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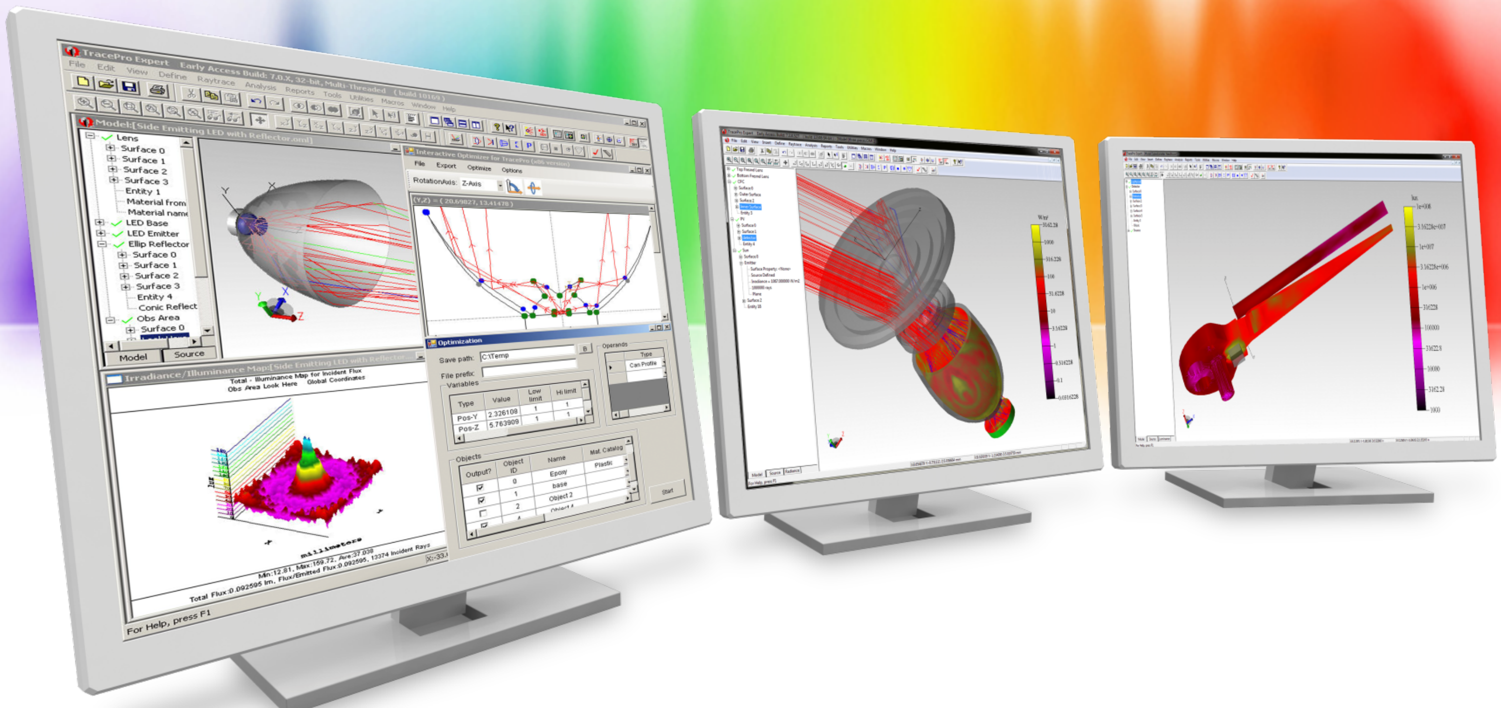

DESIGNING AND OPTIMIZING LIGHTGUIDES/ PIPES – TIPS & TRICKS FOR A STREAMLINED PROCESS

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Agenda

- Setting Specifications for Light Guide/Pipe Design
- Design Constraints
- Principles
- Basics
- Design Tips
- Design Basics
- Example 1
- Example 2
- Conclusions

Setting Specifications for Light Guide/Pipe Design

Be careful when selecting your source.

Do you have enough LED power to achieve your goal?

Set an output specification with the following in mind:

- Illuminance
- Efficiency
- Angular Output
- Uniformity
- Luminance & Lit Appearance

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Design Constraints & Principles

- Snell's Law
- Fresnel Loss
- Critical Angle and TIR
- Bending Curvatures
- Etendue
- Light Guide Design Basics
- Single & Multiple LED advantages
- Top- vs. Side-emitting LEDs
- Positioning of the LED
- Add White Powder for Diffuse output
- Using Textured Surfaces on Input/Output Surfaces
- Examples

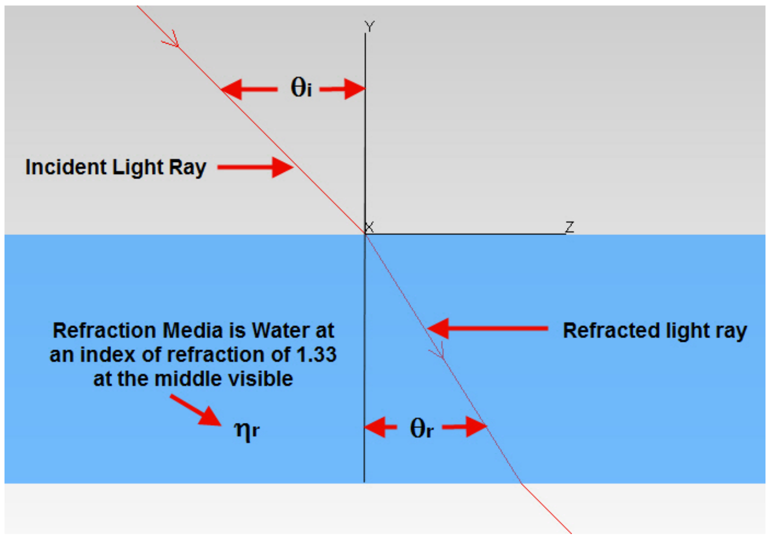
Principles - Understanding Snell's Law

One of the most important laws in optics is Snell's law. This formula describes the interaction of light with a material i.e. glass or plastic for example. When light travels from one material into another it bends or refracts at the boundary. For a ray that enters a material with an incident angle of θi into a material with an index of refraction ni, the angle of refraction θ_r in a material n_r can be defined as:

$$n_i \sin\theta_i = n_r \sin\theta_r$$

Material	Refractive Index, n
Air	1.0
Water	1.33
Schott Bk7 Glass	1.517
Acrylic	1.49207

Table 1 – Refractive indices for common materials at .5461 microns



So for an incident ray entering the water at 45 degree incidence, we can find the refracted angle in the media by using Snell's law, sin (45) = 1.33 sin(Θr) or (Θr) = 32.117 degrees.

Principles - Definition of Fresnel Loss

Frensel Loss occurs when light rays cross the boundary from one medium into another. There is a loss due to the reflection at the boundary which is called Fresnel loss and can be calculated using the equation shown below:

$$\text{Fresnel Loss} = [(n_i-n_r)/(n_i+n_r)]^2$$

So for plastic to air and glass to air interface boundaries the Fresnel loss is around 4 to 5% but becomes quite large when dealing with the infrared wavelengths where index of refraction can be 4.

Note this equation has been simplified to apply to only rays normal to the surface.

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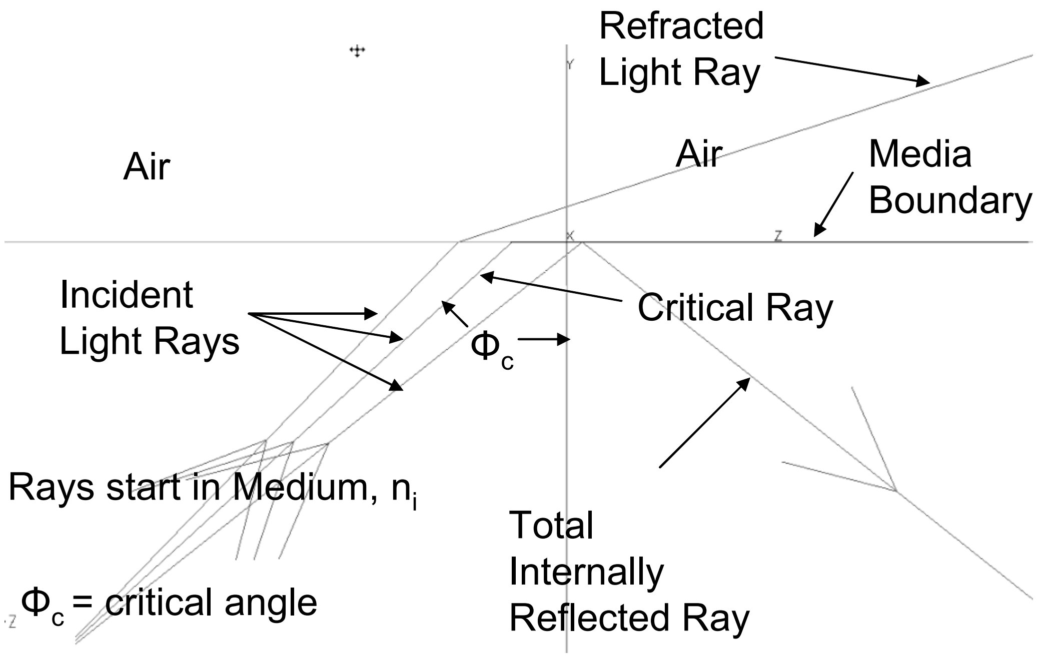
Principles - Critical Angle & TIR

TIR occurs when light passes from a medium of high refractive index into a material of lower refractive indices. If the angle of incidence is greater than the critical angle then the light will be reflected.



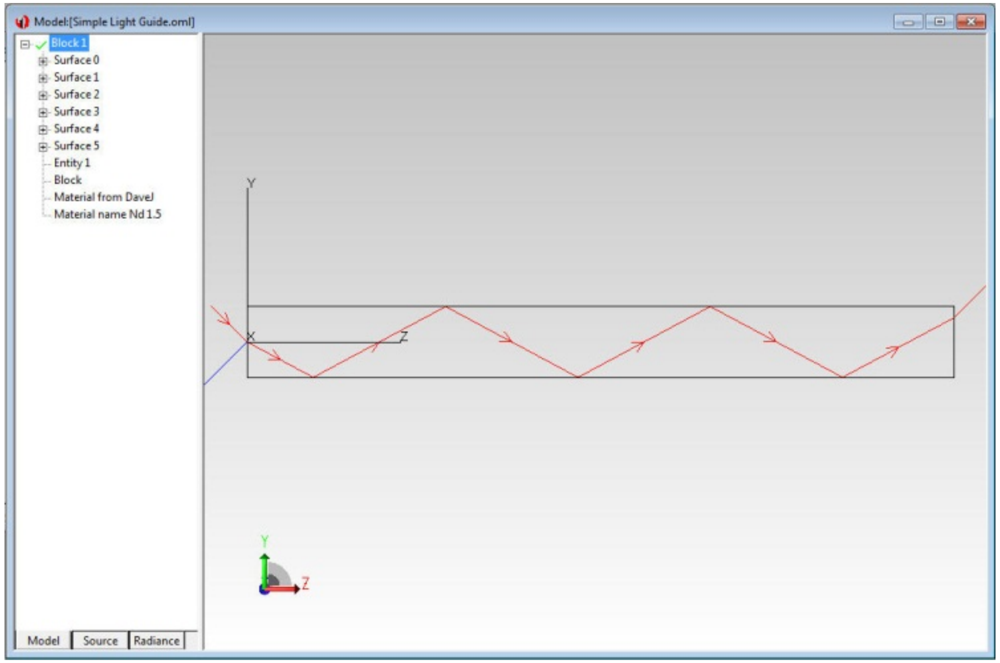
The critical angle is defined where the sin θ_r (90°). Since sin(90°) = 1, this then reduces Snell's law to: Sin $\theta_c = n_r/n_i$ where $n_r = 1$ (air) and n_i is plastic around 1.5. The critical angle is usually around 42 degrees for most plastics and BK7 glass in the visible wavelengths.

Principles – Critical Angle

- Critical Angle is the incident angle of light, relative to the surface normal, at which TIR occurs

- Light at an incident angle greater than the Critical Angle is TIR'ed. Light at an angle less than the Critical Angle will be partially reflected and partially refracted out of the light guide/pipe.

- The Critical Angle varies with the indices of refraction of the light guide/pipe material and the surrounding material (typically Air)



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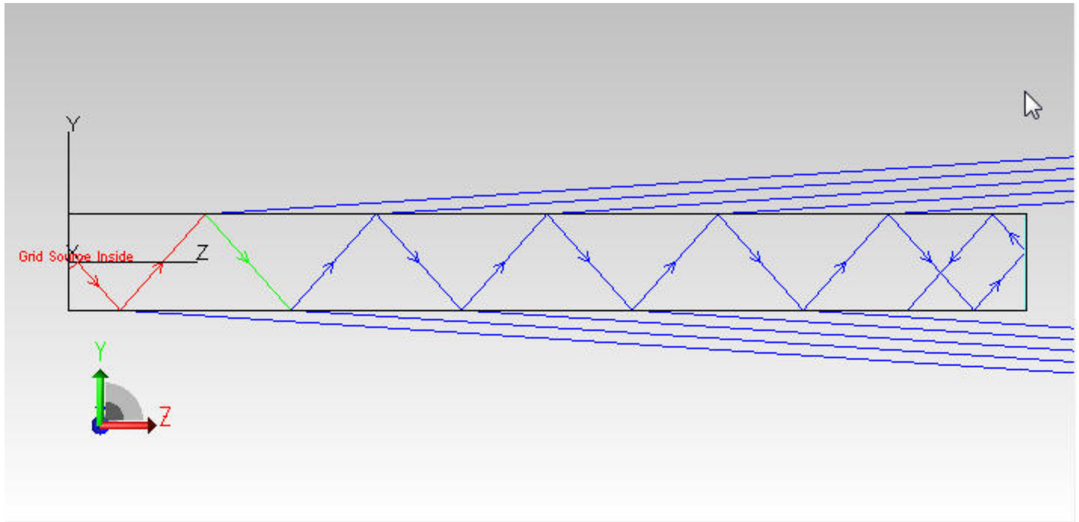
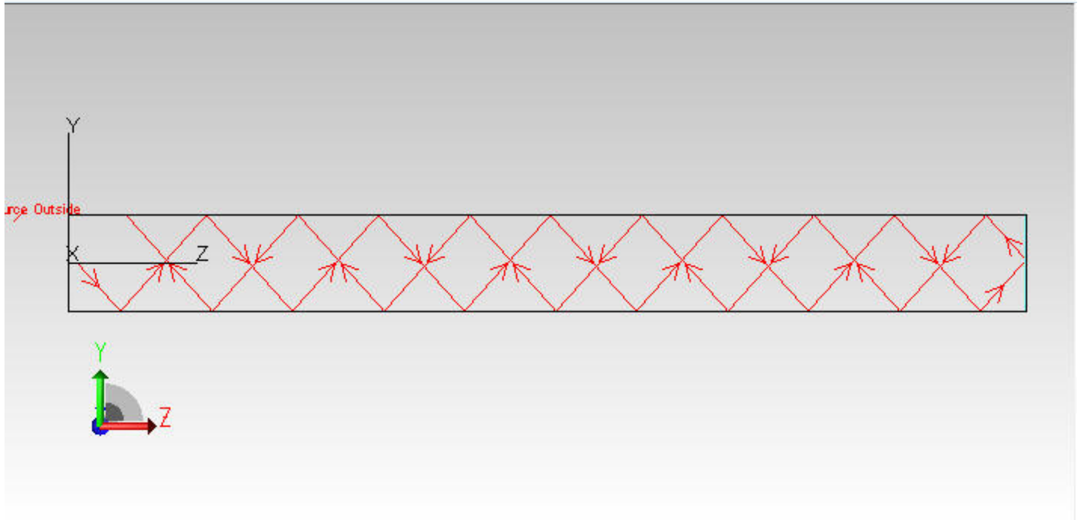
Principles – Calculating the Critical Angle

$\theta_i = 41.7°$



$\theta_i = 41.9°$



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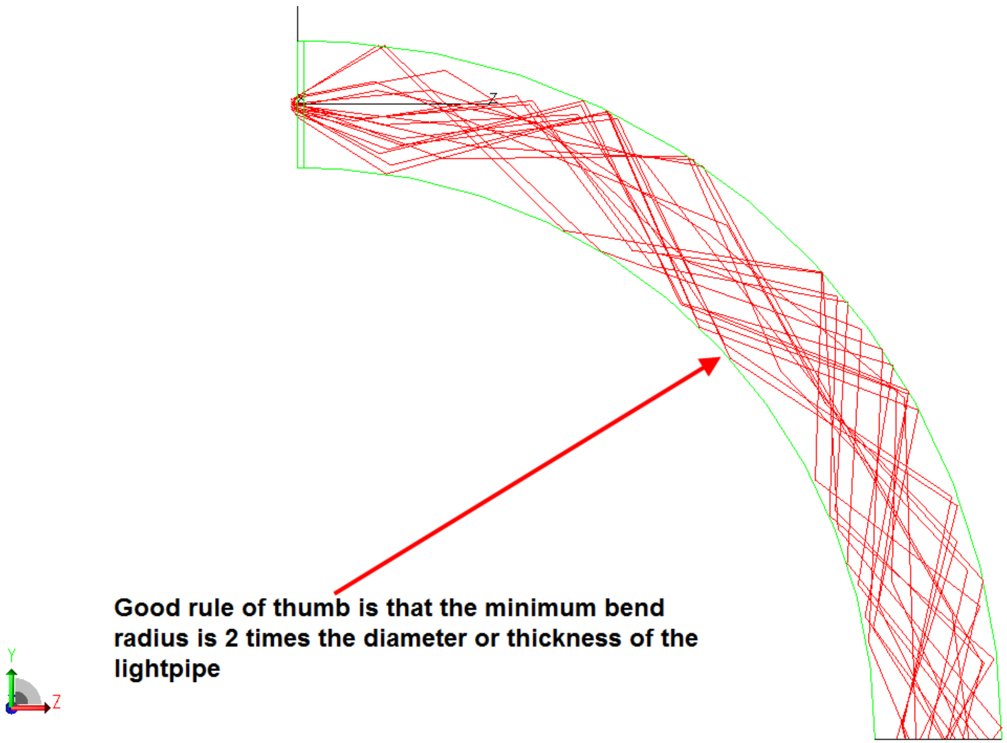
Basics – Bending Curvatures

Keeping the critical angle in mind is important when curving light around mechanical structures. To keep light contained inside the pipe remember to use gentle curves when possible and remember the critical angle of around 42 degrees to contain large angular emitting LEDs. There will almost always be losses at bends in any light pipe since it is difficult to contain the +/- 90 degree emission of a normal LED. The job is to try and keep as much light as possible from exiting the pipe.



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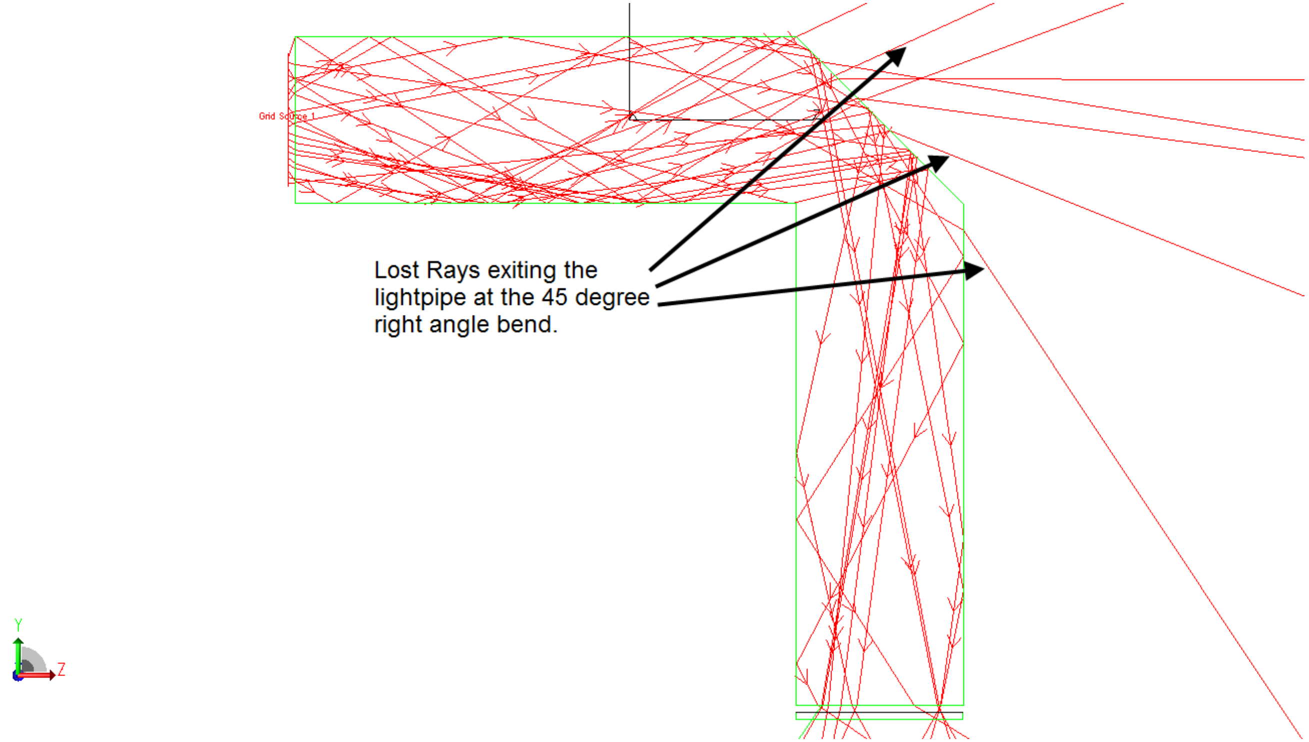
Basics – Using Light Guide/Pipe Mirrors

When you want to bend light quickly by 90 degrees use a 45 degree right angle bend in the light pipe. If the light is perfectly collimated all the light will be reflected but with an LED with lambertian emission you will usually end up with at most 50 percent of the light exiting from the output surface of the light pipe.



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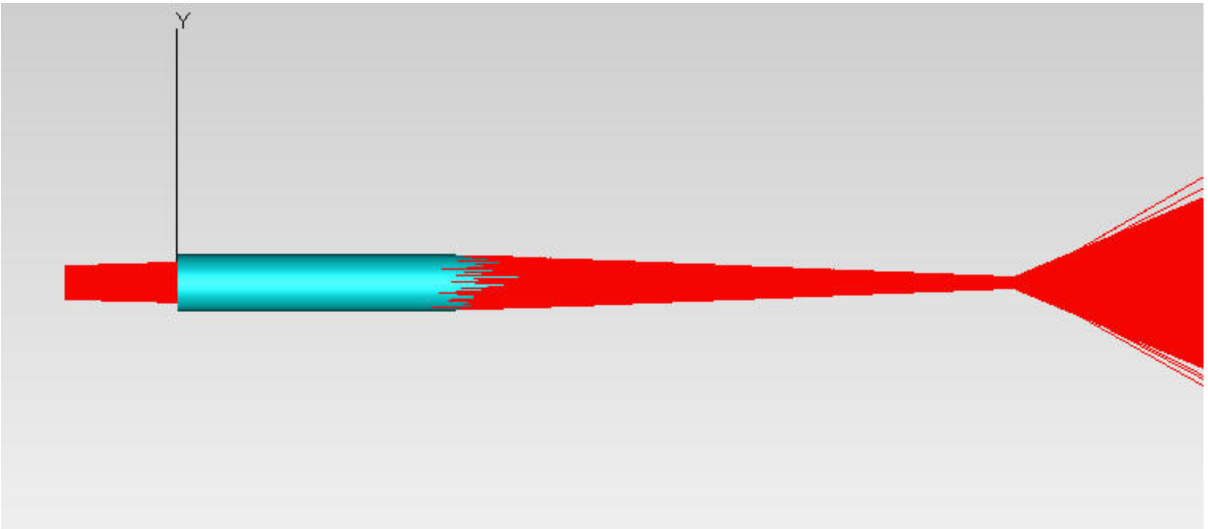
Principles - Etendue

Etendue is a measure of geometrical efficiency - $G = \pi S \sin^2 \Omega$

Where: G = etendue, S = area of source, beam, or optic, Ω = half angle of beam, in degrees

A consequence of the conservation of etendue is that when the area of a beam is concentrated, the angular distribution of the illumination will spread. From the source point of view, it is the product of the area of the source and the solid angle that the system's entrance pupil subtends as seen from the source. Equivalently, from the system point of view, the etendue equals the area of the entrance pupil times the solid angle the source subtends as seen from the pupil. Definition courtesy of Wikipedia Etendue page.



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Basics - Light Guide/Pipe

- Light guides typically guide, or direct light by total internal reflection (TIR)
- Common materials for light guides are plastic or glass
- The index of refraction of the light guide material will affect the coupling of light into the light guide and the light guiding properties
- Surface properties can be applied to a light guide/pipe to improve performance

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Best Practices

- It is Important to have high reflectance at the light guide/pipe boundaries (TIR)
- A diffuse surface is usually good practice to allow light to exit from the output/exit surface of the light pipe. With perfectly flat exit surfaces light can TIR back and forth between the entrance and exit surfaces.
- Roughened surfaces, scattering dots or breaks in the light guide/pipe can force the exit of light where needed

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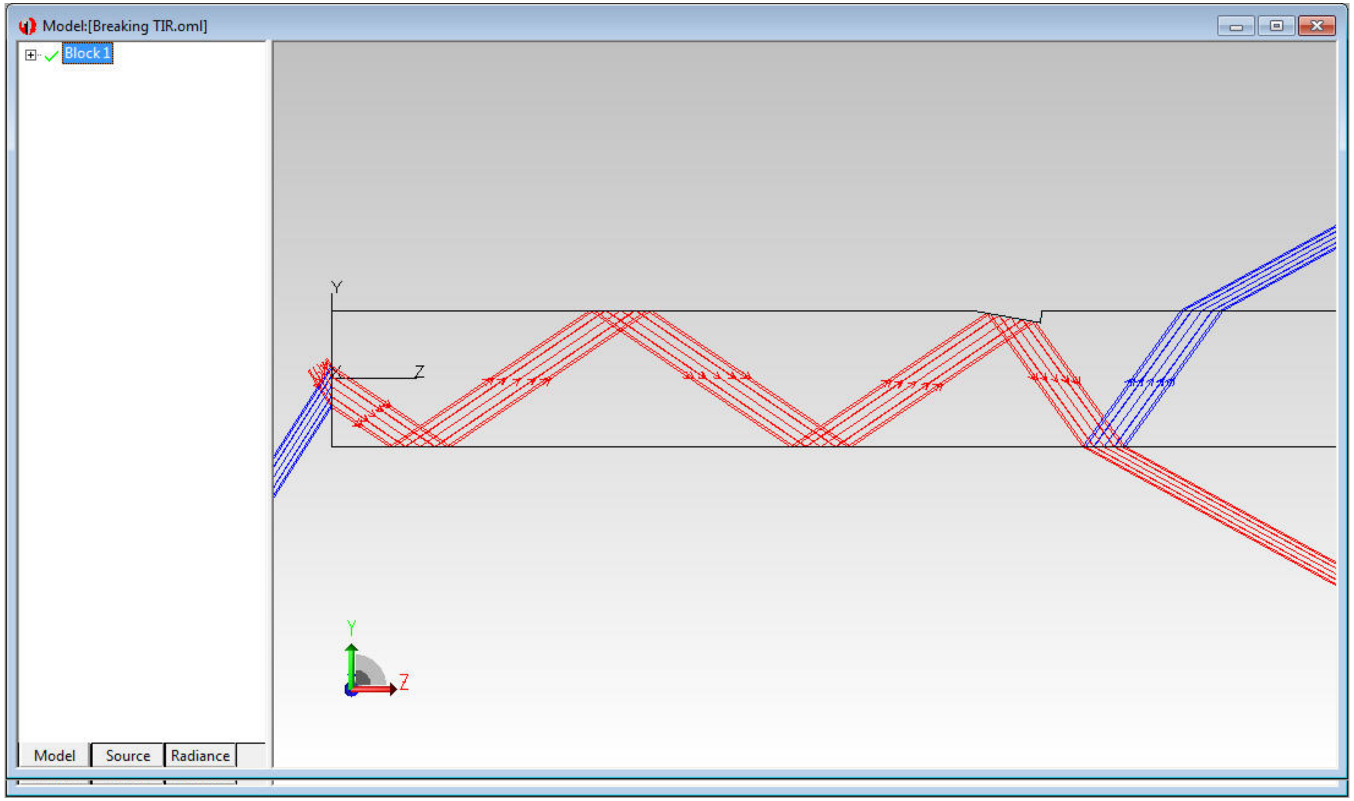
Basics – Breaking TIR



Add a physical feature to the surface of the light guide. An example would be a backlight light extractor.

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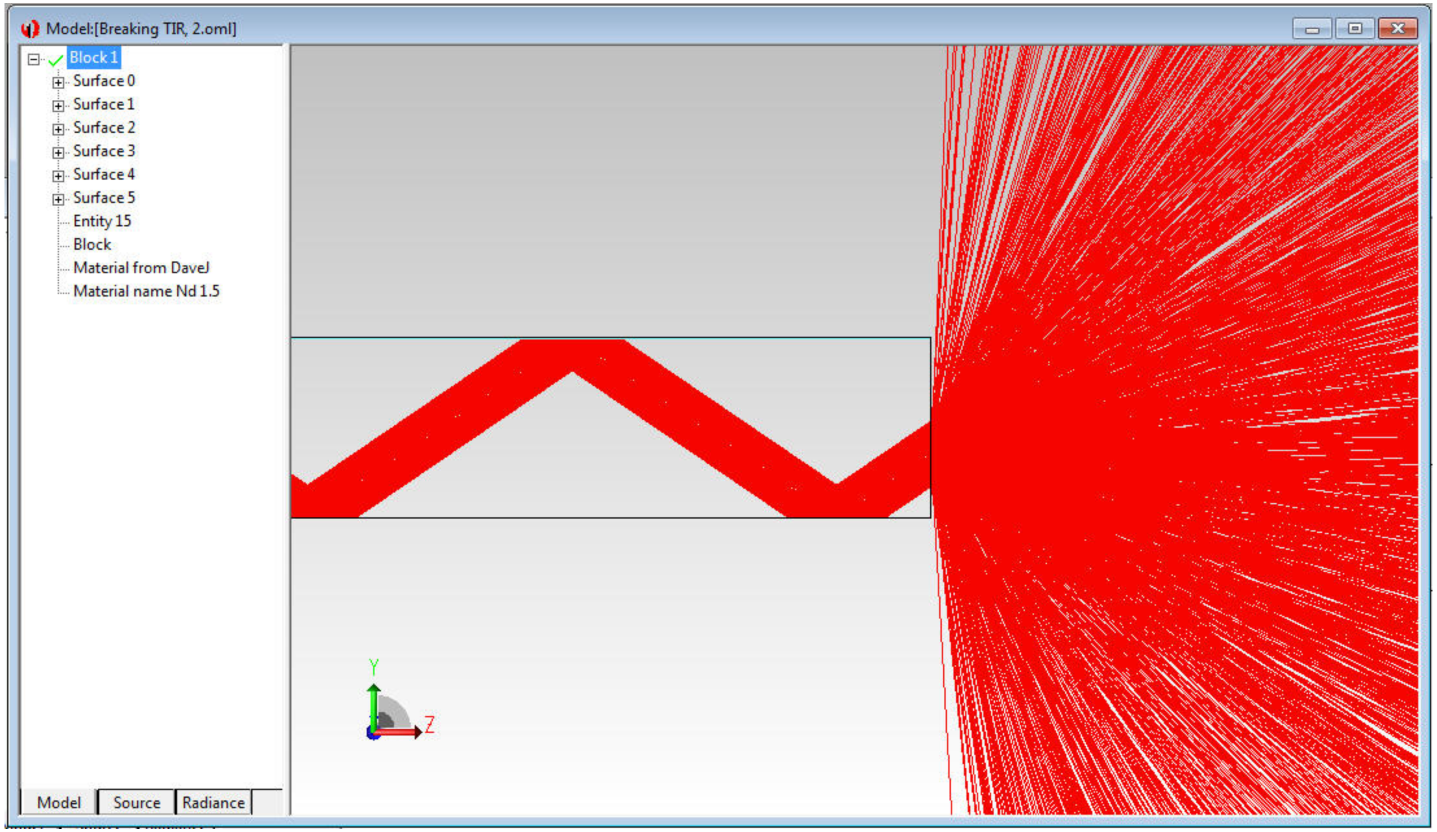
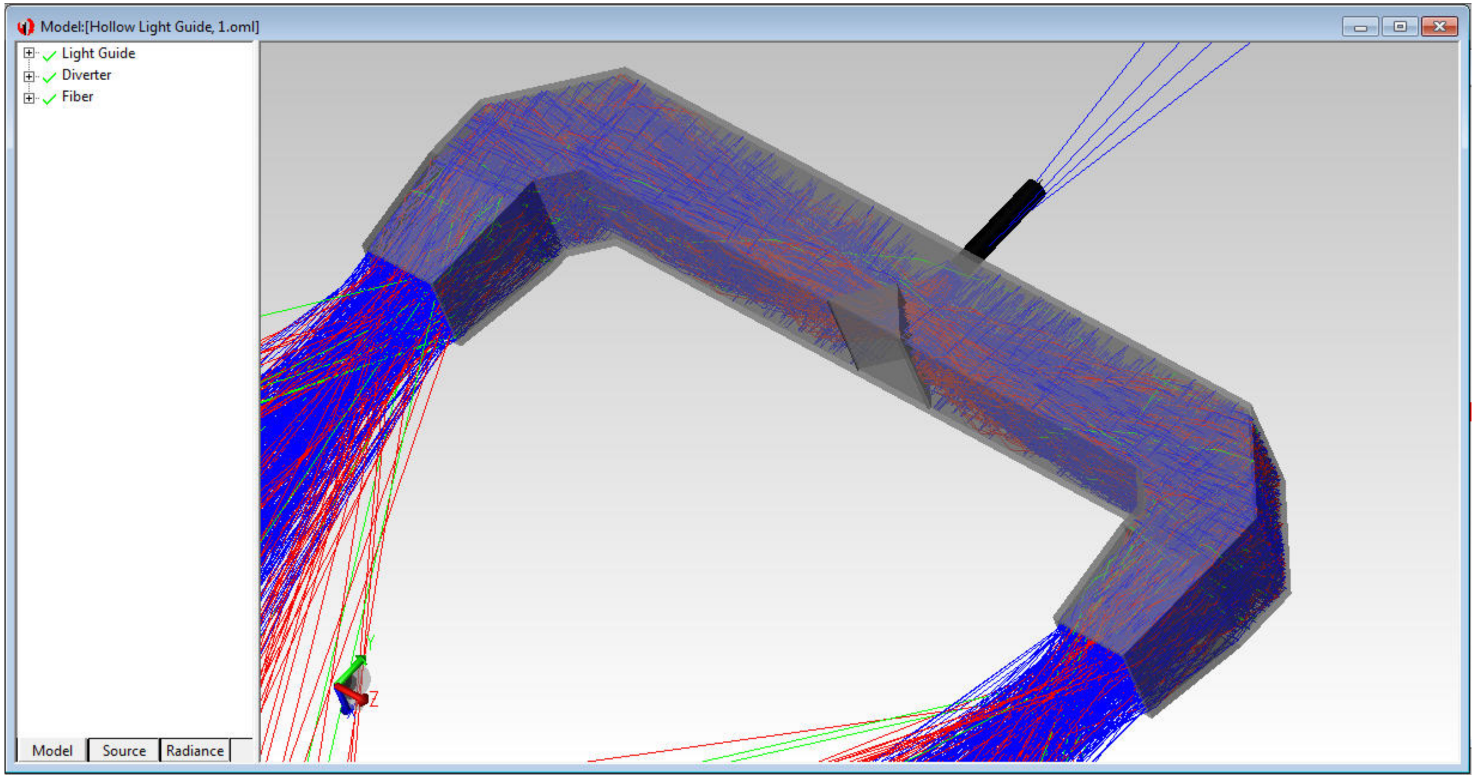
Basics – Breaking TIR



Add a texture to the surface of the light guide.
An example would be a roughened surface for a indicator display.

Basics – Non-TIR



Not all light guides use TIR. An example is a hollow light guide with a reflective interior for a UV application.

Design Software Features

- Extensive property catalogs including Material, Surface, & Surface Source
- Catalogs are user extendable
- Utilities:
  - IES/LDT Analysis
  - Surface Source Property Generator
  - Texture Optimizer
  - 2D and 3D Interactive Optimizers

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Design - Tips

- Avoid sharp corners
- Keep light guide bend radii as large as possible. Use gentle bends if possible and right angle bends only when necessary to maximize light transmittance.
- Use an accurate source models
- To improve efficiency, use scattering surfaces only where necessary
- Trace enough rays to get an accurate answer – both during optimization and in the final analysis

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Design - Tips

- Coupling LED emission into the light pipe for minimal loss, try multiple scenarios to try and maximize LED coupling.
- Consider Light Pipe shape, round, square, rectangular, hexagonal or octagonal are possibilities
- Create uniform angular and positional output on the exit surface of the light pipe if you want the viewer to see light pipe output in a hemisphere around the output surface as a best practice.
- Make sure light can escape from the exit surface

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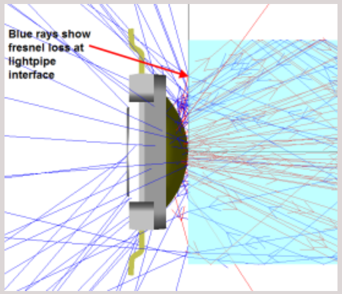
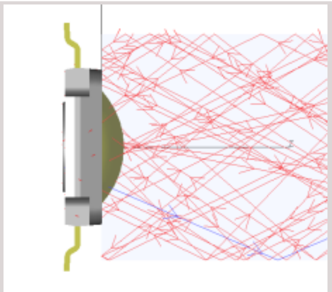
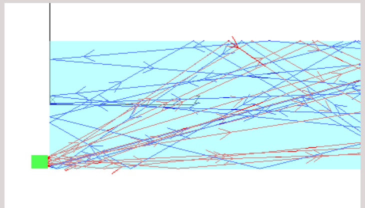
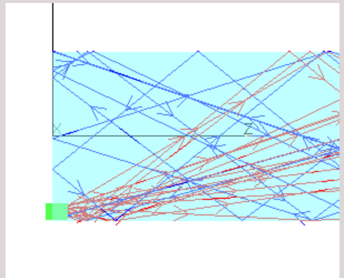
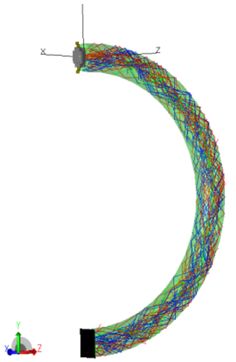
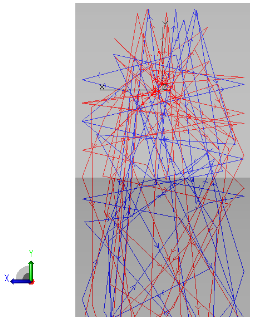
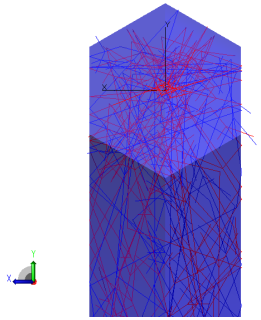
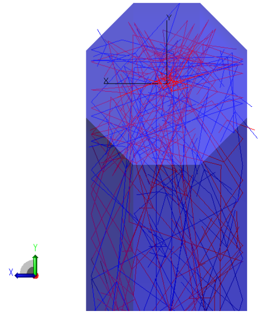
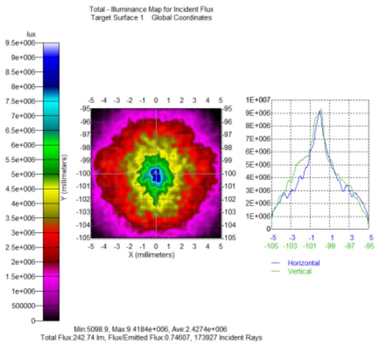
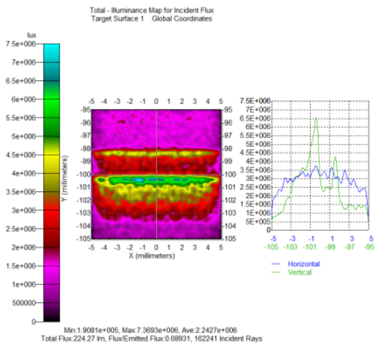
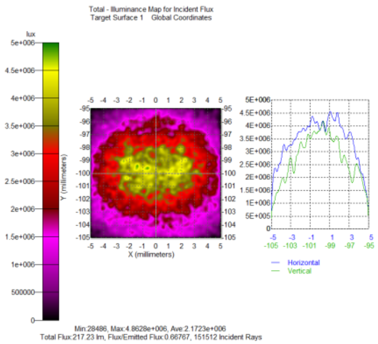
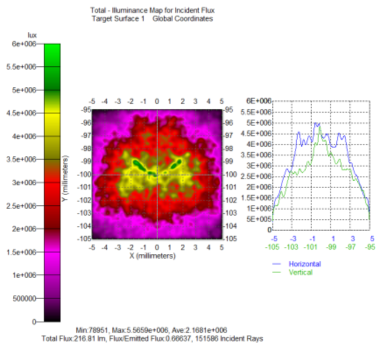
Basics - LED Coupling into the Pipe

Four possible scenarios, LED against the light guide/pipe, LED inside the light guide/pipe

	Round LED against pipe	Round LED inside pipe	Flat LED against pipe	Flat LED inside pipe
Picture of Setup				
Coupling Loss	Fresnel Loss at light pipe	No loss if epoxied into the pipe	Fresnel Loss at light pipe	No loss if epoxied into the pipe
Distance required	Some distance due to size of lens	None	None	None
Tooling	No	Yes	No	Yes
Efficiency	Approx 76%	Approx 42% (TIR Problem)	Approx 76%	Approx 37% (TIR Problem)

Basics - Shape of the Light Guide/Pipe

Lets look at four scenarios, round, rectangular, hexagonal or octagonal sections

Round	Rectangular	Hexagonal	Octagonal
			
			

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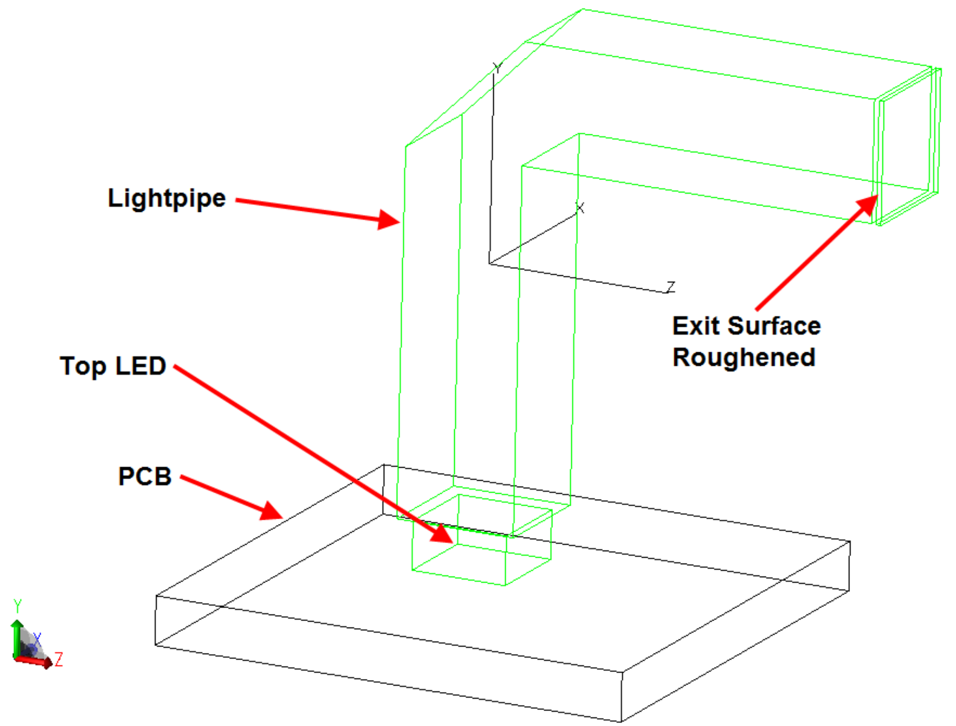
Basics - Picking & Modeling the LED Source

Top Emitting LED Design



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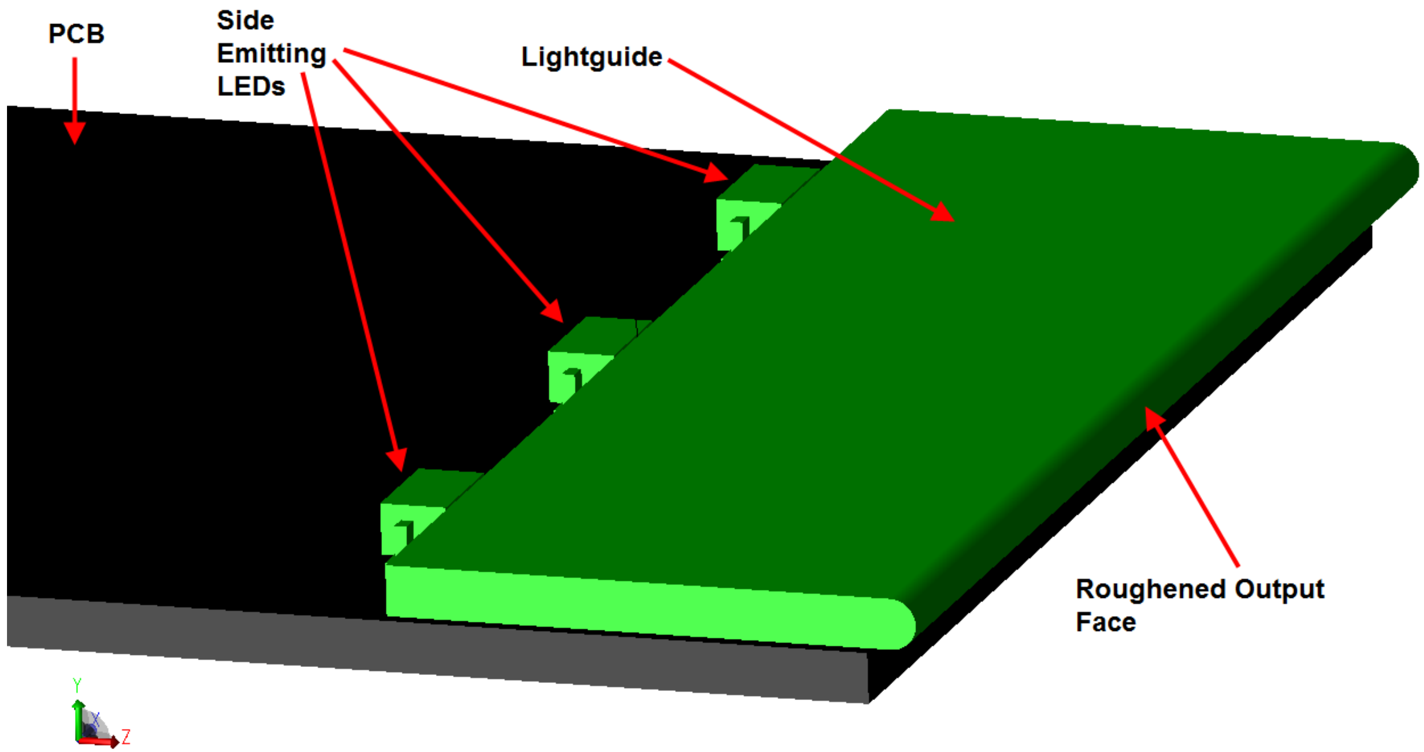
Basics - Picking & Modeling the LED Source

Side Emitting LED Design



Diffusers & Textures

- You can download the TracePro MoldTech Diffuser Catalog at

http://secure.lambdares.com/downloads/TracePro_Properties/Moldtech_DiffuserSurfacePropertyCatalog.txt

- The Luminit catalog at:

http://www.lambdares.com/CustomerSupportCenter/Properties/Luminit_SurfacePropertyCatalog

- The Bayer Makrolon Catalog at:

http://www.lambdares.com/CustomerSupportCenter/Properties/Bayer_SurfacePropertyCatalog.txt

- The Brightview Catalog at:

http://www.lambdares.com/CustomerSupportCenter/Properties/BrightView_SurfacePropertyCatalog.txt

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First Light Guide/Pipe Design Example

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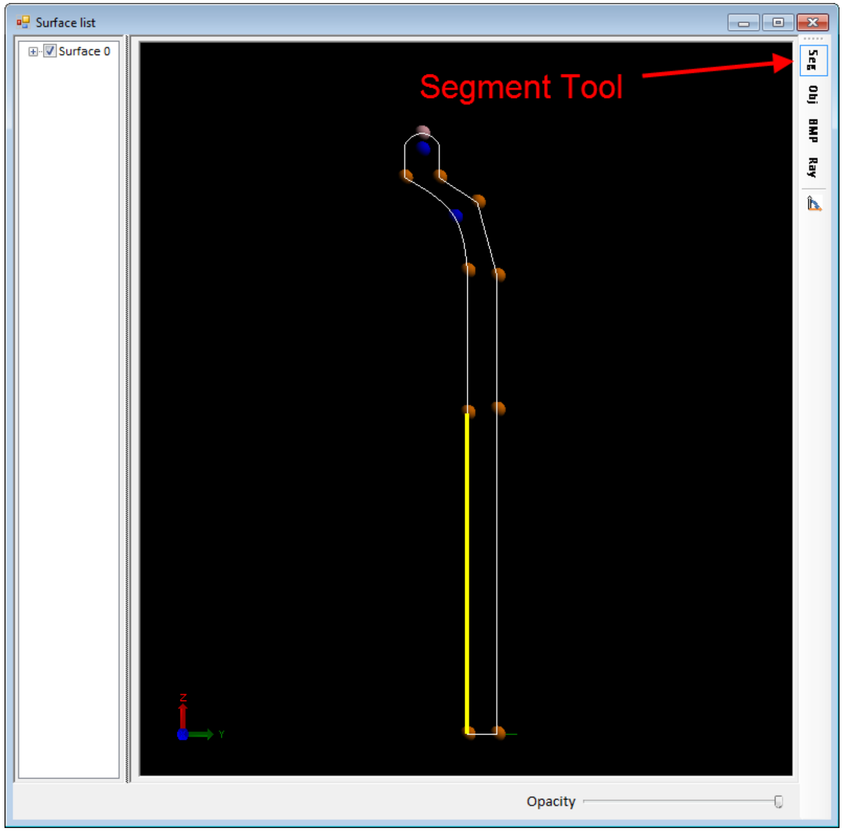
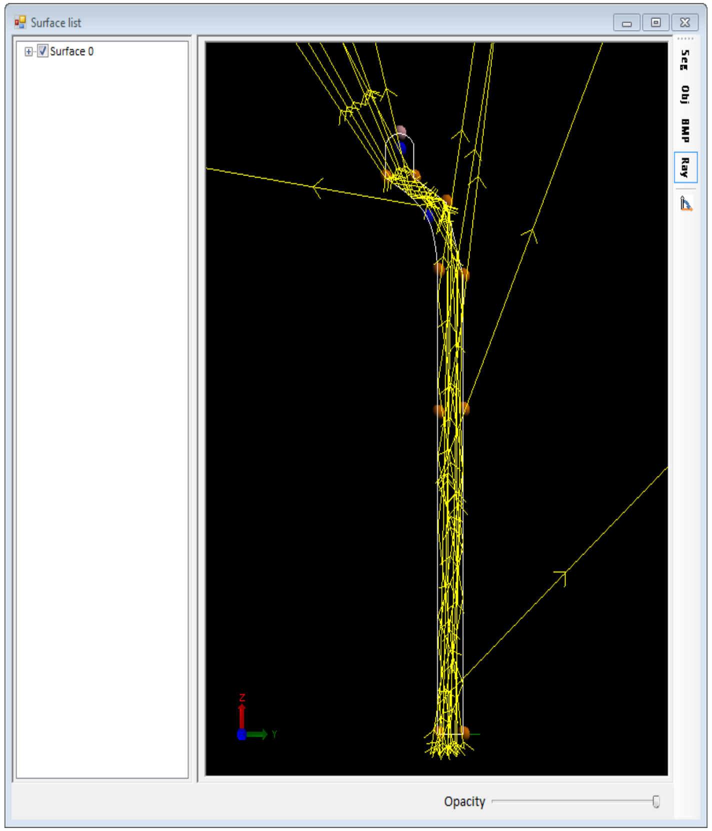
Using the 3D Surface Sketcher to Start with an Initial Good Design

Use the segment tool to layout the profile of the light pipe by creating linear and spline segments



Use the Ray tool to trace rays. Pull on segments to create a good initial design.



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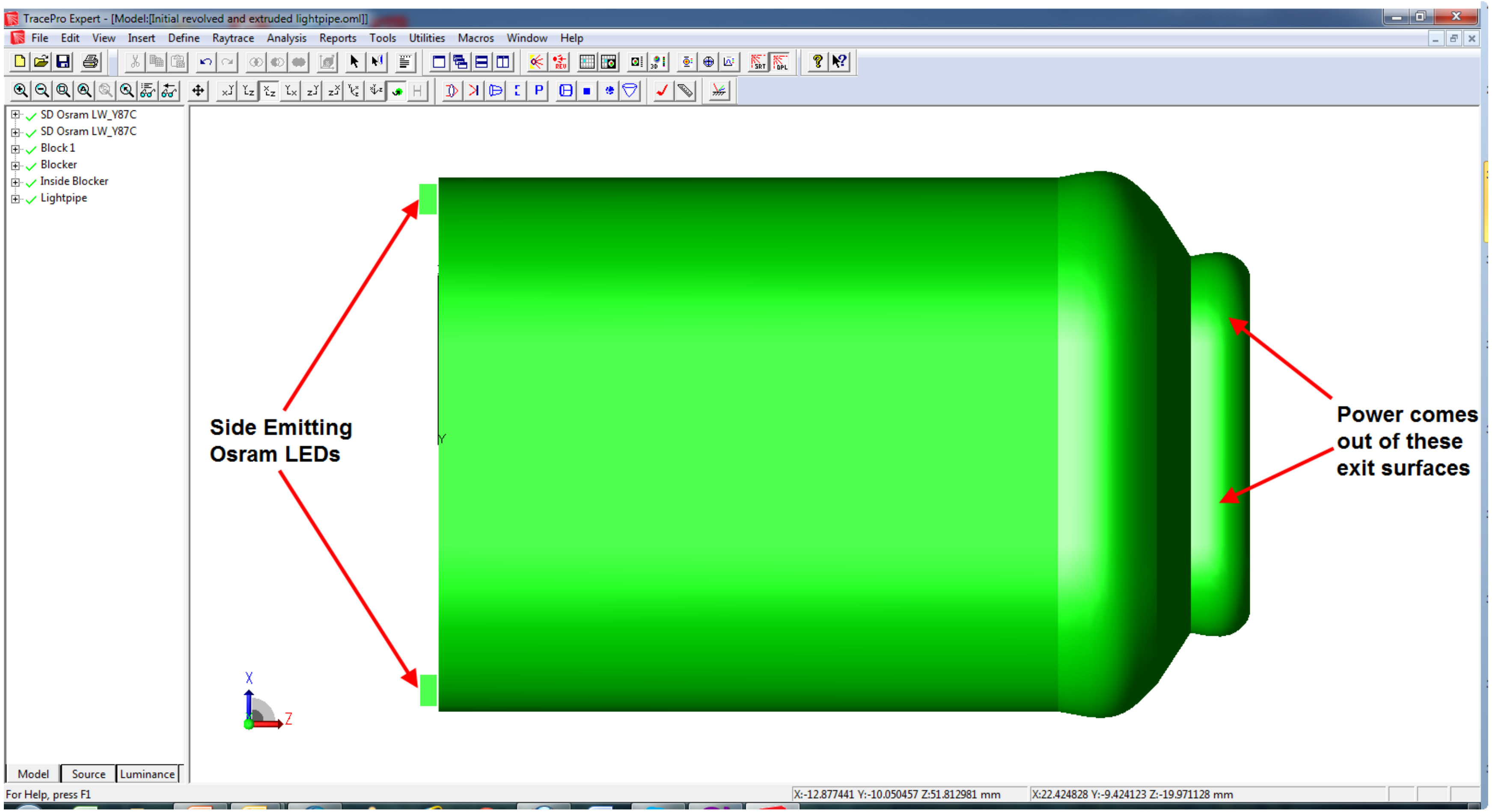
Setting Up the Static System



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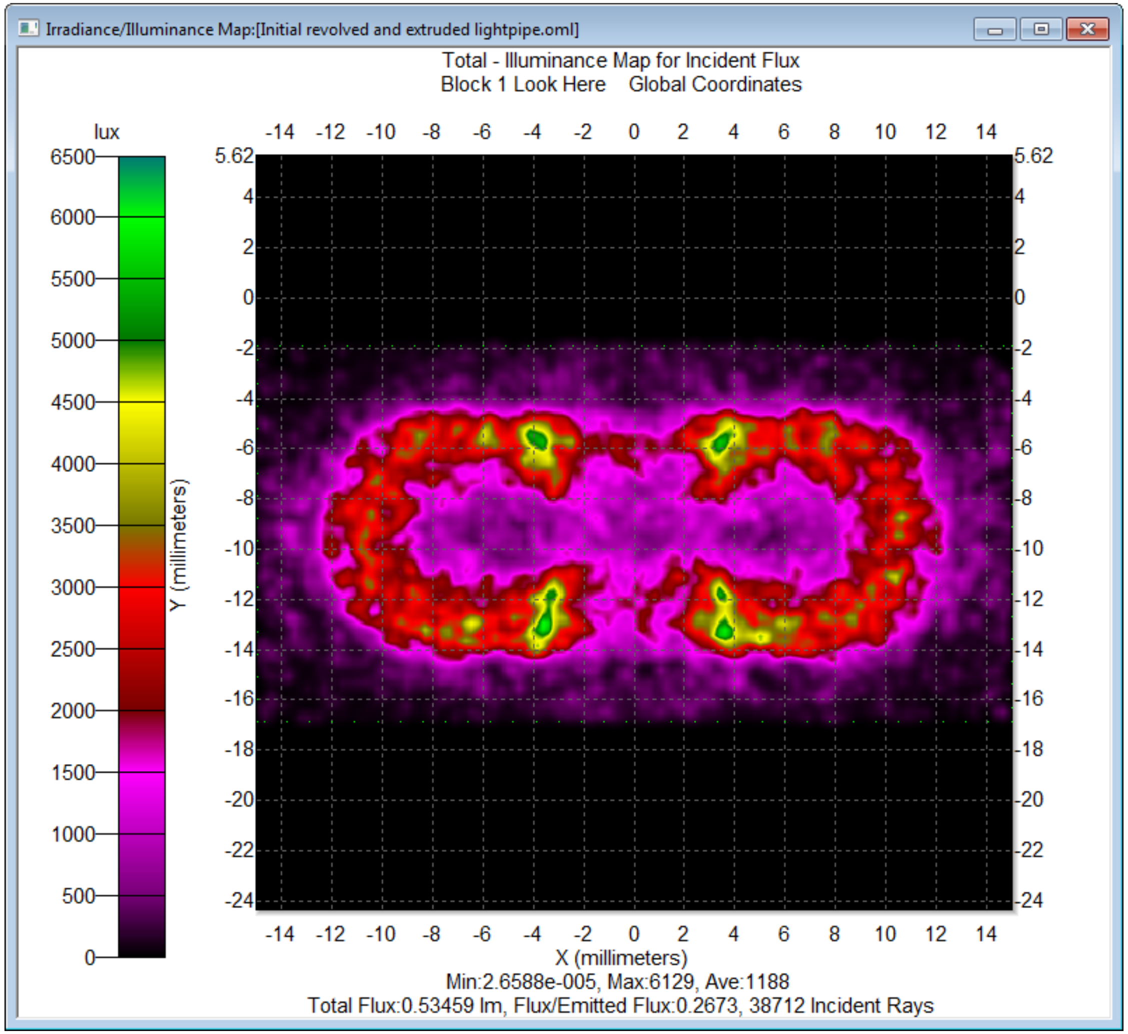
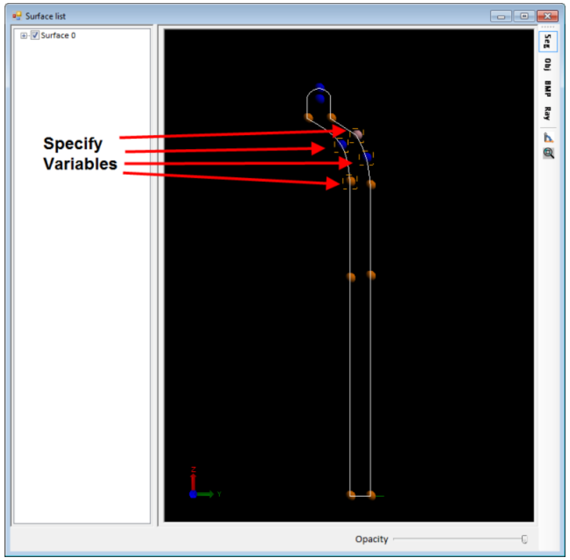
Initial Revision, 26% Efficiency, Poor Uniformity



Setting Up the Optimization

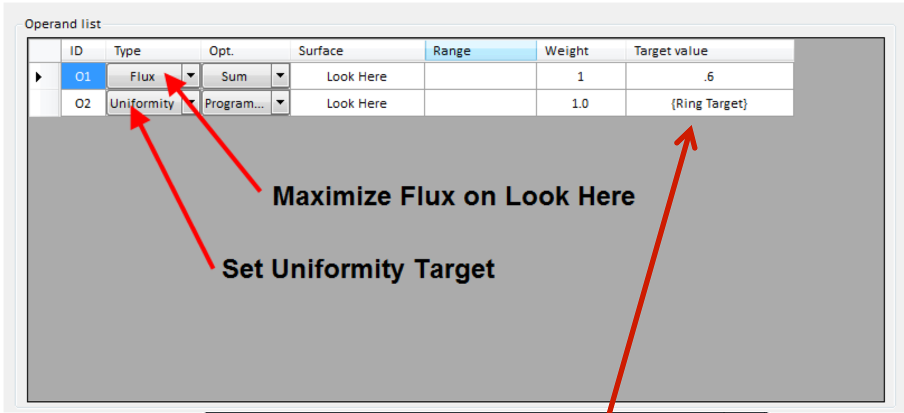
Specify Variables

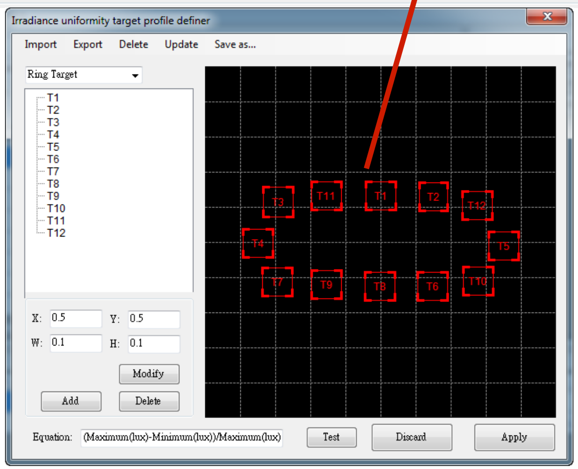


Variable list

	Included?	Item	Object	Var. type	Value	Lo lmt.	Hi lmt.
▶	☑	Position-Y	Seg Pnt:4@Surf:0	RelativeVariable	0.315918266773...	1	1
	☑	Position-Z	Seg Pnt:4@Surf:0	RelativeVariable	47.034854888916	1	1
	☑	Position-Y	Seg Pnt:8@Surf:0	RelativeVariable	1.465048789978...	1	1
	☑	Position-Z	Seg Pnt:8@Surf:0	RelativeVariable	53.92963790893...	1	1
	☑	Position-Y	Ctrl Pnt:0@Seg...	RelativeVariable	51981306076...	1	1
	☑	Position-Z	Ctrl Pnt:0@Seg...	RelativeVariable	51.94477844238...	1	1
	☑	Position-Y	Ctrl Pnt:0@Seg...	RelativeVariable	2.823112249374...	1	1
	☑	Position-Z	Ctrl Pnt:0@Seg...	RelativeVariable	50.79564666748...	1	1

Specify the operands for the Merit Function





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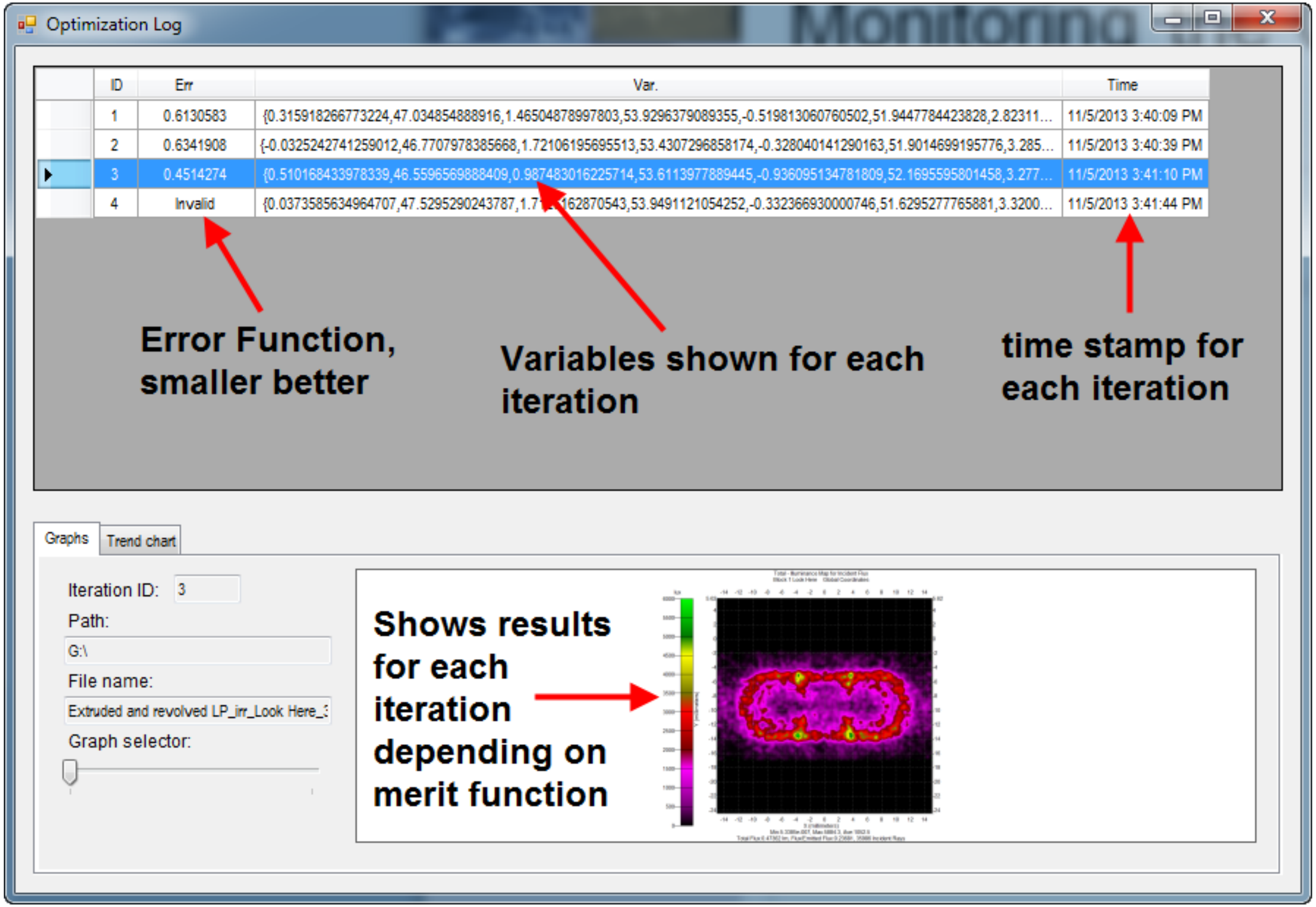
Monitoring the Optimization Process



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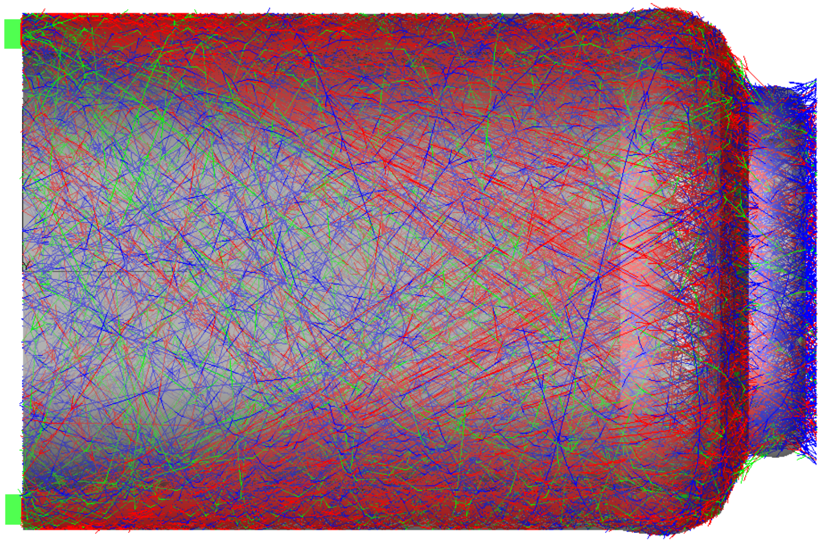
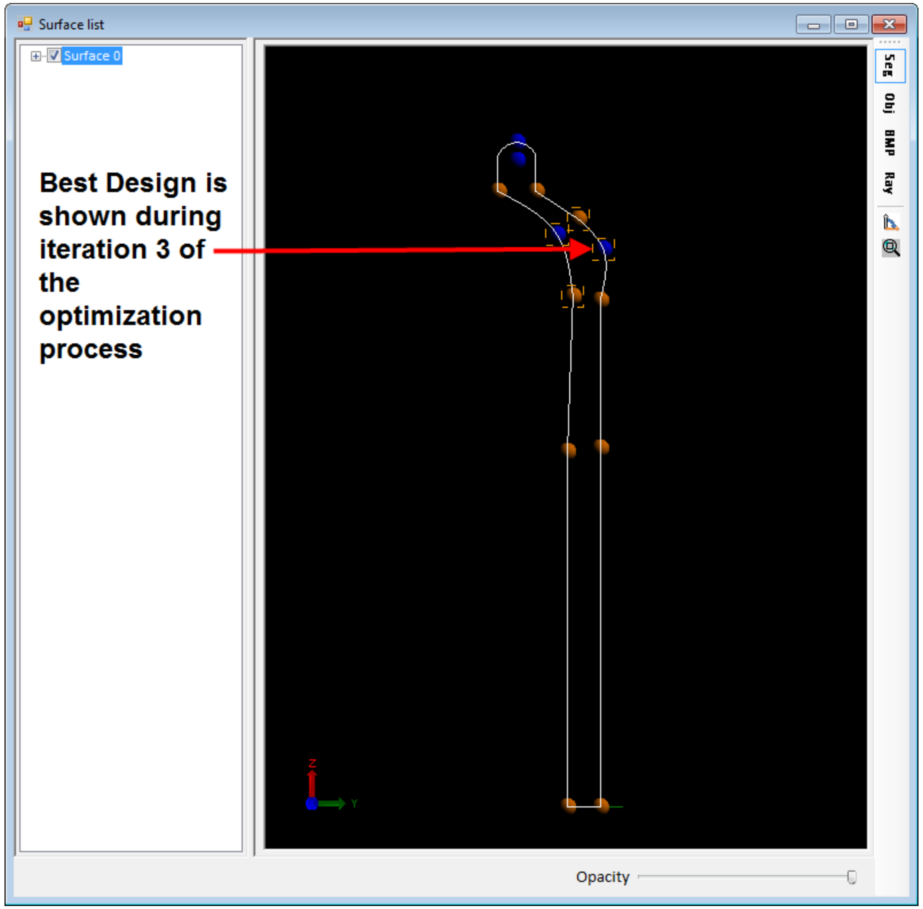
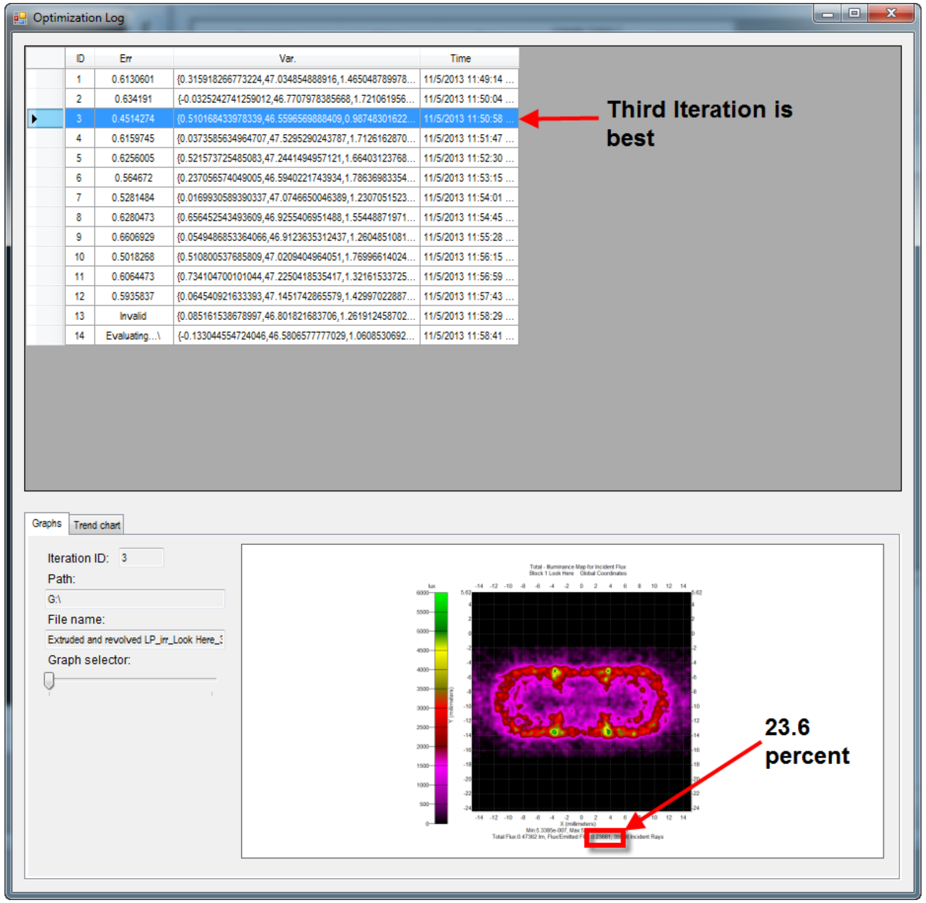
Monitoring the Optimization Process



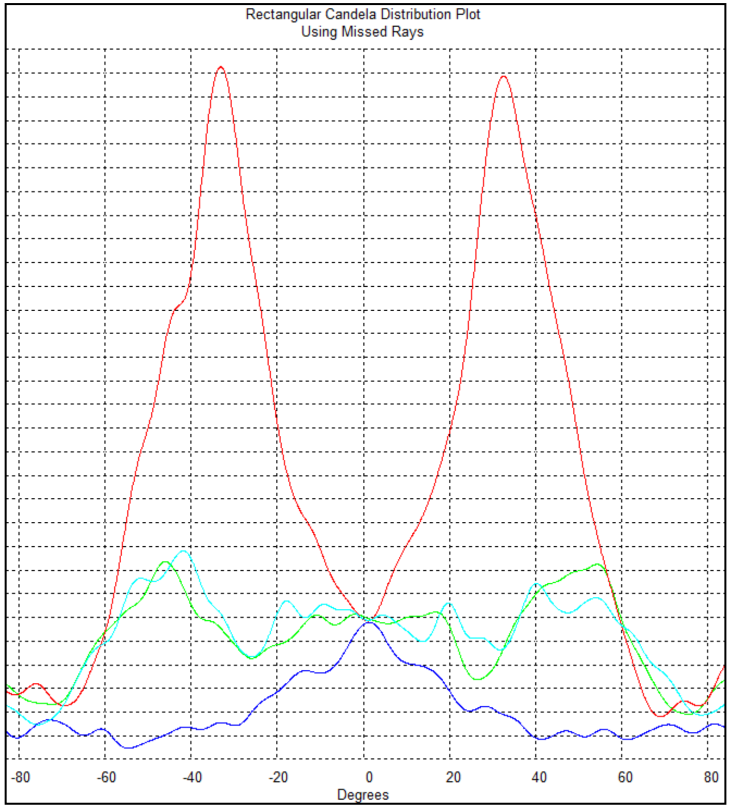


How to Evaluate the Best Iteration

Efficiency 23.5%



Angular Output



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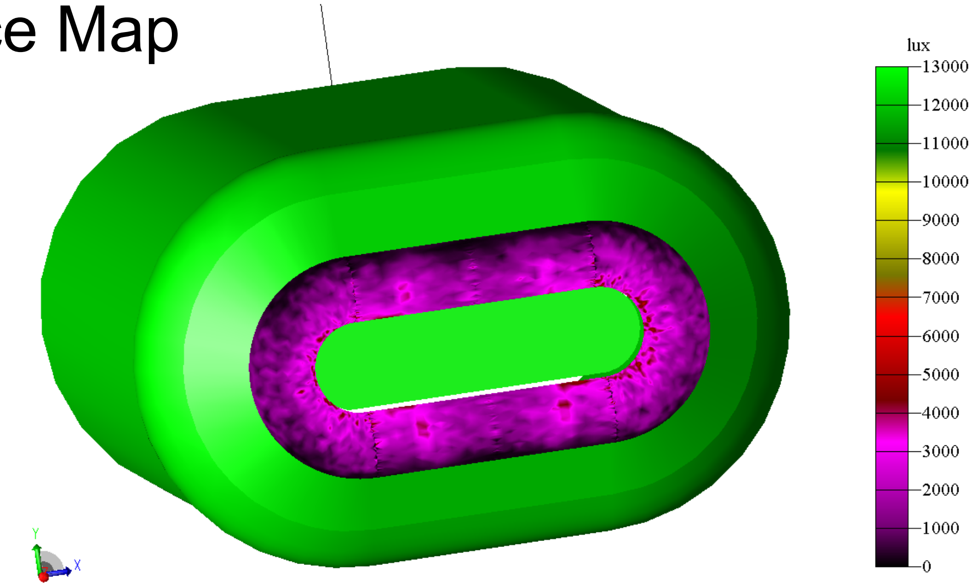
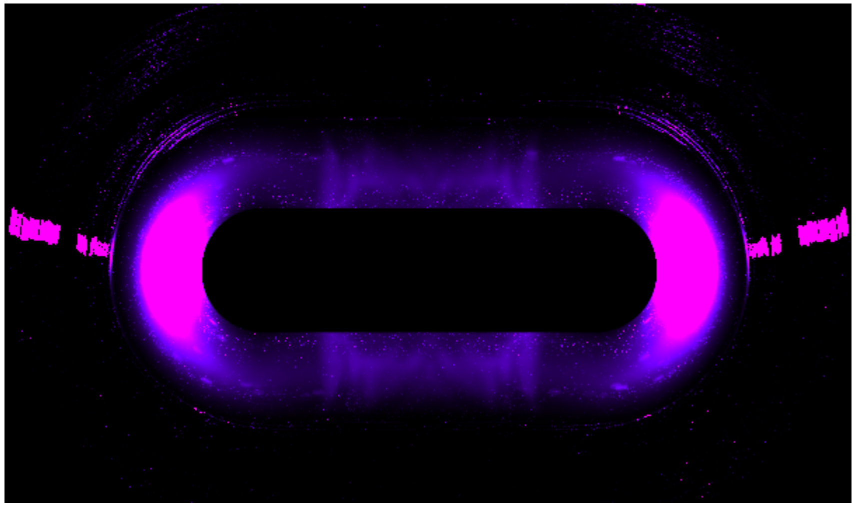
How to Evaluate the Final Iteration

3D Irradiance Map





Photorealistic Rendering

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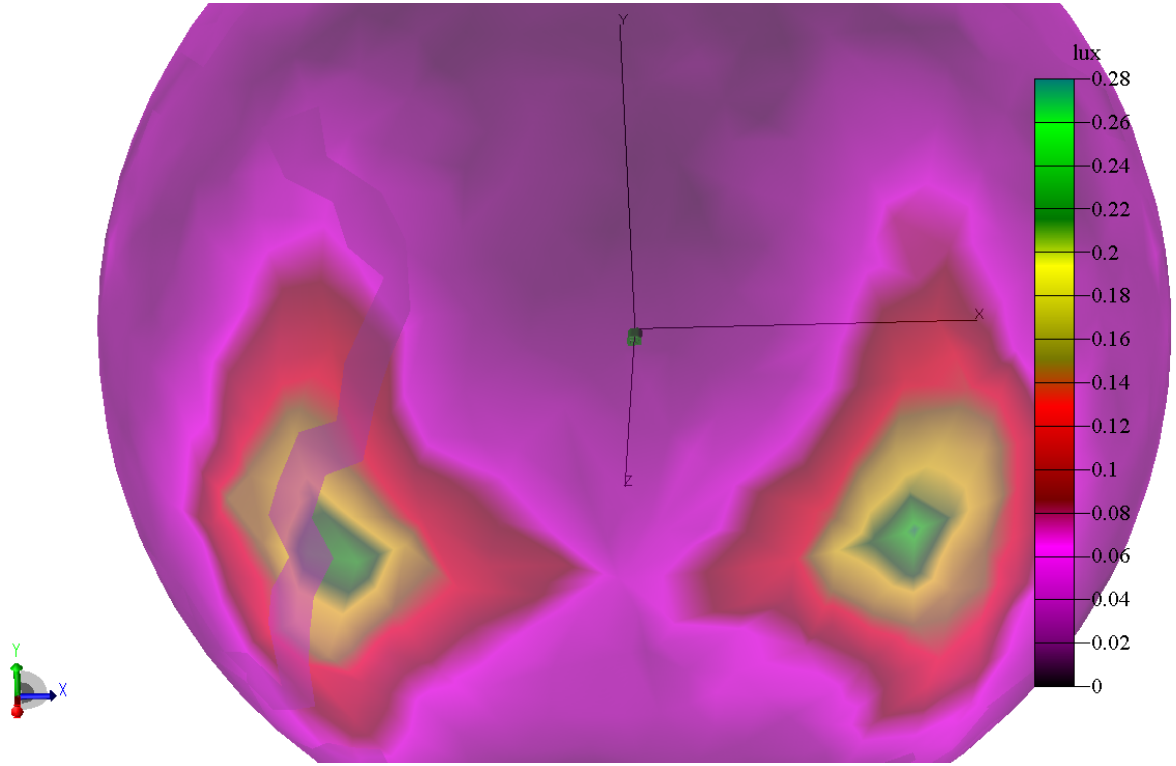
Verifying Angular Output Using a Sphere that's a Large Distance from the Light Guide/Pipe

Another way to see the uniformity of the light exiting the light pipe is by placing a sphere a far distance away and doing a 3D irradiance on the sphere. As can be seen in the figure above there are two hotspots at either side of the exit surfaces indicating very poor uniformity out of the light pipe.



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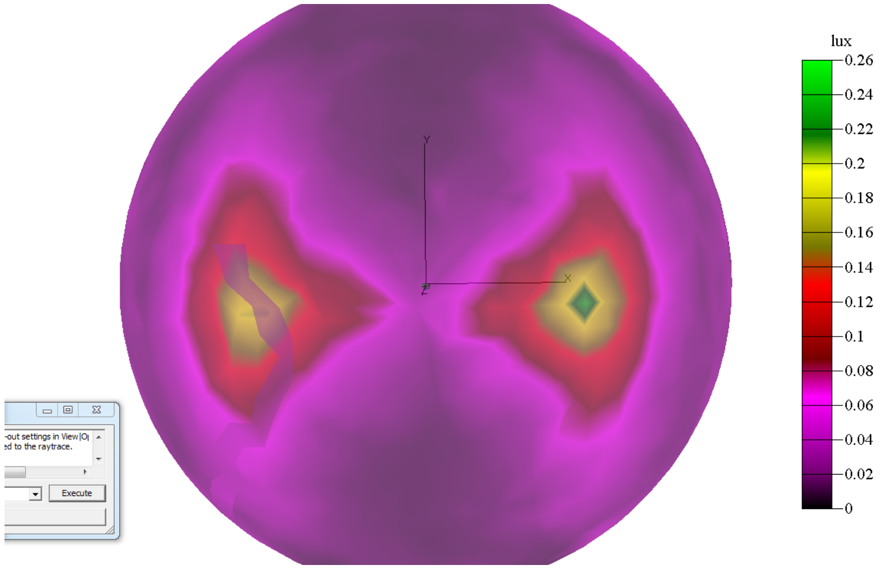
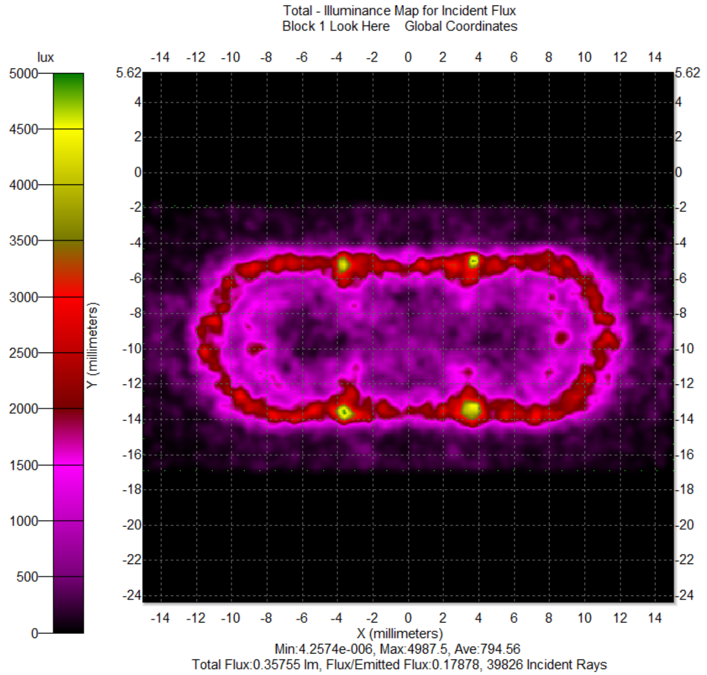
Trying Different Textures on Exit Surfaces to Increase Uniformity



Moldtech texture 11007 was used on the exit surfaces of the light pipe, better positional uniformity, less efficiency and about the same angular uniformity.



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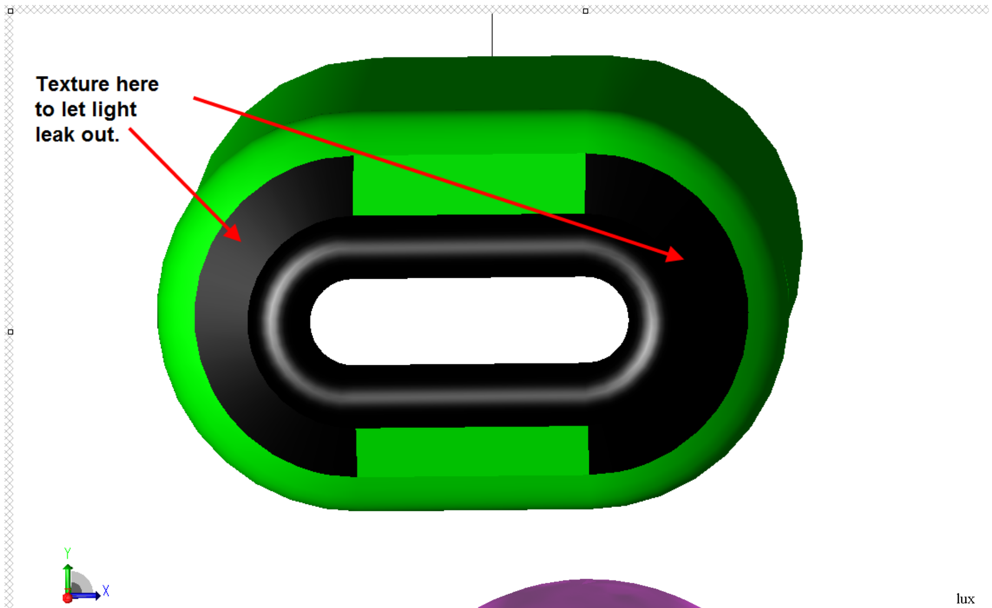
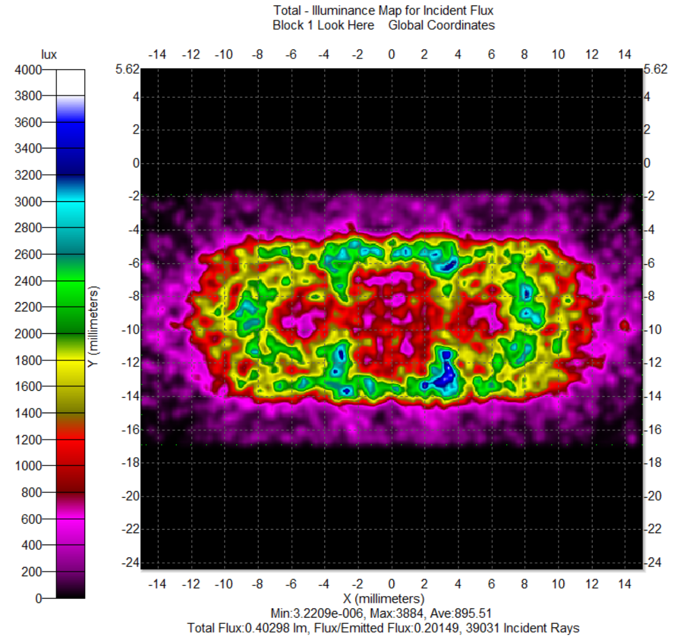
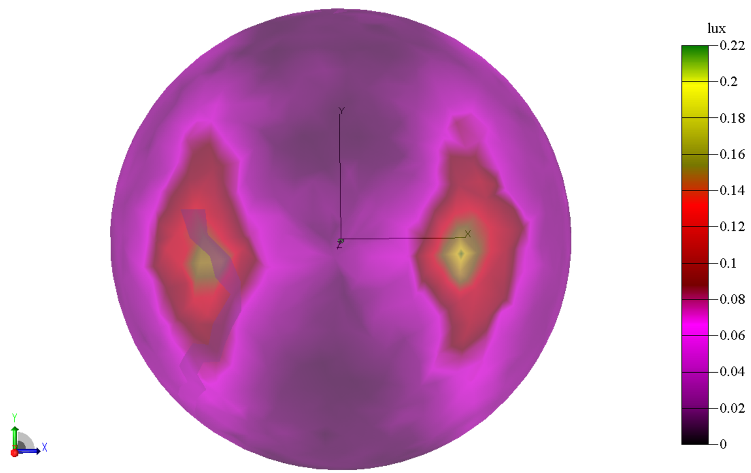
Adding Texture Around Exit Surfaces to Leak Light Out Where You Don't Need It!







Texture all exit surfaces as shown in the upper left figure, better uniformity, good efficiency and better angular output.

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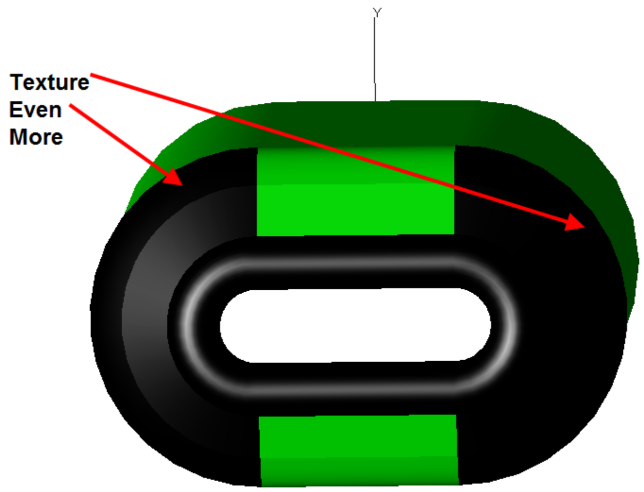
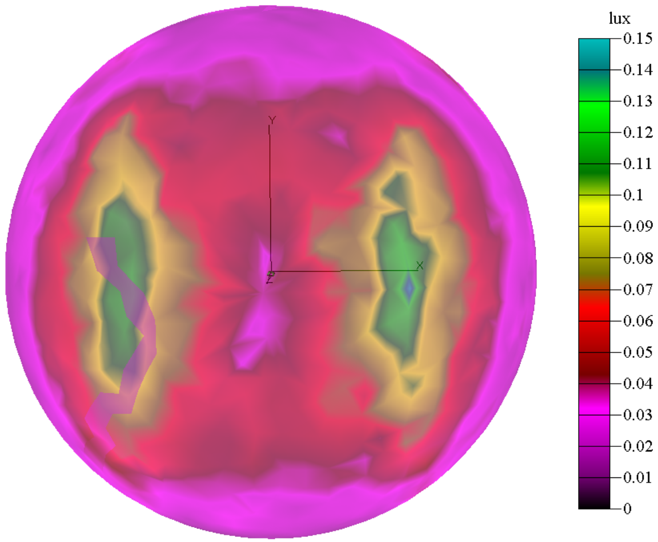
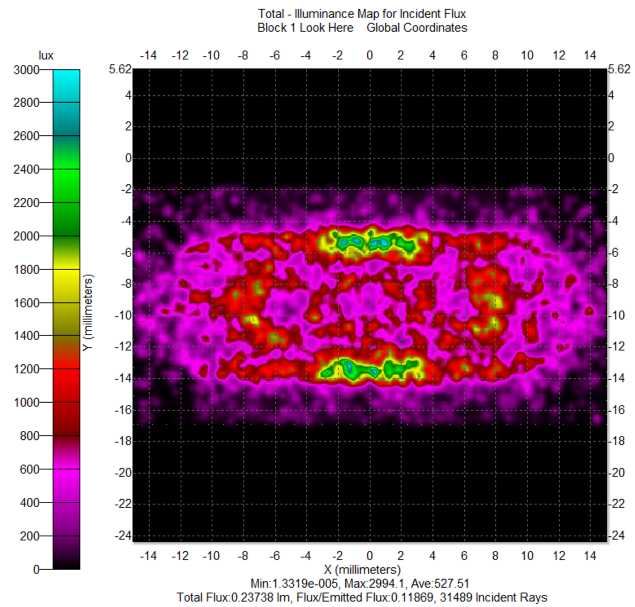
Adding Even More Texture Around Exit Surfaces lets Light scatter around more!

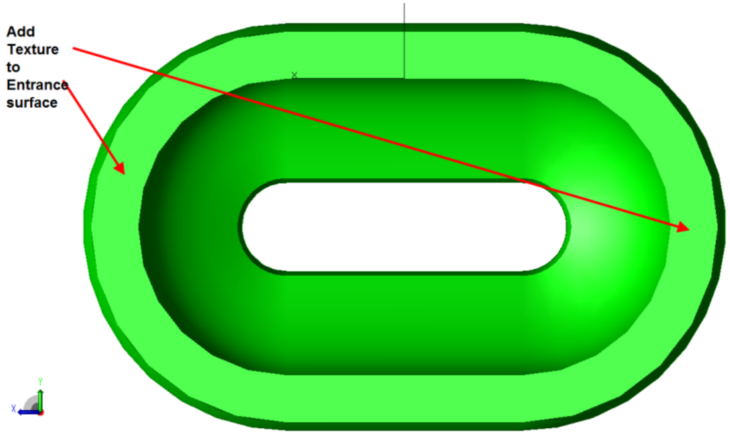


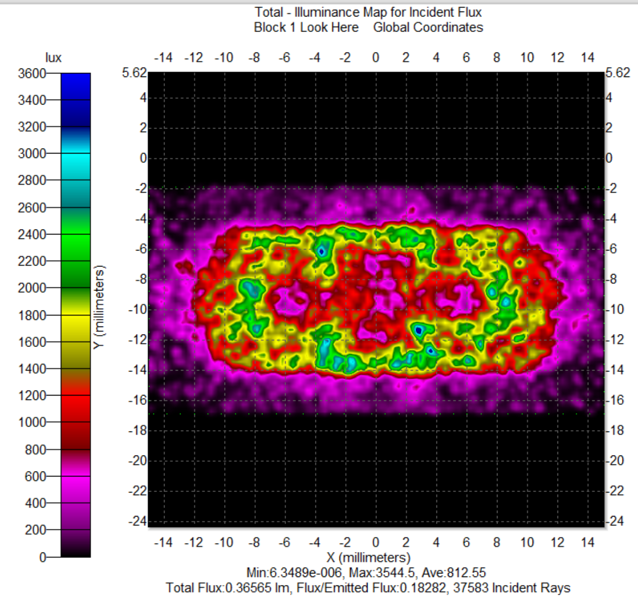


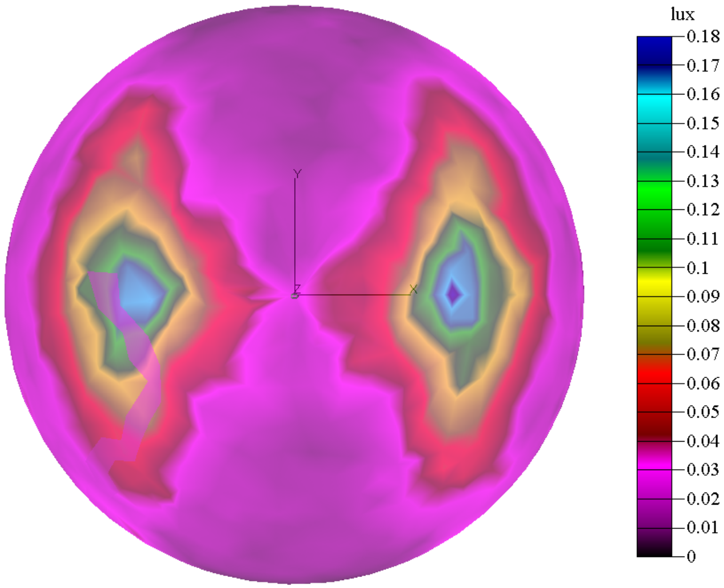


Texture even more surfaces on the front of the light pipe as shown in the upper left figure, uniformity is not as good, efficiency reduces dramatically but better angular output.

Adding Texture to the Entrance Surfaces to Diffuse Light Out to the Outer Angular Areas!







Adding texture to the entrance and exit surfaces diffuses the LED emission outward both entering and leaving the light pipe. For this scenario we have good angular and position uniformity, and good efficiency.

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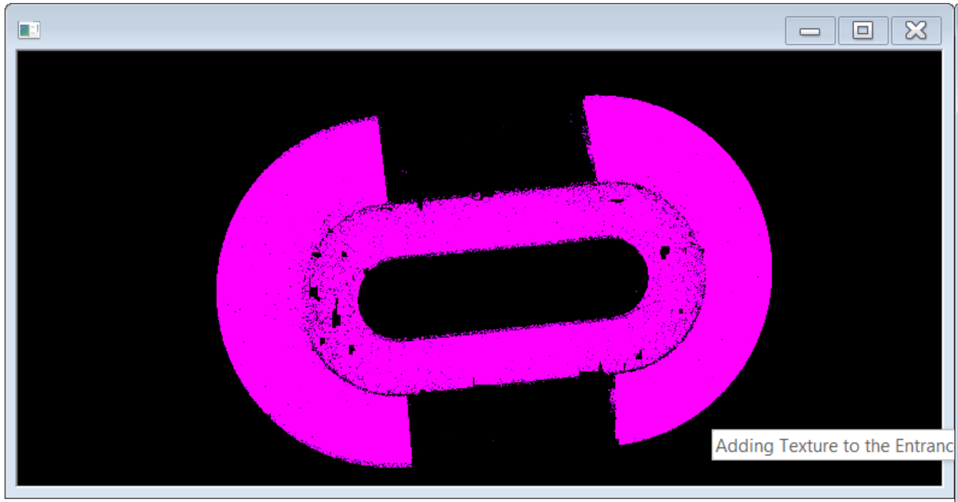
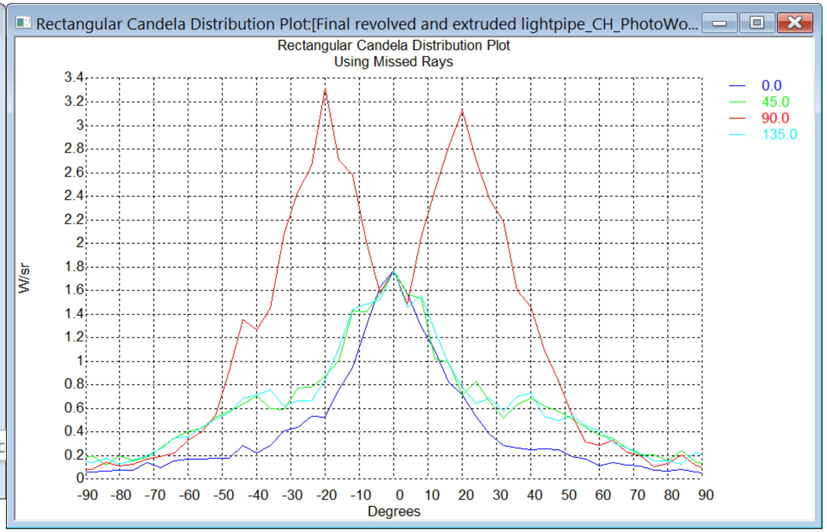
Photorealistic Render of the Light Pipe with Texture on the Entrance and Exit Surfaces





Adding texture to the entrance and exit surfaces diffuses the LED emission both entering and leaving the light pipe. Looking at the photo realistic render we can see light exiting from the diffuse textured areas. Even though the areas that are textured include the area around the exit surface, this is what we need to create good angular and positional uniformity. This areas will be blocked by a housing that absorbs the light.

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Second Light Guide/Pipe Design Example

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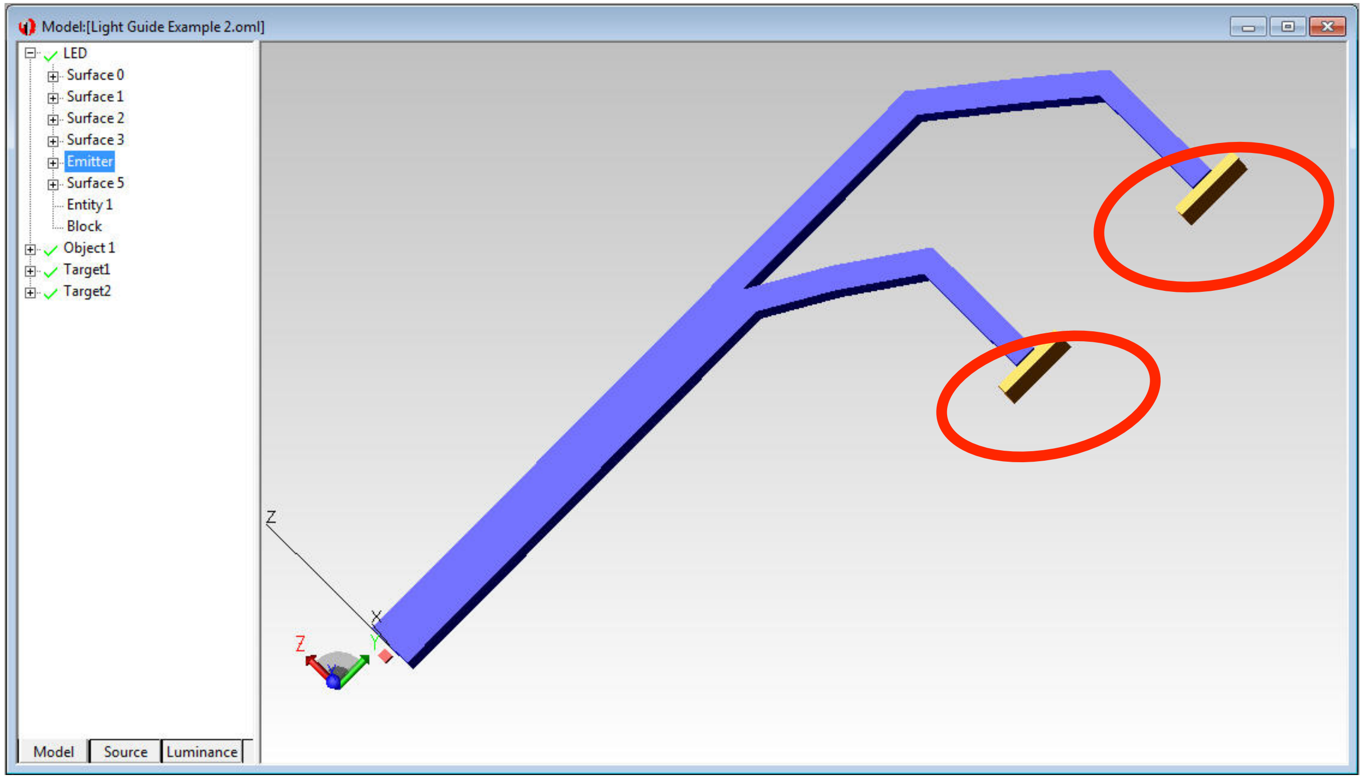
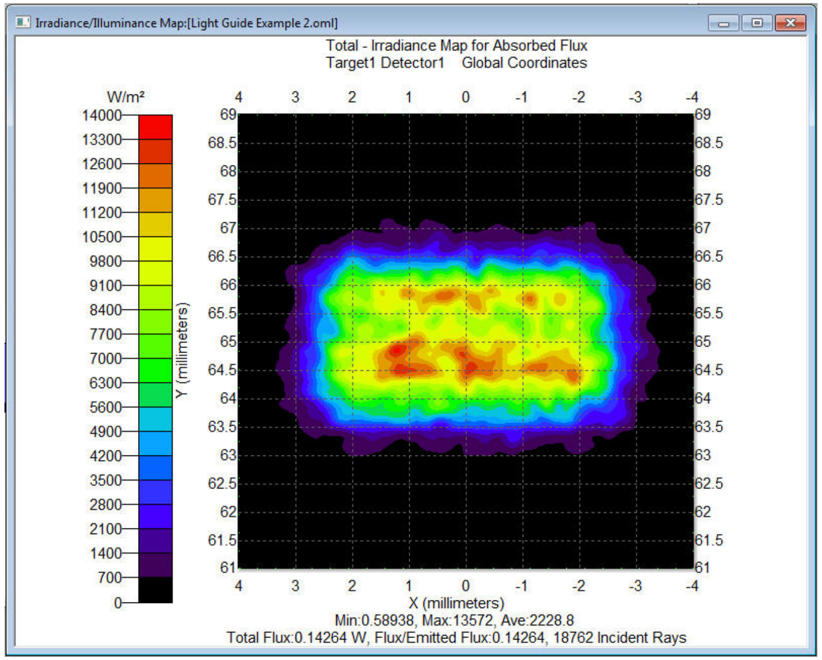
3D Interactive Optimizer



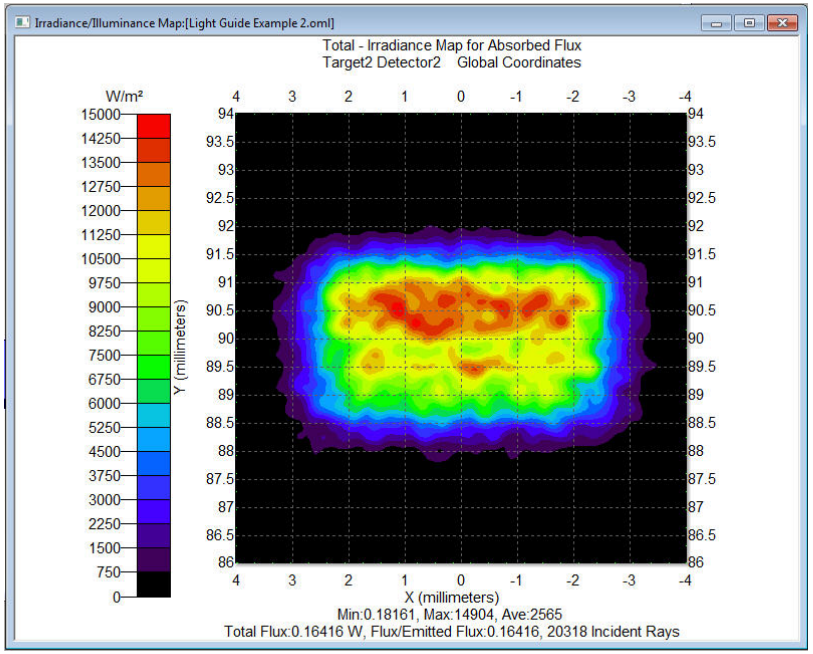
Goal is to optimize the bends in the light guide for equal light at both outputs with the best efficiency

3D Interactive Optimizer

Initial Irradiance Maps – 1-watt source



Leg 1
0.143 watts



Leg 2
0.164 watts

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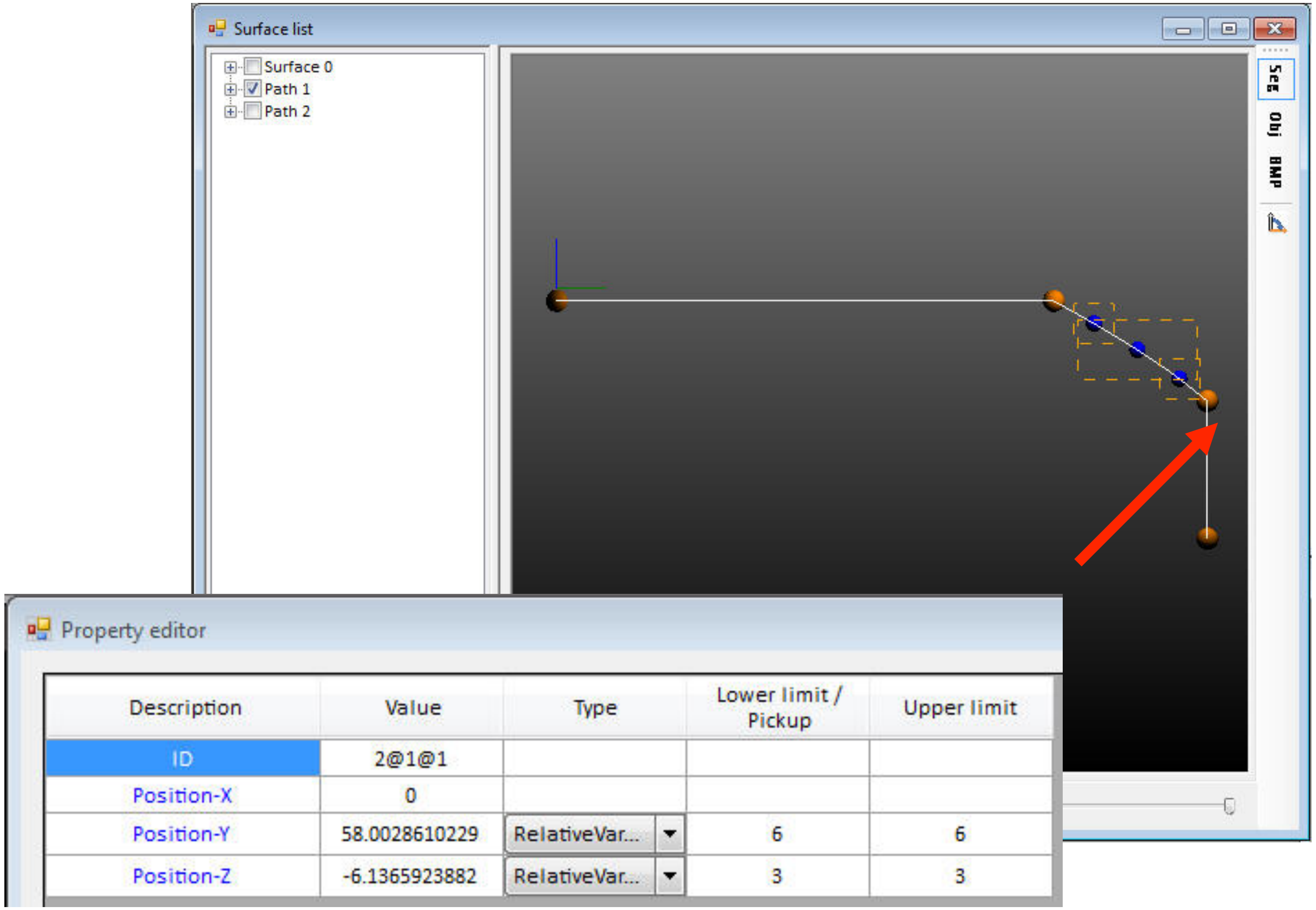
3D Interactive Optimizer

Leg 1 Optimization variables – 3 spline control points



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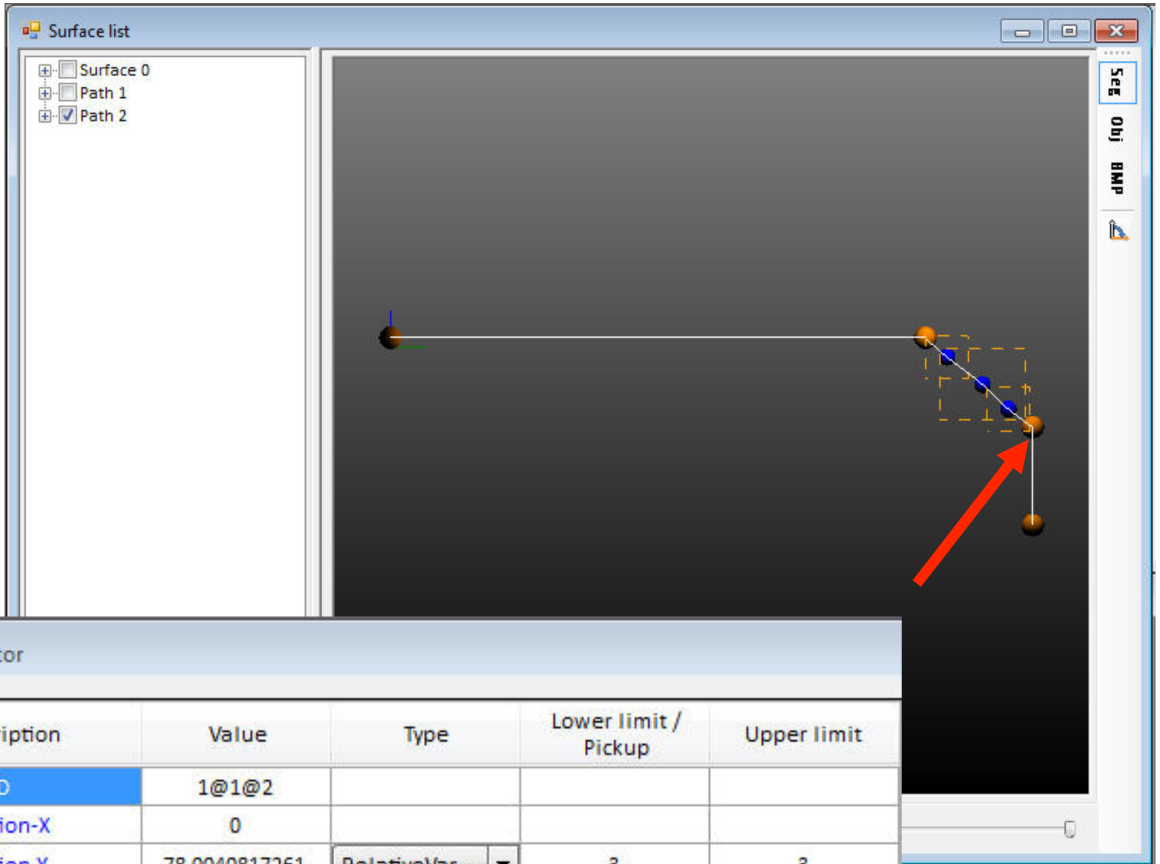
3D Interactive Optimizer

Leg 2 Optimization variables – 3 spline control points



Property editor

Description	Value	Type	Lower limit / Pickup	Upper limit
ID	1@1@2			
Position-X	0			
Position-Y	78.0040817261	RelativeVar...	3	3
Position-Z	-1.4731316566	RelativeVar...	3	3

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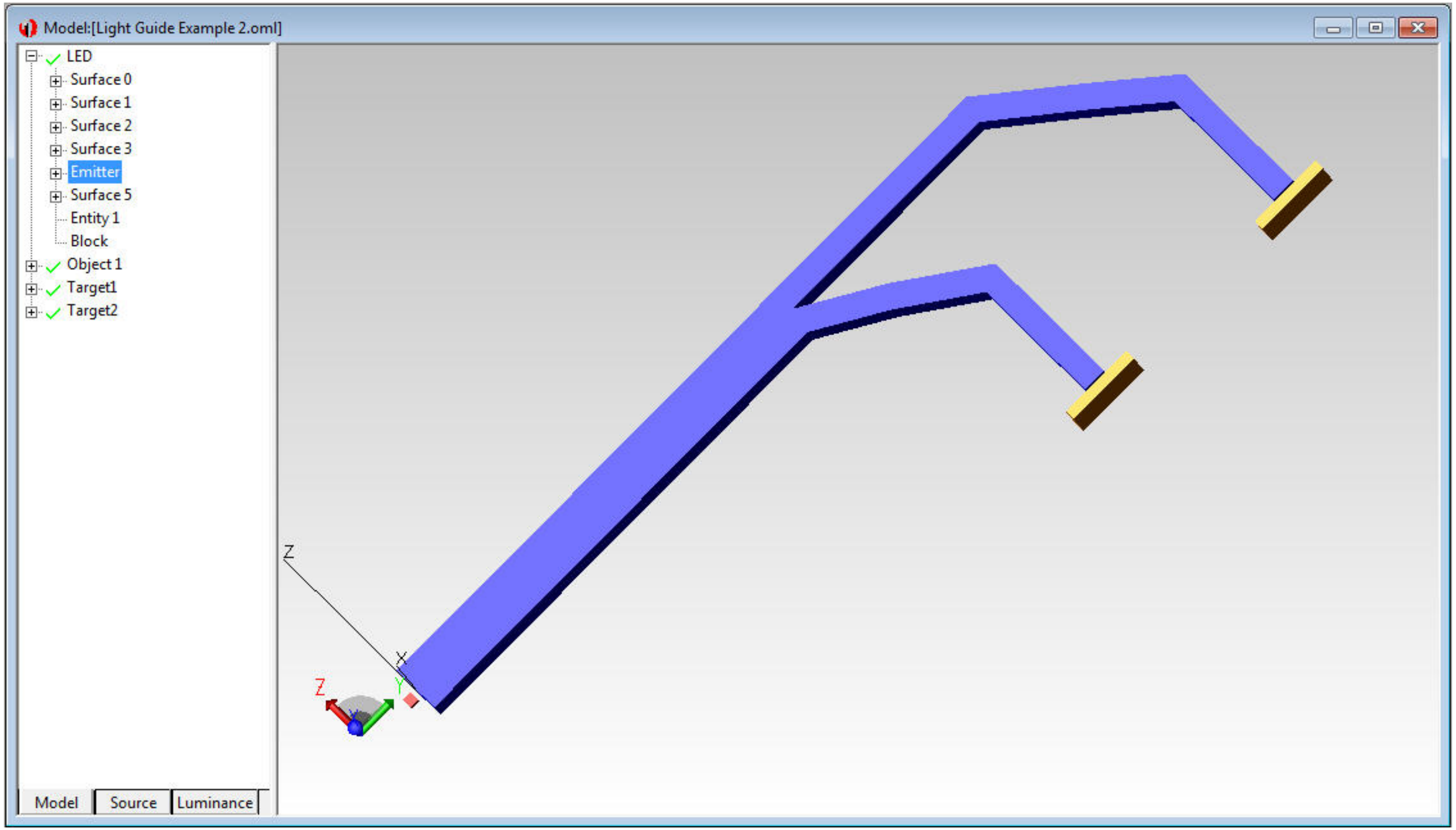
3D Interactive Optimizer

Setting up the Model



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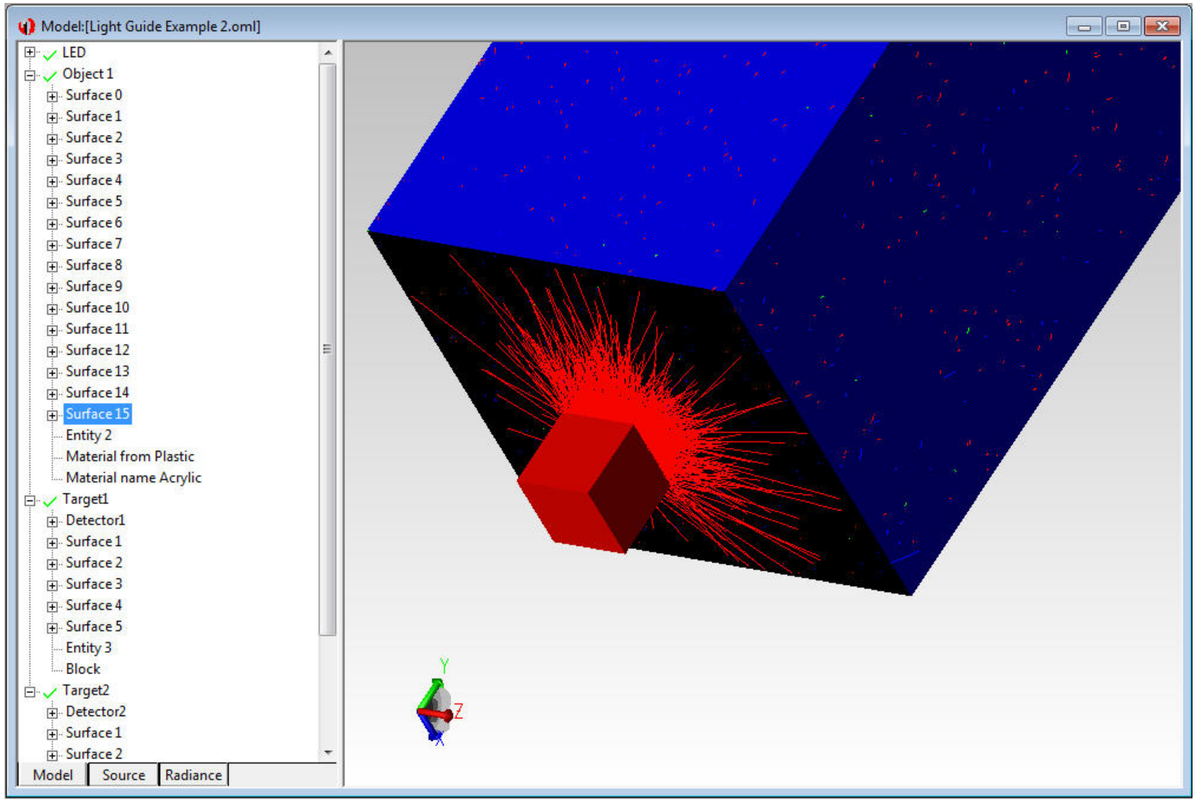
3D Interactive Optimizer

Setting up the Model – LED Source



Cree XP-E White LED Surface Source Property

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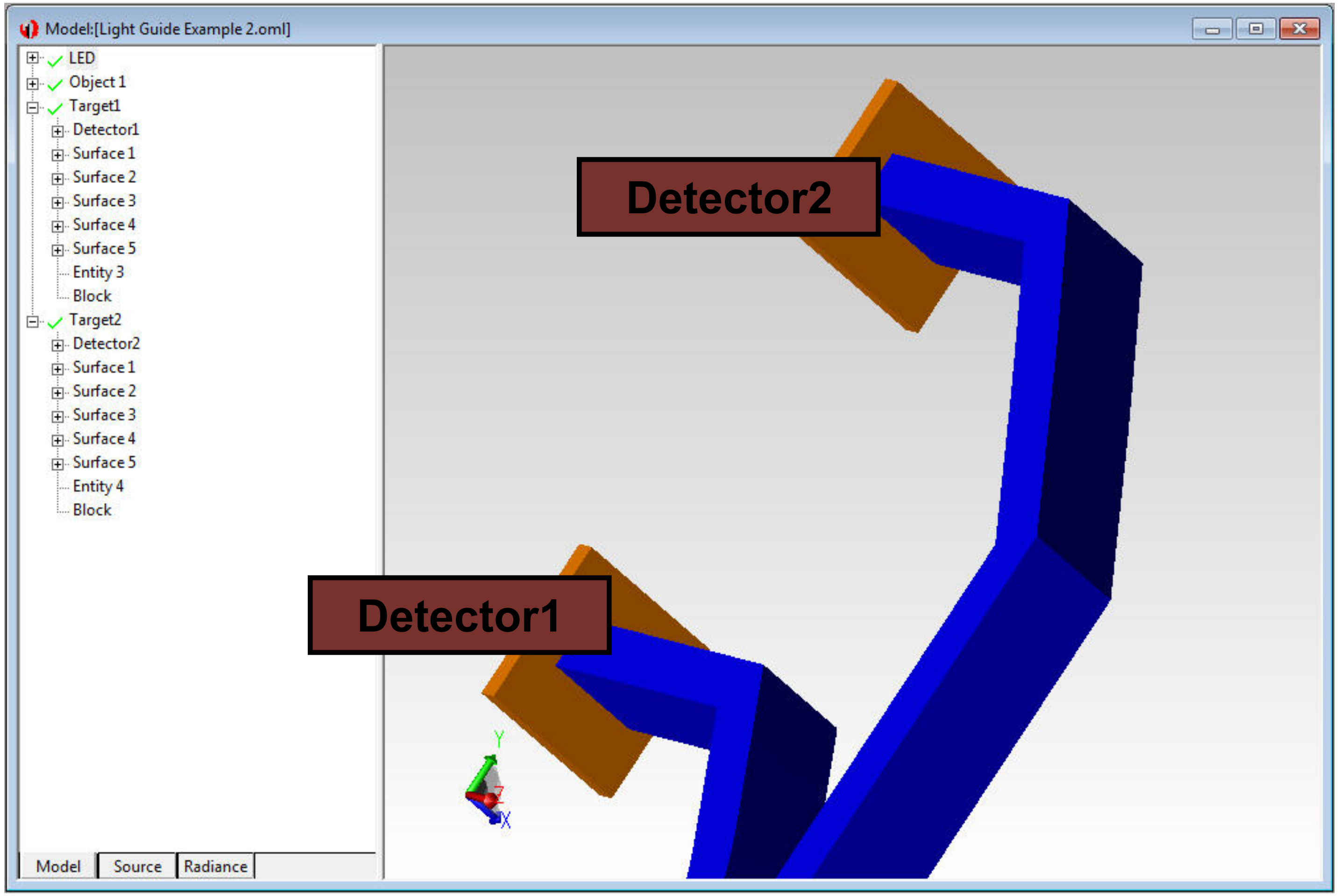
3D Interactive Optimizer

Setting up the Model - Targets



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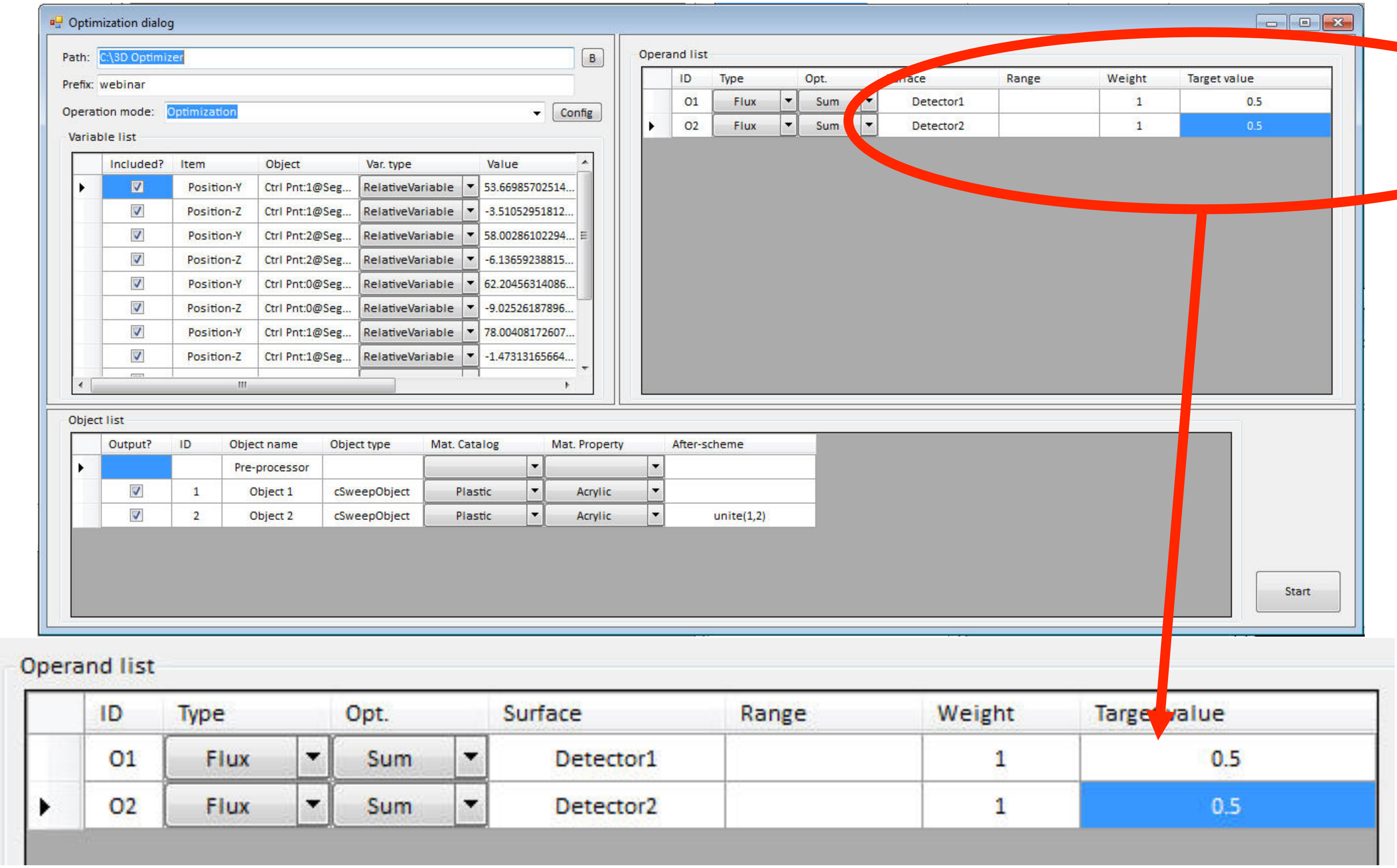
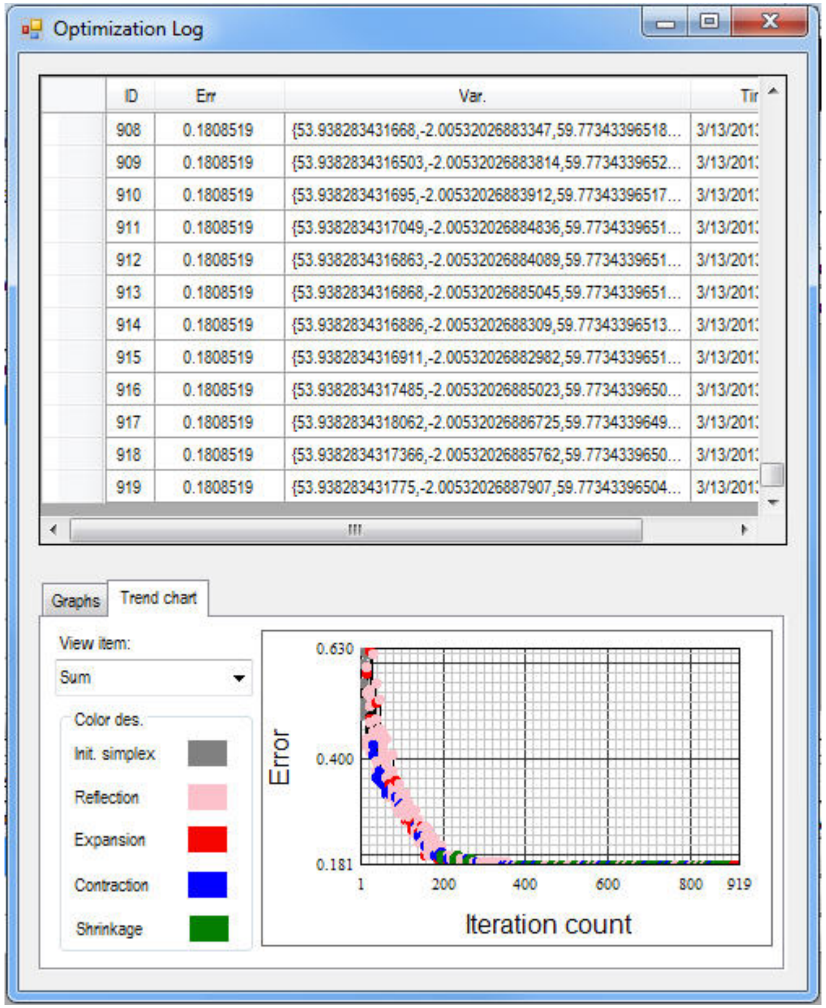
3D Interactive Optimizer

Optimization Operands



3D Interactive Optimizer

Optimization Results – Optimization Log

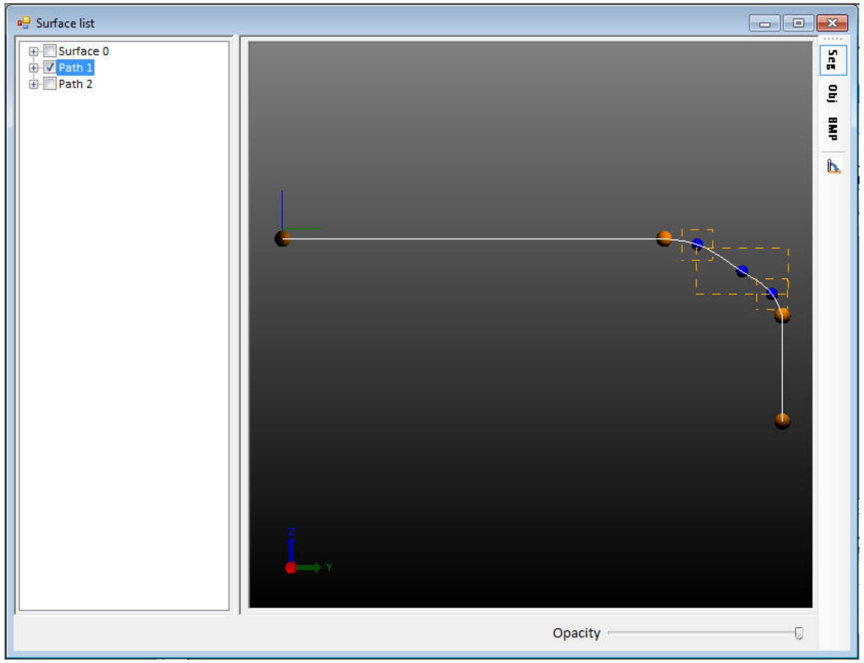


919 iterations

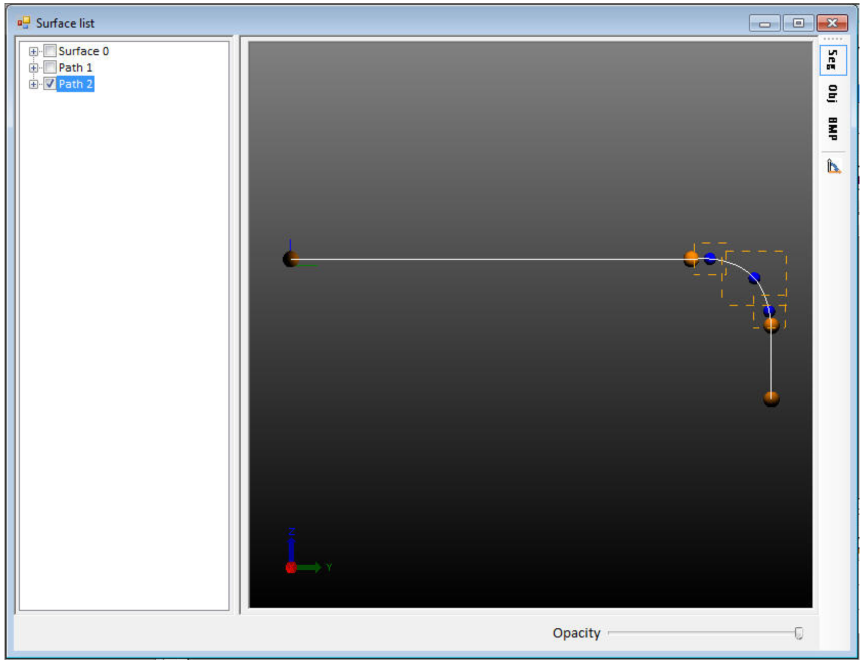
Best result at iteration **483**

3D Interactive Optimizer

Optimization Results – New Sweep Paths



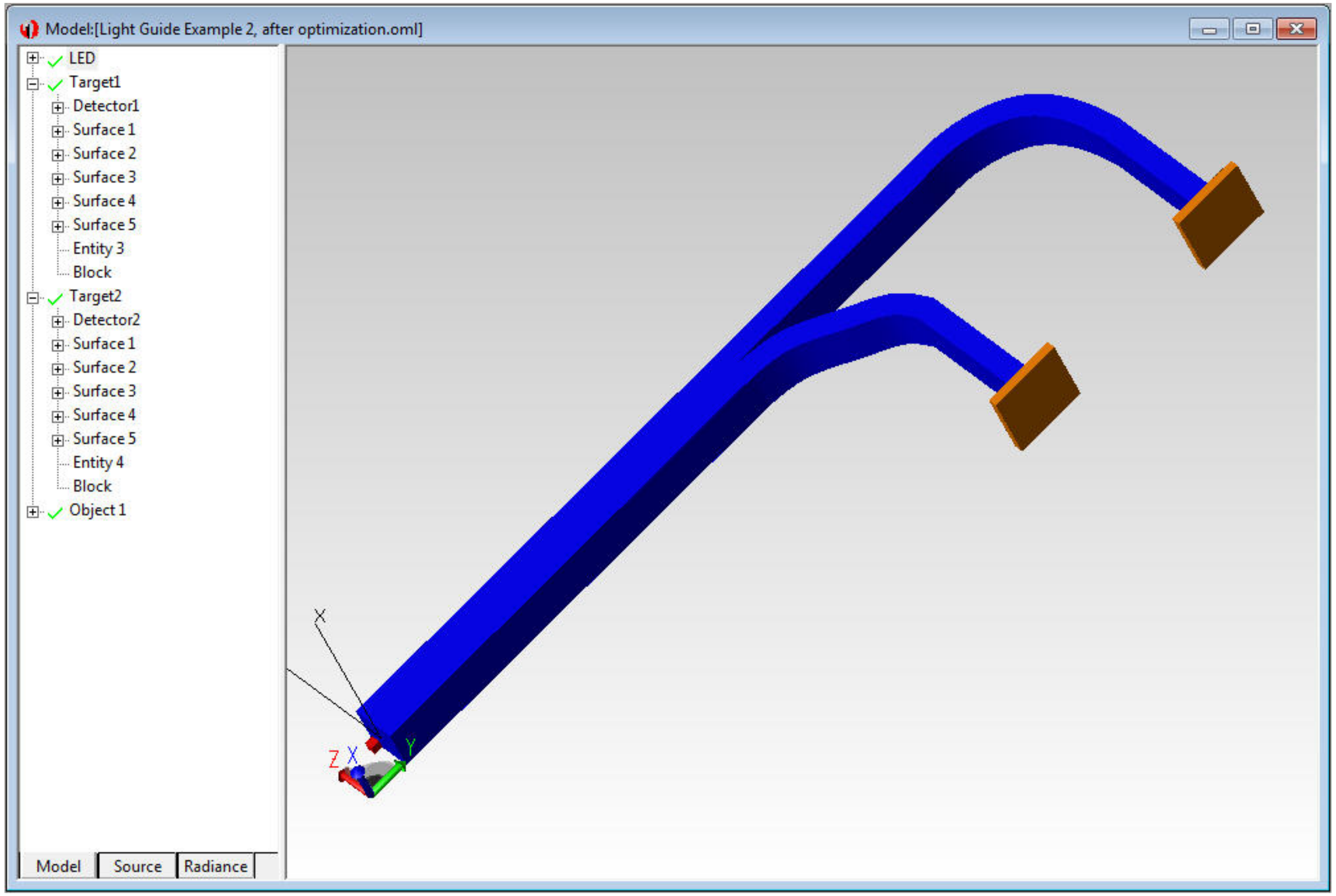
Leg 1 Sweep Path



Leg 2 Sweep Path

3D Interactive Optimizer

Optimization Results – Model



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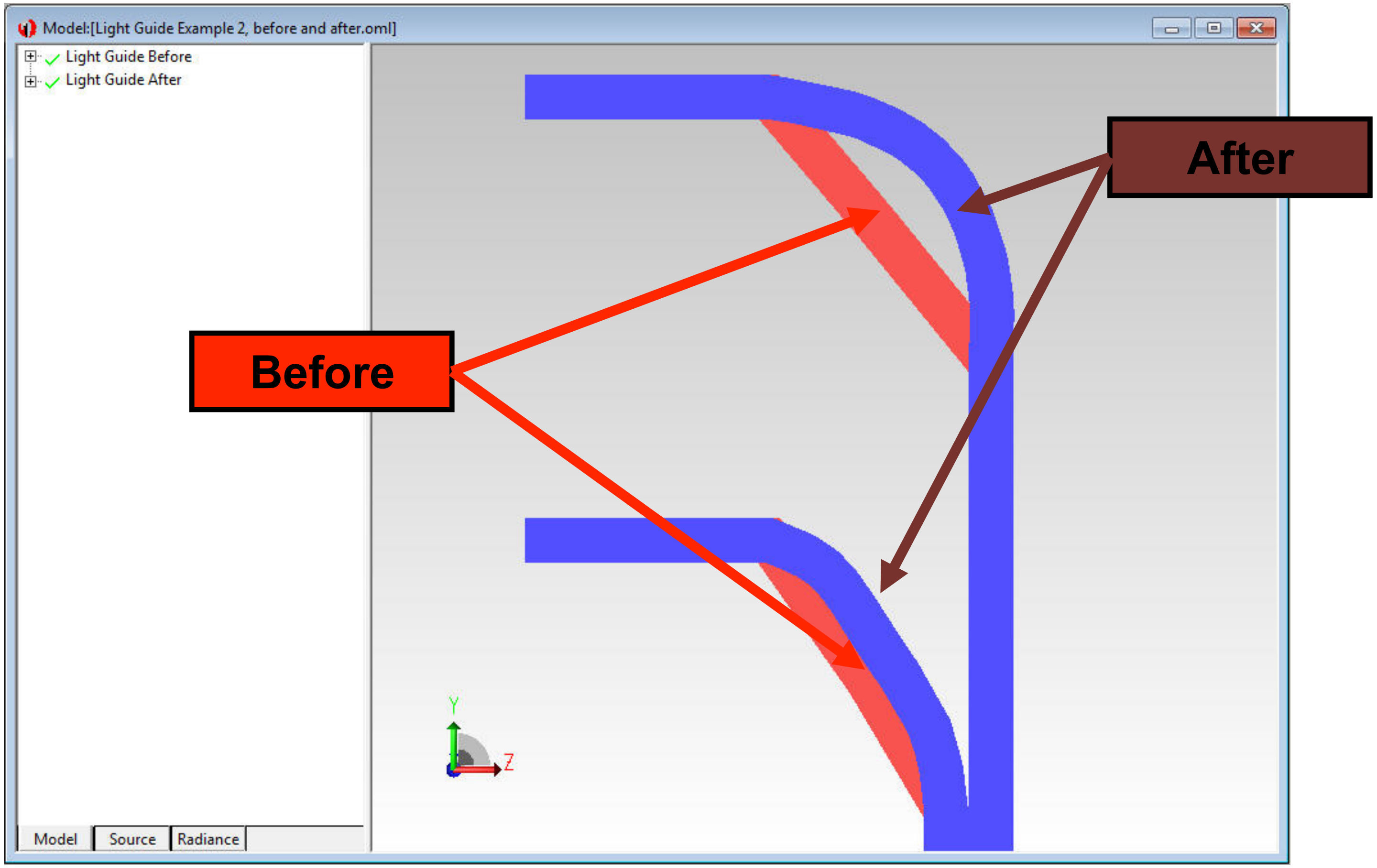
3D Interactive Optimizer

Optimization Results – Before and After Optimization



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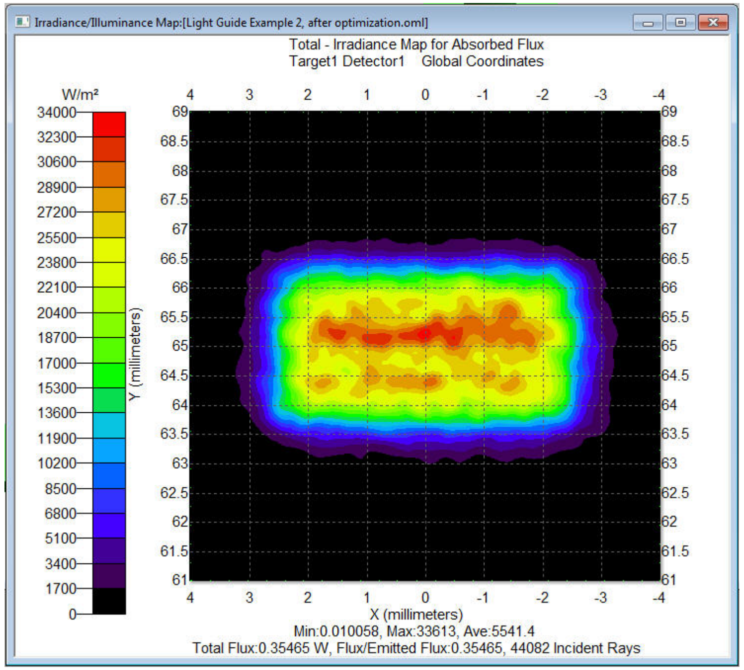
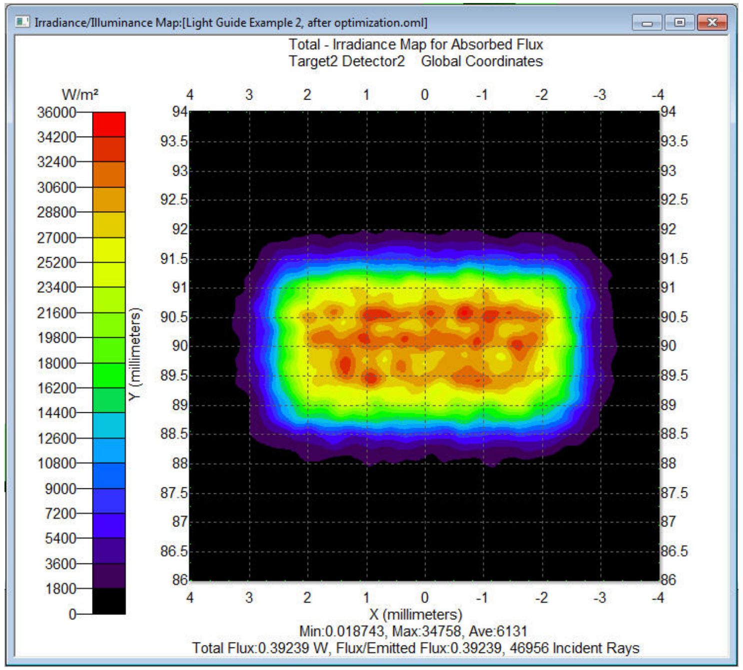
3D Interactive Optimizer

Final Irradiance Maps – 1-watt Source



Leg 1
0.355 watts



Leg 2
0.392 watts

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Conclusion

Use the Interactive Optimizers with enough variables and multiple optimization operands, uniformity and total flux for example, to improve results.

Use the Analysis Tools to Verify Results:

- Irradiance/Illuminance Maps
- 3D Irradiance/Illuminance Maps
- Candela Plots
- Luminance/Radiance Maps –
  Multiple “eye” positions if possible
- Photorealistic Rendering
- Path Sorting to see ray paths

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Questions & Answers

Thank You!!

Interested in Learning More?

Sign up for a **free** 30-day trial of TracePro at:
http://lambdares.com/trials

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