SIMULATION OF THE BSDF MEASUREMENT CAPABILITIES FOR VARIOUS MATERIALS WITH GCMS-4 GONIO-SPECTROPHOTOMETER

D.D. Zhdanov[a,b,c], I.S. Potemin[a,b], V.G. Sokolov[b], A.A. Garbul[a,c], A.G. Voloboy[b], V.A. Galaktionov[b]
[a]ITMO University; [b]The Keldysh Institute of Applied Mathematics RAS; [c]The Vavilov State Optical Institute

In this paper, the authors analyzed the accuracy of BSDF shape measured for later use of measurements in special software for photorealistic visualization and virtual prototyping. Visual and numerical analysis were done.

Introduction

Physically accurate lighting simulation requires precise account of the optical properties (BSDF) which are usually measured using gonio-spectrophotometer. Goniometric spectrophotometer is a precision instrument which measurement errors (both geometrical and optical) are given in the device data sheet. However, along with the inaccuracies specified in the data sheet such as angular accuracy, the stability of the light source radiation and photocell errors there is a number of methodological errors related to either the limited aperture of the radiation source and detector or inconsistencies of observation and illumination areas of the sample surface. The value of such methodological errors depends on the optical properties of the sample. In particular, in the case of measuring BSDF of sample with a pronounced peak near direction of specular reflection or refraction (e.g., low surface roughness), the error will be determined mainly by the angular sizes of light source and detector. Also, when the surface of the test sample is illuminated under large angles of incidence, a part of the illuminated spot is not visible to the observer (detector), which may lead to an underestimation of the reflected energy and hence a measurement error. Therefore, when using a goniometric spectrophotometer for BSDF measurement one should take into account the specifics of the measurement process and characteristics of the sample.

In this article, the authors attempted to analyze the methodological errors of measurements on the goniometric spectrophotometer GCMS-4 and to show how BSDF shape depends on the type of sample to be measured and how the measurement errors effect on photorealism of synthesized image of scenes containing the investigated surface.

Measurement device and its model

In our investigation we used BSDF data measured with Gonio-spectrophotometric Color Measurement System GCMS-4 produced by Murakami Color Research Laboratory [1]. The scheme of device is presented on the fig.1.

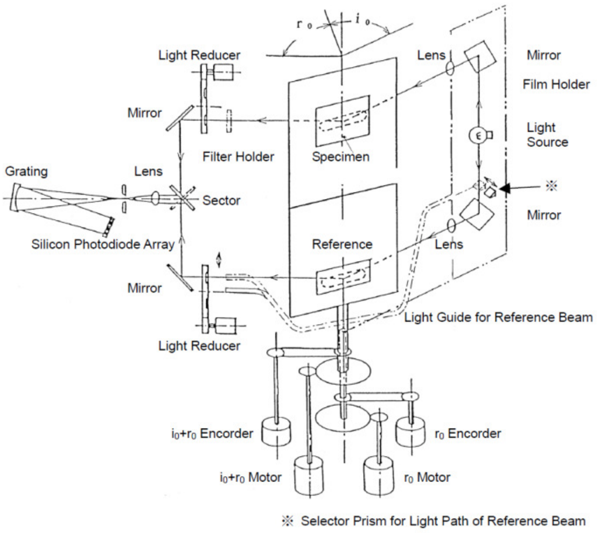

Fig.1. Scheme of GCMS-4

A double beam system is used in this device. In this case comparison with the light reflected from the reference white plate is always executed in. It provides stable measurement and the readings are indicated with radiance factor as the effect of angle on reflected light can be also corrected.

The incident and receiving angles can be freely changed by the computer's command has ensured to effectively take goniophotometric measurement which produces a lot of readings.

The device allows measurements with angular accuracy within ±0.5 degrees. Viewing area is 8 x16 mm for zero angle of receiving and 8 x 106 mm for 81 degrees receiving angle. The light source angular aperture in plane of measurement (plane containing axes of incident and receiving beams) is 2.1 degrees and in plane perpendicular to the plane of measurement – 4.2 degrees. For detector the angular aperture value is 1.6 x1.4 degrees for two mutually perpendicular sections.

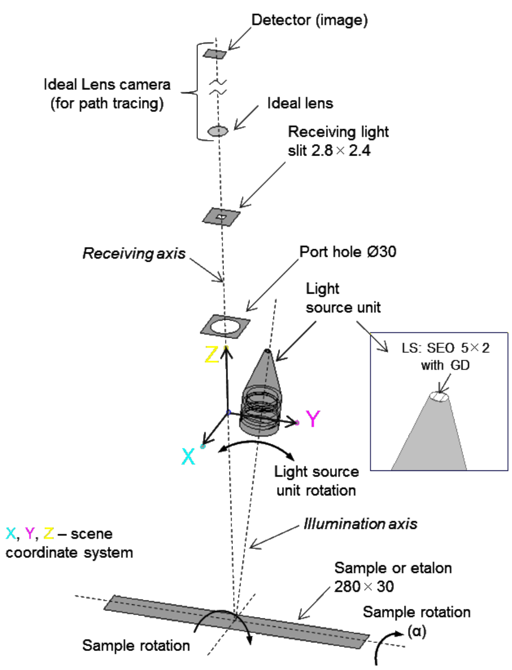

Fig.2. Scheme of the computer model scene

The computer model of measurement device is presented on the fig.2. In the model we used a single beam system. It includes only one light source unit which illuminates the sample. In case of simulating the reference sample (etalon) we just change properties of the surface. In case of simulation light source properties are always stable. So there is no necessity to keep two channels. Light source unit includes the source itself presented as luminous rectangle with sizes 5mm X 2mm and the optical system which forms the illumination beam in accordance with specification of GCMS-4 above.

The ideal lens was used to form the image of receiving slit 2.8mm x 2.4mm at the detector surface.

The procedure of simulation is the following:

- We specify the properties (BSDF) of sample surface both the etalon and testing sample.
- Then the angular orientation of light source unit and the sample surface is specified in accordance with the angular grid used during measurement with real device GCMS-4.
- Run lighting simulation itself.

Method of lighting simulation

To construct a virtual model of the goniometric spectrophotometer the authors used physically correct model of propagation of the light rays from the light source, the collimation of radiation on the sample, the light scattering on the sample and accumulation of the light on detector of radiation. Simple lighting formulas for calculating the illumination of the test sample and the luminance in the direction of observation are not applicable because the model of the measuring installation comprises two optical systems used for lighting and detection of luminance. Such complication of the model makes it necessary to calculate the caustic illumination on the sample surface and the luminous flux of the detector surface.

Implementation of the possibility of the lighting calculations focused on the physically accurate calculation of the light flux coming to the spectrophotometer radiation detector, should be based on physically accurate models of light propagation in optically complex three-dimensional environment and effective mathematical and software models of integration of local luminance component forming the luminous flux. The models and methods developed in computer graphics for photorealistic rendering of three-dimensional scenes can serve as a basis for such lighting calculations. Photorealistic rendering of optically complex scenes reduces to solving the rendering equation [2] for each point of the scene image. For static scenes the rendering equation can be written as follows:

$$L(\vec{p},\vec{v},c)=\tau(\vec{p},\vec{v},c)\begin{pmatrix} L_0(\vec{p},\vec{v},c)+ \\ \frac{1}{\pi}\int\limits_{4\pi} BSDF(\vec{p},\vec{v},\vec{v}',c)L(\vec{p},\vec{v}',c)(\vec{n}\cdot\vec{v}')d\omega \end{pmatrix} \tag{1}$$

As for solving the rendering equation we used the method of "Russian roulette", then to calculate the luminance function value the most appropriate method is the method of stochastic ray tracing. Many modifications of the method of stochastic ray tracing are applied in computer graphics. This is a forward stochastic ray tracing [3], backward stochastic ray tracing [4] or Path Tracer, various combinations of simultaneous backward and forward ray tracing [5], [6]. In this case, the authors had developed and applied an approach based on the method of stochastic path tracing of backward rays with limited diffuse depth and generating the visibility maps of the scene where the following forward Monte-Carlo ray tracing with unlimited depth accumulates of all components of the illumination. Equation (1) allows accumulating the luminance in the direction of observation. However, in the case of construction of the virtual model of the measuring device it is necessary to calculate luminous flux on the light detector. So to calculate luminous flux it is necessary to apply double integration of the luminance on the exit lens pupil and the detector area. To calculate local illuminance value we can use well know dependence between the luminance of the small pupil area and illuminance from this light area:

$$dE(\vec{p},c)=L(\vec{p}_i,\vec{v}_i,c)(\vec{n}\cdot\vec{v}_i)d\omega_i \tag{2}$$

where $L(\vec{p}_i,\vec{v}_i,c)$ – the luminance of the pupil area in the point $\vec{p}_i$ and direction to the pupil area $\vec{v}_i$,

$d\omega_i$ – the solid angle from the image point $\vec{p}$ to the pupil area in the point $\vec{p}_i$,

$\vec{n}$ – the direction of the exit pupil normal.

The figure 3 illustrates the method of the local luminance calculation.

Whole illuminance in the image point $\vec{p}$ is an integral of all local illuminances calculated from all exit pupil areas. The stochastic path tracing which applies uniform distribution of all local areas $\vec{p}_i$ on the exit lens pupil provides correct illuminance integration scheme. However, the case of uniform distribution of the ray paths on the exit lens pupil differs from the uniform distribution on solid angle corresponding to the exit pupil and the special weight component compensating the difference should be added to the integration procedure. If the plane of the exit pupil is parallel to the image plane the dependence of the weight of the ray path on the view direction has the following view:

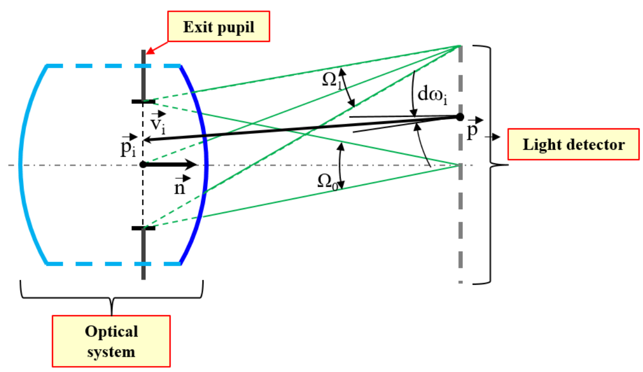

Fig.3. Local illuminance calculation from the lens exit pupil area

$$W(\vec{p},v_i)=(\vec{n}\cdot\vec{v}_i)^4 \tag{3}$$

In the case of circular shape of the exit pupil, the integration of local luminances to the illuminance of the image point has the following view:

$$E(p,c)=\frac{\pi\cdot r^2}{N\cdot s^2}\sum_{i=1}^{N}W(\vec{p},v_i)L(\vec{p}_i,\vec{v}_i,c) \tag{4}$$

where N – the number of random ray paths uniformly emitted from the image point to the exit lens pupil.

Finally, luminous flux on the detector is integral of the illuminance by whole detector area S.

$$F(c) = \int_S E(\vec{p}, c) d\vec{p} \tag{5}$$

Using developed solution authors created physically correct model of virtual goniometric spectrophotometer and made a number of virtual measurements of BRDF and BTDF. The virtual model is applied to the investigated BRDF (or BTDF) and repeating this model for the defined set of samples (pairs of illumination and observation directions) allows constructing whole model of BRDF (BTDF). Comparison of initial BRDF (BTDF) with the results of virtual measurements allows estimating the measurement errors and choosing the minimal set of samples, which can provide sufficient accuracy of the BRDF (BTDF) measurements.

Simulation results

The simulation of BSDF and comparison with corresponding measurements were fulfilled for a number of diffuse samples with different degree of scattering. Numerical and visual simulation results are presented. The graphs show the comparison of BSDF shapes for investigated samples in the plane of incidence (α = 0). The left sphere properties correspond to simulated BSDF and the right sphere - to measured BSDF.

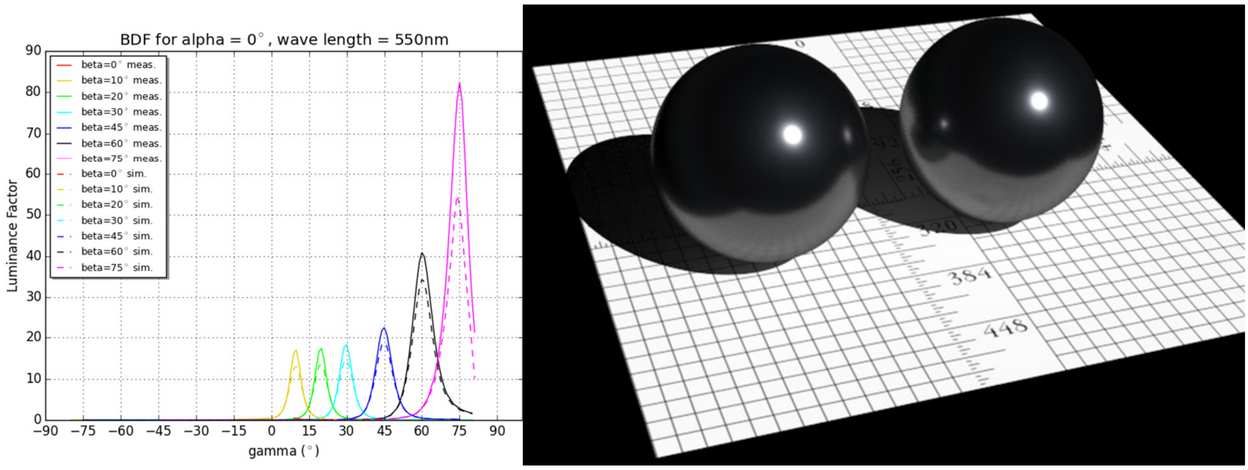

Fig.4. BRDF sample with perceptible specular peak

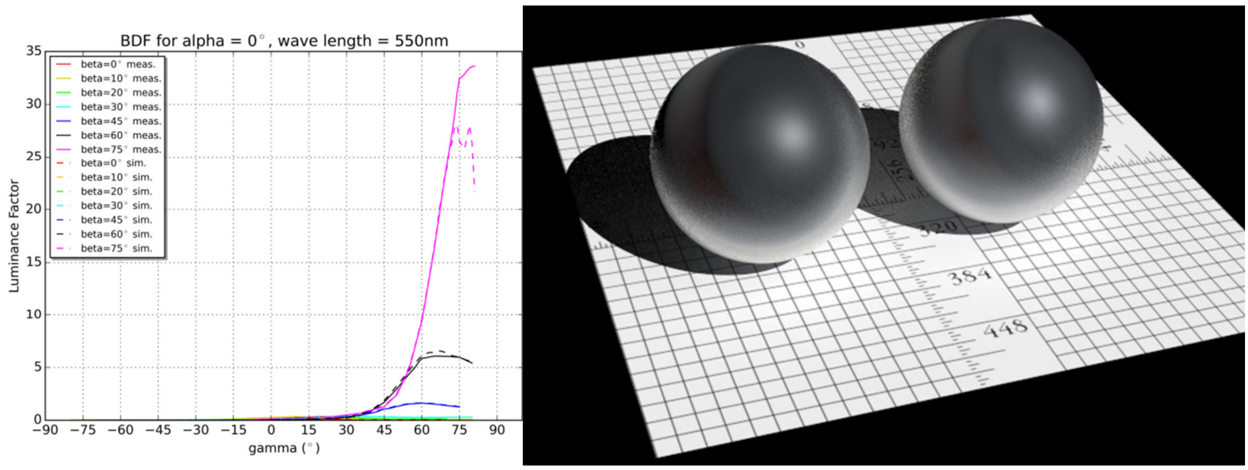

Fig.5. BRDF sample with wide peak

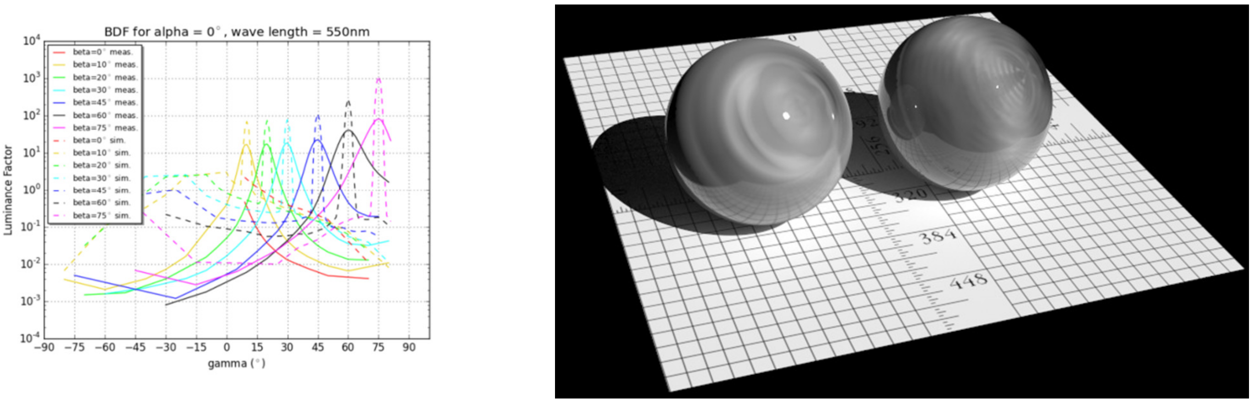

Fig.6a. BRDF sample with backscattering

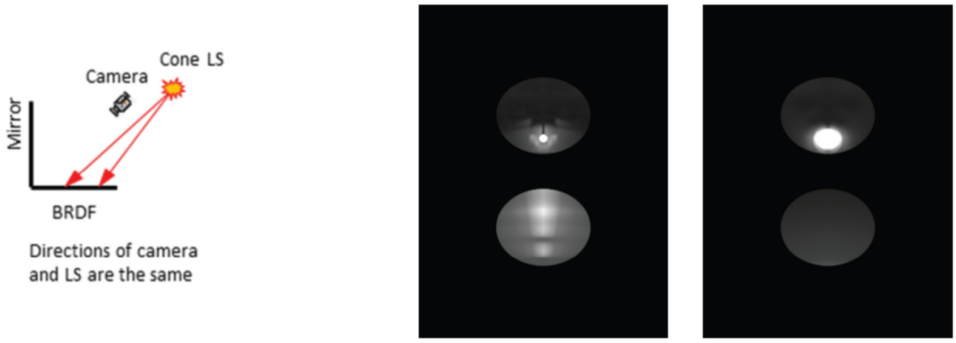

Fig.6b. BRDF sample with backscattering

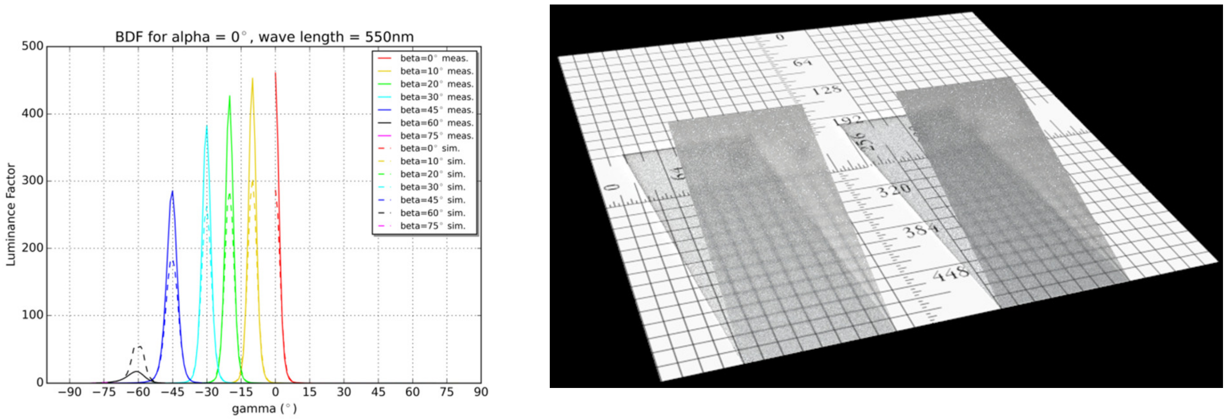

Fig.7. BTDF sample

Conclusion

The authors built a virtual model of the measurement setup, which has become the main tool of analysis of BSDF measurement error. Basing on the construction of the virtual model and synthesized data of various types of BSDF we have identified the main causes of the methodological errors and show how the optical properties of the samples affect the accuracy of BSDF measurement.

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