The Abdus Salam International Centre for Theoretical Physics

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Winter College on Optics and Energy

8 - 19 February 2010

Lighting and illumination engineering
III. Solid-state lighting

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III. Solid-state lighting

16 February 2010 – 11.30 to 12.30

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Introduction

- LEDs are increasingly being used as a light source in architectural lights, displays, automotive lamps, etc.

Power Conversion for "White" Light Sources

	Incandescent* (60W)	Fluorescent* (Typical linear CW)	Metal Halide‡	LED
Visible Light	7.5 %	21 %	27 %	15-25%
Infrared	73.3 %	37 %	17 %	~ 0 %
Ultraviolet	0 %	0 %	19 %	0 %
Total Radiant Energy	80.8 %	58 %	63 %	15-25%
Heat (Conduction + Convection)	19.2 %	42 %	37 %	75-85%
Total	100 %	100 %	100 %	100 %

Light Type	Data Sheet lm/W	Usable* lm/W	Lifetime (hrs)
Incandescent	17	10-17	3k
Halogen	20	12-20	10k
T12 fluorescent	60	40-50	20k
Metal halide	65-70	35-40	10k-20k
T8 fluorescent	85-90	65-70	20-30k
T5 fluorescent	90	62	30k
High-pressure sodium	95-110	55-65	24k
Best-in-Class Power LED	99	65-75	> 50k
Low-pressure sodium	120-140	65-75	16k

R. Liu, Independent Study Project, UA, 2009.

- Issues:
  - Designing the optics: efficient design and etendue
  - Color mixing or effects: need to mix discrete color LEDs
  - Thermal effects: output efficiency decreases as temperature increases
  - Binning of the LEDs: no two LEDs are made the same
  - Tolerances of the optics: illumination systems made cheaply and quickly
  - Currently very expensive

Designing the SSL Optics

Tailored Nonimaging Optics Design

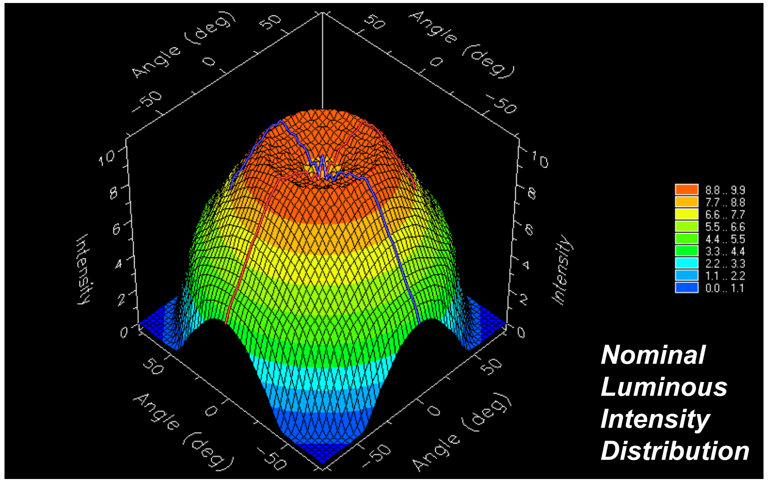
Nonsequential Ray-Tracing Optimization

How Do You Shape the Distribution from an LED?

- Lumileds LED:
  - LXHL-PL01 Luxeon I Lambertian LED
  - "Lambertian" angular output, spatially non-uniform output
  - Amber spectrum (590-nm peak)
  - 42-lumen flux (no thermal derating)
  - Used FRED source model
    - Includes geometry
    - Includes ray set based on measurements

The "big" need in SSL: desired distribution at high efficiency with a desired look

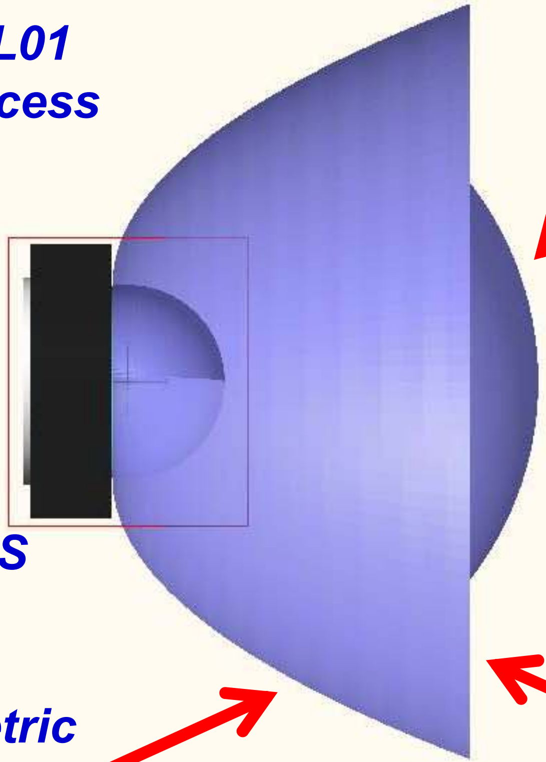
LXHL-PL01 Package



Nominal Luminous Intensity Distribution

Step 1: Optic Design Setup – Hybrid Optic

LED:
- *Lumileds LXHL-PL01*
- *In Conforming Recess*
- *Small Air Gap*



Front Lens:
- *Collimate Direct Output*
  - *Convex*
- *"Contain" Other Light*

- *Described by NURBS*
- *Two End Points*
- *One Control Point*
- *Rotationally Symmetric*
- *Can Extend to Limits*

Side Walls:
- *Described by NURBS*
- *Two End Points*
- *One Control Point*
- *Rotationally Symmetric*

- *Collimate High Angle Output*
  - *Parabolic*
- *"Contain" with TIR*

Annulus:
- *Linear*
- *Transition Walls-Lens*

Step 2: Tailored Design Theory

- Design Around a Source of Intensity $I_{src}(\phi)$.
- Equation That Governs Optic Shape, Where a is the Radius of the Source:

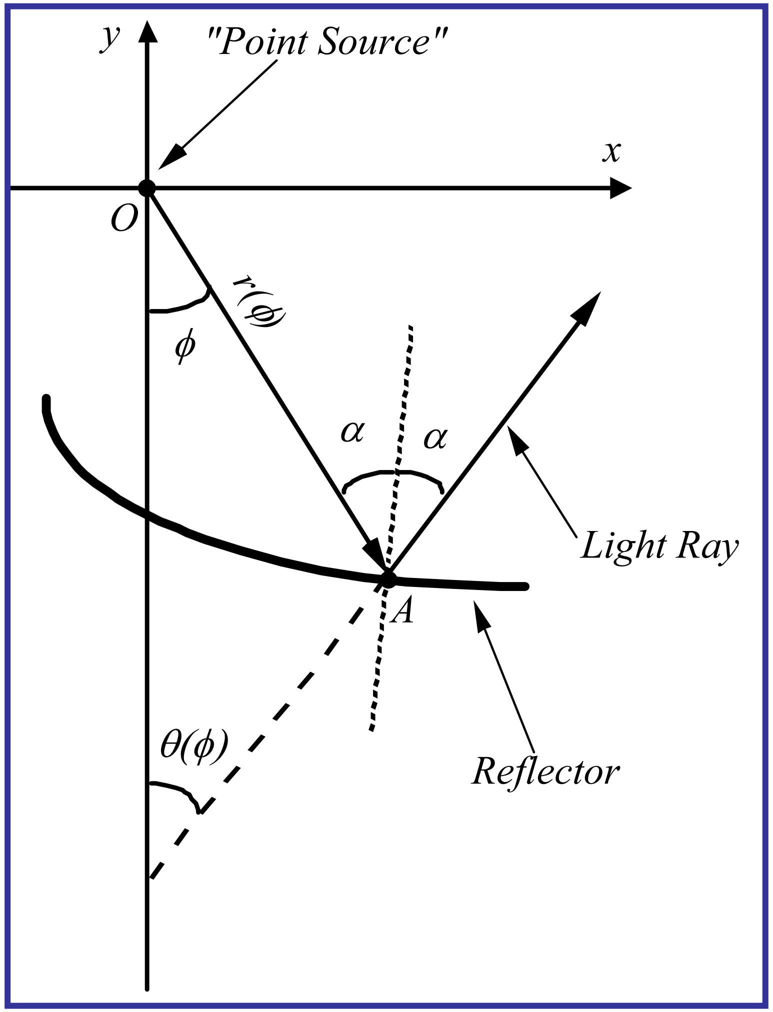
$$\frac{d\ln(r(\phi))}{d\phi} = \tan(\alpha) + \frac{a}{r(\phi)}$$

- The Reflector Shape for a Point Source:

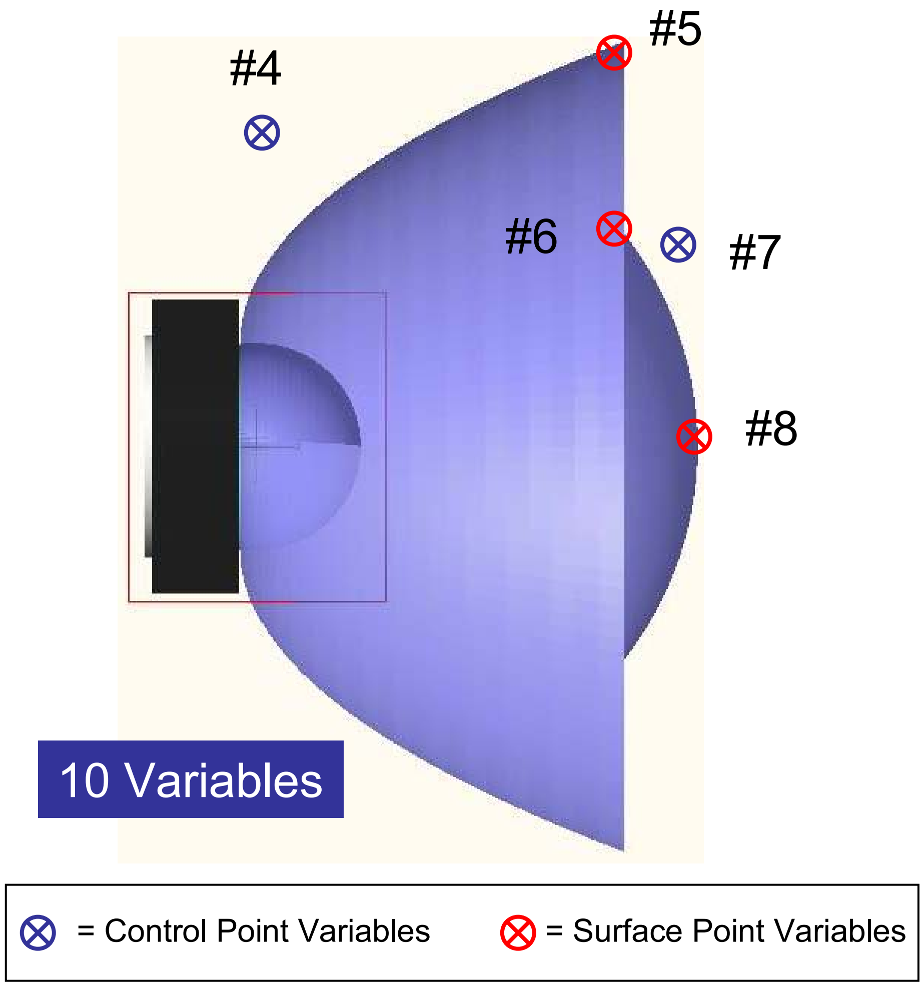
$$r(\phi) = r_1 \exp\left[\int_{\phi_1}^{\phi} \tan\left(\frac{s-\theta(s)}{2}\right) ds\right]$$

- The Intensity Distribution for Target Uniformity is:

$$\theta(\phi) = \arctan\left[\tan\theta_1 + \int_{\phi_1}^{\phi} I_{src}(v)\,dv\right]$$



Step 3: Optimization Variables



- Point 4: y4, z4, w4
- Point 5: y5, z5
- Point 6: y6
- Point 7: y7, z7, w7
- Point 8: z8

- Positions:
  - Coordinates in mm
  - Minimum z = 2.801 mm
  - Maximum z = 12.7 mm
  - Minimum y = 2.801 mm
  - Maximum y = 12.7 mm
- Weights:
  - Minimum = 0.001
  - Maximum = 1000

Target and Merit Function

- Merit Function 1:
  - Maximize Transfer Efficiency to Target
- Merit Function 2:
  - Maximize Transfer Efficiency to Target
  - Maximize Uniformity

Target

Intensity into ±10° around optical axis (Z)

$$FOM = \frac{1}{\eta_t^2}$$

$$FOM = \frac{\sigma_{Int}}{I_{Peak}} \frac{1}{\eta_t^2}$$

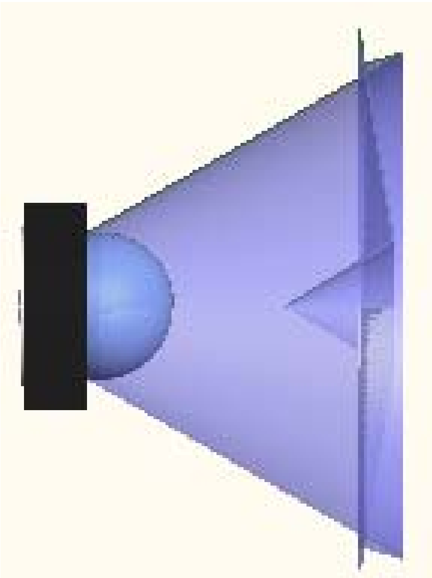
Stopping Condition

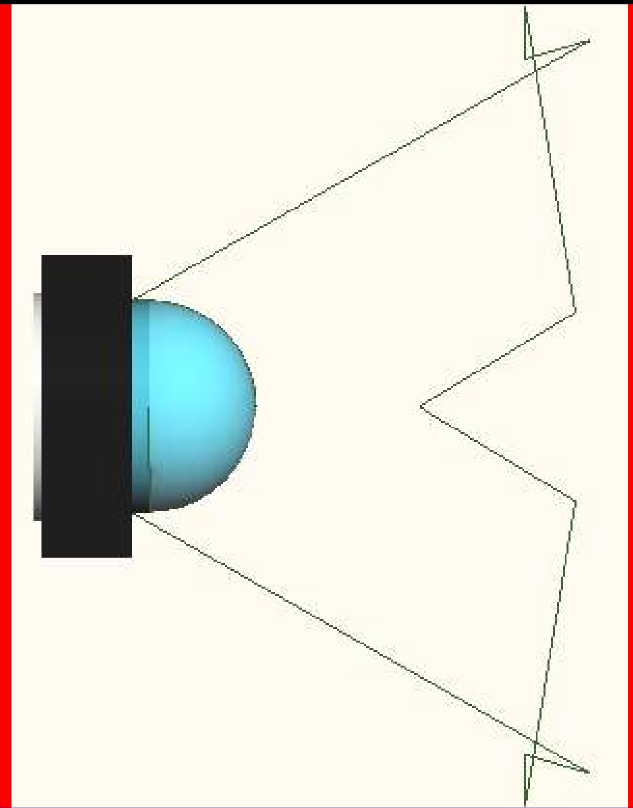
Size of the Test Point Volume (SNR Calculation)

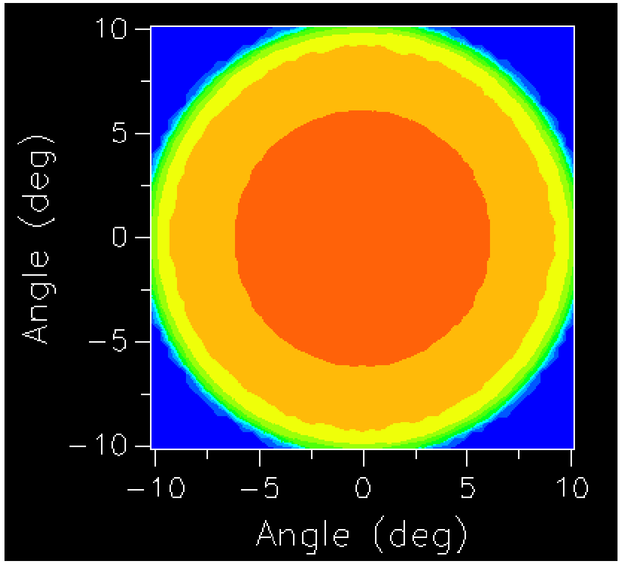
$$\sqrt{(N+1)\sum_{i=1}^{N} \frac{\sigma_i^2}{\overline{x}_i^2} - 1} \leq Tolerance = 0.001$$

Optimization Results

Merit Function 2: Transfer and Uniformity

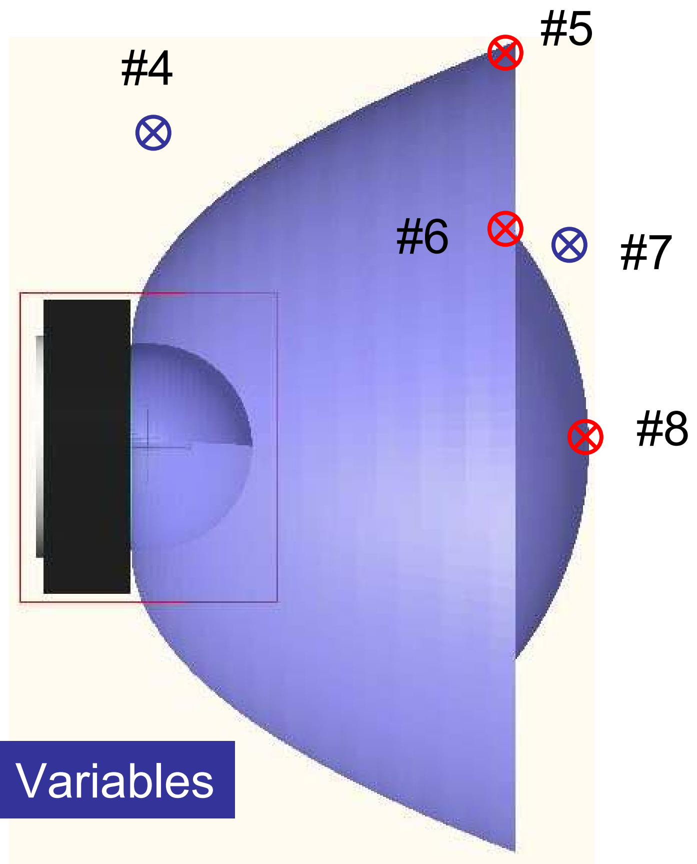






Can We Manufacture That?

Optimization Variables Take Two



⊗ = Control Point Variables ⊗ = Surface Point Variables

- Point 4: y4, z4, w4
- Point 5: y5, z5
- Point 6: y6
- Point 7: y7, z7, w7
- Point 8: z8

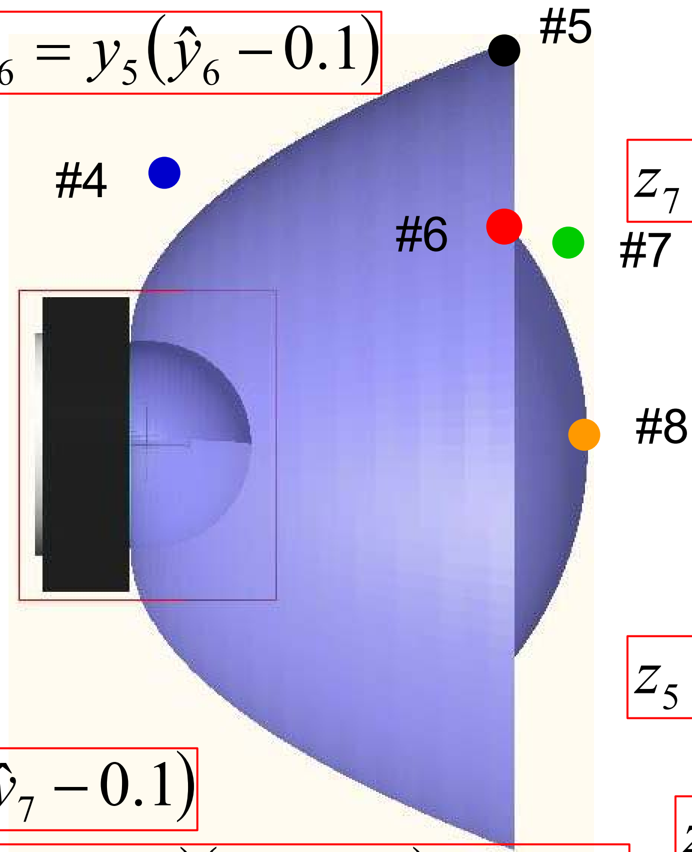
- Positions:
  - Percentages to maximum value or another point's value
  - Offset by +0.1
  - Range = [0.1, 1.1]
- Weights:
  - Log base 10 of the weight factor
  - Offset by +3.1
  - Range = [0.1, 5.1]

Dynamic Variable Dependencies

y5: $y_5 = 9.88(\hat{y}_5 - 0.1) + 2.801$

y6(y5): $y_6 = y_5(\hat{y}_6 - 0.1)$

$z_8 = 9.439(\hat{z}_8 - 0.1) + 2.801$:z8



$z_7 = (z_8 - 2.801)(\hat{z}_7 - 0.1) + 2.801$:z7(z8)

$w_4 = 10^{(\hat{w}_4 - 3.1)}$:w4

$w_7 = 10^{(\hat{w}_7 - 3.1)}$:w7

y7(y6):

y4(y5):

$y_7 = y_6(\hat{y}_7 - 0.1)$

$y_4 = (y_5 - 2.801)(\hat{y}_4 - 0.1) + 2.801$

$z_5 = (z_7 - 2.801)(\hat{z}_5 - 0.1) + 2.801$:z5(z7)

$z_4 = (z_5 + 0.46)(\hat{z}_4 - 0.1) - 0.46$:z4(z5)

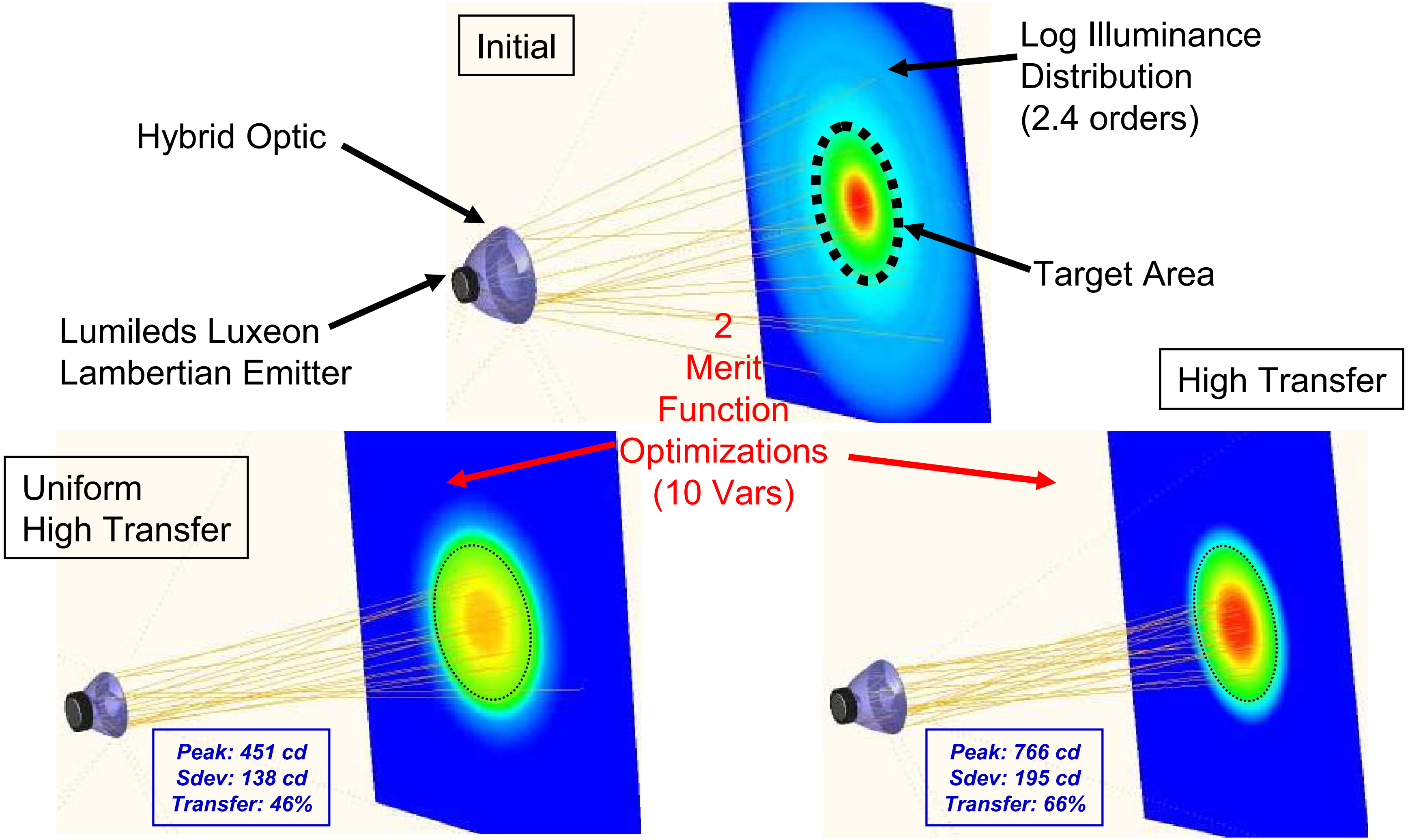
Complex Dependencies

Includes all the constraints to keep the object realistic and bounded

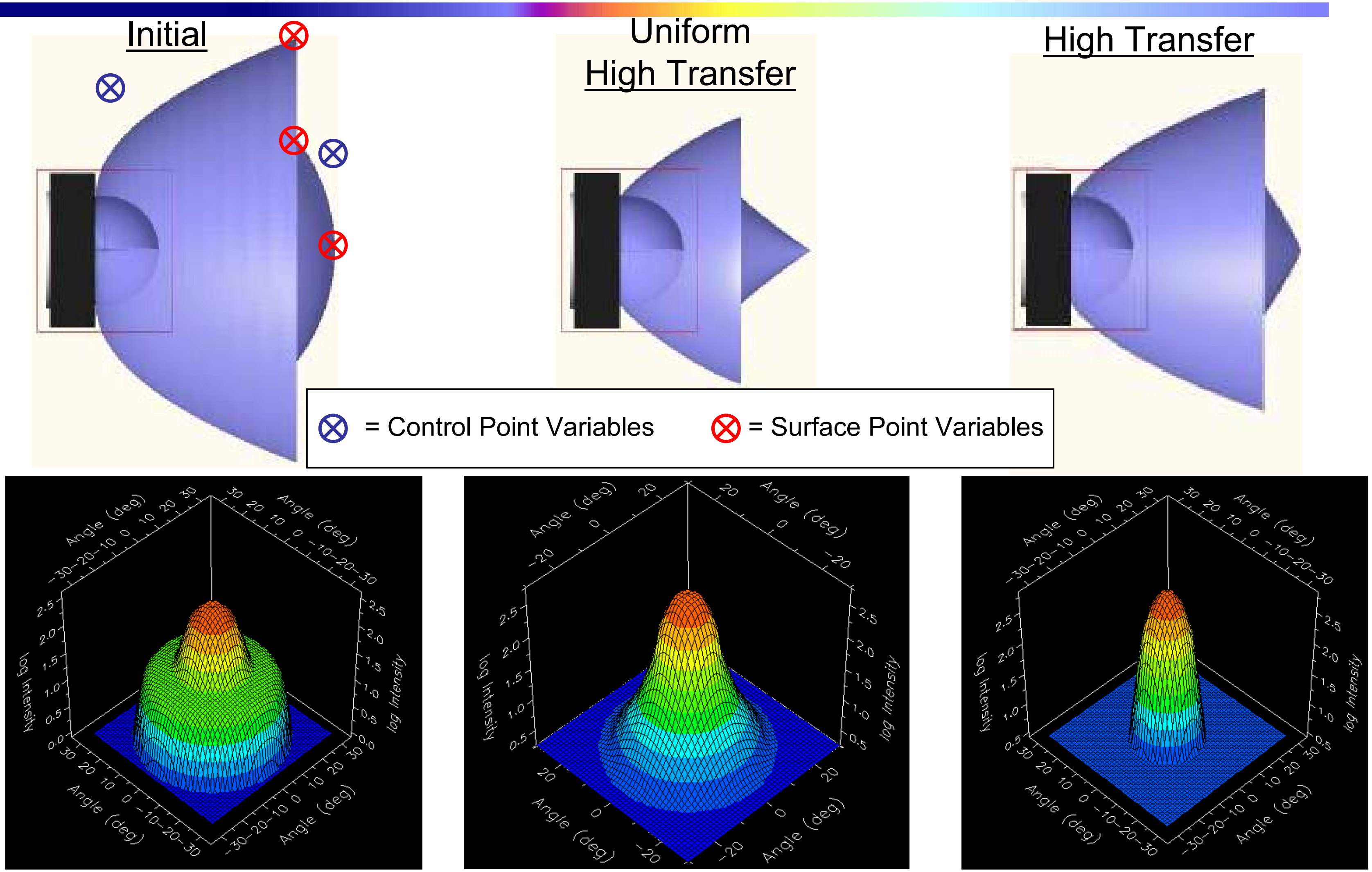
$$z_4 = \left[9.439\left(\hat{z}_8 - 0.1\right)\left(\hat{z}_7 - 0.1\right)\left(\hat{z}_5 - 0.1\right) + 3.261\right] \times \left(\hat{z}_4 - 0.1\right) - 0.46$$

This would have been "impossible" to do through normal constraints – the coding would have been extensive

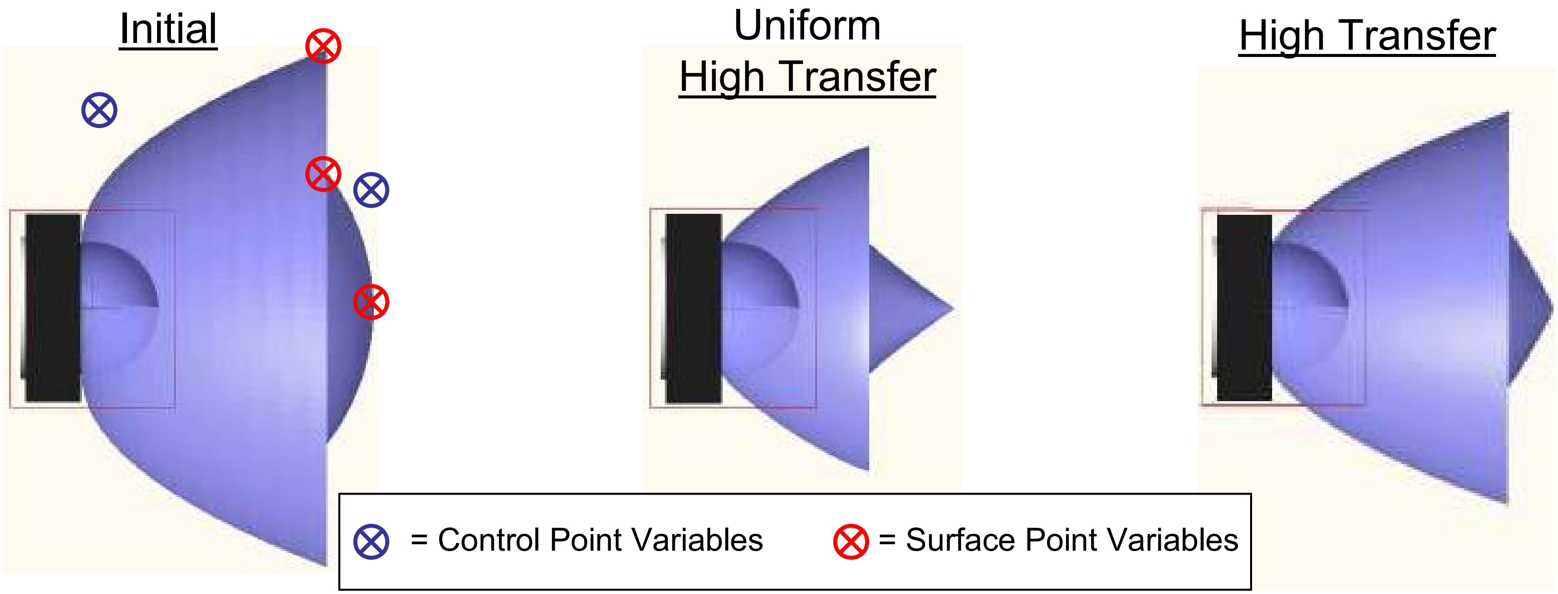
Hybrid Optic Simplex Optimization



Log Intensity: Hybrid Optic Optimization



Discussion: Hybrid Optic Optimization



- TIR-Parabolic NURBS surface: collimates high-angle rays
- Lens-NURBS surface: collimates low-angle rays
- Does not conserve étendue
- “Leaks” some moderate angle rays
- Parameterized: 10 variables

- Reduced the optic size to control leakage
- Reduced size also helps to fill +/- 10 degree ROI
- Strong traditional axicon in center attempts to constrain rays to ROI
- TIR surface is parabolic like - helps to collimate extended source.

- Increased size to previous provides better flux transfer via étendue conservation
- Weaker axicon compared to previous keeps low angle light better collimated over ROI
- TIR surface is more parabolic like for better collimation

Tolerancing the SSL Optics

Thermal Effects

Binning Variation

Fabrication Tolerances

Motivation

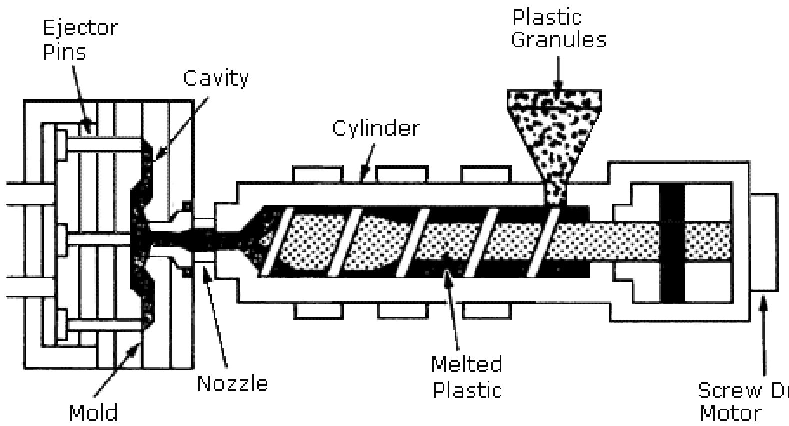
- Lengthy design time for illumination systems:
  - A few components comprise the system yet the shapes are complex (e.g., faceted reflectors).
- Source variation is typical:
  - The system with nominal source model provides required performance.
  - Not always true in lab or measurement – LEDs especially.
  - LED errors: die position, flux output, color output.
- Fabricated optics do not agree with model:
  - Shape errors occur during fabrication, especially important for costly injection-molded tools/parts.
- Established ISO Standards do not work for illumination system tolerancing:
  - ISO 10110-5: Surface form tolerances.
  - ISO 10110-6: Centering tolerances.

ISO Standards

- ISO Standard 10110-5: Surface Form Tolerances
  - Determine tilt, sagittal error, and surface irregularity
  - Surface form deviation equals difference between actual and theoretical
  - In all cases the treatment expects "imaging" type surfaces!
- It expects surfaces to be parameterized
  - Illumination surfaces are often numerical in nature.
- ISO Standard 10110-6: Centering Tolerances
  - For spherical/aspherical surfaces
  - Expects reference position and/or axis
  - Assumes "imaging" type surfaces
- What about freeform optical surfaces?
  - Illumination surfaces are often freeform, segmented, or faceted
  - Positions and axes can be hard to define

System Tolerances – Injection Molding

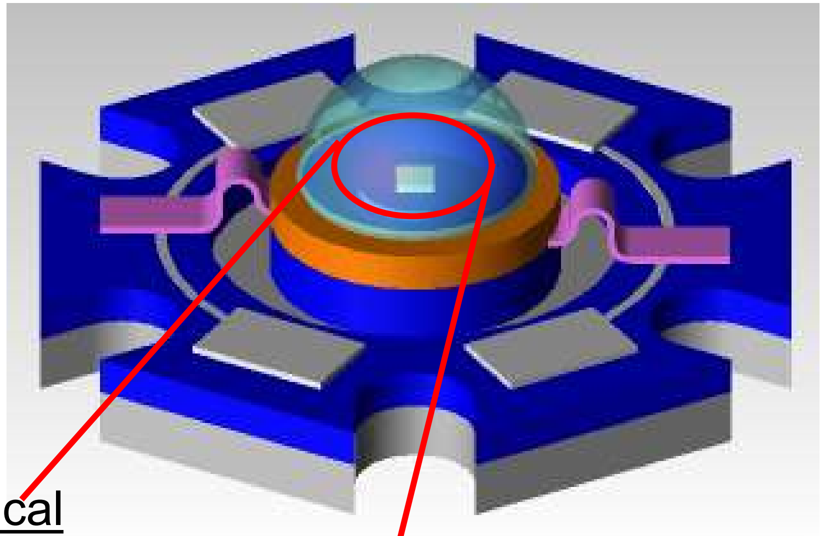
- System Errors:
  - Source to optic position errors - die offsets, etc.
  - Misalignment - of optical components
- Gross (Tool) Errors:
  - Slope errors of surfaces
  - Offset errors of surfaces
- Injection-Mold Process Errors:
  - Sinking - dimple in the surface
  - Warping - bending of surface
  - Ripples - due to cooling of part
  - Corner round off
- Surface Roughness Errors:
  - Microstructure introduced from the tool/process



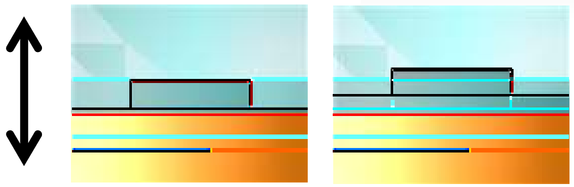
http://www.osha.gov/dts/osta/otm/otm_iii/otm_iii_1fig08.gif

http://www.active-burgess.com/gallery.asp

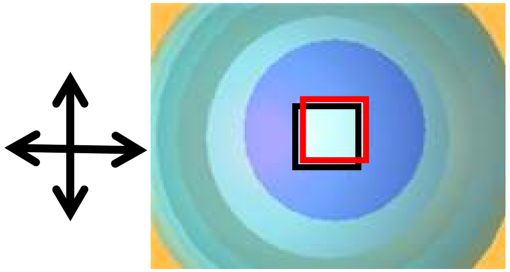
LED Source Errors



Geometrical



Axial Die Position



Tangential Die Position

Optical

Bin Code	Minimum Dominant Wavelength (nm)	Maximum Dominant Wavelength (nm)
2	613.5	620.5
4	620.5	631.0
5	631.0	645.0

Color or Spectrum

Bin Code	Minimum Photometric Flux (lm)	Maximum Photometric Flux (lm)
J	6.3	8.2
K	8.2	10.7
L	10.7	13.9
M	13.9	18.1

Flux Output

www.lumileds.com/pdfs/AB21.pdf - Luxeon Product and Binning and Labeling 5/06

Overview of Errors

Error Type	Deviation	Severity	Study	Example
System	Varies	Varies	Parameter	Source Offset
Gross	Small	Small		Tool Error
Process	Medium	Large	Exp to Model	Surface Ripple
Roughness	Large	Small	Exp to Model	Rough Surface

Overview of Errors

Error Type	Deviation	Severity	Study	Example
System	Varies	Varies	Parameter	Source Offset
	Correct with careful binning of sources			
Gross	Small	Small		Tool Error
	Correct with new tooling			
Process	Medium	Large	Exp to Model	Surface Ripple
	Correct with process time/tooling			
Roughness	Large	Small	Exp to Model	Rough Surface
	Correct with polishing of tool			

System: Binning Variation

Example
Hybrid LED Collimating Optics
To Mix RGB LEDs

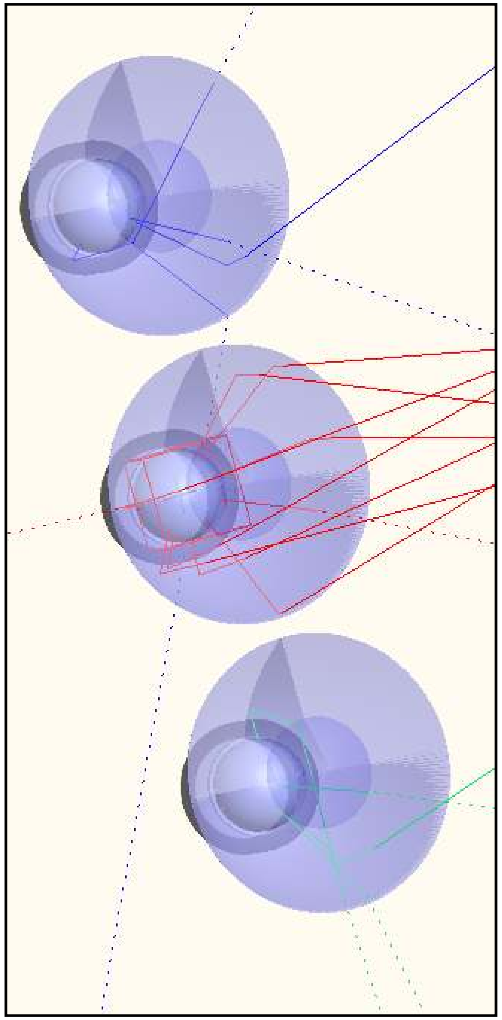
System Setup

System Setup

- System:
  - Source: Three LED-Collimator combination: Red, Green, and Blue
  - Optic: PMMA Hybrid Optic
  - Target: Overlap on wall 3-m distant

- LED Characteristics:
  - Luxeon I Lambertian Emitters
  - Select Single Bins for Each LED

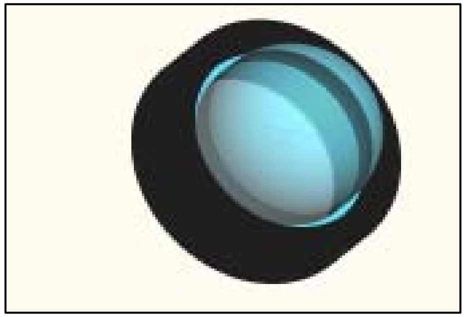
- Surrounding optic:
  - Designed with Fractional Optimization of FRED



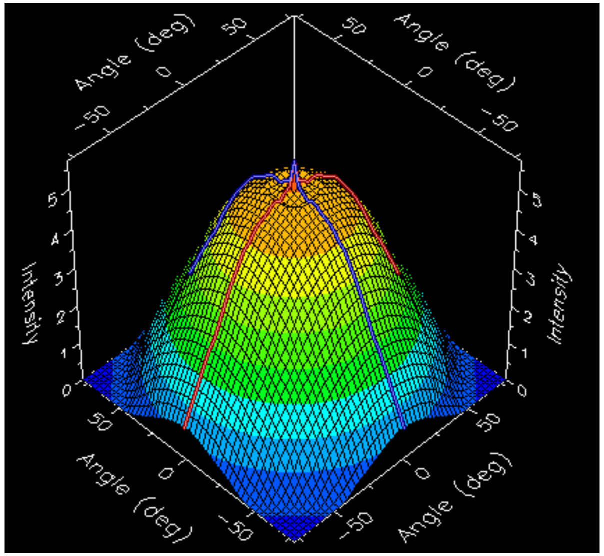
LED Setup

Luxeon 1 Lambertian Emitters

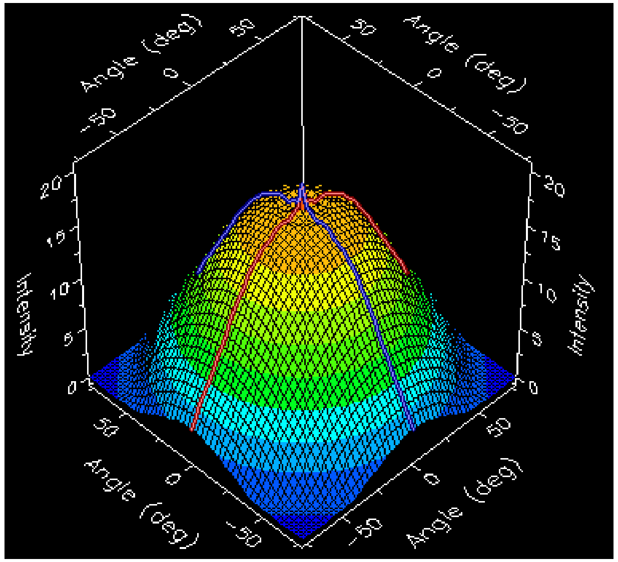
Blue	LXHL-PB01	16 Lumens
Green	LXHL-PM01	53 Lumens
Red	LXHL-PD01	44 Lumens



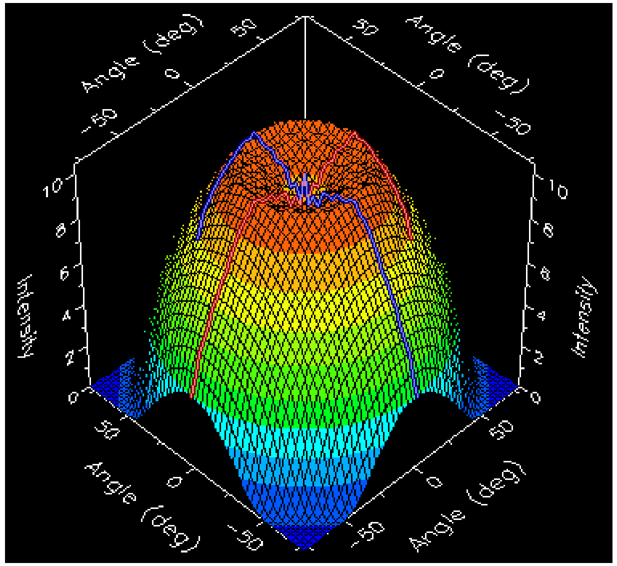
Blue: LXHL-PB01 (16 lum)



Green: LXHL-PM01 (53 lum)



Red: LXHL-PD01 (44 lum)



System: Binning Variation

Example

Hybrid LED Collimating Optics

To Mix RGB LEDs

Initial Study

Binning Variation: Typical λ

- LED Binning:
  - Luxeon I Lambertian Emitters
  - Typical Values per Luxeon I Data Sheets

	Flux	Wavelength
• Red	R	4
• Green	S	2/3
• Blue	M	2/3

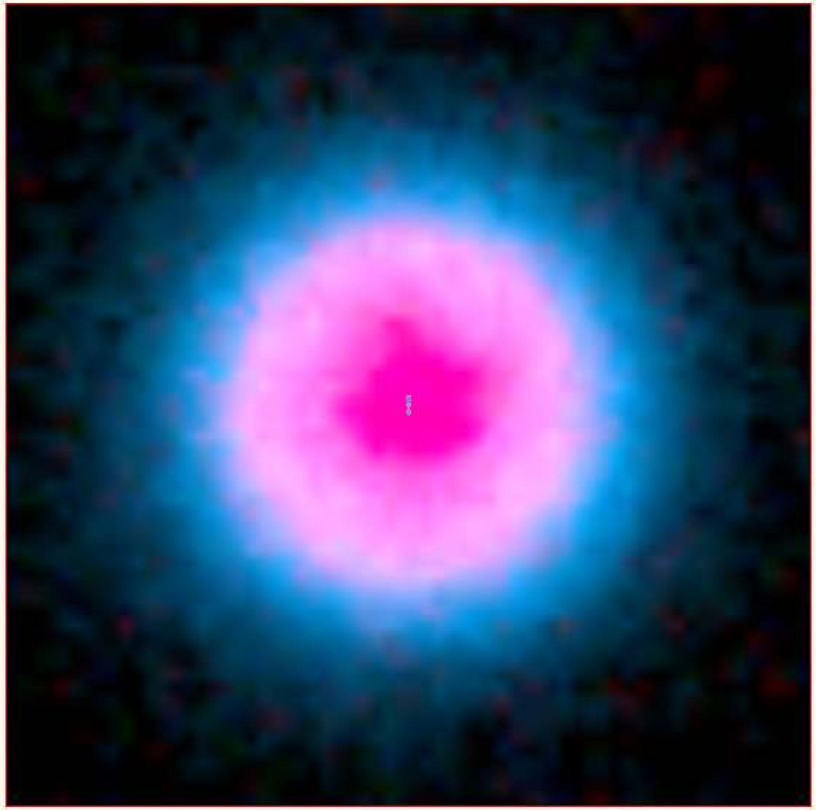
- Flux Ranges (lumens):

	Min	Typ	Max
- Red R	39.8	**44**	51.7
- Green S	51.7	**53**	67.2
- Blue M	13.9	**16**	18.1

- Wavelength Ranges (nm):

	Min	Typ	Max
- Red 4	620.5	**627**	631
- Green 2/3	525	**530**	535
- Blue 2/3	465	**470**	475

Typical Fluxes and Typical Wavelengths



First Design Lesson

- Emission from Discrete LED Spectral Emitters:
  - Highly Dependent on LED Material
  - Optical Design is Thus Dependent on the Material
- Design Methods:
  - Design Distinct Optics (i.e., Hybrid Optics)
  - Incorporate a Pre-Mixer
    - Lightpipe
    - Edge-Ray Type Device
    - Diffuser

Binning Variation: λ Variation

Minimum Wavelengths	Typical Wavelengths	Maximum Wavelengths



Wavelength Ranges (nm):

	Min	Typ	Max
Red 4	620.5	627	631
Green 2/3	525	530	535
Blue 2/3	465	470	475

Binning Variation: Φ Variation

Minimum Fluxes	Typical Fluxes	Maximum Fluxes



Flux Ranges (lumens):

	Min	Typ	Max
Red R	39.8	44	51.7
Green S	51.7	53	67.2
Blue M	13.9	16	18.1

Binning Variation: All Variation

Minimum Values	Typical Values	Maximum Values
		

Wavelength/Flux Ranges:

	Min	Typ	Max
Red 4	620.5/39.8	627/44	631/51.7
Green 2/3	525/51.7	530/53	535/67.2
Blue 2/3	465/13.9	470/16	475/18.1

System: Binning Variation

Example

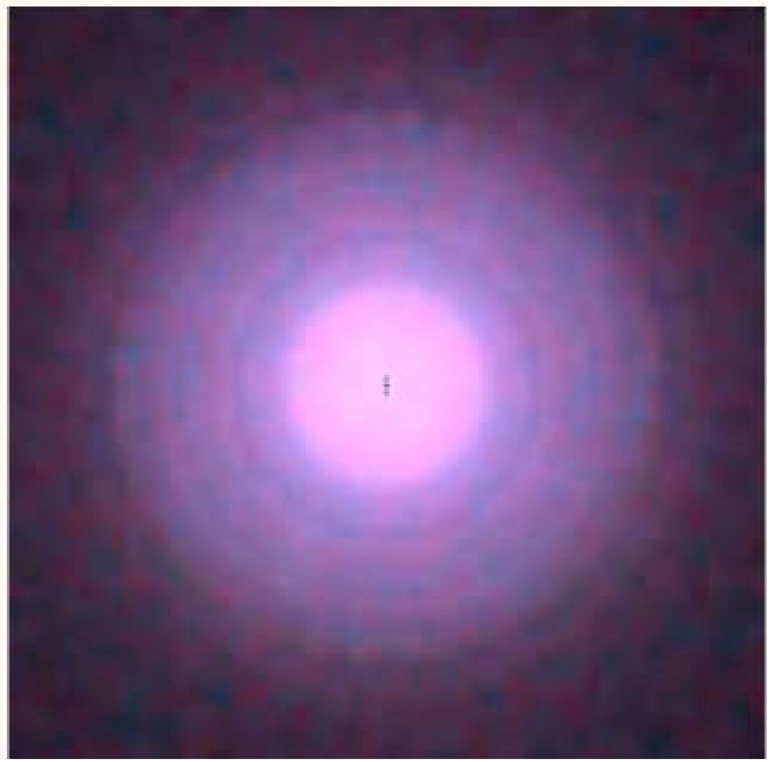
Hybrid LED Collimating Optics

To Mix RGB LEDs

Pre-Mixer Optics

Pre-Mixer: Lightpipes

- Geometry:
  - Uses Same Hybrid Optic
  - Straight Lightpipe
  - Scatter at End of Each Lightpipe
- Results:
  - Better Mixing
  - Same Optics
  - Reduces Efficiency
  - Have to Redesign the Hybrid Optic

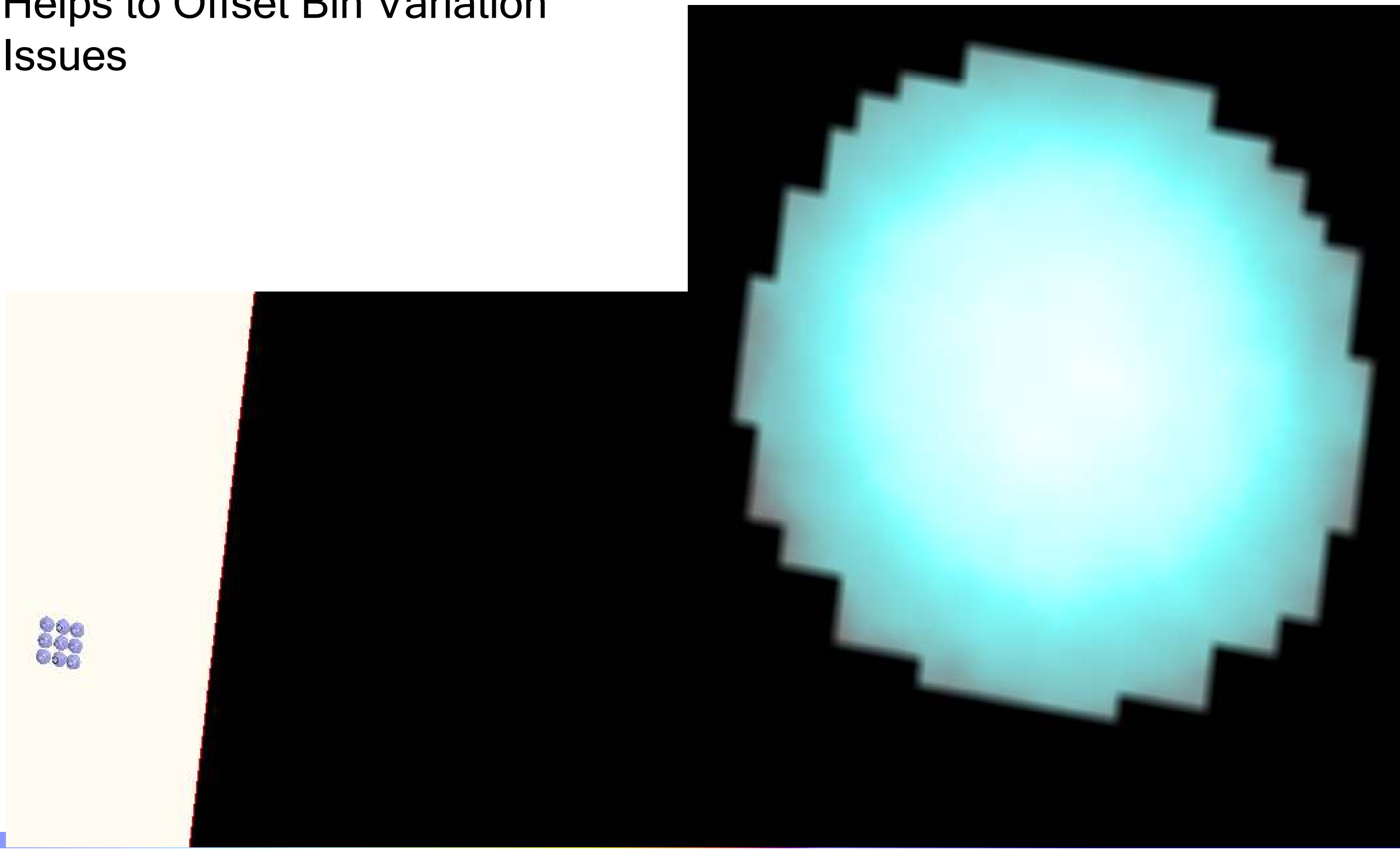


Second Design Lesson

- Tight Binning Control of LEDs – Order of Importance:
  - Wavelength Variation
  - Flux Variation
- Design Methods:
  - Mix Several LEDs of the Same Part Number and Bin
  - Beneficial Crosstalk/Leakage Between Neighboring Channels

Mixing Several LEDs

- Overlap Distributions at the Wall
- Helps to Offset Bin Variation Issues



Third Design Lesson

- Must Control Temperature at the Junction:
  - Flux and Wavelength Can be Adversely Affected
  - Red/Amber LEDS Especially Affected
- Design Methods:
  - Thermal: Measure Temperature of LED Case
  - Optical: Pickoff Piece of the Emission (Leakage) from Each LED to Measure Flux and Spectrum
  - Combination: Do Both Methods

System: Binning Variation

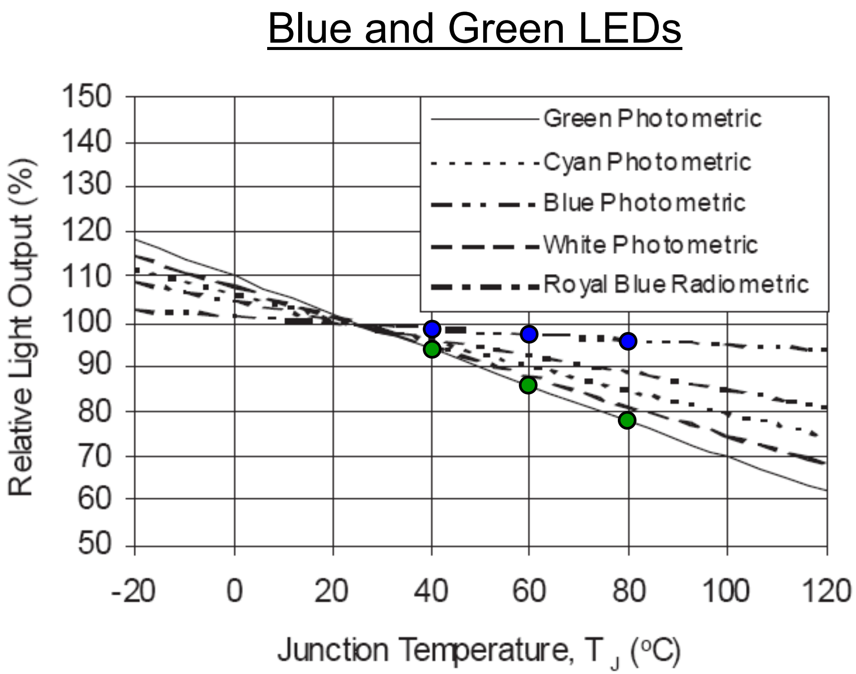
Example

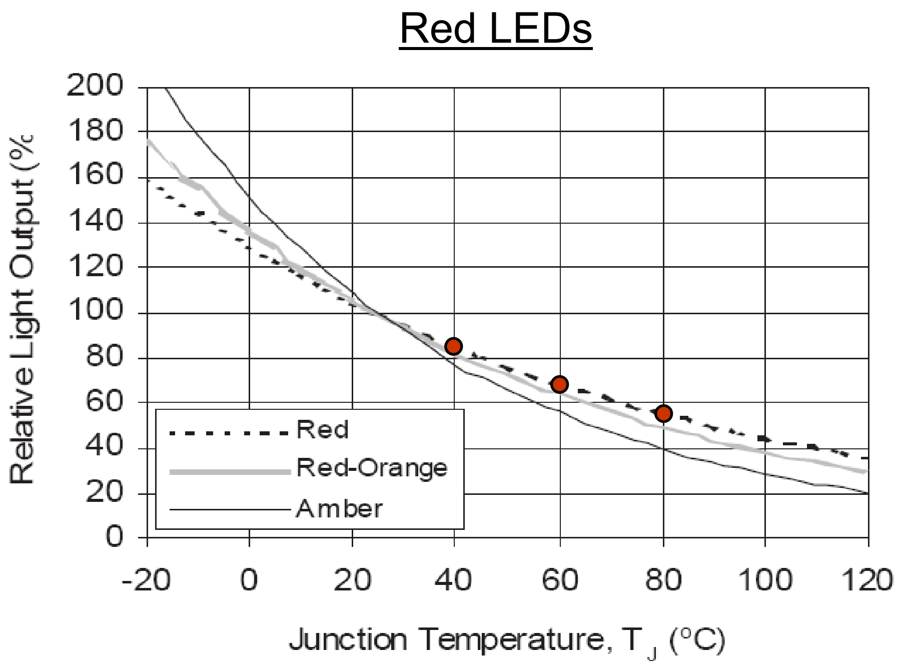
Hybrid LED Collimating Optics

To Mix RGB LEDs

Thermal Effects

Thermal Effects





Technical Sheet DS25 - Luxeon Emitter Datasheet 5/07

To Date I Have Been Showing Operation at Junction Temperature of 25° C. What Happens if the Junction Temperature Can Range from 40° C to 80° C?

Binning Variation: Typical, Thermal

40° C Junction

60° C Junction

80° C Junction

Next Include the Wavelength and Flux Binning Variations to Fully Understand the Color Shifts

College of Optical Sciences
The University of Arizona

Discussion

- It is a long process to design a solid-state lighting system:
  - First: must design a complex optic with tailored optical design
  - Second: to improve design, optimization is employed to bring in real source issues
  - Third must: contend with tolerances:
    - LED binning
    - Thermal effects
    - Optic manufacture variation (this is an additional lecture)
  - Fourth: It has to have the right look and feel
    - It is not as easy as designing the most efficient, best distribution on the target
    - You must contend with the subjective appearance: both lit and unlit
      - This is called lit-appearance modeling, and it is a completely additional lecture