Characterizing Full BSDF Data for Light Guide Extraction Features

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Abstract:

Characterizing the complete scattering properties of a textured or micro-structured light guide surface for light incident from both the outside medium and as well as from within the inside medium is not easily done. A physical sample of the material required to characterize the scattering properties of a single textured surface would only have the texture applied to one surface of the part while the other surface would be smooth. Directing light onto the textured side of such a sample could be done for a full range of incidence angles from normal to grazing, but when the light exits the smooth side, it will refract back into air. So the measured scattering properties of the light exiting back into air won't accurately represent the scattering properties within the material immediately after passing through the textured surface. Likewise, directing light onto the smooth side of the sample in an attempt to characterize the scattering properties of light exiting the textured surface has the same problem of including a refraction into the material from air. Furthermore, this refraction limits the range of incidence angles onto the textured surface to angles all just under the critical angle at which total internal reflection (TIR) occurs. Different physical sample configurations can partially mitigate these problems, but a preferred method is to simulate the scattering properties from the full range of angles onto both sides of the surface if the surface geometry and material optical properties are known. The simulation can avoid the refraction effects of the smooth surface by allowing the light scattering distribution from light entering the textured surface from air to be quantified within the material. Additionally, light incident onto the textured surface from within the material can cover the full range of incidence angles onto the surface since that light can originate from within the material. Accurate modeling of light interacting with a textured material at all incidence angles is especially important for applications such as light guides and diffuser panels where light typically enters the material through an edge of a sheet and can therefore be incident onto the textured surface at near grazing angles. This paper outlines a software modeling process to characterize the full scattering properties of a textured material using an example commercially available diffuser material, Evonik Acrylite P95.

Background:

In order to model light's interaction with a textured or micro-structured surface in raytracing software, directly modeling the surface geometry is generally the preferred approach, but results in a more complex and thus slower simulation. LTI Optics has developed a Material Lab tool that takes a representative section any surface geometry as input, simulates a collimated beam incident onto the geometry from a range of angles, and outputs a Bidirectional Scattering Distribution Function (BSDF) data file to be used in Photopia optical models. BSDF is the general term encompassing both the Bidirectional Reflectance Distribution Function (BRDF) and the Bidirectional Transmittance Distribution Function (BTDF). The BSDF data is stored in a .material file that is then assigned to a simple flat surface in the Photopia model so that rays interacting with the surface incur the same reaction as if the detailed texture geometry was included.

Physical Measurement Problem:

Textured materials need to be accurately represented in raytracing software in order to design effective optics, such as light guides and diffuser panels. Whether using the Material Lab simulation tool or measuring an actual material sample in a lab, the biggest challenge is how to characterize the behavior of light that is inside of a material and incident onto a textured surface at near grazing angles. This situation is common in light guides and edge-lit panels as light travels along the length of the optic at angles beyond the critical angle.

Take for example Evonik Acrylite Satinice 0F00 SC (P95) at 4.5 mm thickness, a typical diffuser sheet material. A graphic illustration is shown in Figure 1. One side of the material is smooth (which will be referred to as the entrance surface) (a) and the opposite side is textured (which will be referred to as the exit surface) (b) in order to provide diffusion. A collimated beam is directed onto the smooth entrance surface (c) and the distribution exiting from the textured surface (d) can then be measured to characterize the behavior of light interacting with the exiting surface. The collimated beam orientation can be varied to test a range of incidence angles (e), but the beam will refract upon entering (f), resulting in a smaller incidence angle onto the exiting surface. High angle incidence light beyond the critical angle onto the exiting surface (g) therefore cannot be measured in this way. In an application such as a light guide, a significant amount of light will be traveling through the medium at high incidence angles, so characterizing the properties of the textured surface is necessary.

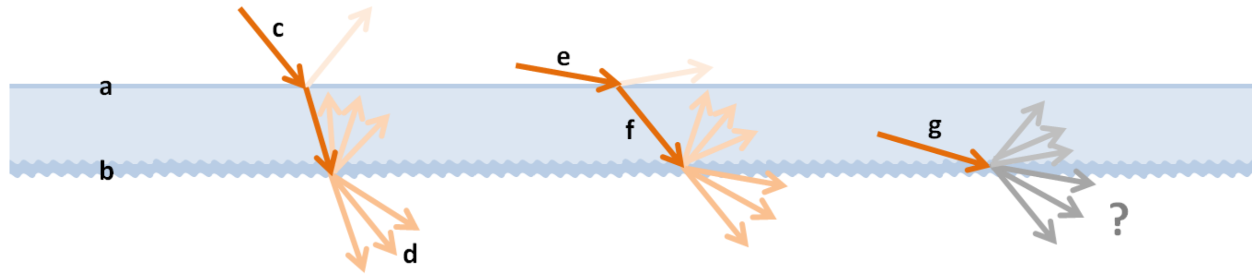

Figure 1: A graphic model of a material sample that is smooth on one surface (a) and textured on the other (b). Collimated light (c) is directed onto one surface and the resulting distribution out the other surface (d) can then be measured. The angle of the collimated beam can be varied (e) to test a range of incidence angles, but refraction upon entering the material (f) limits the range of angles incident onto the texture surface. This limitation prevents characterizing high incidence light onto the texture surface (g).

Directing the collimated beam onto the edge of the material can add to the range of angles incident onto the exiting surface (as shown in Figure 2), but this is less practical for a systematic measurement process of multiple materials. The material thickness would need to be thick enough to allow a collimated beam of finite size to be incident, but the material may not be readily available at a sufficiently large thickness. Also, the material sample would need to be carefully cut and polished to give a smooth entrance for the edge surface. These preparations may not generally be practical.

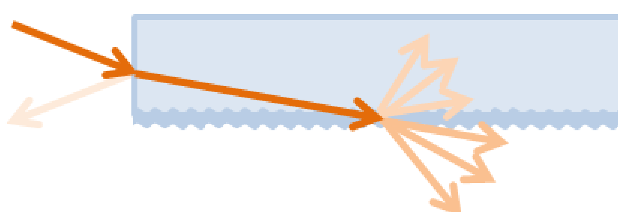

Figure 2: Directing the collimated beam onto the sample edge allows a higher range of incidence onto the textured surface, but the setup required for such measurements is less practical.

Directing the collimated beam onto a hemispherical entrance surface should allow the beam to enter the material at normal incidence without refraction and allow high incidence angles onto the exiting surface. This could be setup by adhering a hemispherical lens to the sample that is made of the same material as the sample, using an index-matching gel between the two parts, as shown in Figure 3.

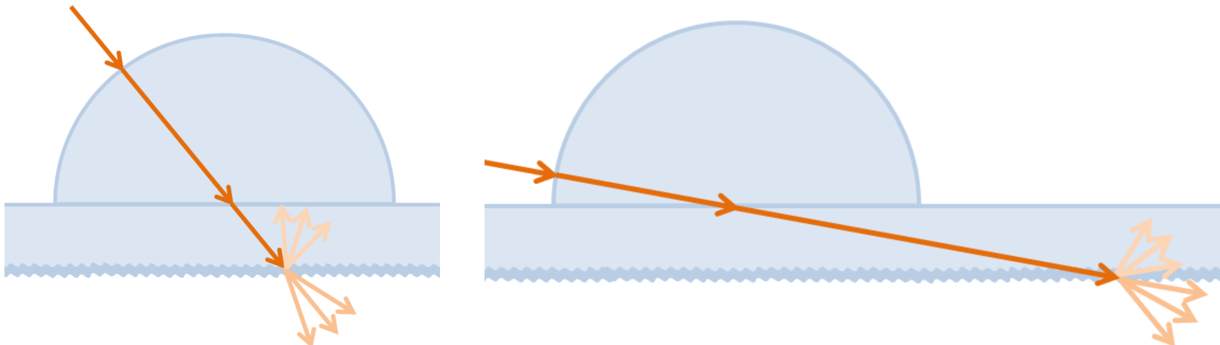

Figure 3: A hemispherical lens with index-matching gel between the lens and the material sample can theoretically allow a full range of incidence angles onto the textured surface.

However, in practice there will always be a finite size to the collimated beam cross section and the beam will therefore be incident onto the hemispherical surface from a range of incidence angles as illustrated in Figure 4. The converging rays of the collimated incident light will result in a measured scatter wider than it should be. The larger the hemisphere the less the effect, but a larger hemisphere also increases the difficulty of setting up such a sample configuration. There are also challenges in getting hemispheres made at all required indices along with the required range of index matching gels.

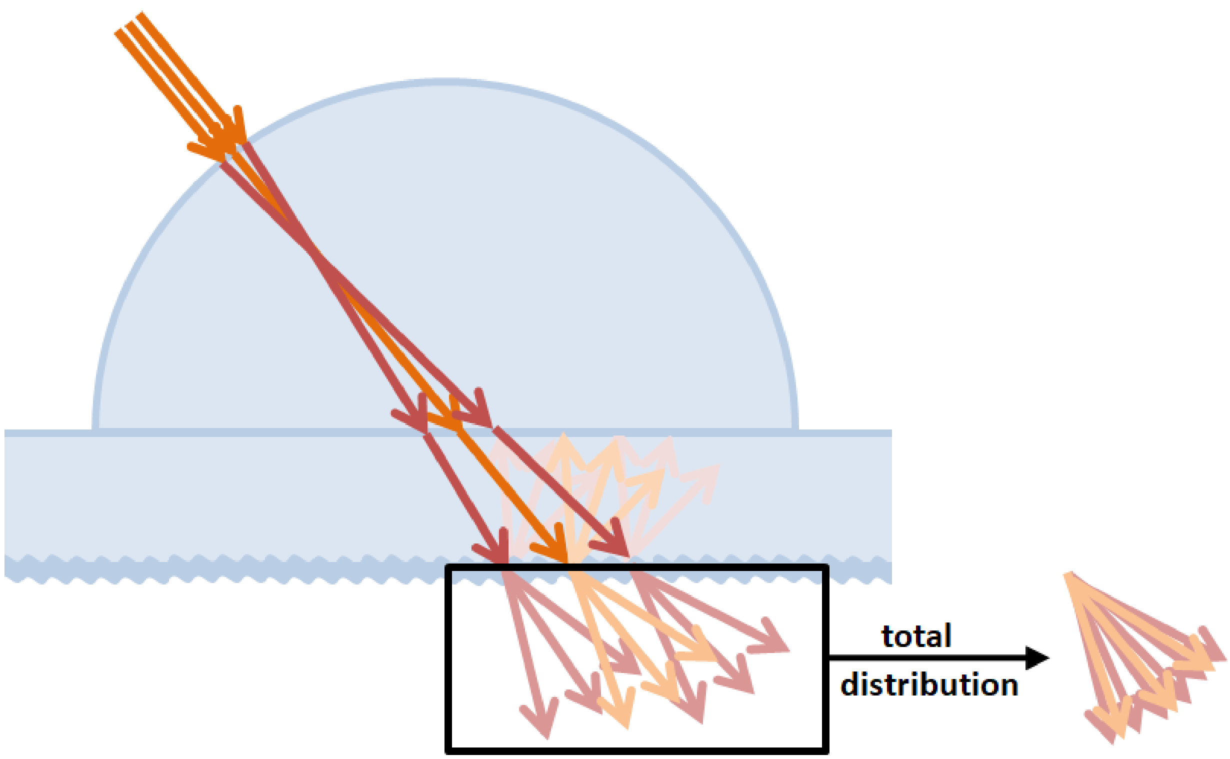

Figure 4: In practice, setting up a sample with a hemispherical lens of an appropriate size to mitigate the extra scatter caused by the range of angles onto the lens becomes quite difficult.

Software Solution:

Simulating the theoretical ideal measurement setup for a material sample allows the physical measurement challenges to be avoided. The Material Lab tool can be used to simulate any range of incidence angles onto the textured surface from both outside and inside the medium of the material. This solution is described through the following example.

Example Process:

In this example we apply this BSDF modeling process to Acrylite Satinice 0F00 SC (formerly P95), made by Rhoem USA. Figure 5 shows a photo of the material's magnified texture.

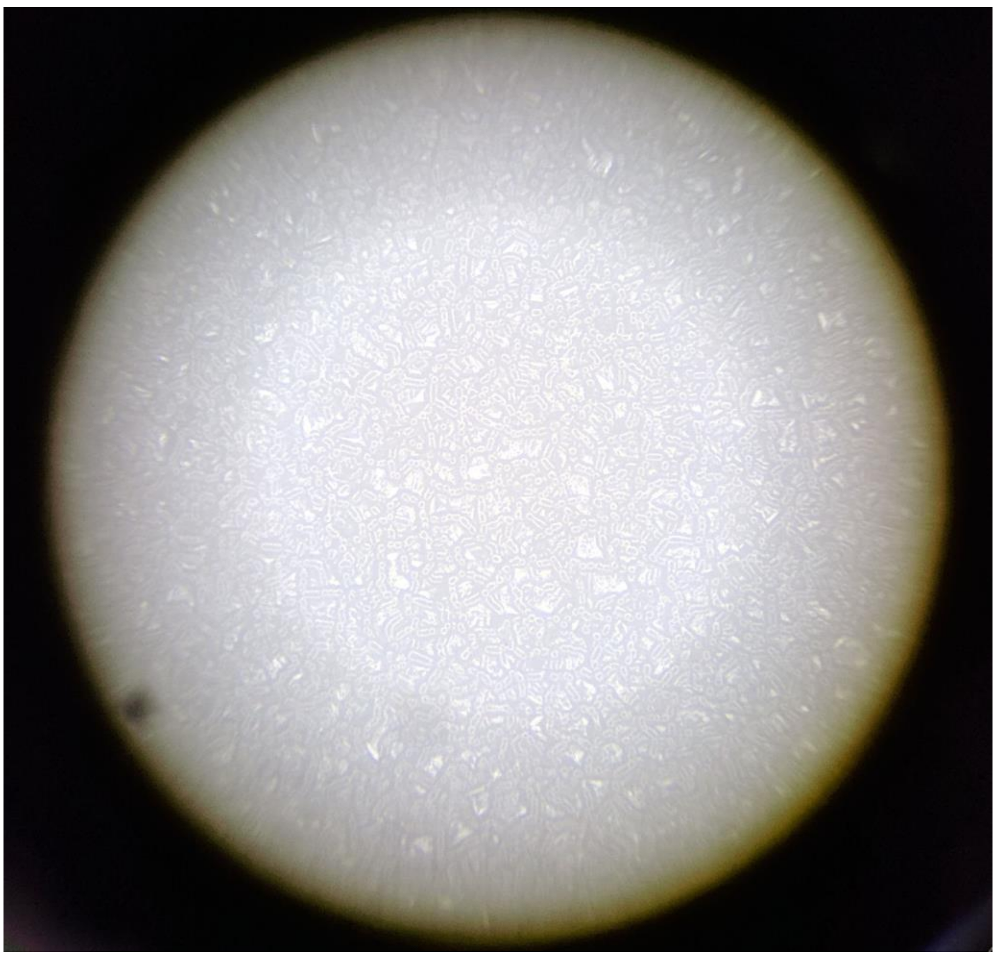

Figure 5: 400X magnification of the texture of Evonik Acrylite Satinice 0F00 SC

The detailed texture geometry was laser scanned and translated into CAD geometry. The geometry was then scaled by a factor of 15 to reduce any issues with CAD precision limits. A 12mm x 12mm section of the material was imported into Photopia, as shown in Figure 6. This size is large enough to include a representative sample of the variable texture features.

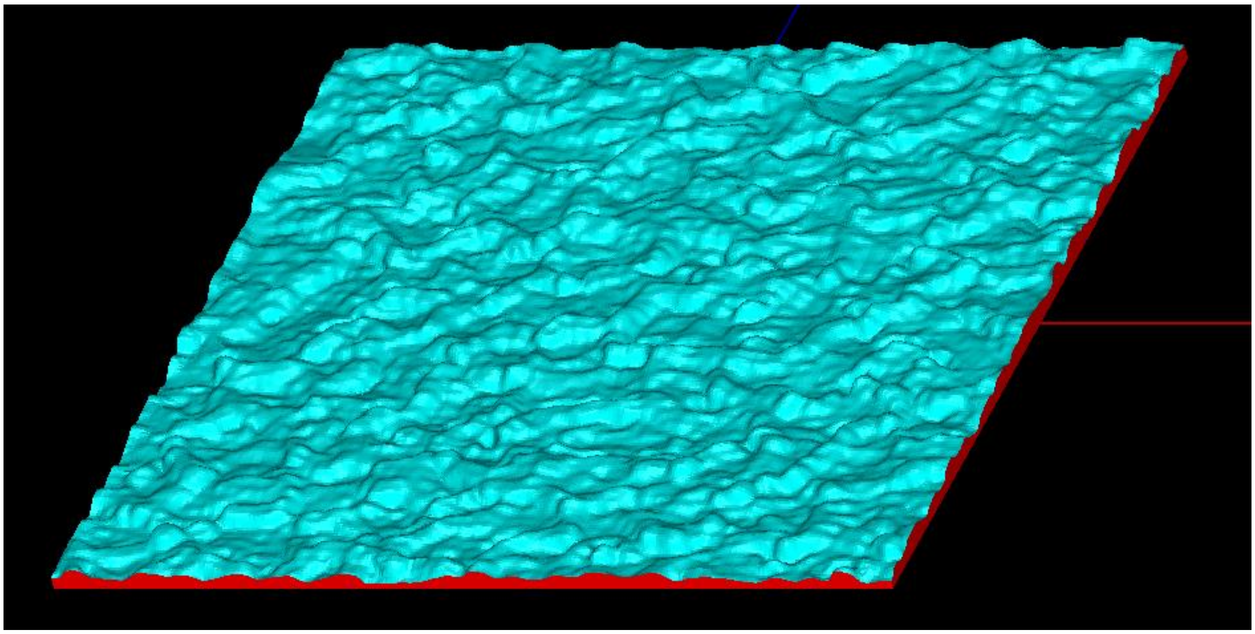

Figure 6: CAD representation of Evonik material sample, including texture detail

In order to properly setup the material geometry for the Material Lab tool, the sample geometry was oriented within world XY plane and centered around the world origin. The textured geometry was oriented towards the positive Z-axis. A flat side was added and oriented towards the negative Z-axis, and edge geometry in between the textured and flat sides was also included. These additional surfaces were added to the CAD model of the scanned surface. The total thickness of this geometry should be kept to a minimum. The minimum thickness is driven by the Z dimension range of the textured surface. Therefore, surfaces with deeper textured features should be made wider. We recommend making the aspect ratio of the model (width/thickness) 25 or greater. The reasoning for this will become clear later.

This P95 material is acrylic. However, special versions of acrylic material files were assigned to specific surfaces in order to model the desired conditions. Using these special material files allows a full range of incidence angles to be directly defined without the adjustment or limitations of refraction upon interaction with the flat surface.

1. A "no reaction" acrylic, the ACRYLIC1NR refractive material in the Photopia library, was assigned to the flat surface. This material allows rays to enter or exit a refractive medium without any change in direction or absorption loss, thus removing the optical effect of the flat surface from the simulated performance.

2. A “no loss” acrylic, the ACRYLIC1NL refractive material in the Photopia library, was assigned to the textured surface. This material ignores any bulk absorption effects since we want to isolate the geometric refraction effects of the textured surface. The bulk absorption losses of the acrylic will be accounted for in the actual light guide simulation of which this P95 material is a part, as rays travel inside the specific geometry of the light guide design.
3. A perfect absorber, the ZERO refractive material in the Photopia library, was assigned to the edge geometry between the textured and flat sides. This material absorbs all light interacting with it since we don’t want any artifacts from this edge surface in the CAD model to affect the BSDF data. We made the edges relatively thin compared to textured surface of interest in order to minimize light interacting with the edge surfaces.

The Material Lab tool was then run. During this automated process, a collimated light source is directed onto the material sample at a range of incidence angles, onto each side of the textured surface. The light incident from the +Z direction represents light from air onto the material. Light incident from the -Z direction represents light incident onto the textured surface from within acrylic. The resulting BSDF data due to the refraction of the textured surface at each incidence angle is written to a .material file produced by the Material Lab tool.

The .material was named P95 from Rhoem USA and added to the Photopia library as a refractive material. A simple light guide project was then created in Photopia (Figure 7) to show how this new material file is used. The light guide itself was 40mm x 40mm and 2mm thick, with 10 LEDs arrayed against each of two opposing edges and a WhiteOptics F23 backing included behind the light guide and on each side. The light guide model was represented by flat surface geometry only. Textured CAD is unnecessary for the overall model, since the behavior of the texture is stored in the .material file assigned to any flat surface.

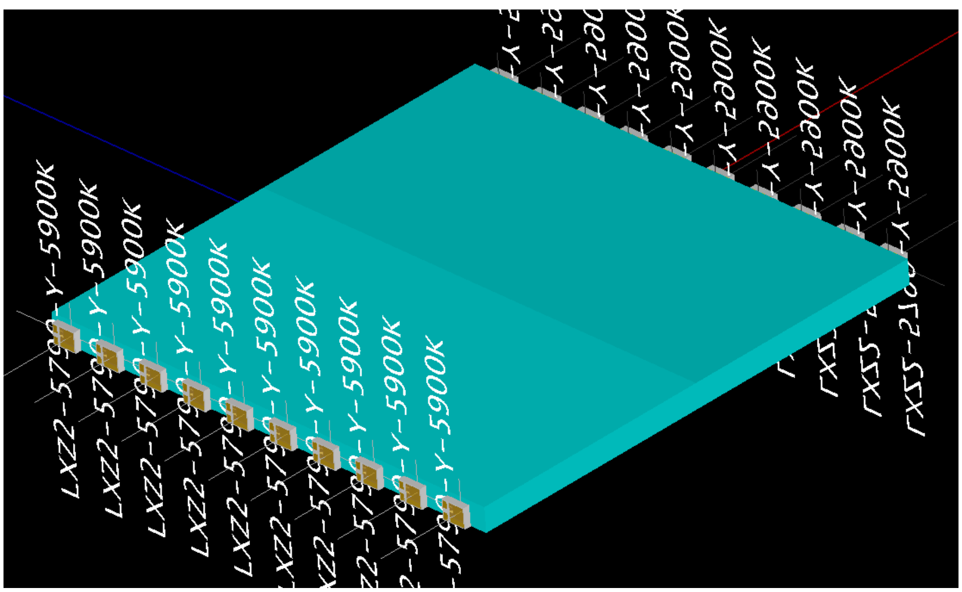

Figure 7: An example light guide was modeled in Photopia. The light guide geometry is shown in cyan, and there are 10 LEDs arrayed against each of two opposing edges. Not shown in this figure, a white backing was included behind the light guide and to each side.

The project was run three times using different material configurations for the light guide part: all clear acrylic, texturing just the exit surface, and texturing both large flat surfaces using the new material. Figure 8 shows the ray behavior in a cross-sectional view of the light guide entrance for each variation.

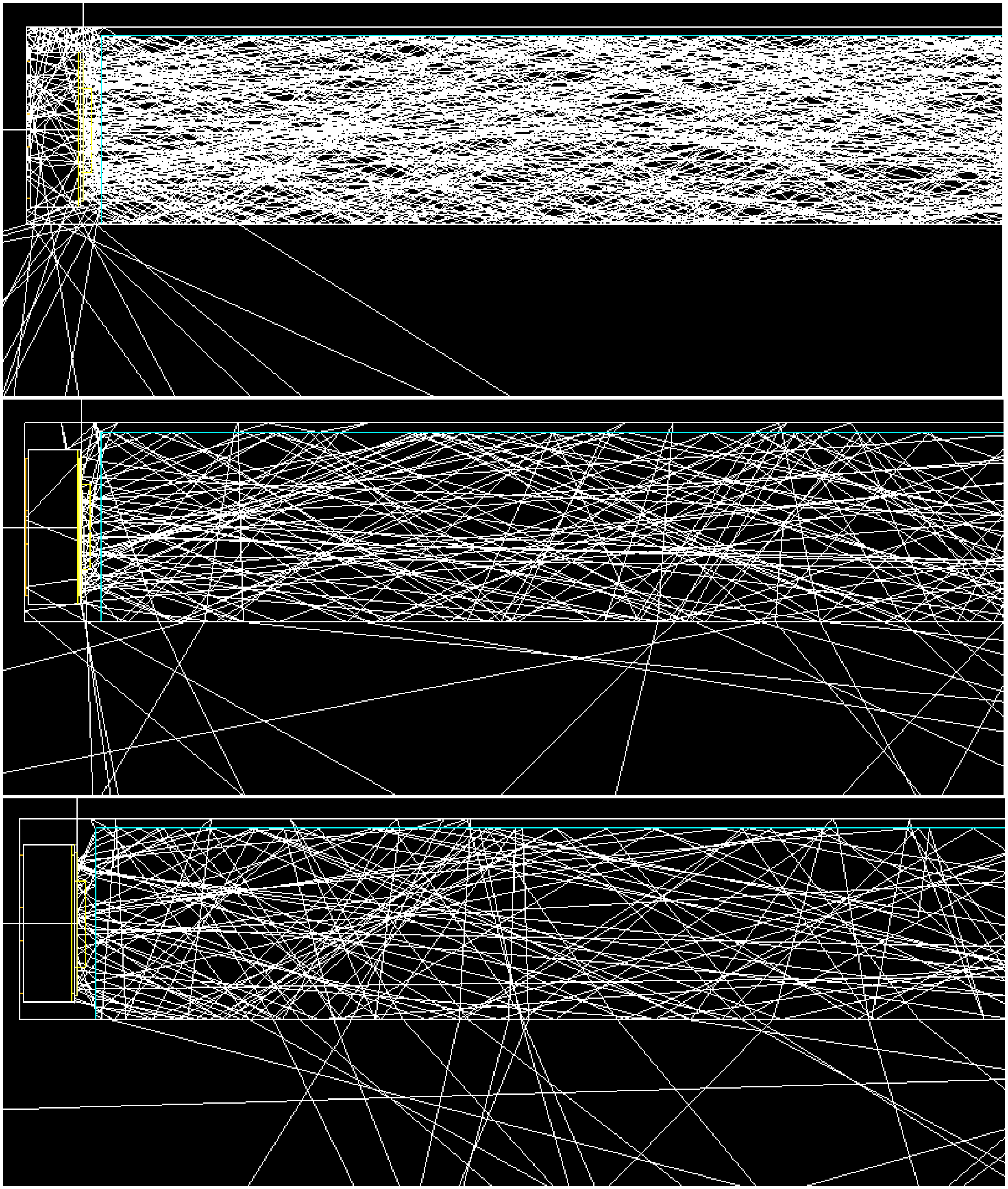

Figure 8: Sample ray geometry shown in a cross section view at the light guide entrance, for all clear surfaces (top), for the Evonik texture model on the exit surface (center), and for the Evonik texture model on both large surfaces (bottom). Increasing texture use causes more extraction near the entrance of the light guide.

An illuminance plane was included just outside of the exit surface to graphically illustrate the light emitted by the light guide. Figure 9 shows the illuminance plane results of the three variations. As expected, light is not extracted across most of the clear light guide surface, it is relatively evenly extracted from the single-side textured light guide, and it's extracted more quickly with the double-side texture, resulting in brighter regions closer to the LEDs.

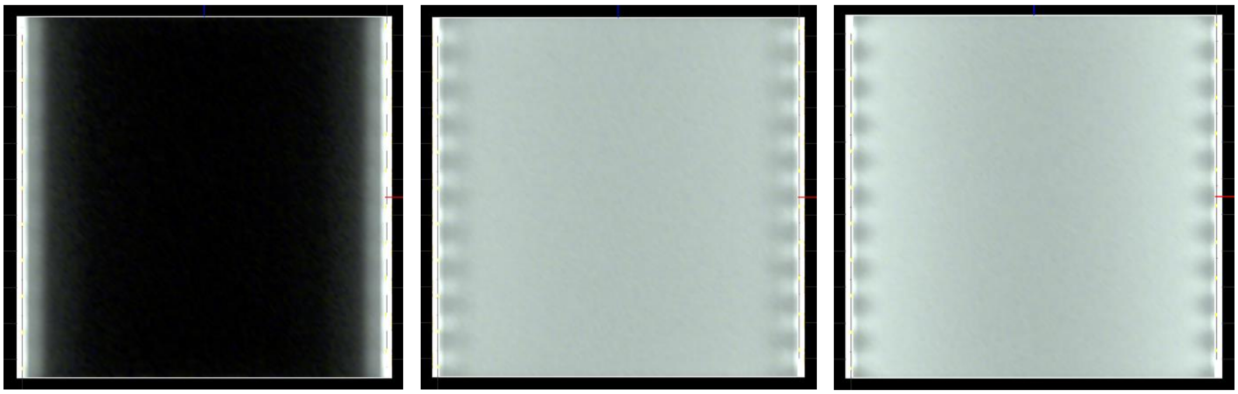

Figure 9: Illuminance plane results onto a plane just outside of the light guide's exit surface, for all clear surfaces (left), for the P95 texture model on the exit surface (center), and for the P95 texture model on both large surfaces (right).

Conclusion:

The process described allows complete BSDF data to be generated for textured or micro-structured surfaces used in light guide applications. This in-turn allows for quicker simulations of light guides without the need to directly model the micro-structed surface geometry. This is important as the quicker simulations mean more design iterations can be evaluated to obtain your desired performance. While more accurate simulations with full angle range BSDF data means the simulated results can be trusted. The more accurate the simulation results, the more likely your physical prototypes will perform as expected, reducing prototype iterations.