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# Reducing Anisotropic BSDF Measurement to Common Practice

Greg Ward[1], Murat Kurt[2] and Nicolas Bonneel[3]

[1]Lawrence Berkeley National Laboratory
[2]International Computer Institute, Ege University
[3]Harvard University and LIRIS/CNRS

**Abstract**

*We address the problem of measuring and representing reflection and transmission for anisotropic materials without relying on mathematical models or a large sample database. By eliminating assumptions of material behavior, we arrive at a general method that works for any surface class, from metals to fabrics, fritted glazing, and prismatic films. To make data gathering practical, we introduce a robust analysis method that interpolates a sparse set of incident angle measurements to obtain a continuous function over the full 4-D domain. We then convert this interpolant to a standard representation tailored for efficient rendering and supported by a common library that facilitates data sharing. We conclude with some remaining challenges to making anisotropic BSDF measurements truly practical for rendering.*

Categories and Subject Descriptors (according to ACM CCS): I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—Color, shading, shadowing, and texture

## 1. The Challenge

The principal difficulty with measured anisotropic Bidirectional Scattering Distribution Functions (BSDFs) is in gathering enough incident and reflected directions to completely characterize a material. The usual approach is to take a small number of accurate measurements or, equivalently, a large number of noisy measurements, and fit them to an appropriate Bidirectional Reflectance Distribution Function (BRDF) or Bidirectional Transmittance Distribution Function (BTDF) model [WMLT07]. This fitting process smooths out noise and reduces the number of dimensions by orders of magnitude, but requires that the data fit a known model a priori. In many applications, this undercuts the purpose of taking measurements, which is to *discover* and *characterize* a material's behavior. Particularly in cases where a material has been custom-designed to have unusual scattering properties, measurements are needed for the very reason that there are no models to fit the data. Data-driven methods have been proposed to solve this problem for dense isotropic BRDF data [MPBM03, PCS*12], but achieving good results with sparse anisotropic data is an open challenge.

Complete anisotropic BSDF measurements are of course possible, but they require days if not weeks of measurement time for a single material in order to gather hundreds of millions of data points for a simple interpolation scheme. For this reason, most measurements and most research to date have been restricted to isotropic measurements.

A secondary factor curtailing the adoption of measured BSDFs for rendering is the absence of any widely supported representation. There are a number of informal standards that typically list measured values at specific angles on an angular coordinate grid or individual point samples, but there is no obvious way to apply such data. If the data is dense enough, linear interpolation may be used to estimate unmeasured positions, but this threshold is almost never reached for anisotropic distributions. In addition to the impractical measurement times, there is the problem of missing angles due to instrument self-interference. A robust interpolation method is required to arrive at a complete BSDF representation, which must be stored in a standard format supported by a majority of physically-based rendering software packages. Only then will we have a common practice for measured materials.

## 2. The Vision

Our solution to anisotropic BSDF data measurement is outlined in five parts. First, we describe a commercial goniophotometer that captures dense enough scattering angles to char-



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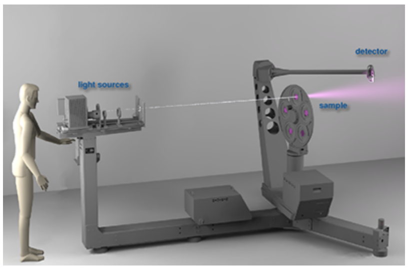


**Figure 1:** *An overview of pgII goniophotometer [AB14].*

acterize peaks in the BSDF. Second, we show how to smooth and interpolate incomplete measurements captured by this device. Third, we convert the intermediate representation to a standard format suitable for rendering. Fourth, we describe a BSDF library that supports this format and provides functions for interrogating and generating stratified Monte Carlo samples in a space- and time-efficient manner. Fifth, we suggest a means for sharing measured data between software packages and users, leveraging these techniques.

### 2.1. Anisotropic BSDF Measurements

We employ the pgII goniophotometer designed and built by Peter Apian-Bennewitz of Freiburg, Germany to measure materials for lighting and energy simulation. This apparatus brings a high degree of automation, programmability, and precision to the characterization of flat material samples [AB14] (See Fig. 1). A sample rotator allows us to measure almost any desired incident and reflected angles up to about 82$^\circ$ from normal, excepting some unavoidable source-detector interference near retroreflection. Also, the total measurement time goes up linearly with the number of incident directions, moving in the direction of "days" as we pass a few dozen angles.

Scattered directions are captured at a high sampling rate during sweeps of the detector arm, which follow longitudinal paths, but may be programmed to capture higher density in areas of interest using additional spiral or sine-wave patterns. This yields many low-noise BSDF measurements along overlapping longitudes with supplementary samples like those shown in Fig. 2(a). The smooth and continuous motion of the detector arm is key to the outstanding accuracy and repeatability of this device. Typically, incident directions are spaced apart 10$^\circ$ or 15$^\circ$ in altitude and 15$^\circ$ or greater in azimuth as shown in Fig. 2(b). This results in between 50 and 100 incident directions for each hemisphere – two hemispheres are captured for materials that transmit as well as reflect light. The number of incident angles required may often be reduced by a factor of two or four if the material's microstructure has bilateral or quadrilateral symmetry, respectively. The number of scattered directions usually runs into tens or hundreds of thousands of sample points per incident direction that do not fit a grid pattern. The only assumption we make is that there are enough scattered directions to capture the important peaks in the data, although these peaks may be quite distinct between different incident measurements, as shown in Fig. 3(a,b).

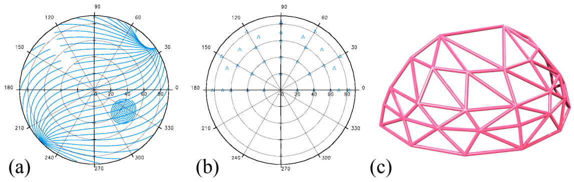


**Figure 2:** *(a) Example measured pgII scattering directions for a single incidence. (b) Example set of incident directions for a material with bilateral symmetry. (c) Incident directions from (b) organized into triangle mesh for interpolation.*

### 2.2. BSDF Interpolation

One reason we do not see direct renderings of measured materials is that there are invariably holes and noise in the data. There must always be some BSDF model, or another intermediate representation that fills in and smooths out the raw measurements to suit them for rendering. Anisotropic materials are particularly challenging in this regard, and most data-driven methods are isotropic, leaving us only with a handful of mathematical reflectance models, and nothing at all for transmission.

To resolve this problem, we have created a method for interpolating reflectance and transmittance data that makes no assumptions about material behavior and requires no database of measurements other than the particular BSDF of interest. We extend the mass-transport solution of Bonneel et al. [BvdPPH11] to drive a set of radial basis functions fitted to each measured distribution. This allows us to interpolate between sparse incident directions, arriving at a continuous, smooth description of the BSDF over the entire four-dimensional (4-D) domain. Incident direction measurements are organized into a spherical Delaunay mesh like the one shown in Fig. 2(c).

An example of our interpolation technique is shown in Fig. 3, where we compare a naive linear interpolation method to our mass-transport solution. While changing the linear interpolation coordinates to a Rusinkiewicz [Rus98] basis would certainly improve results for isotropic materials, it relies on assumptions about the surface microstructure that do not apply to anisotropic materials in any general way. We could in principle design a custom coordinate system that worked for a particular material, but only if we knew how it behaved, which is presumably why we need measurements in the first place. We opt for the much simpler and more direct solution of employing an interpolation method that fits whatever behavior we measure. Our interpolant is a spherical mesh of radial basis function sets (or systems), one set per incident angle vertex, which describes the scattering distribution. The vertices are interpolated in two dimensions

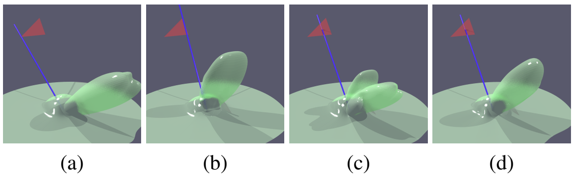


**Figure 3:** *(a) Reflectance distribution for one incident measurement direction. (b) Distribution at another incidence. (c) Linear interpolation of three distributions. (d) Lagrangian mass transport.*

using *transport plans* computed along each edge with a mass transport solver. Each plan is represented as a sparse matrix, and each radial basis system is a list of Gaussian lobe positions, widths, and maximum values. This reduced data is then written to an intermediate file, which is used to generate a BSDF representation for rendering as described below.

### 2.3. BSDF Representation

While we could render directly from our interpolant, it is more efficient to convert it to a form that is tailored for fast queries and Monte Carlo sample generation. To this end, we have created what we call the BSDF *tensor tree* representation [WKB12]. The incident and reflected hemispheres are projected onto disks, then mapped to Cartesian coordinates over the unit square using the Shirley-Chiu formula [SC97]. These two squares represent the four dimensions of a rank-4 tensor that gets subdivided as a hextree (16 children per node). In this manner, high-resolution peaks anywhere in a distribution may be captured without requiring equivalent high data density everywhere. In the case of anisotropic BRDF measurements, we can add an averaging step between complimentary incident and reflected directions according to Helmholtz reciprocity. This guarantees physical behavior while minimizing unwanted variations in the reconstruction.

For stratified importance sampling, we need to sort our leaf nodes at a given incident direction into a one-dimensional (1-D) sequence that preserves locality. We employ the Hilbert traversal shown in Fig. 4, which maximizes locality while keeping a direct relationship to the output quadtree branching [GL96]. Working in a square slice corresponding to the exiting hemisphere for the queried incident vector, we order a cumulative table along the Hilbert path. This path traverses the $[0,1]^2$ square with a $[0,1]$ line segment such that any given fraction of the line segment covers the same fraction of the area. This is the key to converting our two-dimensional (2-D) sampling domain into a 1-D cumulative table based on projected area. Larger leaf nodes will skip further along the path, but we never have the problem of re-entering a node since the Hilbert curve respects the quadtree's boundaries at each level of detail.

While we have found the tensor tree to be fast and efficient for rendering, other applications may prefer a different representation. For example, the three-phase method for annual daylight simulation [MJA*13] works best when a BSDF is stored as a fixed-size matrix corresponding to incoming and outgoing directions using a particular subdivision of the hemisphere. Starting with our mass-transport interpolant, we can compute such a matrix representation.

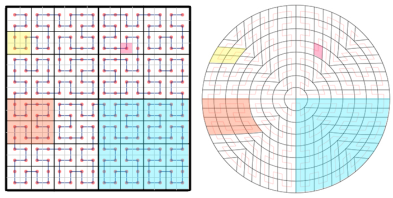

**Figure 4:** *A Hilbert 2-D space-filling curve drawn to the 4th level. Different regions illustrate a hypothetical tensor tree's subdivision of exiting directions where samples might go.*

Fig. 5 shows a rendering comparison between these two representations, demonstrating the superiority of the tensor tree in this case. However, when we want to simulate the appearance of a space as daylight changes and the shades on the window adapt dynamically, a matrix representation reduces the calculation time to a tiny fraction of what it would be otherwise, and permits one to try out different shading solutions and controls at little added cost.

A standard XML file format for the matrix and tensor tree representations has already been defined, and we expect to refine and extend this over time. Supporting this standard is a C library that interprets the XML files in a backwards-compatible fashion, so updating the library is all that is needed to support extensions to the XML representation.

### 2.4. BSDF Software Library

We have implemented the following queries for matrix and tensor tree sampling in an ANSI-C library with a fixed API:

(a) Get a BSDF value for a pair of directions.
(b) Get the directional hemispherical scattering for a given incident direction.
(c) Get the projected solid angle sample size for one or two directions.
(d) Get a probability-based importance direction and weight for the given input direction.

The caller may in practice treat the BSDF as a single entity, or may access it as components. These components include transmission, front reflection and back reflection, each further divided into Lambertian and non-Lambertian components, any of which may be zero. The library further supports multiple non-Lambertian components, which may provide for more efficient representations in the future.

In the simplest use of our library, the application makes a single call at each surface evaluation to generate a sample ray direction and weight using method (d). The weight would always be the same, although the spectrum might

(a) (b) (c)

**Figure 5:** *(a) Matrix-based BRDF rendering of anisotropic Ward model. (b) Reference image. (c) Tensor tree BRDF rendering of the same model. Insets show color-coded maps which represent a probability that an average observer will notice a difference between the reference image and rendered image [MKRH11].*

change for different importance samples. Multiple rays can be generated to reduce variance, and the tensor tree representation maintains any stratification present in the passed random variable. New representations as well as extensions to existing types may be added to our library without altering the interface, which is more general than the existing XML specification. The library also supports loading and caching BSDF data and vector operations for surface reorientation.

While we have tested this API for our own purposes, our goal is to provide it to the rendering and simulation communities as a C library to facilitate BSDF data sharing and re-use based on a standardized XML format.

## 3. Data Sharing and Remaining Challenges

It is unclear how BSDF data sharing will eventually work, but once we have the capability to characterize materials, a standard means to represent them, and widespread software to make use of these data, manufacturers will most likely want their products included. Similar to the IES and EULUMDAT standards for luminaire data, we expect to see companies offering measured BSDFs they either create themselves or hire an independent laboratory to create for them. We plan to seed this process by measuring a number of materials and providing them with our BSDF library.

In order to create sufficiently compelling examples of this new capability, we have a few issues we must still address. First, we need to find a satisfactory method for extrapolating data to grazing angles. Backlit appearance is important to our judgement of materials, and getting this right is challenging, even for smooth surfaces. The limited ability of most goniophotometers to measure low angles due to edge effects and illumination/acceptance apertures forces us to rely on grazing models to fill in these important regions. Unfortunately, this is also where most mathematical models are weak and do not represent real-world materials accurately. Further research is needed to resolve this problem. Second, there is the question of what to do when there are very narrow peaks in the distribution. While the tensor tree can resolve peaks down to a fraction of a degree, mirror-like reflections and glass-like transmission beg for a different representation altogether. Is it possible to represent directional-diffuse with such specular peaks together in a common format? We have not found a good solution to this issue, and we do not know how critical it will be in practice. Third, we need to experiment with different spectral representations to find the best compromise between accuracy and computation requirements. There probably is no "one-size-fits-all" solution, but having a small set of common approaches would be very helpful.

**Acknowledgements**

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## References

[AB14] APIAN-BENNEWITZ P.: Building material examples (BME) BRDF and BSDF database., 2014. URL: http://www.pab.eu/gonio-photometer/demodata/bme/. 2

[BvdPPH11] BONNEEL N., VAN DE PANNE M., PARIS S., HEIDRICH W.: Displacement interpolation using lagrangian mass transport. *ACM TOG 30*, 6 (2011), 158:1–158:12. (Proc. SIGGRAPH Asia '11). 2

[GL96] GOTSMAN C., LINDENBAUM M.: On the metric properties of discrete space-filling curves. *IEEE Transactions on Images Processing 5*, 5 (1996), 794–797. 3

[MJA*13] MCNEIL A., JONSSON C., APPLEFELD E., WARD G., LEE E.: A validation of a ray-tracing tool used to generate bi-directional scattering distribution functions for complex fenestration systems. *Solar Energy 98, Part C* (2013), 404–414. 3

[MKRH11] MANTIUK R., KIM K. J., REMPEL A. G., HEIDRICH W.: HDR-VDP-2: A calibrated visual metric for visibility and quality predictions in all luminance conditions. *ACM TOG 30*, 4 (2011), 40:1–40:14. (Proc. SIGGRAPH '11). 4

[MPBM03] MATUSIK W., PFISTER H., BRAND M., MCMILLAN L.: A data-driven reflectance model. *ACM TOG 22*, 3 (2003), 759–769. (Proc. SIGGRAPH '03). 1

[PCS*12] PACANOWSKI R., CELIS O. S., SCHLICK C., GRANIER X., POULIN P., CUYT A.: Rational BRDF. *IEEE TVCG 18*, 11 (2012), 1824–1835. 1

[Rus98] RUSINKIEWICZ S. M.: A new change of variables for efficient brdf representation. In *Proc. of Eurographics Workshop on Rendering* (1998), Springer, pp. 11–22. 2

[SC97] SHIRLEY P., CHIU K.: A low distortion map between disk and square. *Journal of Graphics Tools 2*, 3 (1997), 45–52. 3

[WKB12] WARD G., KURT M., BONNEEL N.: *A Practical Framework for Sharing and Rendering Real-World Bidirectional Scattering Distribution Functions*. Tech. Rep. LBNL-5954E, Lawrence Berkeley National Laboratory, October 2012. 3

[WMLT07] WALTER B., MARSCHNER S. R., LI H., TORRANCE K. E.: Microfacet models for refraction through rough surfaces. In *Proceedings of the 18th Eurographics Conference on Rendering Techniques* (2007), EGSR'07, pp. 195–206. 1