

Modeling Custom Surface Roughness with LucidShape 2D Scatter Curve BSDF Material

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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 by $\theta_{in} = \theta_{out}$. If perturbed by a rough surface, the outgoing ray is scattered. Figure 1 shows a geometric representation of the surface profile from a randomly rough surface.

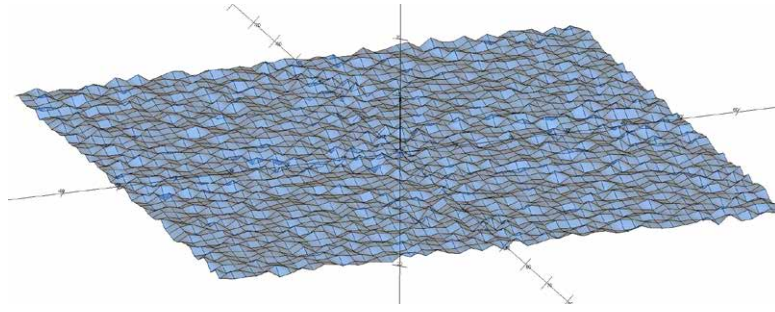


Figure 1: Rough texture with a random surface profile (with triangle mesh approximation)

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.

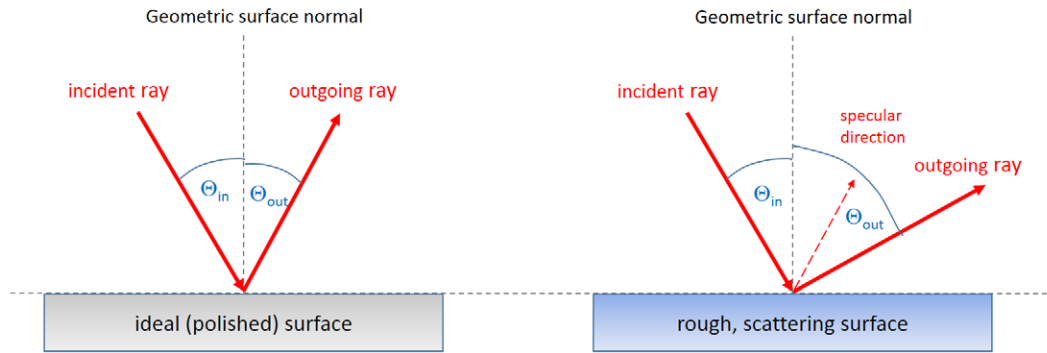


Figure 2: Ideal (left) and scattering (right) reflective surfaces; the angle of incidence θ_{in} is the same for both cases. For the ideal surface, the law of reflection dictates that the outgoing angle is equal to the incoming angle (in absolutes) counted against the surface normal. The scattering surface adds the scattering effect by altering the angle of the outgoing ray; this change in the outgoing angle can be a direct input from measured light spread angles (e.g., from a goniometric measurement) or follow an analytic formula.

Figure 3 compares an ideal surface to a rough surface modeled by adding a perturbation or randomization to the surface normal of the geometry.

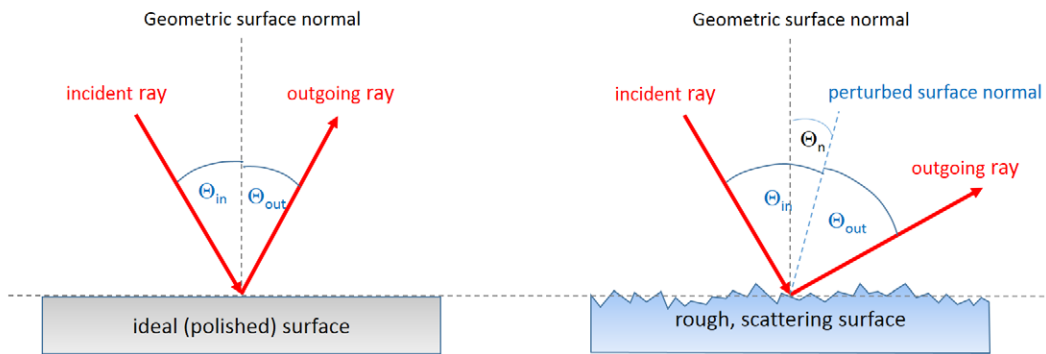


Figure 3: Ideal (left) and scattering (right) reflective surfaces; the angle of incidence θ_{in} is the same for both surface types, but at the point of ray intersection with the surface, the rough surface has a different surface normal than the normal vector of the ideal geometric surface. The surface normal is changed by an angle θ_n against the geometric surface normal, and the resulting outgoing ray propagates at a different outgoing angle out. At a different intersection point on the surface, the local surface normal is again different; therefore, the surface slope distribution across the complete geometric surface is represented for simulation purposes by a surface normal distribution curve (or function). The surface normal distribution as a function of the angle (ratio or density or frequency of a specific surface normal θ_n) needs to be included in the model definition, not the light spread function. The law of reflection is used in this scatter model. For each intersection, the small part of the surface hit by the ray is considered to be specular. The rough surface can be considered a random landscape of specular micro-facets.

The LucidShape 2D scatter curve supports both direct light scatter and surface normal scatter methods. Direct light scatter is used in the *beta angle mode*, and surface normal scatter is used in the *theta angle mode*. This is important to remember when assigning the material. In this paper, we refer to the theta mode only, so we will use a surface-normal perturbation model. Figure 4 schematically illustrates the workflow for preparing this surface material model.

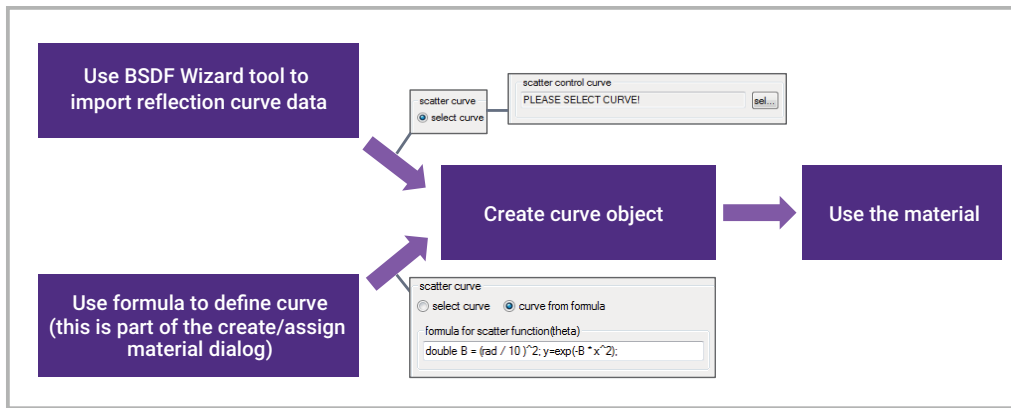


Figure 4: Simplified workflow diagram for the creation of a 2D scatter curve material in LucidShape

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 BSGF 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 BSGF 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 topology, as this is the landscape in which incident rays may hit the surface multiple times before finally being reflected. If a surface modulation is rather flat, single scattering is the dominant effect. Figure 5 illustrates the modelling of a multi-scatter type surface roughness by a single-event model.

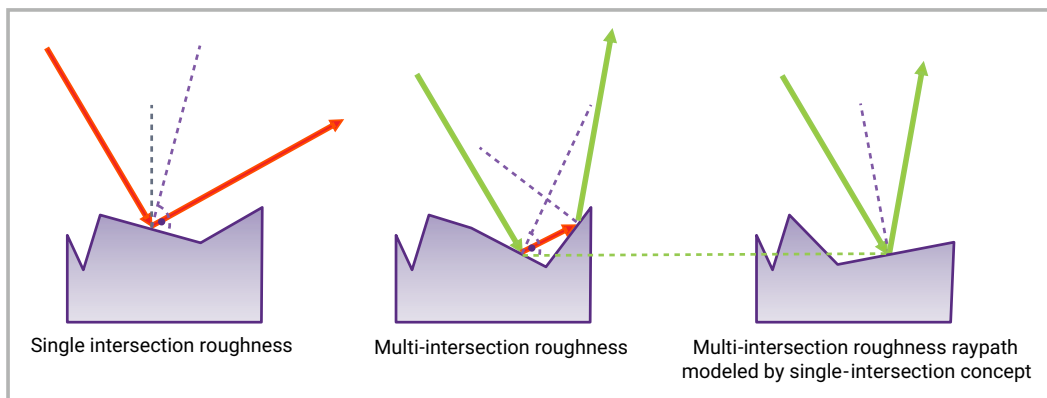


Figure 5: Single-intersection event (left), multi-intersection scattering (middle), and the deduced surface normal assumption by which a single-intersection model would describe the incoming and outgoing rays of this multi-scattering process (right).

For roughness on refractive surfaces, modeling with single-scattering is limited to certain scatter widths due to the nature of Snell's law. A narrow scatter beam is usually described accurately, so relatively weak scatter can be modeled without accuracy problems. For wider scattering angles, multi-intersection processes become dominant. This is what happens also in the reflective case, but total internal reflection at the interface to air will have a strong impact on rays trying to exit the refractive medium, making refractive surface roughness modeling much more sensitive to the shares of single- and multi-scattering. As a rule of thumb for a typical refractive index of about 1.5, only scattering up to a FWHM of about 30° is correctly modeled by a surface-perturbed Gauss model with a single-intersection approach.

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

The BSGF 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 BSGF 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 BSGF Wizard, select the menu **Materials > BSGF Curve Wizard**. In this paper, we use sample data provided in the LucidShape installation directory in the folder `samples\BSGFwizard\sampleReflet\reflet1_HiRes`.

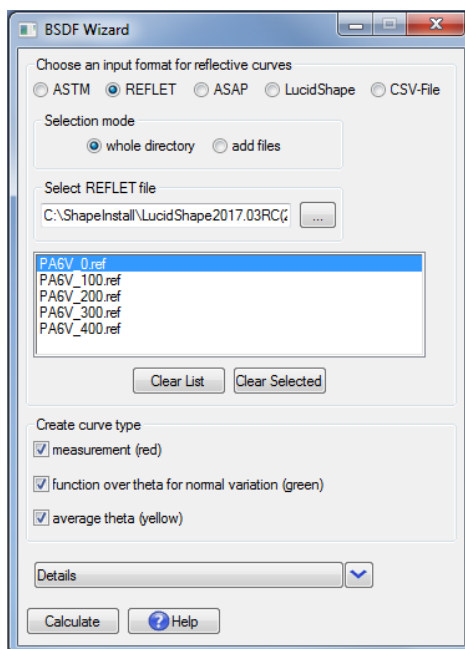
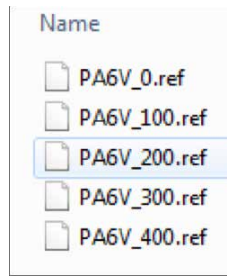


Figure 6: BSGF Wizard after loading the REFLET sample data

The `sampleReflet\reflet1_HiRes` folder contains five files from a reflection measurement. Each file represents a reflection curve of light scatter for a specific angle of incidence. The curves contain measurement artifacts; in this case, it is the shadowing by the source inlet that makes the data not directly usable. Before using the data, we must make sure we use only representative data, and not include measurement-related artifacts embedded in the data.



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 (function over theta for normal variation) (green); and a single, average, surface-normal distribution curve (yellow) as a mean curve to all the (green) surface normal curves. It is the yellow, average curve that we want to use as the input parameter curve to the 2D scatter curve material.

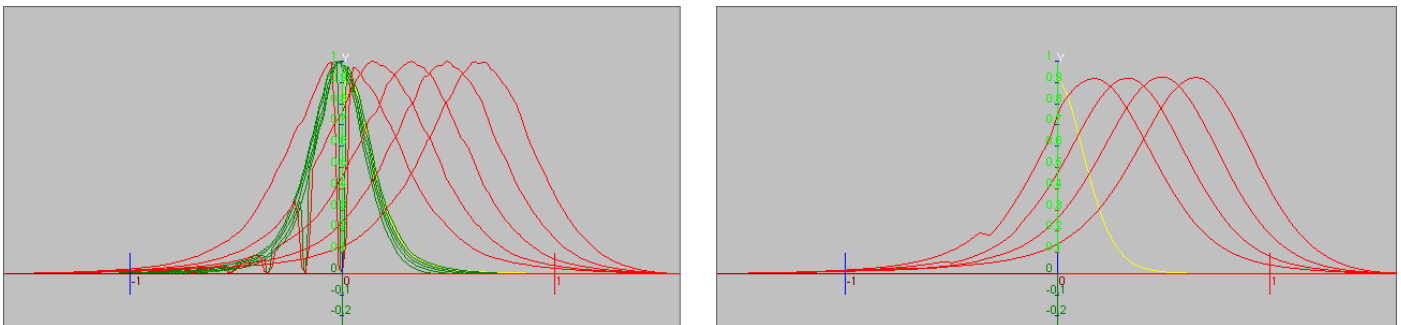


Figure 7: (Left) The BSDF Wizard default output curves to a low resolution REFLET sample data set; the wizard creates curves in the XY plane as geometric objects. The yellow, average curve is the mean surface-normal distribution calculated from all angles of incidence, and it can be selected to define the surface-normal distribution (theta) in the 2D scatter curve material. (Right) We look at only the measured curves (red) and the average (yellow).

The red curves in Figure 7 show a shift in the peak position from one curve to another. This is an effect of the different angles of incidence of each curve. For this data set, the angles are 0°, 10°, 20°, 30°, and 40°. This information must be obtained from the light spread files (file names or headers) or taken from a measurement protocol if it is not in the files themselves.

In the BSDF Wizard, we can eliminate the green curves by de-selecting the function over theta for normal variation (green) checkbox and clicking the Calculate button. We can then see (Figure 7, right) that the center light spread curve (red, 0°) has a “dip” around the center of our coordinate system. Also, the other red curves show similar artifacts at shifted positions. From knowledge of the measurement, we understand that this is not a sample property, but an artifact of the measurement system. The illumination source for the 0° curve is at 0° (angle of incidence) and is therefore blocking detection at this angle. In case of the other curves, the sources are moved to 10°, 20°, and so on, so it is not blocking the center peak, but the side slopes of the light scatter curve. We should not use these data points because they do not contain information about the optical response of the sample.

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

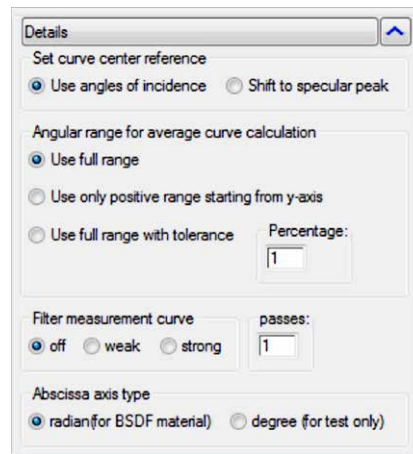


Figure 8: BSDF Wizard dialog box, Details section

- **Set curve center reference—Use angles of incidence:** uses the available angles of incidence stored in the data files of the selected curve data (as in REFLET format) or provides the option for you to manually enter a list of incident angles in degrees (°). Each curve needs to have the correct angle of incidence assigned. **Shift to specular peak** ignores all angle of incidence settings or data in the curve files, performs a maximum peak analysis of each curve and defines the angular position identified maximum value to be the angle of incidence.
- For smooth curves with a defined peak, the shift to specular peak option can compensate for misalignment effects from the measurement (angular deviations), but in the case of noisy curves or curves without the maximum value located at the center peak position, the **Use angles of incidence** setting should be used.
- **Angular range for average curve calculation:** limits the amount of data used to calculate the resulting average curve. Use full range applies all curve data; **Use only positive range starting from y-axis** omits all the left parts of each measurement curve (helpful if there are any artifacts in the left half of the measurement). **Use full range with tolerance** defines a confidence interval around the mean curve to eliminate artifacts outside the boundary of the specified percentage of the average y-value for a given angle on the x-axis.
- **Filter measurement curve:** applies a curve filter to smooth the measured light scatter curve data before the average surface normal curve is calculated. This is useful for noisy measurement data, such as data detected from very low reflectance samples. It can be set to **off**, **weak** or **strong**. The only parameter is the number of passes, which defines how many times to apply the filtering.
- **Abscissa axis type:** (set the x-axis angular system) is set to **radian (for BSDF material)** by default. LucidShape uses the radian arc length measure internally, and any 2D BSDF material works only in this angular measurement. To double-check a calculation or to reference data from another source, the output can be set to degree of angle with the **degree (for test only)** setting.

In the case of high-resolution REFLET example data, useful settings in the BSDF Wizard could include the following:

- Select the curve named **PA6V_0.ref** and click **Clear Selected** to delete it.
- Select **Use only positive range starting from y-axis**.
- In the **Filter measurement curve** area, select **strong** and set the number of passes to 1.
- Leave **Abscissa axis type** set to **radian (for BSDF material)**.

The resulting average curve is shown in Figure 9. By deleting PA6V_0.ref, the curve has been healed from the center dip caused by the “00” curve. Other artifacts have been ignored by selecting **Use only positive range starting from y-axis**. The 1x strong filtering has noticeably smoothed the average curve, curing all measurement noise.

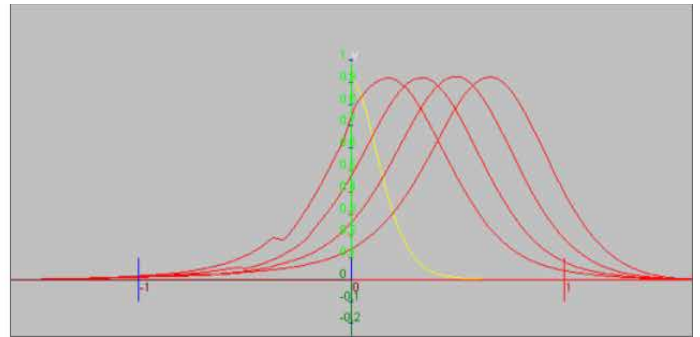
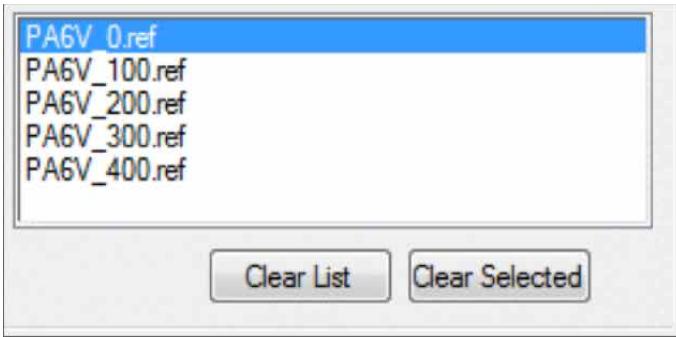


Figure 9: (Left) Delete a curve from the active list by selecting it and then clicking the Clear Selected button. (Right) Average curve after deleting the PA6V_0 curve and applying appropriate details in the BSDF Wizard. Only the curve data in the positive x-range is used, and not the “left” parts of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

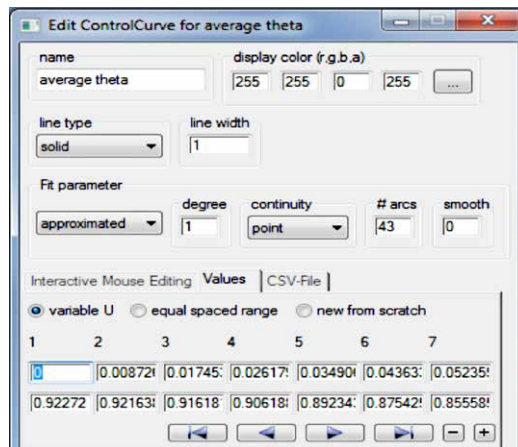


Figure 10: Edit Control Curve dialog box after double-clicking the average curve in the TreeView. Selecting the Values tab provides access to the curve data. The selected X value number 1 must be zero (0), as shown.

Measurement data sometimes does not have a data point at $x=0$ (which is the surface normal direction), but it is necessary for the material definition in the software to set a value at this point of $x=0$. The curve needs to be defined at this point.

Using the 2D Scatter Curve Material in LucidShape

To assign a 2D scatter curve material to any geometry in LucidShape, select the menu **Materials > Assign Material**, or select any of the **Geometry > Create Surface Shape** options to directly assign the actor material.

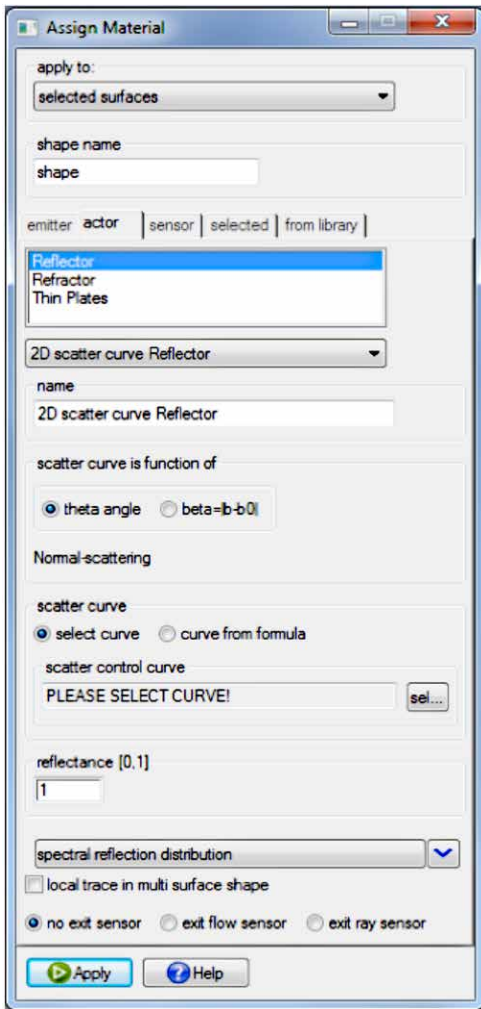


Figure 11: 2D Scatter Curve controls in the Assign Material dialog

In the Assign Material dialog box, select the **actor** tab and then choose the **Reflector** material class.

In the pull-down menu, select **2D scatter curve Reflector**.

There are options to use either a theta or a beta model as the basis for the scatter curve definition. The beta model is an in-plane scatter model (Harvey-Shack). Here, we will select the **theta angle** model in combination with the **select curve** option.

LucidShape offers two ways to define the scatter curve: select a geometric curve object (**select curve**) or a **curve from formula**.

Note: Beta angle defines a direct light spread distribution function for a Harvey-Shack scatter model. Theta angle allows you to define a surface normal distribution curve, specifically to select average surface normal distribution curves created with the BSDF Wizard.

It is a good practice to copy the average curve into the design model to save it in the model (.lug) file. We also suggest assigning a descriptive name to the curve.

To select an existing curve object (from the wizard, for example):

- Press the **sel...** button in the scatter control curve field to open the selection dialog box.
- Choose the curve from the TreeView (see the left image in Figure 12).
- Press **selection done** to close the selection dialog box.

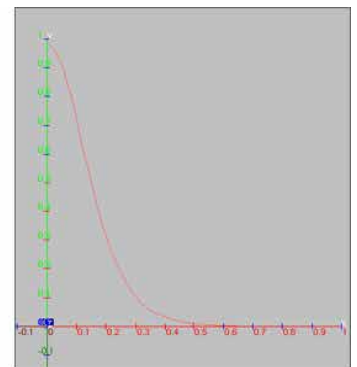
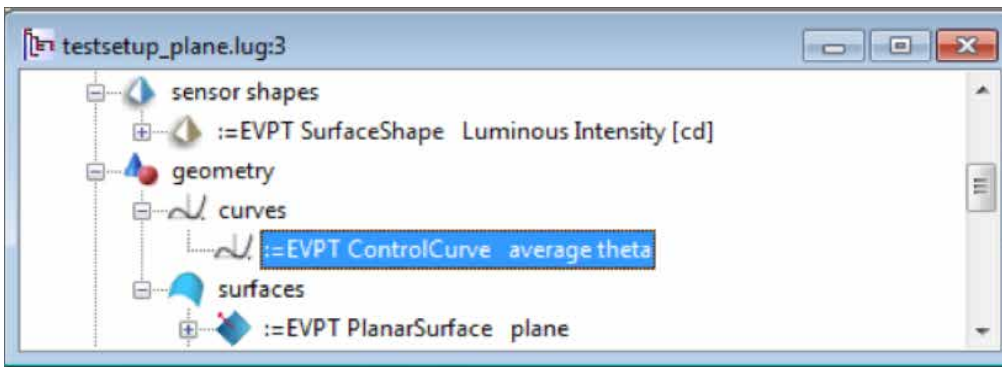


Figure 12: (Left) Average curve selected in the TreeView; (Right) Selected curve is visible in GeoView in the XY-plane.

After you select the curve, it is necessary to select the desired geometry to assign the material to it. Otherwise, LucidShape will report that there was no surface selected. When the curve is created correctly, the internal LucidShape curve test creates the material as specified, and no error messages are displayed.

The newly created shape is displayed in the TreeView. You can verify the material definition in the TreeView. Figure 13 shows an example of a TreeView entry for the created shape. You can see that the geometry is a plane and the material is a 2D scatter curve reflector. The used curve is still accessible as a child object to the material definition in the TreeView. You can also see that the curve named average theta is the last entry in the material path of the TreeView for this object.

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

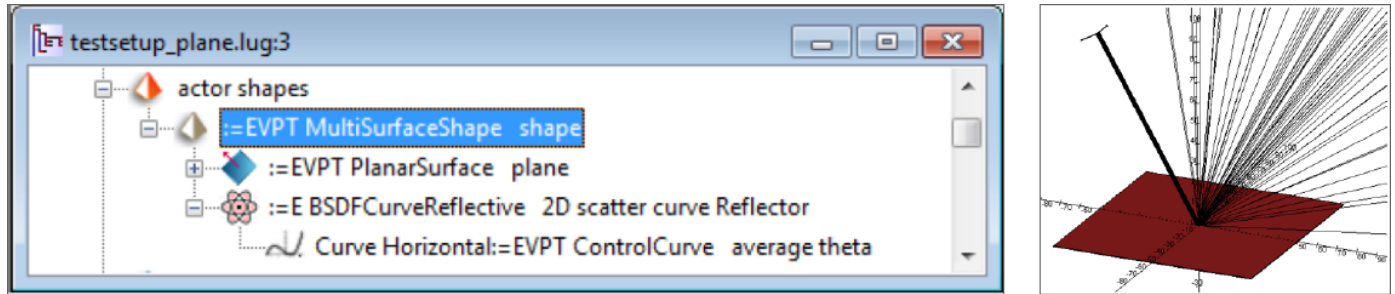


Figure 13: Assigned 2D scatter curve material on a planar surface shows the defined scattering behavior with random rays from a directional source at an arbitrary angle of incidence.

Summary

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.

To Learn More

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.