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Efficient methods of BSDF reconstruction from the micro-relief dataset for the lighting simulation tasks

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ABSTRACT

A physically accurate description of the optical properties of surfaces is the one of the most important requirements in optical simulation for both imaging and non-imaging optics. Uncertainty in the specification of the optical properties might influence the simulation image or the spatial distribution of radiation in optical system. One of the ways of describing the optical properties is using the Bidirectional Scattering Distribution Function (BSDF). As a rule, BSDF is measured by goniospectrophotometers, but sometimes it is not possible to perform such measurements. In some cases, the measurement should be done inside the material, but it is impossible to measure BSDF of the boundary there. One of the possible solutions is to measure the microrelief heights distribution by profile measurement machine or atomic force microscope and assign measured data for given model. But, not every optical design software solution has the ability to specify microrelief directly, while majority of them just have the ability to specify BSDF. In this article, authors show methods of BSDFs generation from measurements of the real microrelief in the form of spatial distribution of heights.

Keywords: BSDF, BSDF measurements, BSDF reconstruction, roughness, LGP, wave optics, ray optics.

1 INTRODUCTION

In modern optical devices the components with rough surfaces are used quite often. There are two main applications of rough surfaces: either to provide the special light intensity distribution curves (LID, LIDC), showing light intensity distribution in dependence with the angle in one or several planes, or to obtain the desired spatial luminance distribution for various optoelectronic devices. Devices that use such optical elements include lighting fixtures, LCDs, car dashboards, light indicators and other. Also, that approach is used in producing anti-reflecting films. In such cases, polymers could be used as optical materials. Producing roughness on surface is not very difficult process, it could be produced, for example, by laser, by chemicals or mechanically. Different types of the optical surface roughness application methods can provide big variety of profiles. The profile sizes could be in the range from dozens of nanometers to dozens of micrometers. For the simulation of the light propagation inside material, optical designers are in need of optical properties of the rough surface boundary between the two media while the optical properties of the whole optical element are quite senseless. Moreover, the properties are individual for the each side of the light incidence on the rough surface. So, the correct light simulations have to apply the properties taking into account the side where the beam hits.

An example of applying of the rough surface is shown on Figure 1. Dots with microrelief are distributed on the bottom side of the light guiding plate (LGP). They are rough scattering surfaces. A light ray propagates in LGP due to total internal reflection. After the scattering on the dots, the ray deviates from the total internal reflection direction and can leave LGP. Variable density of the dots allows obtaining a uniform brightness distribution along the output surface.

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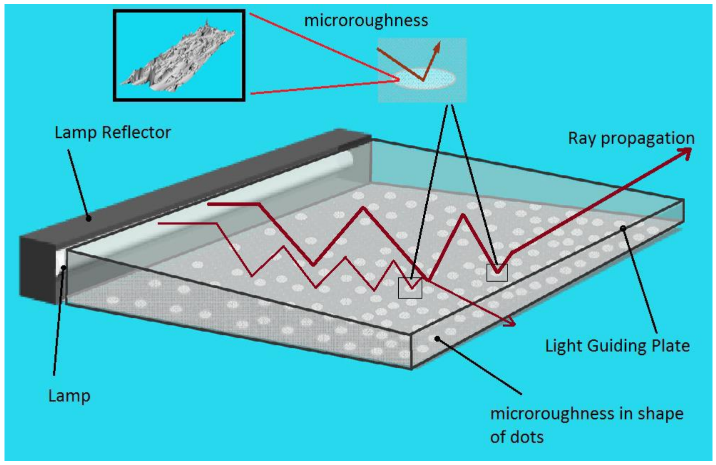

Figure 1. An example of the application of the LGP with rough dots

To describe the scattering behavior in optical modelling system, the bi-directional scattering function (BSDF) is used. This function has a complex multi-dimensional formulation and depends on many parameters: direction of the incident light, direction of the output light, and the spectrum (color). Also, BSDF consists of two functions: Bi-directional Reflectance Distribution Function (BRDF) and Bi-directional Transmittance Distribution Function (BTDF). For flat thin samples, like the one shown in Figure 2a (‘‘surface’’ model), the BSDF can be measured by any goniophotometer. If the thickness of the sample with roughness can be omitted and the BSDF is assigned to the single surface, the measured BSDF model can be considered physically correct. The model can be applied to various diffusers and filters. Unfortunately, the model is not applicable if the thickness of the element with the roughness is important for the light propagation inside the transparent element. The “solid” model presented in Figure 2b should be used in this case. It means that we need two BSDFs of the rough surfaces, one is for the “from the air to the glass” side and another one is for “from the glass to the air” side.

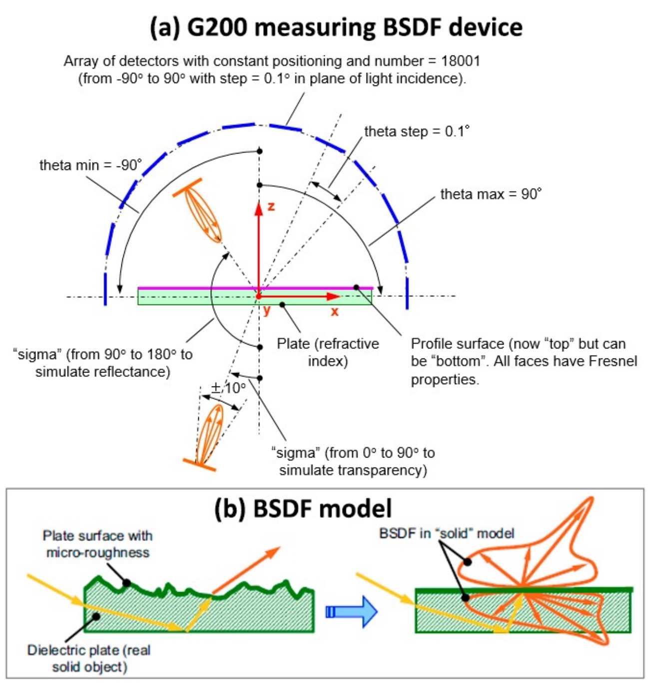

Figure 2. a) ‘‘Surface’’ vs. b) ‘‘Solid’’ BSDF application models.

The main problem is that the BSDF of the rough surface cannot be measured directly. There are several reasons for this. At first, there might be multiple reflections inside the measured sample between all surfaces. Secondly, it is impossible to illuminate the sample or to detect the light emission under the grazing angles of the light incidence (detection) to the rough surface. A solution of this problem is very expensive and requires special measurement equipment to exclude multiple reflections between sample faces and refraction on the side opposite to the measured rough one.

An alternative way of BSDF obtaining is to generate this function according to the data of the microrelief on the boundary of the sample media[1]. This indirect way has a number of disadvantages as well. In particular, variation of the surface profile can be comparable with a wavelength of the illuminating light. It means that computations have to apply the wave optics approach which, at first, is very complex and, at second, can be inaccurate due to not sufficient accuracy of the surface profile measurement.

In the current article, two approaches are proposed. The first approach is based on the reconstruction of BSDF from the measured micro-relief (height distribution). The second approach is also based on the reconstruction of BSDF but in addition to measurements of height distribution we utilize BSDF of plate sample with given micro-relief.

2 NUMERICAL METHODS OF THE BSDF RECONSTRUCTION

There are several numerical approaches of the BSDF calculation for rough surface based on an approximation of the ray optics as well as the wave optics. Reconstruction of the BSDF of the plate with the rough surface could be based on two sets of measured data: the microprofile height distribution and the BSDF of the entire sample (transparency and/or reflectance). An example of the approach based on the ray optics is the micro facet model[2]. More accurate solution applies the ray tracing inside the micro facet layer. In situation, when sizes of the profile heights are bigger than the wavelength, the ray approach is used. For surfaces where sizes of the profile heights are smaller than the wavelength, Kirchhoff approximation is used[3]. Our research demonstrates that both these approaches have weaknesses. At first, the criterion of the applicability of the method is rather vague. Both methods are very “sensitive” to the quality of the micro roughness measurements and even a small noise in measurements can lead to the essential inaccuracy of the resultant BSDF. Secondly, Kirchhoff solution does not take into account the light inter-reflections on the micro facets and can be applied only to a smooth relief. Also, reconstruction requires complex optimization of the microprofile (reducing to scaling and filtration of the profile). However, sometimes the filtration cannot guarantee the success.

2.1 Cook-Torrance model

Cook-Torrance model is an analytic BRDF model based on the principals of the microfacet theory[7]. Real world materials have a lot of optical characteristic of a surface such as reflectance, glossy or specular highlights, anisotropy, etc., which could be used in computer graphics and optical modelling systems. Analytical reflection models attempt to describe certain classes of the Bi-directional Reflectance Distribution Functions (BRDF) using a mathematical representation involving a small number of parameters. The Cook-Torrance model[8] is an analytical isotropic BRDF model belongs to a physically based model and is based on the microfacet theory of inter-reflection of the light at rough surfaces. It extends the Torrance-Sparrow reflectance model[9]. The Cook-Torrance model describes the intensity and the spectral composition of the reflected light reaching the observer.

The total intensity of the light reaching the observer is the sum of the reflected intensities from all light sources plus the reflected intensity from any ambient illumination. So, the basic reflectance model becomes (1).

$$I_r = I_{ia} R_a + \sum_l (sR_s + dR_d) I_{il} (N \cdot L_l) d\omega_{il} \tag{1}$$

This formula accounts the effect of the light sources with different intensities and different projected areas which may illuminate a scene.

The facet slope distribution function *D* represents the fraction of the facets that are oriented in the certain direction. Various facet slope distribution functions have been considered by Blinn[10] including the Gaussian model:

$$D = ce^{-(\alpha/m)^2}, \tag{2}$$

where c is normalization constant.

Also, there is a model, which describe scattering of waves from rough surfaces[11], and is applicable to a wide range of surface conditions ranging from smooth to very rough:

$$D = \frac{1}{m^2 \cos^4 \alpha} e^{-(\tan\alpha/m)^2}. \tag{3}$$

In these cases, the spread of the specular component depends on the root mean square (RMS) of the facet slope m. Small values of m signify gentle facet slopes and give a distribution that is highly directional around the specular direction, while large values of m imply steep facet slopes and give a distribution that is spread out with off-specular peak modeled by the Beckmann distribution. For general surfaces with two or more scales of surface roughness, the slope m can be modeled by using a convex weighted combination of two or more distribution functions[12]:

$$D = \sum_j w_j D(m_j). \tag{4}$$

where m_j is RMS slope and w_j the weight of the jth distribution respectively.

The geometrical attenuation factor G accounts for the shadowing and masking of one facet by another and is presented by Torrance et al[9] and Blinn[10]. The following expression is derived for G for microfacets (Figure 3):

$$G = \min\left\{1, \frac{2(N\cdot H)(N\cdot V)}{(V\cdot H)}, \frac{2(N\cdot H)(N\cdot L)}{(V\cdot H)}\right\}. \tag{5}$$

where H is normalized vector in the direction of the angular bisector of V and L, and defined as:

$$H = \frac{V+L}{|V+L|}. \tag{6}$$

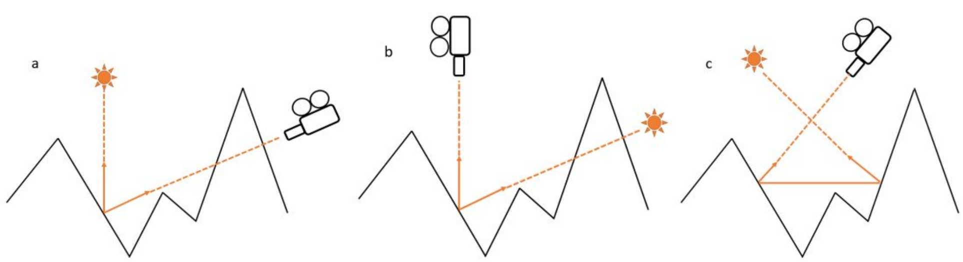

Figure 3. Geometric attenuation due to microfacets. (a) Masking. (b) Shadowing. (c) Inter-reflection

Being a physically-based reflectance model, the Cook-Torrance model has been widely used in computer vision and computer graphics for modeling the appearance of real world materials.

2.2 Reconstruction of BSDF basing on the density of normals distribution

The second approach is also based on the density of normals distribution and uses Monte-Carlo ray tracing methods to calculate the intensity distribution scattered from the surface facets. All facets of the roughness have a normal with different orientation and similarly to the Cook-Torrance model can reflect, refract and shadow rays. To calculate intensity distribution the boundary between the two media accepts the roughness corresponding to the normal variation with the specified density. This is an analog of so-called random bump mapping. The infinity thin beam of rays illuminates the boundary under the fixed inclination angle to the sample. Taking into account that the boundary normals are not fixed and have statistical distribution with the specified density then each incident ray meets its own normal (or facet orientation) and is probabilistically reflected (refracted) according to the current Fresnel properties (calculated for all normal and ray directions). After the reflection (refraction), we check new ray direction. First of all, the new direction have to be correct. That is the reflected ray should be oriented toward of the medium of an incidence. It is not allowed that after reflection the ray can be found in the medium opposite to the medium of the incidence. The similar situation is for refracted rays, which have to be found in the medium opposite to the medium of incidence. Figure 5 illustrates this process. However, sometimes after the reflection (refraction) on random normal the new ray can get an incorrect direction. In this case, we continue the ray propagation and cycle the ray reflection (refraction) on new random normal until the ray gets the correct direction. Moreover, there are "doubtful" results of the ray transformation when ray leaves boundary of the media in proper direction but under grazing angles. It means that the ray has a chance to meet another facet. To process this situation, we added a special function which forces ray to propagate in the layer of a random normal until the ray leave the boundary in the proper direction. This function has probabilistic pattern with maximal values under grazing angles of ray incidence and zero value in the direction of the base surface normal. When ray leaves the boundary its energy is accumulated on goniometrical detector that allows accumulating scattered intensity distribution for the specified direction of the ray incidence. By repeating the procedure for other angles of incidence and other wavelengths we calculate the 5D function of the ray scattering. After normalizing and reducing this function to a relation of scattered luminance to the incident illuminance, we get the whole 5D BSDF of the rough surface. This function was implemented in the OPTOS MicroRelief tool[4] of Lumicept[5]. Due to a simplicity of the ray tracing procedure the method is very fast and can be used in the optimization procedures[13].

Unfortunately, the physical correctness of this method is not very high. We compared the simulation results with the results of the BSDF measurement of the real sample. We measured the height distribution of the sample and transferred it to the density of the facet normals distribution. On the other hand, we measured the sample BSDF by the Integra's spectral scatterometer[6]. For simplification of the comparison of the measurement and simulation results, we used the same scheme of the BDF simulations and measurements. Figure 4 presents measured and simulated angular distribution of light flux that was transmitted through the plate sample with one rough surface and accumulated on light detector. The combined graph contains the light transmittance for all measured incident light directions. The measurements and simulations were fulfilled for the following directions of the light incidence: 0º, 15º, 30º, 45º, 60º, 75º (angle between the normal to the sample and an incident light direction). They are marked with different colors. Note that all measurements and simulations results are represented in the plane of light incidence. The solid plots present result of the real sample measurements. Dash-line plots correspond to the simulated sample with the reconstructed BSDF. It is seen that there is the essential difference between the simulated and measured results. Moreover, highest differences between simulation and measurement appears in the areas of the high angles of the light incidence where artificial heuristic returning ray to the propagation process with grazing angles is applied. The same tendency can be observed on graphs with the reflectance data (omitted in this article).

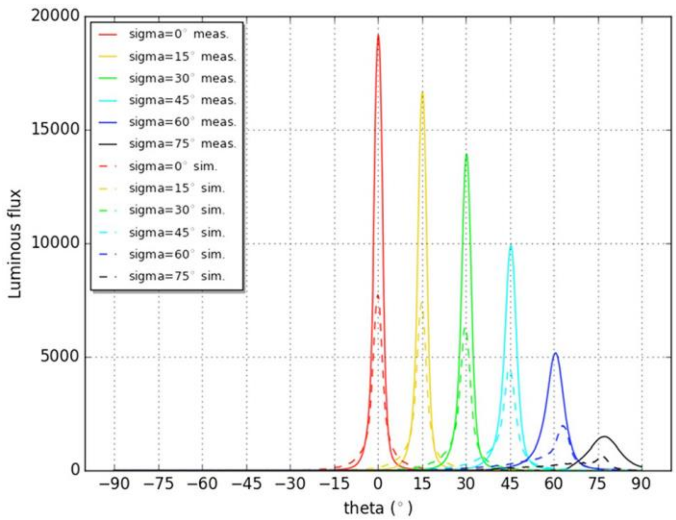

Figure 4. Comparison of the measured and calculated transparency.

2.3 Ray approach

The third approach is based on the Monte-Carlo ray tracing solution with the real sample microrelief. Also, in this case rough surface is measured by a profile measurement machine or an atomic force microscope. This data is used in the modelling: roughness presented as a distribution of the profile deviation, with maximum and minimum values. In this case, the BSDF is calculated separately as BRDF + BTDF = BSDF (Figure 5) on different light detectors. This method is analogous to the previous one and the only differences are that the ray searches for an intersection with the real facets and instead of an infinity narrow ray beam we fire a wide beam of parallel rays with an aperture about the measured sample size. As a result, all inter-reflections between facets, appearing under grazing ray propagation in the microrelief layer, are processed more correctly. But the error can appear on the boundaries of the relief when the ray propagating inside the layer cannot leave the layer through the bottom or top boundaries. To avoid additional errors, we mark these rays as incorrect and exclude from the simulation result. However, this boundary effect can distort result BSDF for grazing angles of incidence.

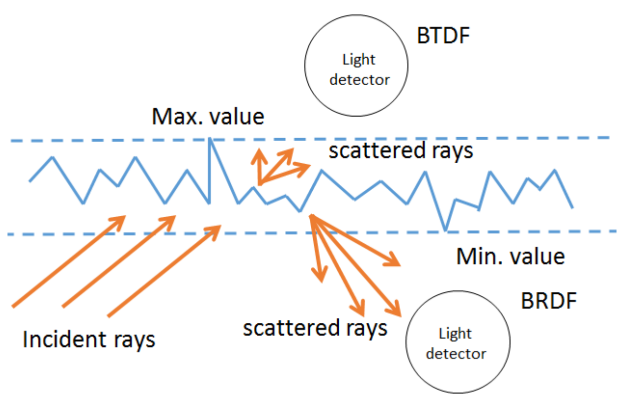

Figure 5. Scheme of ray approach

This method is fast and convenient, but it has one important disadvantage: ray approach cannot separate the specular component of the BRDF. For example, in case when it is needed to measure the anti-reflecting film (Figure 6), in areas with specular characteristic some roughness could appear. One of the reasons is that the measurement equipment has very high resolution, and noise of that measurements provides micro roughness, which really does not produce the light scattering, or the light scattering is much narrower than the ray solution produces.

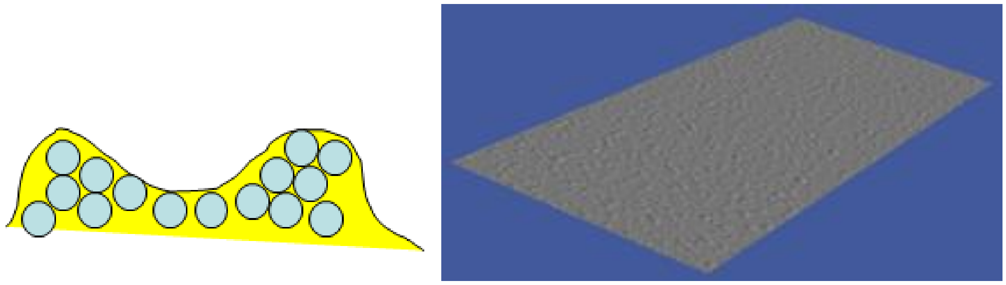

Figure 6. Structure of anti-reflecting films. Models of profile (left) and entire surface (right).

In such difficult cases we need to use another approach, which can solve this problem physically accurate. That approach is based on the wave solution, which is described by the Kirchhoff solution. The figure 7 shows the differences between these two approaches.

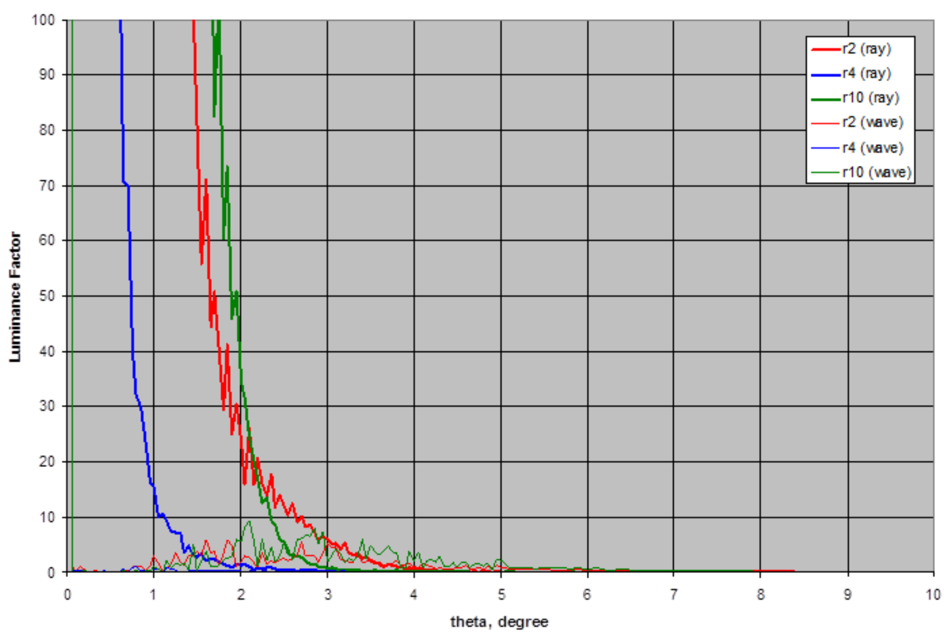

Figure 7. Ray and wave solution in modelling smooth surfaces.

As can it can be deduced from the above figure, thick solid lines represent the ray approach and thin lines represent wave approach. Wave approach can separate the specular component and diffuse components, further it is necessary to consider properly that approach.

2.4 Wave solution

The problem is formulated in a frequency domain (usual for diffraction). Formally, this means that illumination is exactly monochrome, or coherent:

- Coherent illumination. A plane coherent monochrome wave is incident onto the surface. We record scattered field in the *far zone* and obtain its angular distribution as in far zone only *direction* makes an effect. Repeating this while varying illumination direction and wavelength we eventually obtain a BSDF. It can then "substitute" for relief in ray tracing applications.
- Role of incoherence. The above is a classical treatment of diffraction problem[3, 11]. However, for relief samples with a large horizontal size it is not very practical, because it is hardly possible to create illumination coherent over a large area. Say, laser beam, as the most coherent among practical sources, is coherent over its spot, which has diameter not more than about 1 mm. Sunlight has even smaller length of coherence: about 60 microns. This is why classical solution of scattering of coherent light on a snow flake of size 1 mm, would not help us to calculate skylight in a snowfall.

  That is why for large-scale objects we must calculate the diffraction from an incoherent illumination. For a 3D object, even formulation of such problem is very difficult and even cannot fit in a frequency domain formulation. However, for a surface (thin relief) scattering it is relatively simple. We model incoherent illumination just by taking phase of incident wave to be not constant but correlated at a random field along the surface. If coherence length is much greater than wavelength (as it is usually in nature), then we may retain not only a frequency domain formulation but even fully reuse mathematics and algorithms from coherent case.

  The main effect of the coherent illumination is that it "enhances" wave (interference) effects and moves us "further" from ray optics, where no coherence exists at all. Under incoherent light, interference effects (e.g. diffraction grating maxima) are weakened. Also, incoherent light by definition brings a divergence of the beam (angular divergence ~ wavelength to coherence length ratio). So light distribution is as if it is "filtered", orsmoothed. E.g., specular component "diffuses" into Phong peak.

  One must realize that as incoherent illumination is random by definition, we are in need of some averaging over it. If the sample size is much greater than the coherence length, this results in spatial averages because illumination in points separated by more than correlation length is essentially independent. If correlation length is larger, the "effective number of independent patches" is insufficient for averaging. So, we must add an averaging over an instance of illumination (i.e. generate various in-stances of illumination, calculate scattering for them and then average their results).

Peculiarities of wave optics solution depend on particular relief and illumination. However, some points are rather common:

- Interference makes angular distribution of scattered light to be jaggier than in ray optics.
- BDF is "colored" i.e. depends on wavelength. For "red" end, it is sharper than for "blue" end.
- For coherent illumination, there is a specular component even if the relief does not contain flat areas. It increases with the wavelength. For incoherent illumination, it converts into sharp "Phong-like" peak.
- For incoherent illumination, BSDF resembles that for coherent one filtered (averaged) over a spot with an angular spread about λ/l (where l is the coherence length). E.g. the specular peak converts into Phong one.

General-purpose diffraction volumetric solvers can handle mathematical methods of the solution of the diffraction problem, but this is quite expensive. Though in some cases[14] a notable simplification is possible that allows to use specialized thus more cheap surface solvers:

- "Small" roughness, when dimensions (rather volumes) of bumps are small as compared to wavelength. This scattering by small inhomogenuities can be handled by Rayleigh method and its modifications.

- Smooth reliefs, when radius of the curvature is much greater than the wavelength. Locally scattered wave is about the same as in the ray optics, diffraction effects being mainly created by interference of waves from different bumps[15]. The core of method solution is Tangent Plane Approximation: locally reflected/refracted wave is approximated by what we would have neglecting curvature i.e. replacing the relief surface with its local tangent plane. This gives us an approximation of the field at the surface, and then it is "propagated" way from it using Kirchhoff integral.

In their basic form, both these approaches effectively neglect inter-reflections (i.e. multiple scattering). Thus, they work badly for grazing incidence/observation angles.

Some extensions/improvements here are possible. Say, for "small roughness" case we may promote Rayleigh method to Born series[14]. For smooth reliefs, there are attempts to account for the curvature[14].

However, these modifications still remain asymptotic methods and so still loose in accuracy to general-purpose solvers (that do not impose restrictions of roughness at all) while are sophisticated, difficult to implement and require much more resources (memory, run time).

Obtained solution of diffraction problem is then converted into BSDF. General limitation is that the solution of diffraction problem is not generally a smooth angular distribution of energy. Therefore, its conversion into a BSDF usually introduces some distortion. The relevant method keeps it as small as possible, but it is possible.

Conversion to BDF includes adaptive filtering. As currently conversion is dome independently for each illumination direction and wavelength, the optimal filter found may be different for adjacent wavelengths and/or directions of incidence. Then BDF sections for them look differently, e.g. one wavelength is more heavily filtered than another one is. However, in an integral sense they approximate similar distribution of light.

3 OPTIMIZATION OF BSDF RECONSTRUCTION PROCEDURE BASED ON SPATIAL DISTRIBUTION OF HEIGHTS

Reconstruction of the BSDF on the base of the measured microrelief may be not quite accurate. There are different reasons of the inaccuracy. One reason is the numerical limitations of methods of the BSDF reconstruction (based both on ray or wave theories). Another reason is an insufficient size of the sample with the measured microprofile or not representative view of the microrelief. In both cases, the BSDF will be not quite accurate. To reduce the problem dealing with BSDF reconstruction we propose to apply an optimization procedure. The procedure includes additional measurements of the BSDF sample. Note that BSDF of transparent sample does not coincide with reconstructed BSDF of the sample boundary. Because of the inter-reflections inside of the sample the whole BSDF can be significantly different from the BSDF of the boundary while accurate simulations of the different light guiding devices requires BSDF of the boundary but not of the whole sample. Figure 8 illustrates the whole optimization process.

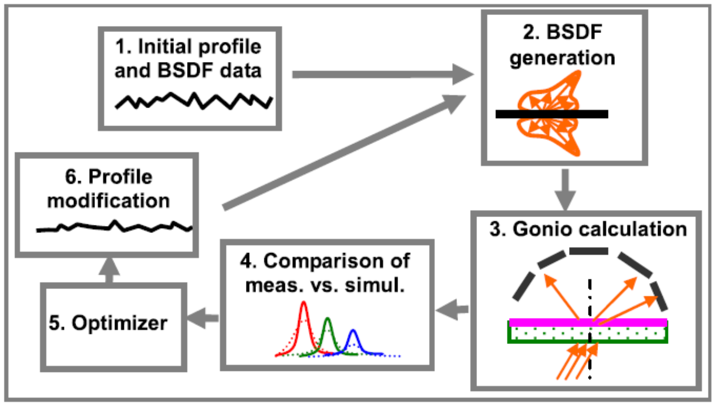

Figure 8. Scheme of BSDF optimization procedure based on spatial distribution of heights.

The optimization procedure consists of 5 steps:

1. Collecting the initial data for optimization (results of the measurements of the height distribution of the microrelief and the BSDF of the plate sample with rough microrelief from one side) and preparation of the scene of the sample with microrelief.
2. Numerical generation of the BSDF of rough relief. Depending on the height deviations, the proper solution (ray or wave) is applied.
3. Numerical calculation of the whole BSDF of the plate sample with rough surface calculated on step 2. The units of the calculations have to coincide with the units of the measured data.
4. Calculation of the difference between the simulated and measured plate sample BSDF. The difference is calculated as RMS. If RMS is less than the defined threshold then the optimization process is finished, else we go to the next step.
5. Optimization of parameters of the roughness structure. For optimization we use standard optimization functions from NUMPy library. These functions optimize abstract parameter of the optimization function. In our case parameters of optimization provide the global modification of the microrelief.
6. Modification of the scene (heights of the microprofile distribution). Two types of surface profile modification are applied: (1) gauss filtration to a smooth profile (it allows to reduce diffuse scattering of the profile); (2) scaling of roughness heights (it is allow to increase diffuse scattering of the profile).

This optimization procedure allows improving accuracy of the BSDF reconstruction of boundaries of the transparent objects.

4 EXAMPLE OF THE OPTIMIZATION RESULTS

As an example, we restored the BTDF of the rough boundary of the transparent sample. Moreover, the BTDF of the sample was measured. At first, we compared our simulation with measured data. To do it we created the scene with the microrelief and calculated flux distribution on the light detectors corresponding to the detectors of the measuring device. Figure 9 presents the measurement and simulation results. The measurements and simulations were fulfilled for the following directions of the light incidence: 0º, 15º, 30º, 45º, 60º, 75º (angle between normal to the sample and an incident light direction). They are marked with different colors. Note that all measurements and simulations results are represented in the plane of the light incidence. The solid plots present result of the real sample measurements. Dash-line plots correspond to the simulated sample with the reconstructed BSDF. It is seen that there is the essential difference between the simulated and measured results.

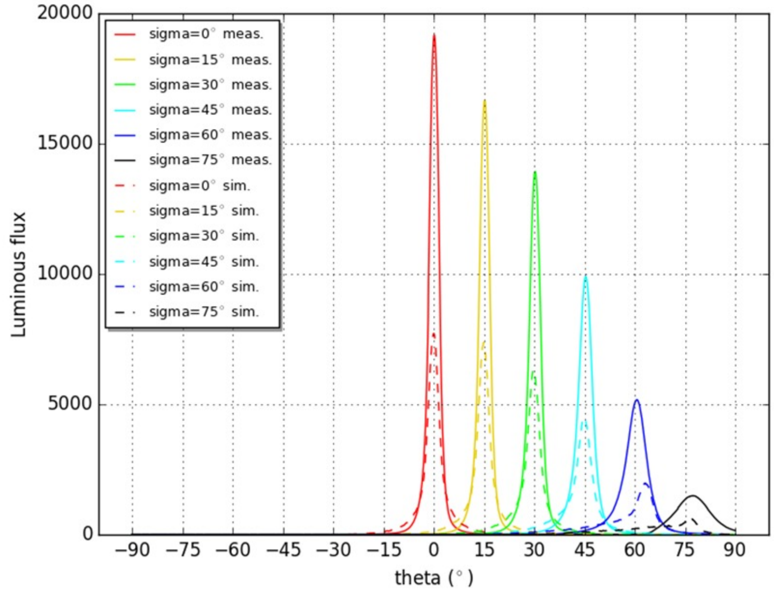

Figure 9. Measured and simulated intensity distribution of light. BSDF reconstruction based on the distribution of heights.

Then we ran the procedure of the BTDF optimization described in the previous chapter. After the optimization completion, the BTDF of the sample with BSDF attached to the boundary became much closer to the measured BSDF. Figure 13 demonstrates good agreement between the measured and optimized result. It means that the BTDF of the sample boundary became much more accurate.

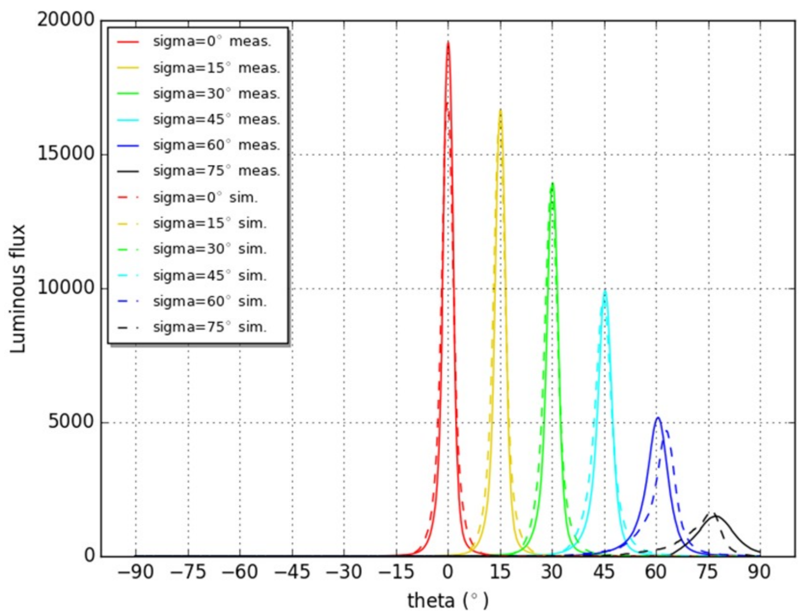

Figure 10. Results of BSDF reconstruction based on Cauchy function.

We can finally say that the optimization results of the distribution of heights show good agreement with the desired output at least in the scope investigated samples[1]. In addition, we can see the acceptable agreement for incident angles far from the normal direction. In this article, we demonstrate the results for the light transmittance only. However, the optimization procedure can be applied to the reflectance as well. Usually, an optimization of the transparency results improves the reflectance too.

Also, we made a photorealistic rendering of the plate with a rough surface. The visual appearance of the plate with the rough surface BSDF before optimization (i.e. when initially measured profile was used) is presented in Figure 11a. The visual appearance of the plate with the optimized rough surface BSDF is presented in Figure 11b. The images on Figure 11 were synthesized with the physically accurate rendering tool based on path tracing integrated into the Lumicept software package[5]. The scene consists of a plate with BSDF assigned to the outer plate surface. The plate is placed over a chessboard-like substratum and is illuminated with a set of light sources creating complex diffuse illumination.

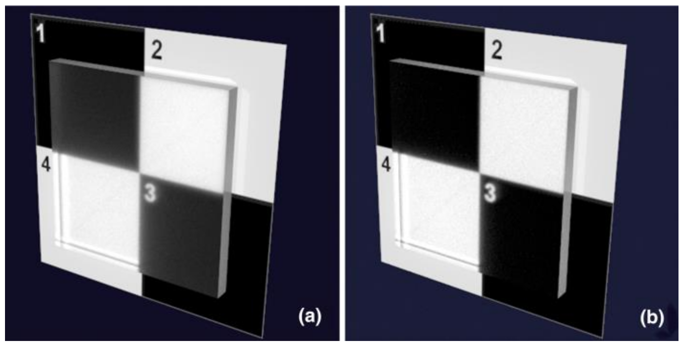

Figure 11. Visual appearance of a plate with rough surface.

5 CONCLUSION

The physically correct modelling of the complex optical devices with the scattering elements requires accurate specification of the BSDFs of these elements. We developed a number of methods for reconstructing the BSDF of the rough surface. Depending on parameters of the surface roughness it is possible to choose one of the reviewed methods of BSDF reconstruction, based either on the ray approach, or on the wave approach, or their combination. In addition, the combined method of the BSDF reconstruction based on the simultaneous measurements of the sample BSDF and its microprofile was proposed. The combined method allows improving accuracy of the BSDF reconstruction for grazing angles of the light incidence and reconstructing of the BSDF of the dielectric boundary of the transparent material when the direct BSDF measurements are impossible and the BSDF, reconstructed from the microrelief data, cannot provide sufficient accuracy.

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