Workshop on Material Appearance Modeling (2014)
H. Rushmeier and R. Klein (Editors)

Scanning Gonio-Photometers for Asymmetric Acquisition of Fine-structured BSDF

Peter Apian-Bennewitz[†]

Abstract

Results of building and running out-of-plane scanning gonio-photometers for a number of years and projects are presented. Key concepts are a fast drive system and adaptive scan pattern to sample peaks at higher angular resolution. It is suggested to scan the BSDF asymmetrically, at a finer angular resolution for the outgoing directions than the incident directions.

Categories and Subject Descriptors (according to ACM CCS):

1. Introduction

While many BSDF research papers in Computer Graphics (CG) are focused on fast measurement set-ups to acquire a BSDF together with the shape and texture of an object, (e.g. [SSWK13]), discussions of precise, basic measurements techniques have been mostly confined to Physics publications. However, CG algorithms for BSDF data handling and rendering are used in physics/engineering simulations too. Furthermore, many engineering applications require accurate rendering of the visual appearance of non-standard materials. This text describes experiences with classical out-of-plane scanning PG2 gonio-photometers and an asymmetric approach to BSDF incident/outgoing angular measurements for modelling materials.

1.1. Mathematical definition and consequences

It is worth to quickly recall the implicit and most general definition of the BSDF:

$$\mathcal{L}_{out}(\vec{x}_{out}) = \int_{\vec{x}_{in}}^{\Omega_{in}=4\pi} BSDF(\vec{x}_{out},\vec{x}_{in})\, \mathcal{L}_{in}(\vec{x}_{in})\, \cos(\theta_{in})\, d\Omega_{in} \qquad (1)$$

with incident and outgoing Radiance $\mathcal{L}_{in}$, $\mathcal{L}_{out}$, infinitesimal solid angles $d\Omega_{in}$,$d\Omega_{out}$, and directions $\vec{x}_{in}$,$\vec{x}_{out}$. This includes the often seen simpler form $BSDF = \mathcal{L}_{out}/\mathcal{E}_{in}$, which is valid for ideal "parallel" incident light *only*. Equation 1 holds for *any* material and illumination, from highly polished mirror ($BSDF \approx \delta(\vec{x}_{in} - \vec{x}_{out})$) to Lambertian scatters ($BSDF$ = const.). Thinking of the BSDF as a kernel folding $\mathcal{L}_{in}$ to $\mathcal{L}_{out}$ immediately motivates the importance of solid angles when measuring a *BSDF* with fine angular structure. Additional variables of $\mathcal{L}$ and *BSDF* may include wavelength and polarisation.

This motivates a class of *BSDF* measurement devices that seem "classically simple" but which, equipped with state-of-the art mechanics and signal processing, have proven to be adaptable and reliable in measuring even "exotic" *BSDF*s.

1.2. Finely-resolved BSDF

Materials of this type are frequently found in illumination applications that scatter or redirect light. Examples include LED lighting and glazing materials to redirect sunlight, or modelling of stray light in optical designs.

Applications require a high level of data integrity, adaptable data import into simulation programs and capable algorithms to get simulation results as images (e.g. glare analysis for window glazings) and numerical data (e.g. predictions of illumination levels).

1.2.1. Simple case with peak at ideal position

A simple type of BSDF shows a peak around the direction of ideal reflection: Figure 1 shows the reflection of a coated Aluminium cladding intended for a building in sunny desert climate conditions. Renderings, glare and energy calculations are based on this. The plot shows the reflected BSDF: the hemisphere is projected onto a disc, θ_{out} is 0^o in the centre (parallel to surface-normal) and 90^o at the rim. ϕ_{out} is plotted $0..360^o$ CCW along the disc (all coordinates according to [AST05]). The scan paths for full coverage of both

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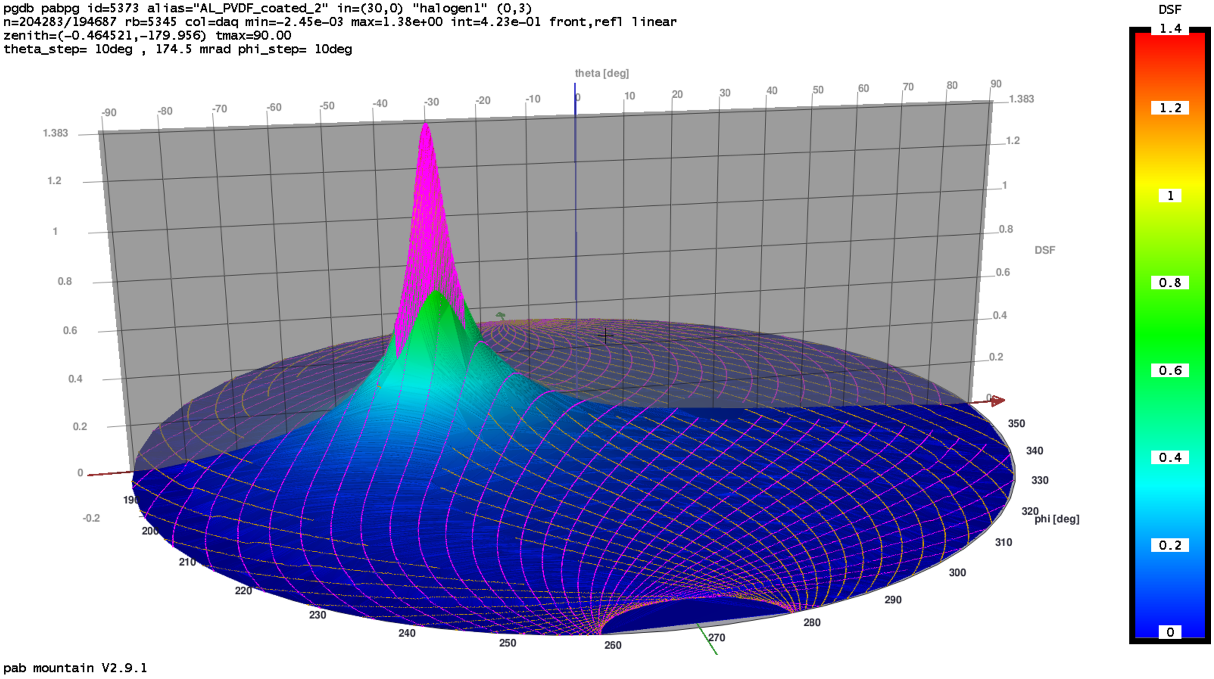
[†] pab advanced technologies Ltd

DOI: 10.2312/mam.20141291



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theta_step= 10deg , 174.5 mrad phi_step= 10deg
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Figure 1: *Reflection DSF data of coated aluminium, architectural project for desert building site. Units: DSF=BSDF* $\cos\theta_{out}$.

hemispheres generate an X-shaped stitch pattern of measurement points, this is combined with a finely resolved path around peaks. Z-scale is linear in this plot, and measurement points are shown as pink dots. Out of 204283 data-points, 153618 sample the peak adaptively for increased precision. Figure 2 shows a close-up of the peak area, with sample spacing, measurement time was 7 minutes.

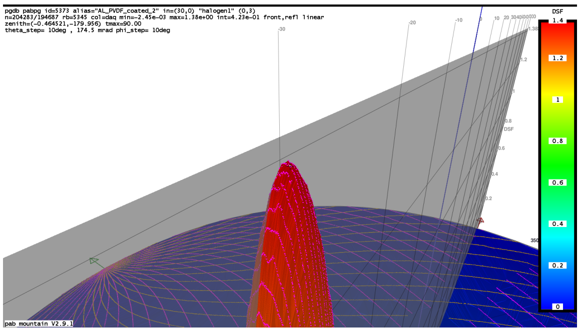

Figure 2: *Closeup of data from Figure 1, spacing of datapoint is below 0.6' (0.01deg)*

1.2.2. General case of complex BSDF pattern

Figure 3 shows a set of transmission BSDFs with a peak *off* the ideal, forward-scattered position: This commercial material is under development and uses an internal, linear micro-structure to deflect light. It is intended for day-lighting glazings to enhance illumination levels in the interior space. A crucial aspect in this technology is glare, which is partly caused by the peaks next to the main peak. Therefor, additional scans have been placed along the "ridge-line".

1.3. Asymmetric angular sampling

It is the author's long standing opinion [AB94] that an *asymmetric measurement* of the BSDF is advisable:

While a high resolution of outgoing angles for one fixed incident direction is mandatory to get the full BSDF structure, this structure changes relatively smoothly and predictably with incident angle. Measurements with too closely spaced incident angles give redundant information: BSDF data for in-between-angles could be interpolated by algorithms that take into account the change in position and shape of the BSDF structure. Therefor the incoming direction can be sampled with much lower angular resolution than the outgoing side.

Figure 3 shows the BSDF of the micro-structured sample for five different θ_{in}, with a coarse step-width of 10^o: The topology of this BSDF consists of three peaks along a "ridge", plus some background. While the position, height and width of these peaks change with incident angle, the topology itself remains the same. A meaningful interpolation between these datasets should be feasible.

This reduces both measurement time and required data storage significantly.

The idea prioritises scanning of BSDF structure in outgoing angles over incident angles and resolution of the BSDF with position on the sample. However, it could measure wavelength or polarisation states in parallel.

1.4. Data processing and model-less interpolation

This data can be processed for rendering in two ways:

First, parameters of a suitable model are fitted to the datasets, and then used in the simulation. The model is typically a mix of physically based insight into the material (e.g. symmetries, dependency of overall transmittance on incident angle) and heuristics. This procedure is a very verifiable path to simulation, since, at each measured incident angle, model and original data can be compared. The error budget of material modelling is well known. Secondly the method generates in-between incident angles smoothly and without numerical surprises, since the dependency is purely functional, without numerical interpolation and lookup of data.

The drawback is the mental time to come up with a functional model for the material class, which somewhat limits an automated data handling. And it requires a functional language in the simulation program to describe a BSDF.

The second way is to see the interpolation between incident angles as a problem of morphing the BSDF ”shape” of neighbouring incident angles. One idea was the similarity to finding motion vectors of MPEG video compression.

Recent research by Greg Ward et al [WKB14] indicates that solutions to this long advocated problem [AB11] exist.

2. Parameters of current out-of-plane scanning gonio-photometer

BSDF peaks and patterns of fine angular resolution require a high angular resolution in the outgoing direction $\vec{x}_{out}$. Typical requirements in projects are: A mechanical resolution better 0.1 mrad, a dynamic range of 7+ decades and an error budget below 5%. For consulting work, a measurement principle with as few error sources as possible works best.

These requirements favour a classical scanning concept over image-based ones, with the following advantages: higher signal range, zero crosstalk between neighbouring angles, no extra optics in between, ideal uniform sensor response over all outgoing directions, precise control of incident direction, choice of externally mounted lamps and therefor a clearly defined *instrument signature* (see Figure 6 for cross-sections through beam profiles). The possibility of intrinsic cross-checks of data is an advantage.

A scanning gonio-photometers consists of a detector that is moved mechanically around the sample to capture outgoing directions and a movable light source or sample to adjust all possible incident angles. Traditionally, the concept has been viewed as slow. This main obstacle is overcome by a combination of state-of-the-art drive system, mechanically light-wide, rigid construction and custom signal processing.

State-of-the-art electronics and mechanics allow a 1kHz output data rate with high resolution. Measurements are taken on-the-fly, while the detector moves. Maximum speed is currently 3m/s with a detector distance of 1m. The detector scans both hemispheres and the scan path system allows an arbitrary, adaptive scan pattern to cover peak regions in detail. Additionally options include wavelength resolved measurements, polarisation and near field measurements.

PG2 gonio-photometers are used at research institutions, commercial companies and for the author's own consulting.

3. Conclusions

Using fast scanning gonio-photometers is beneficial for BSDF acquisition with a high signal range, small angular structures of BSDF or high demands for low error in measured BSDF. Measurement time is shortened by applying rigid mechanical construction, high speed drive systems and advanced data processing.

Emphasis is placed on a BSDF averaged over the beam diameter, so spatial resolved BSDF of a sample or shape information of non-flat samples is not gathered.

New algorithms for interpolation data are being developed to supersede the established way of using this BSDF data in rendering programs by fitting a function.

References

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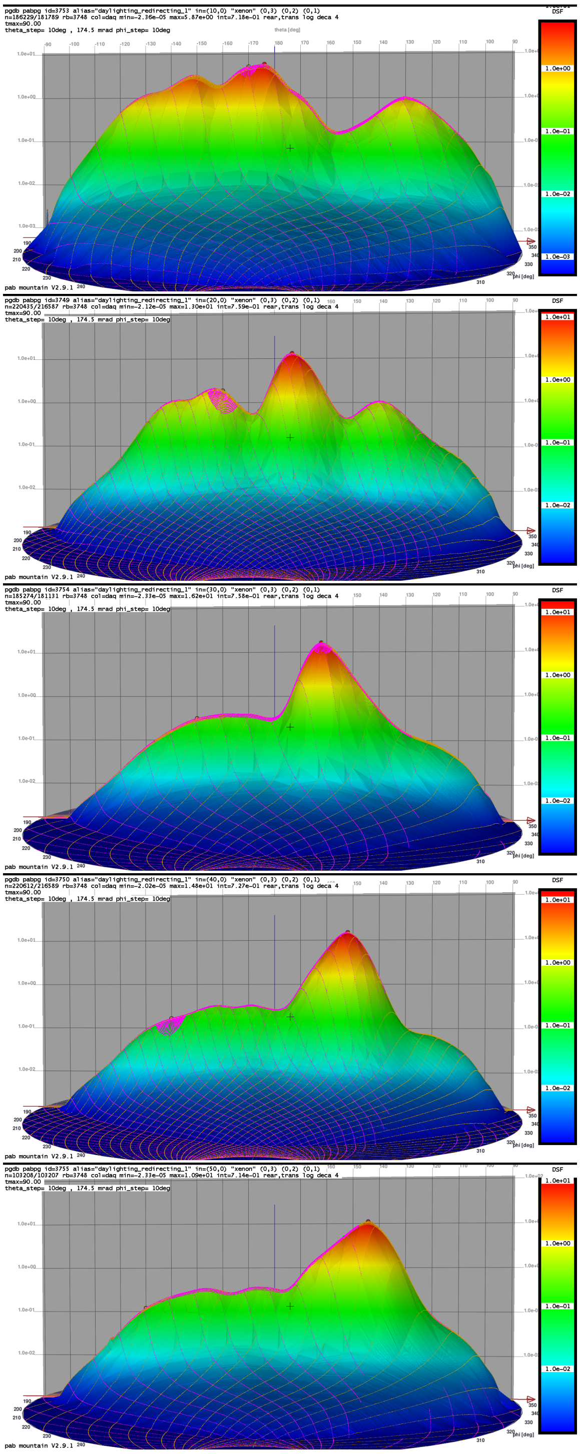

Figure 3: *Transmission dataset of daylighting element: The ideal transmission peak would be at the left side, the peak on the right shows the intended light redirection. Note individual logarithmic Z-scales. Sequence of incident directions* $\theta_{in} = 10, 20, .., 50^o$ *showing no change in BSDF topology for* $\theta_{in} > 30^o$

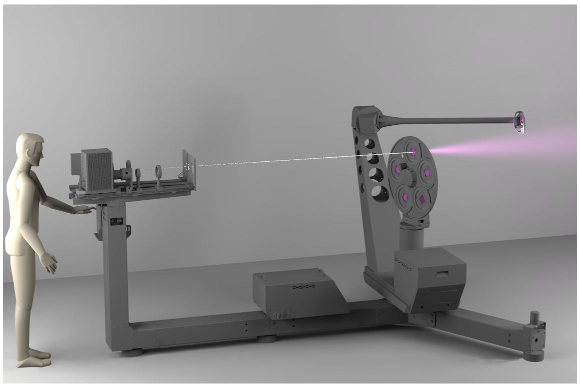

Figure 4: *Scanning, out-of-plane gonio-photometer PG2*

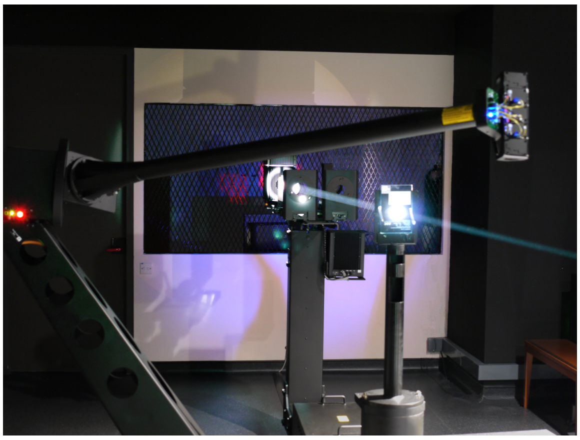

Figure 5: *HDR image of PG2 during installation at SERIS in 2009, with focused Xenon light (towards viewer), without sample. The detector-head is seen in front.*

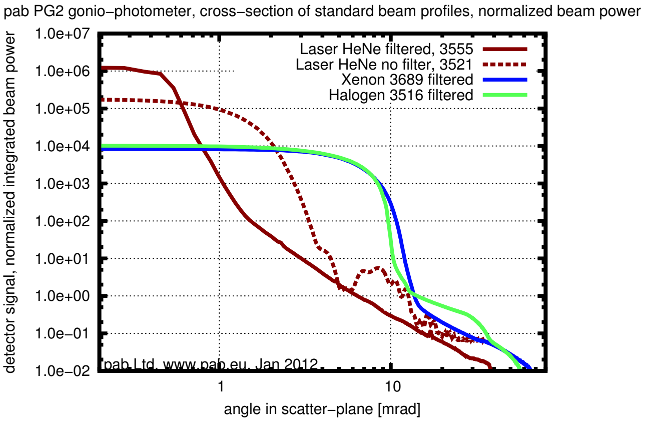

Figure 6: *Detector signal of the unscattered incident beam (*Instrument characteristic*) of PG2. Beams include halogen, Xenon and HeNe-laser. Note log scale on X and Y axis.*