White Paper

LucidShape Spectral Ray Trace Simulations

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Author

Steffen Ragnow
Synopsys

Abstract

This paper discusses the properties and advantages of spectral ray trace simulation over conventional monochromatic ray trace simulation. This paper illustrates the benefits of spectral ray trace handling in LucidShape in several refractor experiments.

Introduction

In modern optical systems, light color has become increasingly important in all areas of lighting design. Colored LEDs, for example, play an increasingly significant role in the design of automotive lamps and operation panels. Color can even impact design in classical applications where white light is used; for example, in a refractive optical system where white light is decomposed into its wavelength parts by lens dispersion. In cases like these, a conventional monochromatic ray trace simulation will not be able to produce sufficiently accurate predictions for the system's lighting functions as it neglects the light's wavelengths.

Figure 1 shows a typical example where a low beam projector type headlamp produces a narrow seam of blue and red colored light above its cutoff line. You can see this effect in the color simulation of such a headlamp.

Figure 1. Results from a color simulation of a low beam lens headlamp (full view of a candela distribution).

A sole monochromatic simulation would not be able to reveal such color seams. Therefore, a physically correct spectral color simulation is essential in all cases where colored light may play a role.

Figure 2. Detailed view of same candela distribution as in Figure 1.

Conventional Vs. Spectral Simulation

Conceptually, a conventional monochromatic ray trace simulation is quite simple because no wavelength information needs to be processed. A single ray starts from its light source (assumed to be monochromatic), hits the optical surface and reaches the (usually two-dimensional) sensor. On its way to the sensor, the ray's direction and intensity is altered on contact with the surface according to the classical reflection/refraction laws of optics and the optics material properties.

Spectral color simulations are more complicated than a conventional ray trace because they need to take into account the spectral wavelength λ. Many scalar-valued parameters from the conventional ray trace must be replaced by λ-dependent functions when performing a spectral ray trace. Note that:

- Each ray must have a wavelength λ.
- Each light source has to be equipped with a *spectral power distribution (SPD) function* that describes the source's relative emitting power as a function of the wavelength. In practice, this function determines the relative frequency of rays produced by the source during the simulation (that is, rays having wavelengths with higher emitting powers are produced more often than those with lower emitting powers). Figure 3 shows an SPD function defined on the visible spectral range that is typical for LED emitters (λ = 380 nm - 780 nm). Another common SPD function is $f(\lambda)\equiv 1$ for all wavelengths λ (this is the case for perfect white light where all λ have the same intensity).
- Refractors contain at least two materials. Each material has refractive and absorption indices that vary as a function of wavelength. The variation in refraction that occurs as a function of wavelength is known as *dispersion*.
- Reflector materials have to be equipped with an absorption function in addition to a reflection coefficient.
- Because sensors are hit by λ-dependent rays, they must themselves depend on the wavelength λ. Otherwise, it would be impossible to differentiate the sensors for λ (and especially, to produce RGB color results like the low beam sensor images in Figures 1 and 2). Effectively, this necessity makes the sensor a 3-dimensional object. In practice, the sensor's continuous dependence on λ is discretized by a number of conventional 2-dimensional sensors, each of them accounting for a limited λ spectral channel.
- In order to cover all the sensor's spectral channels with enough rays, the number of rays for a spectral simulation must be significantly higher than for a monochromatic simulation.

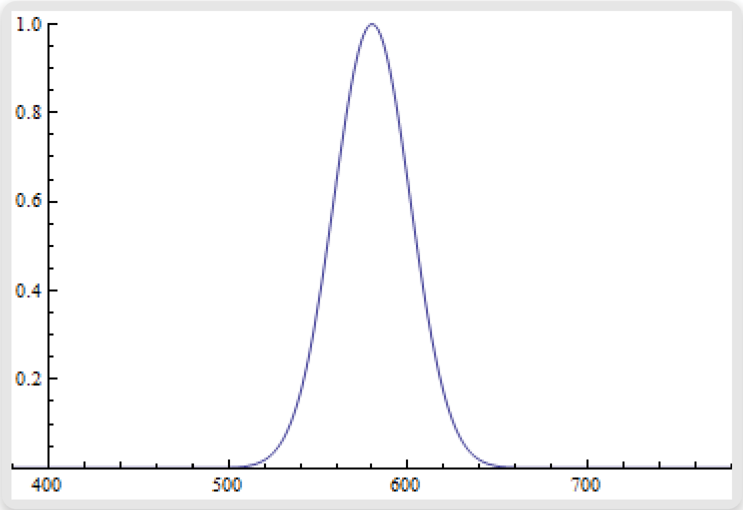
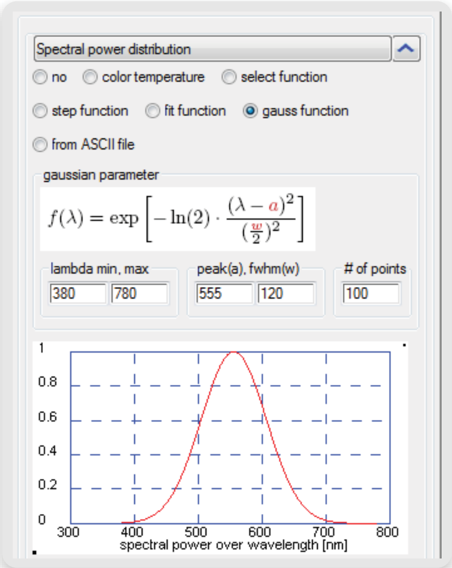


Figure 3. A spectral power distribution function of Gaussian type.

Setting the Spectral Functions

In LucidShape, all relevant λ-dependencies — SPD-function of the light source, dispersion and absorption functions of the refractor's materials, absorption functions of the reflector's material, and λ-discretization of the sensor (~number of spectral channels) — may be set via sub-dialog boxes in LucidShape's *Assign Material* tool. As a representative example, Figure 4 shows detail of the dialog box that assigns an SPD function to an emitter.



Spectral power distribution

○ no ○ color temperature ○ select function

○ step function ○ fit function ● gauss function

○ from ASCII file

gaussian parameter

$$f(\lambda) = \exp\left[-\ln(2)\cdot\frac{(\lambda-a)^2}{(\frac{w}{2})^2}\right]$$

lambda min, max: 380 780

peak(a), fwhm(w): 555 120

# of points: 100

Figure 4. Detail to assign a SPD function to an emitter.

Other spectral functions (e.g., for reflectors and refractors) may be set similarly in LucidShape.

Discussion on a Model Example

We will use the classic example of a prism decomposing white light into a spectrum of colors to illustrate the benefits of a proper spectral simulation. The setup shown in Figure 5 consists of:

- A prism shape made up of two planar faces — an inner and outer face. The shape's material properties are glass with special dispersion and absorption functions.
- A directional planar emitter sends a total amount of 1000 lm of white light in direction of the prism's outer face. The emitter's SPD function is constant on its visible λ range [380,780] nm.
- A 3-dimensional light flux sensor detects rays coming from the prism's inner surface. The sensor's λ range is range is represented by 40 conventional 2-dimensional sensors, each of them covering a narrow spectral channel of the total range of [380,780] nm.

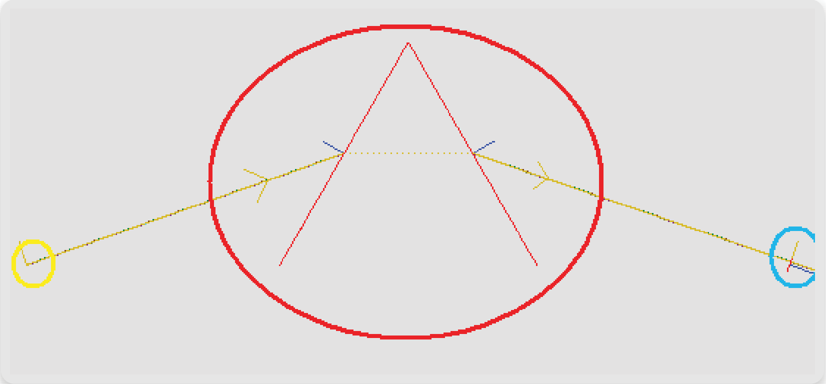


Figure 5. A spectral ray trace setup in LucidShape, consisting of an emitter (denoted by a yellow circle), a prism (red circle) and a sensor (blue circle).

We simulate this experiment with 100e^9 rays and then convert the 40 spectral channels to an RGB image to get the well-known spectral pattern from λ=380 nm (ultra-violet) to λ=780 nm (infra-red) (Figure 6).

Figure 6. RGB plot computed from the sensor's 40 spectral channels.

Then we sum up all 40 spectral channels to gain information about the total intensity (Figure 7).

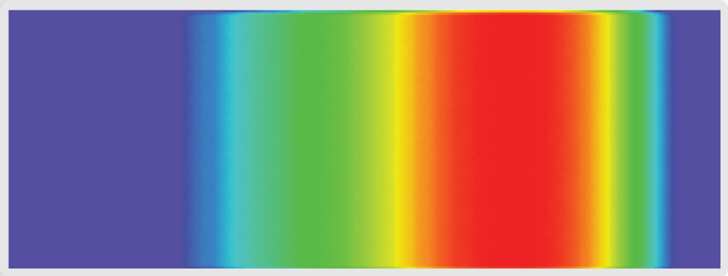


Figure 7. Light flux sensor containing the sum of the intensities of all 40 spectral channels (intensity plot with linear scale, spectral simulation)

Figure 7 shows that there is a bias towards the green/red part of the spectrum. Green/red light makes up more than 85% of the light flux and is sent to a relatively narrow strip in the sensor after refraction.

In contrast, if we perform a conventional monochromatic simulation on the same setup (that is, we omit any wavelength information during the simulation):

- The light source has no SPD function so it emits all rays without any wavelengths
- The prisms glass dispersion and absorption is realized by simple scalar values instead of λ-dependent functions
- The sensor does not differentiate for λ

The conventional light flux intensity plot in Figure 8 fails to give a correct answer. The location of the green/red strip is correct but the plot misleadingly shows that the prism maps *all* light to that narrow strip on the sensor. The correct result in Figure 7 shows that the light is distributed over the sensor's whole vertical range.

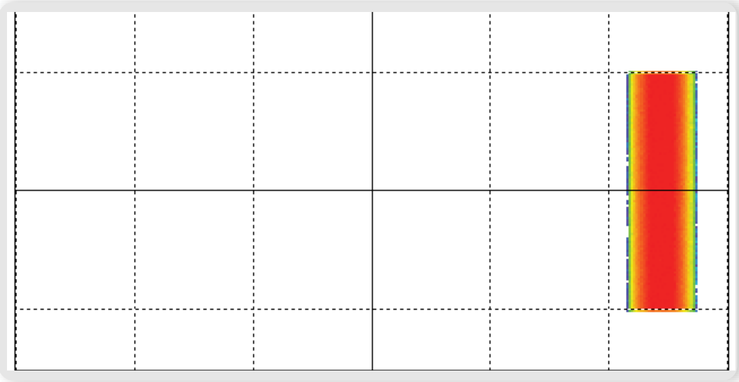


Figure 8. Light flux sensor (intensity plot with linear scale, conventional simulation).

Conclusion

A careful analysis of spectral vs. conventional Monte Carlo ray trace methods reveals that a spectral simulation fully takes into account the optical component's wavelength dependencies., The classical prism model, which was set up and simulated in LucidShape, shows that the conventional ray trace failed dramatically in its results while the spectral ray trace gave us a correct prediction of the prism's lighting effects.

Therefore, a spectral simulation should be considered for any optical system where color may play a role.

To Learn More

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

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