“The Importance of Accurately Modeling Light Scattering in Luminaire Design”

Dave Jacobsen, Senior Application Engineer,
Lambda Research Corporation, 25 Porter Rd. Littleton, MA USA

Abstract

The reflected and transmitted scattering of light in a luminaire can play a major role in the performance of the luminaire. Many times, this is the reason the actual luminaire performance does not match the results predicted in optical modeling, design, and analysis software. This paper, looks at some of the causes of light scattering in a luminaire, particularly scattering due to the surface roughness of reflectors. Modeling this scattered light is a key factor in obtaining accurate computer models and performance predictions during the design and development process. We will also look at how scatter is measured and how these measurements can be used to make accurate properties for use in the computer modeling phase of the design process.

1. What is Scattering?

Scattering is a general physical process where some forms of radiation, such as light, sound, or moving particles, are forced to deviate from a straight trajectory by one or more localized non-uniformities in the medium through which they pass. In conventional use, this also includes deviation of reflected radiation from the angle predicted by the law of reflection. Reflections that undergo scattering are often called *diffuse reflections* and unscattered reflections are called *specular* (mirror-like) reflections. [1] Scattering can vary as a function of wavelength, incident angle, and temperature.

In an ideal world, we could model everything as a perfectly specular mirror, a perfectly diffusing surface, a perfectly transmitting surface, or a perfectly absorbing surface. These options exist in software, but not in real life. Scattering can be a tool for the luminaire designer to use when designing a new luminaire. A key factor though is having accurate measurements of the surface and bulk media scattering and using them properly in optical design and analysis software.

In luminaire design, there are two types of scattering that can be of concern; surface scattering and bulk scattering. Surface scattering is scattering that occurs on the surface of an object. This can be reflected or transmitted scattering. Surface scattering is due to roughness or texturing applied to the surface of a material. This could be due to roughness from the manufacturing process for the material, such as machining or tool marks, or due to a texture applied to the surface by design. Surface scattering is found and used on optical elements such as reflectors, diffusers, backlight light extraction, light guide texturing, and many other applications. Lens surfaces also have scattering due to roughness and manufacturing defects such as scratches. Examples of surface scattering are coatings, paints, diffusers, polished surfaces, etc…Most of this paper will focus on surface scattering, how it is measured, and how it is modeled.

The second type of scattering is called bulk scattering. This is scattering inside of an object, typically by impurities, or by particles added to the material to induce scattering. Bulk scattering occurs in light guides where diffusing materials have been added to the plastic or glass, or by infusing air bubbles into the material, or with textured shapes in volume diffusers. Examples of bulk scattering include human tissue, fluids, opaque materials, etc…

2. Surface Scattering

As mentioned previously, surface scattering is scattering at the surface of an object or material. Many times, this is due to microroughness of the surface or from a texture pattern placed on the surface during manufacturing. Examples of microroughness surfaces are the reflective sheet materials available from manufacturers such as Alanod and Alcoa. These materials have different surface finishes, each producing a different scattering pattern. Machined surfaces can also have microroughness scattering due to tooling and machining marks left of the surface. Examples of surfaces with a pattern embossed or molded onto the surface include materials such as Alanod Miro 9, or the textured surfaces available from Mold-Tech.

The size and shape of the of the surface roughness will play a major role in how light is scattered from a surface. For example, a flat, polished surface will have a different scatter pattern than a surface with a triangular profile, or one with a rounded sine-like profile.

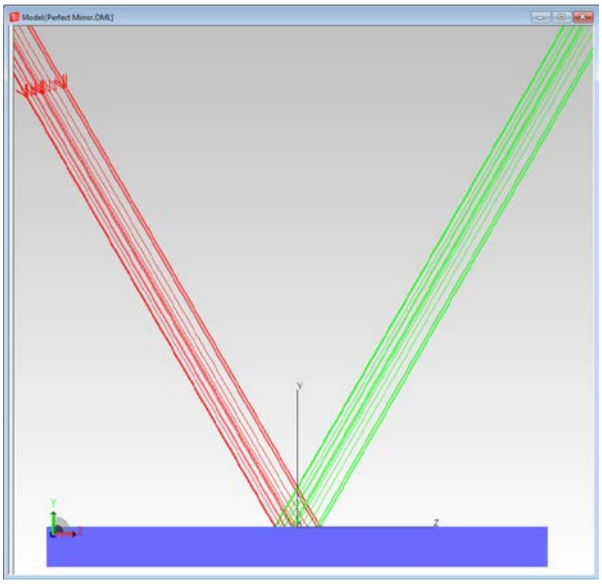

Figure 1: Reflections from perfectly specular surface

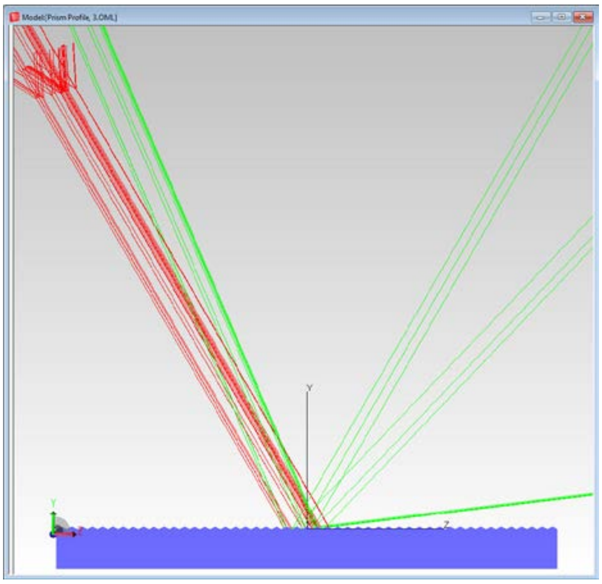

Figure 2: Reflections and scattering from surface with prismatic profile

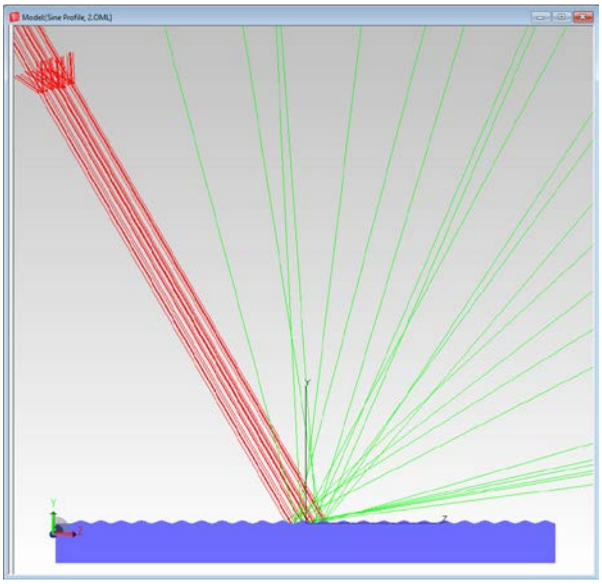

Figure 3: Reflections and scattering from a surface with a sine-like profile

Surface scattering is either isotropic or asymmetric. If the scattering is isotropic, the scatter profile does not change when the surface is rotated about its azimuth. If the scattering is asymmetric, the scatter changes as the surface is rotated about its azimuth. Many smooth surfaces are isotropic, or close to isotropic scattering surfaces. Surfaces with grain or structure may be asymmetric scattering surfaces.

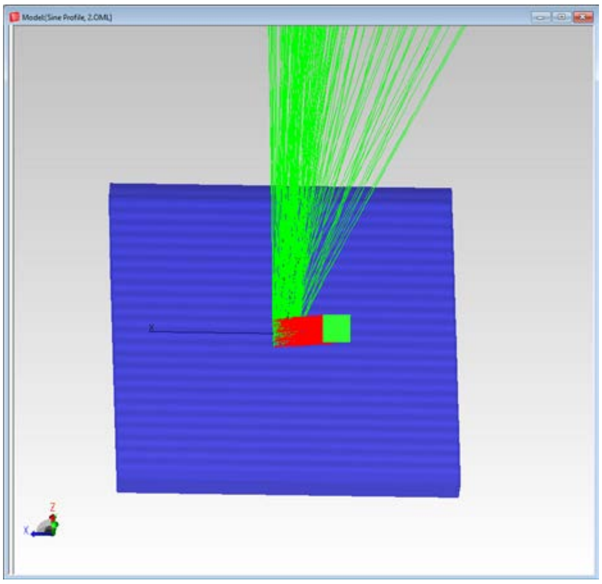

Figure 4: Reflections and scattering from an asymmetric scattering surface

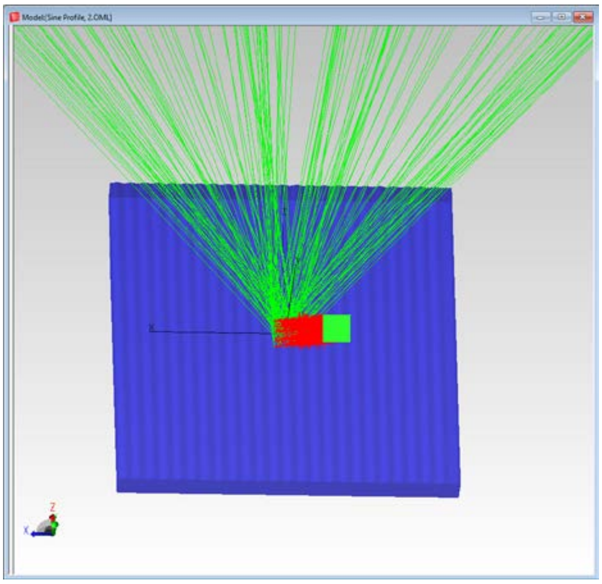

Figure 5: Reflections and scattering from an asymmetric scattering surface, surface rotated 90-degrees

The Harvey-Schack ABg model is a common scatter model in many optical design and analysis programs. This model is useful for isotropic scattering surfaces. The A, B, and g terms are used to fit the scatter curve to the measured scatter data. Other common scatter models include: Elliptical ABg, Elliptical Gaussian, Table BSDF, Asymmetric Table BSDF, and composite BSDF. Models such as the Asymmetric Table BSDF are used when the scatter is not isotropic, or asymmetric.

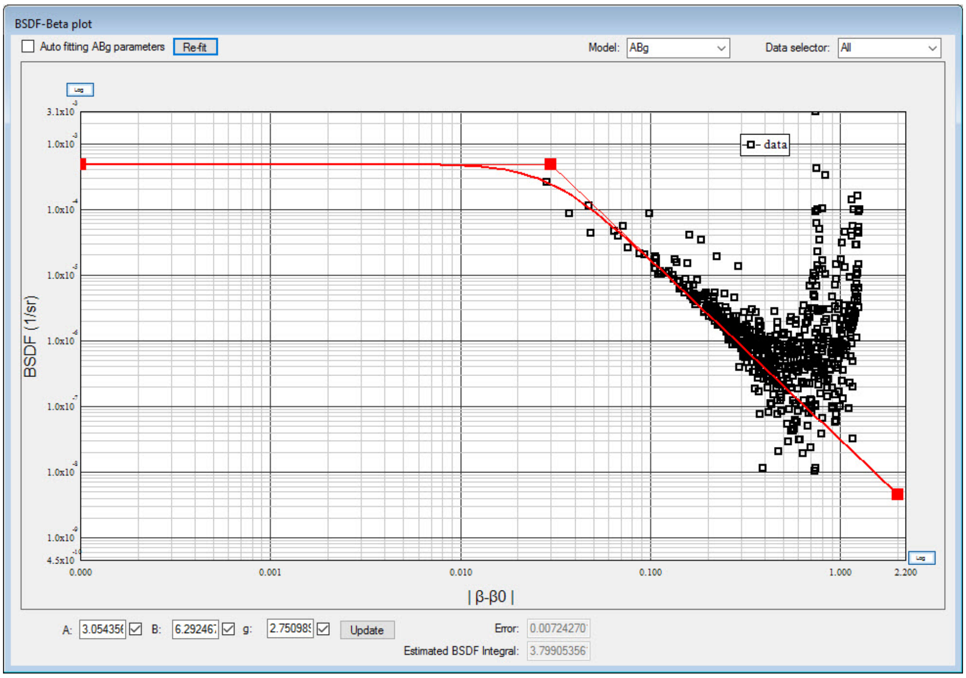

Figure 6: BSDF with fitted ABg curve for Alanod Miro 27 with a 15-degree incident angle

3. How is scatter measured

Scatter measurements are usually taken using a goniophotometer based instrument called a scatterometer. There are also other methods of taking scatter measurements.

To measure scatter, the sample is illuminated with a light source, typically collimated, or as close to collimated as possible. A detector is then rotated around the specular vector, either reflected or transmitter. This data is then plotted, typically on a log-log plot. This process is repeated for additional incident angles, azimuth angles, out of plane scans, and wavelengths. The resulting measured data makes up the BSDF, the bidirectional scatter distribution function. BSDF can be further broken down into BRDF, bidirectional reflectance distribution function, and BTDF, bidirectional transmittance distribution function. For transmission materials, such as diffusers, it is often best to have measurements for both BRDF and BTDF.

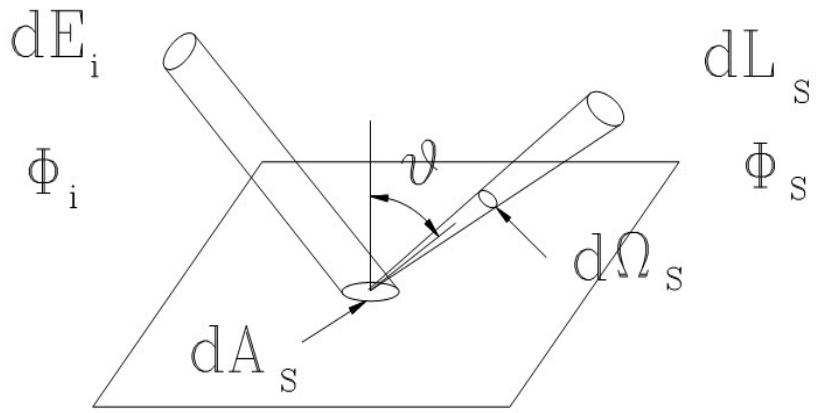

Figure 7: Schematic of typical BRDF scatter measurement

Figure 7 shows a typical reflected scatter measurement for BRDF where dL_s is the radiance scattered from an area dA_s on the sample, dE_s is the incident irradiance on the area dA_s, $\mathbf{r}_i$ is the incident direction, and $\mathbf{r}_s$ is the scattered direction. To measure the scatter, the area dA_s is illuminated, the solid angle $d\Omega_s$ subtended by the measuring detector is calculated, and then the incident flux Φ_i and scattered flux Φ_s is measured. The BRDF is then calculated using these values.

4. How is scatter data used in optical modeling

Measured BSDF data allows computer modeling software to accurately model the scatter during a raytrace. The more accurate the scatter measurements and resulting scatter models, the more likely the chance that the computer simulation will agree with the actual product produced. This accuracy and fidelity of the surface scattering model will allow for luminaires to be designed and evaluated in a virtual, software environment with a high degree of confidence that the simulation results will match the measured results when a prototype is produced and measured.

Depending on the material selected for a given application, its scattering characteristics can change the ultimate shape or profile of the luminaire. The following examples show three optimized designs. The goal was the same in each case. Only the reflector material was changed for each optimization. The materials used were Alanod Miro 2, Miro 5, and White Optics M16. In these examples, the optimization goal was a flat illumination pattern in the central 2/3 of the target area and a flux of 750 lumens. The LED used in the model was a Seoul Semiconductor Acrich2-13W. The following figures show the resulting reflector shapes and illumination patterns for each case.

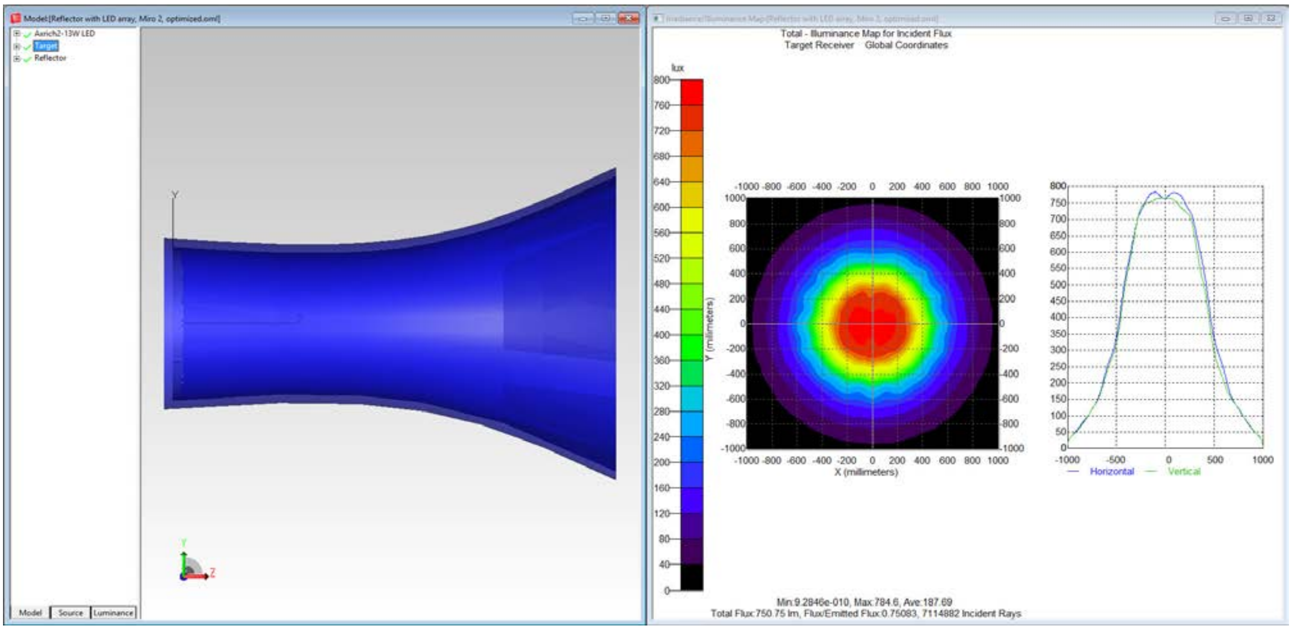

Figure 8: Optimized reflector design with Alanod Miro 2 material

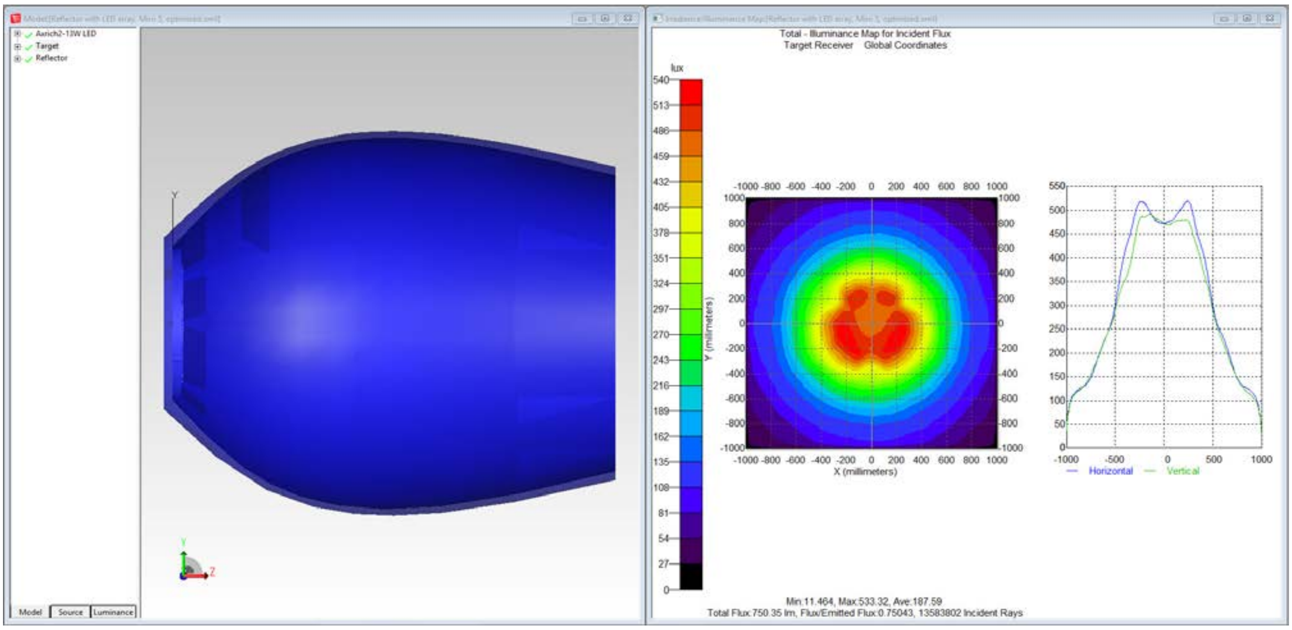

Figure 9: Optimized reflector design with Alanod Miro 5 material

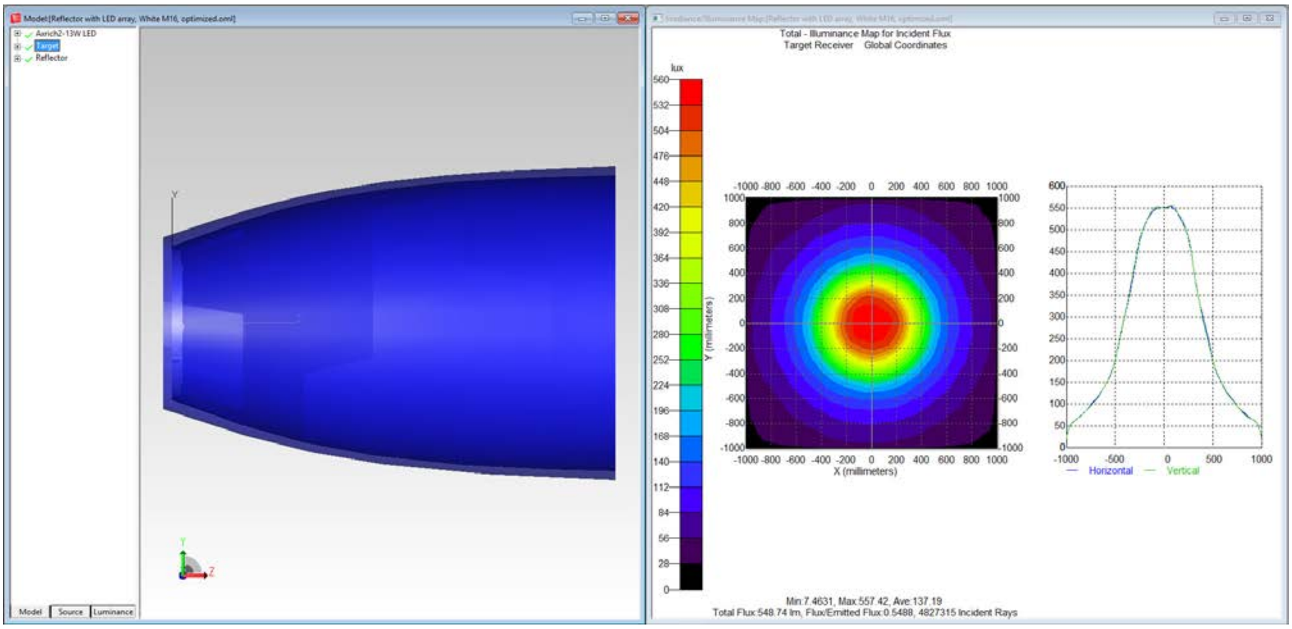

Figure 10: Optimized reflector design with White Optics M16 material

Note that the illumination pattern is similar in all 3 examples, but the reflector shapes are quite different. Only the designs using Miro 2 and Miro 5 met the goal of 750 lumens on the target surface. The example using White Optics M16 only achieved about 550 lumens on the target surface.

It is also possible to change the performance of a given luminaire by changing the material used. The different scattering properties of different materials will produce different illumination and angular distribution plots. The following figures show the results of applying 3 different materials to the same reflector design. The materials used were the same as used above, Miro 2, Miro 5, and M16. In this case the reflector shape did not change. The figures below show the Candela Plots, or angular intensity distribution of the results.

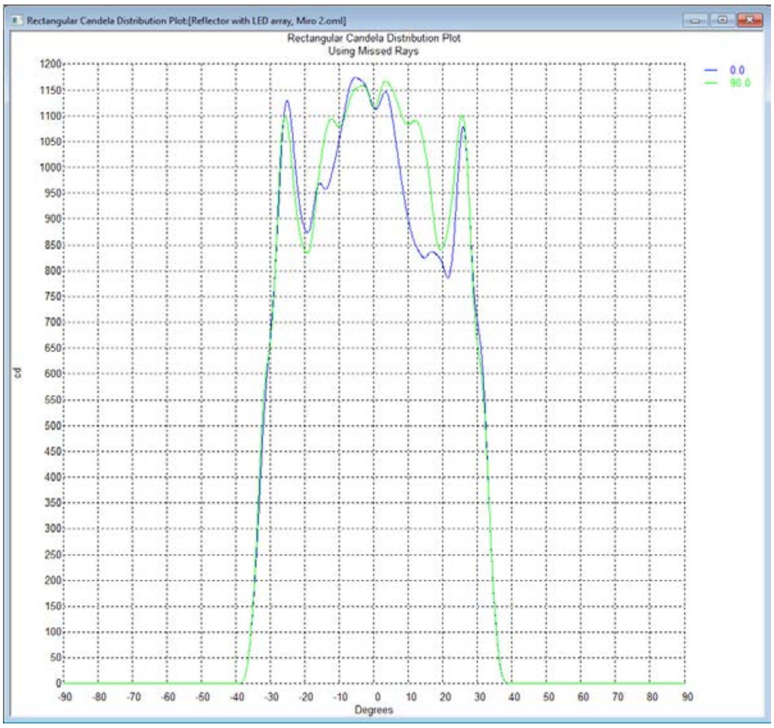

Figure 11: Reflector with Miro 2, Candela Plot

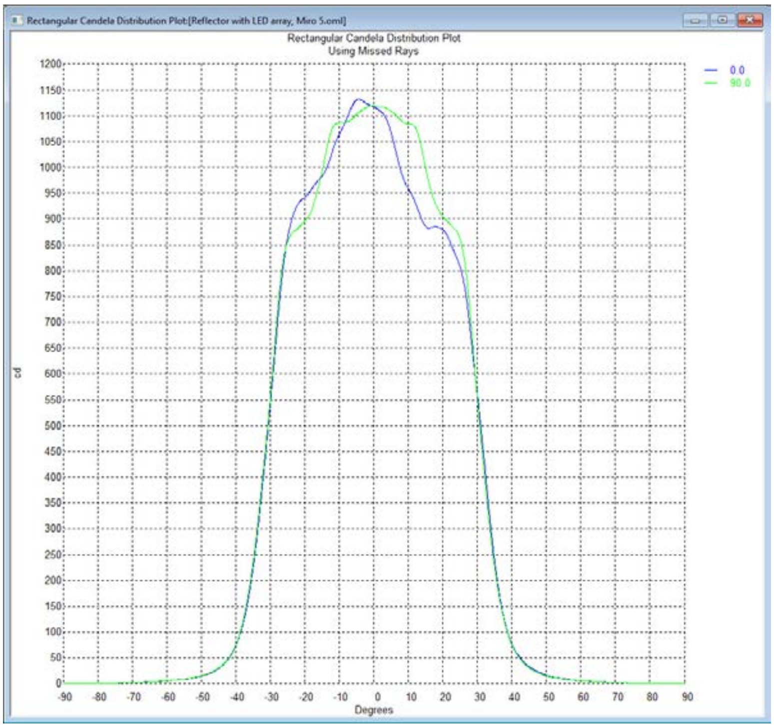

Figure 12: Same reflector as Figure 12, material changed to Miro 5, Candela Plot

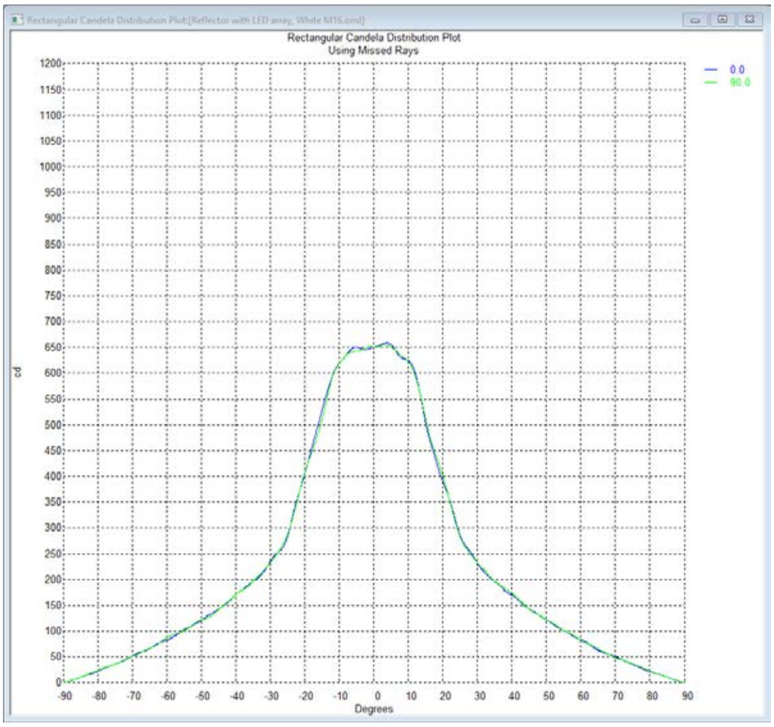

Figure 13: Same reflector as Figure 12, material changed to White Optics M16, Candela Plot

As can be seen in the figures above, changing the material without changing the reflector design can be a method to vary the resulting illumination, without re-designing the reflector. The more specular Miro 2 produces more variation or structure in the Candela Plot compared to Miro 5, which produces a smoother overall distribution. The more diffuse White Optics M16 shows a broader intensity, or beam pattern.

Optical diffusers, such as those used in front of LEDs can also be modeled using scatter properties.

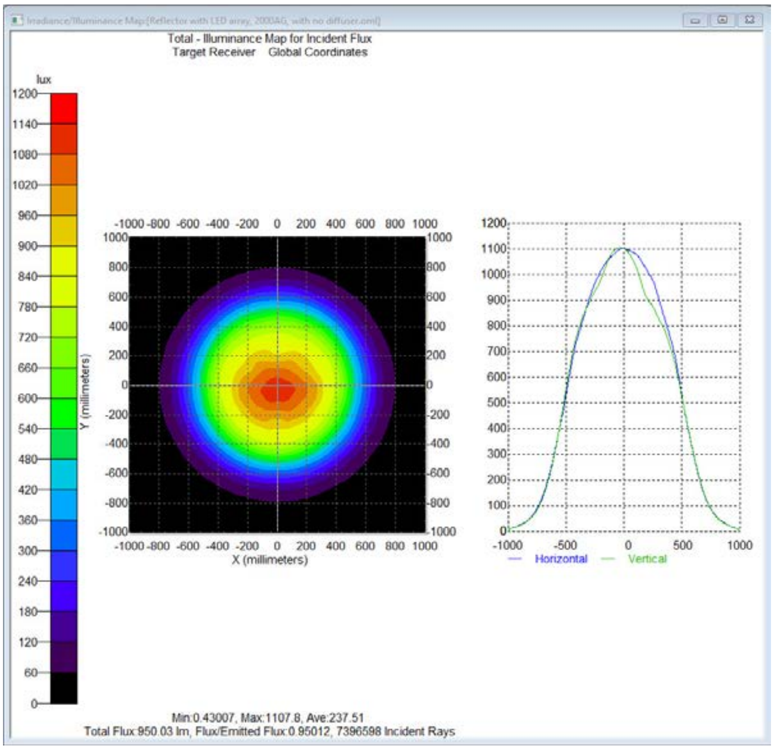

Figure 14: LED and reflector with no diffuser in front of the reflector

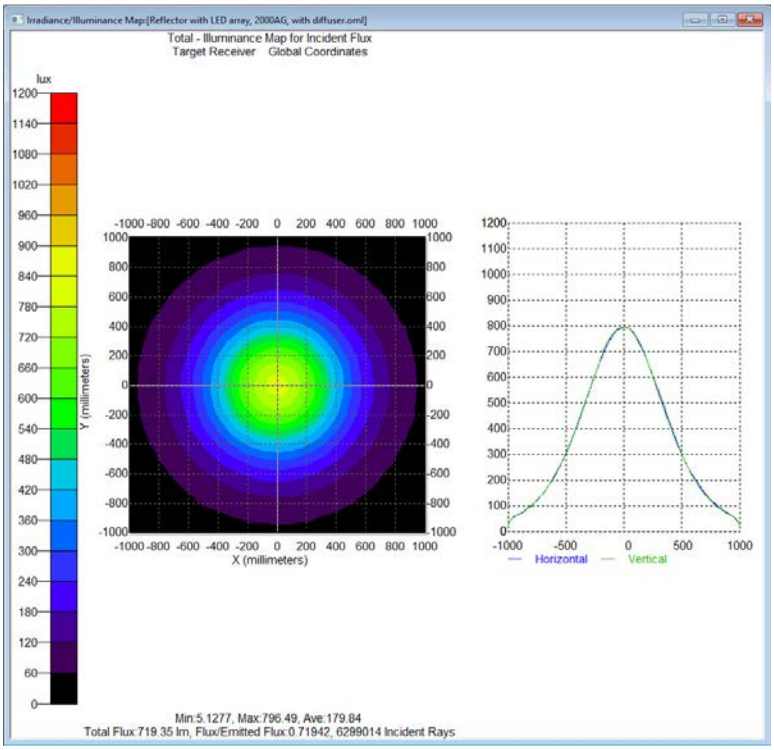

Figure 15: LED and reflector with Luminit 40-deg LSD in front of the reflector

Figures 14 and 15 show the illumination patterns for the same LED and reflector assembly. Figure 15 shows the change in the illumination pattern when a Luminit 40-deg LSD diffuser is placed in front of the reflector assemble.

5. Conclusions

The use of optical design and analysis software allows users to quickly and easily model different luminaire designs, using different materials. A key factor in this capability is the need for accurate scatter characterization of the materials selected and the proper use of that information in the optical software.

The ability to accurately model the scatter of different materials in the software environment also gives the luminaire design another tool to use when designing new luminaires and fixtures. The shape of the luminaire can be changed to use a particular material, or the material can be changed to produce different results from a single design.

6. References

[1] Wikipedia definition of Scattering