting simulation softwares, data postprocessing is therefore necessary. The data have to be filtered and ought to be compressed in data volume. The Numerical Goniophotometer Environment provides an interface to a postprocessor contained in the set of programs described in [7].

4.2.4 Graphical User Interface

To control the interaction of the different parameters, files and programs, a Graphical User Interface is provided. Figure 16 depicts screenshots of the main dialogue, the virtual test-stand configuration and the CFS sample generation and combination dialogue. A help functionality is offered. The system runs under MS-Windows™ operating systems.

Fig. 13. Automatically generated compound system of a Laser Cut Panel between two glazing panes defined with the CFS-Sample Generator.
### System

<table>
<thead>
<tr>
<th>System</th>
<th>Figure</th>
<th>Key Parameters</th>
</tr>
</thead>
</table>
| Prism                         | ![Prism](image) | - index of refraction  
- thickness  
- angle of prism elements |
| Laser Cut Panel               | ![Laser Cut Panel](image) | - index of refraction  
- thickness of panel  
- distance of cuts  
- angle of cuts |
| Light Redirecting Glass       | ![Light Redirecting Glass](image) | Ready to buy light guiding system based on same optical principle as Laser Cut Panel. Can be parametrized for test purposes. |
| Blinds                        | ![Blinds](image) | - specular and diffuse reflection  
- slat curvature: cylindrical or parabolic  
- distance and number of slats  
- slats incline |
| Gratings                      | ![Gratings](image) | - specular and diffuse reflection  
- distance of grating slats  
- incline of grating slats |

### Table 2
Selection of CFS-models currently supported by the CFS-Sample Generator with key configuration parameters.

### 4.3 ENTPE simulation method using Genelux

The Genelux lighting simulation software has been extended to calculate the bidirectional photometric characteristics of samples which can be defined us-
Fig. 14. Photorealistic visualization of room illuminated by standard venetian blinds in the lower facade area and a light redirecting glass in the upper facade area. The light redirecting glass is modelled by a light emitting surface with a candlepower distribution computed from outside illuminance and the system’s BTDF data.

Fig. 15. Comparison of illuminance levels on a work plane by a conventional shading system (left figure) and a system with light redirection properties in the upper window area (right figure).

Internally, a parallel beam of light is illuminating a sample. One detection hemisphere on the incident side is used to record the BRDF data, a second detection hemisphere on the emitting side records the BTDF data. The obtained values were compared to theoretical solutions for samples such as a lambertian diffusor and glazing panes. For different kinds of venetian blinds with planar slats, cut-off angles have been determined and direct hemispherical transmissions recorded. In order to obtain generalized models of the recorded values, a data fitting was attempted that included specularity peak identification, coordinate transformation wherever necessary, and finally nonlinear data fitting of peaks.
Fig. 16. Graphical User Interface of the FHG-IBP Numerical Goniophotometric Environment.

5 Conducted comparisons for validating BT(R)DF data

For the LBNL instrument (see Section 3.1.2), achieved BTDFs were used to predict the performances of multi-layer fenestration systems, and were implemented in matrix-layer calculations to validate this analytical approach against measured solar heat gain values [95, 96, 97]. Besides, an attempt of comparing BTDFs to ray-tracing calculations was made later but proved un-
successful, the discrepancies between measurements and simulations remaining very important from both the quantitative and qualitative points of view [98].

At ISE, Germany, bidirectional results were integrated and validated against Ulbricht integrating sphere measurements performed on the same materials for the first time in 1993. The upgraded device was also validated with directional-hemispherical comparisons with integrating spheres. In addition to this, a comparative study was made with ray-tracing simulations [99] on polymers and aerogels.

The devices developed at TNO (The Netherlands), TUB (Germany) and UTS (Australia) were validated against integrating spheres too [19, 25, 29].

At Cardiff, directional-hemispherical transmittance were again compared to integrating sphere results [18], but also to analytic model predictions [100, 101].

At the LESO-PB/EPFL in Switzerland, different approaches were chosen [12, 102]:

- assessment of error at each intermediate stage of calibration and processing, a final error being deduced;
- bidirectional measurements of systems presenting a known symmetry and verification against standard luminance-meter data or analytical calculations;
- empirical validation based on bidirectional measurements comparisons between different devices;
- assessment of hemispherical optical properties by integrating BT(R)DF data over the whole hemisphere and comparison to Ulbricht sphere measurements;
- comparison of monitored data with ray-tracing simulations to achieve a higher level of details in the BT(R)DF behavior assessment [88, 89].

At FHG-IBP the computer-generated directional-hemispherical transmittances of regular glazing panes, laser cut panels, prismatic elements and venetian blinds with either diffuse or mirrored non-planar slats were compared to either analytical solutions or measured reference values [5, 91].

6 Database of CFS bidirectional measurements

The bidirectional light transmittance through CFS and the dependency on outside illuminance conditions delivers spatial and time variant indoor light penetration of generally much higher complexity compared to standard glazing
systems. These dependencies have to be made transparent to the designer in an easy to handle way, such that for specific problems the best solution can be identified at low expenses. Therefore a database with a graphical user-interface has been developed aiming at software support for CFS selection comparable to luminaire selection in artificial lighting programs. A list of available datasets is provided, followed by a brief introduction of the CFS database functionality.

6.1 Available Datasets

Table 3 presents an overview of the measured BT(R)DF datasets available today for Complex Fenestration Systems (CFS), grouped by type. The table provides the usual name of the prototype, its symmetry indicator (see Appendix A), the number of incident directions that were investigated and the institute that performed the measurements (according to these directions). A more extensive overview of the measurements performed at LESO/EPFL can be found in [12].

Table 4 presents a selection of simulated BTDF datasets. For use in daylight simulations, BTDF datasets of one system have to be available for all 145 incident angles according to [14]. Certain symmetries in the geometry of the samples can reduce the number of BTDF to be recorded.

6.2 Management of CFS database by a graphical interface

The database system works on the raw data sets of the CFS. Content viewers allow to visualize the system’s functionalities. These include among others:

- **System Information**: Graphics, pictures, and texts informing about specific systems. Case studies showing the application of different systems in real and simulated environments.
- **Display of the raw data files**: Display and analysis of the BTDF data and directional hemispherical transmissions.
- **Sky Luminance Distributions**: Display of sky luminance distributions with respect to different facade orientations and inclines. Calculation and display of direct sun interaction for static and dynamic systems.
- **Light emitting surfaces**: Calculation and display of light entering the room through facade systems (alike candlepower distributions in artificial lighting).
- **Room illumination**: Simple room interface illustrating light incident onto surfaces of a shoebox type room under different outside illumination conditions.
<table>
<thead>
<tr>
<th>Type of system</th>
<th>Name of product</th>
<th>Symmetry</th>
<th>Nb inc. dir.</th>
<th>Institute</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diffusing materials</td>
<td>Opal. plexiglas</td>
<td>1</td>
<td>14</td>
<td>LESO/EPFL</td>
</tr>
<tr>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>7</td>
<td>TUB</td>
</tr>
<tr>
<td>&quot;</td>
<td>Opal. plastic</td>
<td>1</td>
<td>3</td>
<td>LESO/EPFL</td>
</tr>
<tr>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>3</td>
<td>TNO</td>
</tr>
<tr>
<td>&quot;</td>
<td>Diffusing paint</td>
<td>1</td>
<td>1</td>
<td>LESO/EPFL</td>
</tr>
<tr>
<td>Sunlight redirect. syst.</td>
<td>Laser Cut Panel</td>
<td>4</td>
<td>56</td>
<td>LESO/EPFL</td>
</tr>
<tr>
<td>&quot;</td>
<td>Acrylic stripes</td>
<td>4</td>
<td>18</td>
<td>LESO/EPFL</td>
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<tr>
<td>&quot;</td>
<td>Lumitop&lt;sup&gt;TM&lt;/sup&gt;</td>
<td>3</td>
<td>76</td>
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<td>3</td>
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<td>LESO/EPFL</td>
</tr>
<tr>
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<td>35</td>
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<tr>
<td>&quot;</td>
<td>Curved squ. mirrors</td>
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<td>17</td>
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<tr>
<td>&quot;</td>
<td>Curved asym. mirrors</td>
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<td>20</td>
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<td>35</td>
<td>LESO/EPFL</td>
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<tr>
<td>&quot;</td>
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<td>113</td>
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<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>33 (poor)</td>
<td>ISE</td>
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<tr>
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<td>4 REVIS samples</td>
<td>1 or 4</td>
<td>3 x 4</td>
<td>LESO/EPFL</td>
</tr>
<tr>
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<td>4 REVIS samples</td>
<td>&quot;</td>
<td>3 x 4</td>
<td>TNO</td>
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<td>Venetian blinds</td>
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<td>OKASolar&lt;sup&gt;TM&lt;/sup&gt; “S”</td>
<td>3</td>
<td>76</td>
<td>LESO/EPFL</td>
</tr>
<tr>
<td>&quot;</td>
<td>9 B.-H.* mirror blinds</td>
<td>3</td>
<td>23 x 9 x 3*</td>
<td>LESO/EPFL</td>
</tr>
<tr>
<td>&quot;</td>
<td>3 Köster blinds</td>
<td>3</td>
<td>23 x 3 x 3*</td>
<td>LESO/EPFL</td>
</tr>
<tr>
<td>&quot;</td>
<td>4 B.-H.* painted blinds</td>
<td>3</td>
<td>7 x 4</td>
<td>LESO/EPFL</td>
</tr>
</tbody>
</table>

Table 3
Overview of the measured BT(R)DF datasets generated at LESO-PB/EPFL, TUB and ISE (physical goniophotometers): *B.-H. stands for Baumann-Huppe; *x 3 because 3 slats configurations were considered for each blind: 0°, 45° and 90°).

As depicted in Figure 17, the system runs under MS-Windows<sup>TM</sup> operating systems. COM-technology [103] allows to define interfaces to other softwares and software components. Therefore manufacturers can plug in own dialogs into the database. Additionally the concept allows to link into daylight calcu-
### Table 4
Overview of the computed BTDF datasets generated at LESO-PB/EPFL and FHG-IBP (numerical goniophotometers):

- *according to the manufacturer’s specifications,
- calculated for different slat inclinations from system open to system closed;
- *calculated for 10 incident directions at slat tilt 0°, at tilt 45°.

The database has been developed within the framework of a joint project with the Fraunhofer-Institute for Solar Energy Systems, system developers, and consultant offices. The database will be available for download under [www.talisys.de](http://www.talisys.de).

#### 7 Conclusion

In order to understand and model the behaviour of complex fenestration systems, the interest in bidirectional transmission and reflection distributions functions (BTDFs and BRDFs) has grown significantly in building science...
over the last two decades. Over this period of time, several experimental test devices have emerged. While integrating spheres are normally used for recording the directional-hemispherical transmission or reflection, goniophotometers allow to assess spatially resolved light transmission or reflection. The paper presents an overview of more than 10 such goniophotometric test facilities. The two different approaches used, a scanning based process and the flux
based process are presented. Scanning based approaches may provide higher angular resolutions, while flux based approaches indicate energetically more robust measurements and generally allow for faster data recording.

Lately the physical measurements have been complemented by numerical ray-tracing based approaches, which all rely on flux-based approaches. These methods require the characterized system to be of well-known properties, that can be modelled with sufficient accuracy both in geometry and coating or material. For these cases the methods promise to be a valuable tool for system design and optimization. Expenses for the construction and maintenance of experimental test facilities can be avoided or reduced. In addition to this, costs for system-prototyping can be significantly lowered.

Important measurement efforts have generated a vast number of BTDF datasets. Over 25 experimentally and 8 numerically recorded datasets of systems are listed. Nevertheless, the use of these datasets in support of daily design decisions still appears to be moderate. The reasons are obvious: the raw data sets are of high complexity and do not directly relate to the later room illumination under specific boundary conditions (e.g. sky luminance distribution, general façade parameters). Also, a lack of simple methods and criteria for intercomparison of CFS can be identified. On the other hand, a diffusion of the datasets over different institutions, with only a few datasets publicly available, significantly more extensive for one institute (LESO-PB/EPFL), might be an obstacle. The presented database, with an intuitive graphical user-interface, is seeking to overcome some of these deficits. Benefits of choosing one CFS compared to another under a variety of boundary conditions can be easily identified. The authors are offering this database as a common platform for photometric data of CFS under www.talisys.de. For inclusion of additional datasets please contact the authors.

8 Acknowledgements

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Jan de Boer was supported by the German Ministry of Economics and Labour (BMWA) under Grant Nb. 0329037G and by the ADELINE User Club.

References


[82] M. Moeck. On daylight quality and quantity and its application to


10 List of Contact Persons

To be provided by OA Nancy Ruck

11 IEA Information

International Energy Agency
The International Energy Agency (IEA) was established in 1974 as an autonomous agency within the framework of the Economic Cooperation and Development (OECD) to carry out a comprehensive program of energy cooperation among its 25 member countries and the Commission of the European Communities.

An important part of the Agency’s program involves collaboration in the research, development and demonstration of new energy technologies to reduce excessive reliance on imported oil, increase long-term energy security and reduce greenhouse gas emissions. The IEA’s R&D activities are headed by the
Committee on Energy Research and Technology (CERT) and supported by a small Secretariat staff, headquartered in Paris. In addition, three Working Parties are charged with monitoring the various collaborative energy agreements, identifying new areas for cooperation and advising the CERT on policy matters.

Collaborative programs in the various energy technology areas are conducted under Implementing Agreements, which are signed by contracting parties (government agencies or entities designated by them). There are currently 42 Implementing Agreements covering fossil fuel technologies, renewable energy technologies, efficient energy end-use technologies, nuclear fusion science and technology, and energy technology information centers.

**IEA Solar Heating and Cooling Programme**

The Solar Heating and Cooling Programme was one of the first IEA Implementing Agreements to be established. Since 1977, its 20 members have been collaborating to advance active solar, passive solar and photovoltaic technologies and their application in buildings.

| Australia | Finland | Portugal |
| Austria   | France  | Spain    |
| Belgium   | Italy   | Sweden   |
| Canada    | Mexico  | Switzerland |
| Denmark   | Netherlands | United Kingdom |
| European  | Commission New Zealand | United States |
| Germany   | Norway  |          |

A total of 35 Tasks have been initiated, 25 of which have been completed. Each Task is managed by an Operating Agent from one of the participating countries. Overall control of the program rests with an Executive Committee comprised of one representative from each contracting party to the Implementing Agreement. In addition, a number of special ad hoc activities-working groups, conferences and workshops-have been organized.

The Tasks of the IEA Solar Heating and Cooling Programme, both completed and current, are as follows:

*Completed Tasks:*

- Task 1 Investigation of the Performance of Solar Heating and Cooling Systems
- Task 2 Coordination of Solar Heating and Cooling R&D
- Task 3 Performance Testing of Solar Collectors
- Task 4 Development of an Insolation Handbook and Instrument Package
Task 5 Use of Existing Meteorological Information for Solar Energy Application
Task 6 Performance of Solar Systems Using Evacuated Collectors
Task 7 Central Solar Heating Plants with Seasonal Storage
Task 8 Passive and Hybrid Solar Low Energy Buildings
Task 9 Solar Radiation and Pyranometry Studies
Task 10 Solar Materials R&D
Task 11 Passive and Hybrid Solar Commercial Buildings
Task 12 Building Energy Analysis and Design Tools for Solar Applications
Task 13 Advance Solar Low Energy Buildings
Task 14 Advance Active Solar Energy Systems
Task 16 Photovoltaics in Buildings
Task 17 Measuring and Modeling Spectral Radiation
Task 18 Advanced Glazing and Associated Materials for Solar and Building Applications
Task 19 Solar Air Systems
Task 20 Solar Energy in Building Renovation
Task 21 Daylight in Buildings
Task 22 Building Energy Analysis Tools
Task 24 Solar Procurement
Task 25 Solar Assisted Air Conditioning of Buildings
Task 26 Solar Combisystems

Completed Working Groups:

CSHPSS ISOLDE
Materials in Solar Thermal Collectors Evaluation of Task 13 Houses

Current Tasks:

Task 27 Performance of Solar Facade Components
Task 28/ Solar Sustainable Housing
ECBCS
Annex 38
Task 29 Solar Crop Drying
Task 31 Daylighting Buildings in the 21st Century
Task 33 Solar Heat for Industrial Processes
Task 34/ Testing and Validation of Building Energy Simulation Tools
ECBCS

45
Annex 43
Task 35 PV/Thermal Systems

Task Definition Phase:

Solar Resource Knowledge Management

To find more IEA Solar Heating and Cooling Programme publications or learn about the Programme visit our Internet site at www.iea-shc.org or contact the SHC Executive Secretary, Pamela Murphy, e-mail: pmurphy@MorseAssociatesInc.com.
A Datafile format for BT(R)DFs

An example of file contents based on the format proposed in [5] is given in Appendix A for BTDF and BRDF values, which would be named “lesoT_Example_48_90.txt” and “lesoR_Example_50_90.txt” respectively.

**BTDF measurements:**

```plaintext
#material: Example  
#manufacturer: Unknown  
#measurement type: Transmission  
#isym = 0 ! symmetry indicator: 0 no symmetry (phi_1 = 0°...360°)  
# 1 rotational symmetry (only for one phi_1)  
# 2 symmetry to phi=0° and phi=180° (phi_1 = 0°...180°)  
# 3 symmetry to phi=90° and phi=270° (phi_1 = -90°...90°)  
# 4 symmetry to phi=0° and phi=180° & to phi=90° and phi=270° (phi_1 = 0°...90°)  
#considered area [cm²]: 78.54  
#thickness [cm]: 2.65  
#comments: additional comments about the sample or the characterisation parameters  
#measurements done at the Solar Energy and Building Physics Laboratory, LESO-PB/EPFL  
#measurements and processing by Marilyne Andersen  
#date of measurement: 08.03.00  
#contact marilyne.andersen@epfl.ch for details  
#light incidence :  
#phi_1: 90° (azimuth)  
#theta_1: 48° (altitude)  
#BTDF values averaged over output directions from (phi_2 - 2.5) to (phi_2 + 2.5) in azimuth  
#and from (theta_2 - 2.5) to (theta_2 + 2.5) in altitude  
#measurements not performed for theta_2 < 94.2  
#light transmittance: 0.09  
#light transmittance calculated from BTDF values, with extrapolated values for 90 < theta_2 < 94.2  
#data  
#phi_2 theta_2 BTDF  
0 95 0.030  
5 95 0.028  
... ... ...  
350 95 0.016  
355 95 0.028  
0 100 0.030  
5 100 0.030
```
**BRDF measurements:**

- **Material:** Example
- **Manufacturer:** Unknown
- **Measurement type:** Reflection
- **Isym = 0**  
  - Symmetry indicator: 0 no symmetry ($\phi_1 = 0^\circ...360^\circ$)
  - 1 rotational symmetry (only for one $\phi_1$)
  - 2 symmetry to $\phi_1=0^\circ$ and $\phi_1=180^\circ$ ($\phi_1 = 0^\circ...180^\circ$)
  - 3 symmetry to $\phi_1=90^\circ$ and $\phi_1=270^\circ$ ($\phi_1 = -90^\circ...90^\circ$)
  - 4 symmetry to $\phi_1=0^\circ$ and $\phi_1=180^\circ$ & to $\phi_1=90^\circ$ and $\phi_1=270^\circ$ ($\phi_1 = 0^\circ...90^\circ$)

- **Considered area [cm$^2$]:** 176.71
- **Thickness [cm]:** 0
- **Comments:** additional comments about the sample or the characterisation parameters
- **Measurements done at the Solar Energy and Building Physics Laboratory, LESO-PB/EPFL**
- **Measurements and processing by Marilyne Andersen**
- **Date of measurement:** 08.03.03
- **Contact:** marilyne.andersen@epfl.ch for details
- **Light incidence:**
  - $\phi_1$: 90$^\circ$ (azimuth)
  - $\theta_1$: 50$^\circ$ (altitude)
- **BRDF values averaged over output directions from ($\phi_2 - 7.5$) to ($\phi_2 + 7.5$) in azimuth**
- **And from ($\theta_2 - 5.0$) to ($\theta_2 + 5.0$) in altitude**
- **Blind zone around output direction ($\theta_2,\phi_2$) = (50,90), where BRDFs are put to NaN**
- **Measurements not performed for $\theta_2 > 84.0$**
- **Light reflectance:** 0.67
- **Light reflectance calculated from BRDF values, with extrapolated values for 84.0 < $\theta_2$ < 90**

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<th>$\phi_2$</th>
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<td>0</td>
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<td>0.230</td>
</tr>
<tr>
<td>15</td>
<td>80</td>
<td>0.128</td>
</tr>
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<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>330</td>
<td>80</td>
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<tr>
<td>345</td>
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<tr>
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<td>70</td>
<td>0.230</td>
</tr>
<tr>
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<td>70</td>
<td>0.230</td>
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a.s.o.

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END