Scattering Analysis Using BSDF Data and Importance Sampling

LightTools® provides several ways of using measured BSDF data and the ability to direct the scatter from a particular surface towards an aperture. These options are important when performing many types of scattering analysis, such as stray-light analysis. This paper will describe the process of performing a typical stray-light analysis in *LightTools*.

Scatter Models

There are several models in *LightTools* that can be used to model the scattering characteristics of a surface. Scattering models will split an incident ray into one or more transmitted or reflected (or both) rays, and assign the directions and amplitudes of the scattered rays according to a mathematical formula. Most scatter models can operate in shift-invariant mode, which means their scattered energy distributions are a function of the shift-invariant scatter angle θ_d, which is defined as

$$\theta_d = \sin^{-1}\left(\left|\sin(\theta_i) - \sin(\theta_s)\right|\right)$$

where θ_i is the angle of incidence from the surface normal and θ_s is the scatter angle. Shift-invariance implies that the shape of the scattered energy distribution does not change in direction-cosine space with angle of incidence, and is the result of treating the scattering surface as a linear superposition of diffraction gratings[1]. Reciprocity is also preserved when a scatterer is shift invariant.

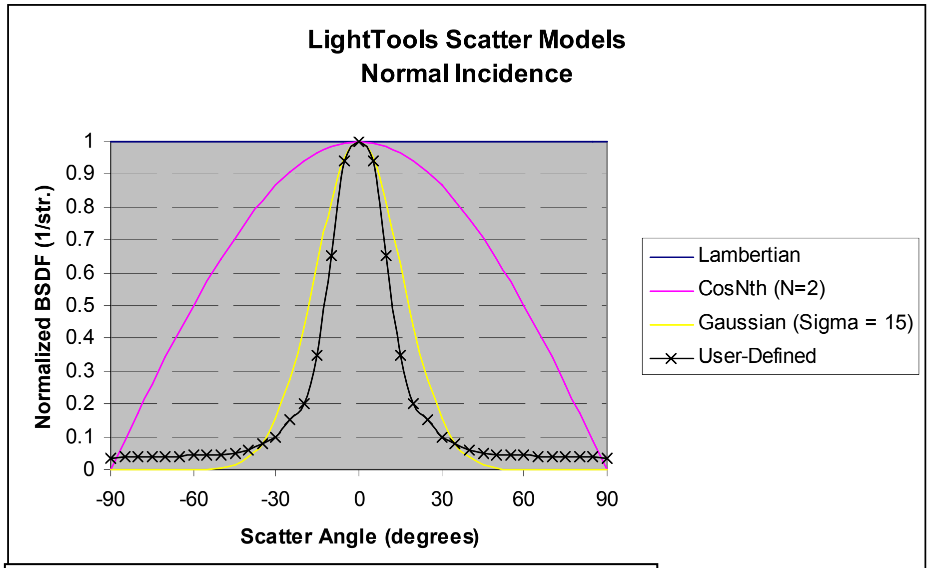

Figure 1. Examples of scatter model profiles in LightTools

The choices of scattering models in *LightTools* are:

Lambertian: A model of a perfectly diffuse surface.

$$BSDF(\theta_s) = \text{constant}$$

CosNth: A general-purpose scattering model.

$$BSDF(\theta_d) = \cos^N(\theta_d)$$

Gaussian: A general-purpose scattering model.

$$BSDF(\theta_d) = \exp\left[-\frac{\theta_d^{\,2}}{2\sigma^2}\right]$$

where σ is the standard deviation of the gaussian energy distribution.

Elliptical Gaussian: A general-purpose scattering model which can be used to model surfaces with anisotropic scattering distributions, such as brushed metal surfaces and light shaping diffusers.

$$BSDF(\theta_d, \phi) = \exp\left[-\frac{\theta_d^{\,2}}{2}\left(\frac{\cos^2\phi}{\sigma_x^{\,2}} + \frac{\sin^2\phi}{\sigma_y^{\,2}}\right)\right]$$

where ϕ is the azimuthal scattering angle, and σ_x and σ_y are the standard deviations of the gaussian energy distribution along the surface x and y axes, respectively.

User-defined: Uses measured BSDF data directly to define the model. Linear interpolation is performed between adjacent data points.

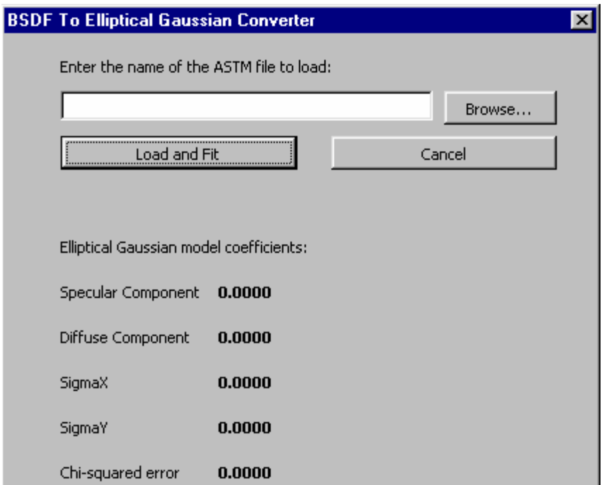

Figure 2. Dialog box interface for the Excel BSDF Macro

Figure 1 shows the plotted profiles of some of the built-in scattering types in *LightTools*. The Elliptical Gaussian is similar to the Gaussian model, except that different σ values can be specified along each of the axes of the surface X-Y coordinate system.

Modeling a scattering surface in *LightTools* based on measured BSDF data always involves fitting the data to one of the above scattering models. The simplest way to do this is to use the User-Defined scatter model. The measured BSDF data can be used directly to create the model, and the program will then interpolate by performing a linear fit between adjacent data points. This method works best when you have a lot of data points, and can only be used if the distribution of scattered energy is isotropic; that is, if the energy distribution does not vary as a function of the azimuthal scattering angle.

Measured BSDF data can also be fit to any of the other scatter models. A macro has been written in Microsoft Excel to read in a BSDF data file and fit it to the *LightTools* Elliptical Gaussian scatter model. The macro is available on our website, www.opticalres.com. This model is very general and can be fit well to typical scatter distributions. In addition, the Elliptical Gaussian model is anisotropic, so it can be used to model scattering from such surfaces as a brushed-metal surface, which can have a scattering distribution function that varies with both the elevation scatter angle θ and the azimuth scatter angle ϕ. The Excel macro is executed using the dialog box shown in Figure 2. This dialog box takes as input the name of the file that contains the BSDF data. The macro accepts BSDF data files in ASTM format, which is a standard format used for reporting BSDF data [2]. Once the data is read in from the file, Excel will fit the data to the Elliptical Gaussian function, and the best-fit coefficients will be displayed in the dialog box. These coefficients can then be used to define a scattering surface in *LightTools*. A measure of the error of the fit (Chi-squared) is also displayed, which is equal to the sum of the squares of the differences between the BSDF values of the input data and the BSDF values of the fitted model.

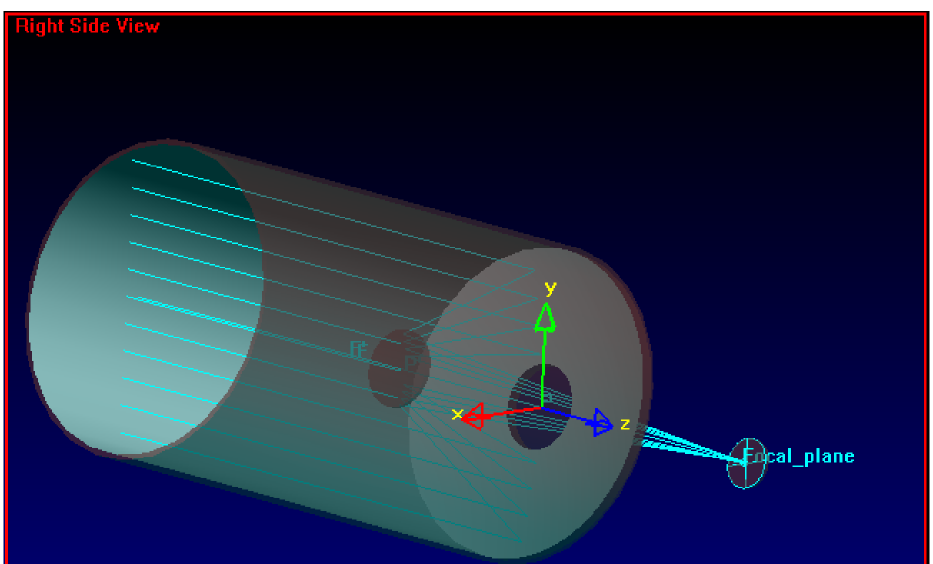

Figure 3. Cassegrain imaging systems with housing. Paraxial rays are shown. The inside of the housing barrel and the inside of the hole in the primary mirror are scattering surfaces.

Stray-Light Analysis

Once the scattering surface has been defined in *LightTools* using the measured BSDF data, a stray-light analysis of the system can be performed using the *LightTools* Illumination Module. Figure 3 illustrates a Cassegrain imaging system with housing surrounding a primary and secondary mirror. A classical stray-light problem occurs when collimated light from the sun hits the inside of the housing and scatters directly to the focal plane. This light is unwanted, and may have a serious impact on the performance of the system. We would like to quantify the amount and distribution of this light, and, if possible, to design a baffle to block it. To perform this analysis, we would first need to measure the BSDF of the housing surface and define a *LightTools* scatter model of it. Next, we would like to efficiently quantify the amount of light in the scatter path. Since we already know the path we wish to investigate, we don't want to trace rays from the source or the scatterer in all directions - we would like to illuminate only the inside of the housing, and trace only those scattered rays which are directed towards the focal plane. We can do this in *LightTools* using aim areas, which are a form of importance sampling. Aim areas are circular or rectangular near-field apertures that can be defined for sources and scattering surfaces and allow the user to direct radiation. In this analysis, we use a point source with an aim area to simulate off-axis solar radiation. The source is located a large distance away from the input aperture, and has an aim area that directs light at an angle of 20° to the z-axis into the input aperture of the housing. Because the source is far away, it is not seen in Figure 3. The source output power is 878.6 Watts, which is the amount of wattage in the visible band (400 nm-700 nm) for the solar blackbody (@ 6000° K). The scattering properties of the housing are based on BSDF measurements of anodized aluminum at 633 nm. The housing also has an aim area, which coincides with the focal plane of the system.

Figure 4 illustrates a ray coming in from the source and scattering off of the housing to the focal plane. Note that some of the rays strike the primary mirror and don't propagate to the focal plane. Since we are not interested in these rays right now, we have chosen to terminate them at the primary.

We can run an illumination simulation to determine the amount and distribution of light on the focal plane due to this scatter path. Note that the magnitude of some of the scattered rays reaching the focal is very low – for this reason, it is important to lower the minimum power threshold of the raytrace to a suitable level to avoid terminating rays prematurely. Figure 5 illustrates the result of this simulation.

We can look at the magnitude of the radiation in Figure 5 and decide if we need to block these rays. There are a variety of ways to do this – we could shorten the housing around the primary, increase its diameter, add a baffle vane to the inside of the housing, or make the hole in the primary smaller.

Sometimes, we may be interested in investigating a more complicated scatter path, such as a double-bounce path. Such a path occurs when incident light scatters off one surface, then another, then hits the focal plane. Light undergoing scattering from more than one surface is usually very dim, but can be a problem for sensitive systems. For instance, in

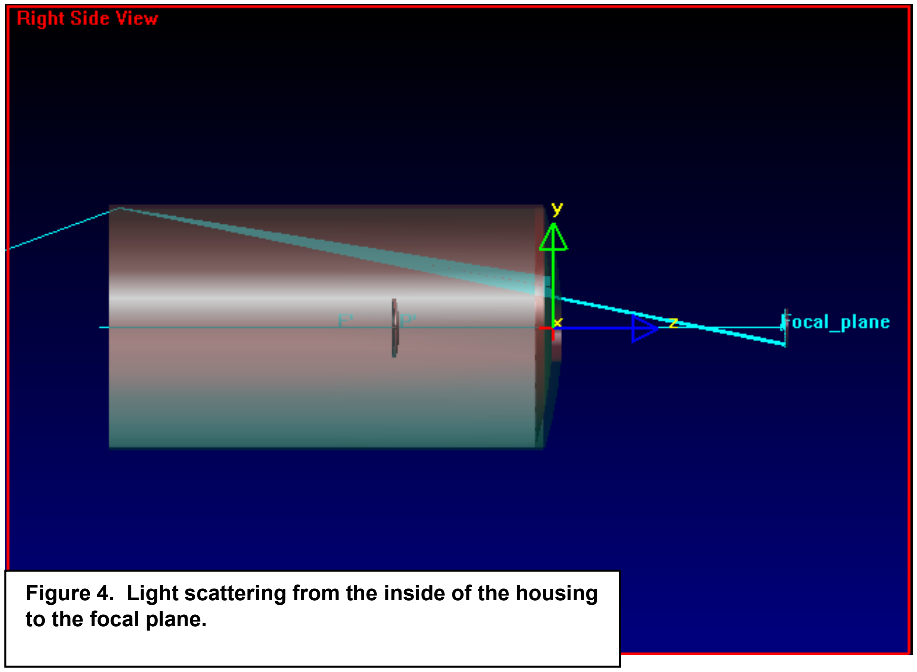

Figure 4. Light scattering from the inside of the housing to the focal plane.

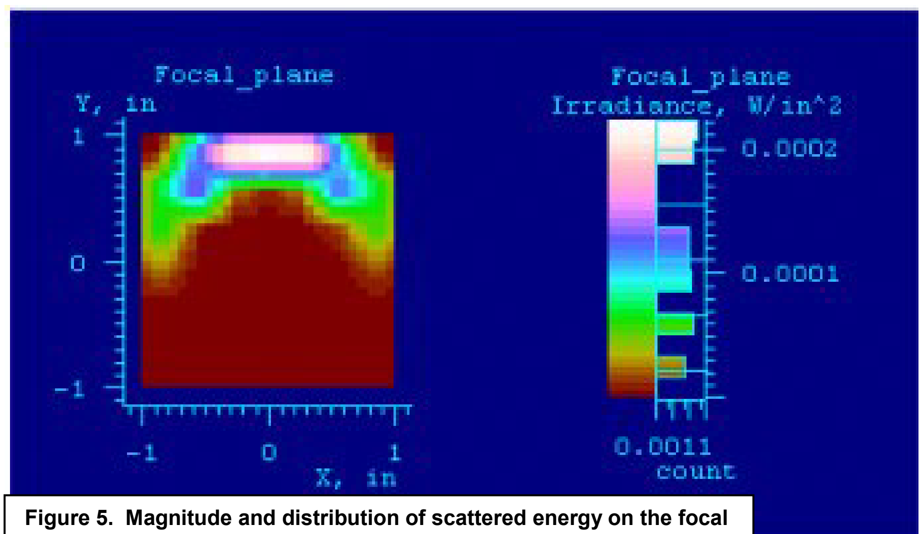

Figure 5. Magnitude and distribution of scattered energy on the focal plane due to the scatter path shown in Figure 4.

our Cassegrain system, we may be worried about scattered light from the housing hitting the inside of the hole in the primary mirror and scattering to the focal plane. In this case, we can use one aim area to direct the scattered rays from the housing to the hole in the primary, and another to direct rays from the hole in the primary to the focal plane. Rays undergoing this path are illustrated in Figure 6, and the resulting energy distribution on the focal plane is shown in Figure 7.

Conclusions

LightTools provides a variety of scatter models and ray-aiming capabilities that can be used to perform detailed scattering and stray-light analyses.

References

[1] "Light-Scattering Characteristics of Optical Surfaces" by James E. Harvey, Ph.D. Dissertation, University of Arizona, 1976.

[2] "Standard Practice for Angle Resolved Optical Scatter Measurements on Specular or Diffuse Surfaces", American Society for Testing and Materials Ref. No. E1392-96, 1999.

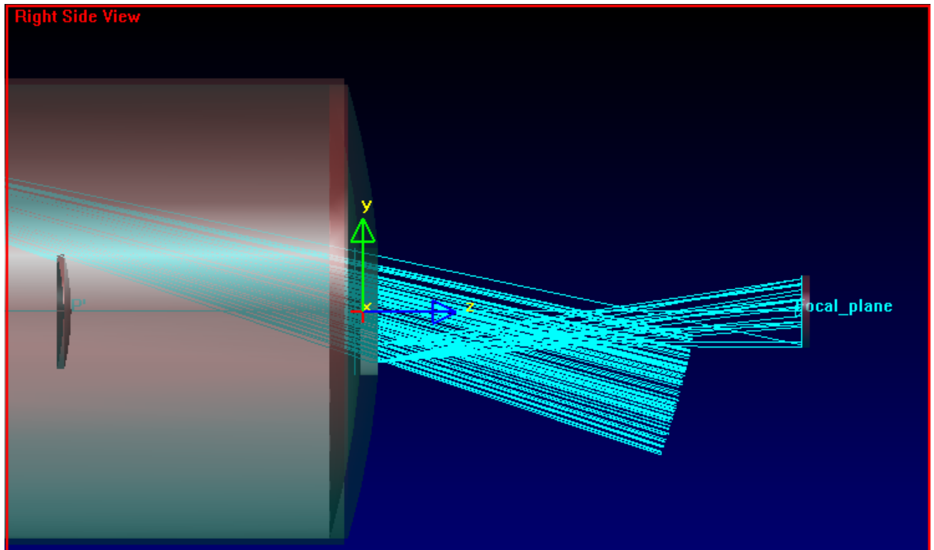

Figure 7. Magnitude and distribution of scattered energy on the focal plane due to the scatter path shown in figure 6.

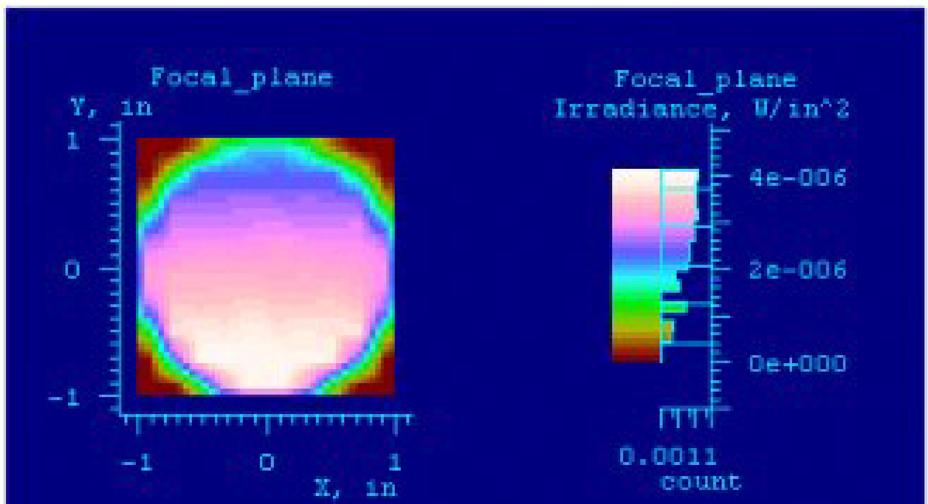

Figure 6. Double-bounce scatter path from the inside of the housing barrel to the inside of the hole in the primary mirror to the focal plane.

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