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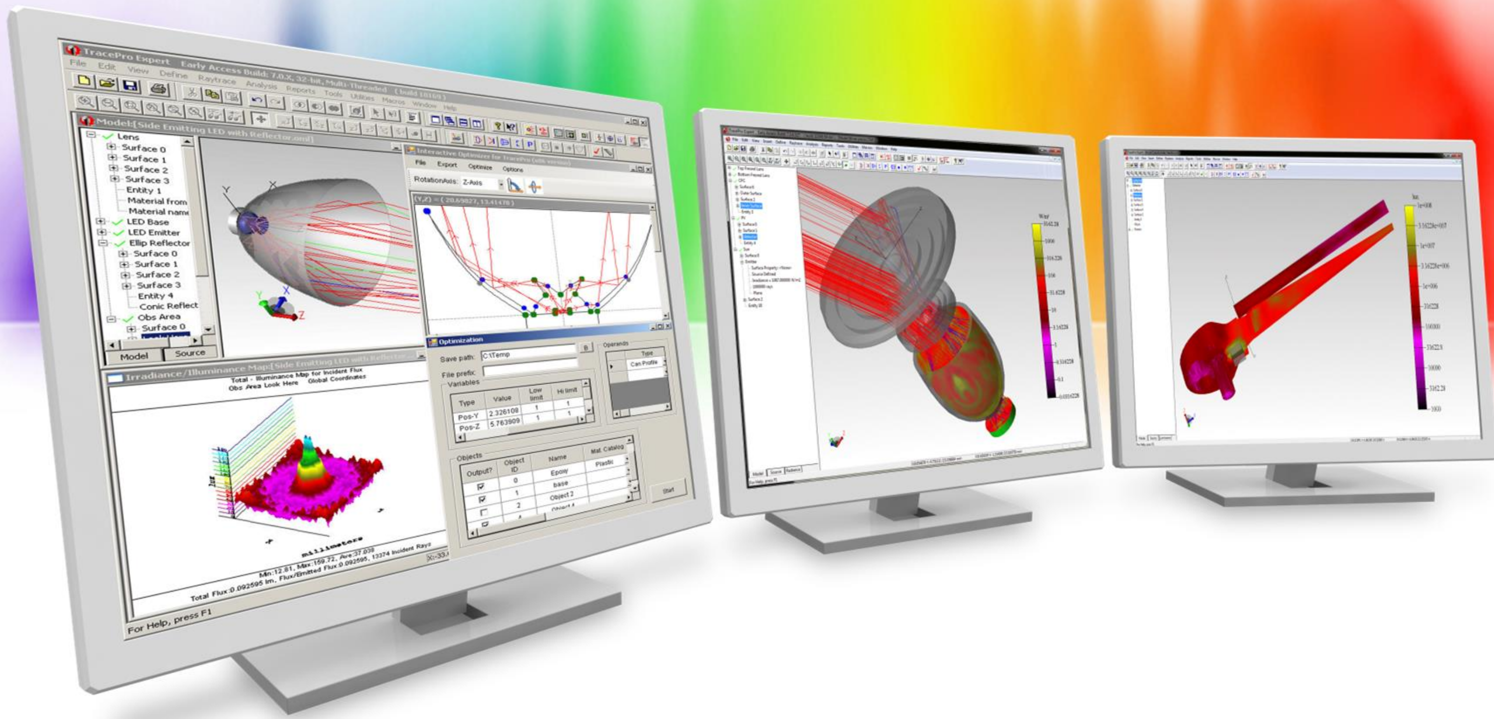

LEARN EFFICIENT LIGHT PIPE DESIGN USING VIRTUAL PROTOTYPING

Presented by :
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Littleton, MA 01460
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Agenda

Efficient Light Pipe Design

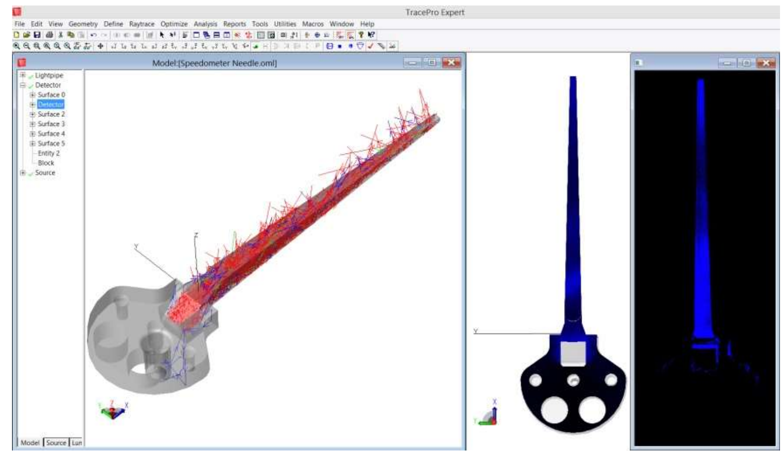
- What is the goal of the design?
- Brief Overview of Light Pipe Basics and Best Practices
- What Tools are Needed for Efficient Light Pipe Design
- Shape Requirements
- How to Let Light Escape by using Periodic Functions, Surface Features and textures

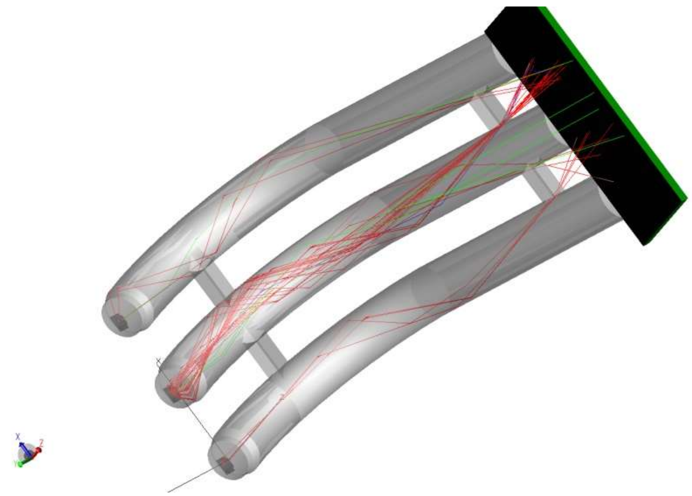
Agenda

- Interactive Optimization – searching for the best result
- Using Lit Appearance to check and improve a design
- Examples 1 & 2
- Conclusions

Goals

- What is the primary use of the light pipe?
- Which of the following output goals are most important?
  - Moving light efficiently around static components on a PCB
  - Uniformity at the exit surface to read information
  - Efficiency at exit surfaces
  - Lit appearance criteria





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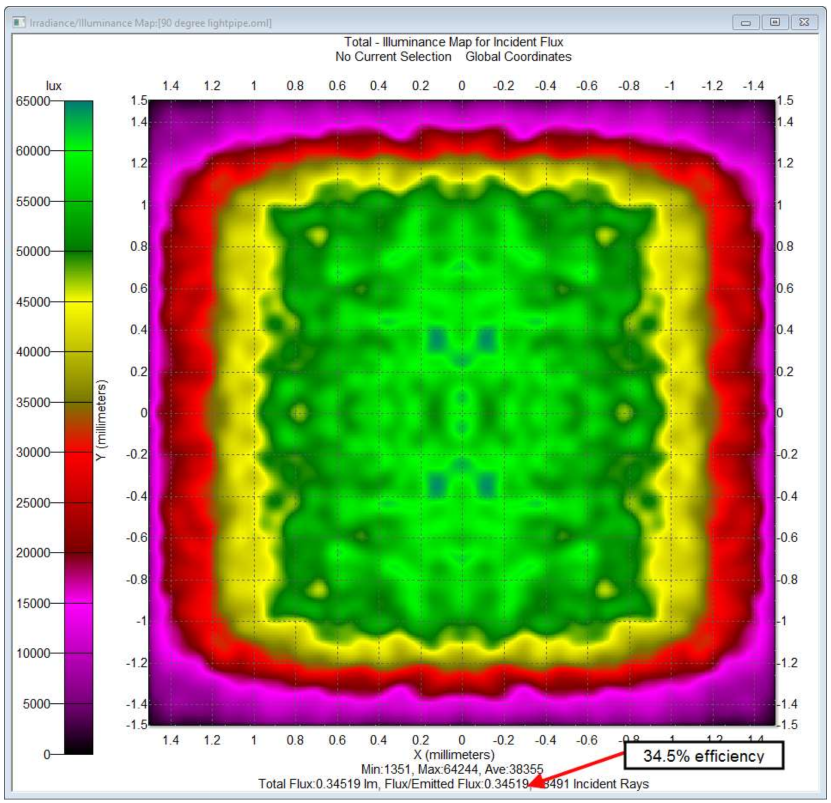
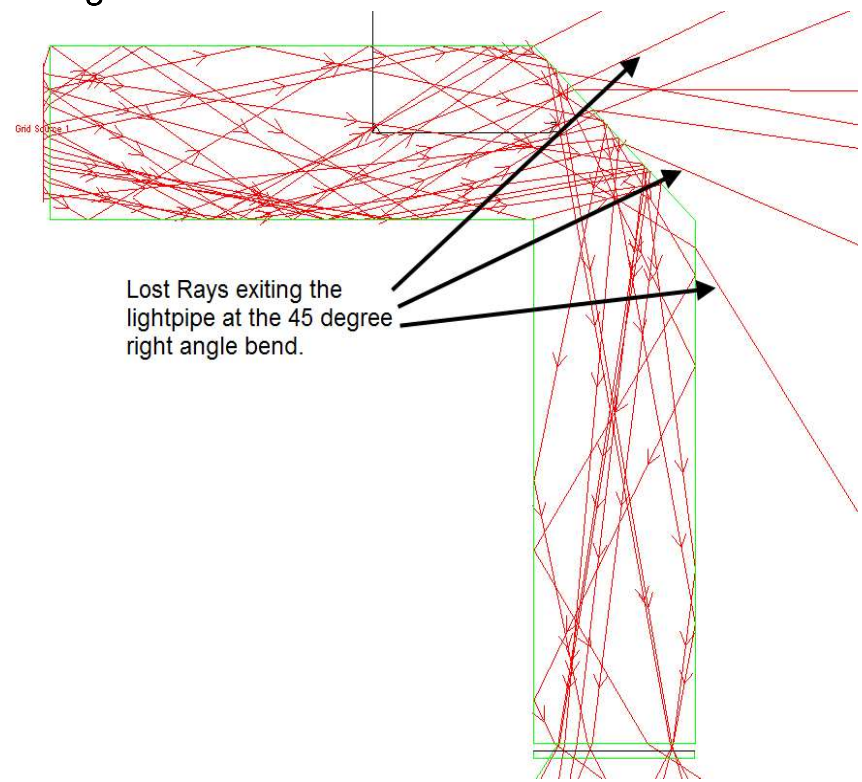
Basics – Using Light Guide/Pipe Mirrors

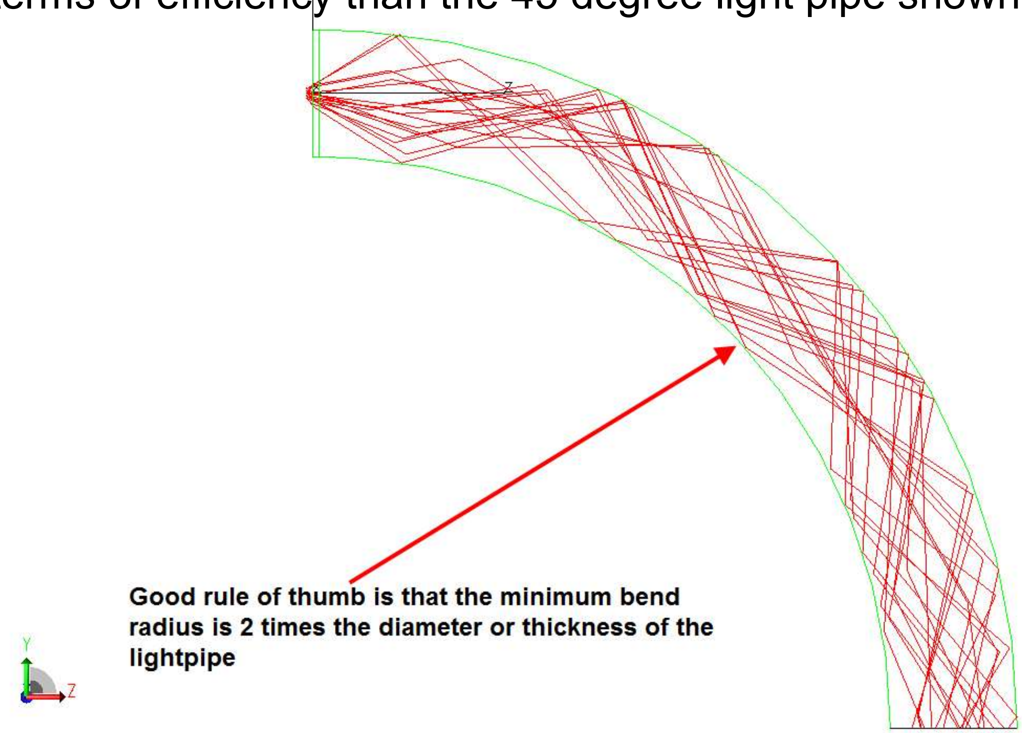
When you need to bend light quickly by 90 degrees, one method is to use a 45 degree right angle bend creating a mirror at the bend. If the light is perfectly collimated all the light will be reflected. But this is not the case with an LED that emits in a Lambertian angular pattern. You will usually end up with at most 50 percent of the light exiting from the output surface of the light pipe. In this case only 34.5% of the light reaches the exit surface.





Basics – Bending Curvatures

Better Method for bending light 90 degrees - keeping almost all of the light contained inside the pipe can be accomplished by using a gently curved pipe by keeping the critical angle at around 42 degrees. This contains the light emitted from large angular emitting LEDs. There will almost always will be losses at bends in any light pipe since it is difficult to contain the +/- 90 degree emission of a normal LED. The critical job is to try and keep as much light as possible from exiting the pipe. The light pipe shown below does a much better job in terms of efficiency than the 45 degree light pipe shown in the last slide.

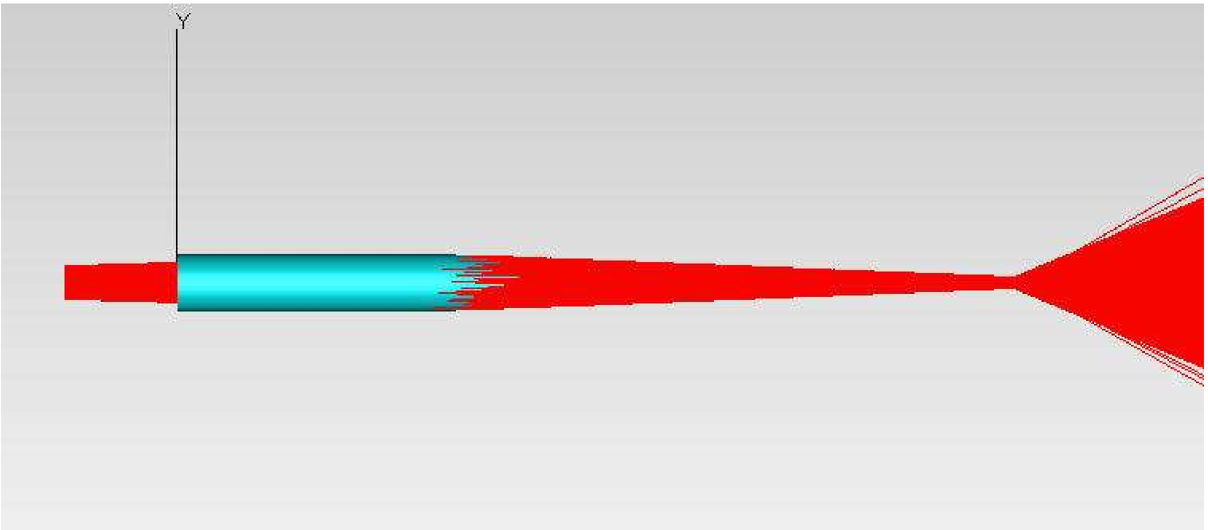


Basics - Etendue

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

Where in this formula: 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
- Light Pipes can be rigid or flexible
- 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 textures can be applied to a light guide/pipe to improve angular efficiency and output

Basics - Best Light Pipe Practices

- It is Important to have high reflectance at the light guide/pipe boundaries (TIR) – light pipes with poor efficiency usually suffer due to rough outer surfaces that leak light

- 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

Basic – Simulation 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 accurate source and surface 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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Basic - Tips

- Coupling LED emission into the light pipe for minimal loss, try multiple scenarios to 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. Check using Lit Appearance simulations.
- Make sure light can escape from the exit surface

Basics - Light Guide/Pipe

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- Surface properties can be applied to a light guide/pipe to improve performance

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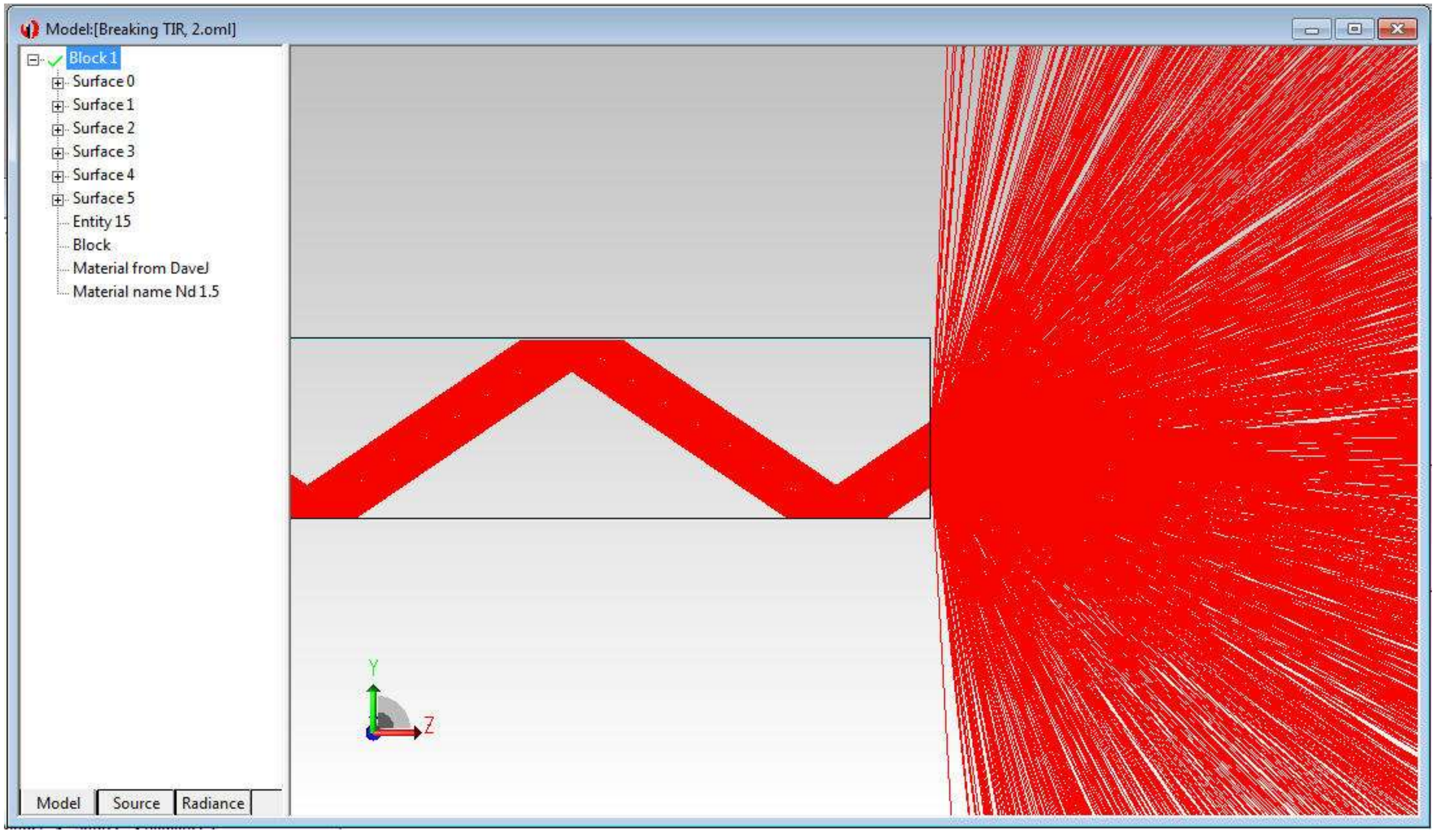
Basics – Breaking TIR



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

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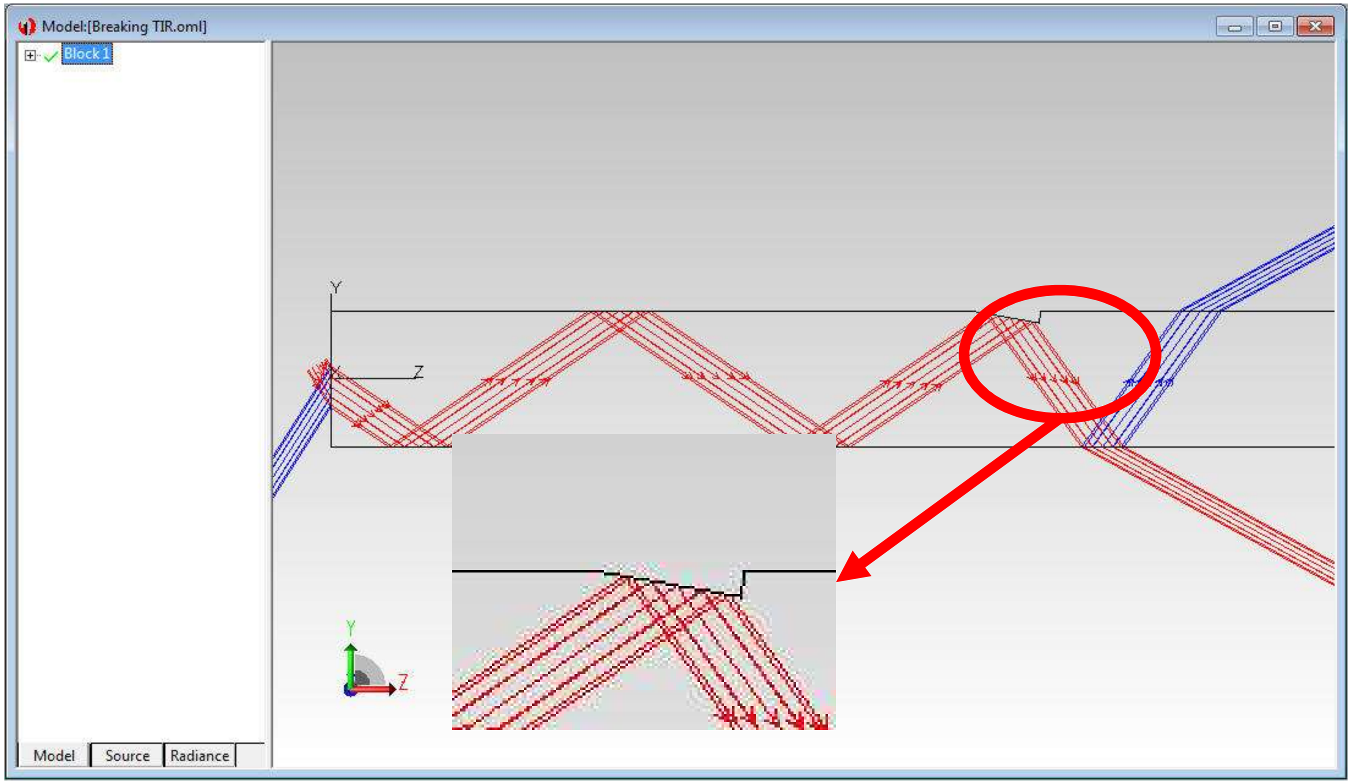
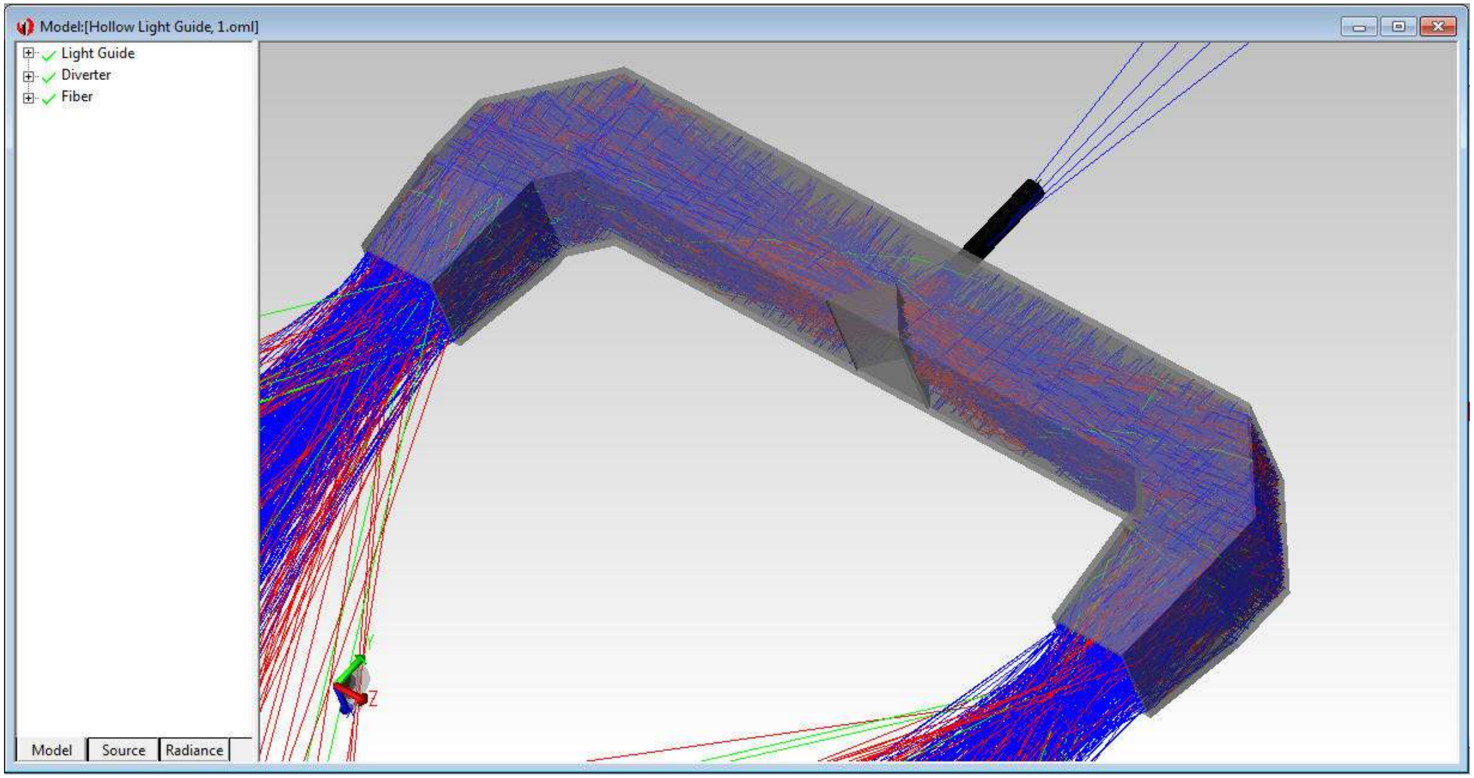
Basics – Breaking TIR



Adding a physical feature to the surface of the light guide breaks TIR and extract light. This is a simple example of a surface break in a backlight to extract light.

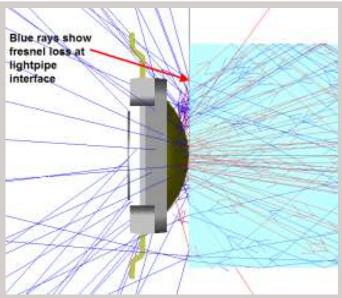
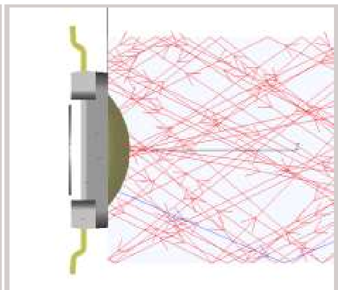
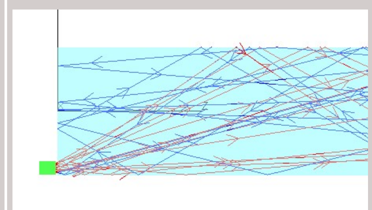
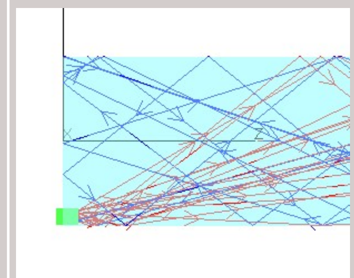
Basics – Non-TIR



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

Basics - LED Coupling into the Pipe

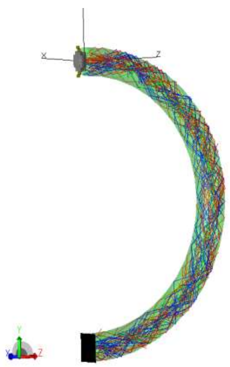
Four possible scenarios, LED against the light guide/pipe, LED inside the light guide/pipe with perfect surfaces

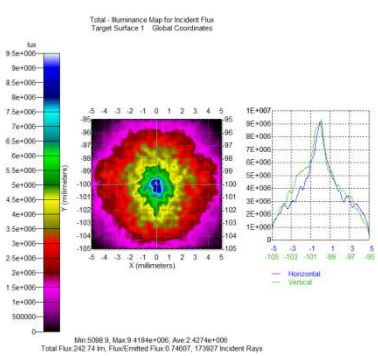
	Round LED against pipe	Round LED inside pipe	Flat LED against pipe	Flat LED inside pipe
Picture of Setup				
Coupling Loss	Fresnel Loss at light pipe	No loss if epoxied into the pipe	Fresnel Loss at light pipe	No loss if epoxied into the pipe
Distance required	Some distance due to size of lens	None	None	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

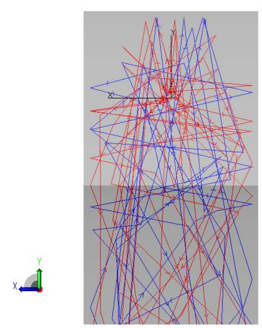
Lets look at four scenarios, round, rectangular, hexagonal or octagonal sections

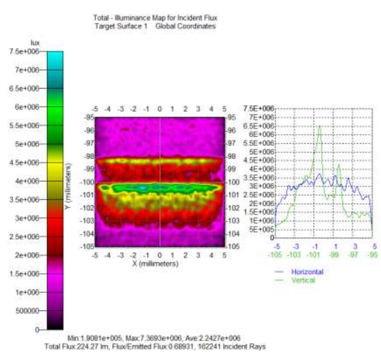
Round



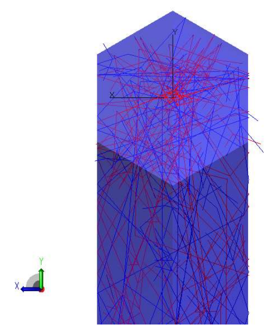


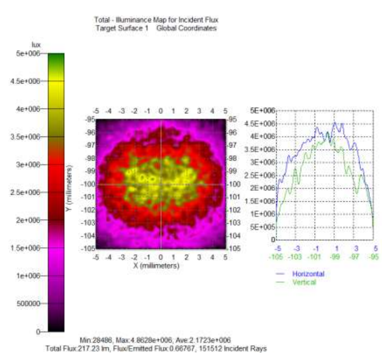
Rectangular



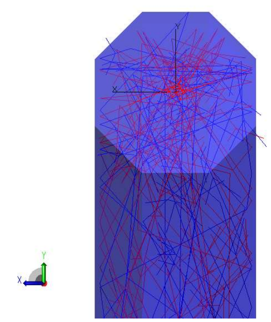


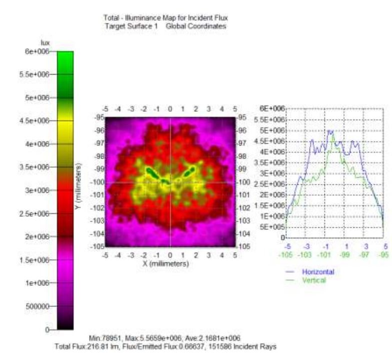
Hexagonal





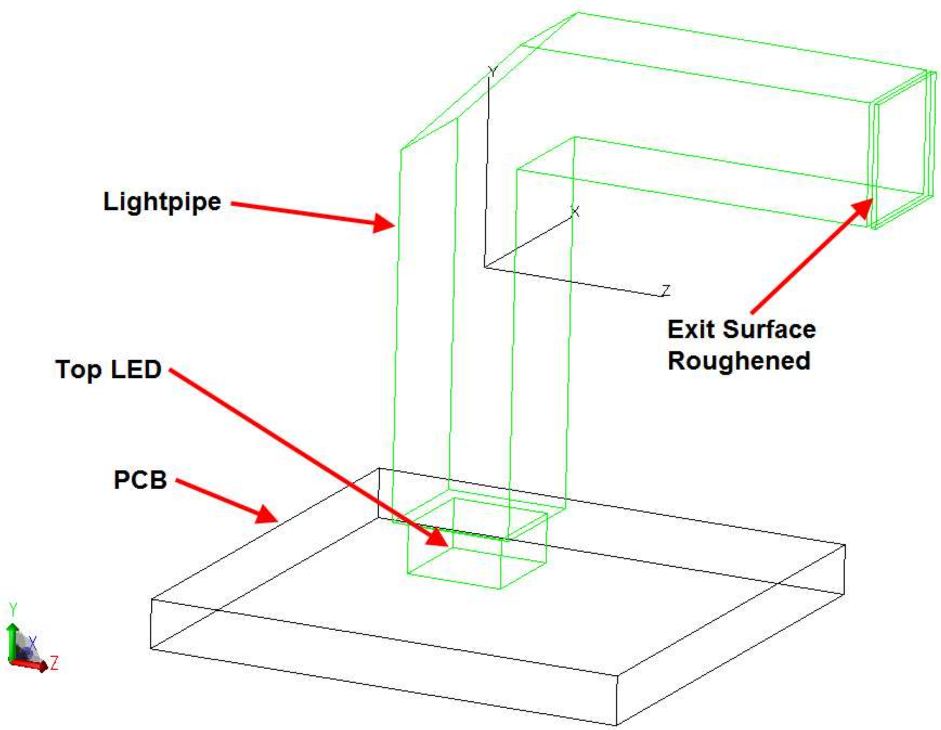
Octagonal





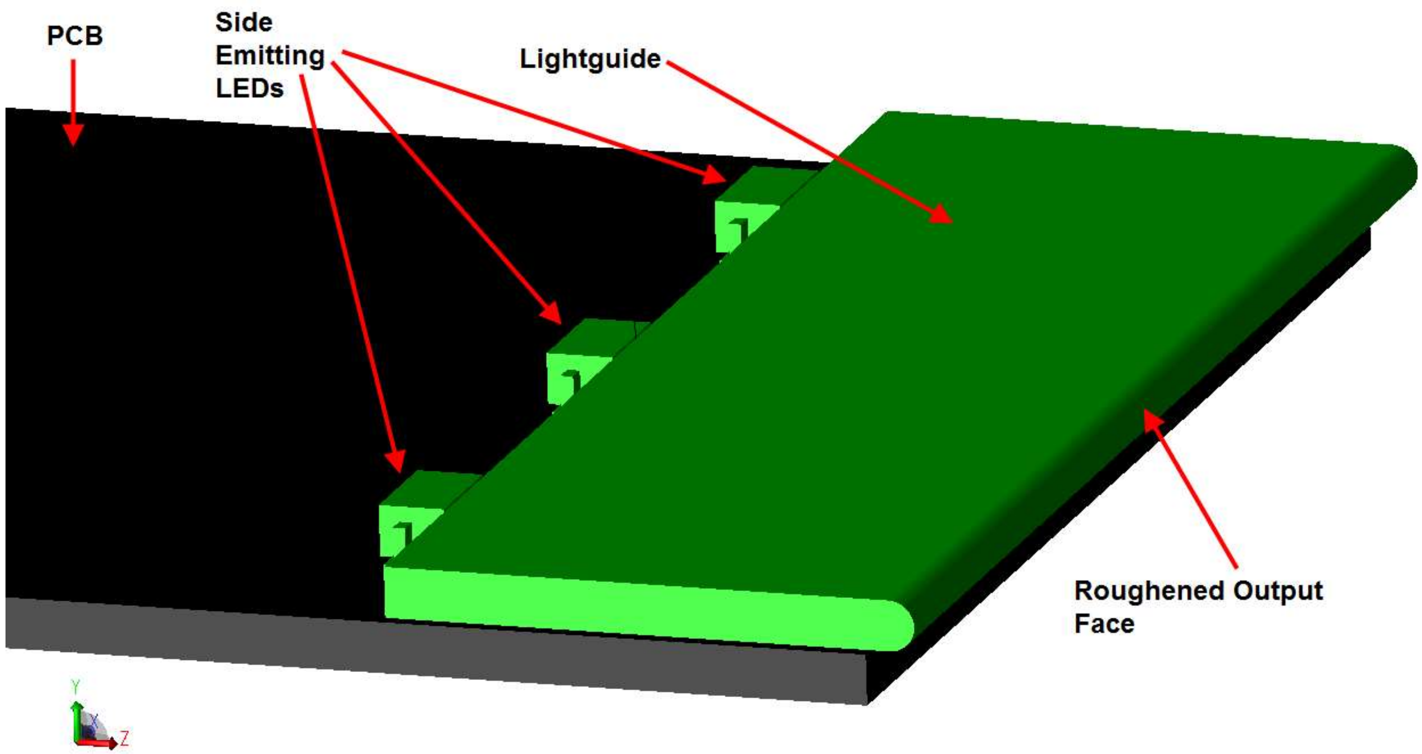
Basics - Picking & Modeling the LED Source

Top Emitting LED Design



Basics - Picking & Modeling the LED Source

Side Emitting LED Design



In this scenario, side emitting LEDs are much more convenient since we want light propagating into the side of the light guide and exiting out the other side.

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Basics– Surface Textures

- Surface textures let light escape from a light pipe. Every surface of a light pipe is imperfect, there is always some surface roughness on every surface of a light pipe.
- If you want to keep light Total Internally Reflecting (TIRing) make the light pipe as smooth as possible. But don't paint a long light pipe with reflective paint to force reflection, reflective paints absorb light and light loss will occur.
- The best long light pipes transmitting light to a final surface use smooth finishes. Request an SPI-A1 or A2 smoothness from your molder. To test for light leakage take your light pipe system into a dark room or do a luminance measurement.
- If you want large angular dispersion at the exit area of your light pipe, use a surface texture to widen the angular dispersion. This is especially a good practice if you want to view the exit surface from many different target angles.

Basics – Surface Finish Guide

Proto Labs (www.protolabs.com) creates injection molded surface finishes ranging from non-cosmetic to high-gloss polish:

Higher Cost

PM-F0:	Non-cosmetic: finish to Protomold discretion
PM-F1:	Low-cosmetic: most toolmarks removed
PM-F2:	Non-cosmetic: Protomold discretion, EDM finish and/or toolmarks permissible
SPI-C1:	600 grit stone, 10-12 Ra
PM-T1:	Protomold texture, SPI-C1 followed by light bead blast
PM-T2:	Protomold texture, SPI-C1 followed by medium bead blast
SPI-B1:	600 grit paper, 2-3 Ra
SPI-A2:	Grade #2 Diamond Buff, 1-2 Ra

Photo and table courtesy of www.Protolabs.com

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Basics - SPI Surface Finish Guide

Specular Surface, Diamond Buff Polish

SPI Finish A-1 -- Grade #3, 6000 Grit Diamond Buff

SPI Finish A-2 -- Grade #6, 3000 Grit Diamond Buff

SPI Finish A-3 -- Grade #15, 1200 Grit Diamond Buff

Non-Glossy Surface, Paper Polish

SPI Finish B-1 -- 600 Grit Paper

SPI Finish B-2 -- 400 Grit Paper

SPI Finish B-3 -- 320 Grit Paper

Rough Surface, Stone Polish

SPI Finish C-1 -- 600 Grit Paper

SPI Finish C-2 -- 400 Grit Paper

SPI Finish C-3 -- 320 Grit Paper

Very Rough Surface, Dry Blast Polish

SPI Finish D-1 -- 600 Stone Prior to Dry Blast Glass Bead #11

SPI Finish D-2 -- 400 Stone Prior to Dry Blast #24 Oxide

SPI Finish D-3 -- 320 Stone Prior to Dry Blast #24 Oxide

Basics – When to Use Bulk Scatter

- Bulk scattering fillers help diffuse light throughout a light pipe to create better uniformity and angular dispersion. This is a cheap method to diffuse light but works poorly to mask the direct LED output.
- Bulk scattering fillers are typically a white or colored powder immersed in the plastic light pipe material to disperse light all along its length. This causes efficiency loss all along the light pipe length.
- Instead of heavy powders, better options are converging and diverging, blocking and collimation surfaces
- Finally, when all else fails, a combination of Bulk scatter fillers and surface texturing helps reduce hotspots
- Bulk scatter fillers are available from Sabic, www. sabic-ip.com

Picture courtesy of Sabic, www.sabic-ip.com

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Virtual Prototyping Tools for Efficient Light Pipe Design

- 3D Sketcher creates surface shapes and periodic features as a design tool
- Interactive raytracing tools visualize light pipe losses and performance problems while designing
- 3D interactive optimizer allows you to understand the optimization process and select from multiple design possibilities.
- Photo realistic rendering can be used to discover uniformity issues from any observation angle and to simulate lit appearance before manufacture to find problem areas.

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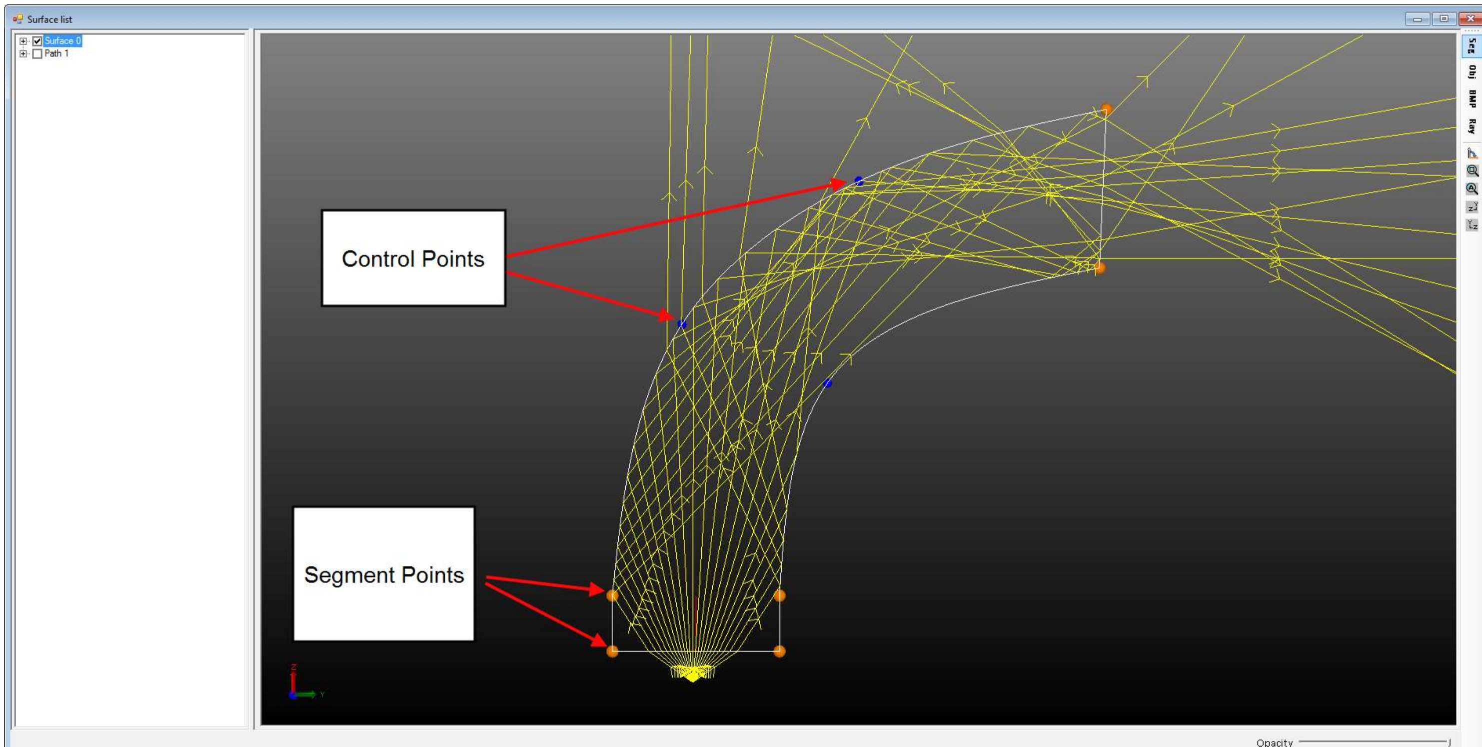
Efficient Methods – Surface sketch utility and Interactive Raytracing

- The interactive surface sketch utility with raytracing is an important design tool. The sketch tool quickly creates complicated surfaces by using user-defined segments and control curve points to create the light pipe geometry. The interactive raytracing tools lets you try multiple scenarios to create the best starting point for a design.



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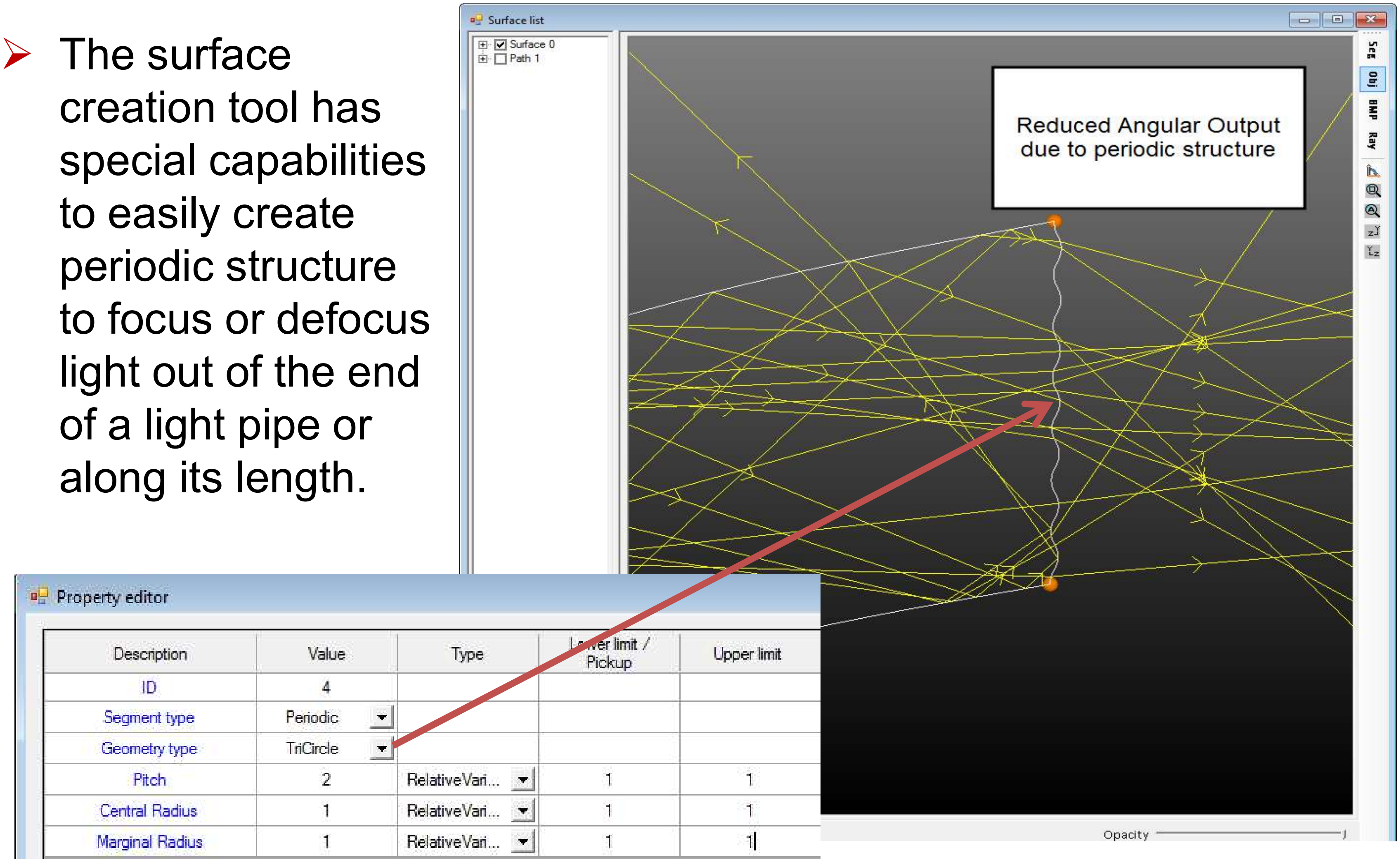
Efficient Methods – Quick CAD Periodic Structure Tool

- The surface creation tool has special capabilities to easily create periodic structure to focus or defocus light out of the end of a light pipe or along its length.



Description	Value	Type	Lower limit / Pickup	Upper limit
ID	4			
Segment type	Periodic			
Geometry type	TriCircle			
Pitch	2	RelativeVari...	1	1
Central Radius	1	RelativeVari...	1	1
Marginal Radius	1	RelativeVari...	1	1

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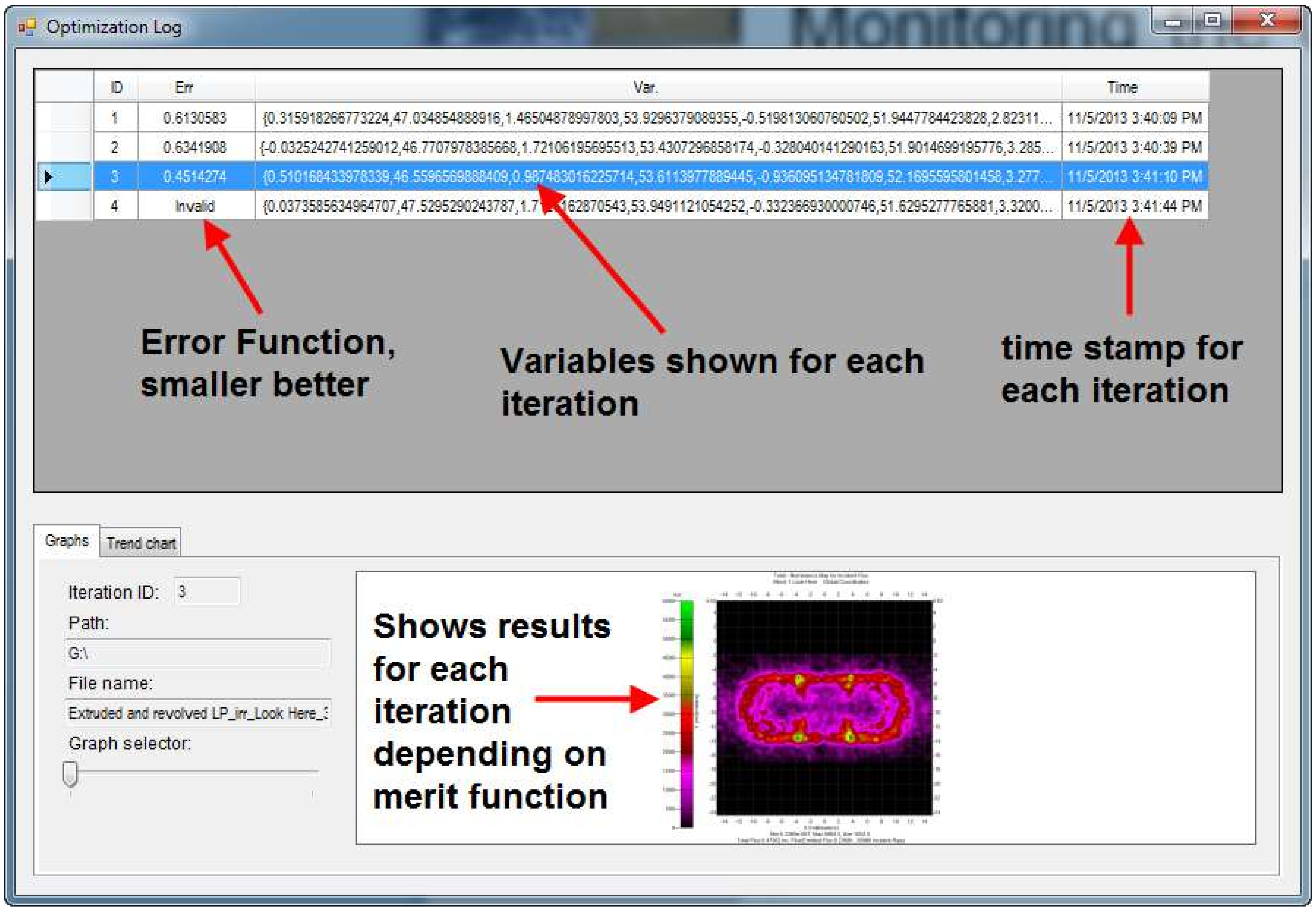
Efficient Methods – Interactive Optimizer

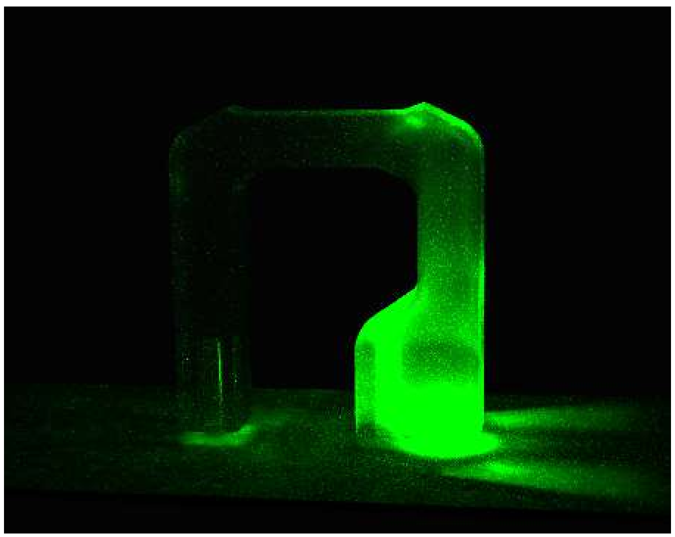
- The ability to watch the optimization in real time gives the user complete control of the optimization process.



Efficient Methods – Using the Photorealistic Rendering to create better designs

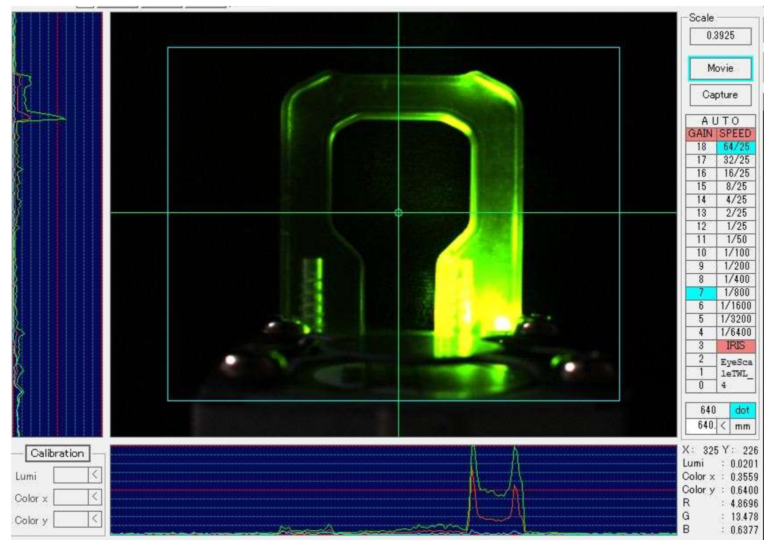
- Photorealistic renderings show the lit appearance from any target and eye position. Illuminance maps only show the power per unit area on a surface and candela plots only show the angular output. The total solution is observing both quantities together creating a true color plot of the actual output.

Simulation Result



Photorealistic Rendering by TracePro – Initial Prototype

Measurement



Measured by Luminance Meter from Ruyico Tech. Corp.

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Best Practices

- It is important to have high reflectance at the light guide/pipe boundaries (TIR), SPI or SP2 grade smoothness for high efficiencies

- A diffuse surface is usually a good practice to use at the exit surface of the light pipe to exit light at a larger angular width and with greater uniformity. Perfectly smooth exit surfaces can TIR light back into the light pipe and even create modes that oscillate between the entrance and exit surfaces and never exit.

- Roughened surfaces, scattering dots or breaks in the light guide/pipe can force the exit of light where needed

More Webinars on Light Pipe Basics and Principles can be found on the Lambda Research Website

- 33 Webinars located at https://www.lambdares.com/su/tracepro-webinars/
- Light Pipe Principles – https://www.youtube.com/watch?v=2olbv6jUD10&t=7s
- Light Pipe Design Basics - https://www.led-professional.com/resources-1/webinars/webinar-designing-optimizing-light-guides-pipes-tips-tricks-for-a-streamlined-process-by-lambda-researchDesign Tips

First Example – Round to Square Light Pipe Example

Round to Square Light Pipe - Goals

- To design a light pipe that uses a round LED and creates a square output to illuminate a square target
- No spot on the target should be twice as bright as any other spot from -25mm to plus 25mm. The target should be easily seen as square in pattern.
- The lit appearance at the exit aperture should be uniform when viewed directly from the forward and side 50mm left and right positions
- Light Pipe should be as efficient as possible using less expensive LEDs when possible

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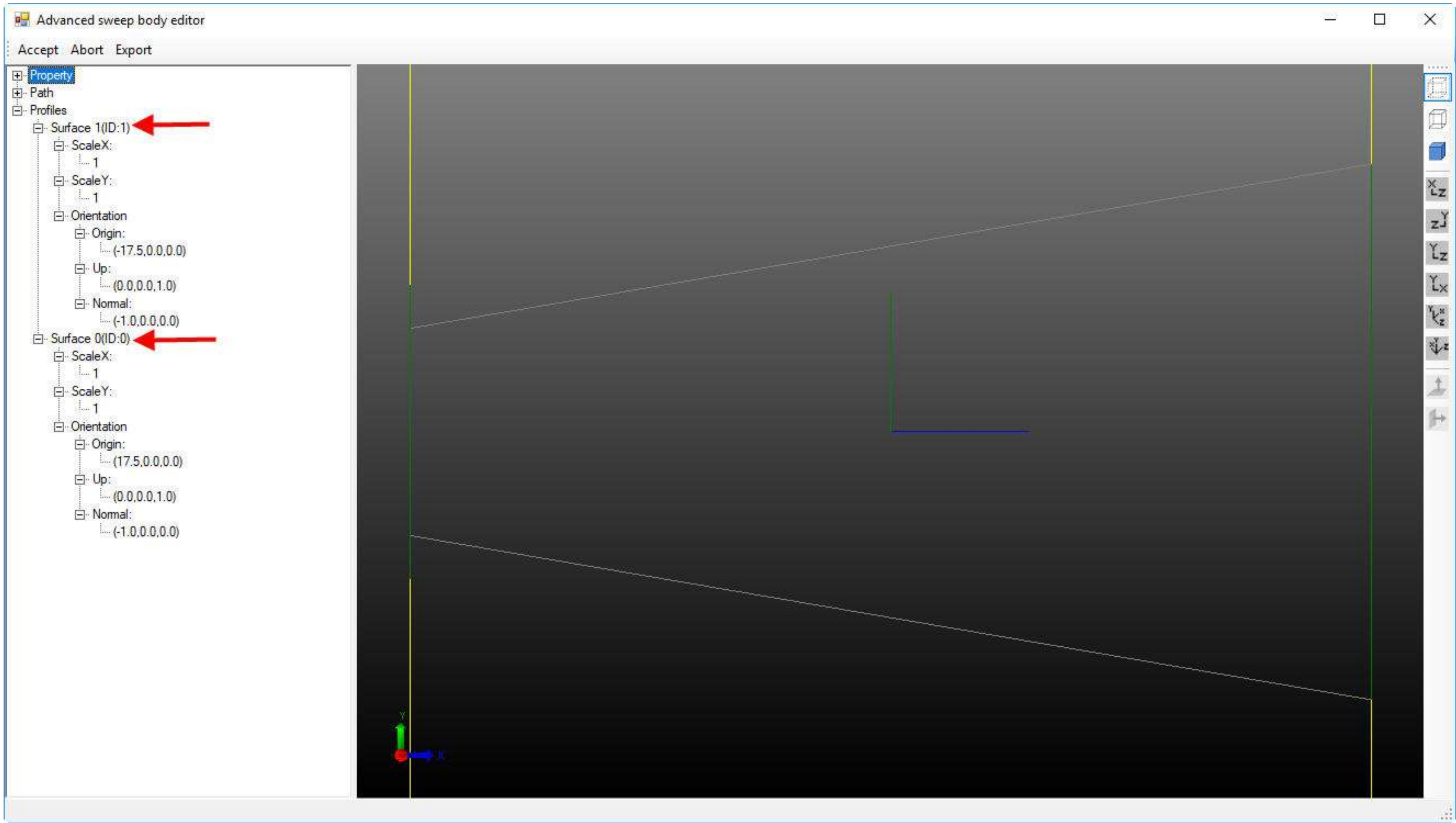
Round to Square Light Pipe Creation



TracePro has an advanced editor where you can create apertures, specify a path and the optimizer will build an object from these apertures following the specified path

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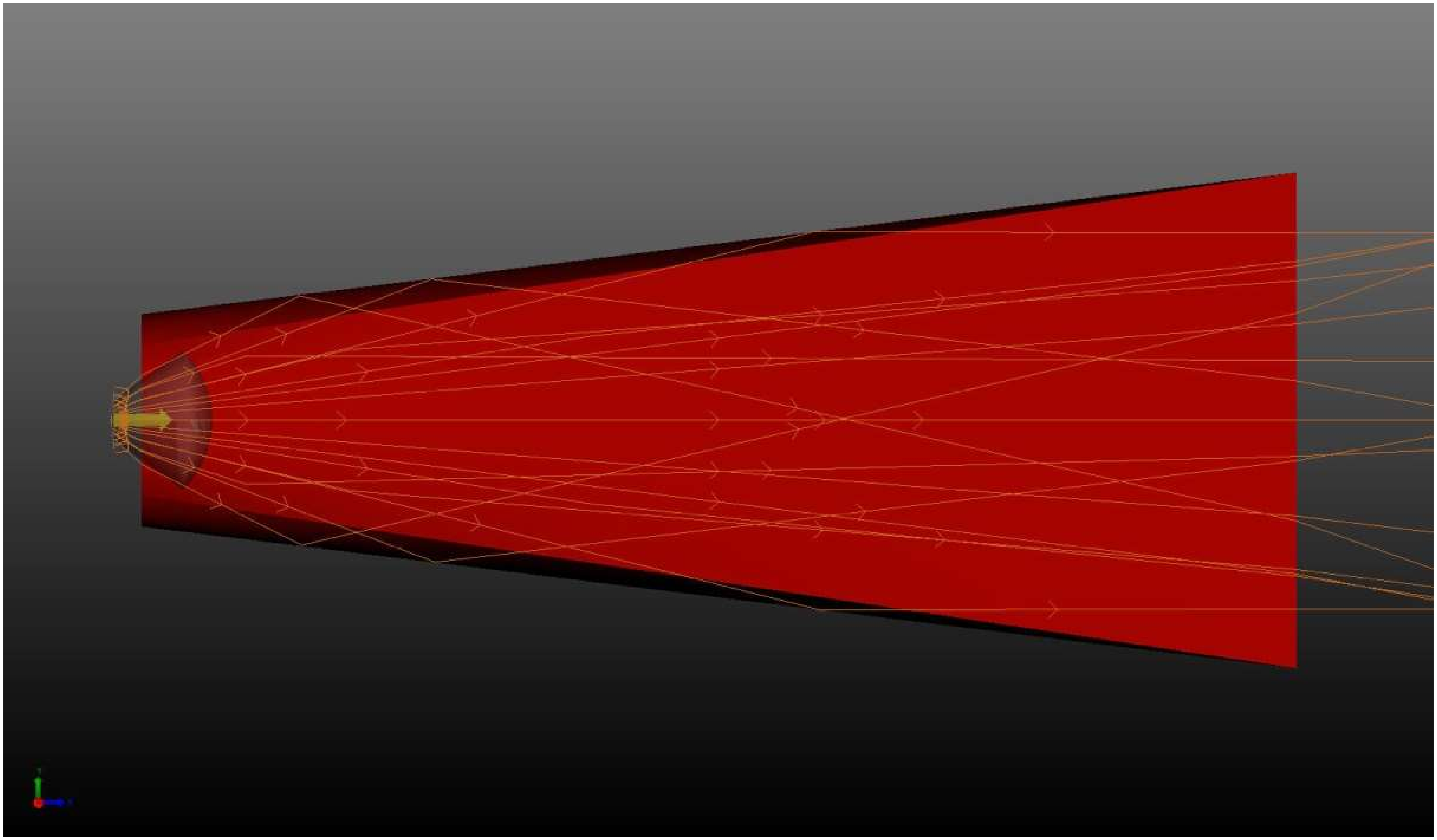
Round-to-Square Light Pipe - Interactive Ray Trace



Use interactive raytracing to come up with an initial good design

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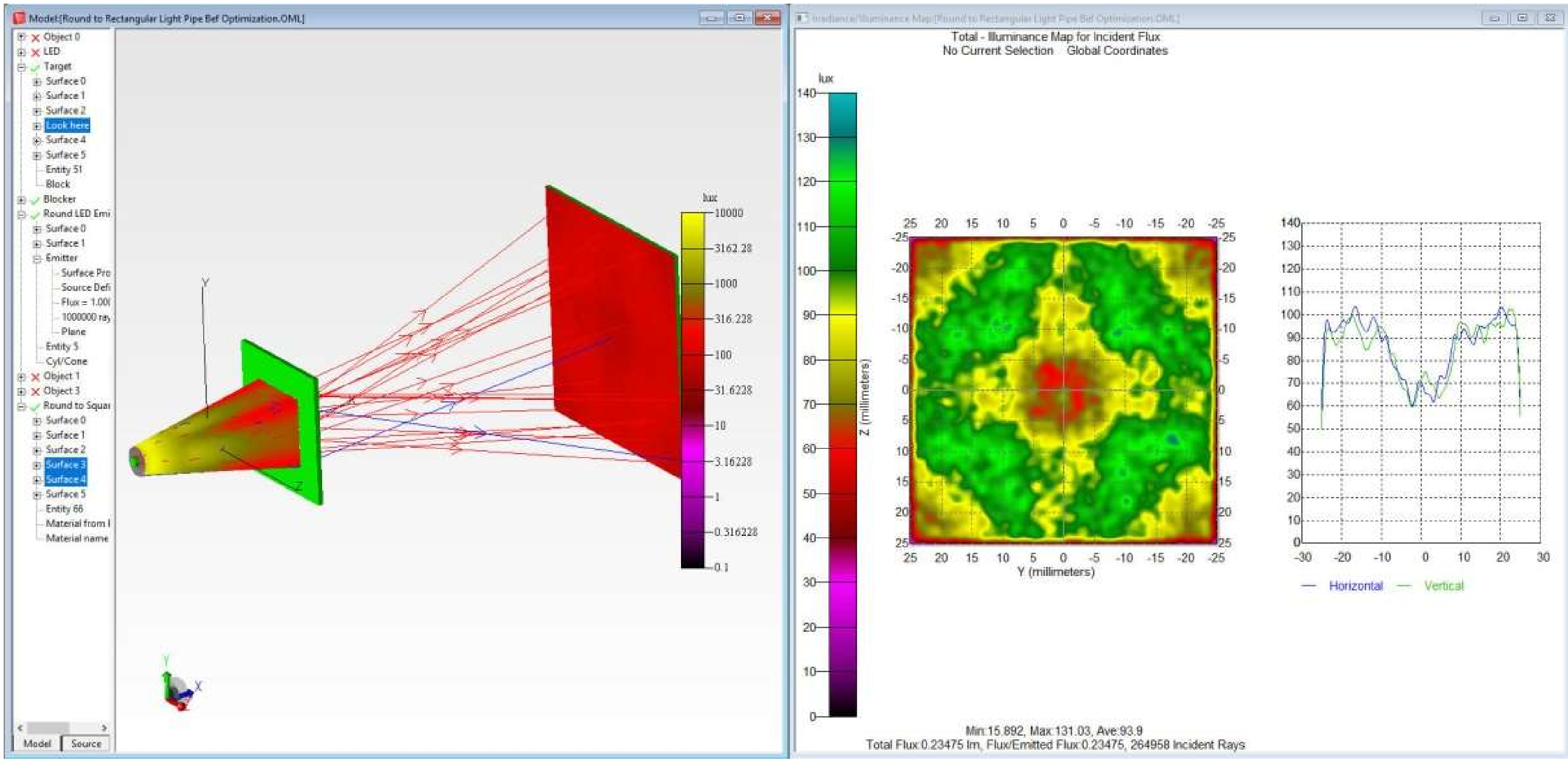
Full System, LED, Light Pipe, Square Blocking Aperture and Target



The first design of a round-to-square light pipe is shown. The 3D power map through the light pipe is shown in the left figure in log scale. The efficiency is 23.475% which is ok, but the uniformity does not meet our specification. The illuminance ranges from a minimum of 50 lux to a max of 131 lux.

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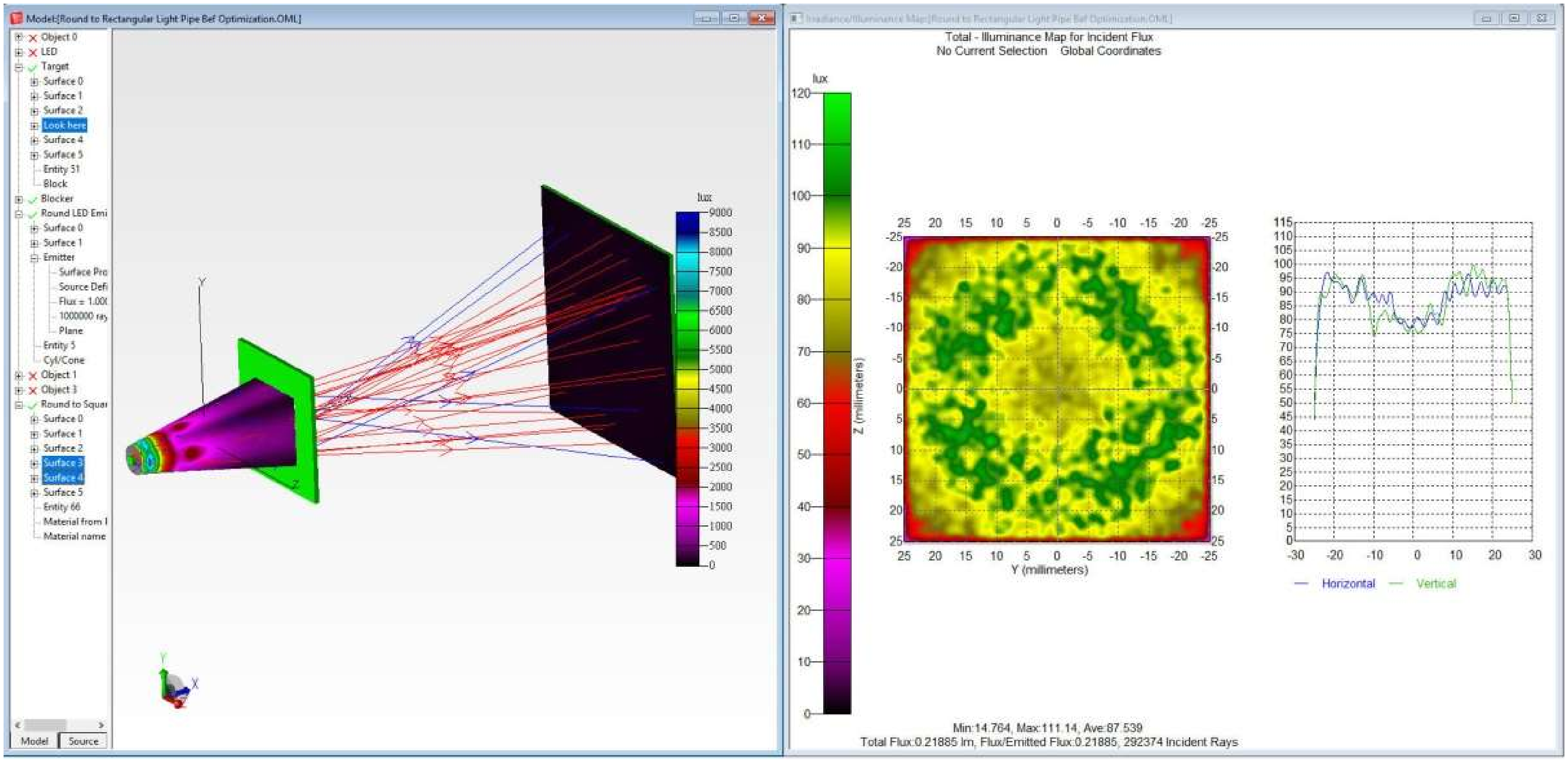
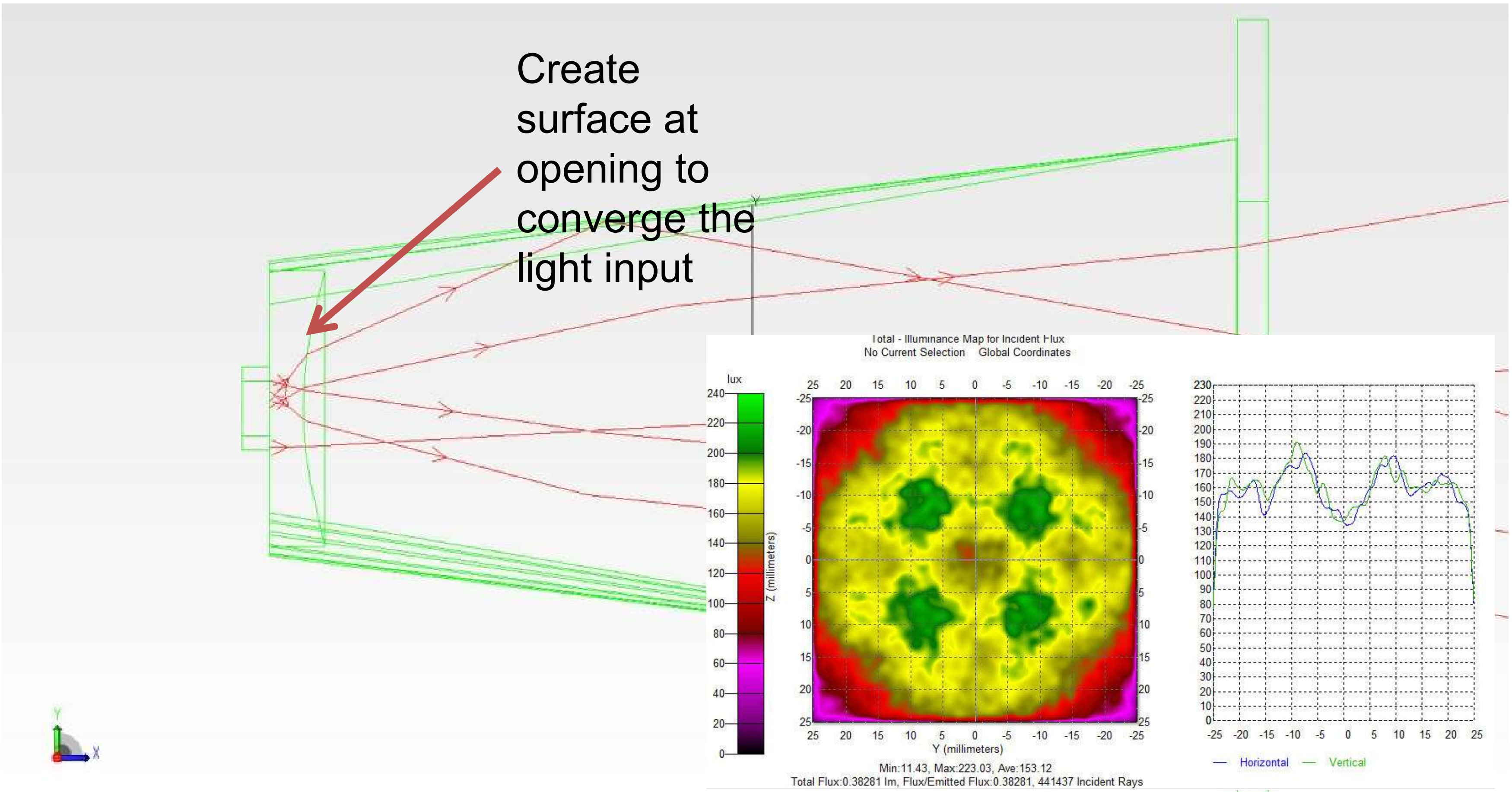
Moldtech 11007 texture added to exit surface of light pipe



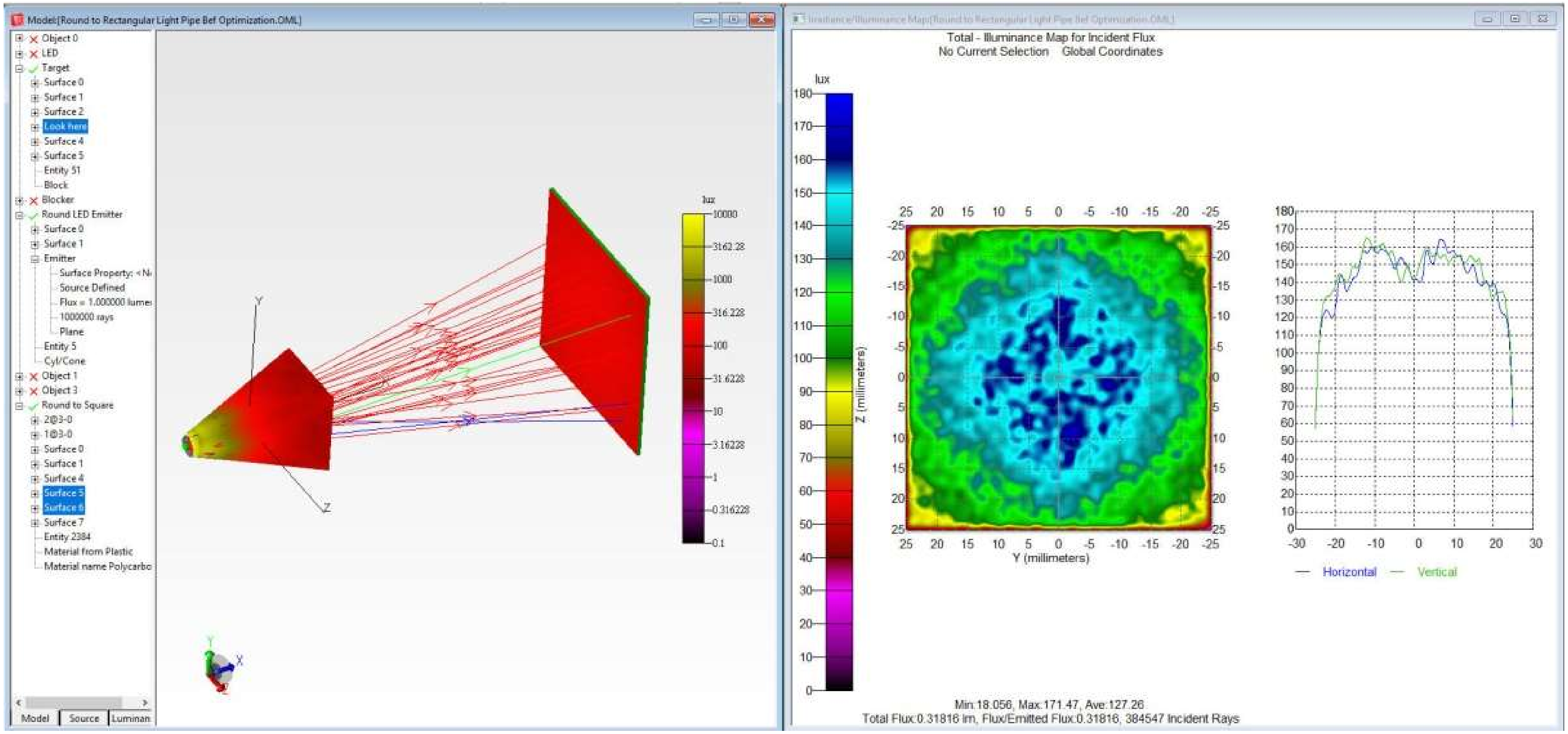
Adding a Moldtech 11007 texture to the exit aperture of the light pipe doesn’t really help here, we still have poor efficiency and the uniformity is only slightly better, mininum of 50 lux and a maximum of 111.14 lux.

Round-to square aperture - create a converging power surface at the entrance aperture of the light pipe



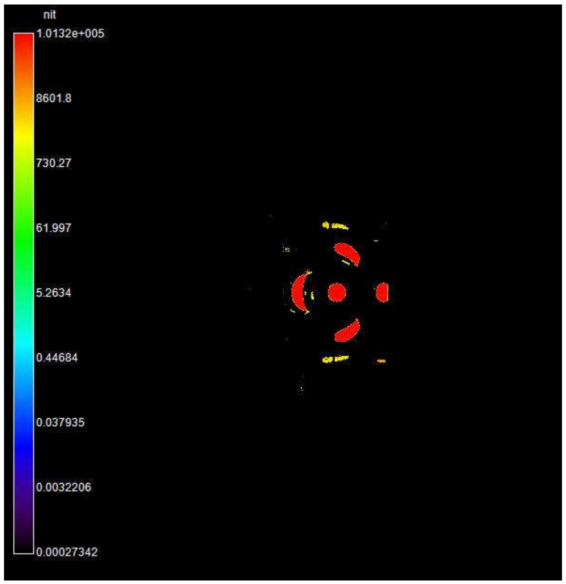
Adding the converging surface increases the efficiency to 38.2 percent, but light at the corners falls off quickly to 60 lux with a max of 223 lux in the center which does not meet the design specification.

Round to Square Light Pipe – Results after optimization

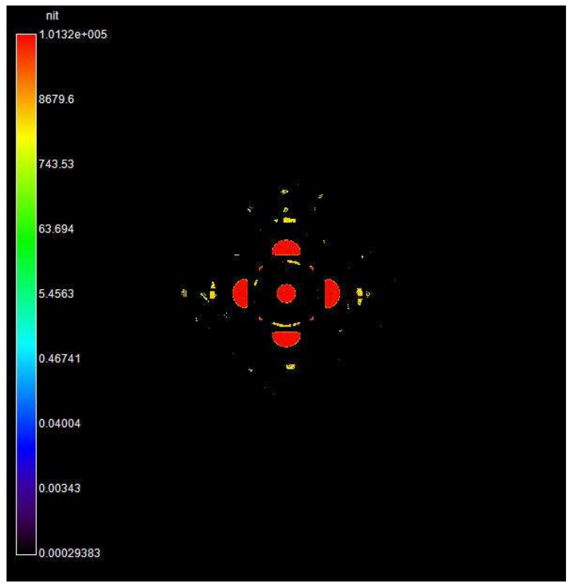


After optimizing, the area from -25 to +25 mm is very uniform with no point varying by more than a factor of 2. This is an acceptable design since the lux ranges from 120 to 171 lux and the efficiency is 31.8 percent. We can also remove the blocking aperture, it is not needed in this design.

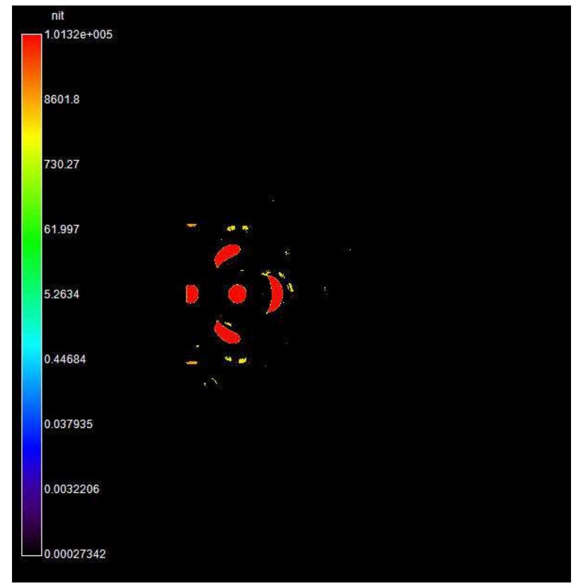
Lit Appearance – Left, Center and Right Eye Positions for Red LED



Left



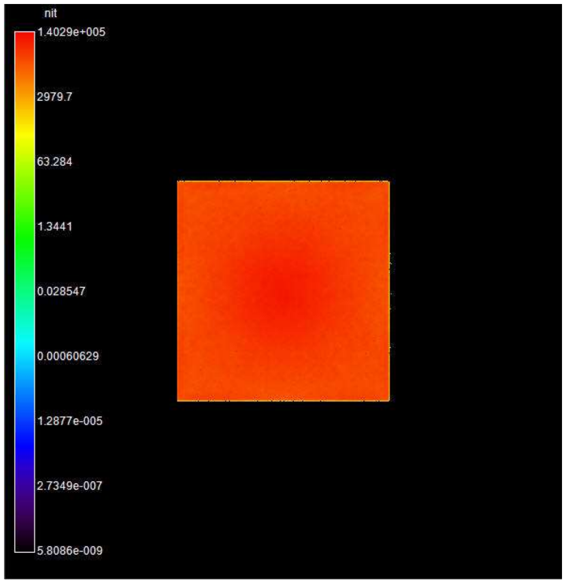
Center



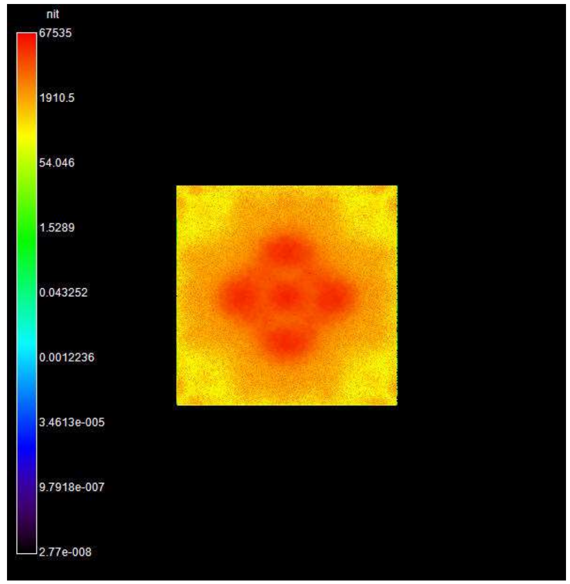
Right

The Lit Appearance of the light pipe in log scale. All positions have a problem where you can see the LED and duplication of the LED due to the round to square geometry and little else.

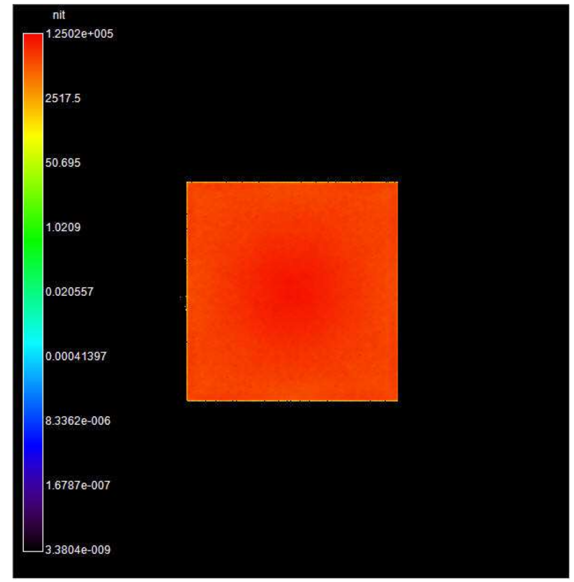
Lit Appearance – Left, Center and Right Eye Positions for LED with Moldtech 11007 texture on exit surface



Left -50mm



Center



Right 25mm

The Lit Appearance of the light pipe in log scale. Only the center position has a problem where you can see the LED and duplication of the LED due to the round to square geometry. This is a difficult thing to mask view, the view directly looking into the light pipe.

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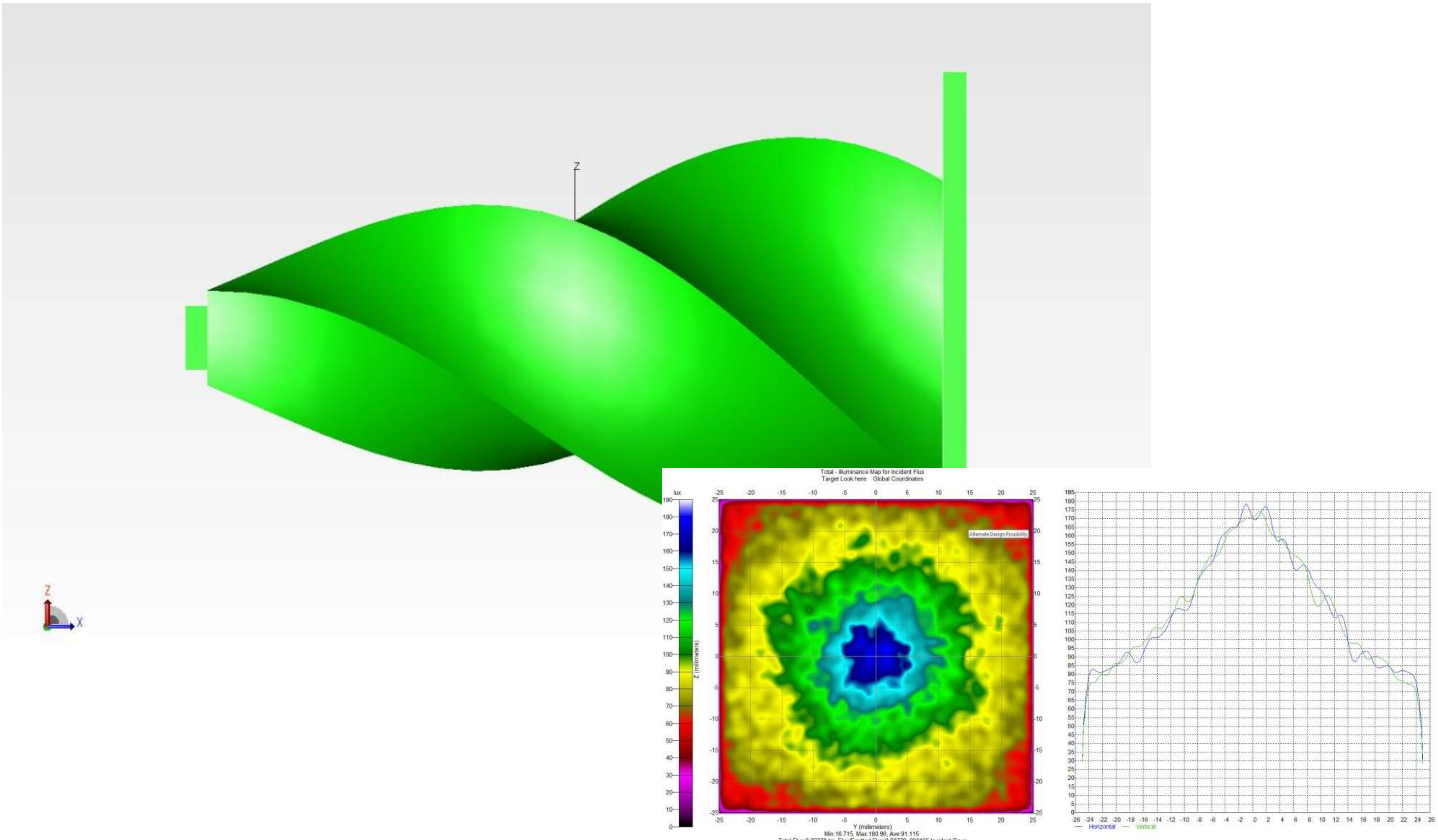
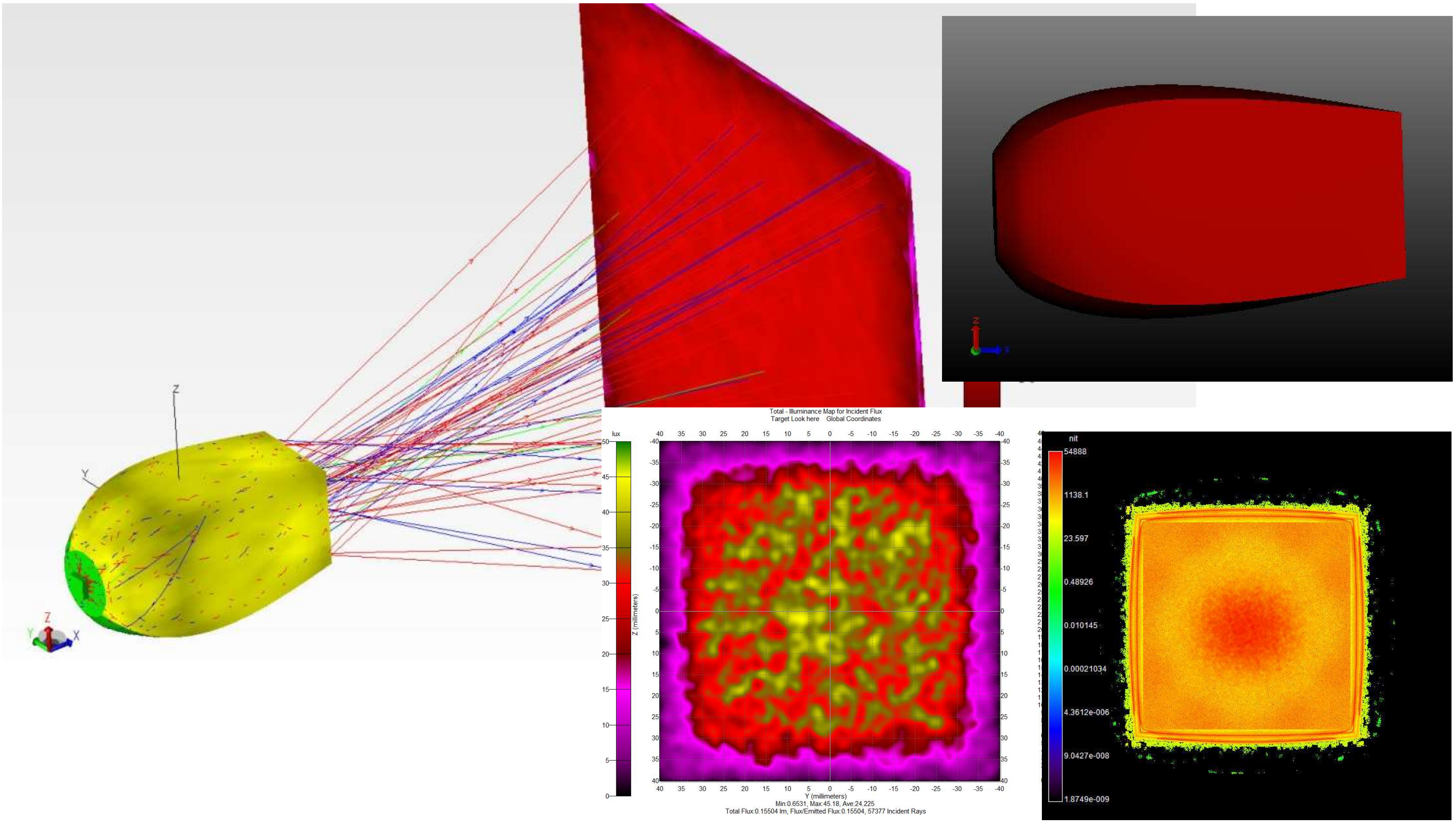
Alternate Design Possibility



The TracePro 3D interactive sketcher allows for alternative designs

Better Alternate Design Possibility with best uniformity



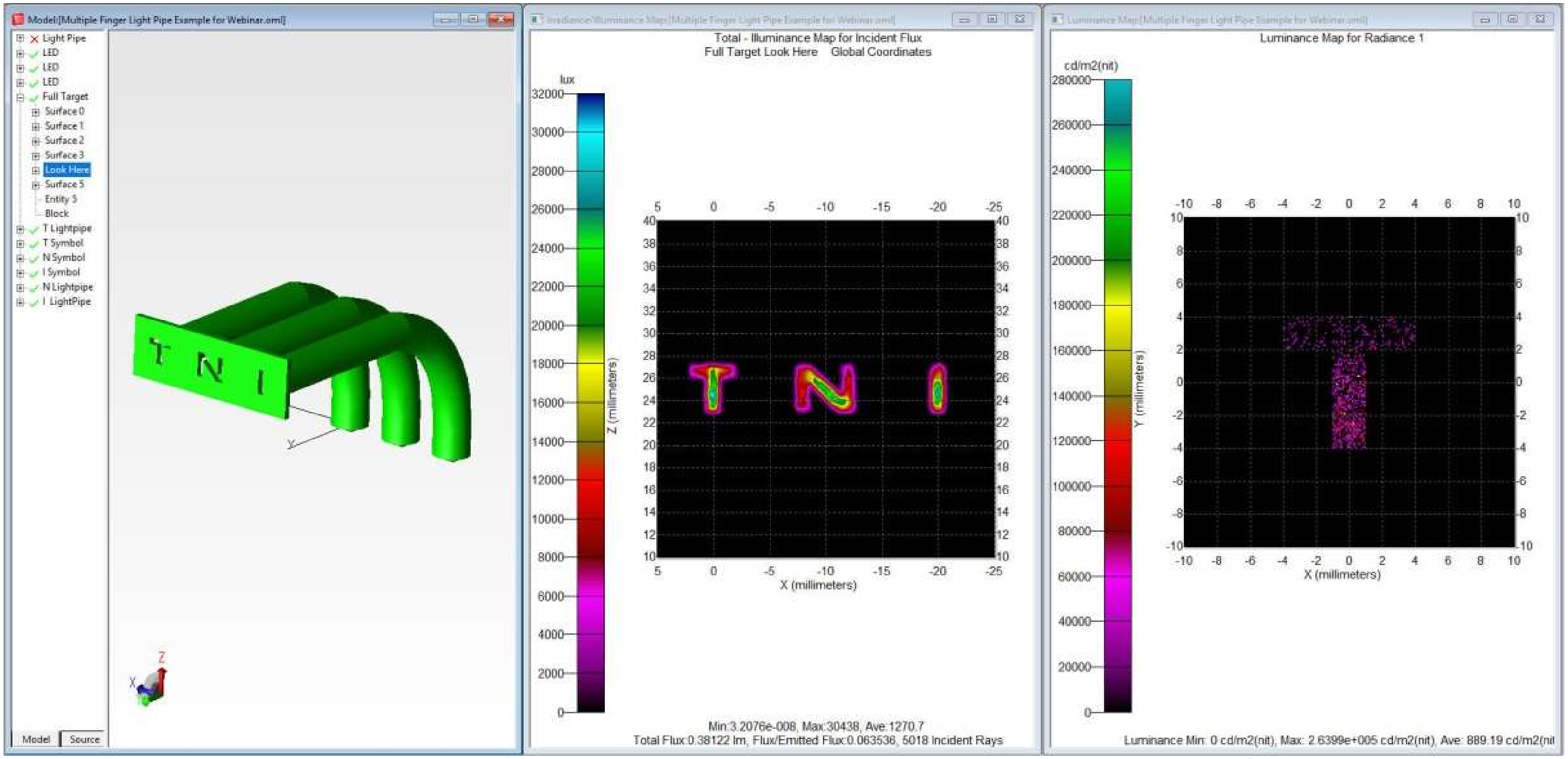
The TracePro 3D interactive sketcher allows for alternative designs. This design has excellent uniformity but the efficiency is only 15%.

Second Light Guide/Pipe - Three Finger Light Pipe Design Example

Three Finger Light Pipe - Goals

- To design an automotive light pipe that illuminates 3 icons, the letters T, N and I with dual LED emitters. Icons should be lit up in yellow for normal driving and in red when an emergency situation occurs
- No spot on the icon should be twice as bright as any other spot. The icon should be easily read
- The icons lit appearance should be uniform when viewed directly from the forward position
- Light pipe should be efficient with any cross-talk between fingers below two orders of magnitude compared to signal at exit surface of icon

Finished 3 Finger Light Pipe Project After Design Phase



Solid Isometric View | Output on target just past symbols | Lit Appearance of T

This system uses 6 LEDS, 2 Yellow and 2 Red side by side for each of the 3 fingers of the light pipe illumination T, N and I symbols in dashboard

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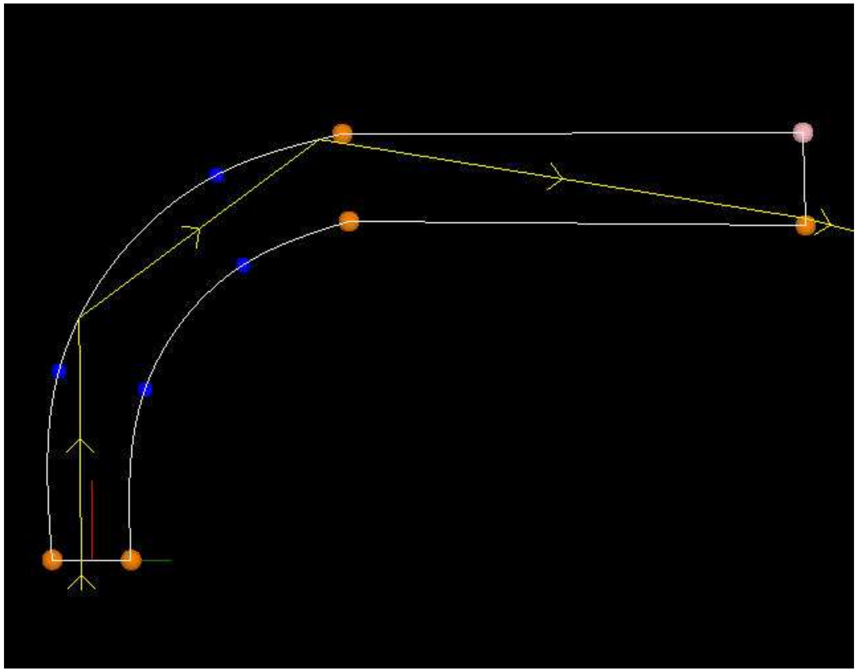
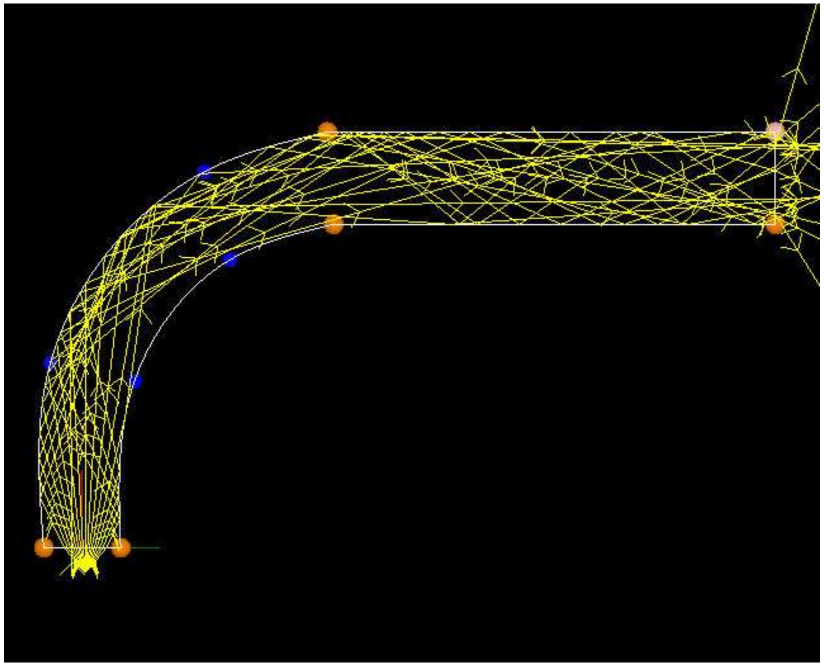
Using the 3D Surface Sketcher to Start with an Initial Good Design

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

Use the interactive ray tracing tool to trace more rays. Pull on segments to create a good efficient initial design.

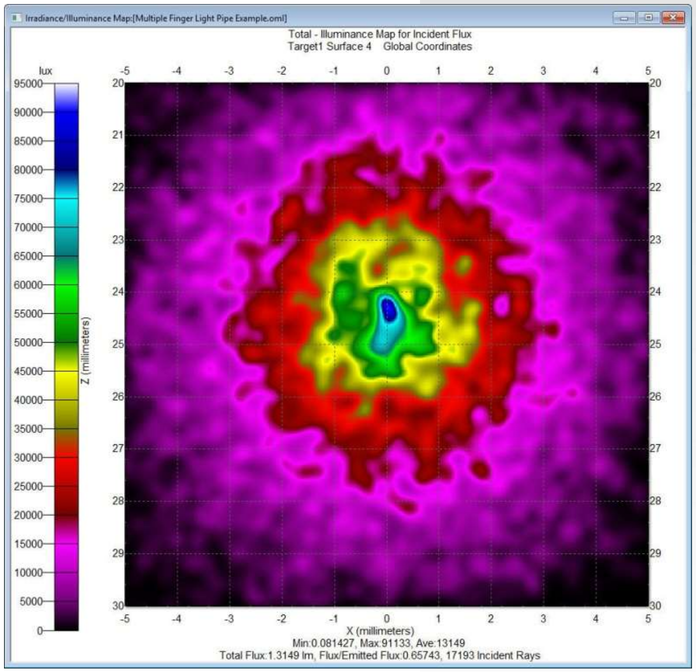


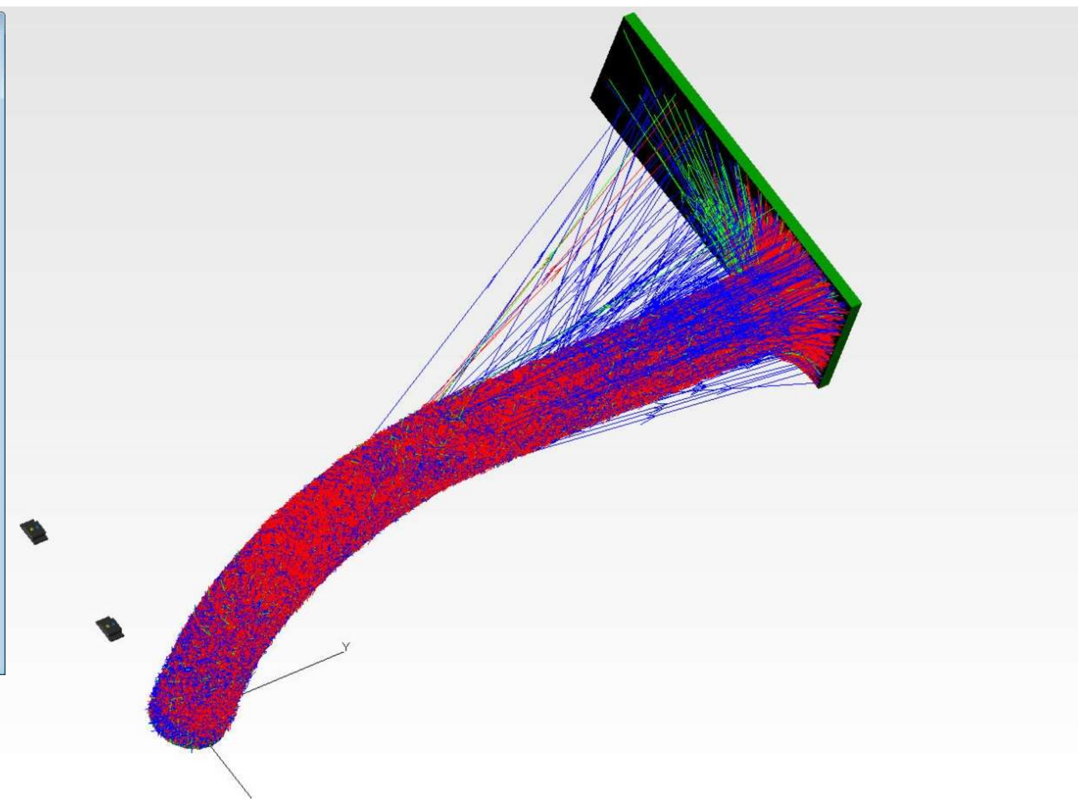


PCB board is on bottom left and light pipe must move the light vertically, 25mm

Setting Up the Static System for one pipe

After exporting the light pipe as a solid, now setup the dual LED sources and a simple target. Check for cross-talk which can be seen exiting to the left of the light pipe onto the target. Initial results are quite good, 65.7% efficiency, uniform throughput over all angles.





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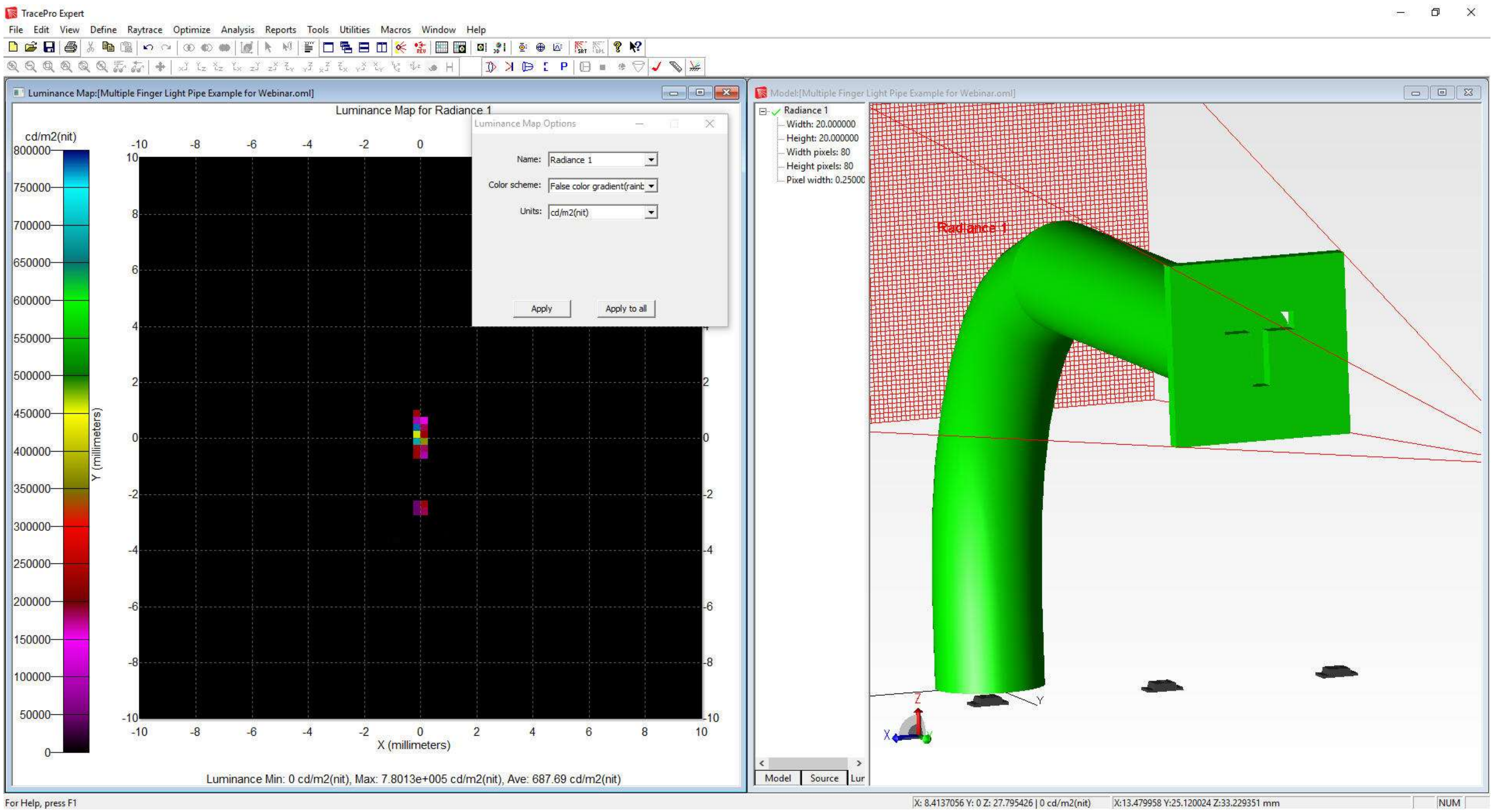
Add icons to singular light pipe, check Lit appearance



Since this is a light pipe used in an automotive application, the letters T, N and I are lit to show emergency information. If we look at the T, we see an immediate problem, only the main vertical bar is lit up. Bad uniformity, we can try texturex to fix the problem or white bulk scattering paint.

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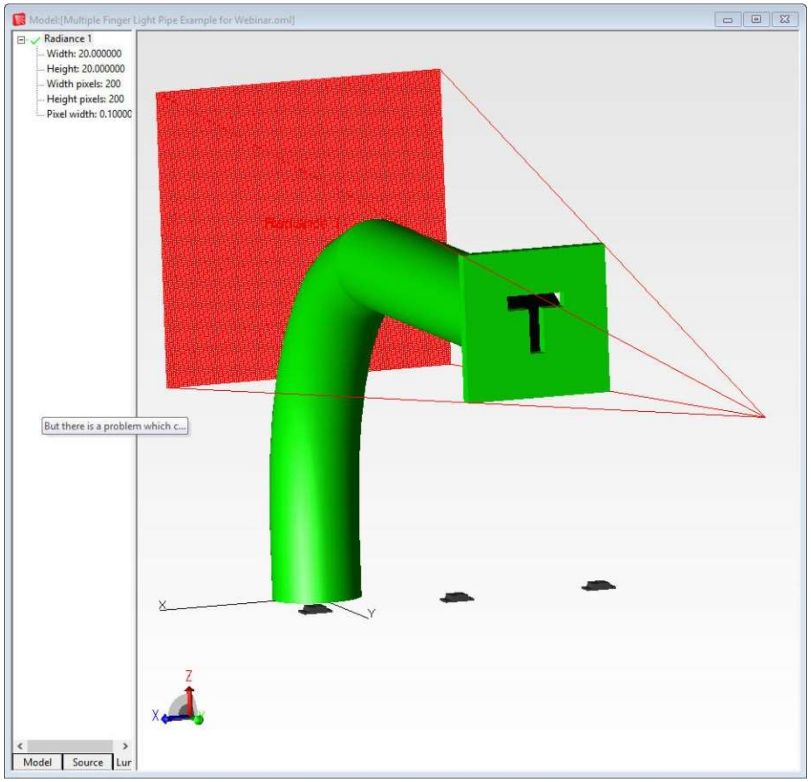
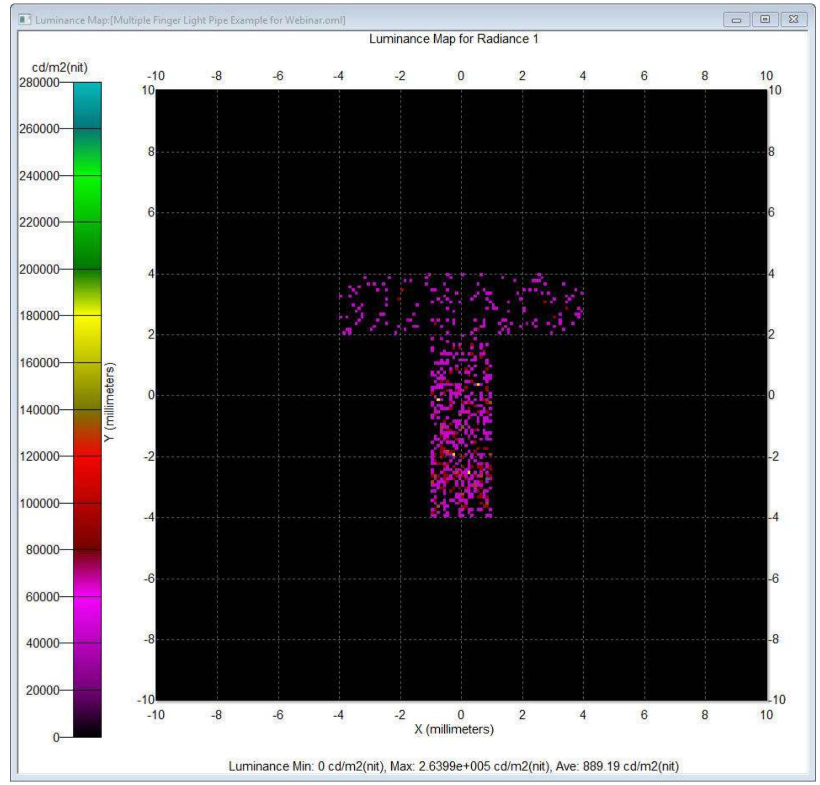
Adding Texture – Moldtech 11007 Results





We can see that by adding a Moldtech 11007 texture to the exit surface, the top of the T icon starts to fill in. We could play around with finer textures or adding white bulk scattering paint, but the Moldtech 11007 is working quite well in terms of uniformity. We need to drop the nits to around 1000 so adding a dense white applique should do the trick.

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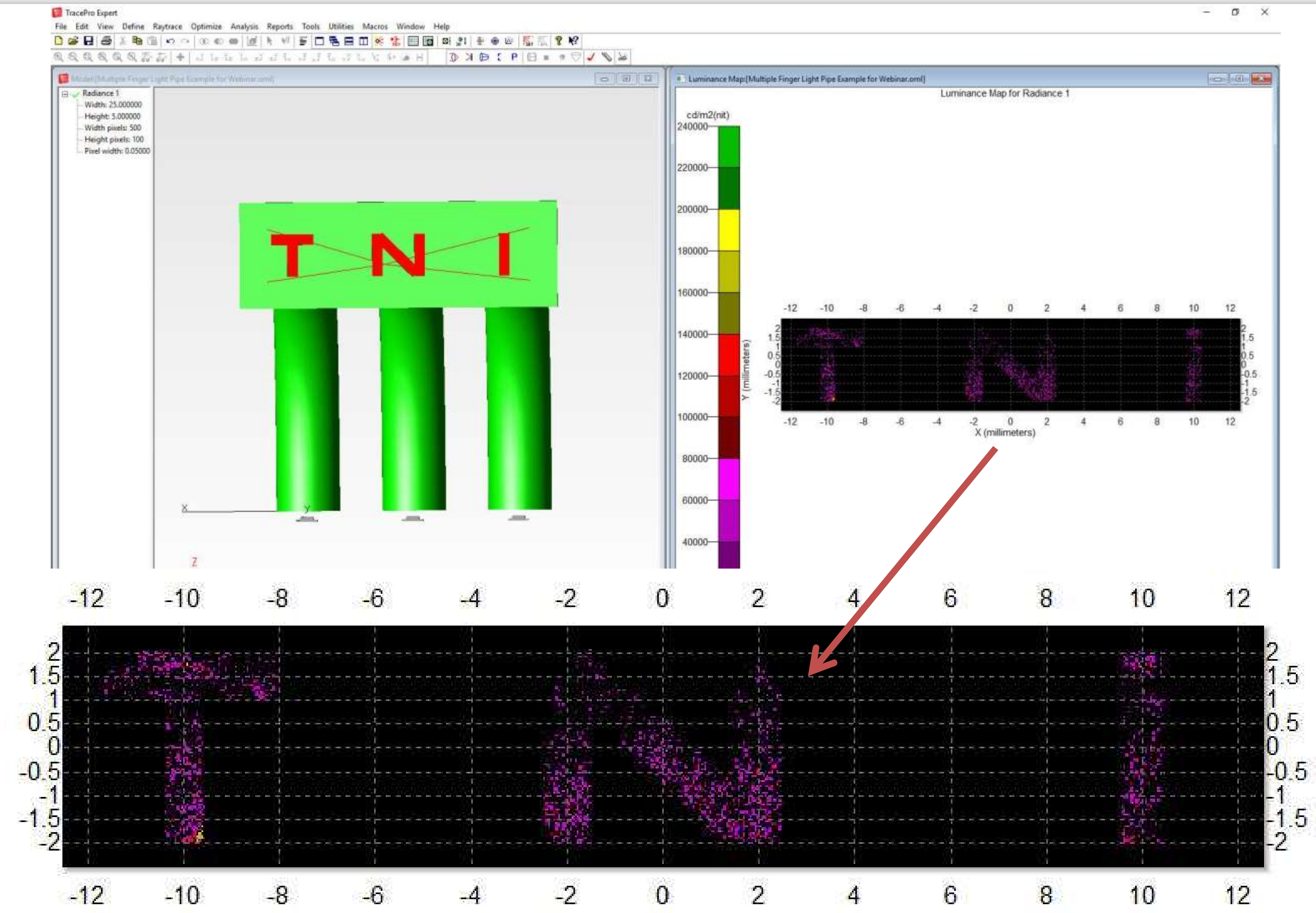
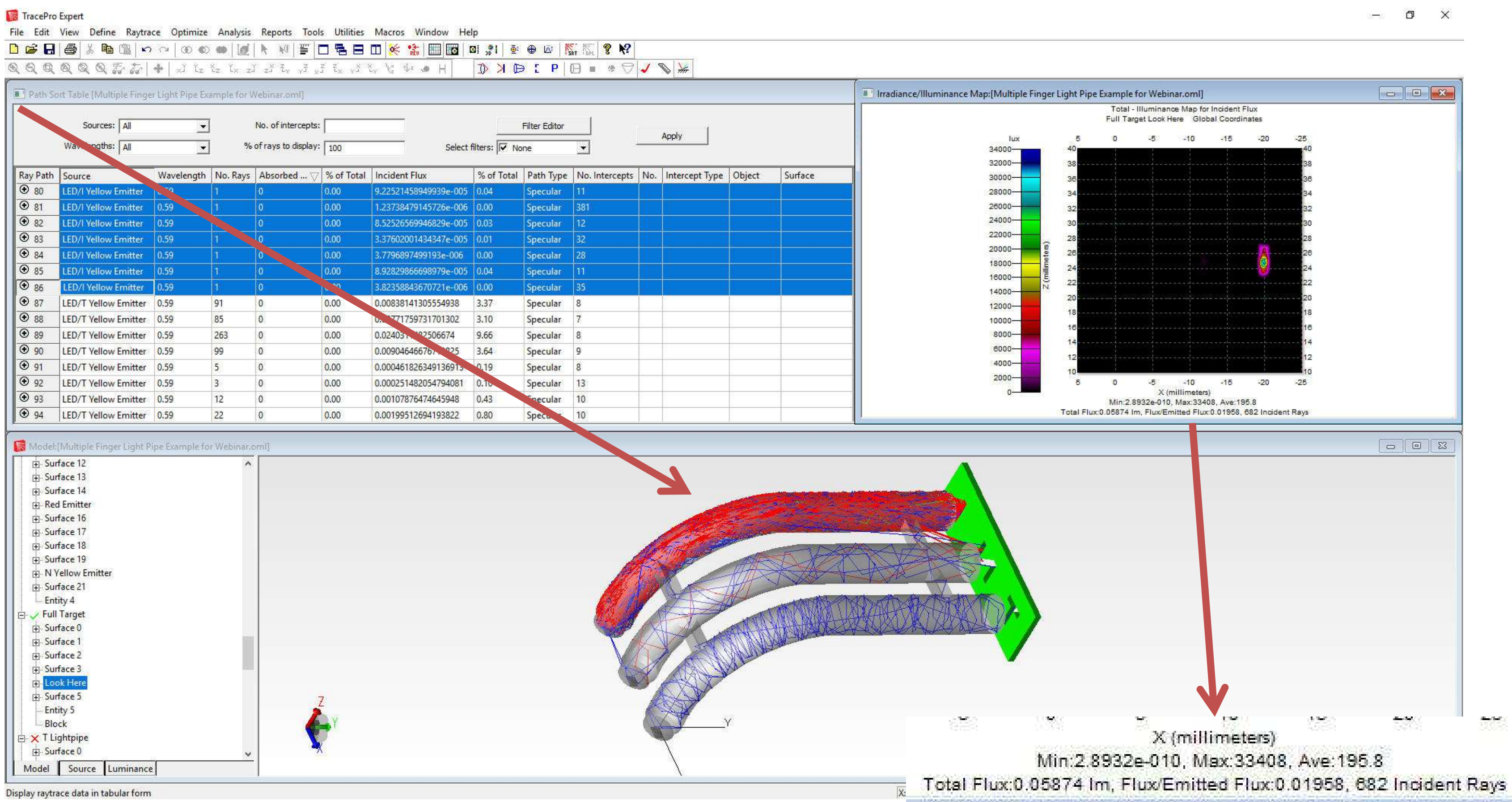
Tracing more rays and checking the full setup of the 3 icons proves that the texturing worked.

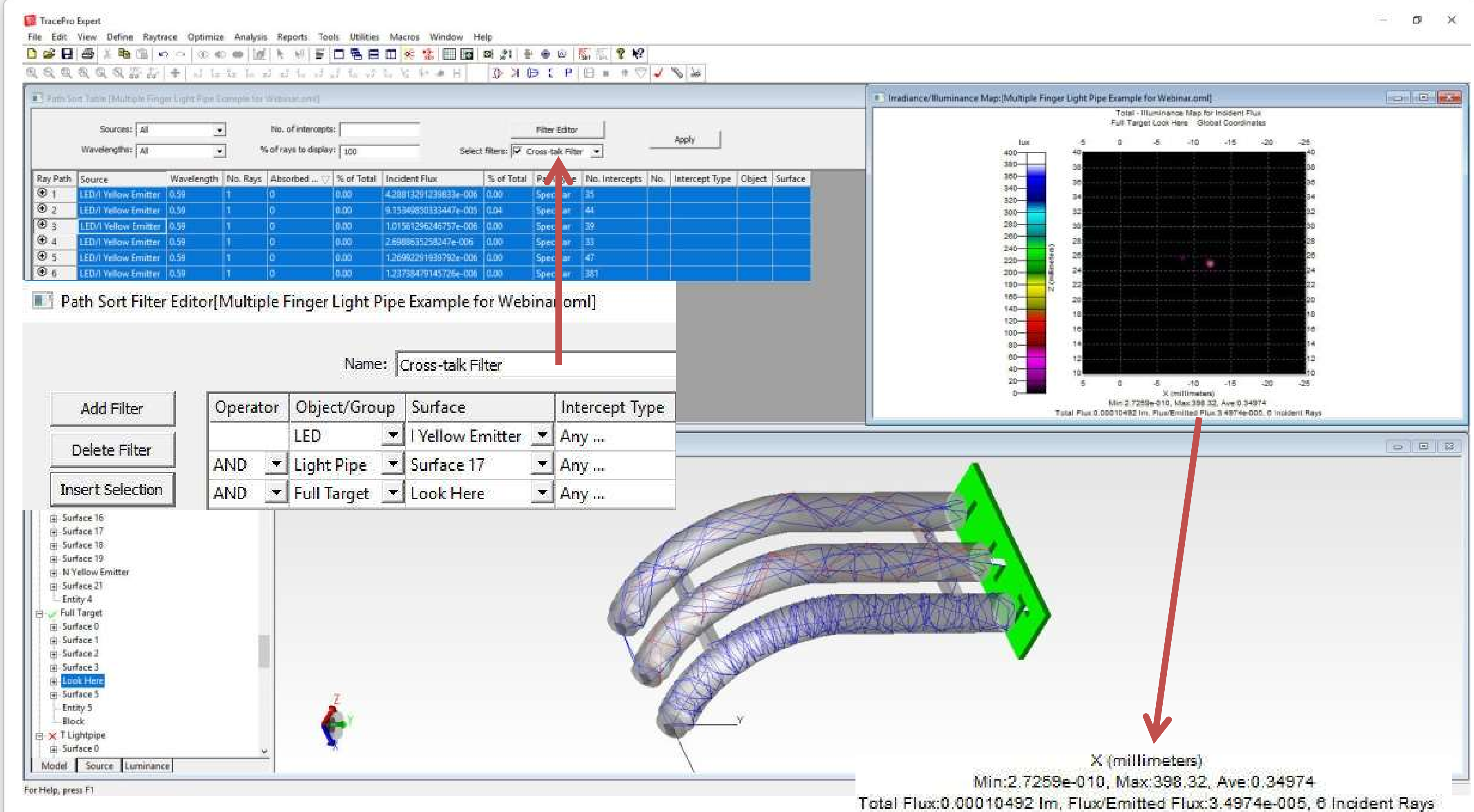


Now we need to check the cross-talk in the final design



The I light pipe yellow emitter propagates .05874 lumens through the I symbol to the target. This is generally the straight through paths off the sides of the light pipe through the icon to the target.

The cross-talk path from the I yellow emitter into the N light pipe is not a problem



Conclusion – No problem with cross-talk paths the straight through path is more than 2 orders of magnitude higher than the cross-talk path

Conclusions

- TracePro's Interactive Optimizers, Luminance and Photo Realistic rendering capabilities provide the simulation tools needed to correctly simulate today's new light pipe designs before manufacturing.

- Virtual prototyping is an efficient known process to reduce time and money versus trial and error prototyping. Further, since the computer is doing the work, hundreds of possible solutions can be investigated and new novel designs discovered in much less time.

- Remember that illuminance and candela maps tell only a partial story and can create nasty surprises once the part is prototyped showing uneven illumination.

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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