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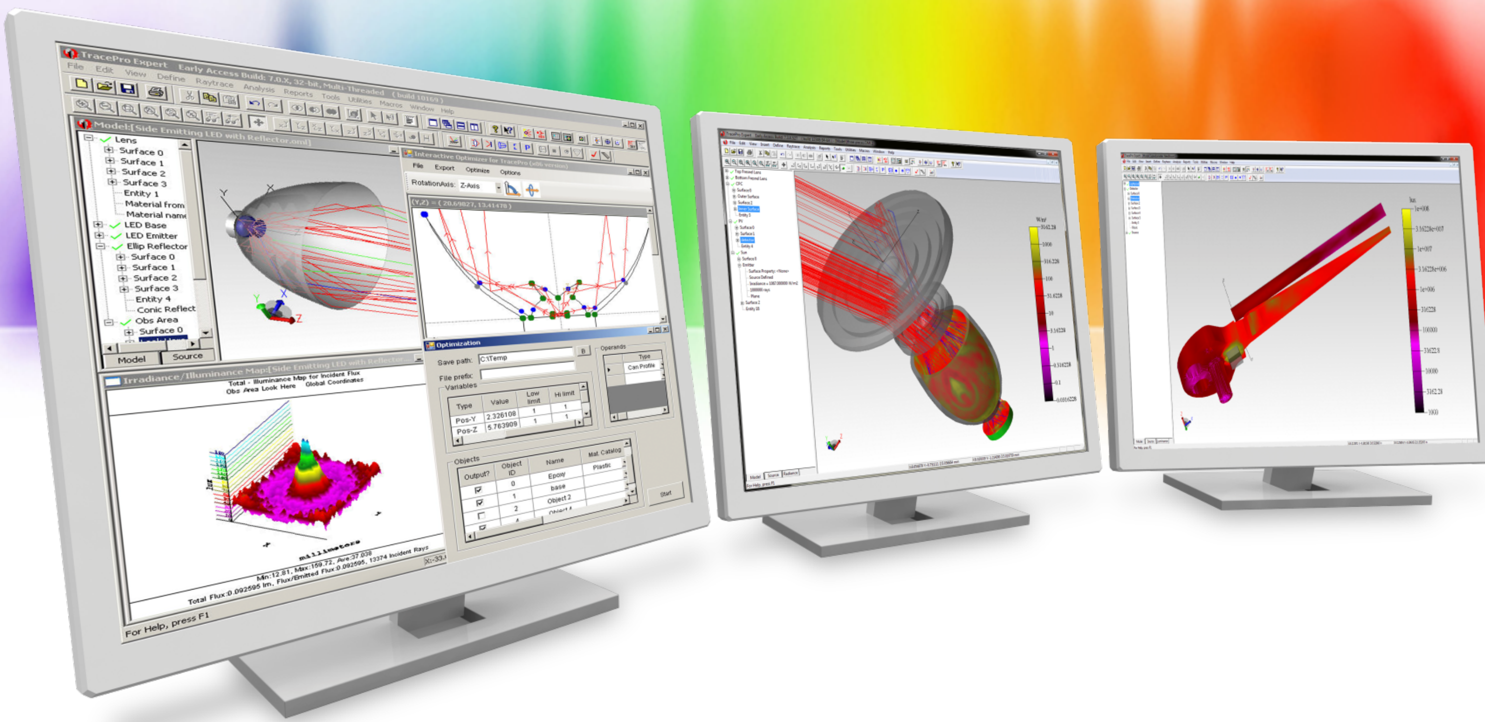

MODELING LED LIGHTING COLOR EFFECTS IN MODERN OPTICAL ANALYSIS SOFTWARE

LED Professional Magazine Webinar

10/27/2015

LAMBDA
RESEARCH CORPORATION

Presenter

- Dave Jacobsen

  Senior Application Engineer at Lambda Research Corporation for over 7 years. Prior to that 20+ years at PerkinElmer, formerly EG&G, as a Principal Optical Engineer working with xenon light sources, lighting, and biomedical systems.

- Lambda Research Corporation

  Celebrating our 22nd year. Makers of TracePro, TracePro Bridge for SolidWorks, and OSLO optical design and analysis software.

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Outline

- Introduction
- What is color?
- Color metrics
- Color effects in LED lighting
- Examples
- Questions and Answers

Introduction

Introduction

- Goals
  - To show how modern optical design and analysis software can be used to model and predict the color effects in LED lighting systems.
  - This can help to shorten the design process, speed time to market, and reduce developement costs by allowing new designs to be created and analyzed virtually, possibly delaying the need for actual prototypes to much further along in the design process.

Introduction

- What do we need to acheive these goals?
  - A good optical analysis software program
  - An accurate 3D solid model of the LED lighting system including accurate surface and material properties
  - An accurate source model, either a surface source model or a rayfile
  - Trace enough rays to get an accurate answer

What is Color?

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What is Color?

- **Color** (American English) or **colour** (British English; see spelling differences) is the visual perceptual property corresponding in humans to the categories called *red*, *blue*, *yellow*, etc. Color derives from the spectrum of light (distribution of light power versus wavelength) interacting in the eye with the spectral sensitivities of the light receptors. Color categories and physical specifications of color are also associated with objects or materials based on their physical properties such as light absorption, reflection, or emission spectra. By defining a color space colors can be identified numerically by their coordinates.

  Source: Wkipedia

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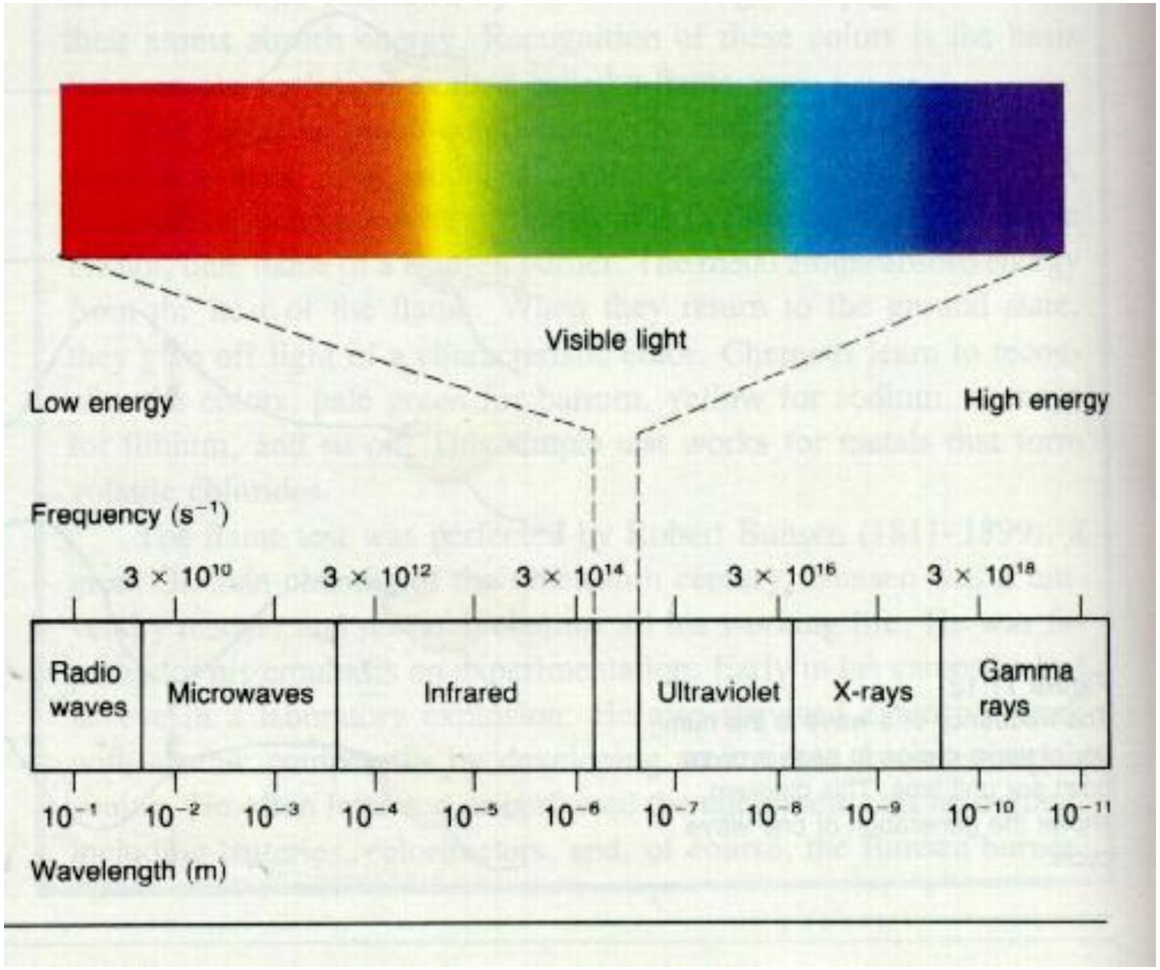
What is Color?

- Visible light spectrum



What is Color?

- Color is an product of:
  - Material properties – glass type, plastic type, color filters
  - Surface properties – paint, coatings, mirror surfaces
  - Source lighting – spectrum and intensity of source illumination
  - Ambient lighting – spectrum and intensity of surrounding light
  - Human Eye effects – color blindness
  - Plus additional factors

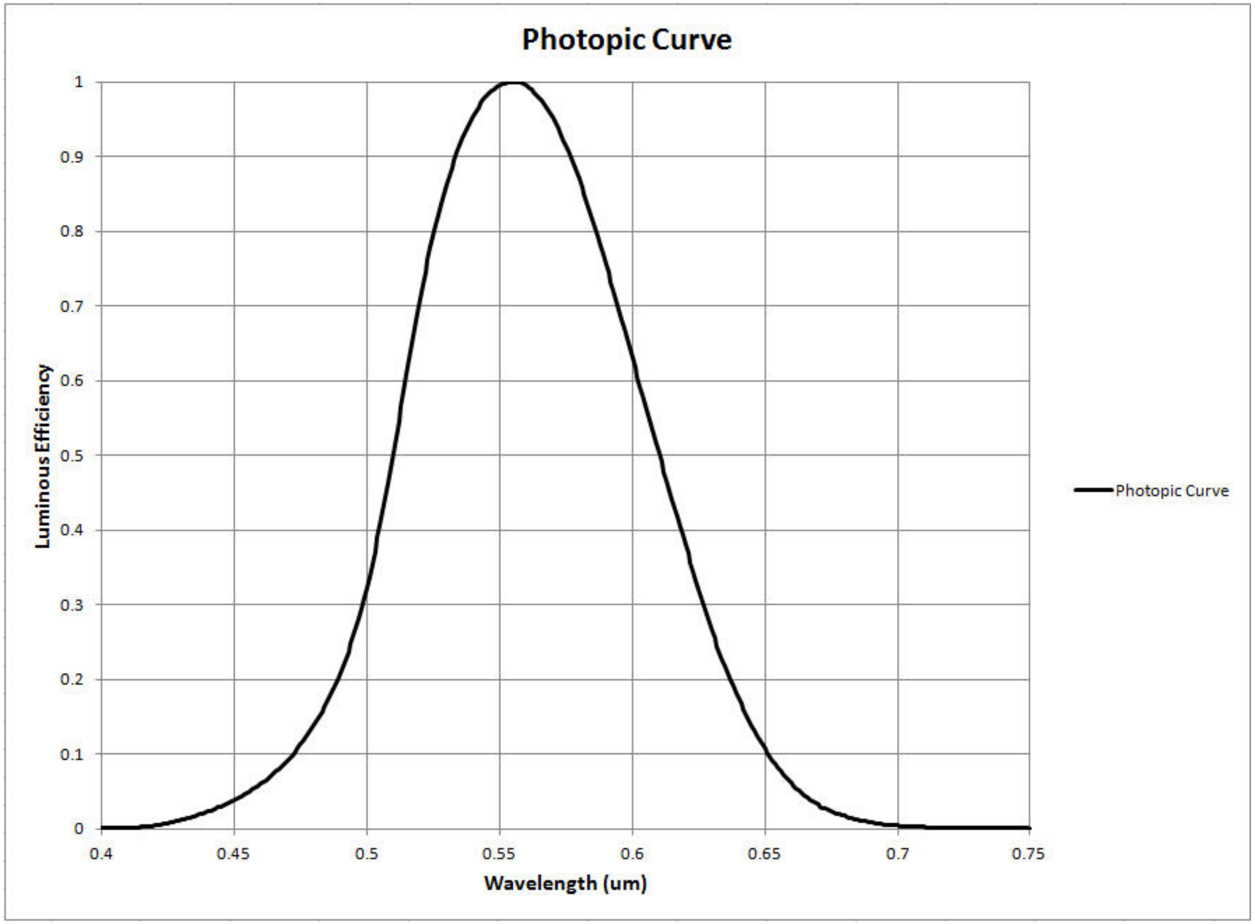
Color Metrics

Color Metrics

- Photometry
  - Photometry is the measurement of light as it is perceived by the human eye
  - The human eye is sensitive to light from about 0.4 – 0.75um, 400-750nm. This is known as visible light.
  - Peak sensitivity for a light adapted eye is at ≈ 0.555um
  - Standard unit of visible, or luminous, flux is the **lumen (lm)**

Color Metrics

- Photopic Curve – Light Adapted Eye



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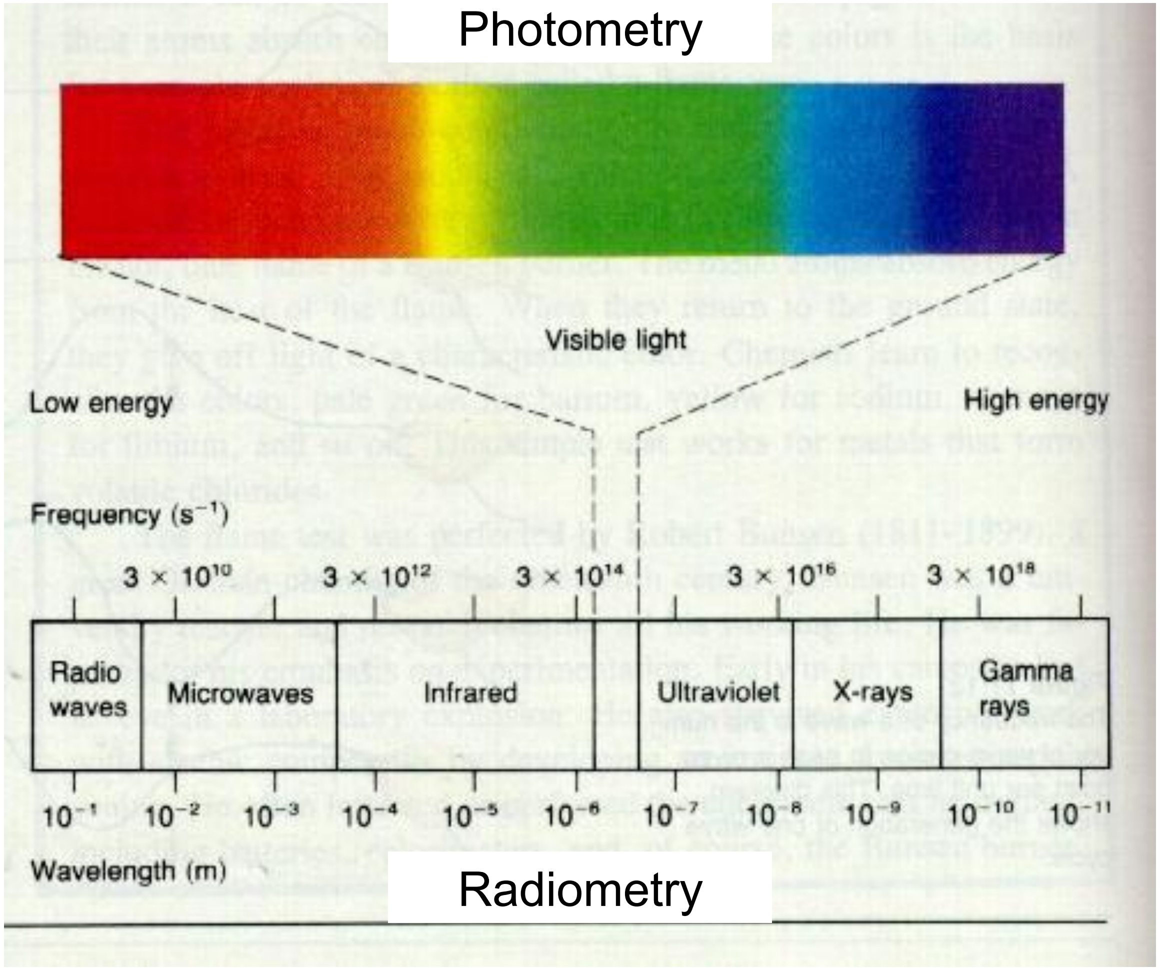
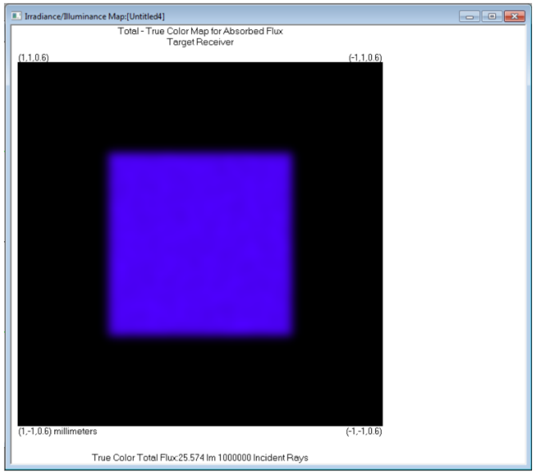
Color Metrics

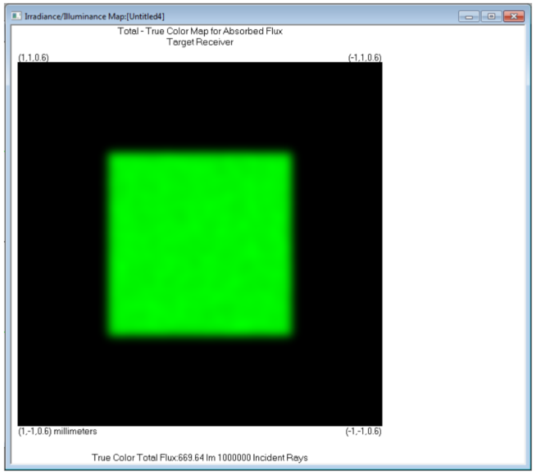
- Radiometry and Photometry

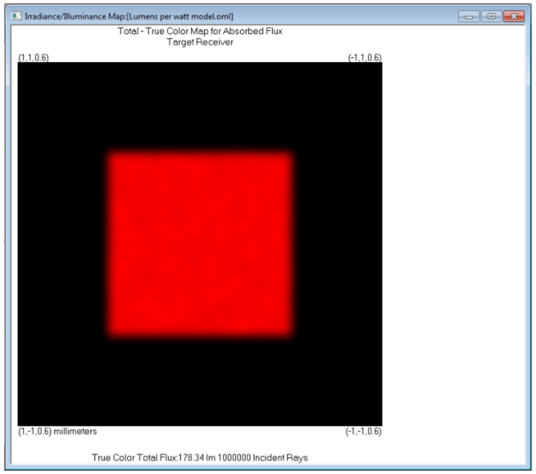


Color Metrics

- Lumens/watt conversion







λ= 0.45um 1 watt ≈ 25.5 lumens	λ= 0.55um 1 watt ≈ 670 lumens	λ= 0.63um 1 watt ≈ 178 lumens

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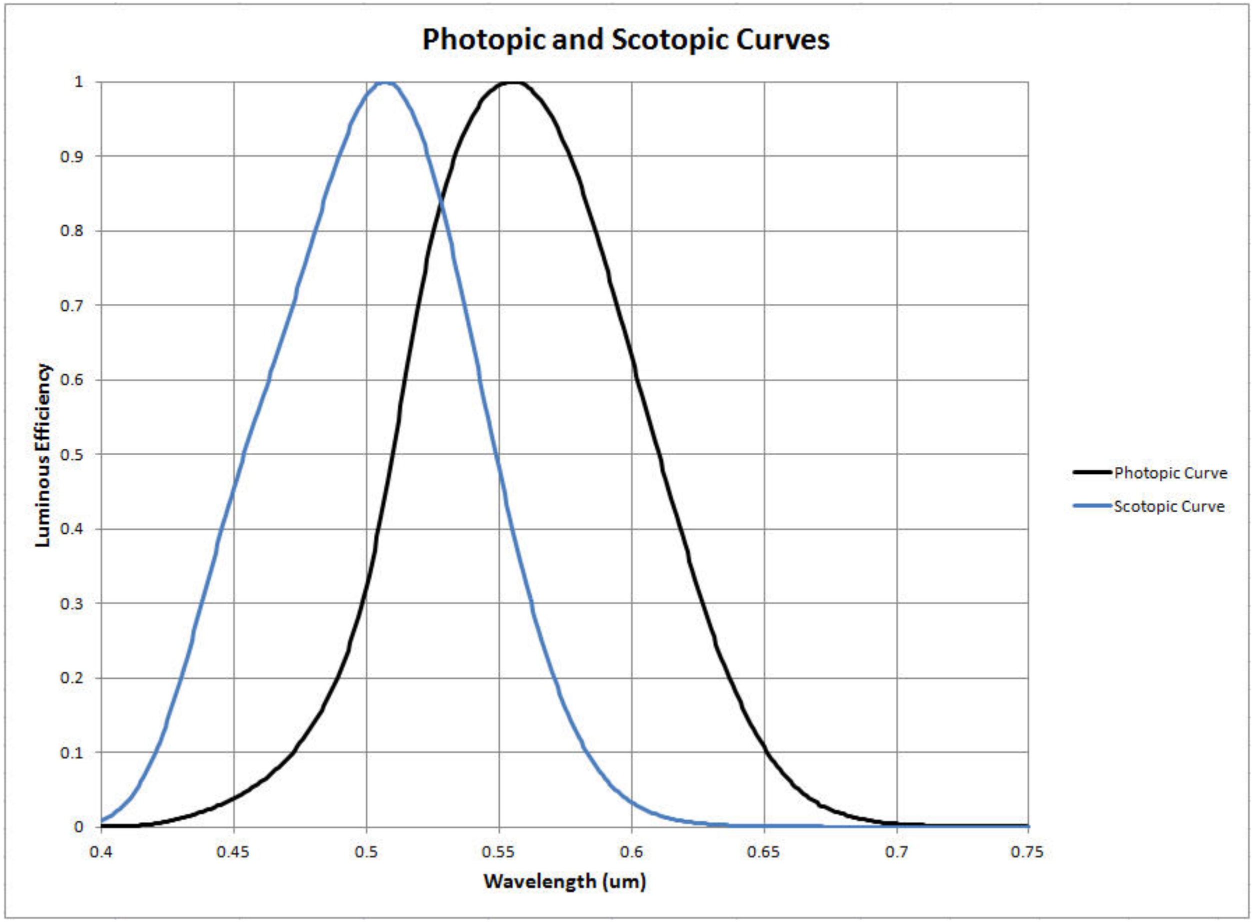
Color Metrics

- Scotopic Curve – Dark Adapted Eye



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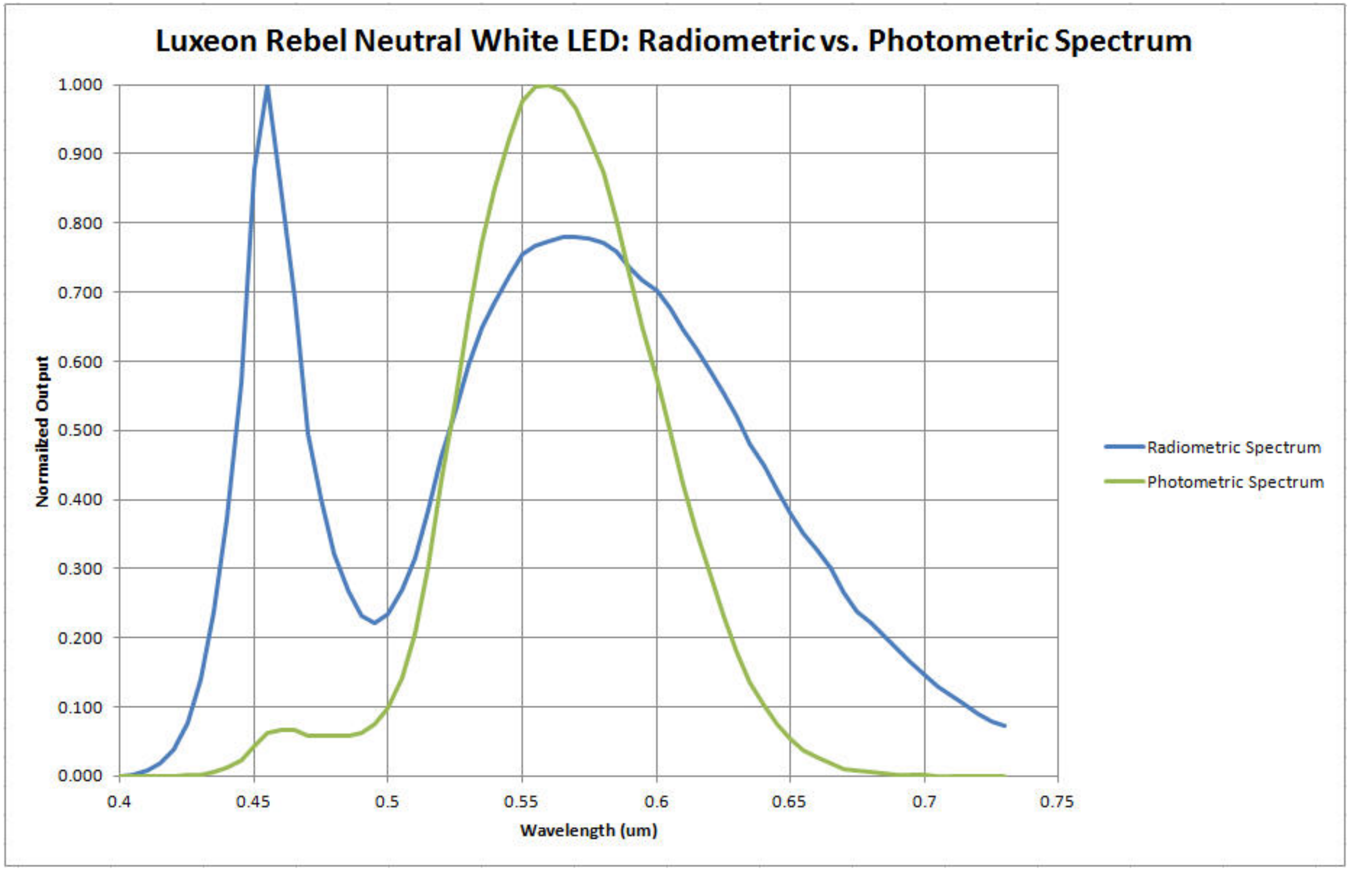
Color Metrics

- Radiometric vs. Photometric Spectrums



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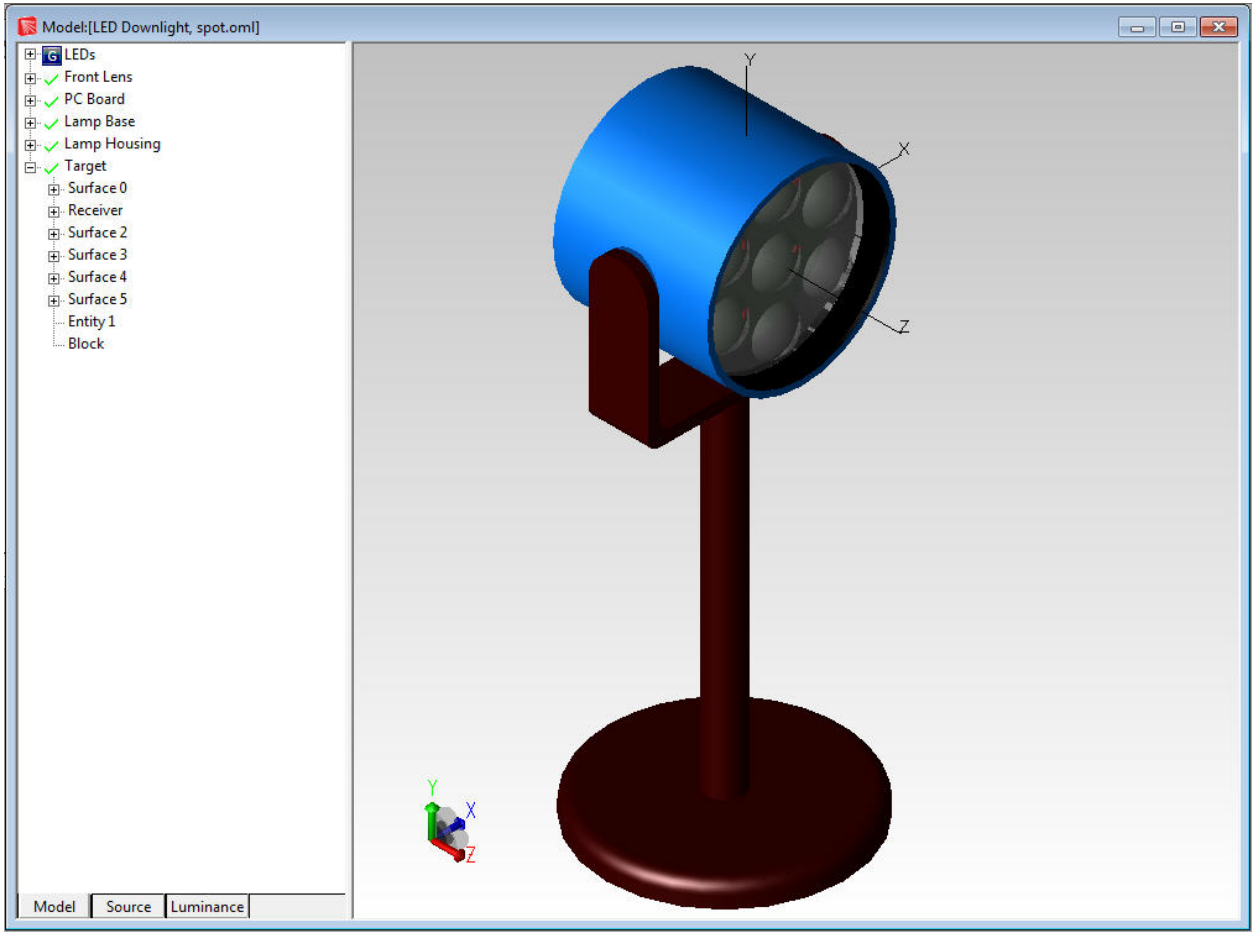
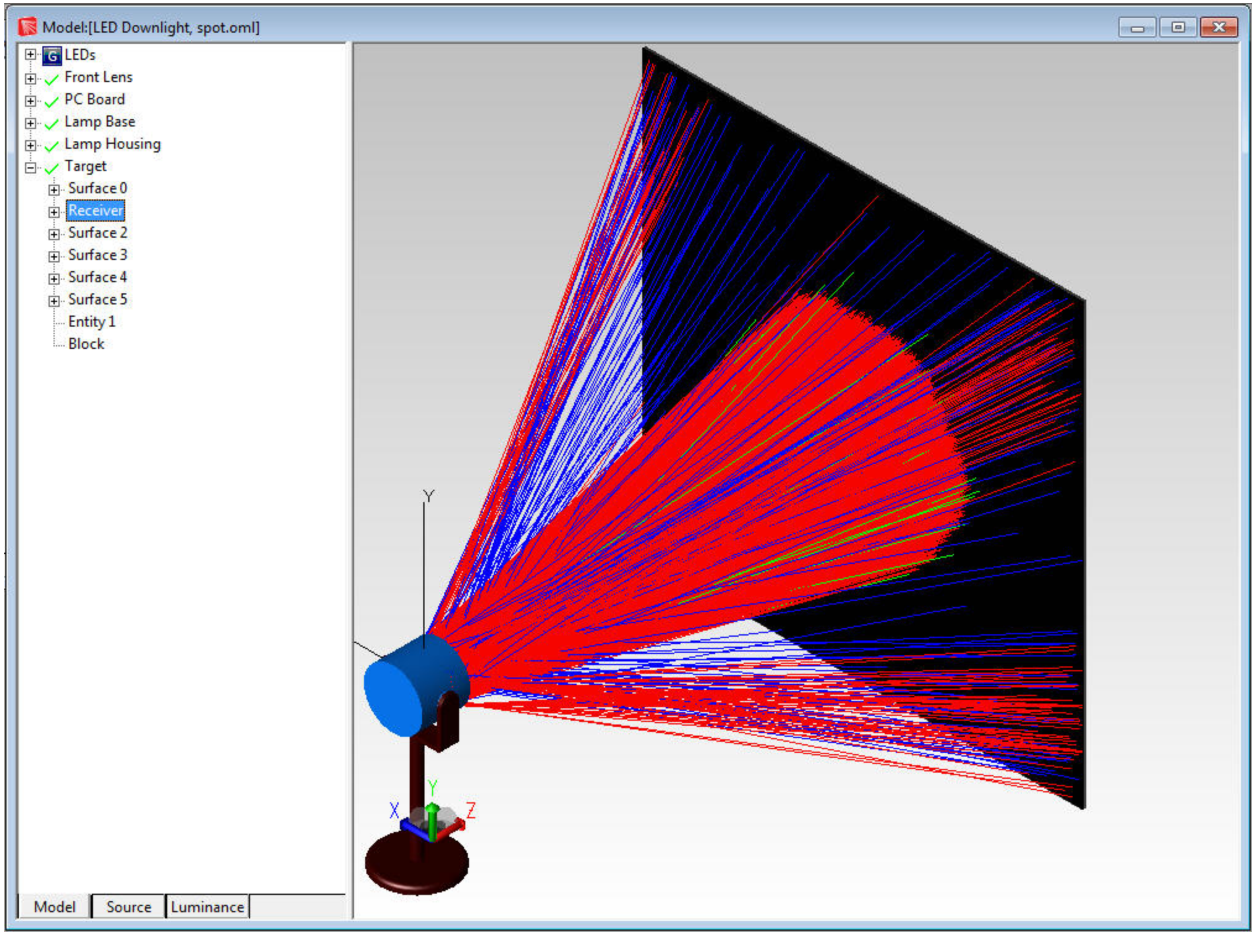
Color Metrics

- LED spot light example



Color Metrics

- LED spot light example with representative rays



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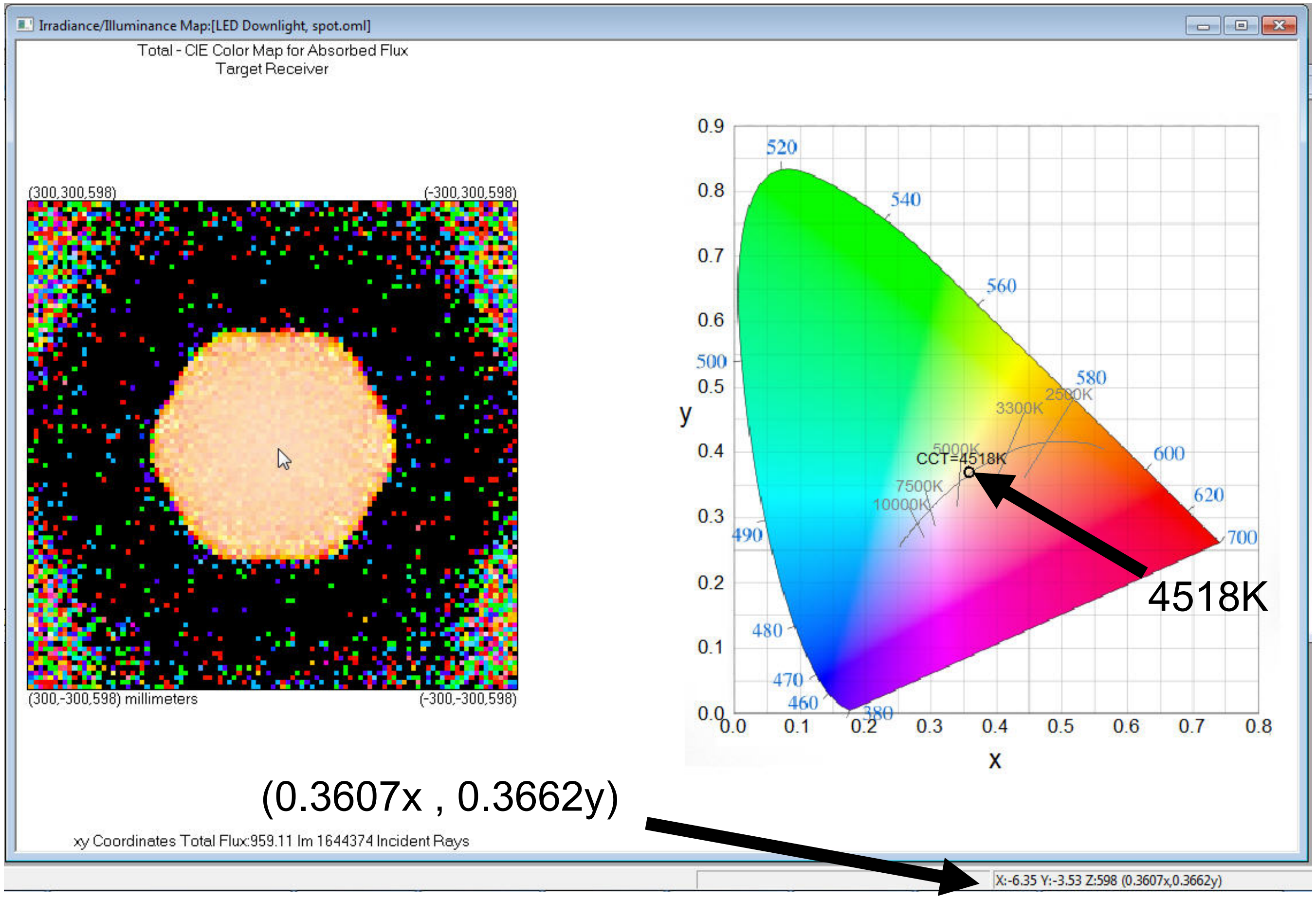
Color Metrics

- Color Coordinates – CIE 1931 xy



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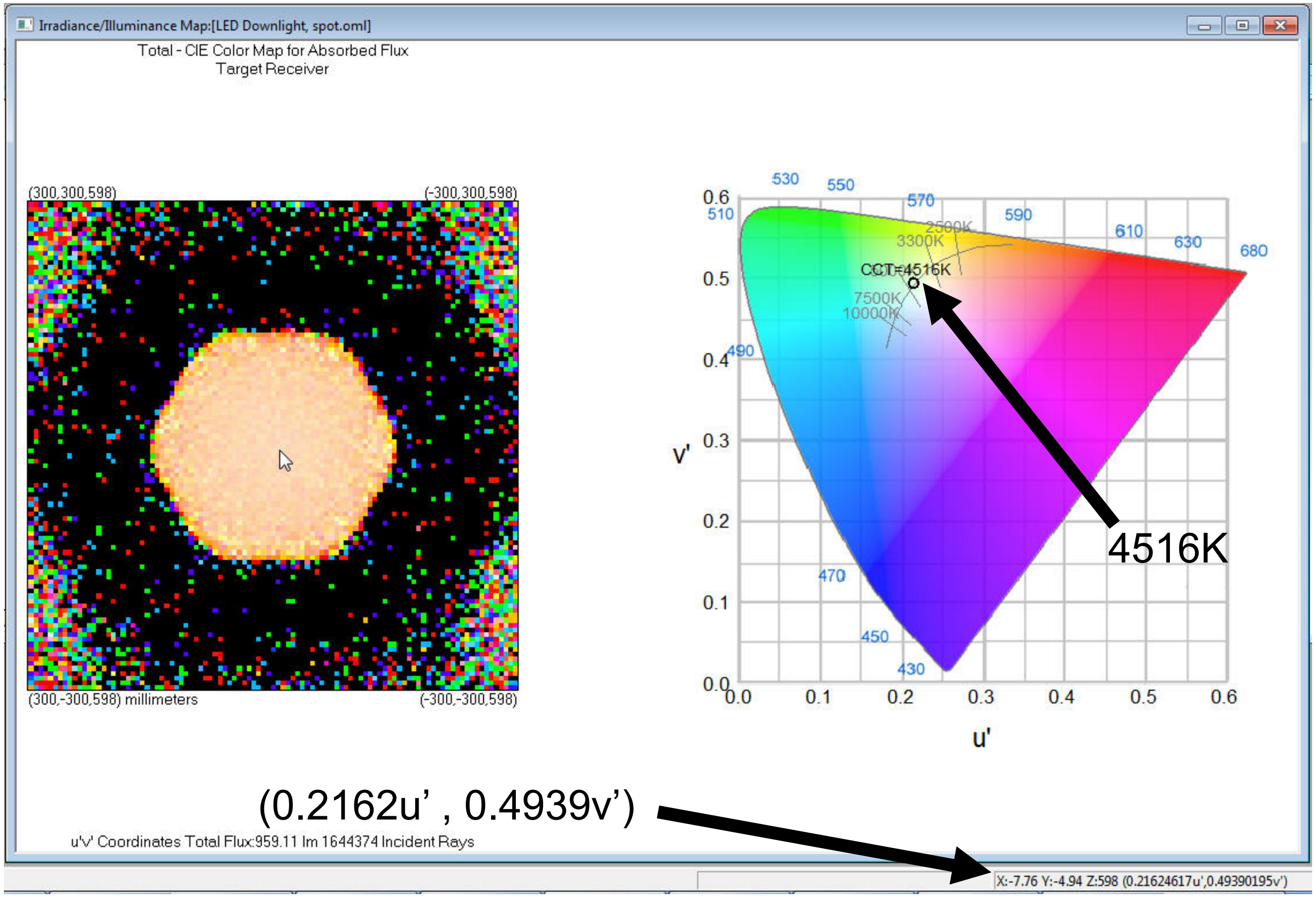
Color Metrics

- Color Coordinates – CIE 1975 u'v'



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Color Metrics

- LED spot light example – Spectrum from LED datasheet
  - Osram Luxeon Rebel – Neutral White

LXML-PW31 (5000K), LXML-PW21 (5700K) and LXML-PW11 (6500K)
at Test Current, Thermal Pad Temperature = 25°C

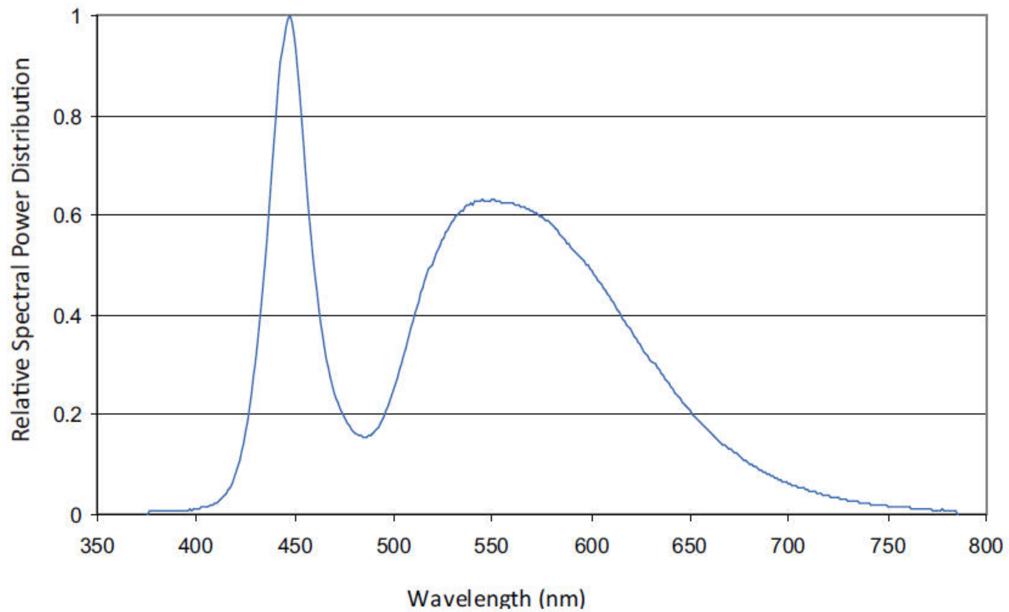

Figure 13. Color spectrum of LXML-PW31, LXML-PW21 and LXML-PW11 emitters, integrated measurement.

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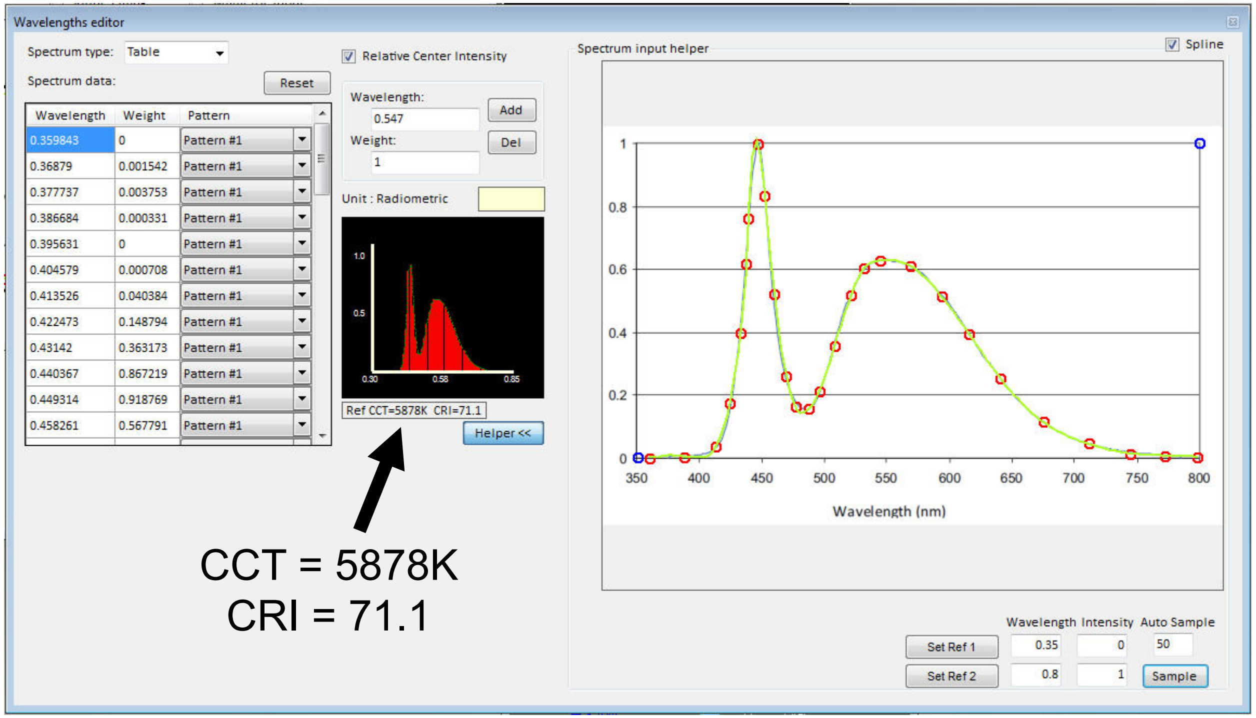
Color Metrics

- Color Rendering Index (CRI)
  - Describes how accurately a source will reproduce colors compared to a standard source. Value ranges from 0-100. The higher the value, the more accurate the color rendition.



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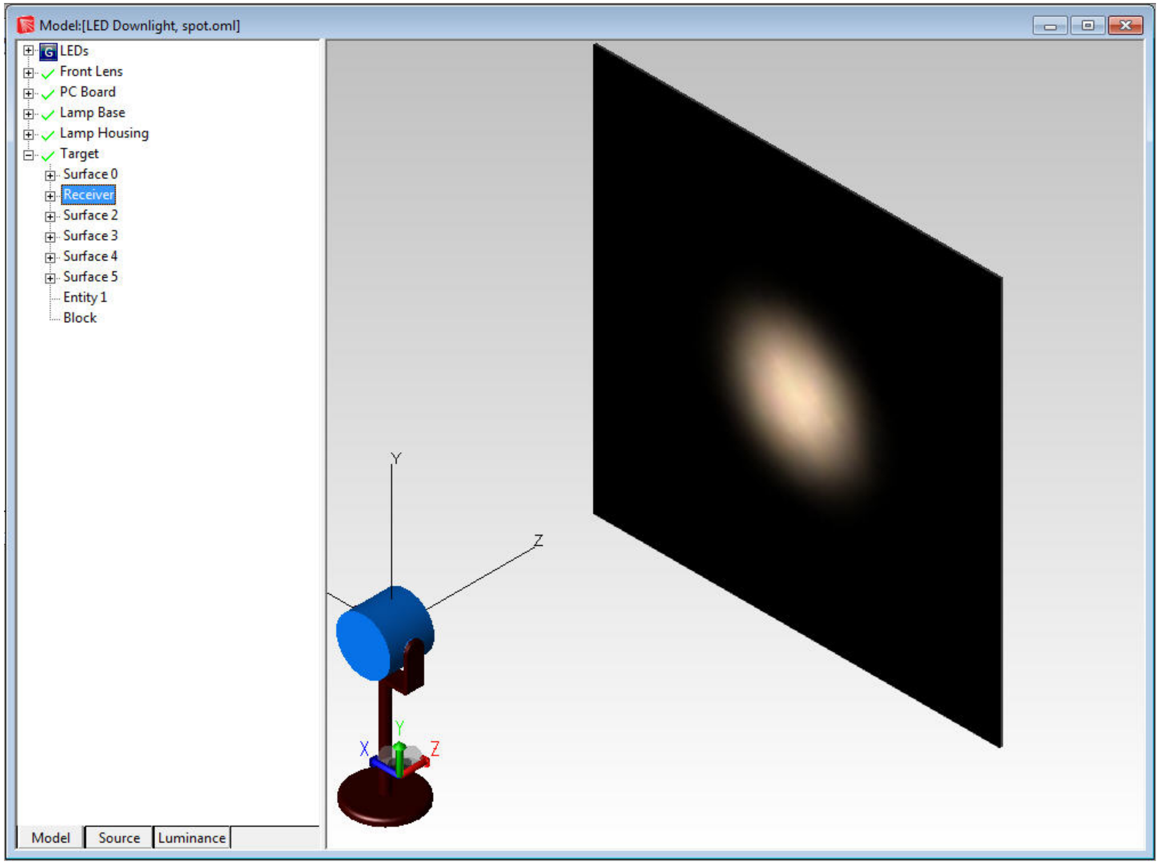
Color Metrics

- TrueColor – RGB values
  - Shows an 8-bit RGB representation of the light falling on a surface



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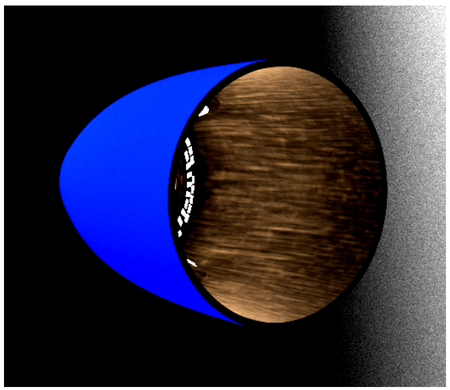
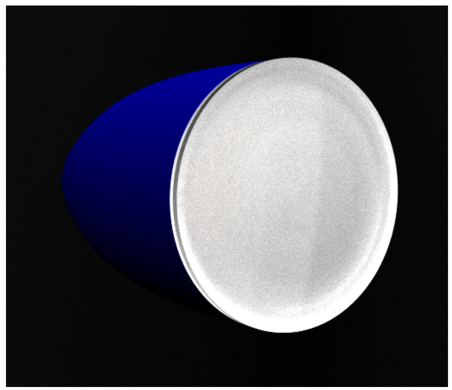
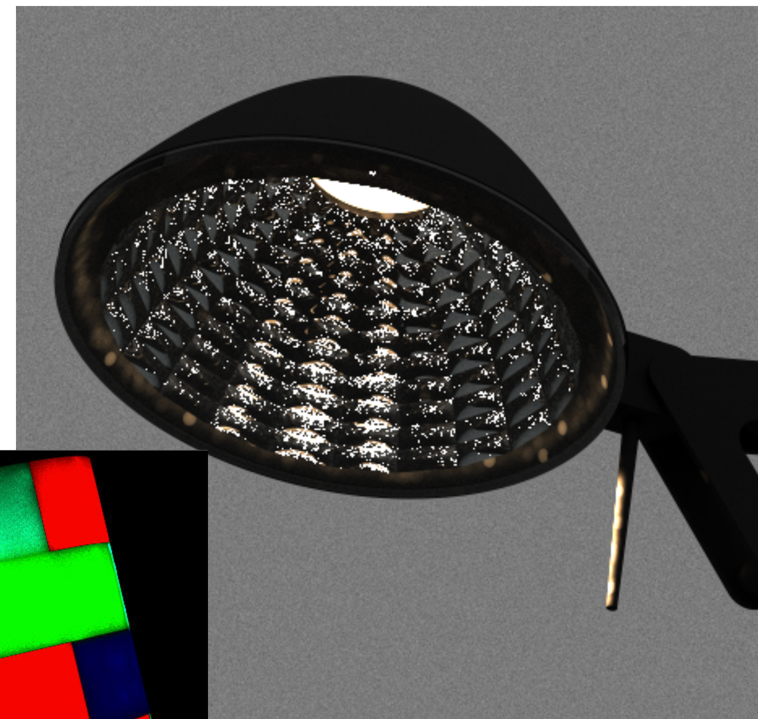
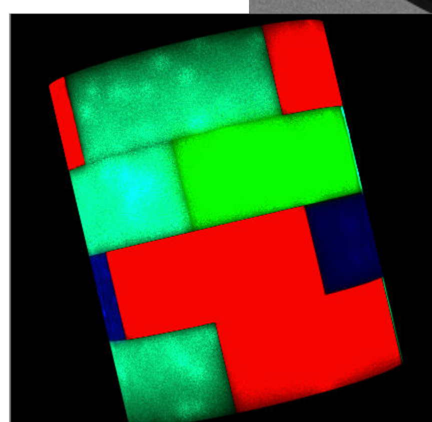
Color Metrics

- Photorealistic rendering
  - Presents a lit appearance view of the luminaire or illuminated surface. Used to show how the light will appear to a viewer.









Color Effects in LED Lighting

Color Effects in LED Lighting

- Factors that can effect color in LED lighting systems
  - Transmission
  - Reflection
  - Refraction
  - Coatings
  - Chromatic aberration
  - Diffraction/Interference
  - Fluorescence

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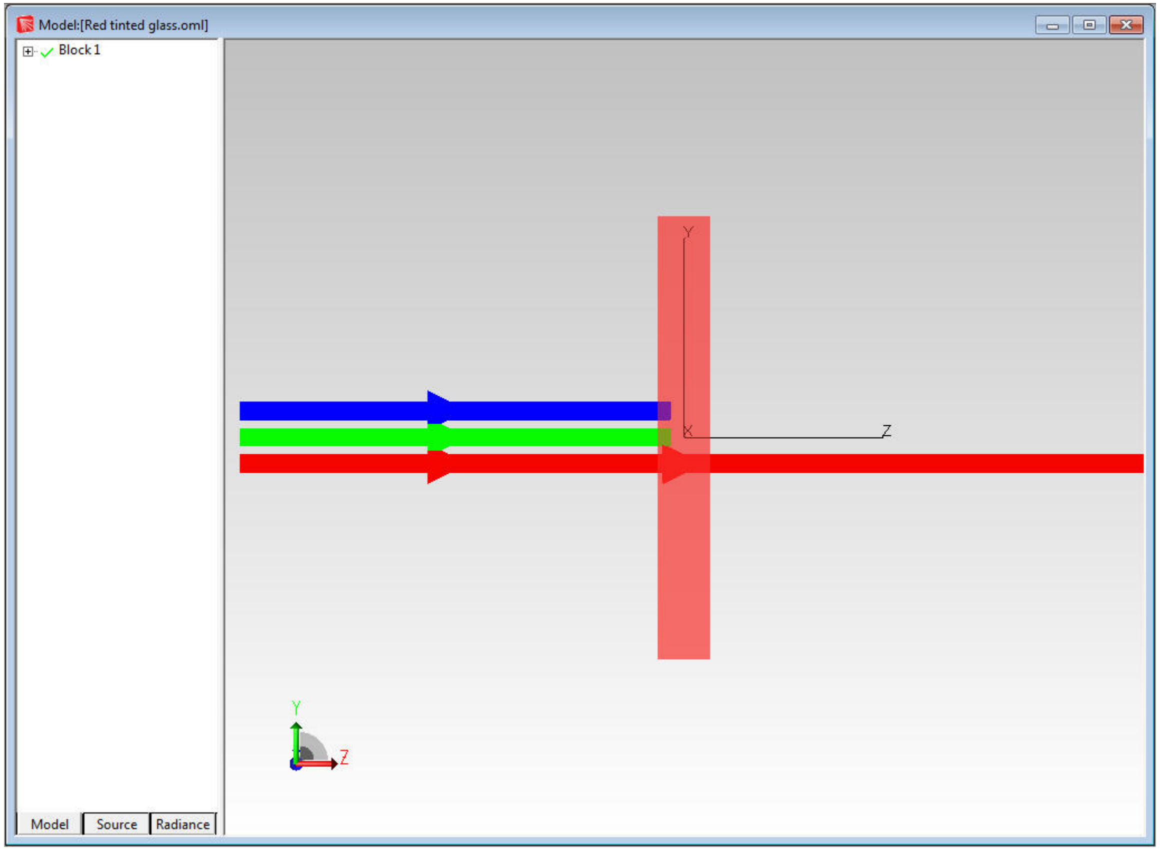
Color Effects in LED Lighting

- Transmission
  - The transmission and absorption of a material as a function of wavelength can affect the color. Red colored glass shown below.



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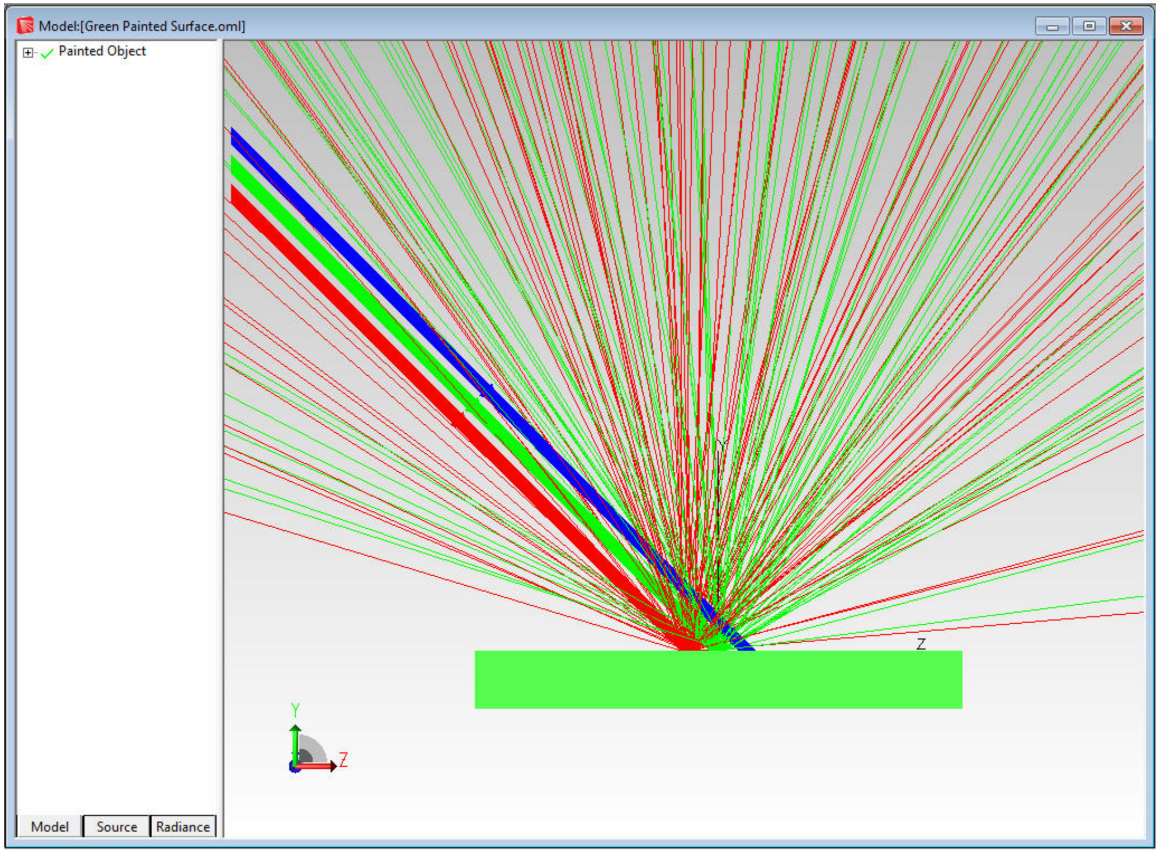
Color Effects in LED Lighting

- Reflection
  - The reflection and absorption of a material as a function of wavelength can affect the color. A green painted surface is shown below.



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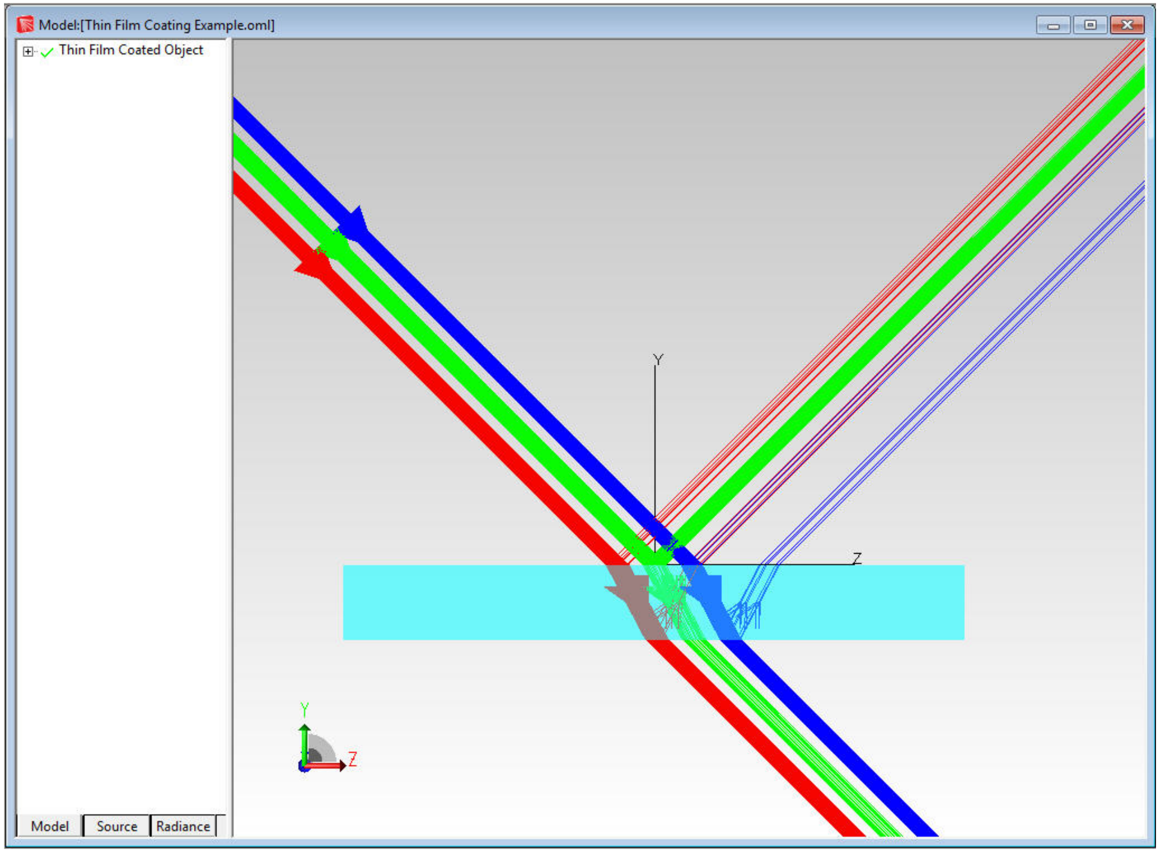
Color Effects in LED Lighting

- Coatings
  - Coatings such as thin film coatings can exhibit a combination of reflection, transmission, and absorption. A Cold Mirror coating is shown below.



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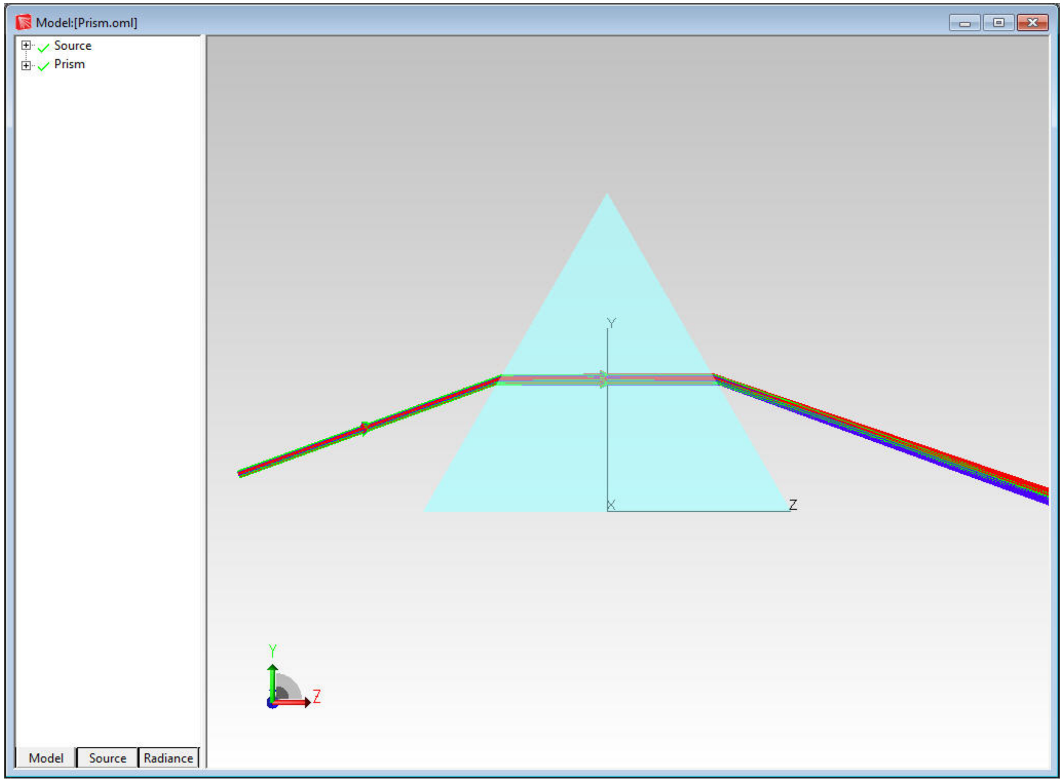
Color Effects in LED Lighting

- Refraction
  - Light is bent at angles as a function of wavelength and difference in index of refraction between incident and surrounding medium according to Snell's Law.



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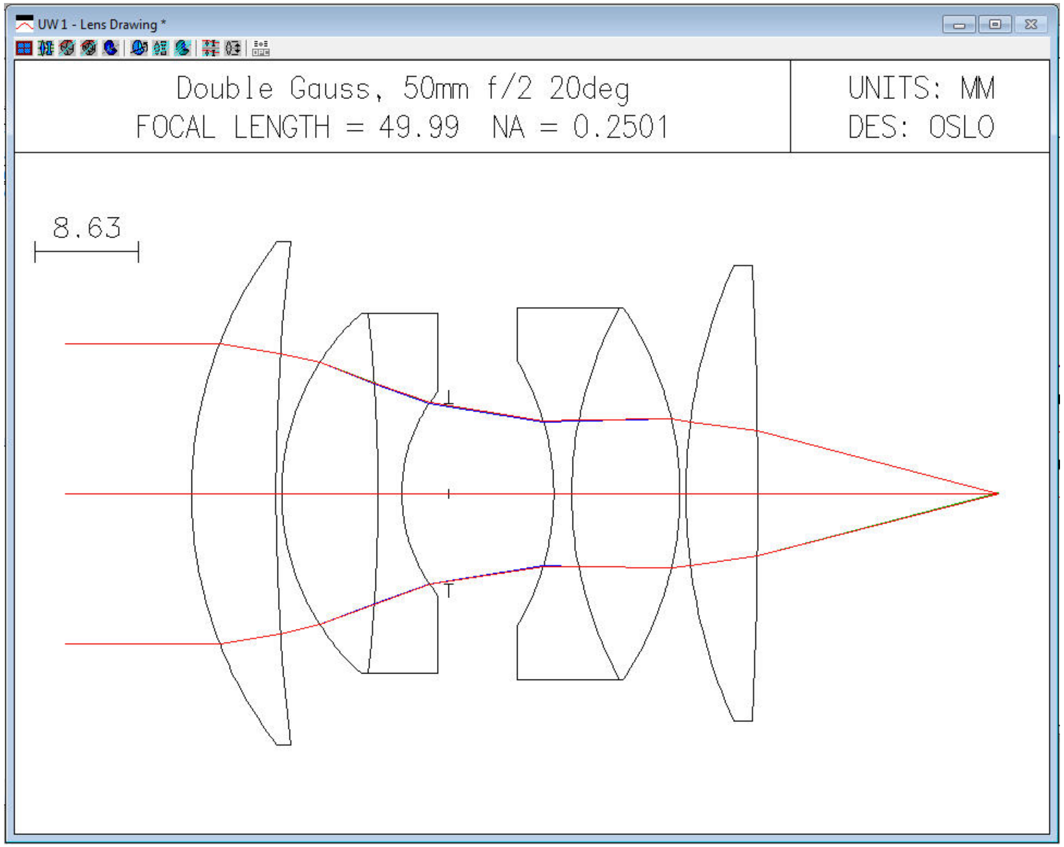
Color Effects in LED Lighting

- Chromatic Aberration
  - Lenses will focus light of different wavelengths to different points due to the differences in index of refraction for the different wavelengths.



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Color Effects in LED Lighting

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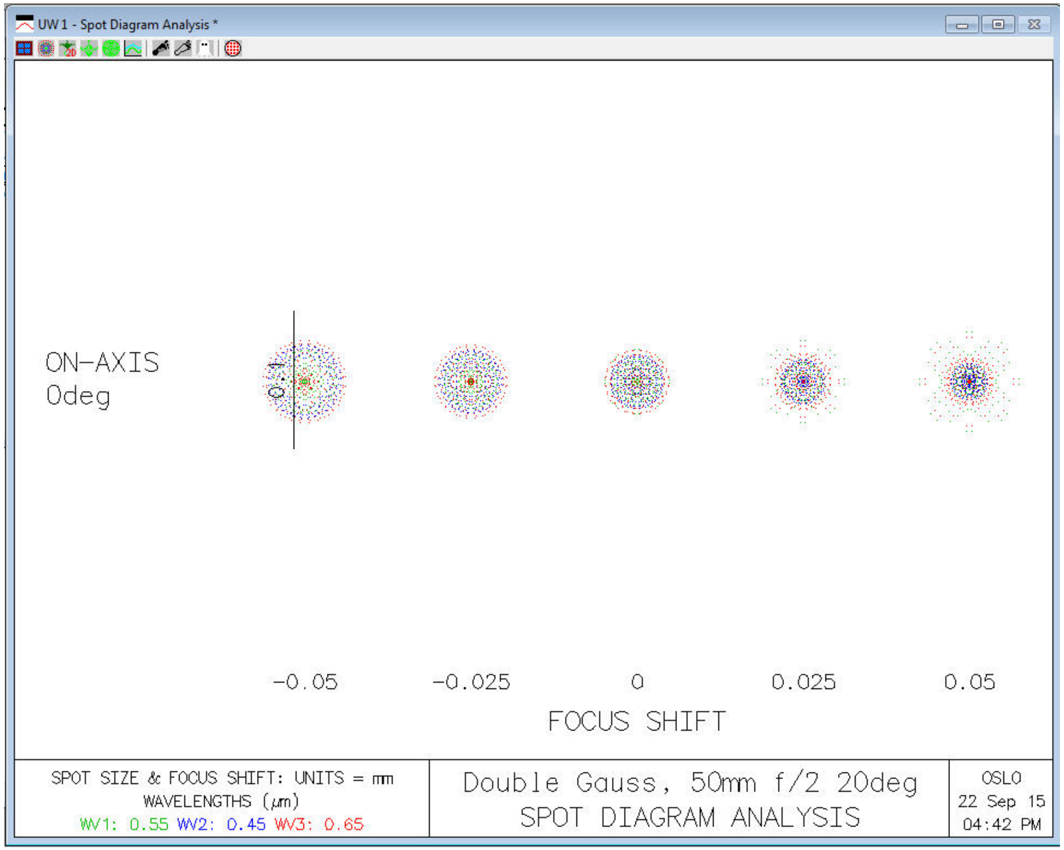
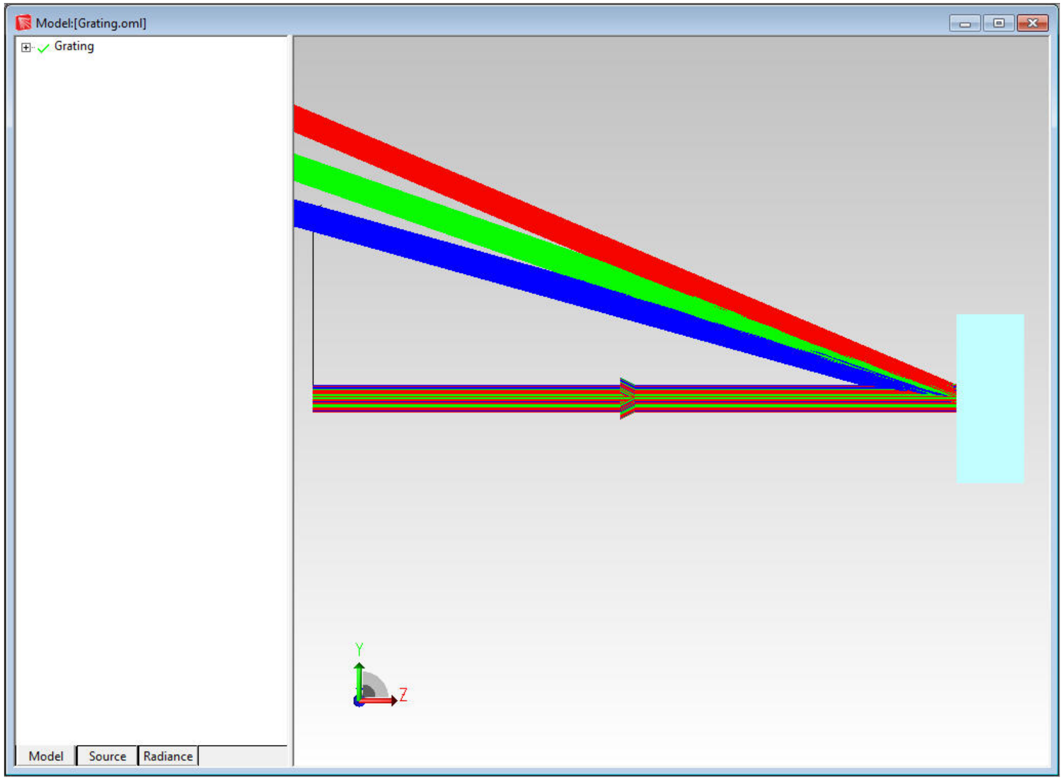


Color Effects in LED Lighting

- Diffraction/Interference
  - Light can be split into different wavelengths by diffraction and interference. For example, a diffraction grating, or a ruled surface with parallel lines/ grooves.



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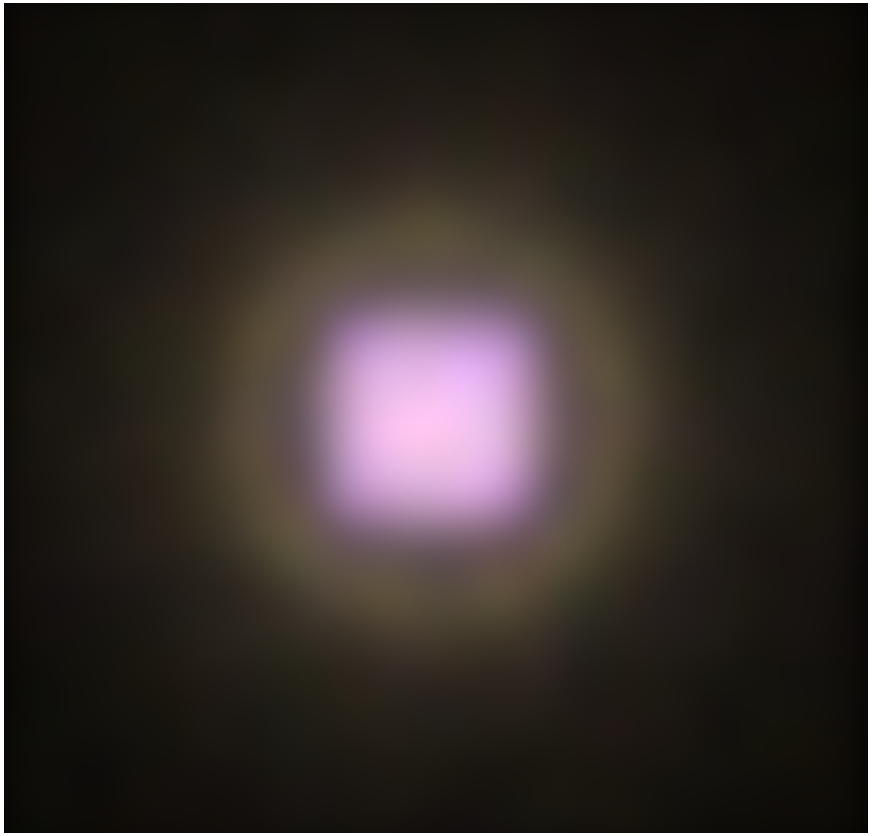
Color Effects in LED Lighting

- Fluorescence
  - Fluorescence from LED phosphors can create rings of different colors arond the central illumination spot of an LED due to light leakage through the phosphor.



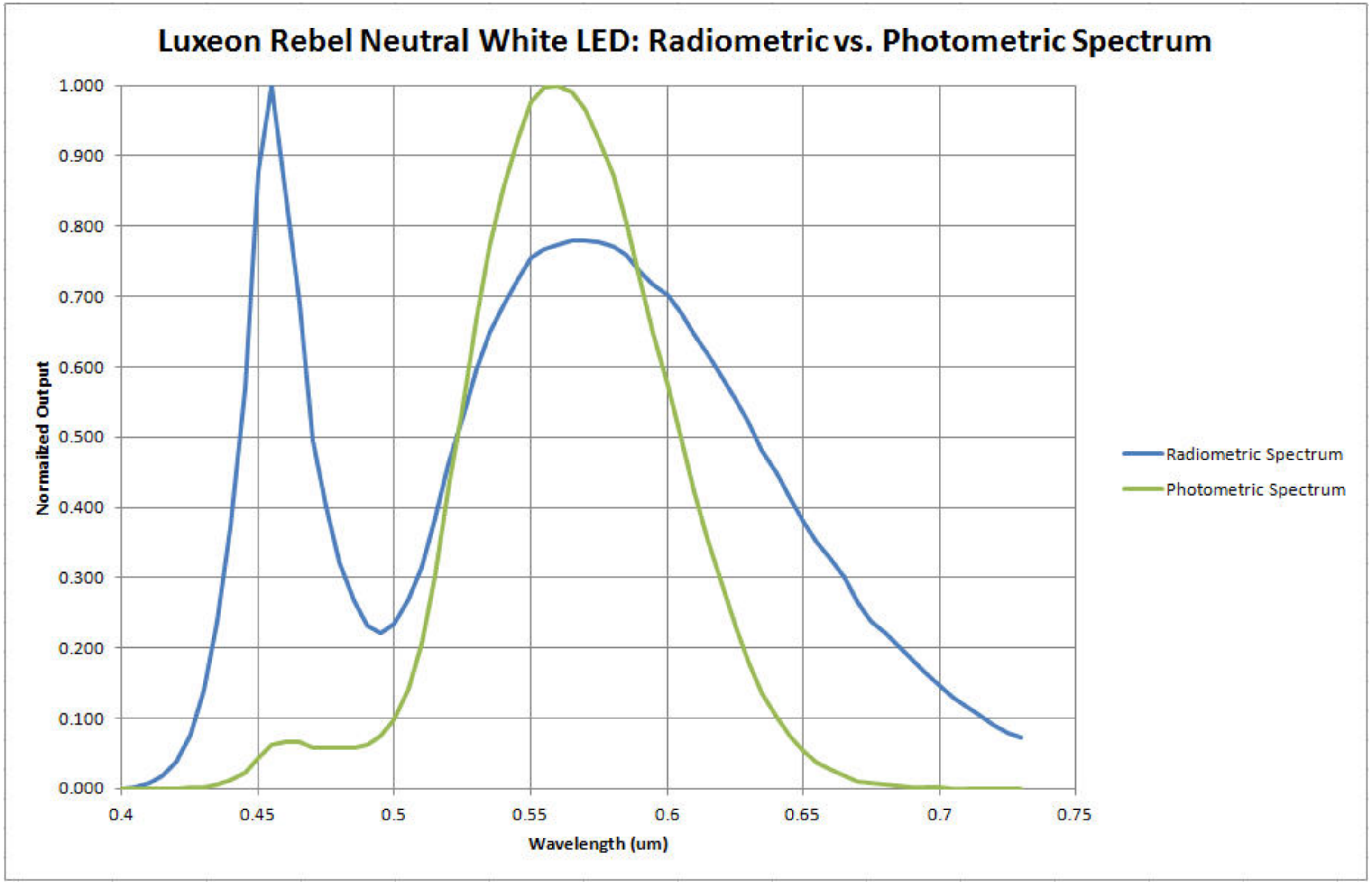
Examples

Examples

- **Example 1**: Radiometric vs Photometric Spectrum Differences

Examples

- Radiometric vs Photometric Spectrum Differences



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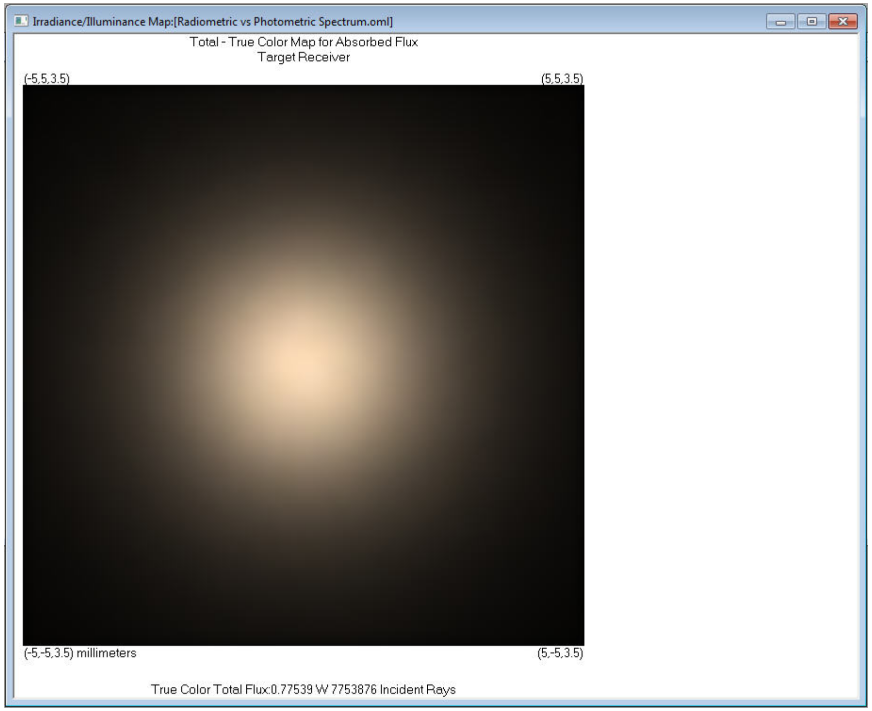
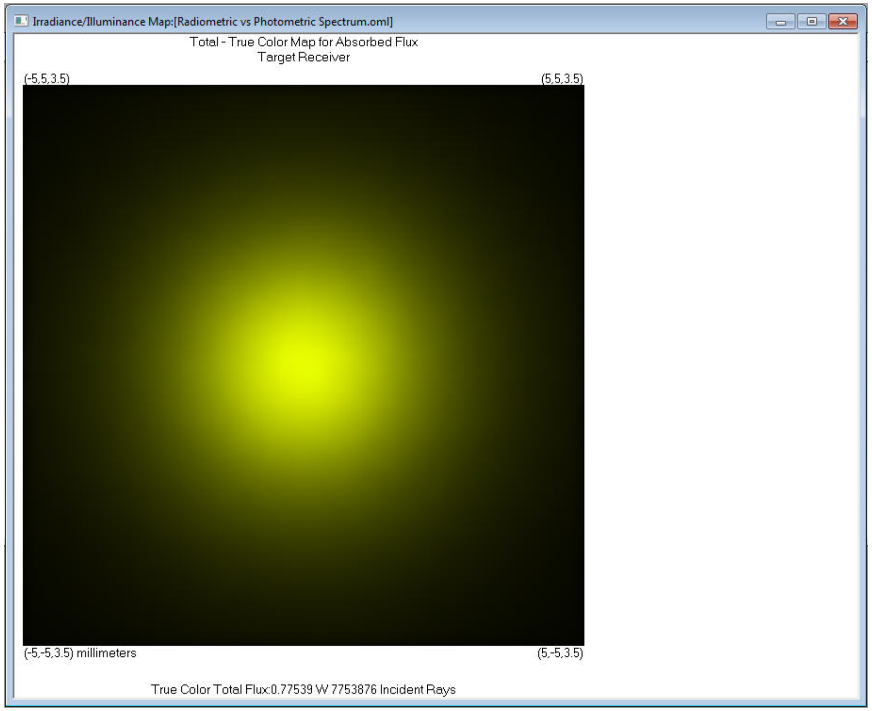
Examples

- Radiometric vs Photometric Spectrum Differences
  - TrueColor – RGB display results



Radiometric spectrum / radiometric units



Photometric spectrum / radiometric units

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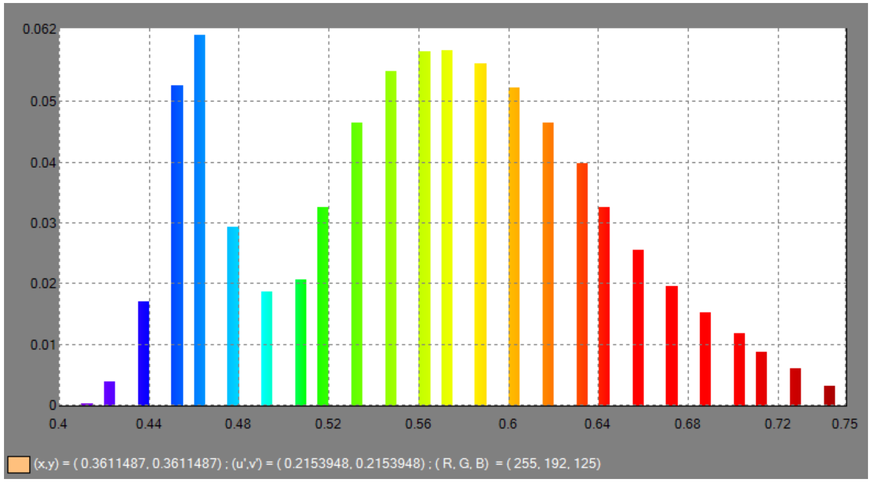
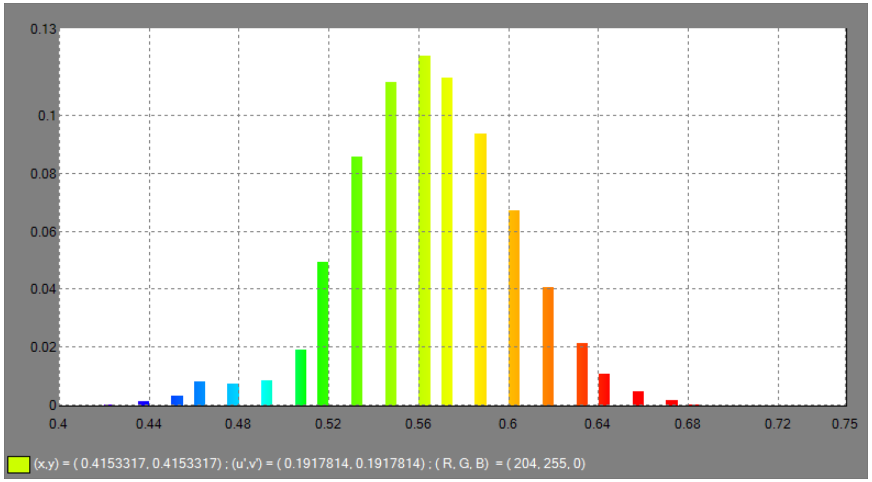
Examples

- Radiometric vs Photometric Spectrum Differences
  - TrueColor – RGB display results



Radiometric spectrum / radiometric units



Photometric spectrum / radiometric units

Examples

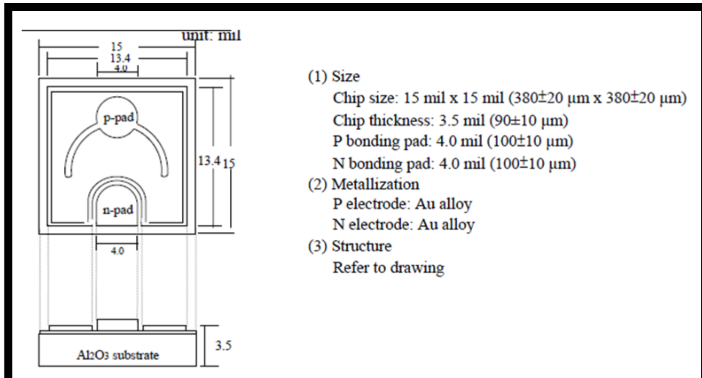
- **Example 2**: Phosphor based white LED example

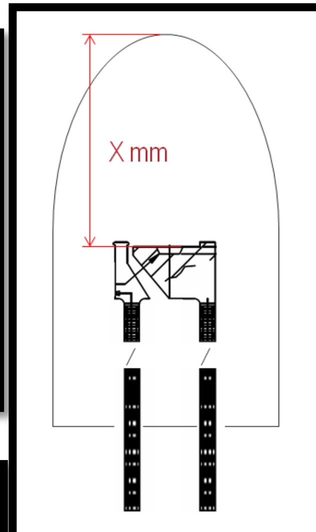
Examples

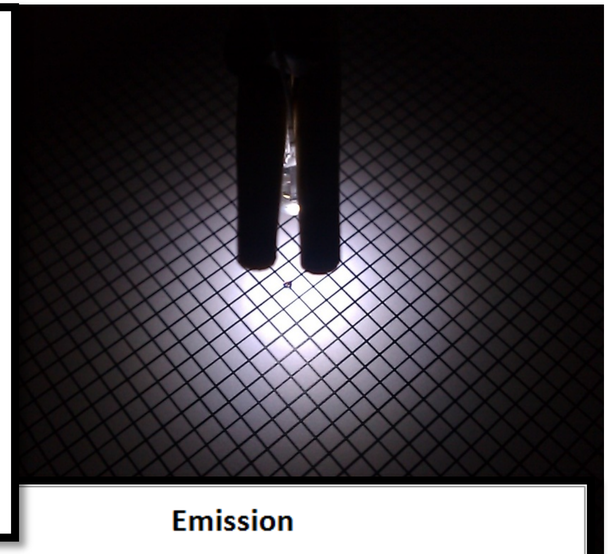
- Phosphor based white LED example
  - Physical information about the LED model including the die and mount
  - Optical properties such as surface properties, material properties, and flux
  - Geometric shape of the optical components, such as the epoxy and/or secondary optics
  - Specifications of the phosphor material including excitation, absorption, and emission spectra
  - Experimental/measured data for calibration of results

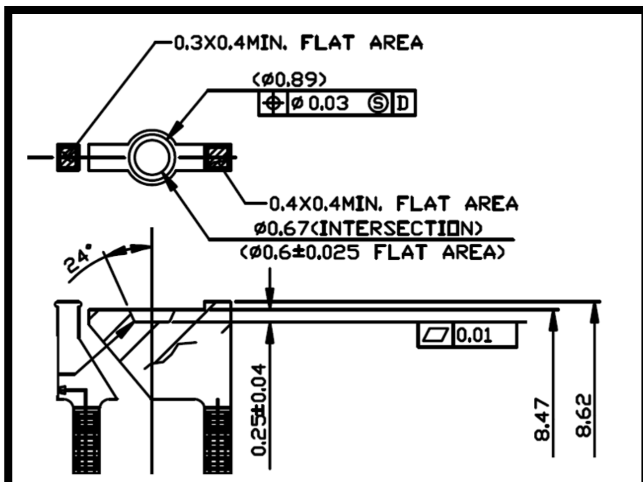
Examples

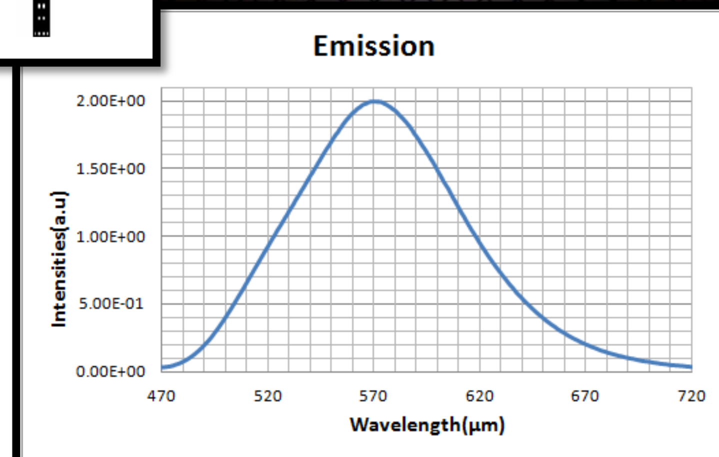
- Phosphor based white LED example





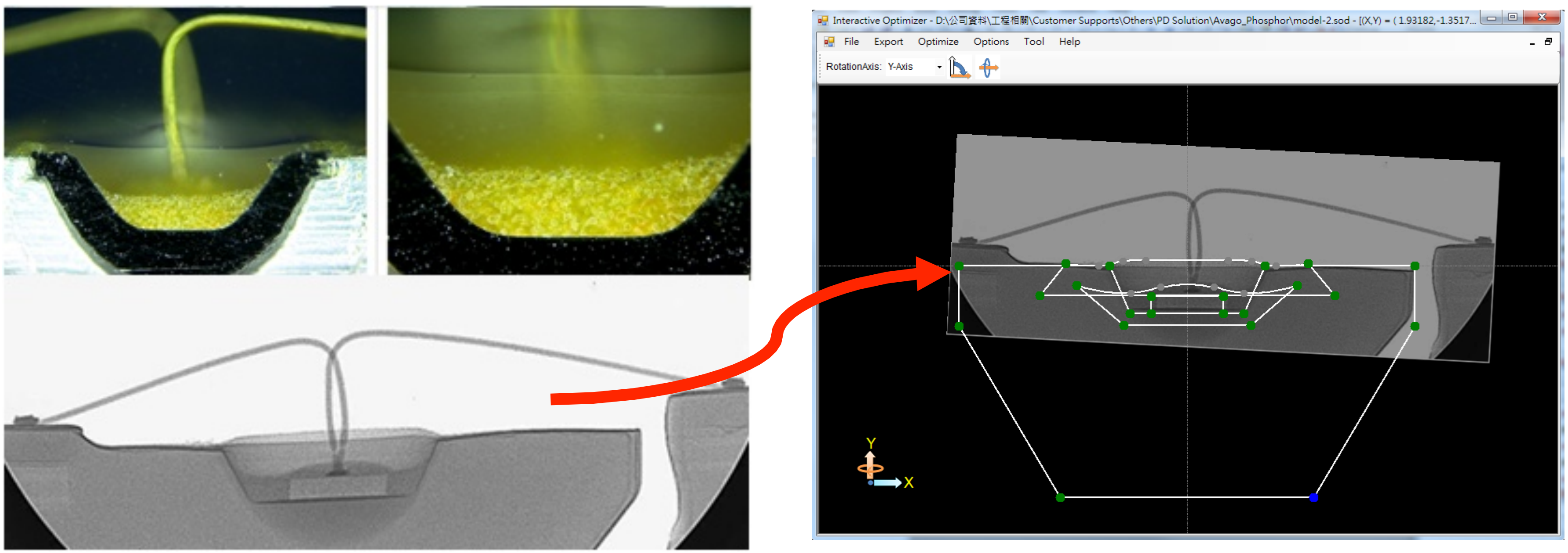






Examples

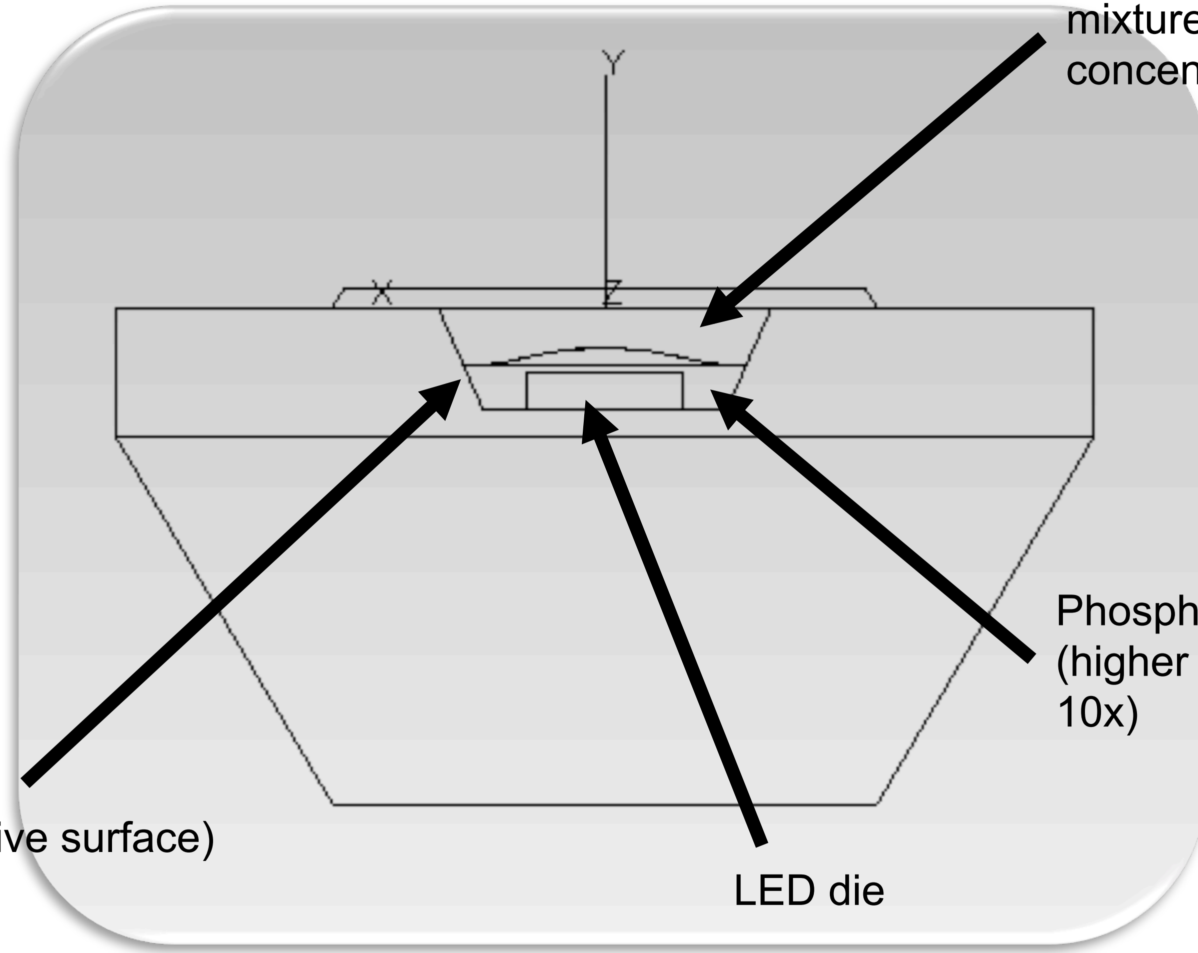
- Phosphor based white LED example



For a layered phosphor caused by sedimentation, the side-view image is used to create the solid model

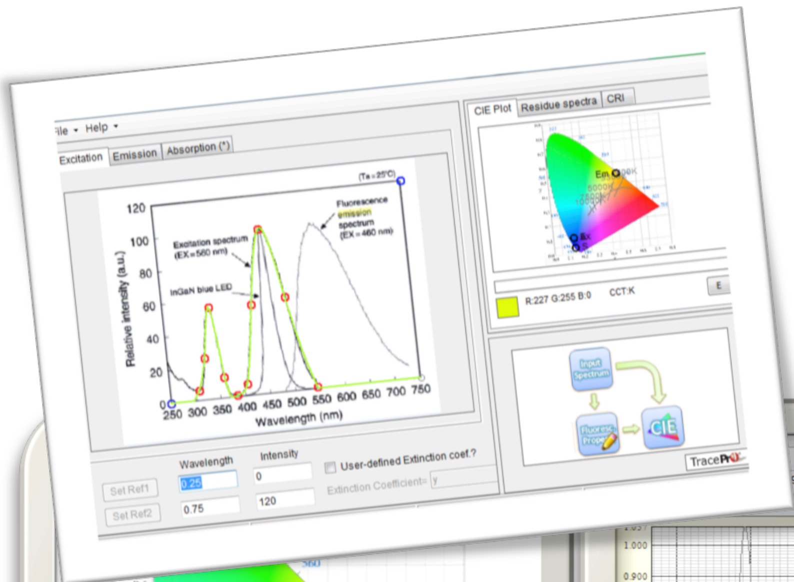
Examples

- Phosphor based white LED example



Examples

- Phosphor based white LED example

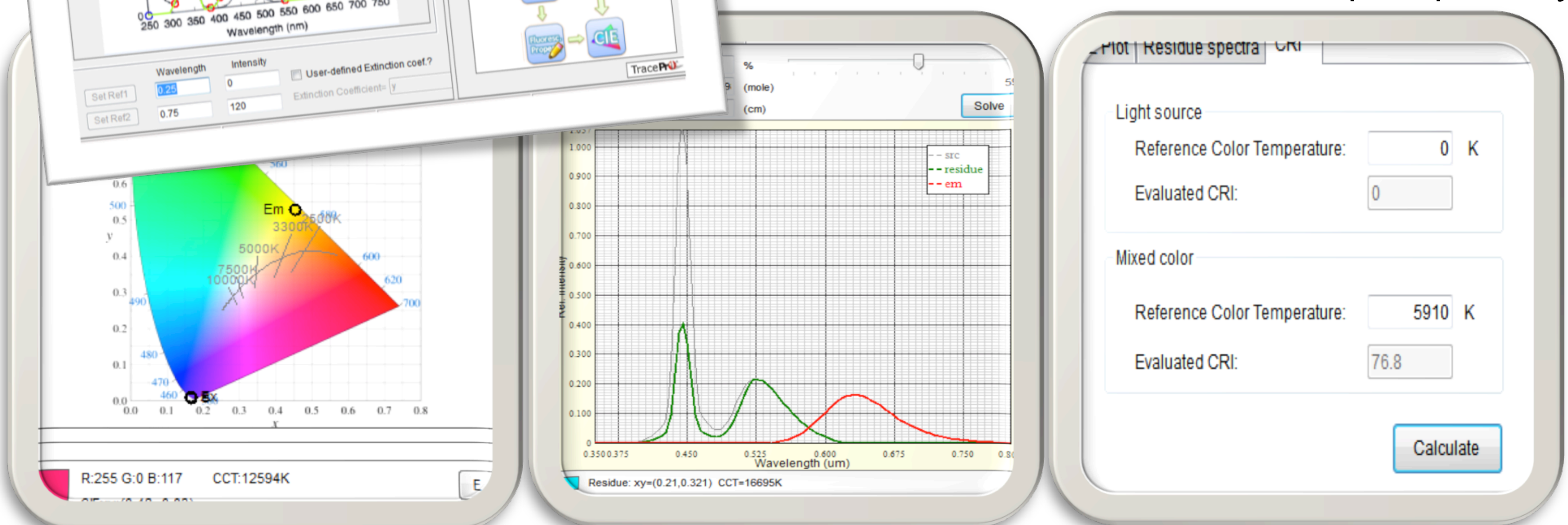


TracePro Fluorescence Property Generator Utility

Color analysis (CIE, CCT, CRI)

Prediction of mixed color

Estimation of the thickness and concentration of the phosphor layer



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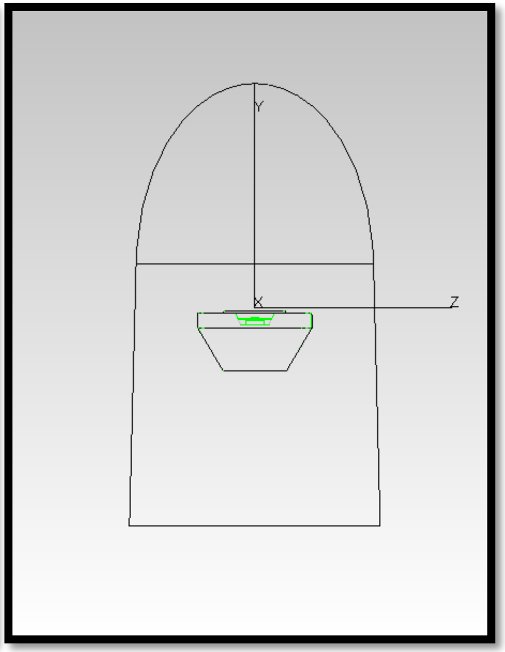
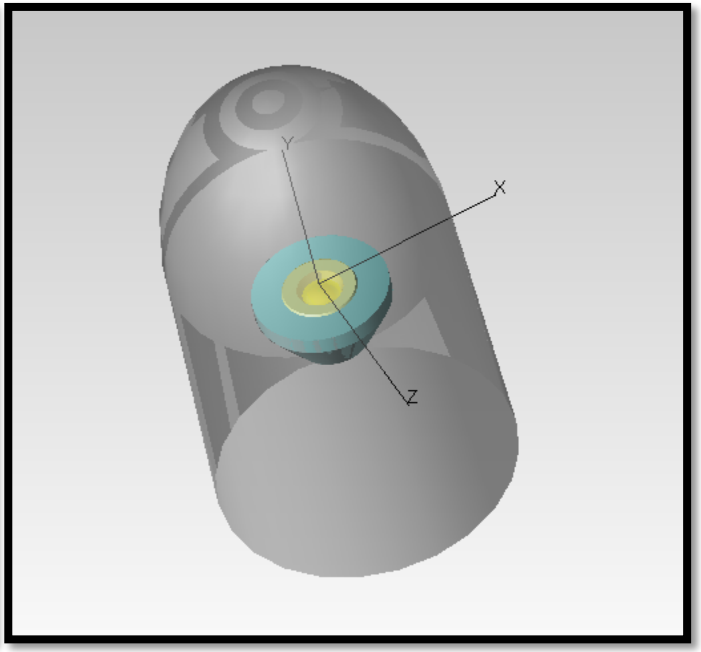
Examples

- Phosphor based white LED example





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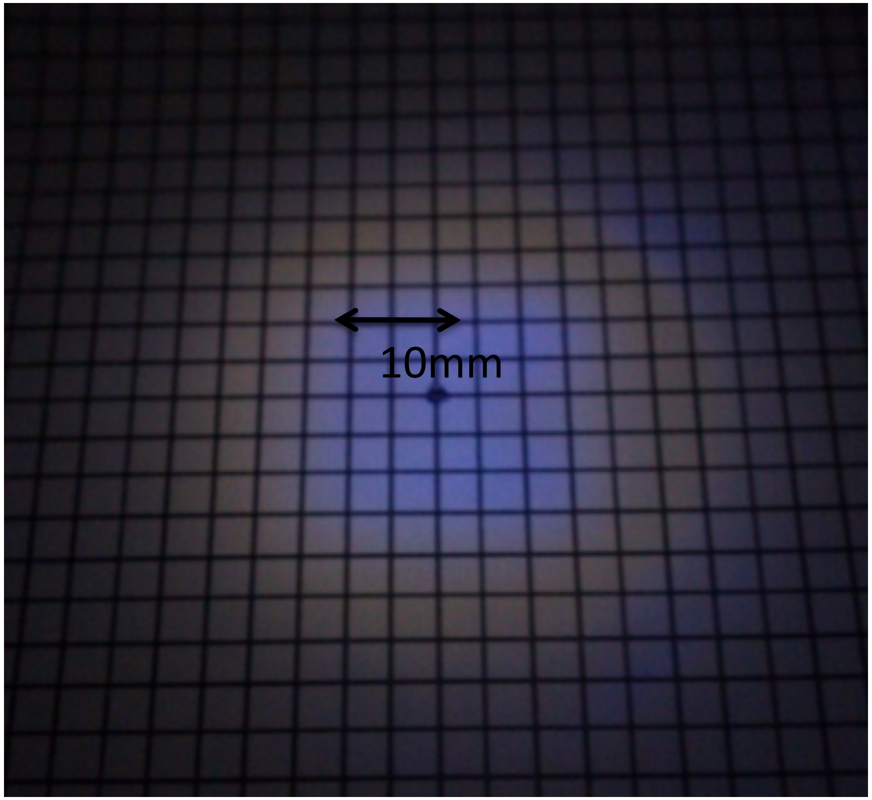
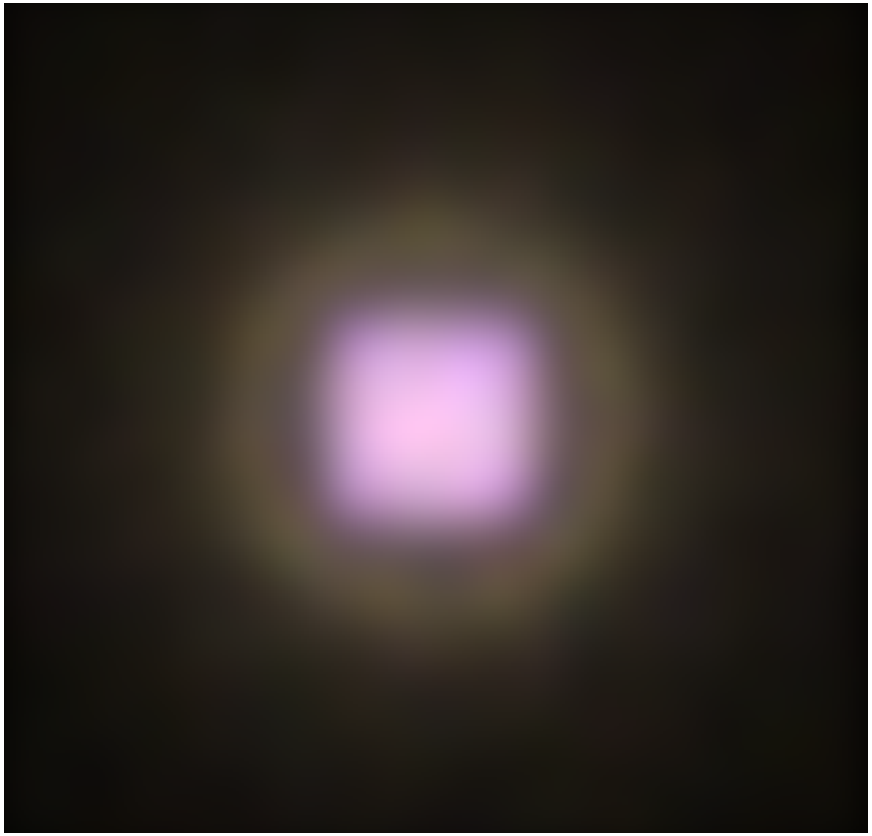
Examples

- Phosphor based white LED example



Picture of actual LED illuminance at a 10cm distance



TracePro TrueColor Irradiance Map raytrace at a 10cm distance

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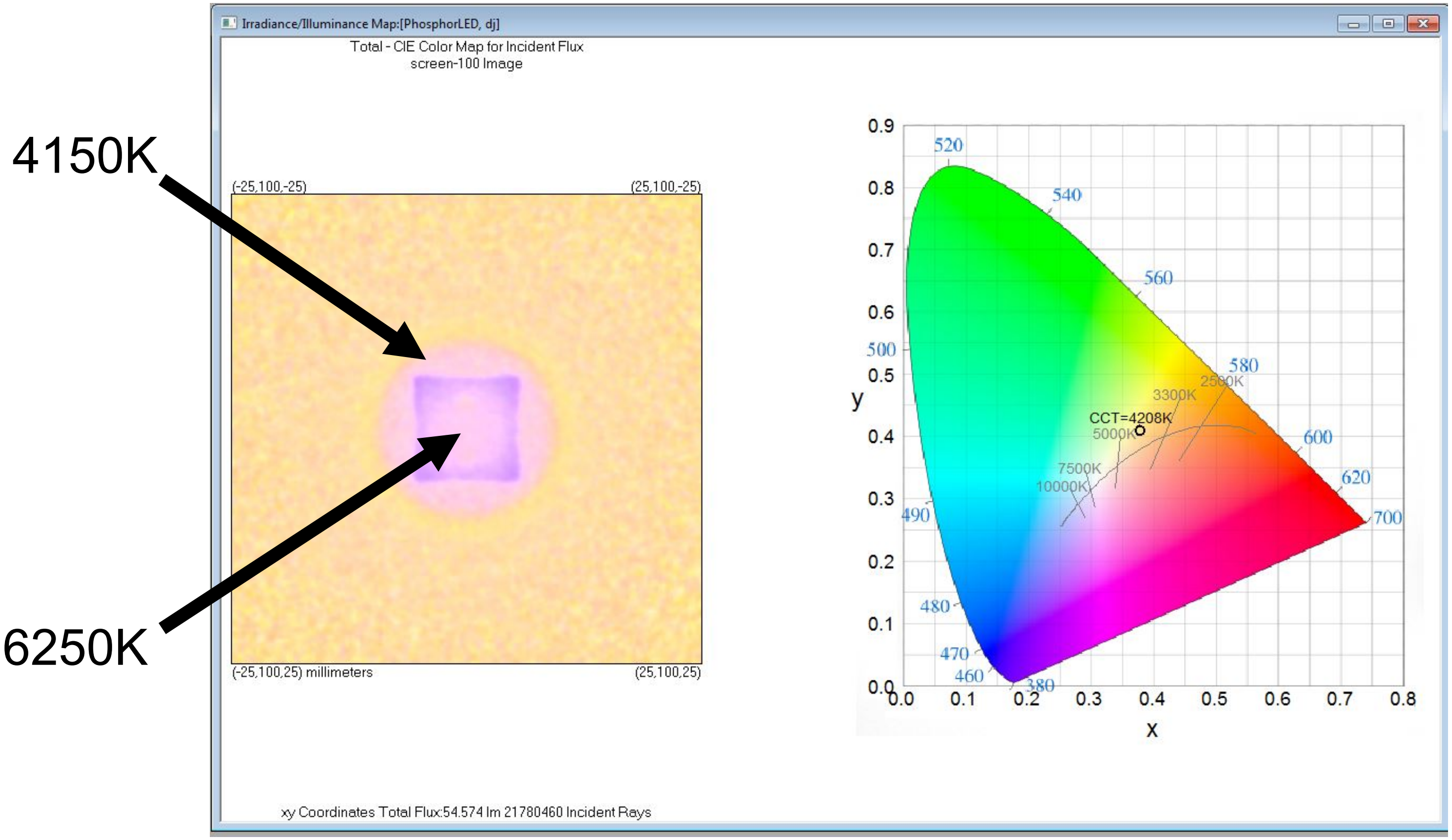
Examples

- Phosphor based white LED example
  - CCT varies depending on the location in the illumination pattern



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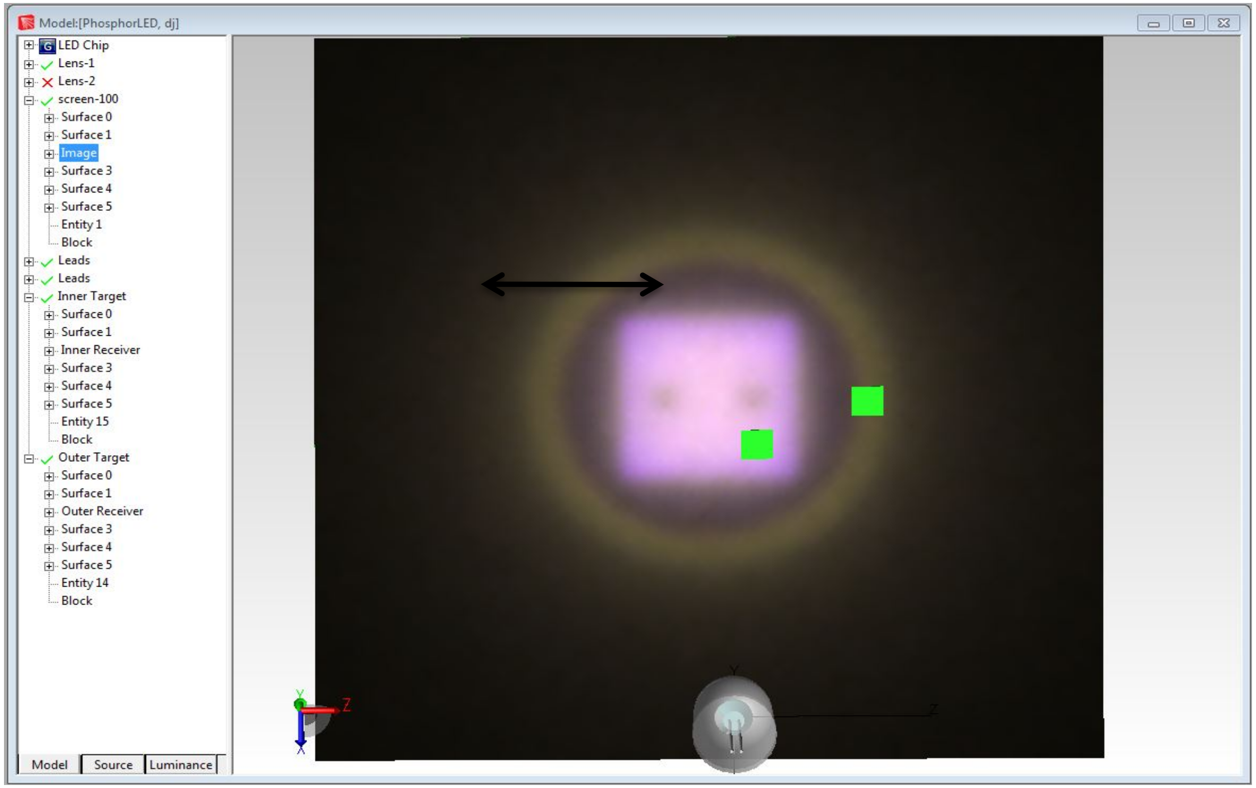
Examples

- Phosphor based white LED example
  - 2 detectors are added to the model to see the spectrum in the center and the surrounding ring of the illumination pattern



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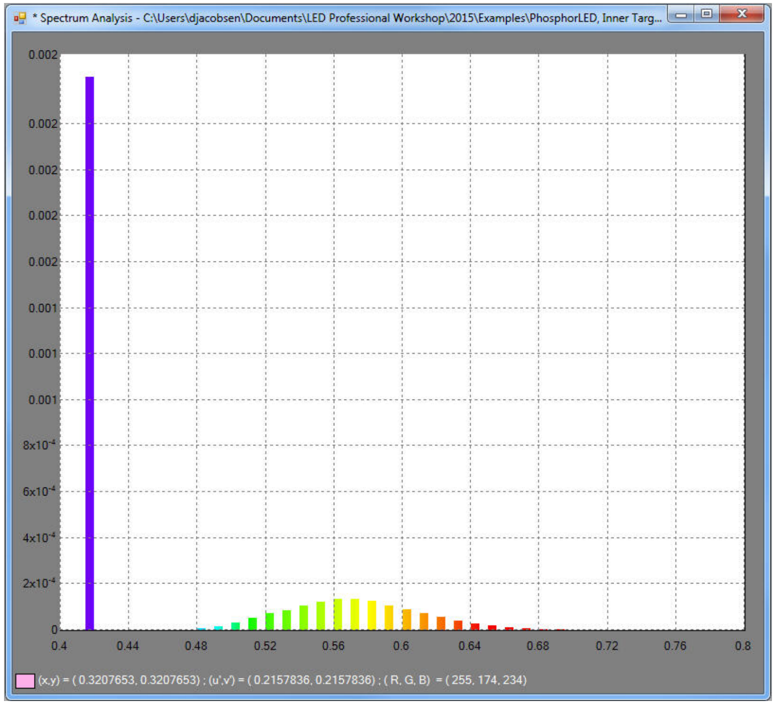
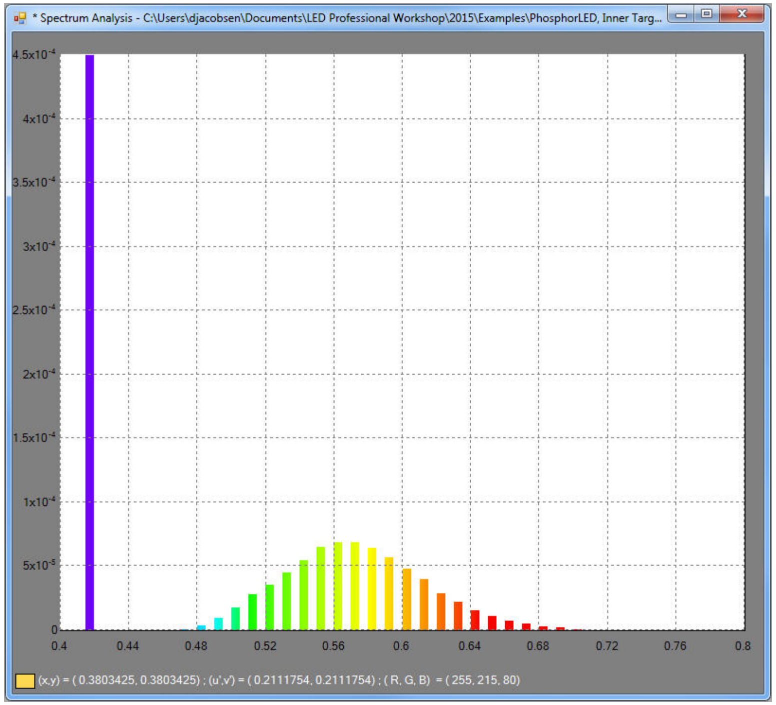


Spectrum in inner portion of LED illumination pattern



Spectrum in outer portion of LED illumination pattern

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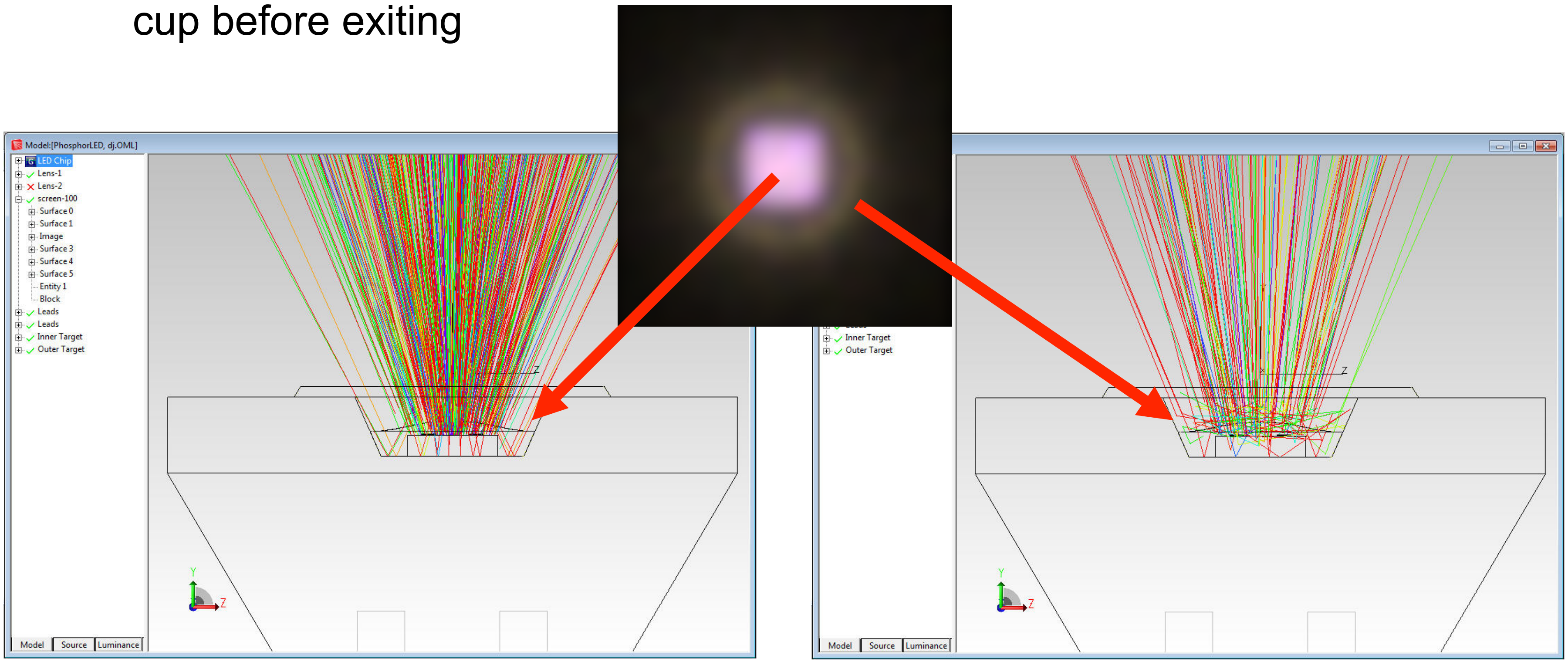
Examples

- Phosphor based white LED example
  - Rays that make up the outer yellow ring bounce around inside the reflector cup before exiting



Rays in central portion of illumination pattern

Rays in yellow ring portion of illumination pattern

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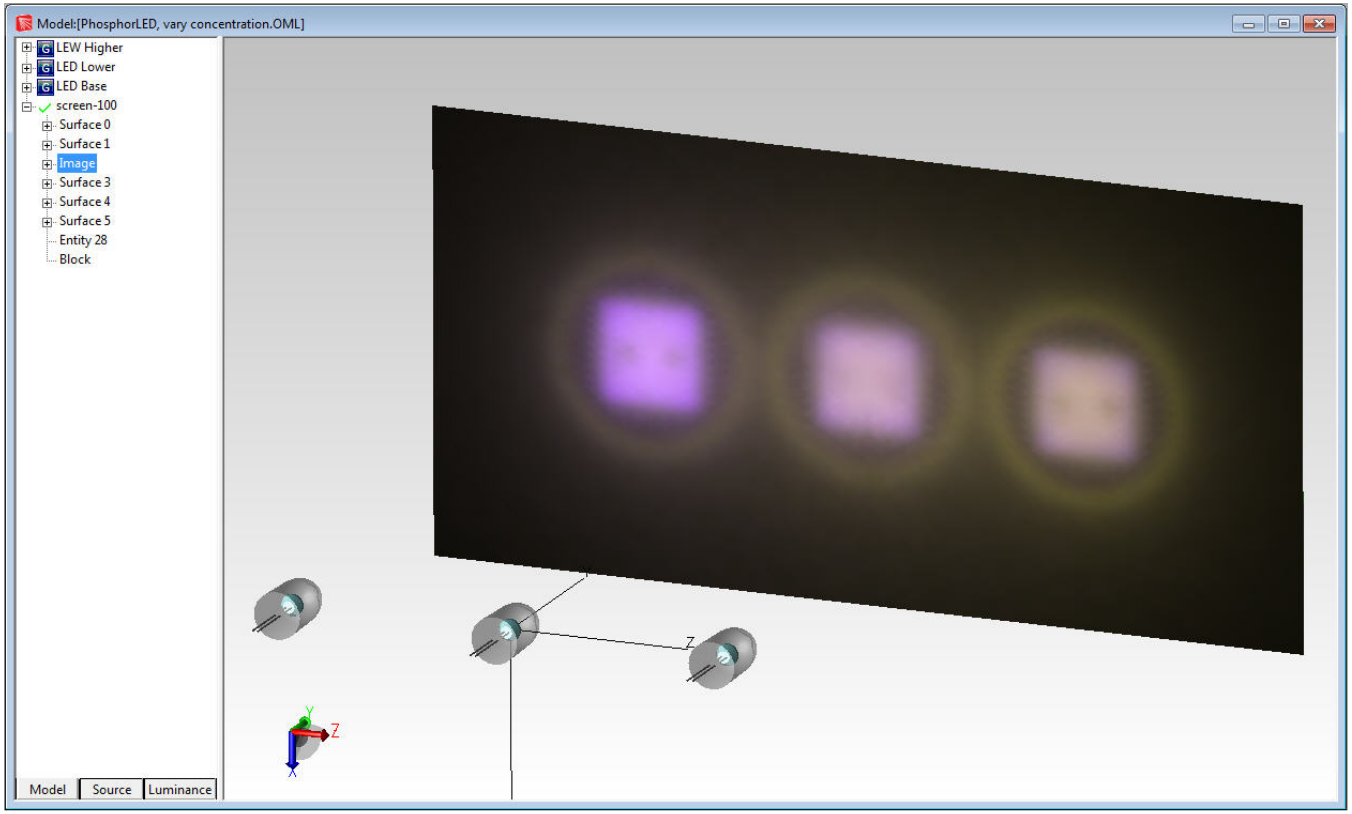
Examples

- **Example 3**: Effect of varying LED phosphor concentration

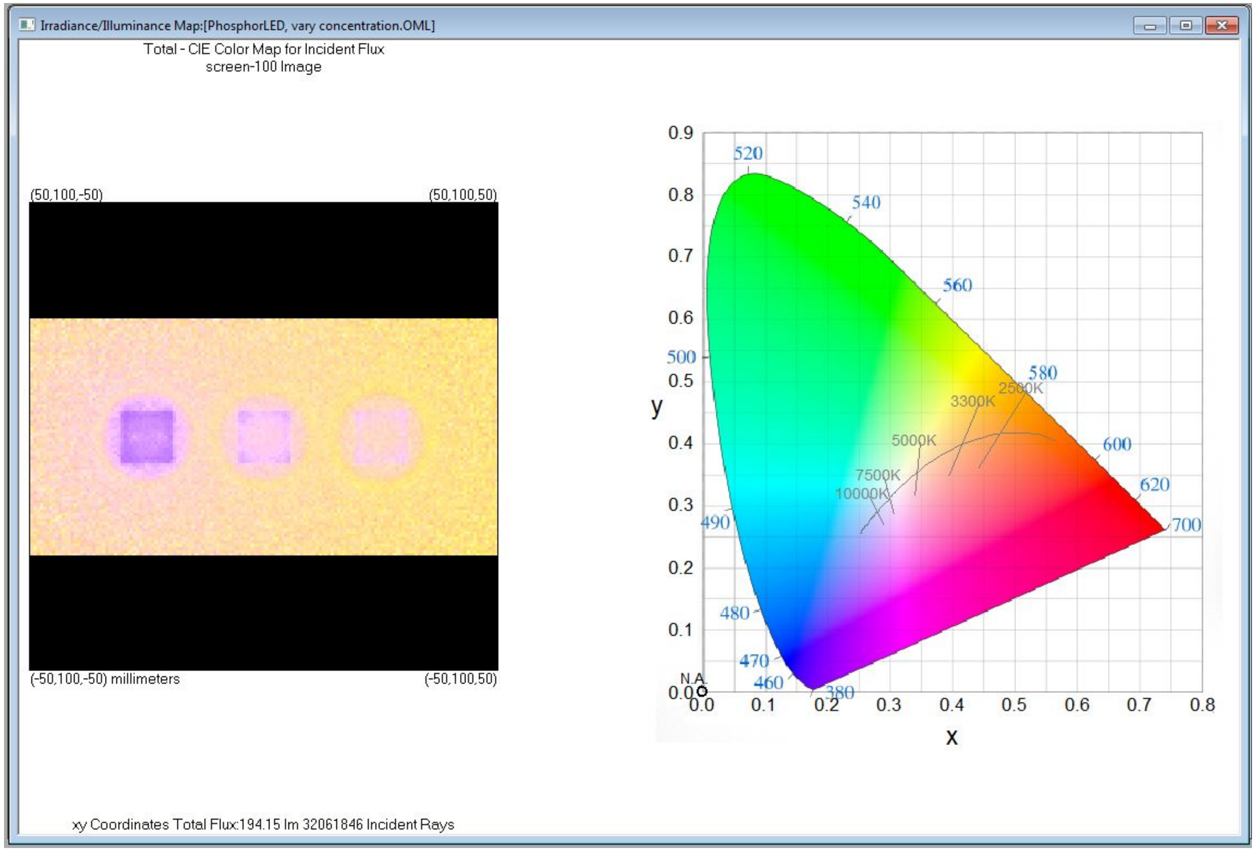
Examples

- Effect of varying LED phosphor concentration
  - Color spectrum can vary with phosphor concentration – TrueColor plot



Examples

- Effect of varying LED phosphor concentration
  - Color spectrum can vary with phosphor concentration – CIE xy plot



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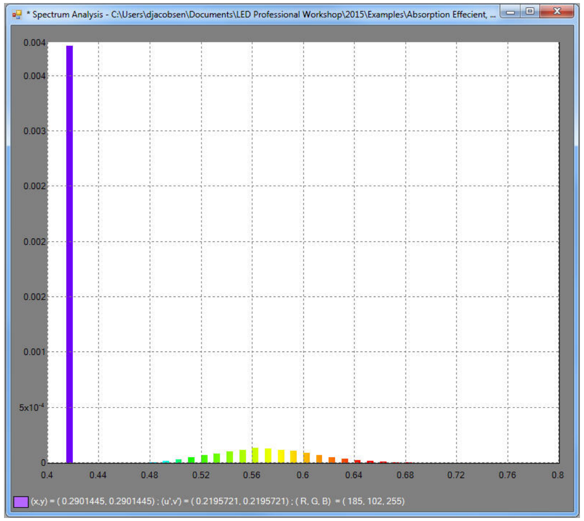
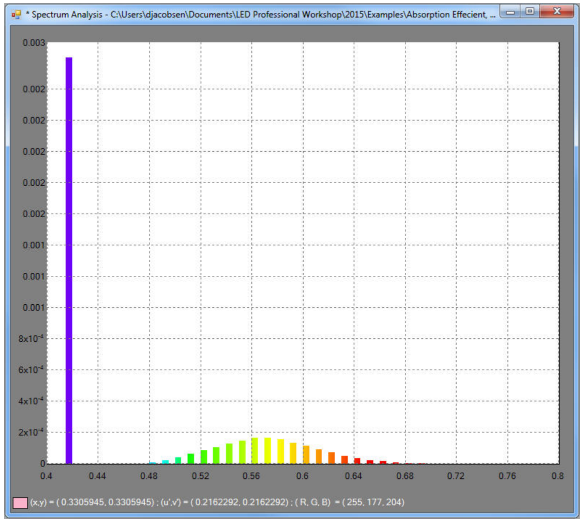
Examples

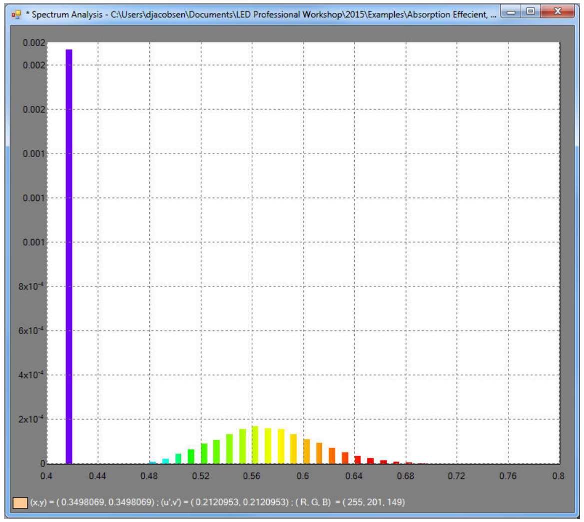
- Effect of varying LED phosphor concentration
  - Color spectrum can vary with phosphor concentration – spectrums



50% lower phosphor concentration



Base phosphor concentration



50% higher phosphor concentration

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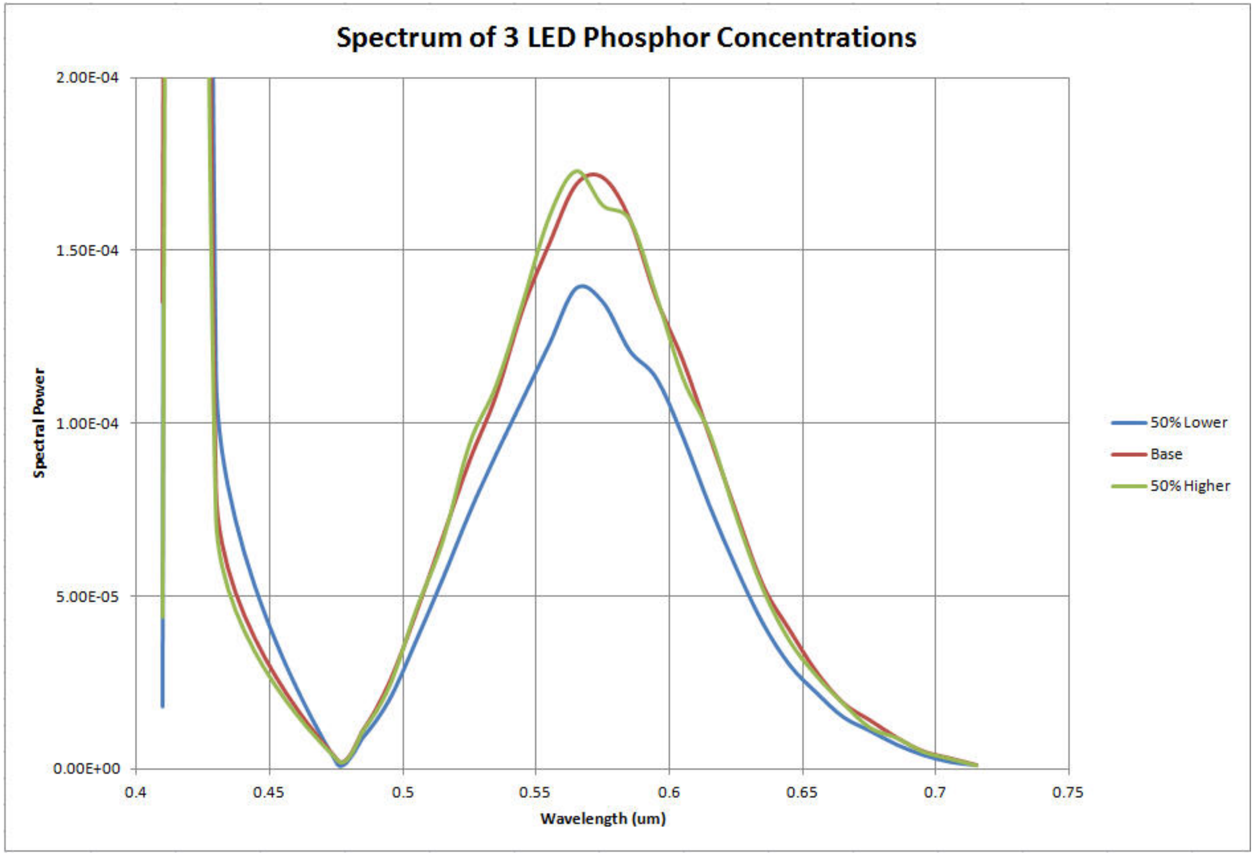
Examples

- Effect of varying LED phosphor concentration
  - Color spectrum can vary with phosphor concentration – spectrums



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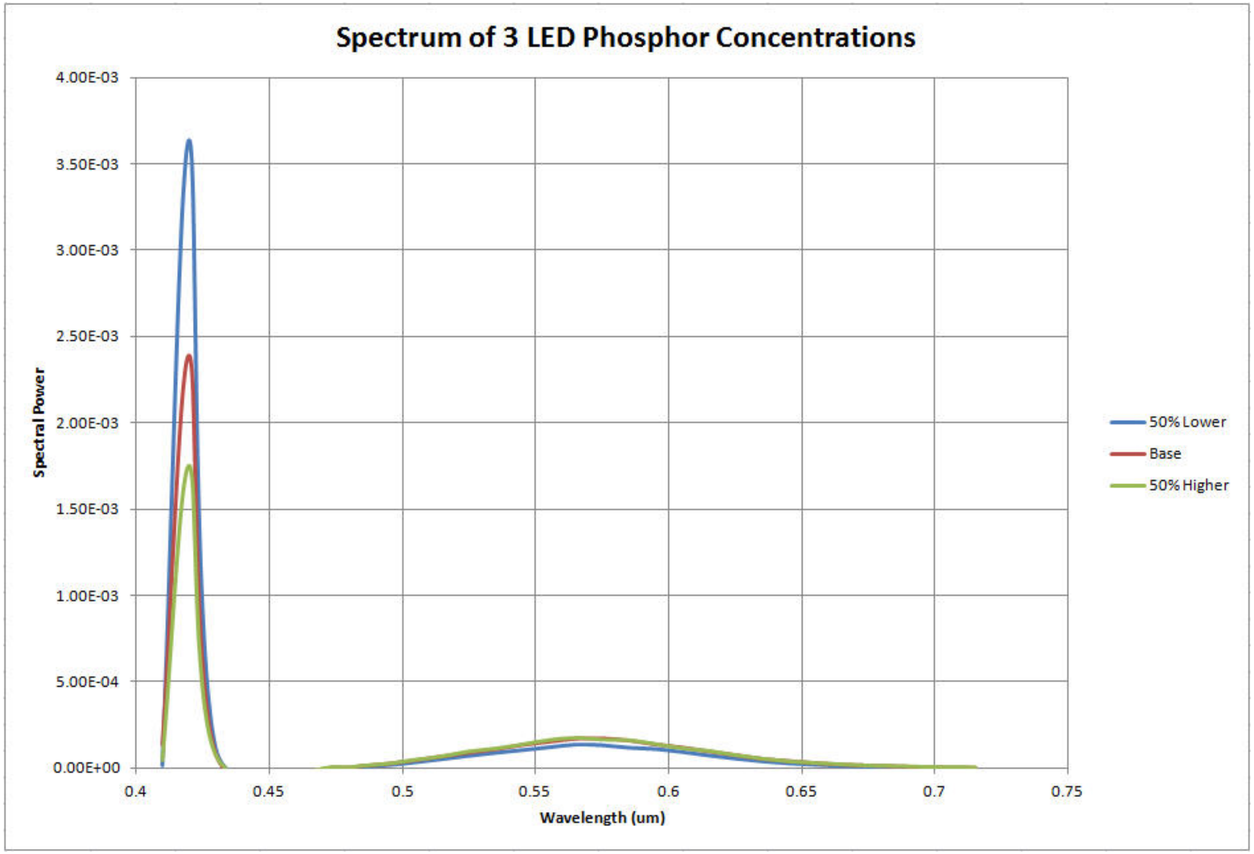
Examples

- Effect of varying LED phosphor concentration
  - Color spectrum can vary with phosphor concentration – spectrums



Examples

- **Example 4**: Using rayfiles to model LED color effects

Examples

- Using rayfiles to model LED color effects
  - Rayfiles are an excellent choice for modeling LED sources as they are based on measurements of the actual LEDs. Since the actual LED is measured, all of the geometry and properties of the LED are accounted for in the measurement and there is no need to make a full 3D solid model of the LED. LED rayfiles are available from most LED manufacturers.
  - But……many rayfiles are defined monochromatically
  - Some rayfiles have multiple color options

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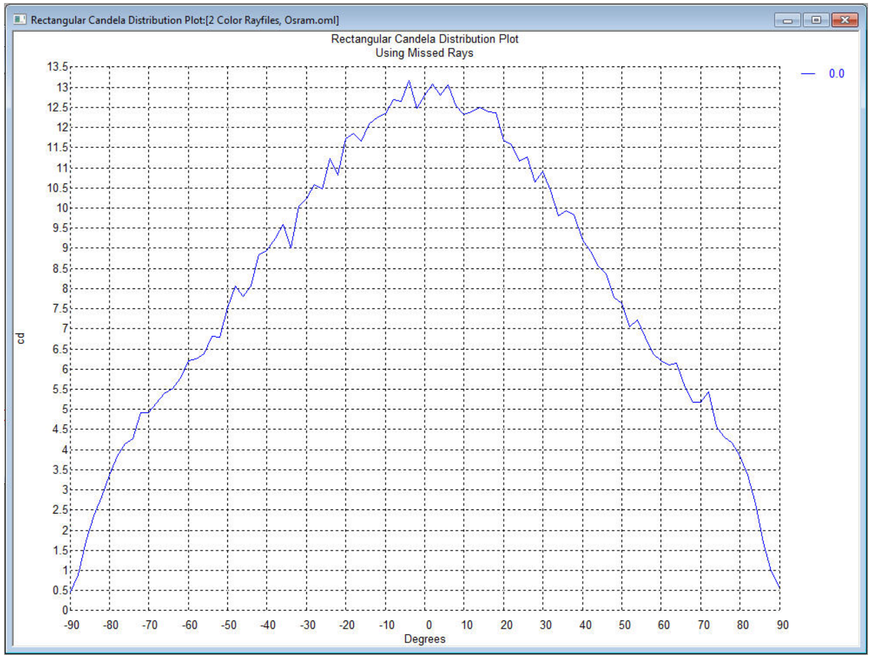
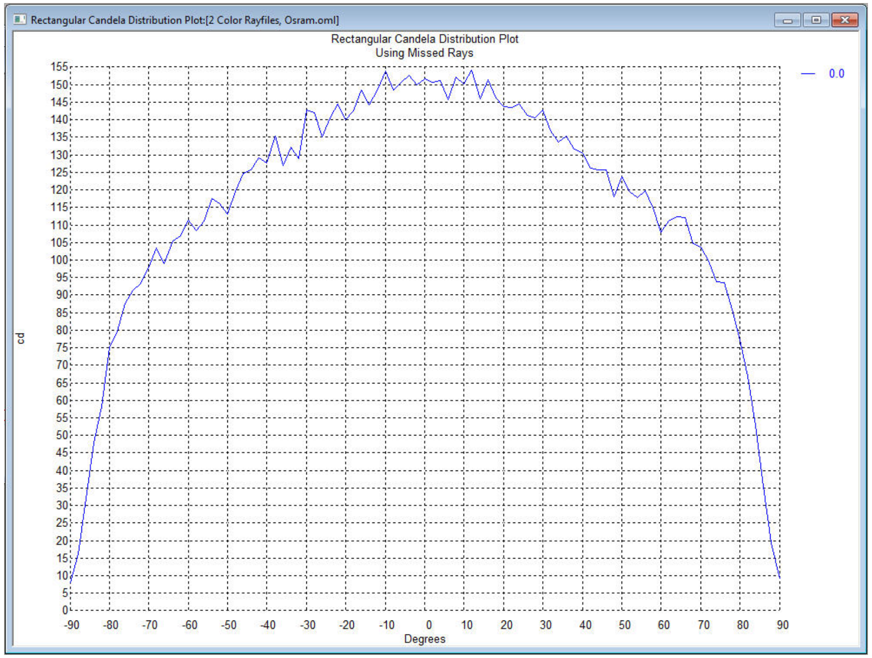
Examples

- Using rayfiles to model LED color effects
  - Candela Plots of 2 LED rayfiles



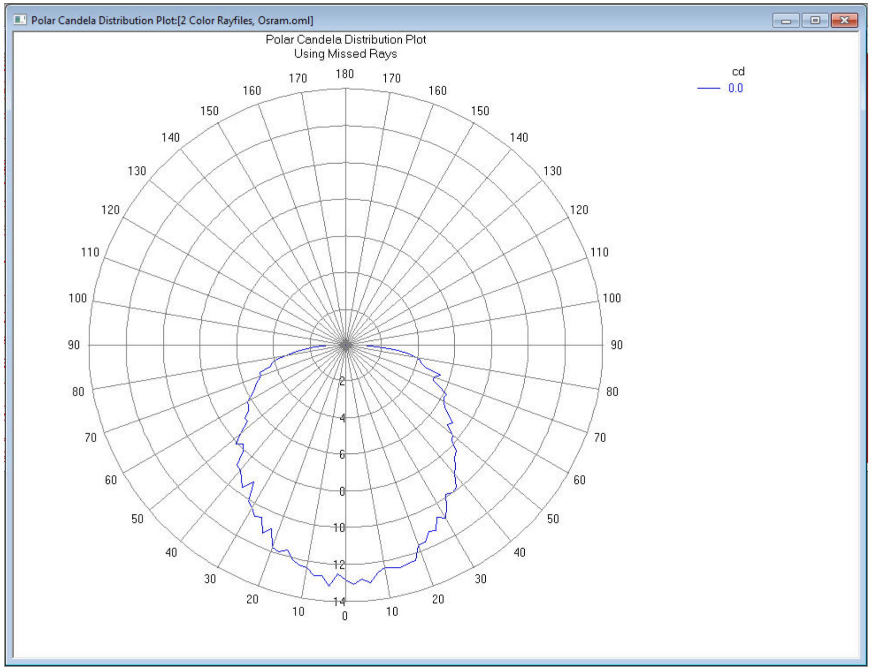
Osram LW-W5AM – Blue (5M rays)



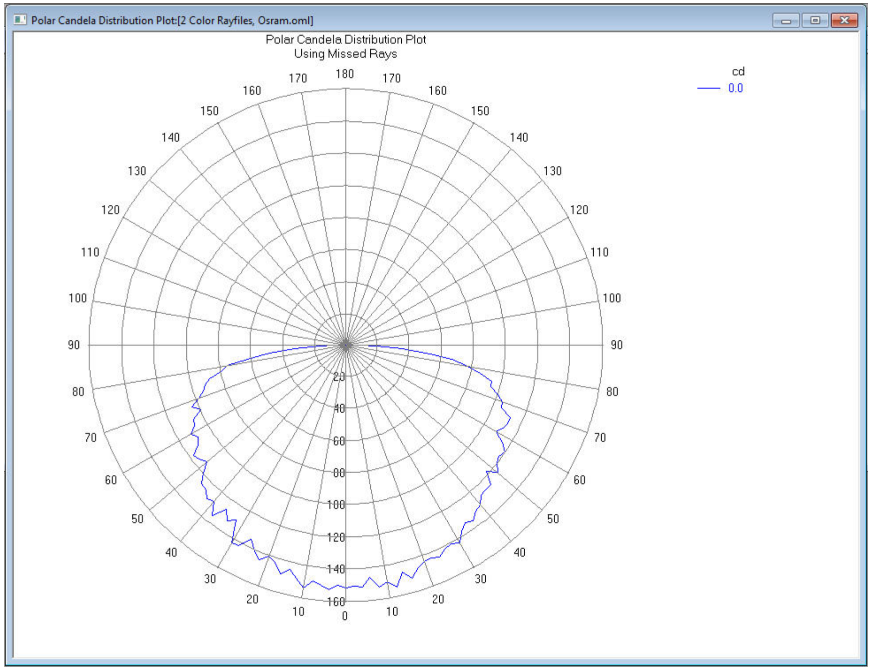
Osram LW-W5AM – Yellow (5M rays)

Examples

- Using rayfiles to model LED color effects
  - Candela Plots of 2 LED rayfiles



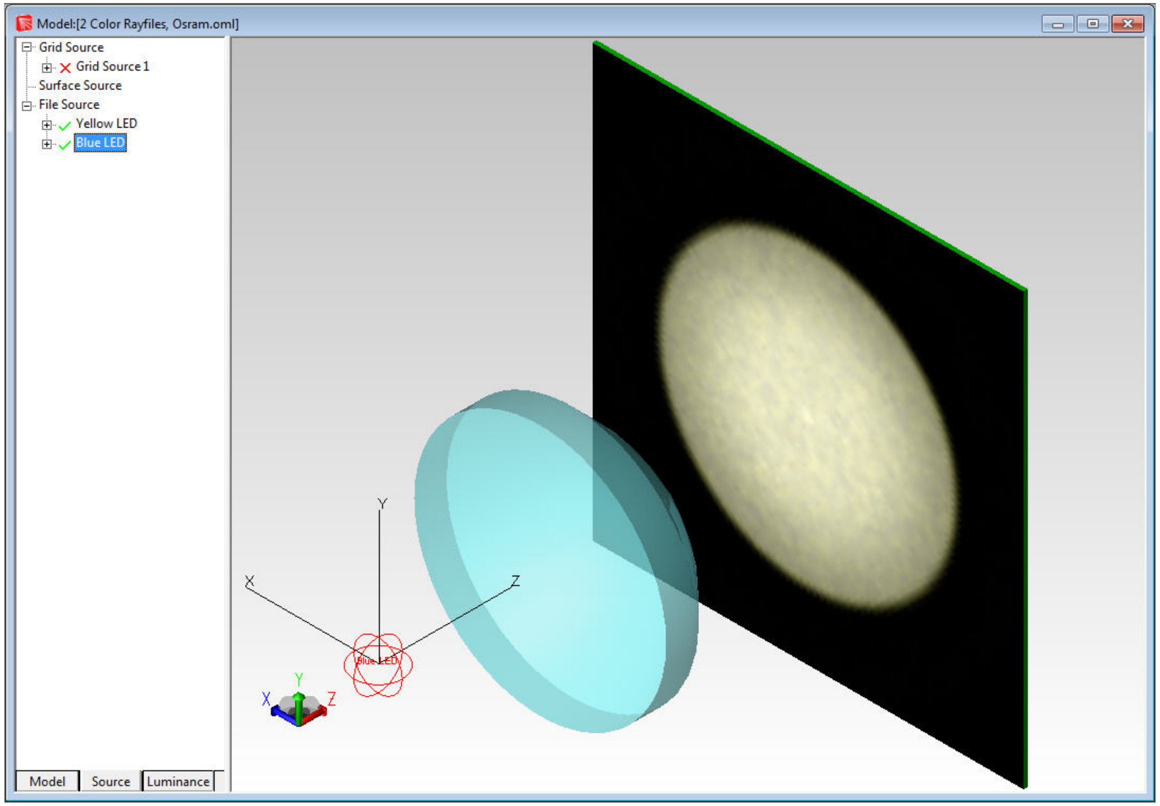
Osram LW-W5AM – Blue (5M rays)



Osram LW-W5AM – Yellow (5M rays)

Examples

- Using rayfiles to model LED color effects
  - Optical analysis software model using 2 LED rayfiles, a lens, and a target



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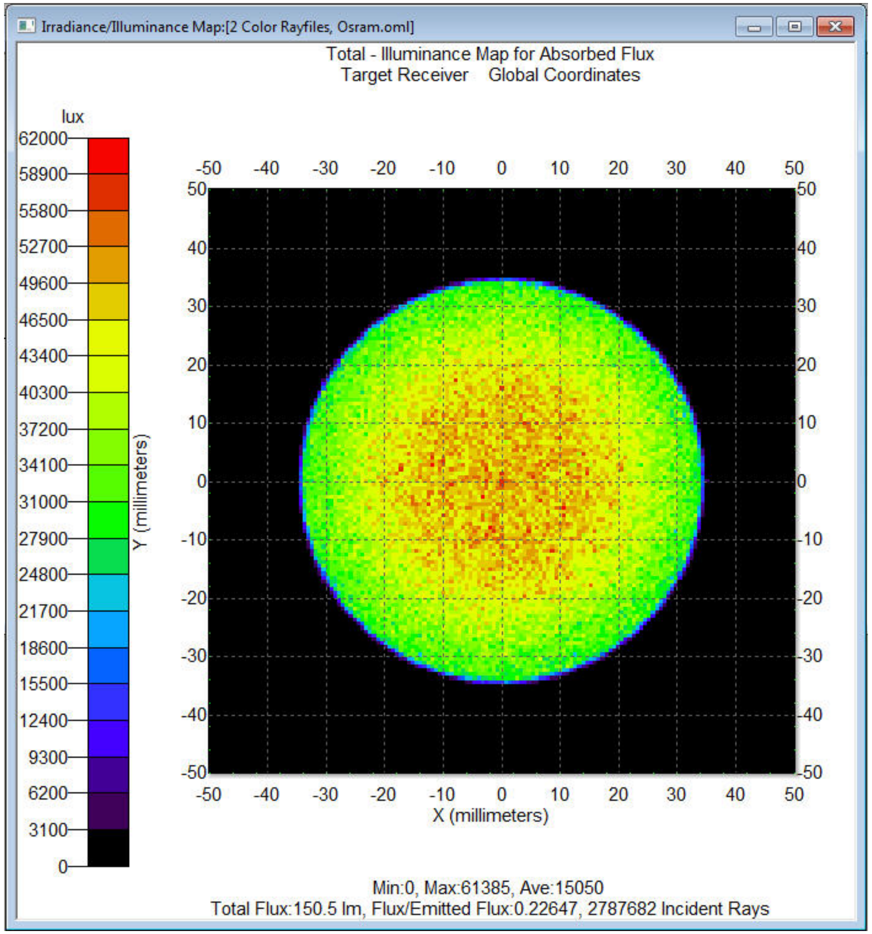
Examples

- Using rayfiles to model LED color effects
  - Illuminance Map



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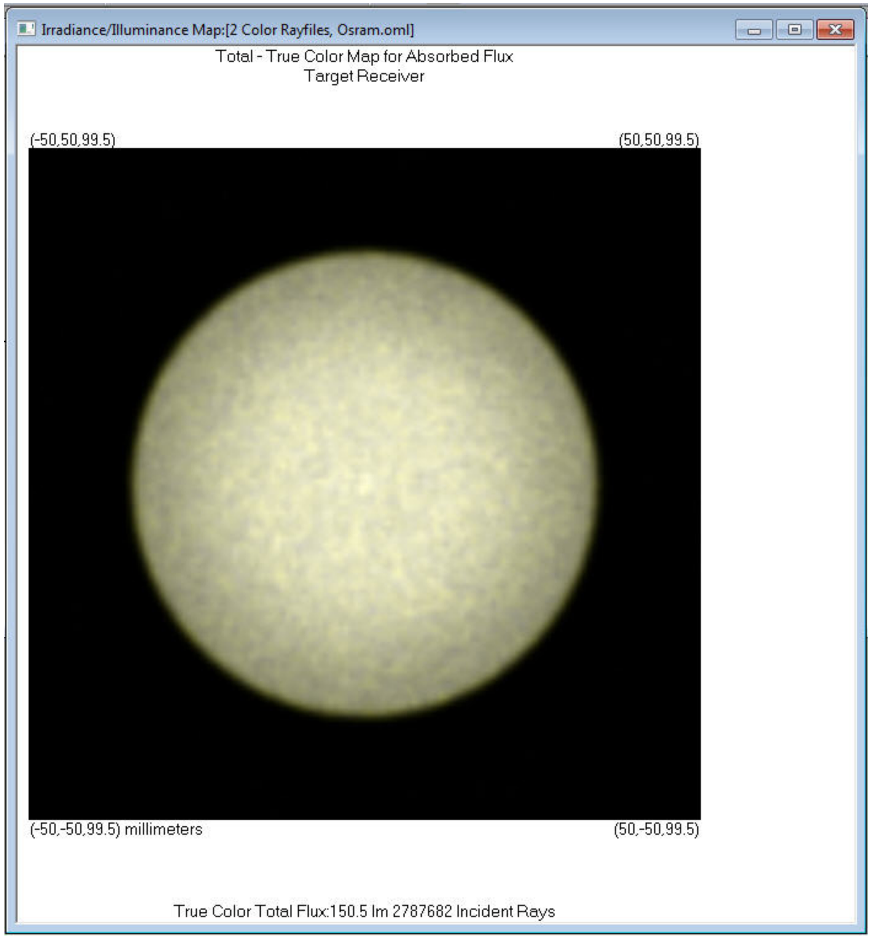
Examples

- Using rayfiles to model LED color effects
  - Illuminance Map



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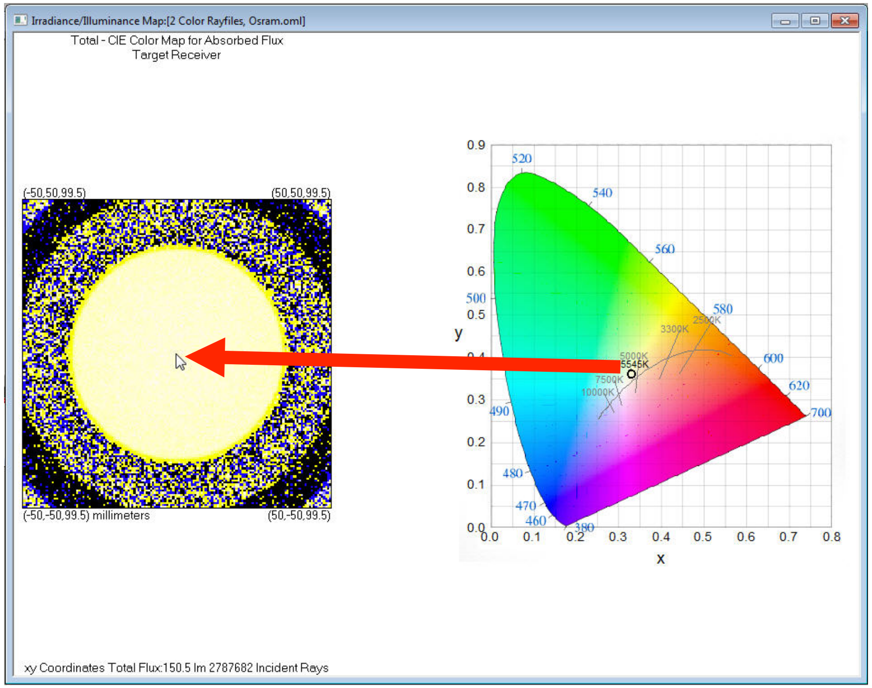
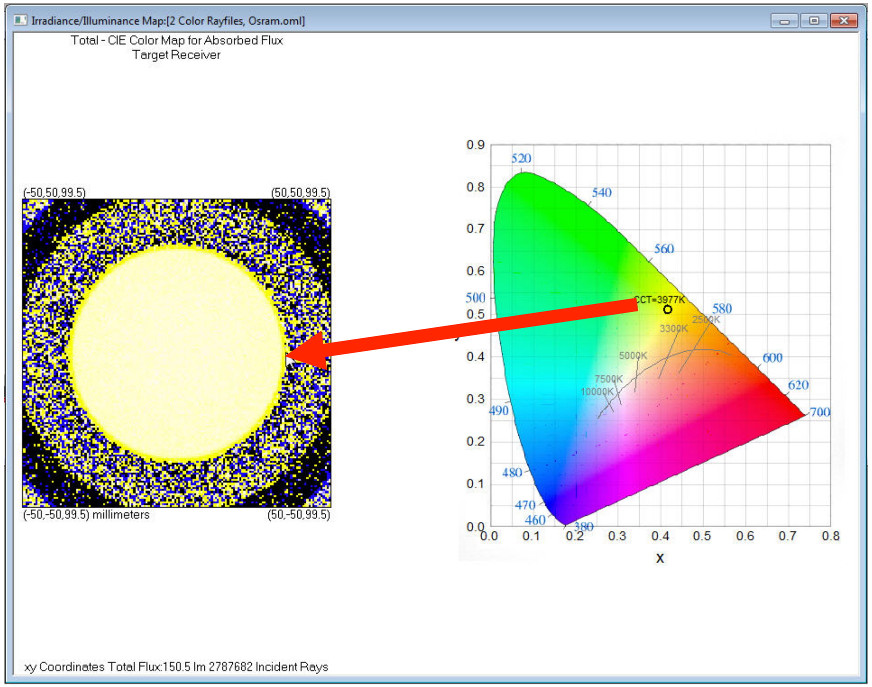
Examples

- Using rayfiles to model LED color effects
  - CIE xy plot





Center CCT = 5545K

Center CCT = 3977K

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Examples

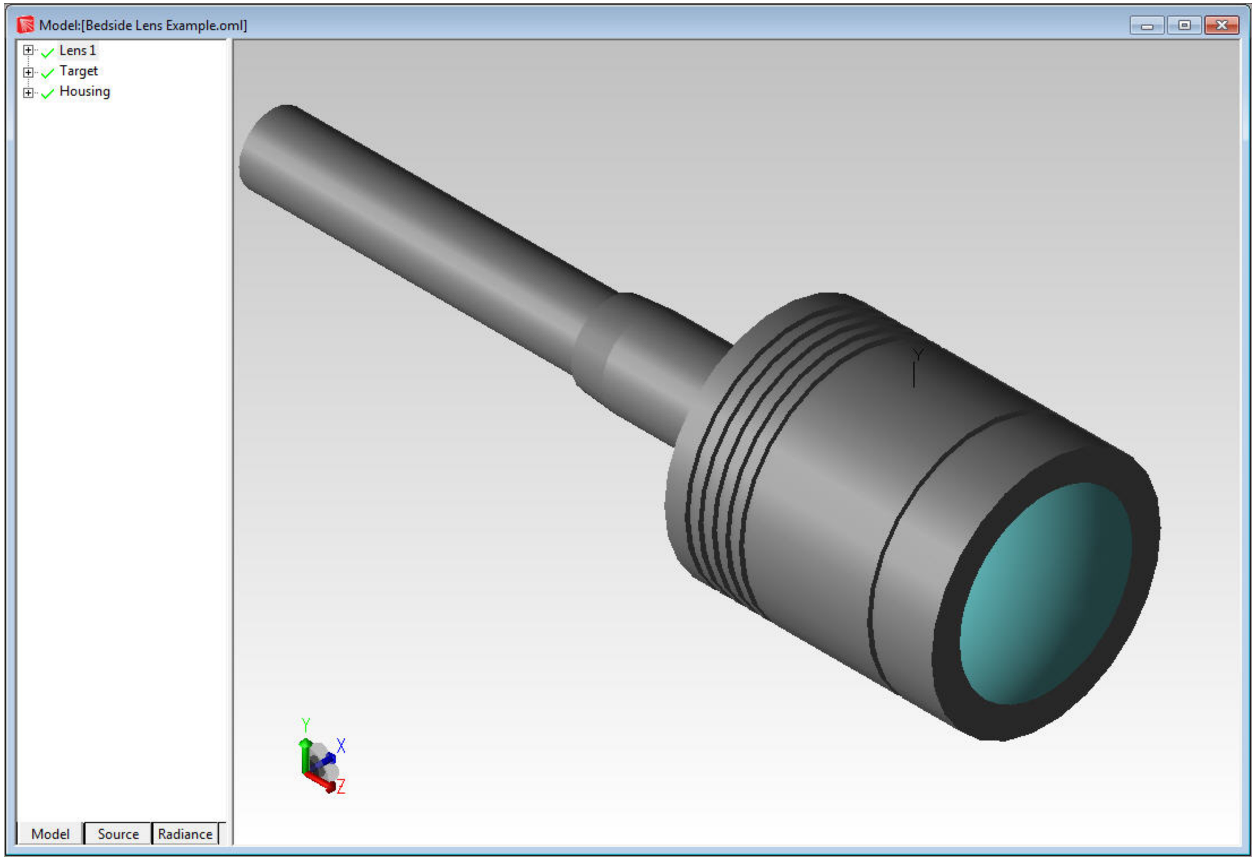
- **Example 5**: LED reading light example

Examples

- LED reading light example

Examples

- LED reading light example
  - Optical analysis software model



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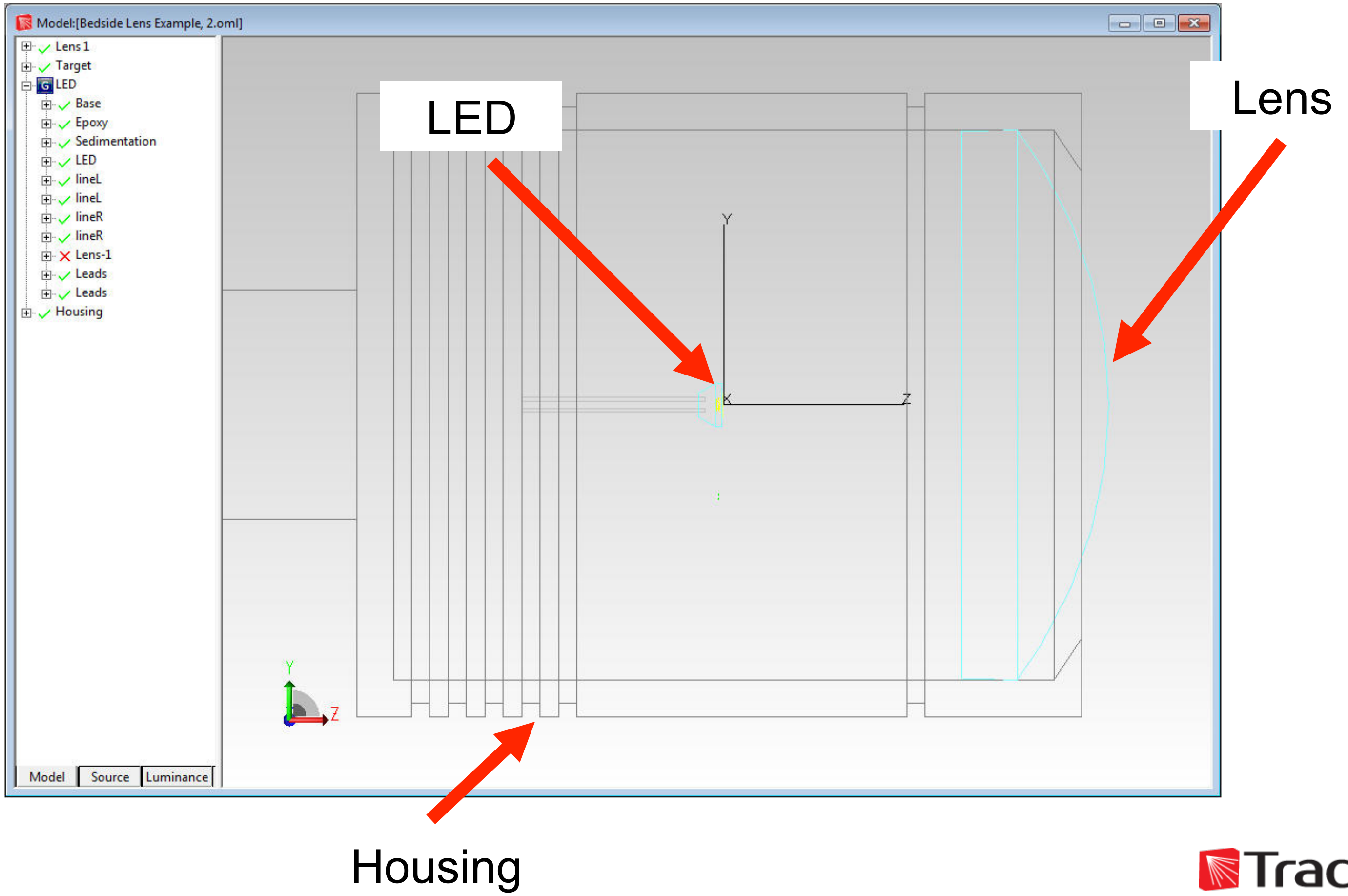
Examples

- LED reading light example
  - Optical analysis software model



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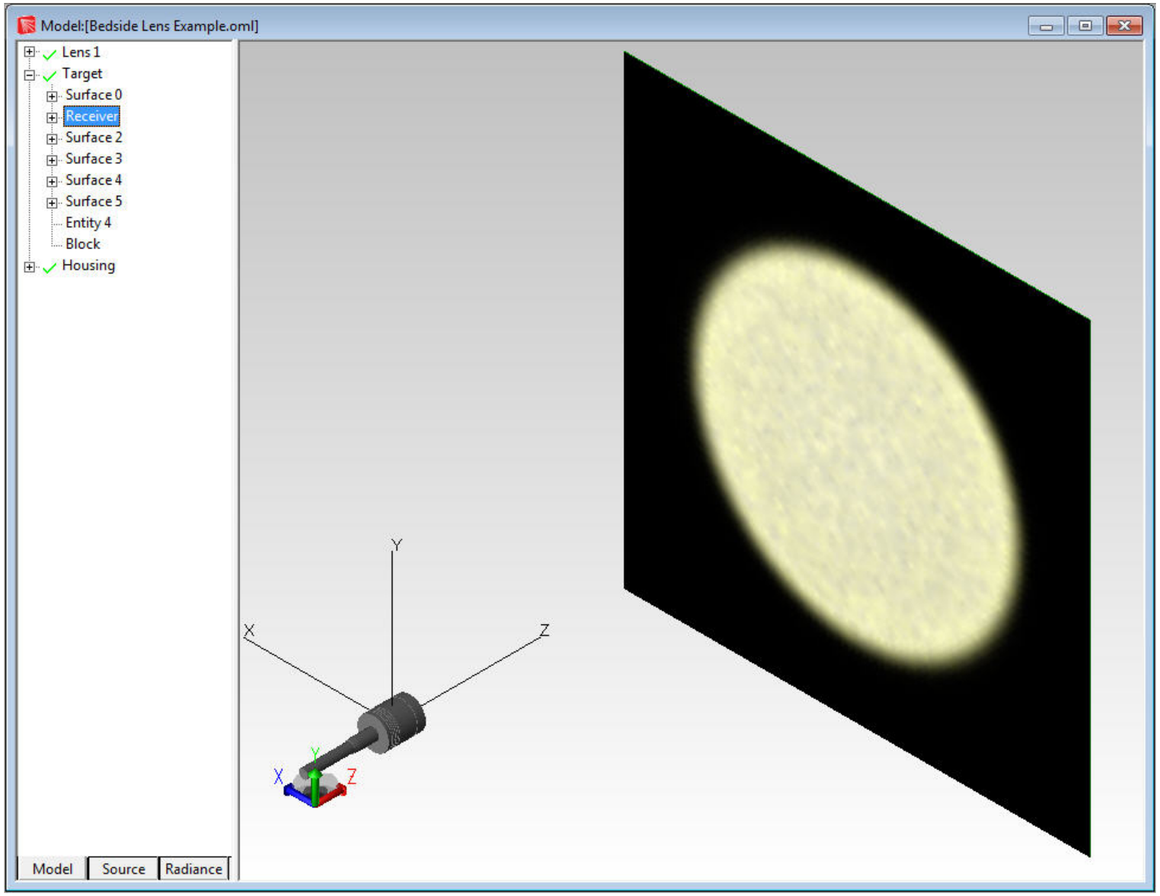
Examples

- LED reading light example
  - Optical analysis software model – 3D Illuminance Map - TrueColor



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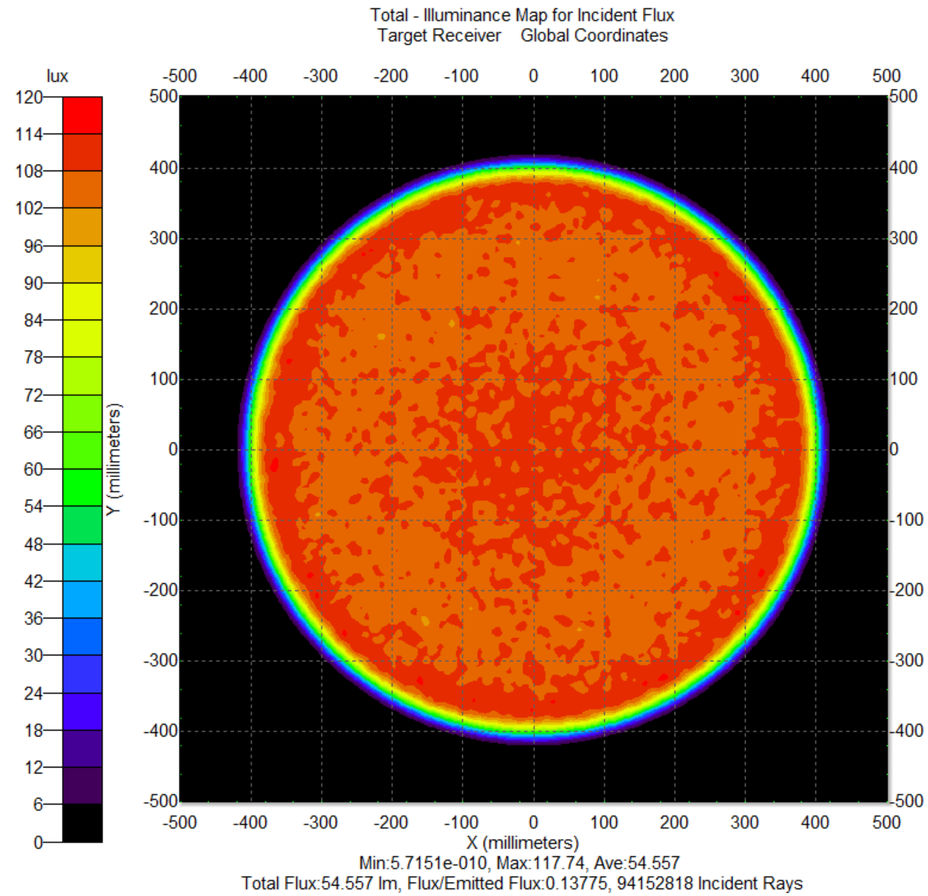
Examples

- LED reading light example
  - Illuminance Map – spatial distribution of light



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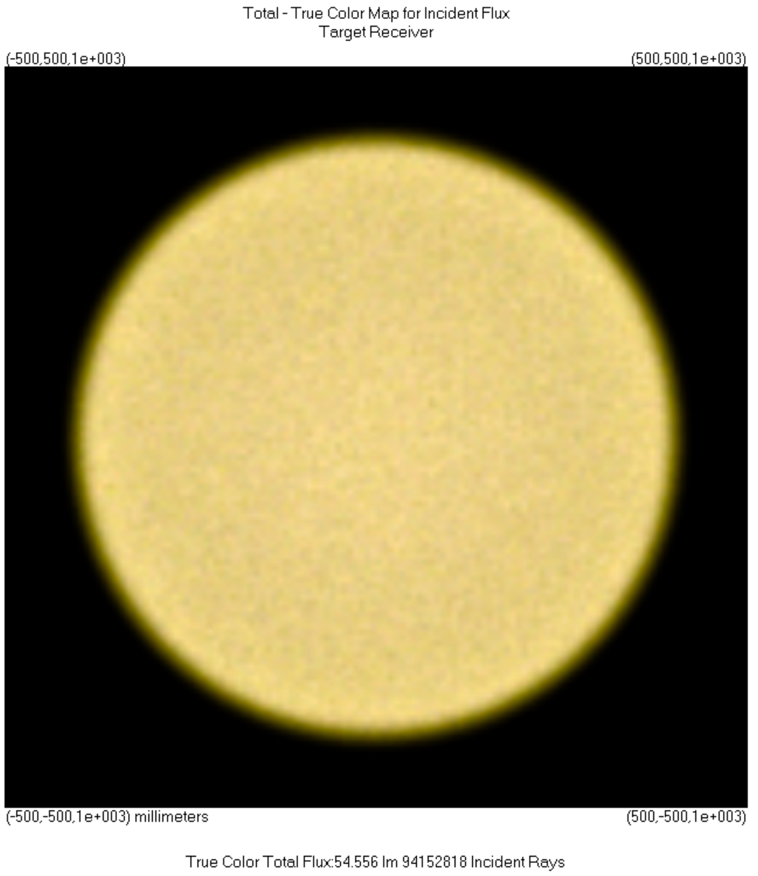
Examples

- LED reading light example
  - TrueColor – RGB display



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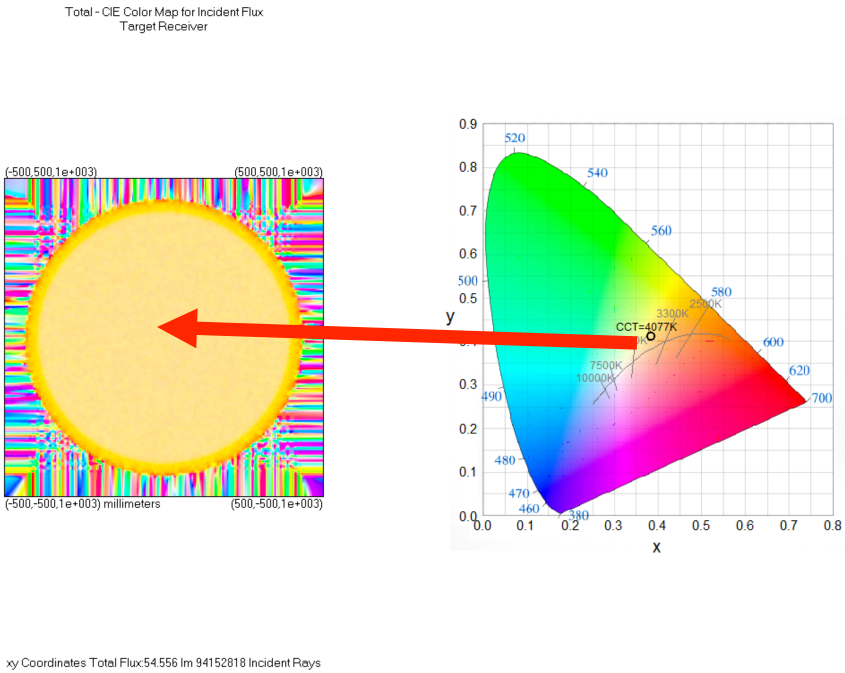
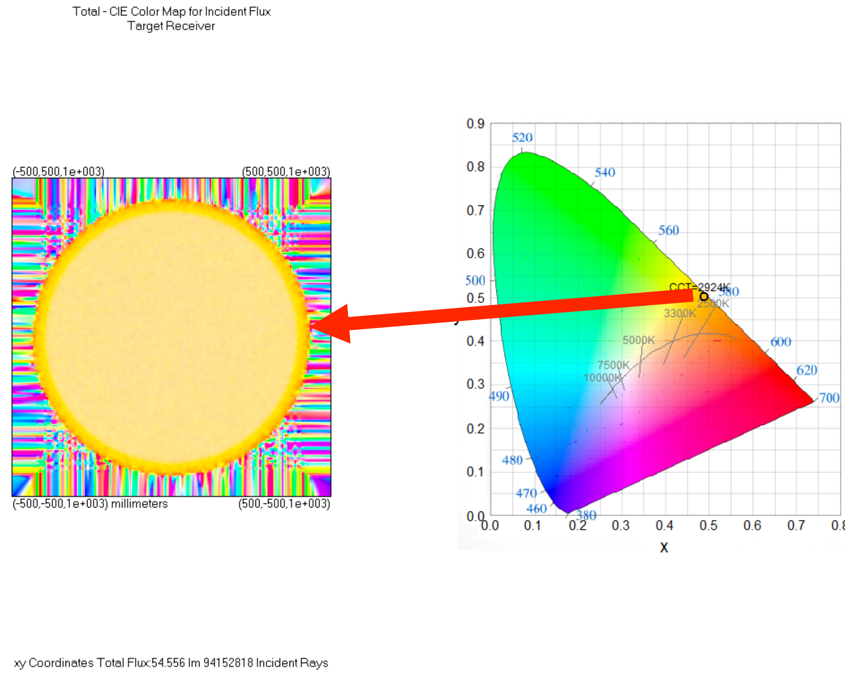
Examples

- LED reading light example
  - Correlated Color Temperature (CCT) – CIE xy color space



Center CCT = 4077K



Center CCT = 2924K

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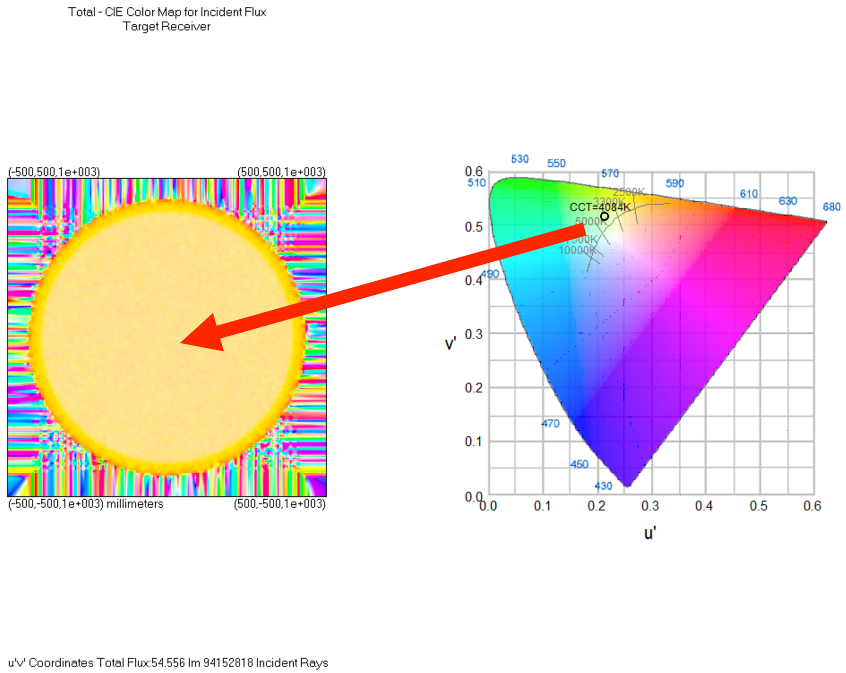
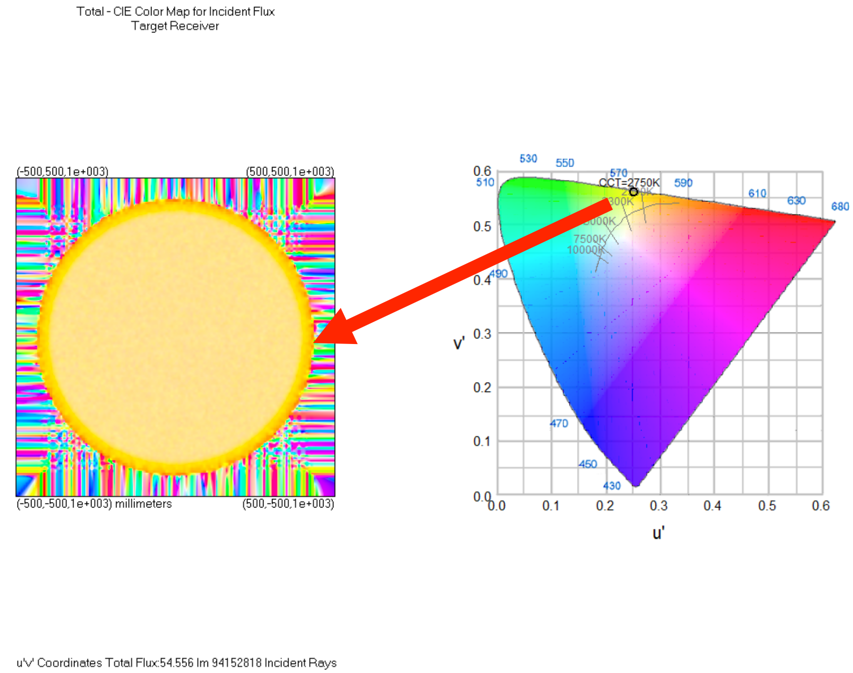
Examples

- LED reading light example
  - Correlated Color Temperature (CCT) – CIE xy color space



Center CCT = 4084K



Center CCT = 2750K

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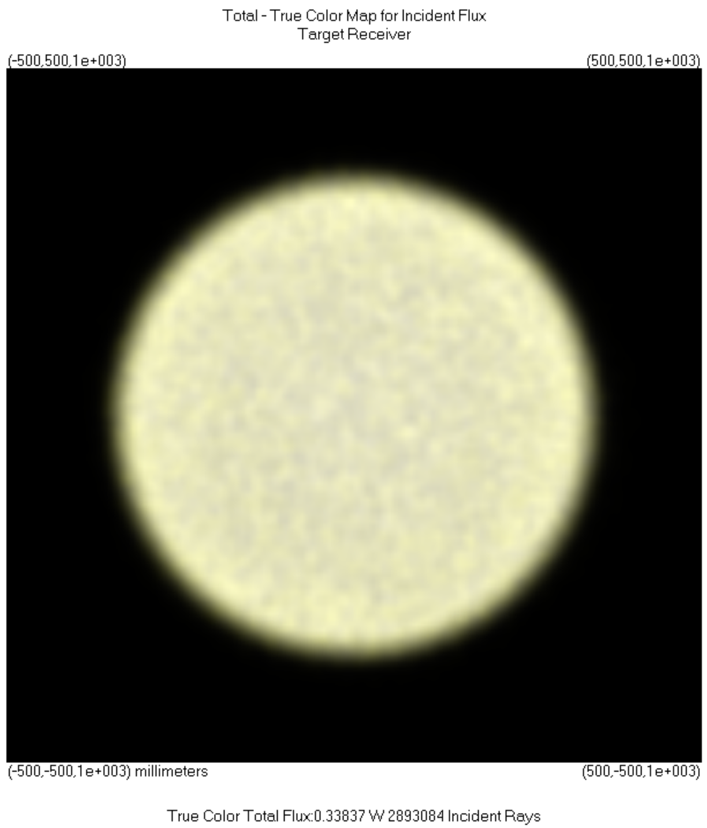
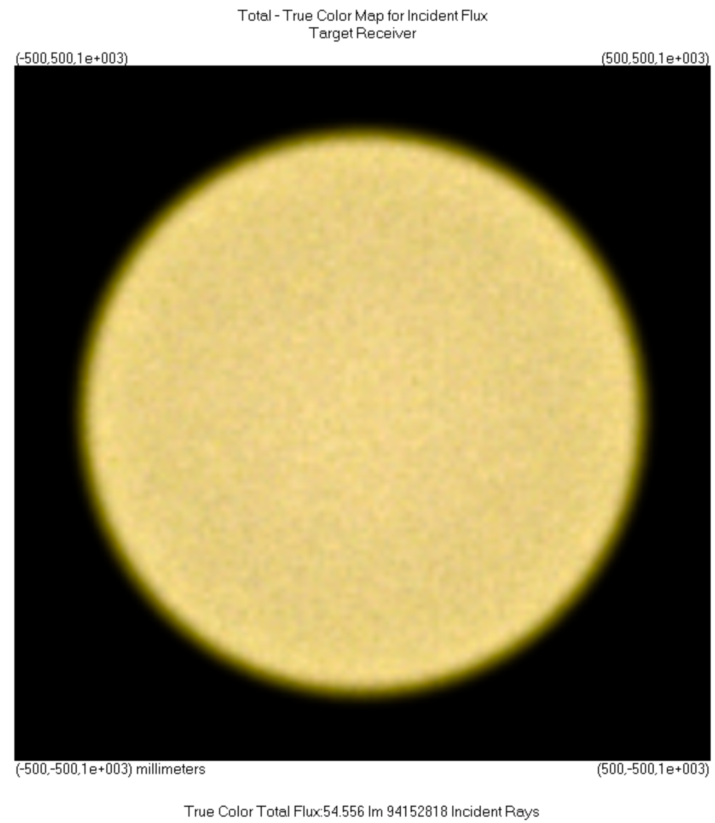
Examples

- LED reading light example
  - Results with different source models



2 rayfiles – blue & yellow



LED phosphor model

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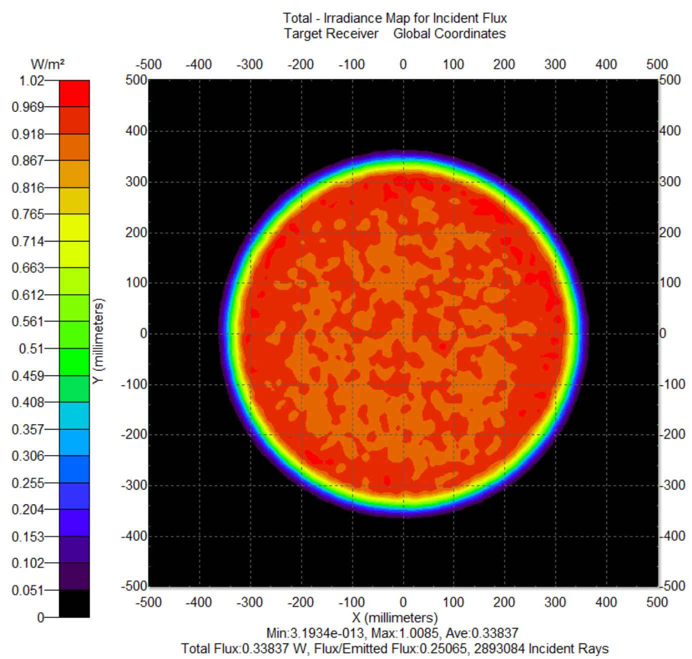
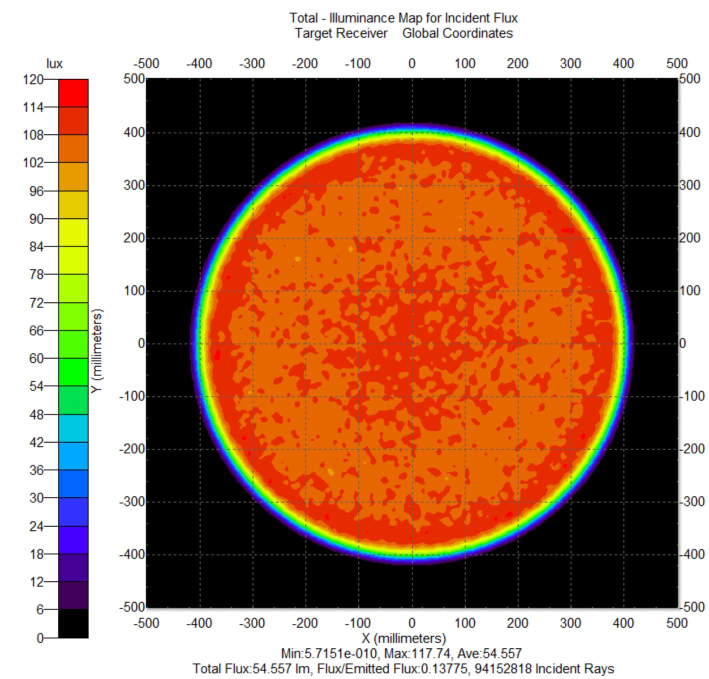
Examples

- LED reading light example
  - Results with different source models



2 rayfiles – blue & yellow



LED phosphor model

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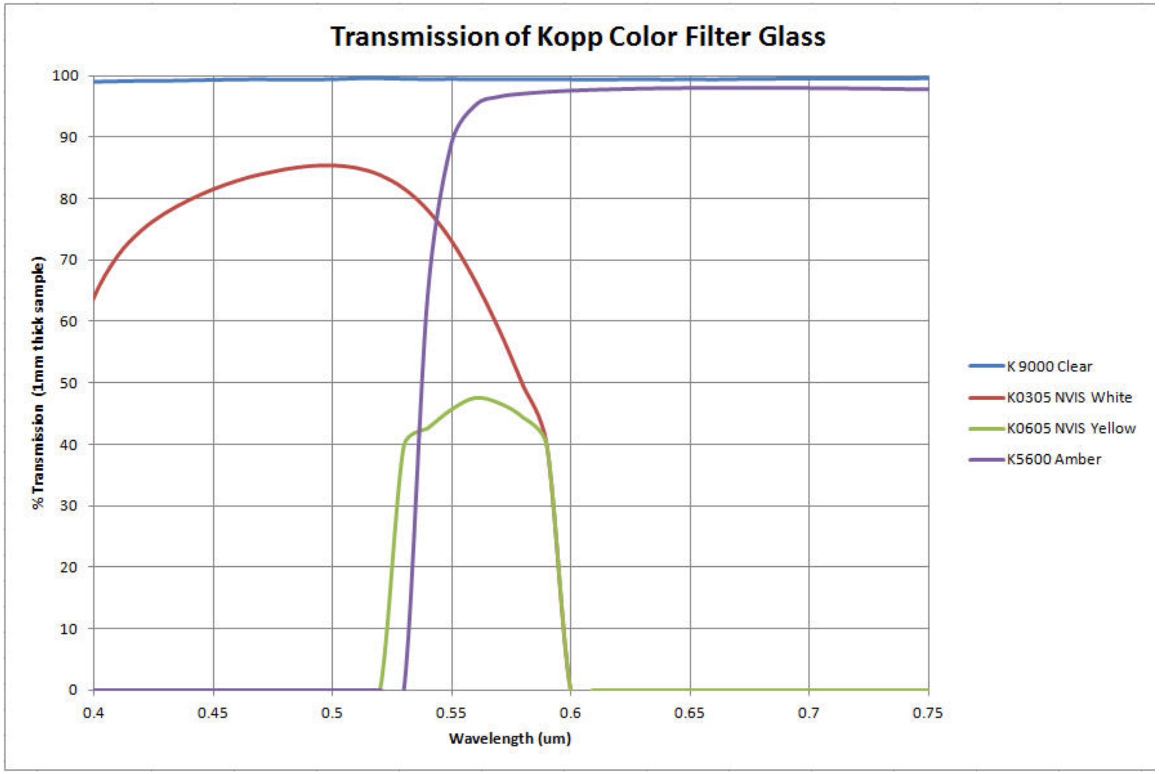
Examples

- **Example 6**: Spectral absorption example

Examples

- Spectral absorption example
  - Glass and plastic absorption properties can effect the spectral content of the LED source



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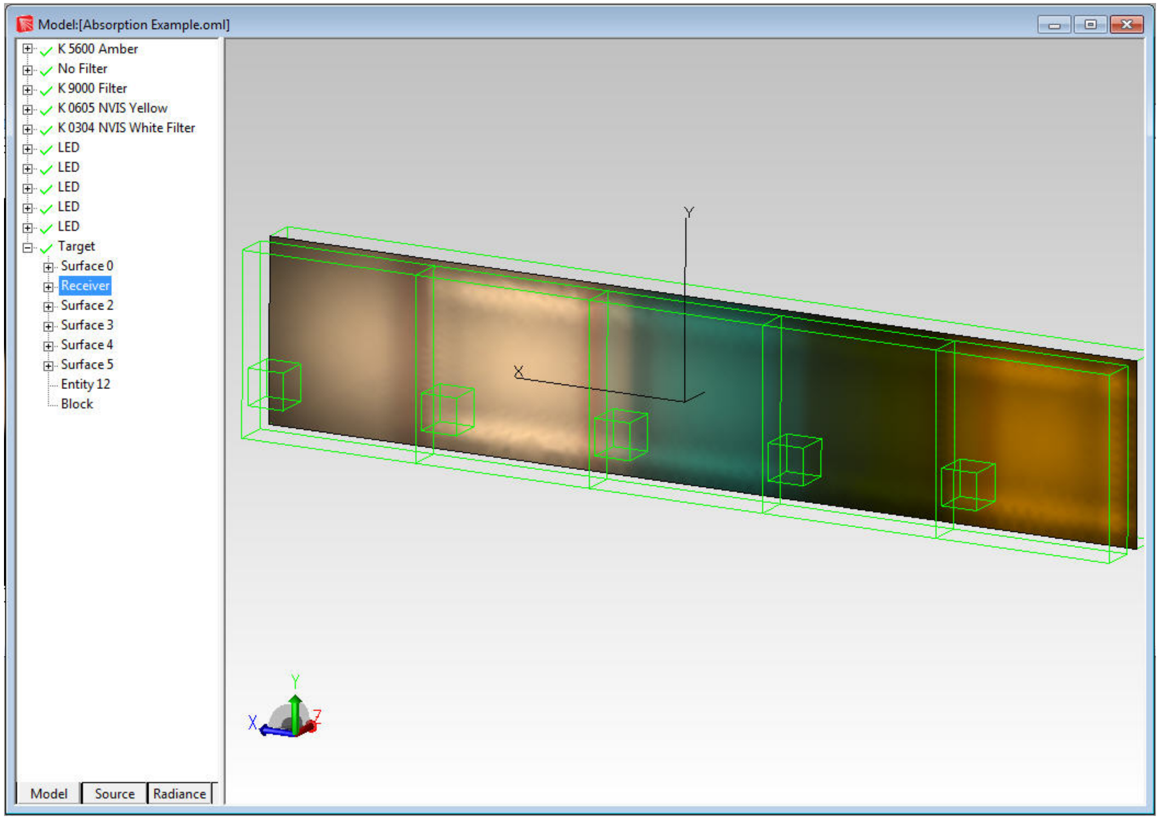
Examples

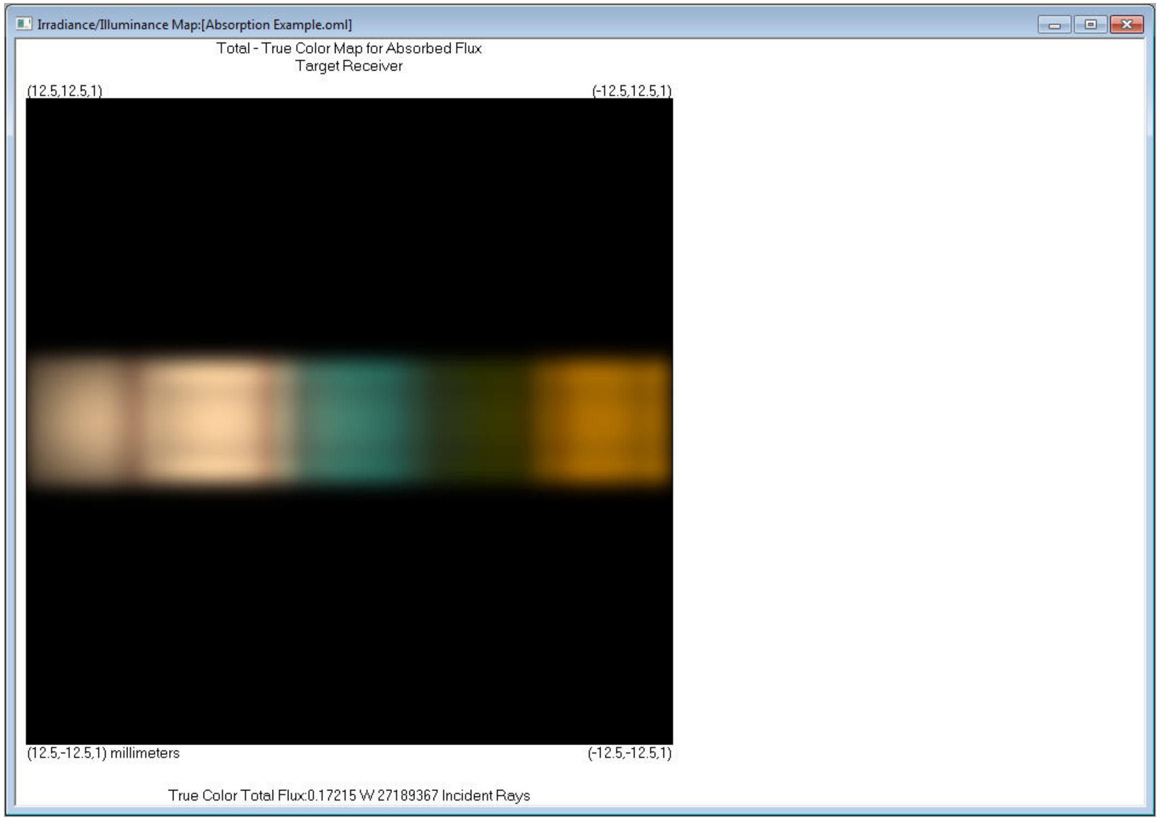
- Spectral absorption example
  - Same LEDs with no filter glass and 4 different color filter glasses – True Color plot



TracePro

Examples

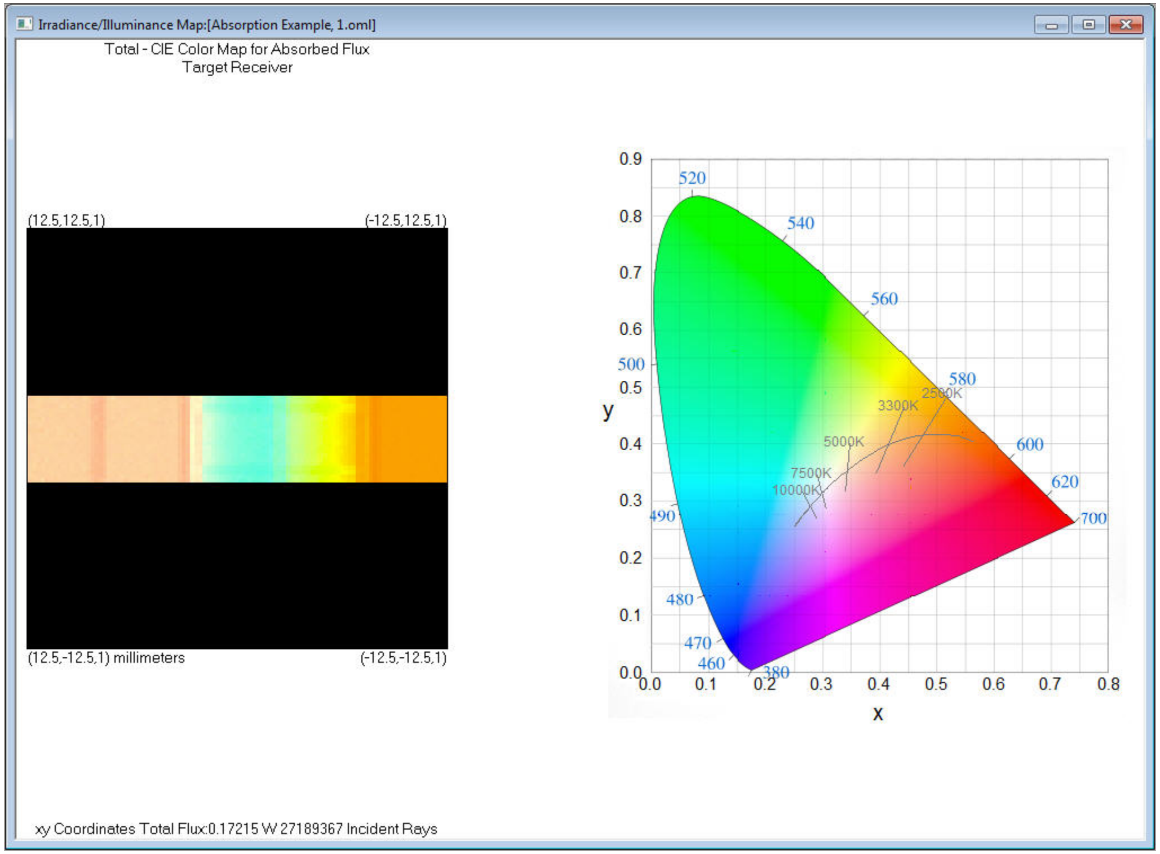
- Spectral absorption example
  - Same LEDs with no filter glass and 4 different color filter glasses – TrueColor plot



TracePro

Examples

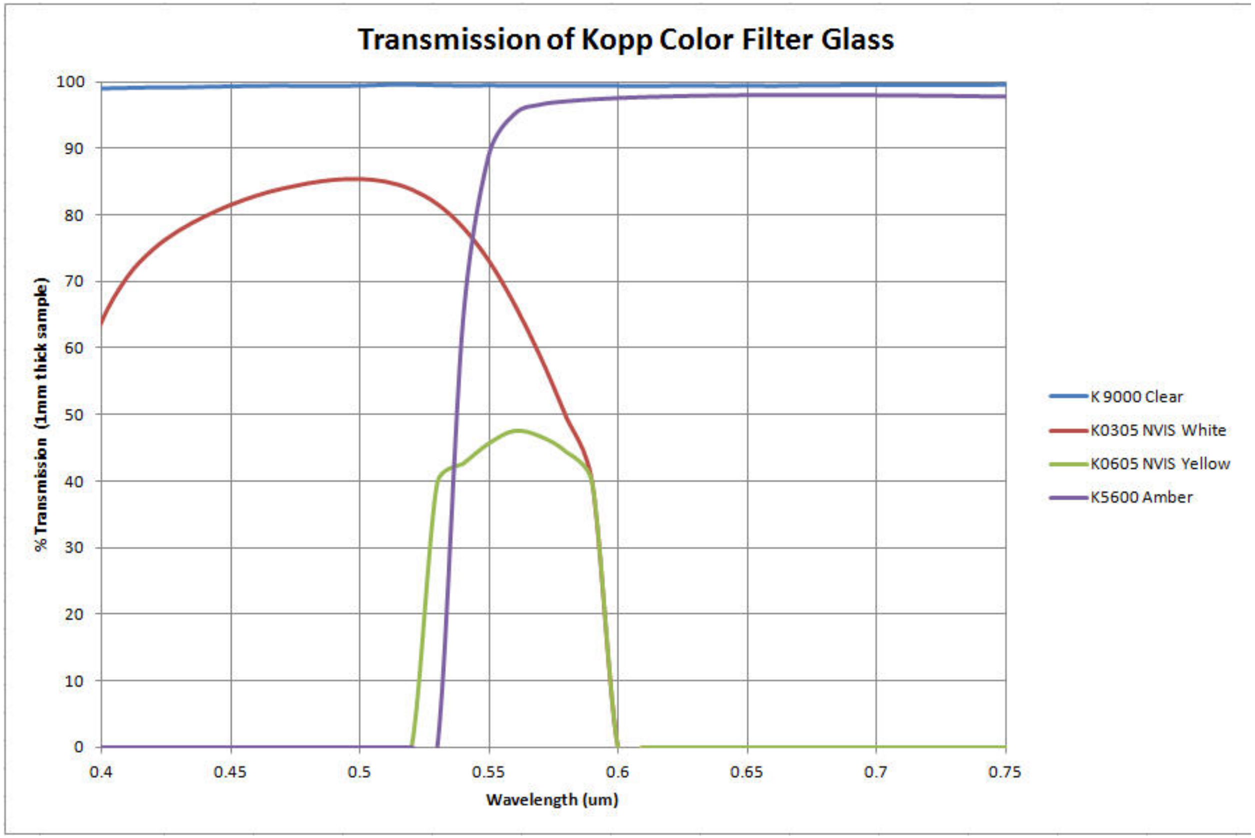
- Spectral absorption example
  - Same LEDs with no filter glass and 4 different color filter glasses – CIE xy plot



TracePro

Examples

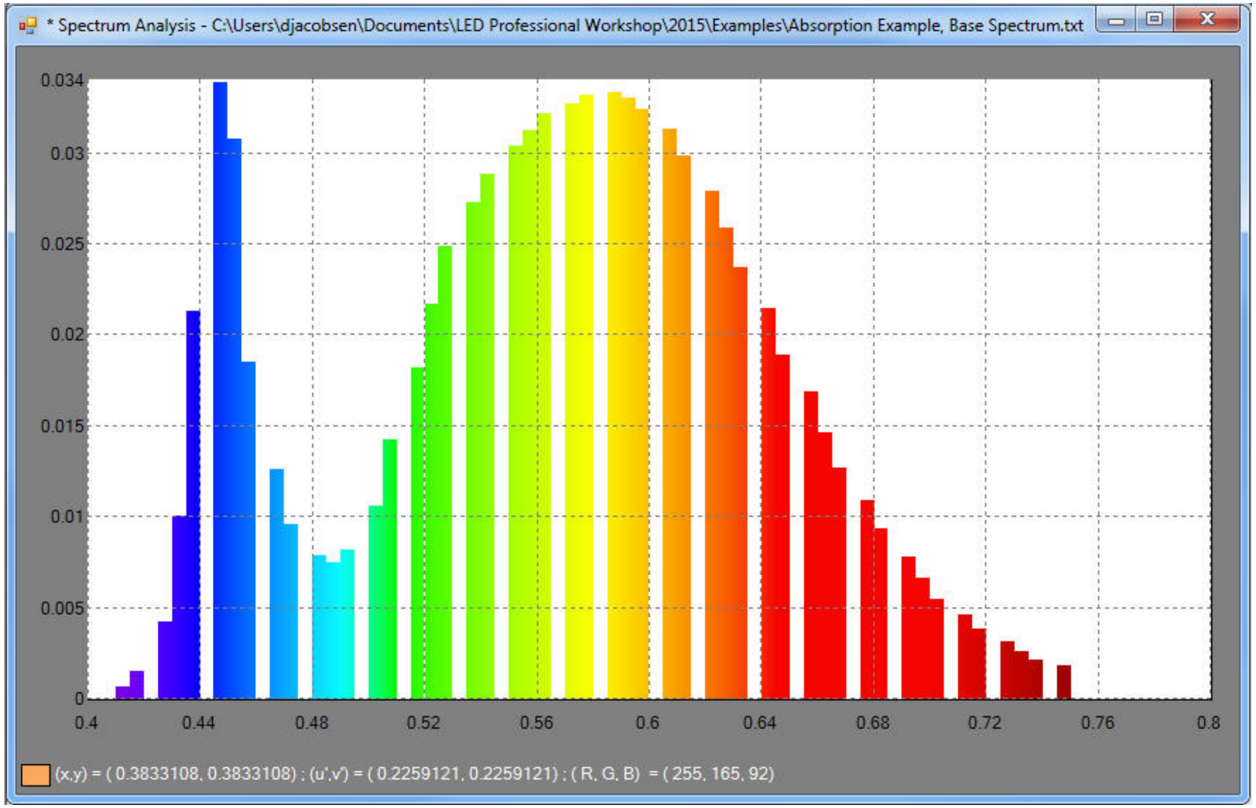
- Spectral absorption example
  - Transmission curves of 1mm thick Kopp color filter glass examples



TracePro

Examples

- Spectral absorption example
  - Spectrum of LED with no color filter



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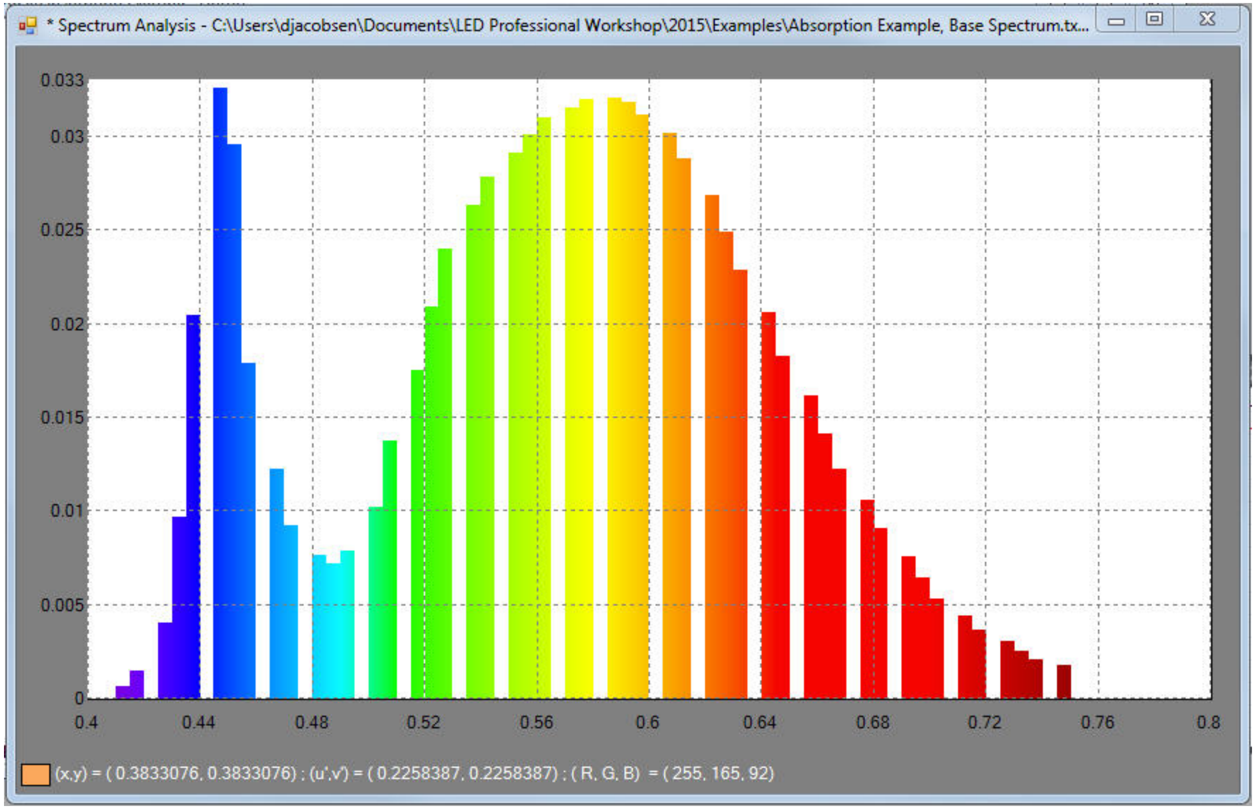
Examples

- Spectral absorption example
  - Spectrum of LED with Kopp K-9000 clear glass filter



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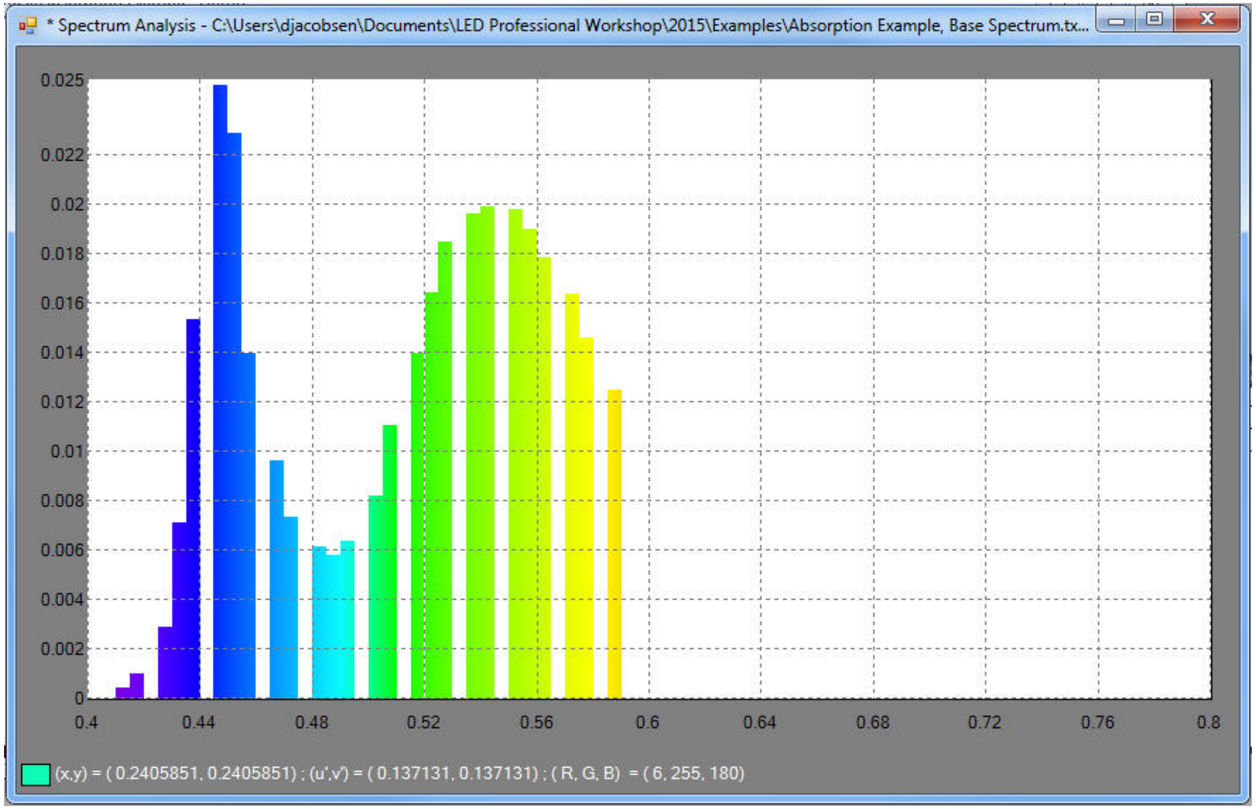
Examples

- Spectral absorption example
  - Spectrum of LED with Kopp K-0305 NVIS white filter

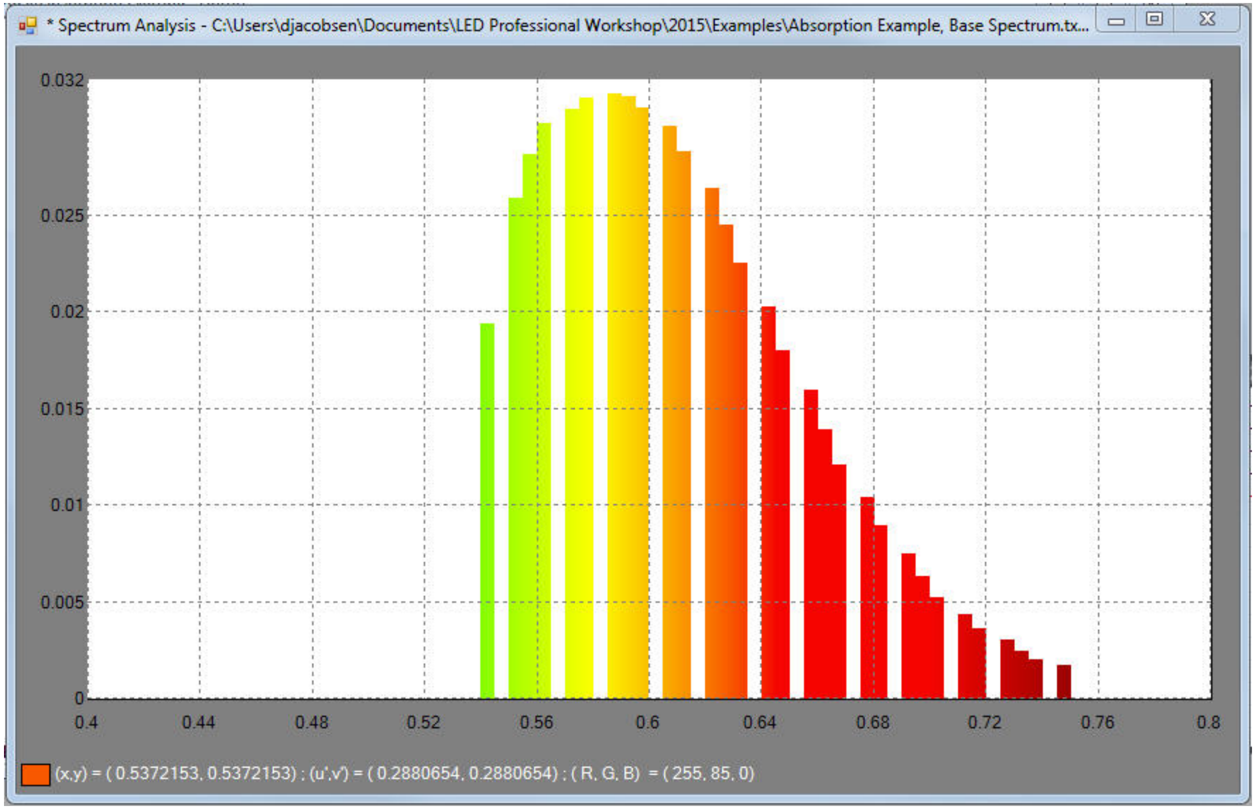


Examples

- Spectral absorption example
  - Spectrum of LED with Kopp K-0605 NVIS yellow filter

Examples

- Spectral absorption example
  - Spectrum of LED with Kopp K-5600 amber filter



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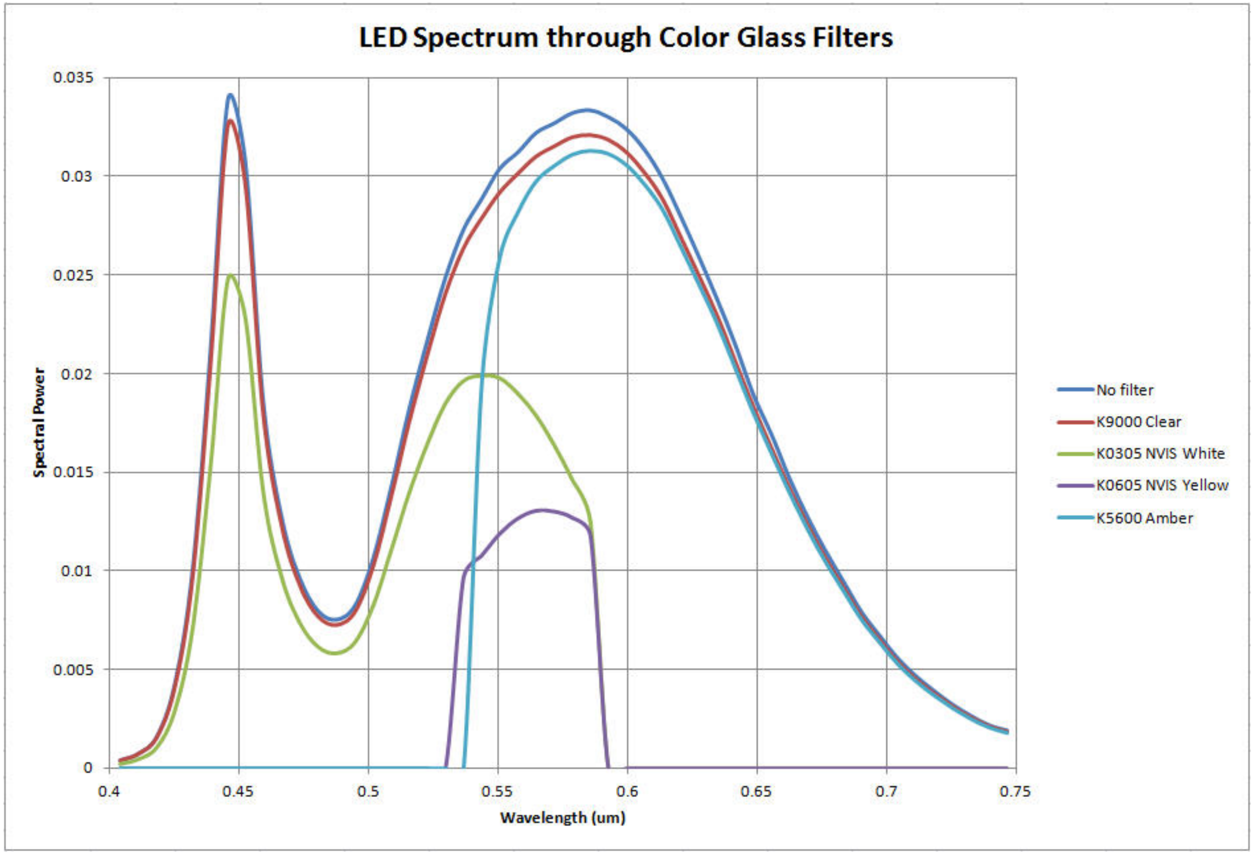
Examples

- Spectral absorption example
  - LED spectrum with no filter glass and 4 different color filter glasses



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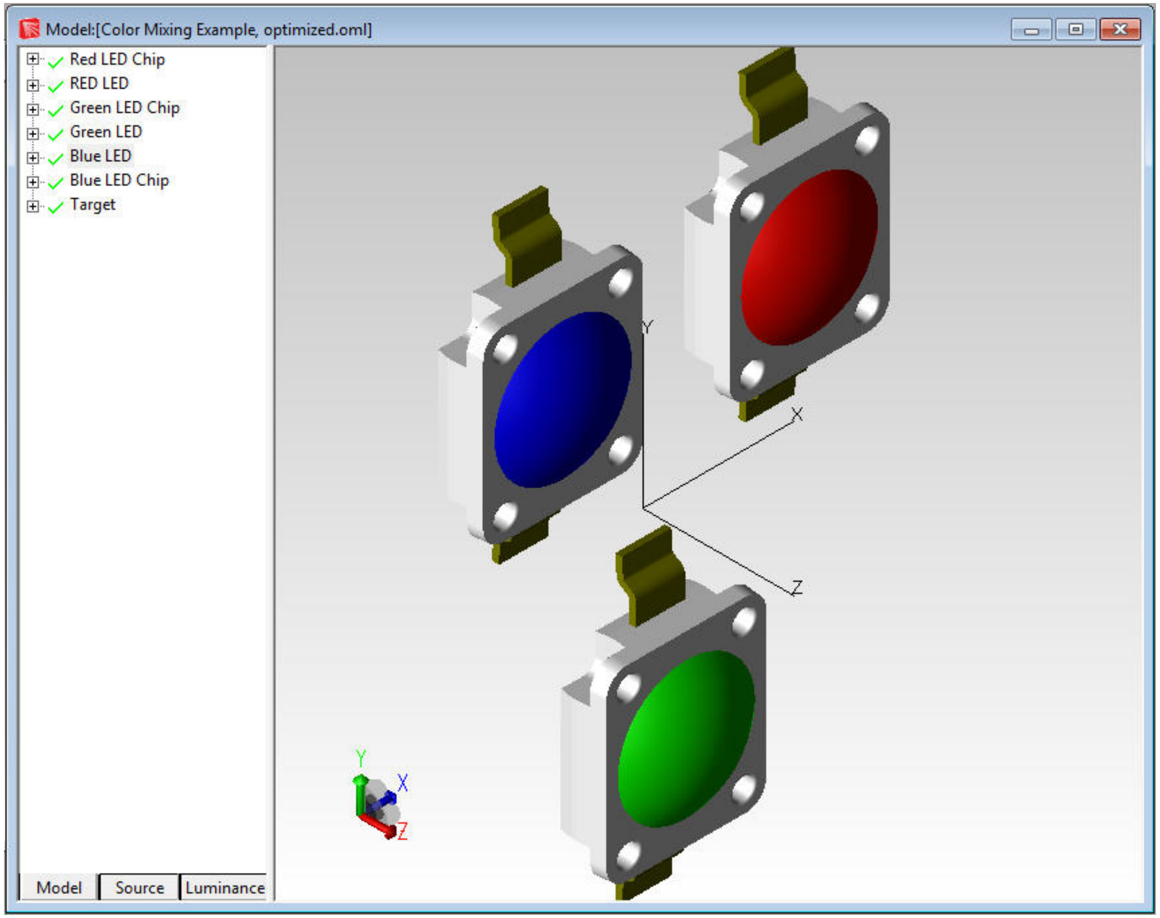
Examples

- **Example 7**: Color mixing example

Examples

- Color mixing example
  - Show resulting color from mixing red, green, and blue LEDs



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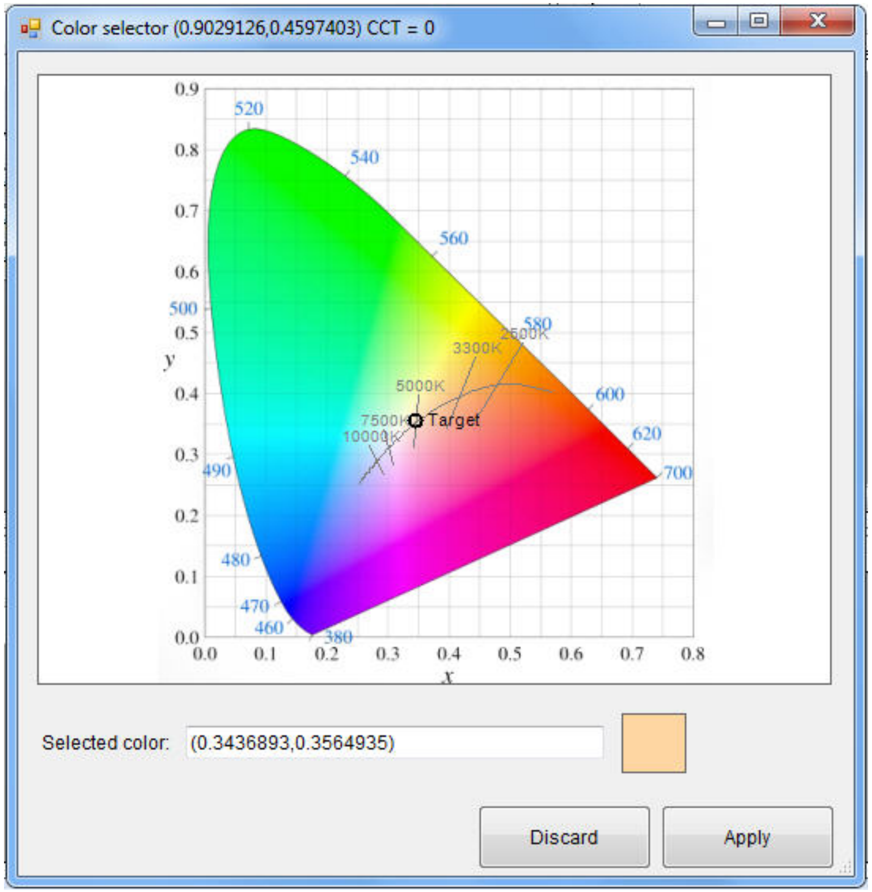
Examples

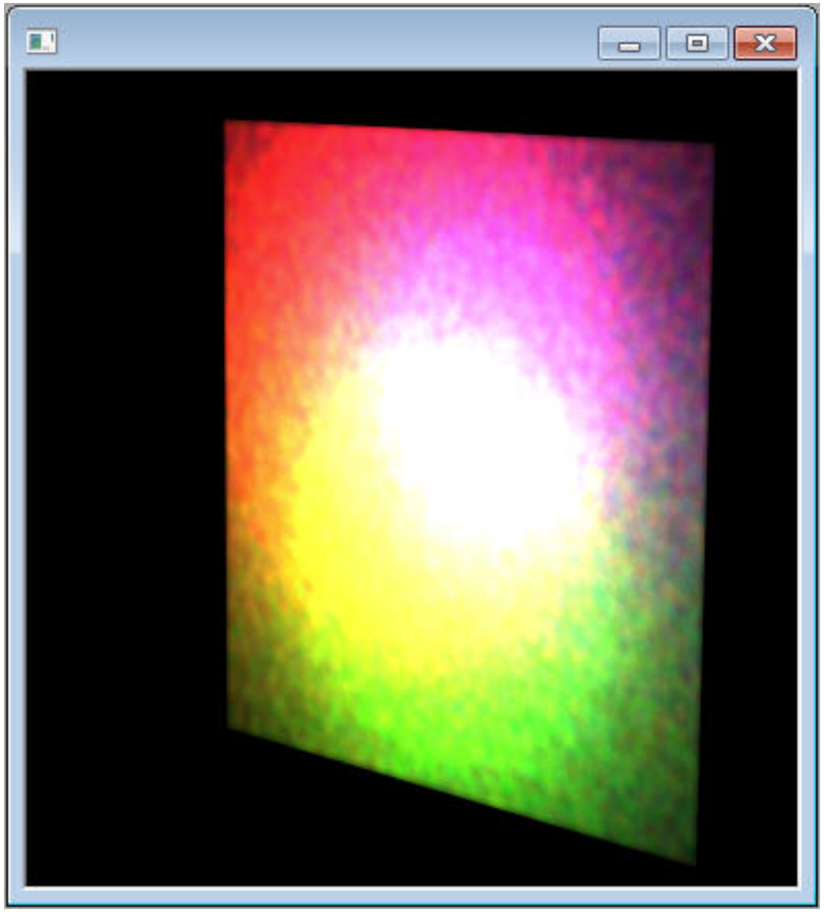
- Color mixing example
  - Goal is CIE xy coordinates of (0.344, 0.356), CCT = 5000K



TracePro

Examples

- Color mixing example
  - Photorealistic rendering plot



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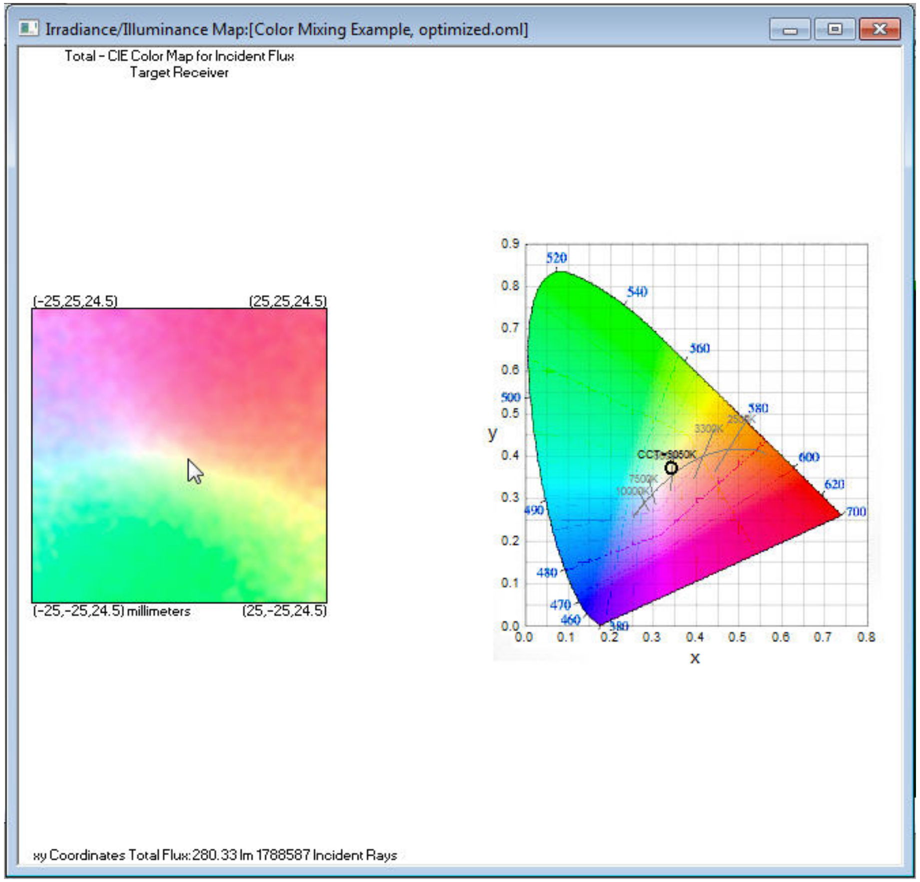
Examples

- Color mixing example
  - After Optimization - (0.3463x, 0.3699y) - CCT = 5000K



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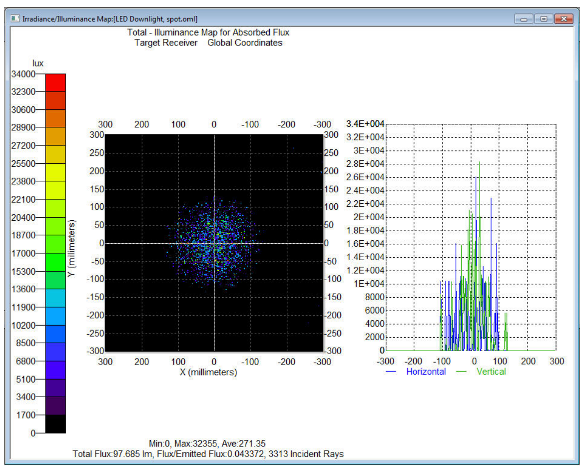
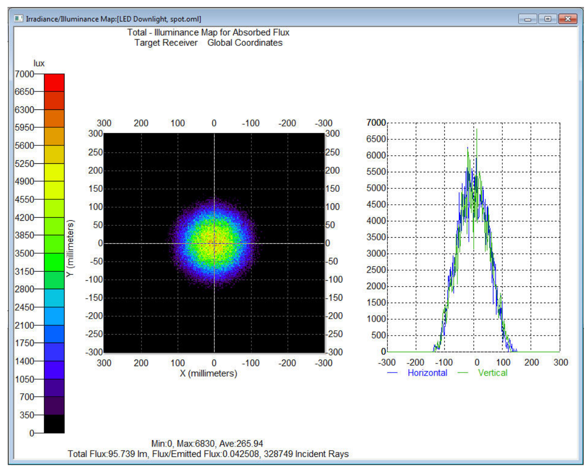
Examples

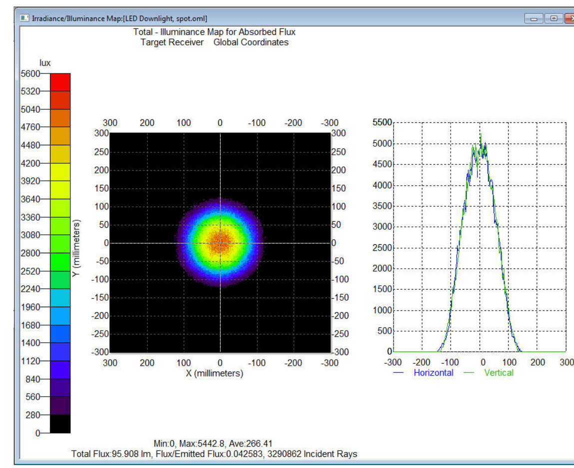
- **Example 8**: Not enough rays traced example

Examples

- Not enough rays traced example
  - If enough rays are not traced, the results will not be accurate. Especially in terms of color metrics.
  - Illuminance Map results







7000 rays traced
4 seconds

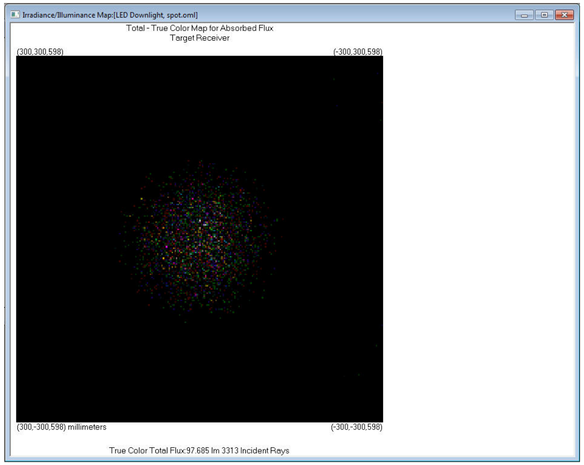
700000 rays traced
1 minute 35 seconds

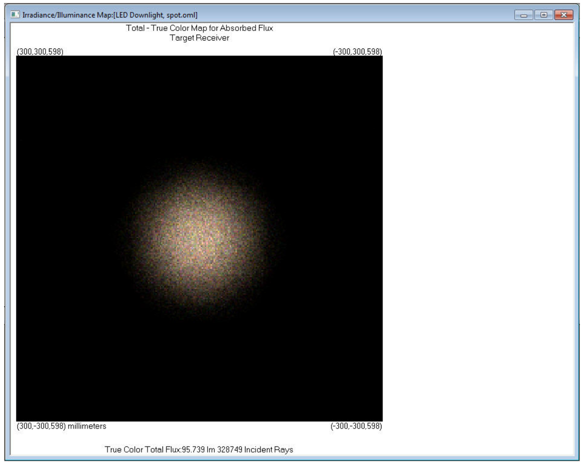
7000000 rays traced
9 minutes 20 seconds

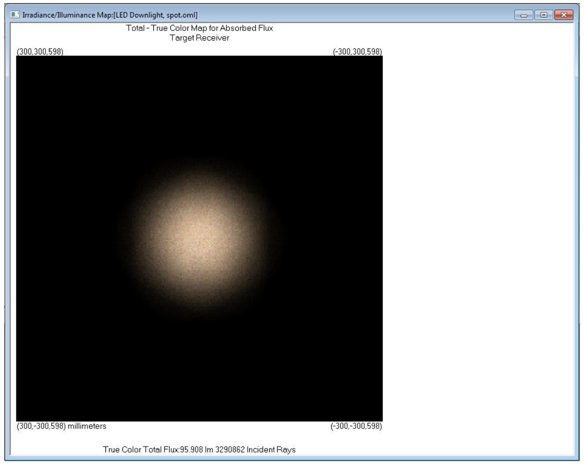
TracePro

Examples

- Not enough rays traced example
  - If enough rays are not traced, the results will not be accurate. Especially in terms of color metrics.
  - TrueColor Plot results







7000 rays traced
4 seconds

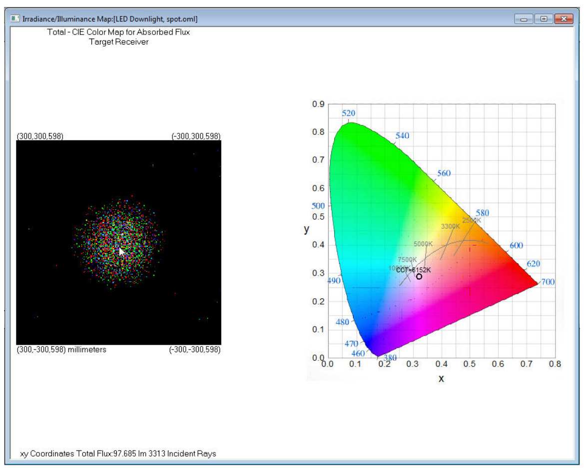
700000 rays traced
1 minute 35 seconds

7000000 rays traced
9 minutes 20 seconds

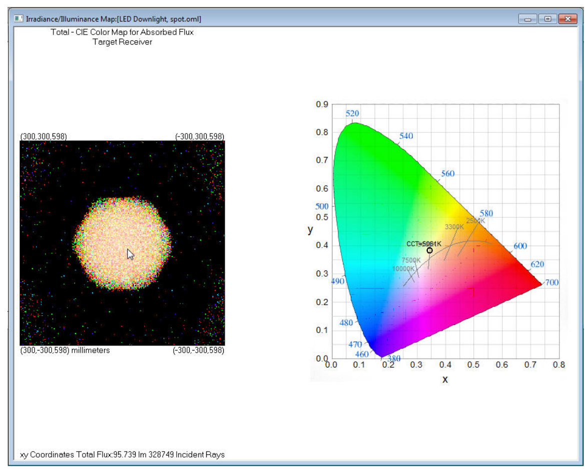
TracePro

Examples

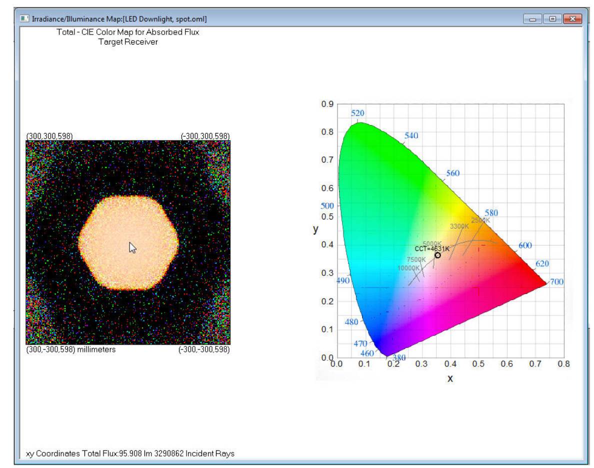
- Not enough rays traced example
  - If enough rays are not traced, the results will not be accurate. Especially in terms of color metrics.
  - CIE xy results



7000 rays traced
4 seconds



700000 rays traced
1 minute 35 seconds



7000000 rays traced
9 minutes 20 seconds

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Summary and Questions

- Optical modeling can be used to shorten the design process and speed the time-to-market by allowing numerous designs to be evaluated in a short period of time virtually rather than as prototypes. The problems can then be found in software rather than hardware.

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Summary and Questions

- What is needed to get accurate results?
  - A good optical analysis software program
  - An accurate 3D solid model of the LED lighting system including accurate surface and material properties
  - An accurate source model, either a surface source model or a rayfile
  - Trace enough rays to get an accurate answer

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Summary and Questions

Thank You

For more information or to sign up for our free 30-day trial please visit us at:

www.lambdares.com

Phone: +1 978-486-0766 E-mail: sales@lambdares.com

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