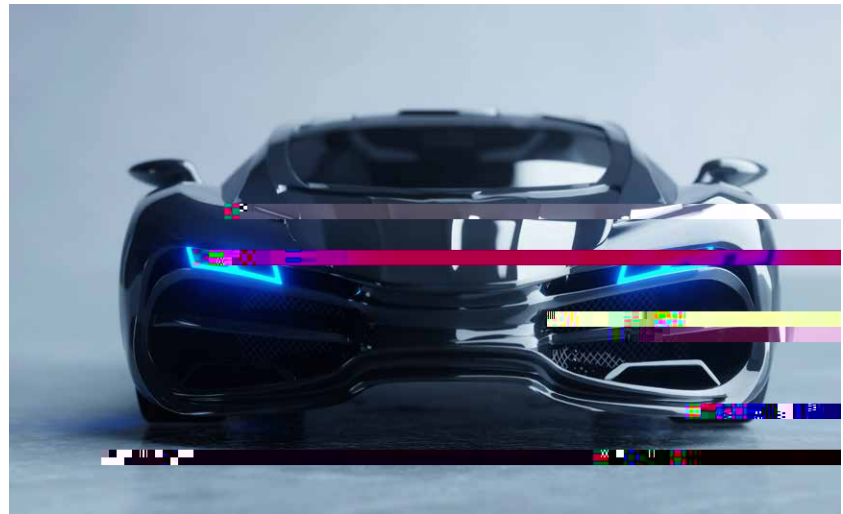


Abstract

LucidShape accurately simulates how light interacts with a surface using surface materials that define interactions in terms of reflection, transmission, absorption and scattering. Because all surfaces scatter light to some degree, surface materials also provide a way to specify a scattering distribution, which is necessary to achieve the most accurate optical simulations.

Surfaces in LucidShape can be of specular (i.e., ideal) quality with no scattering, or you can assign to them any of the available scattering material properties -- Gaussian or Lambertian scattering, user-defined scattering with a table of measured values, scattering based on a 2D scatter curve, and many more.



On a simple, ideal reflective surface (i.e., a polished surface with no scatter), the outgoing ray follows the specular path predicted by the law of reflection; the law of reflection calculates the propagation angle of any outgoing ray hitting the ideal surface from the incoming ray's angle byterials also



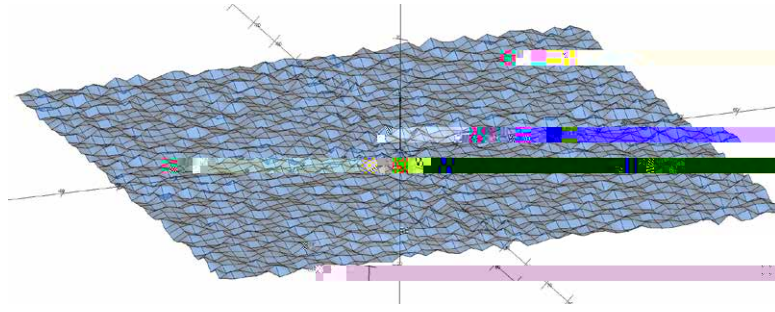


Figure 1: Rough texture with a random surface profile (with triangle mesh approximation)

Light scattering models for surfaces that do not obey the law of reflection require additional input to change the propagation direction for scattering or diffuse surfaces. There are multiple ways to treat this aspect of scattering in simulation software. One way is to define a classic analytical scattering model to calculate light spread, such as a Gaussian or Lambertian scattering model. Gaussian scatter is glossy and depends on the angle of incidence (for example, a sand-blasted metal surface). Lambertian scatter is purely diffuse and does not depend on the angle of incidence (for example, white paper). Another way to define scattering is with a bidirectional scattering distribution function (BSDF), which calculates an outgoing ray from an incoming ray directly, according to a defined function of a measured data set (i.e., a look-up table).

Scattering based on a 2D scatter curve has a rotationally symmetric distribution that calculates reflected or refracted rays for any incident ray angle, and its scatter distribution is calculated by means of a surface-normal perturbation method. This can be described as a statistical, single-interaction, micro-facet surface model using a statistically randomized normal distribution to set the surface normal at any micro-facet. A ray incident on the micro-facet uses the local surface normal to calculate the reflection and refraction angles. This paper explains the principles of the 2D scatter curve method and shows that the required surface normal distribution curve can be calculated from in-plane light scatter measurements with the help of the LucidShape BSDF Wizard. It also describes how to apply the surface normal distribution curve by assigning the 2D scatter curve material.

Surface Roughness and the 2D Scatter Curve Model

The LucidShape 2D scatter curve surface material is a surface-normal perturbation model (surface normal scattering) when the curve is a function of theta angle. With a surface-normal perturbation model, the outgoing ray is not changed directly; instead, the surface normal is "scattered" or randomized to represent a rough surface (see Figures 2 and 3). The law of reflection is used in this type of scatter, but the surface topology of the geometric object is changed for ray tracing purposes according to the specified type of roughness; this means that it is not the geometric surface normal, but the perturbed normal that is used to define the angles of incoming and outgoing rays (see Figure 2 for reference).

A surface-normal perturbation model deals with the variation of the surface normal (or the slopes) instead of the direction of the outgoing light. The surface-normal distribution is assumed to be Gaussian in the case of the LucidShape Gauss Reflector material, but can use any physically meaningful curve in the 2D scatter curve material. For the 2D scatter curve surface material:

- The curve must have a Y value of zero at the X coordinate.
- The curve must be a single curve and must be closed.

Figure 2 illustrates the difference between reflection on an ideal surface and reflection on a scattering surface when using any direct light scatter model such as a BSDF data set. The outgoing ray angle depends on the incoming angle and the surface normal of the geometry.

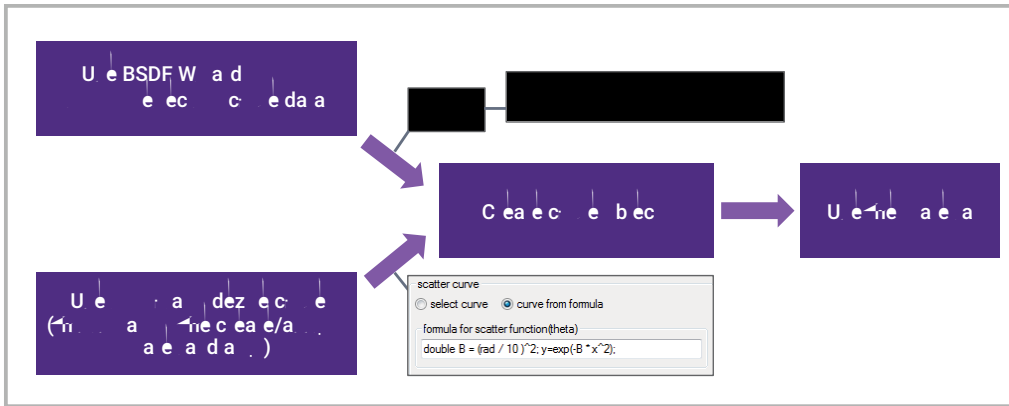


Figure 4: Simplified workflow diagram for the creation of a 2D scatter curve material in LucidShape

The most common method to characterize surface roughness for lighting purposes is to measure light scattering directly. The resulting data can be used to create a formula for use in a light scatter perturbation BSDF model. The LucidShape 2D scatter curve model in theta mode uses the surface-normal perturbation curve. For single-interaction surface reflection, knowing the angle of the reflected ray and the angle of incidence allows us to calculate the surface slope for a specific pair of rays (in, out). This means that for surface scatter dominated by first-order reflection (a single-reflection event, not a multiple-reflection event), we may assume that the surface-normal distribution curve can be obtained from the average light spread curve directly. This is exactly what the LucidShape BSDF Wizard does.

It is important to note that pure single-scattering is not required, but it is advantageous if a specific surface roughness or texture uses single-scatter (or single-intersection events) to scatter most of the luminous flux. In reflection, it is possible to use a single-scatter model to describe scattering caused by multiple events. The model typically loses accuracy toward flat angles of incidence. The surface types most often associated with this kind of multi-scattering have strong aspect ratios, such as steep slopes or deep grooves in their surface topoluit

Calculating the Surface Normal Distribution from Light Scatter Data Using the LucidShape BSDF Wizard

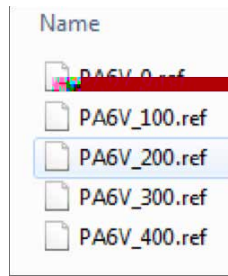
The BSDF Wizard allows you to choose the light scatter curve data, specify the data types, set defined angles of incidence for the curves, and define controls for the accepted input data range. To get a better representation of a sample, scatter is often measured at different angles of incidence, or multiple measurements can be done at the same angle of incidence. For each of the measured light spread curves, there must be a corresponding angle of incidence.

Depending on the data format to import, the reference direction for data input can be set either to follow the "ideal" angles of incidence (from the data or manually input) or to detect the maximum of reflection (specular peak) for each curve.

Additional controls allow you to choose between import (filter) options such as the range of data to use and post-processing options, such as a smoothing filter. When choosing a combination of these options, the impact of measurement artifacts on the resulting normal distribution can be effectively reduced for most measured light spread data.

Note that any measured light spread curves must be generated from reflected scatter. From this data, preferably at multiple angles of incidence, the surface normal distribution is calculated and used as a 2D scatter curve to model the surface characteristics. If refractive materials are to be modeled with this method, only the reflective part of the light measurement can be used in the BSDF Wizard. The relationship between reflective properties (used to model the surface-normal perturbation distribution) and the refractive properties must be verified by comparing simulations with the original measurements of a sample, because not all material texture types support this method with reasonable agreement.

To start the BSDF Wizard, select the menu **Materials > BSDF Curve Wizard**



Multiple measurement curves are useful, because they allow us to establish an average and avoid dependence on the quality of a single measurement curve. This ultimately makes the model more stable.

To load sample data into the BSDF Wizard:

1. Choose the REFLET input format.
2. Select the **whole directory** setting.
The whole directory setting automatically selects all files in the specified folder or directory at once.
3. In the **Select REFLET file** field, browse to and select the folder where the sample data is stored (e.g., C:\LucidShape\samples\BSDFwizard\sampleReflet\reflet1_HiRes).
4. You can select any of the data files displayed for the selected folder. In this example, select the first data set named **PA6V_0.ref**.
You will see that all five curve data sets will be loaded into the BSDF Wizard.
5. Without any additional changes, click **Calculate** to see the output with default settings.

After the REFLET data is loaded, the GeoView displays three sets of curves, shown in Figure 7: the original light scatter measurement curves (red); each calculated surface-normal distribution curve CID 1759 0 0 n.1mo2 59rd

To help with issues like this, the BSDF Wizard offers the following controls in the Details area, shown in Figure 8.

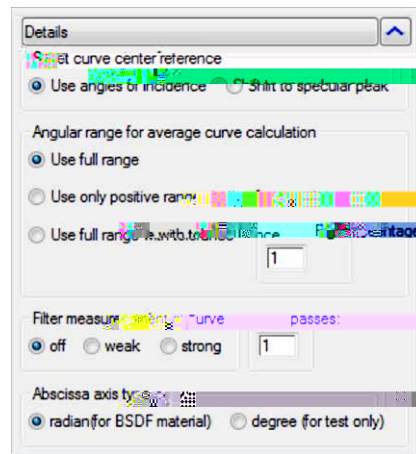


Figure 8: BSDF Wizard dialog box, Details section

- **Set curve center reference—Use angles of incidence:** uses the available angles of incidence stored in the data files of the

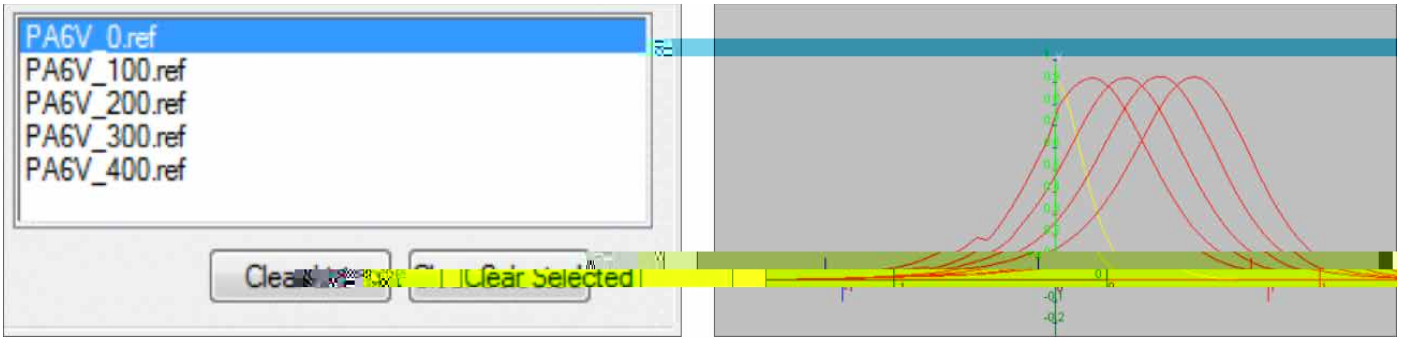


Figure 9: (Left) Delete a curve from the active list by selecting it and then clicking the Clear Selected button. (Right) Average curve after deleting the PA6V_0 curve and applying appropriate details in the BSDF Wizard. Only the curve data in the positive x-range is used, and not the "left" parts of the curve.

A final test determining if the curve is suitable for use in ray tracing will be done by LucidShape when the created average curve is used in the 2D scatter curve material. If the curve is not ray traceable, LucidShape displays an error message. It is a good practice to check one critical property before using the curve: the curve must have a value at $x=0$.

By editing the average curve (double-click in the TreeView), we can access the **Values** of the curve. We need to make sure the x-coordinate of the first value pair (x,y) is zero, as shown in Figure 10.

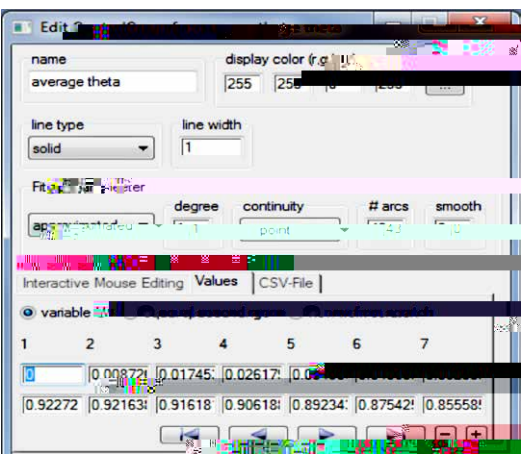


Figure 10: Edit Control Curve dialog box after double-clicking the average curve in the TreeView. Selecting the Values tab provides access to the curve data. The selected X value number 1 must be zero (0), as shown.

In Figure 13, the image on the right shows a random ray simulation where the shape clearly demonstrates the scattering properties.

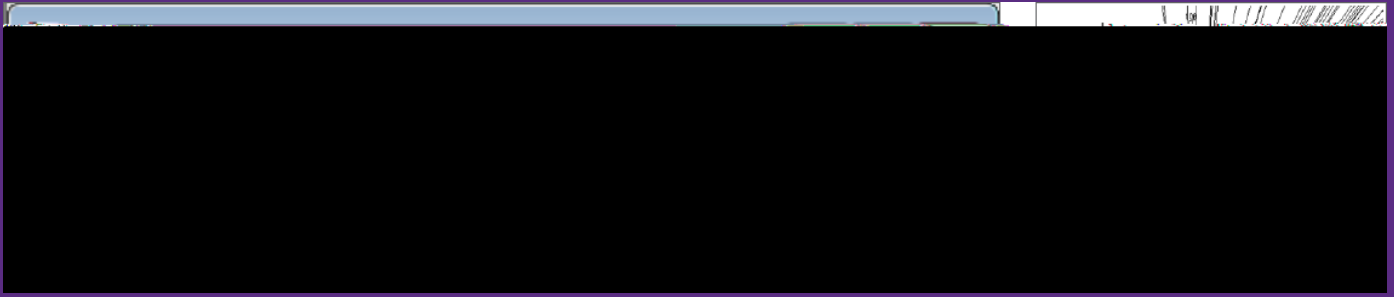


Figure 13: Assigned 2D scatter curve material on a planar surface shows the defined scattering behavior with random rays from a directional source at an arbitrary angle of incidence.

LucidShape's 2D scatter curve material allows you to include light scattering from surface roughness into an optical simulation. It can be based on surface-normal perturbation and will use a surface-normal distribution curve calculated by the LucidShape BSDF Wizard from reflection measurements. When used in combination, the BSDF Wizard and the 2D scatter curve material can integrate scatter information from reflection measurements of rotationally symmetric surfaces into LucidShape.

For more information about LucidShape or to request a demo, please contact Synopsys' Optical Solutions Group at (626) 795-9101 between 8:00am-5:00pm PST, visit <http://www.synopsys.com/optical-solutions> or send an email to lucidshapeinfo@synopsys.com.