Source Modeling in Illumination Optics

Presented by:

OSA NonImaging Optical Design Technical Group

The OSA NonImaging Optical Design Technical Group Welcomes You

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Technical Group at a Glance

- ## Focus
  - Design and characterization of illumination systems using modeling techniques.
  - Non-sequential design techniques, including both software and tailoring methods provide the tools to design efficient optical components that provide the desired distribution at the target.
  - Typical applications include solar energy, lighting, and displays.
  - ## Mission
  - To benefit *YOU* and to strengthen *OUR* community
  - Webinars, podcasts, publications, technical events, business events, outreach
  - Interested in presenting your research? Have ideas for TG events? Contact us at TGactivities@osa.org.
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Today's Webinar

What is etendue, and why is it important?

Julius Muschaweck

CEO, JMO GmbH

julius@jmoptics.de

Speaker's Short Bio:

Julius Muschaweck, a German physicist, has been working on optical design for illumination for over twenty years. After a stay as Visiting Scholar at the University of Chicago with Prof. Roland Winston (well known as the originator of Nonimaging Optics), he was co-founder and CEO of OEC, an optical engineering service which pioneered freeform optics. Later, at OSRAM, where he held the position of Senior Principal Key Expert (the highest rank in the OSRAM/Siemens expert career), he coordinated the over 100 optical designers within OSRAM world-wide. He then joined ARRI, the leading movie camera and lamp head maker, as Principal Optical Scientist. Julius Muschaweck now works as an independent consultant, providing illumination optics solutions to industry clients, teaching courses on illumination optics, and writing about the subject.

JMO Illumination Optics

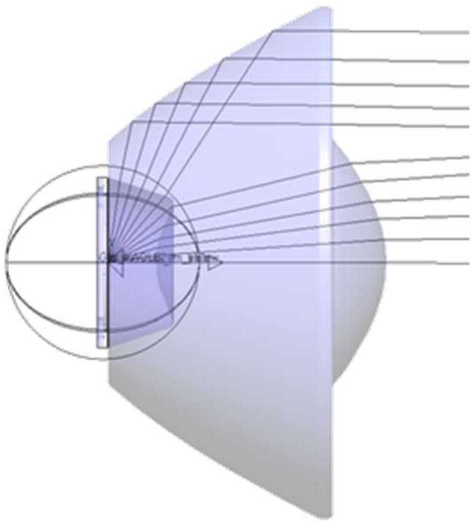
Source modeling in illumination optics

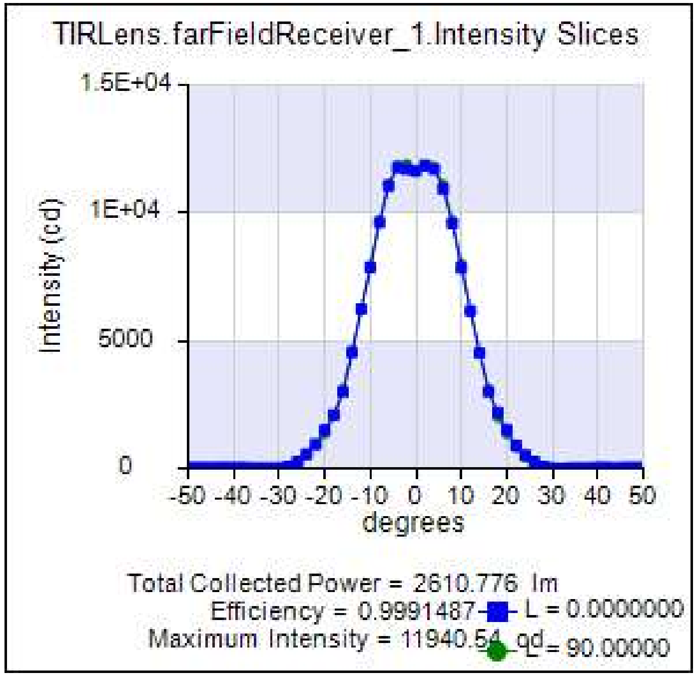
Julius Muschaweck

OSA webinar – Dec. 3, 2019

The problem

- Your task (just an example):
  TIR lens design for a given target intensity distribution
- Let‘s assume you know sufficient optics
- No reliable simulation results **without**
  - accurate geometry representation,
  - accurate material information,
  - accurate surface properties,
  - **a sufficiently accurate source model**





The problem

Illumination Optics

- Your task (just an exar
  TIR lens design for a g
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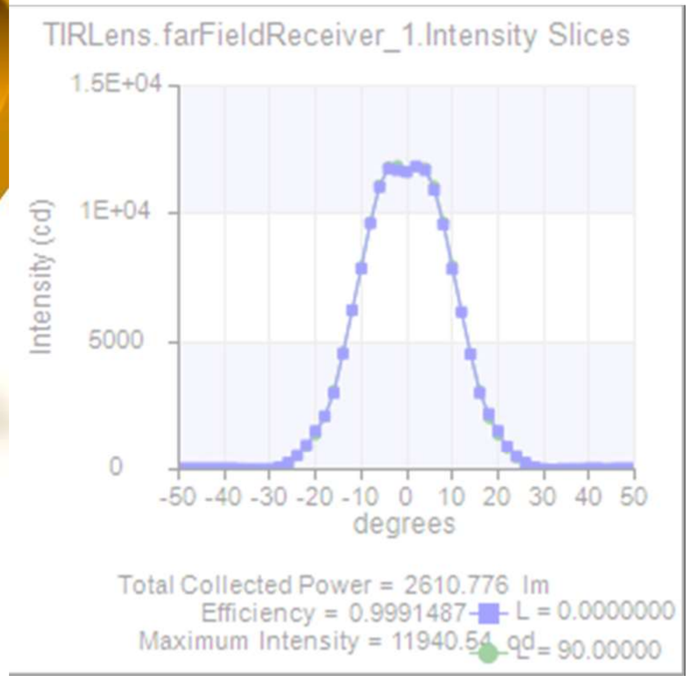
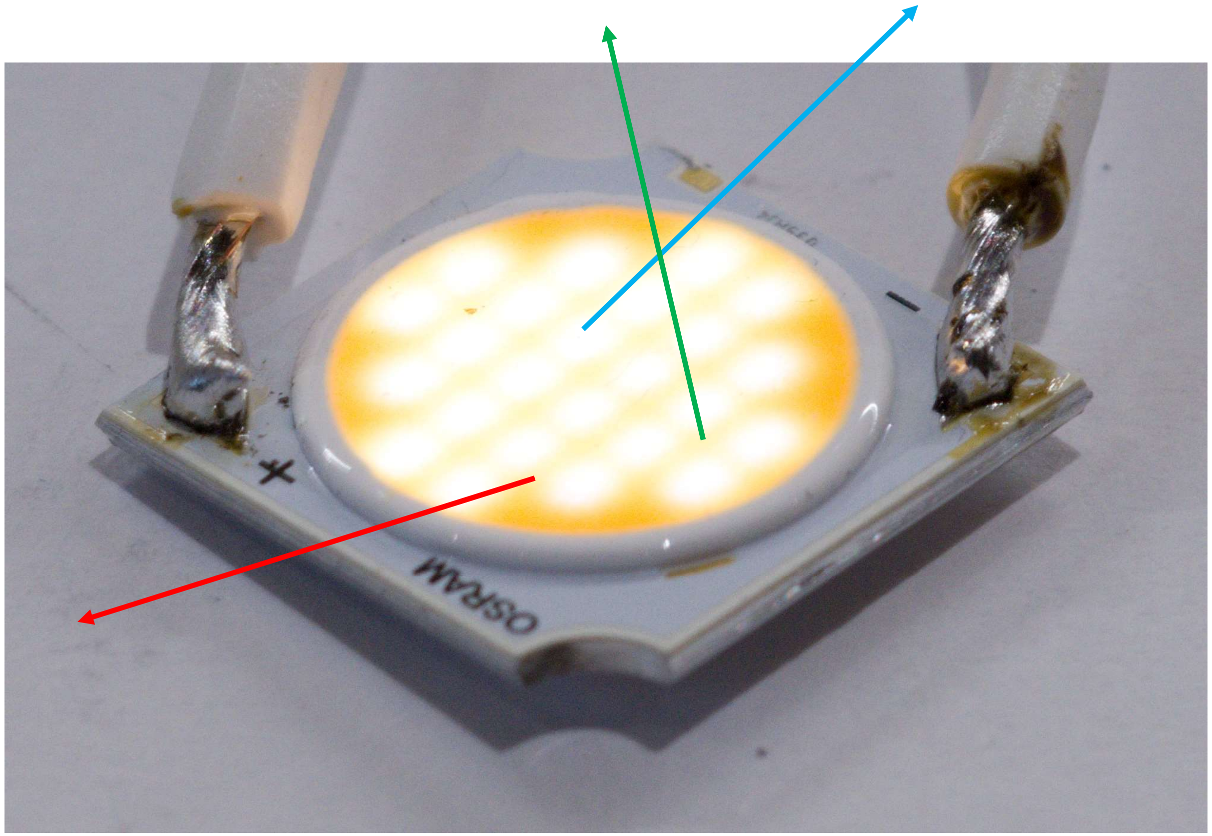
  - accurate geometry representatic
  - accurate material information,
  - accurate surface properties,
  - **a sufficiently accur**



A (nearly) perfectly accurate source model

How much light

- from any point
- into any direction
- at any wavelength?



In more precise terms:

Spectral radiance

$$L_\lambda(x, y, \theta, \varphi, \lambda)$$

Why „nearly“ perfectly accurate?

- Polarization: Stokes vector

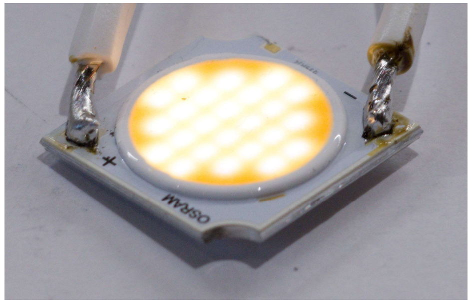
$$L_\lambda(x, y, \theta, \varphi, \lambda) \quad \rightarrow \quad \vec{S}_\lambda(x, y, \theta, \varphi, \lambda)$$

- Coherence: Correlation function

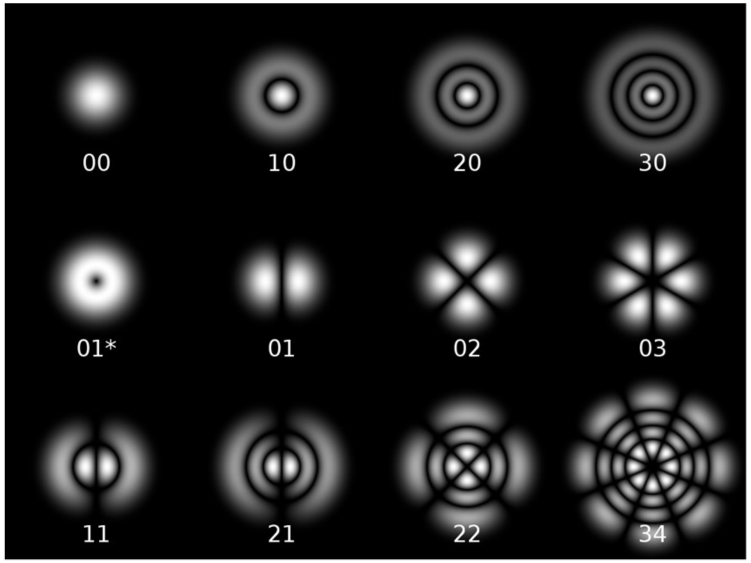
$$g^{(1)}(\mathbf{r}_1, t_1; \mathbf{r}_2, t_2) = \frac{\langle E^*(\mathbf{r}_1, t_1) E(\mathbf{r}_2, t_2) \rangle}{\sqrt{\left\langle |E(\mathbf{r}_1, t_1)|^2 \right\rangle \left\langle |E(\mathbf{r}_2, t_2)|^2 \right\rangle}}$$

- We do not go there. No polarization, no coherence today.

Diffraction



⇒



https://commons.wikimedia.org/wiki/File:Laguerre-gaussian.png

Cylindrical transverse modes

⇒

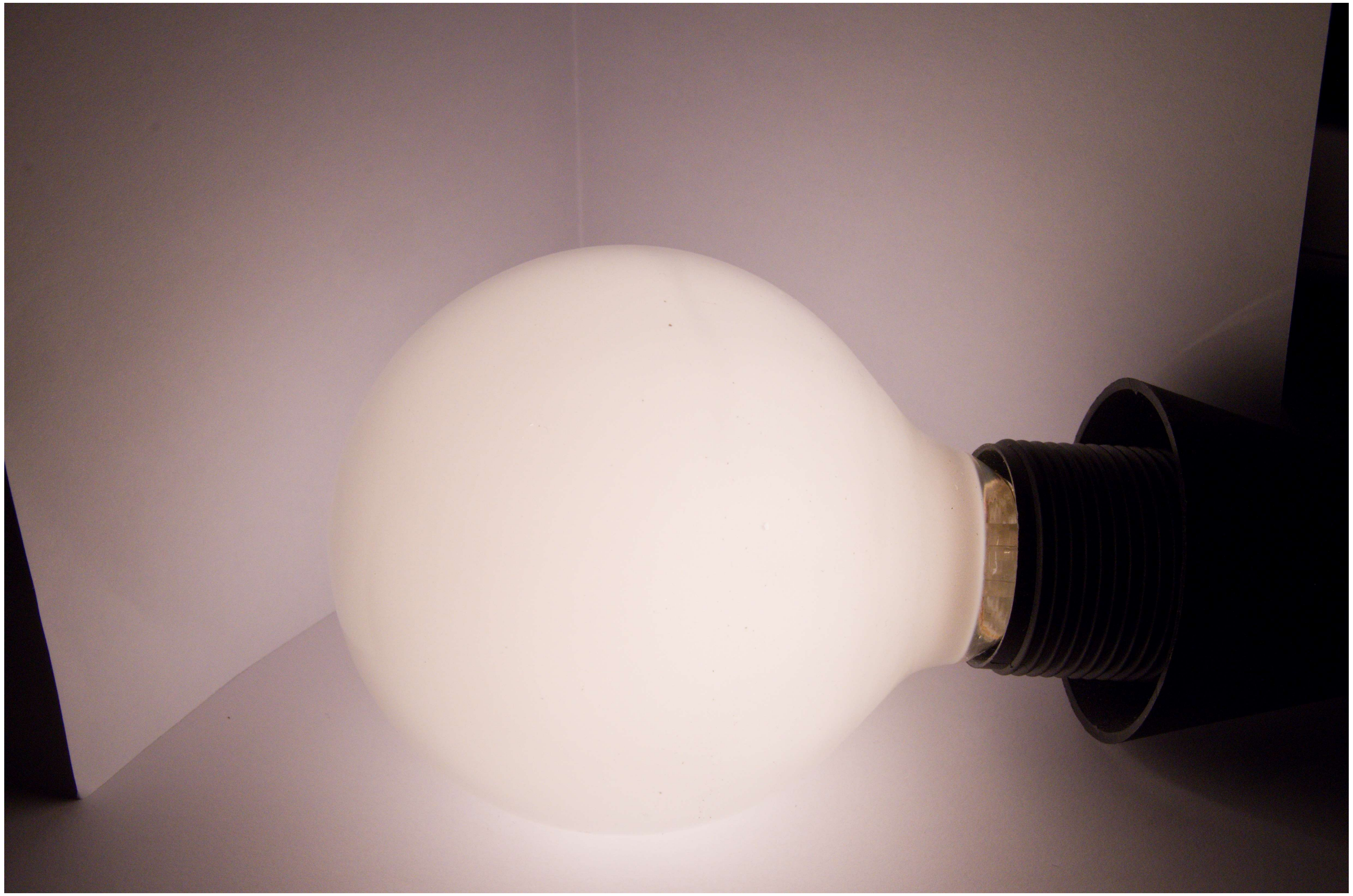
Roughly
250 million modes.

For each wavelength.

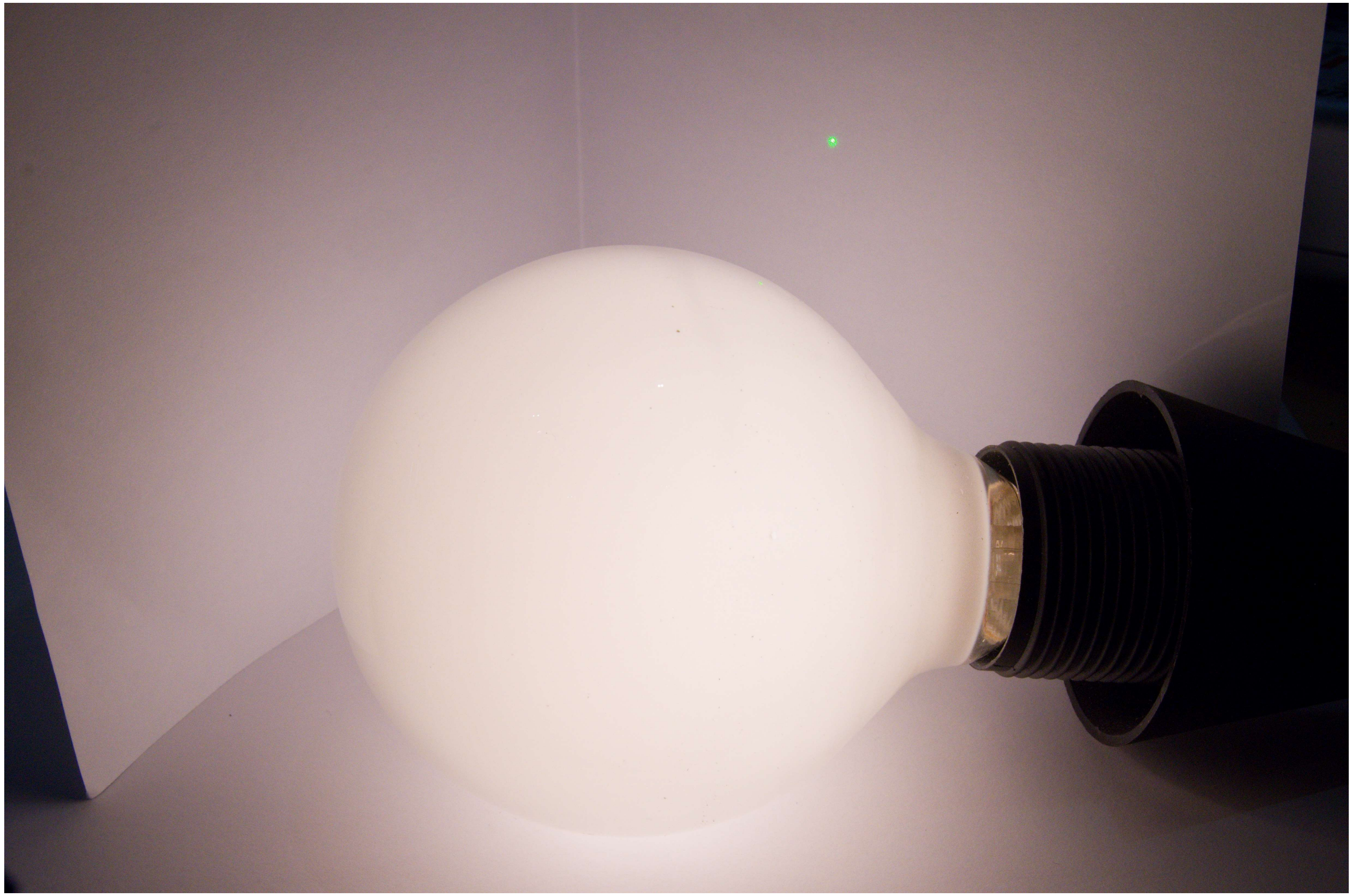
We do not go there.

No diffraction today.

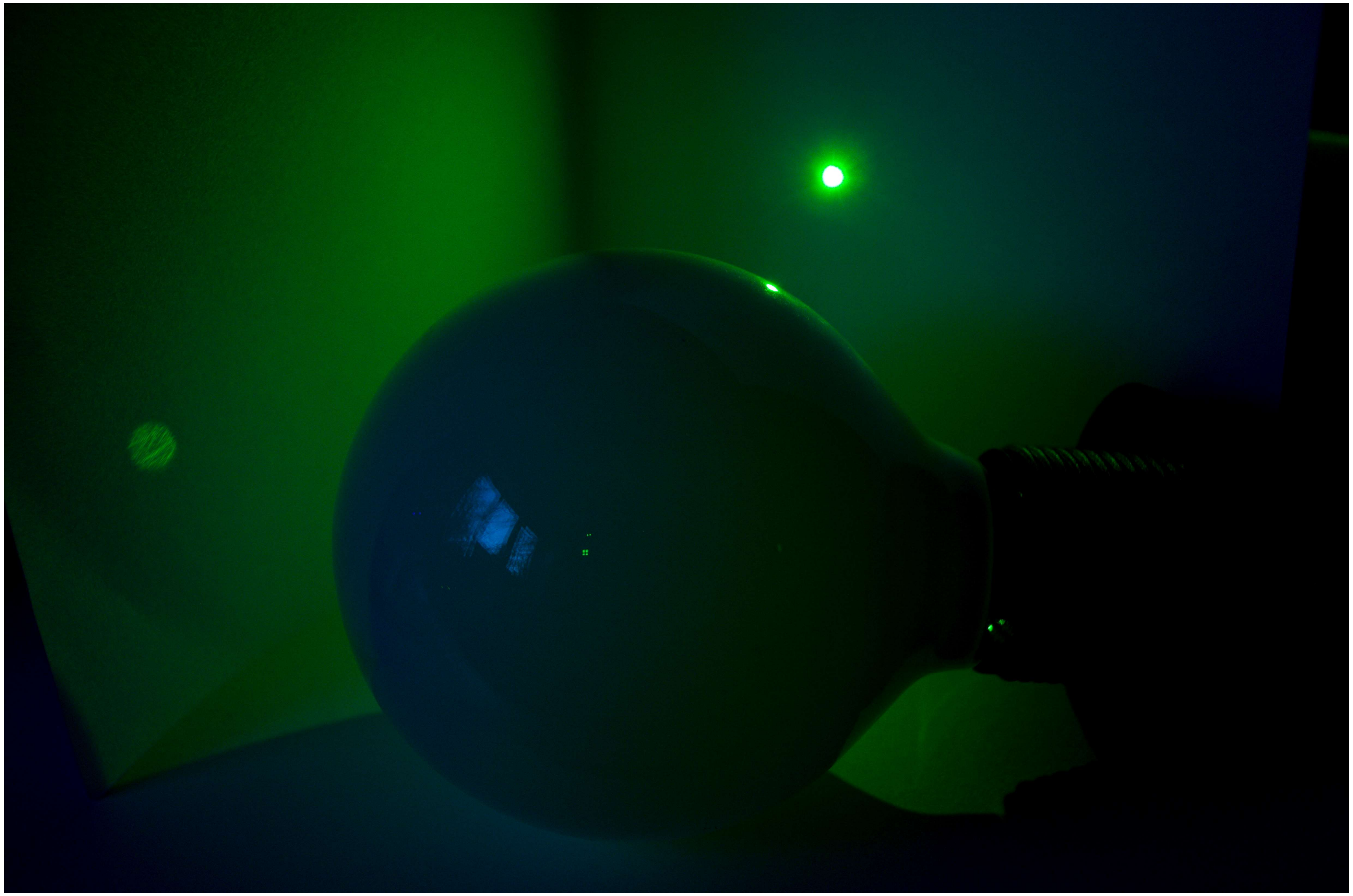
Retroactive effects: Source reflectivity



Retroactive effects: Source reflectivity



Retroactive effects: Source reflectivity

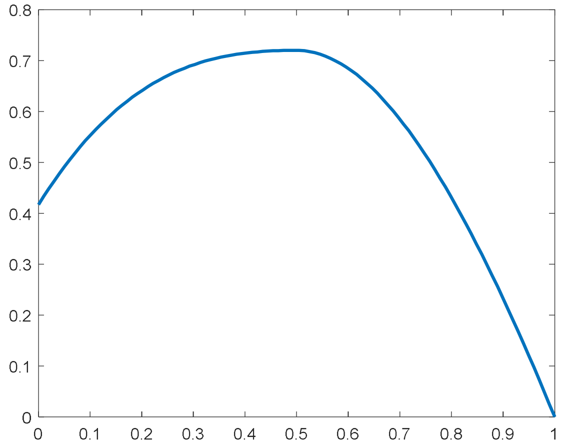


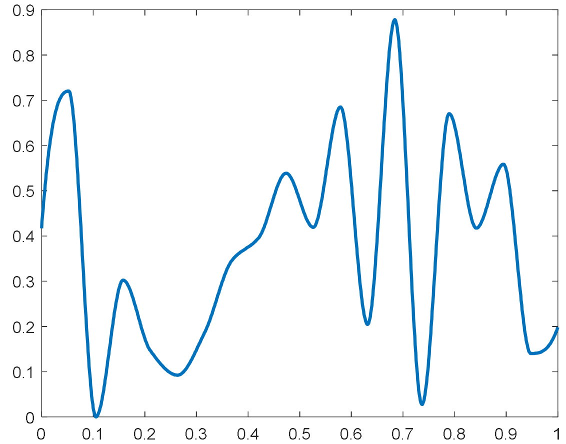
The full beauty source model – a nightmare

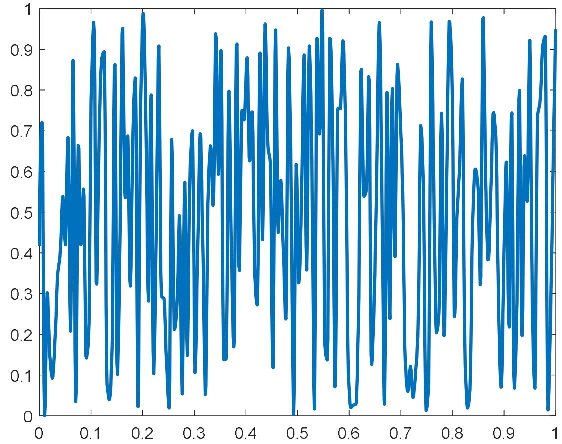
$$L_\lambda(x, y, \theta, \varphi, \lambda)$$

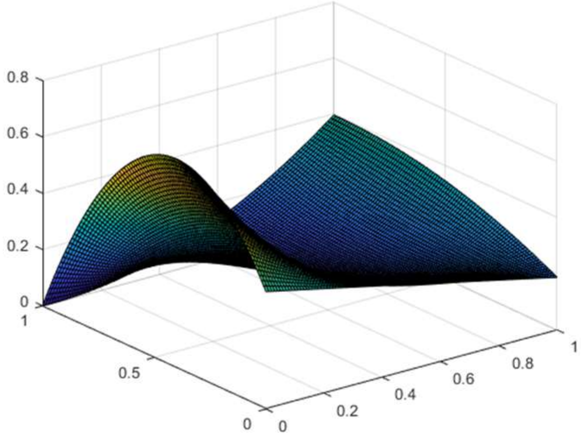
A function „living“ in five dimensions

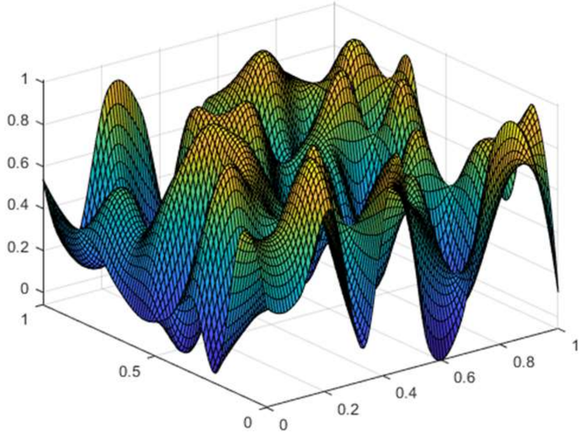
Some arbitrary functions

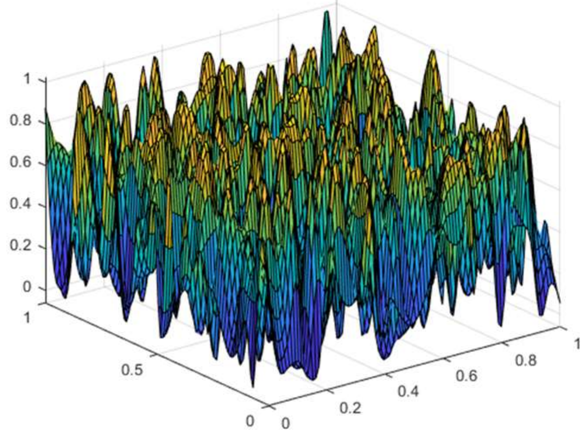












The full beauty source model – a nightmare

$$L_\lambda(x, \ldots, \varphi, \lambda)$$

A function that can … sions

at only 20 data … nsion:

20 × 20 × 20 … numbers

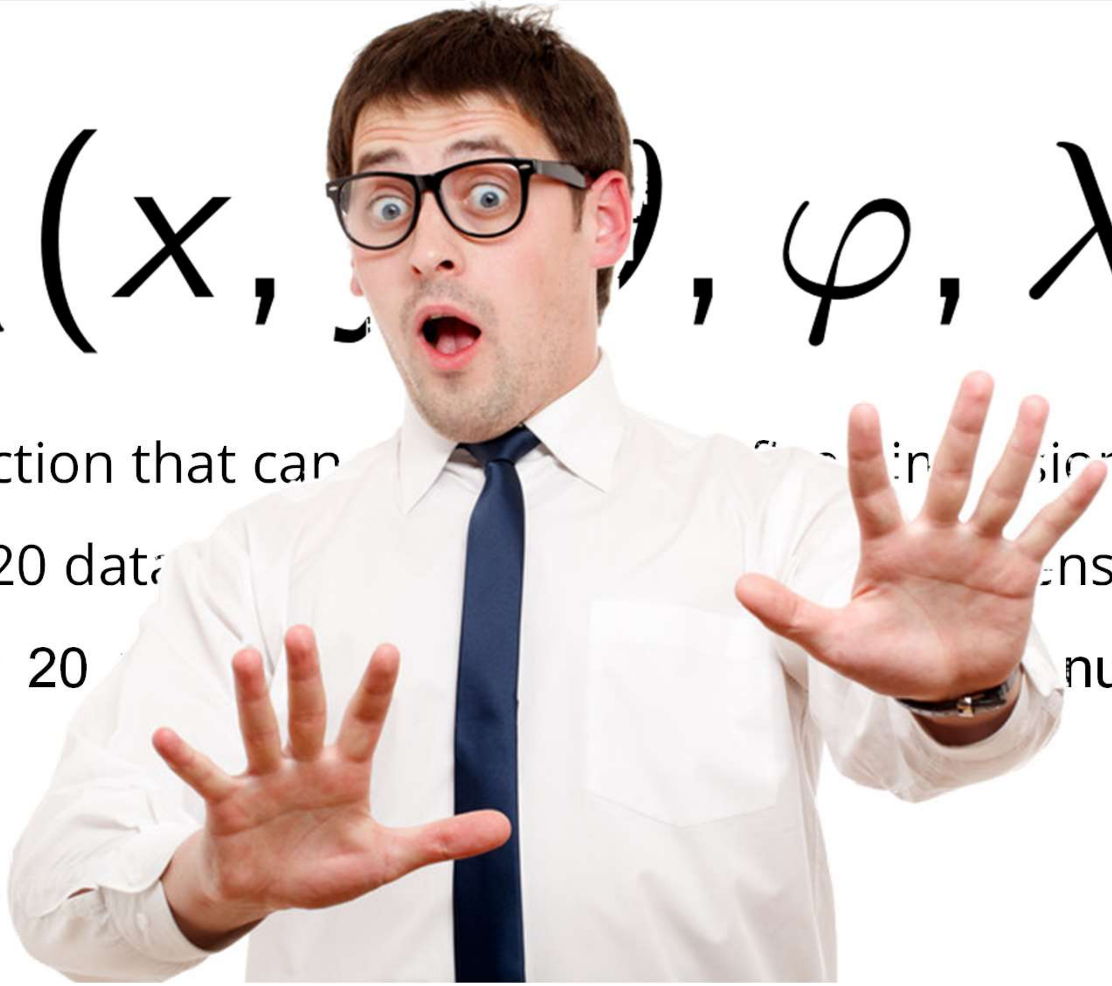


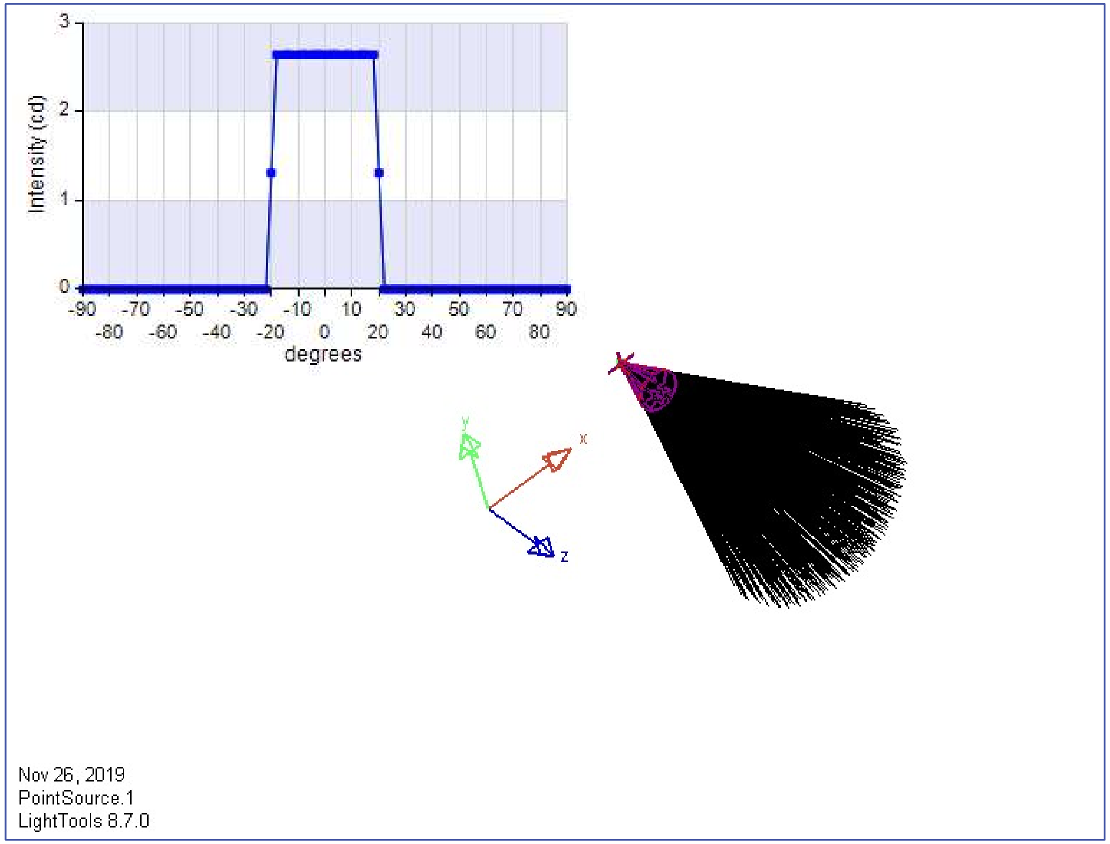
Image © Can Stock Photo

The simplest source model: point sources

Default: isotropic, monochromatic

Five numbers: x, y, z, λ, Φ

Add **aim cone** (e.g. ± 20°)

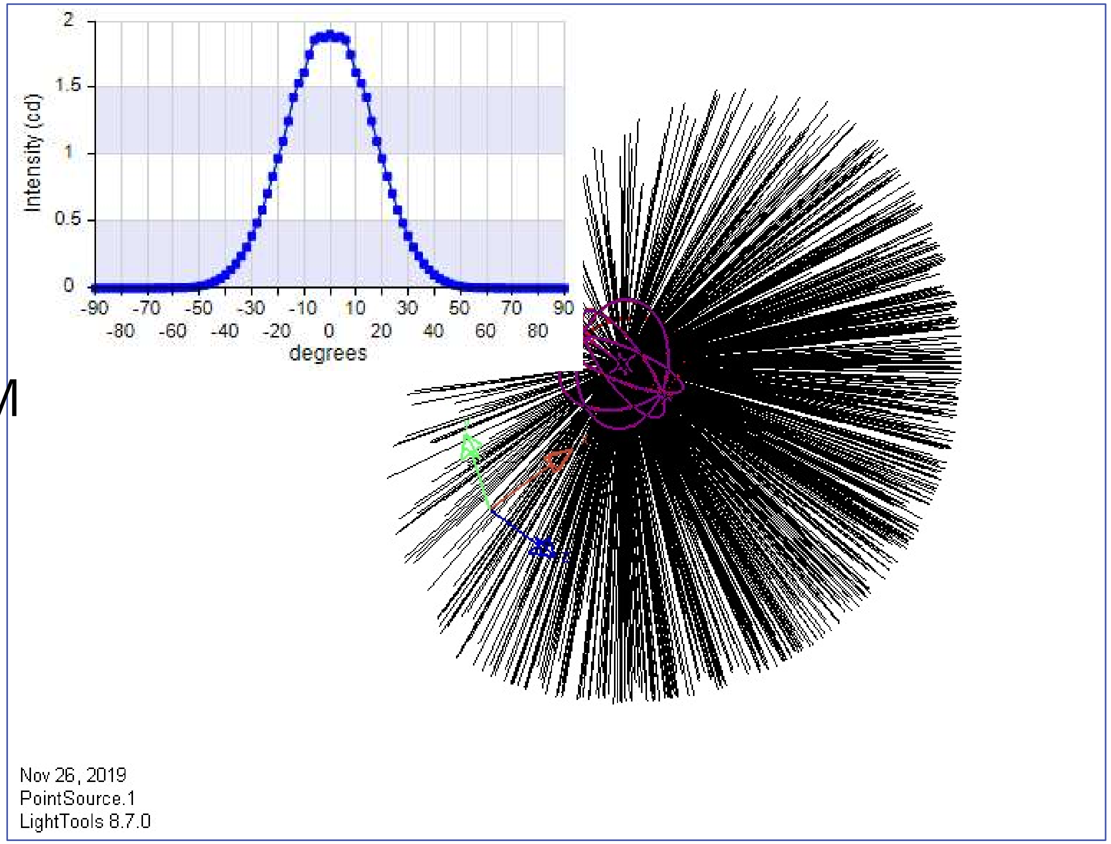


The simplest source model: point sources

Default: isotropic, monochromatic

Five numbers: *x*, *y*, *z*, *λ*, *Φ*

Add **apodization**, e.g. ± 20° = 40° FWHM



A word on intensity

Solid angle Ω = area on unit sphere, $\Omega = \frac{A}{r^2}$

Intensity I:

Choose direction (θ, φ)

Consider tiny solid angle dΩ there

Determine flux dΦ into dΩ

$$I = I(\theta, \varphi) = \mathrm{d}\Phi / \mathrm{d}\Omega$$

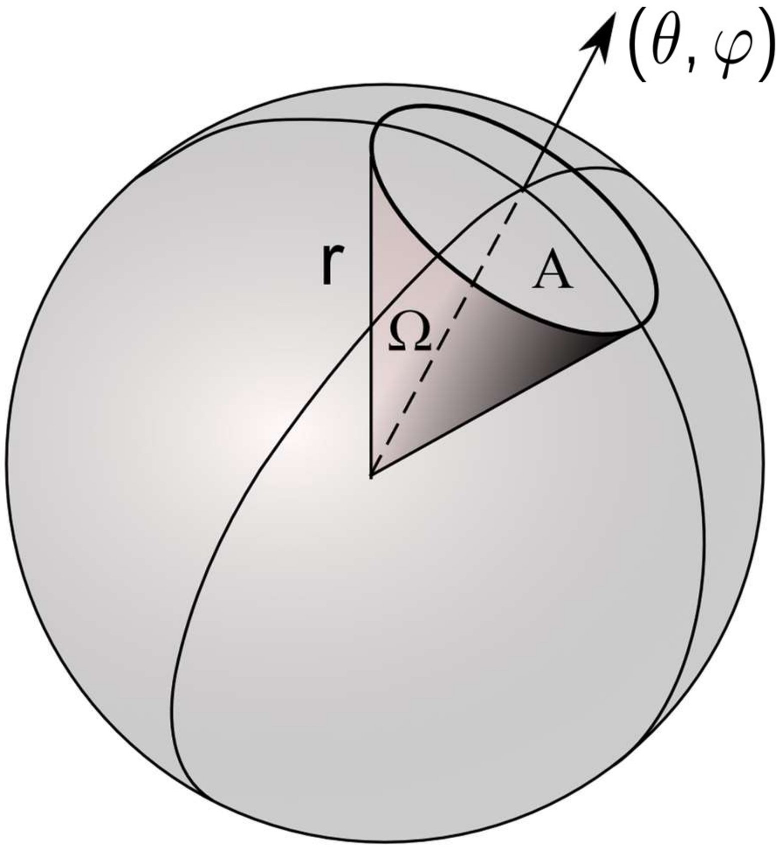


Image: https://de.wikipedia.org/wiki/Datei:Angle_solide_coordonnees.svg, by Haade / *derivative work: Habib.mhenni

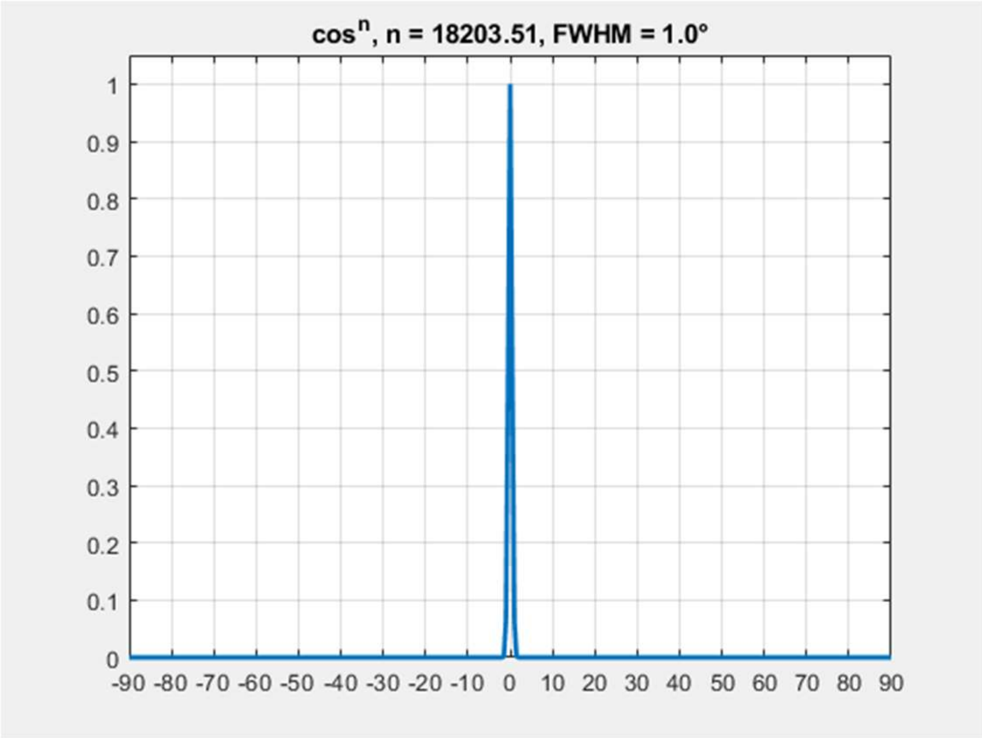
A very useful function to model intensity: $\cos^n$

For planar sources with circular beam:

Gauss ($e^{-\frac{c}{x^2}}$) not very good.

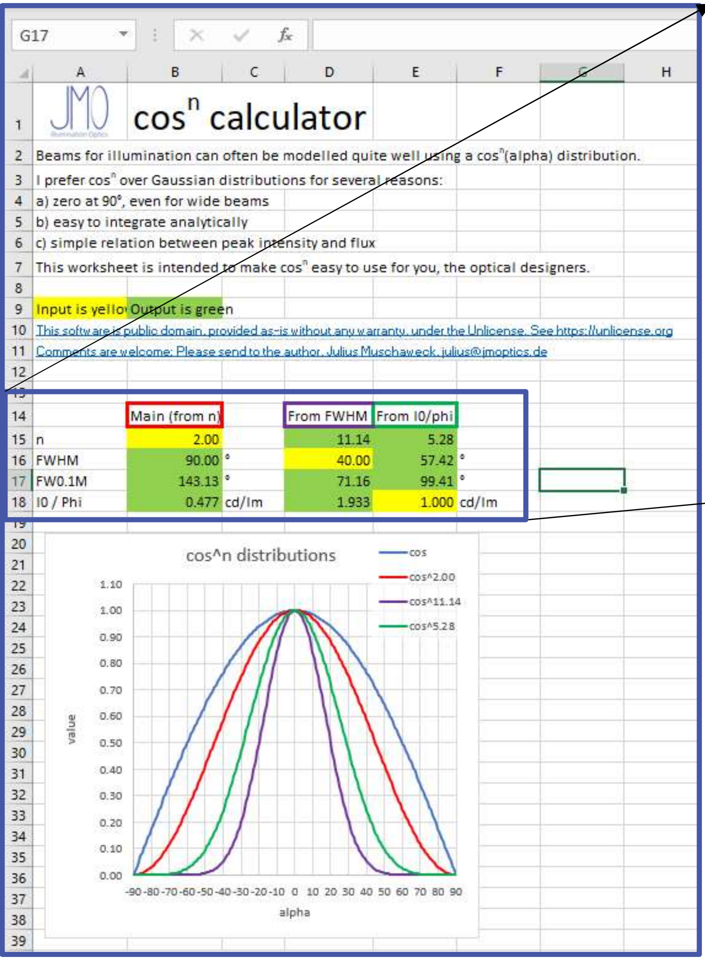
$\cos^n$:

- Full range of beam widths, collimated to isotropic
- Always „nice“
- Always zero at 90° (except when isotropic)
- $\gtrsim$ 50% of flux within FWHM (more for wide beams)



My $\cos^n$ calculator spreadsheet

JMO Illumination Optics



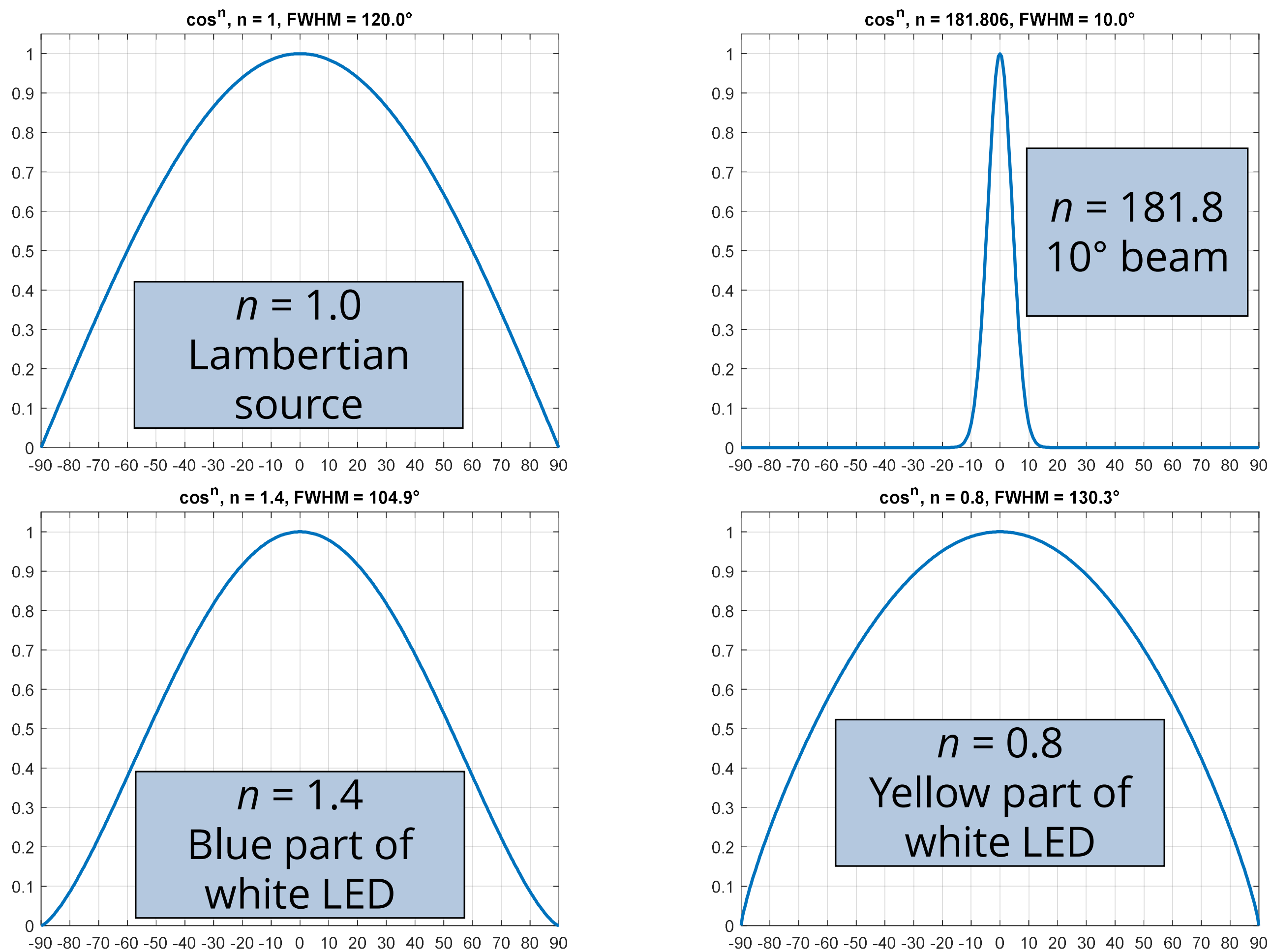
14		Main (from n)		From FWHM	From I0/phi	
15	n	2.00		11.14	5.28	
16	FWHM	90.00	°	40.00	57.42	°
17	FW0.1M	143.13	°	71.16	99.41	°
18	I0 / Phi	0.477	cd/lm	1.933	1.000	cd/lm

Creates LightTools® apodization files,
correctly integrating the distribution over intervals

Freely available at

https://github.com/JuliusMuschaweck/IlluminationDesignTools

Some special $\cos^n$ distributions

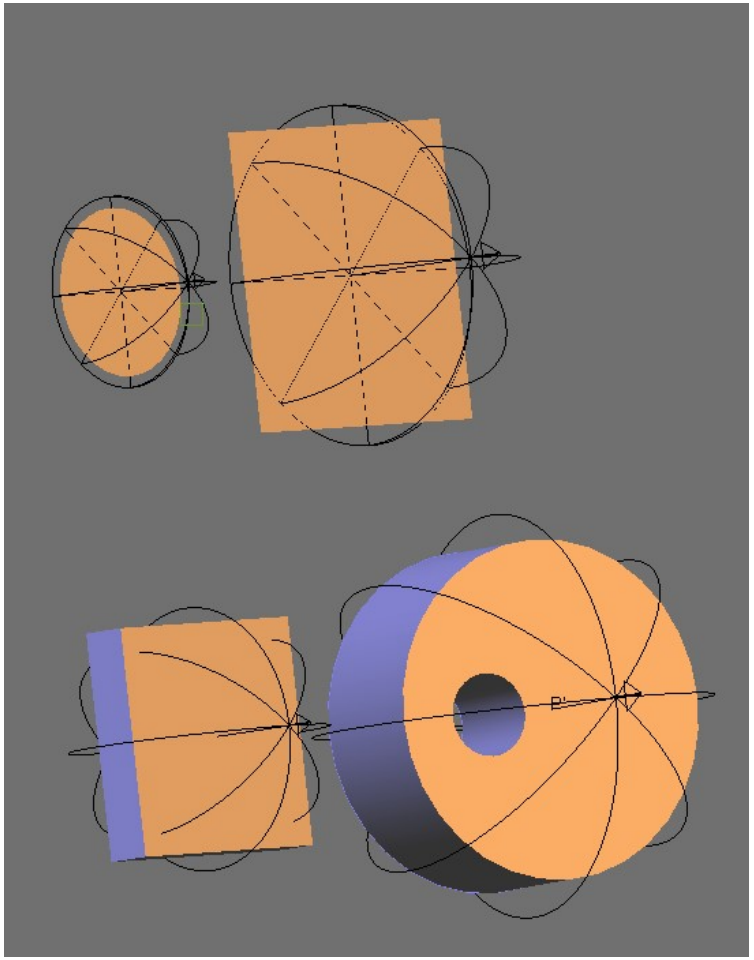


Lambertian sources

By definition: Lambertian means

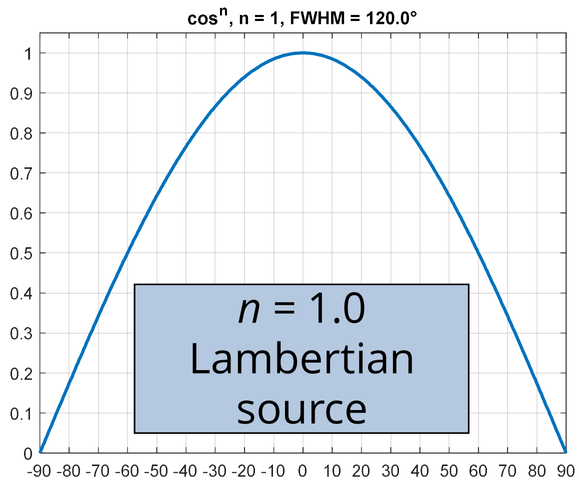
- ✓ planar
- ✓ constant luminance over angle and area

„A planar surface that looks equally bright,
no matter where you look and from where you look“



Intensity distribution:

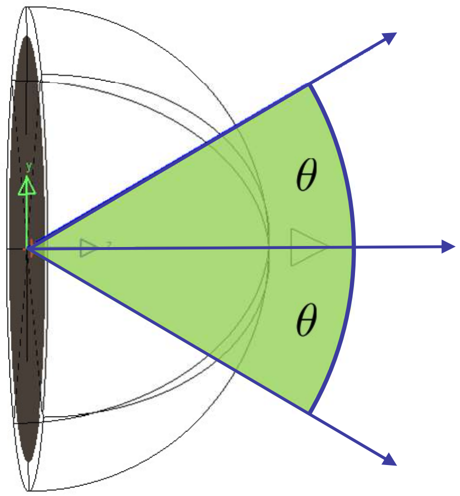
$$I(\theta) = I_0 \cos(\theta)$$

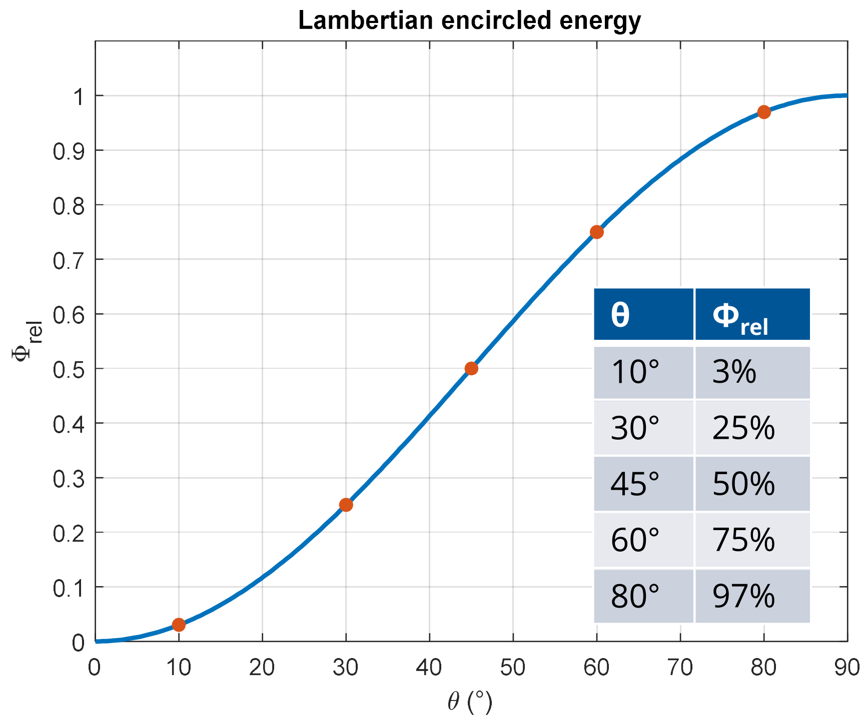


Lambertian sources: Encircled energy

How much flux into ±θ cone?

$$\Phi_{rel}(\theta) = (\sin\theta)^2 = \frac{1-\cos(2\theta)}{2}$$





θ	Φ_{rel}
10°	3%
30°	25%
45°	50%
60°	75%
80°	97%

Lambertian sources: An idealization! Beware deviations at high angles!

A word on irradiance / exitance

How much flux per area
is coming (irradiance) or going (exitance)?

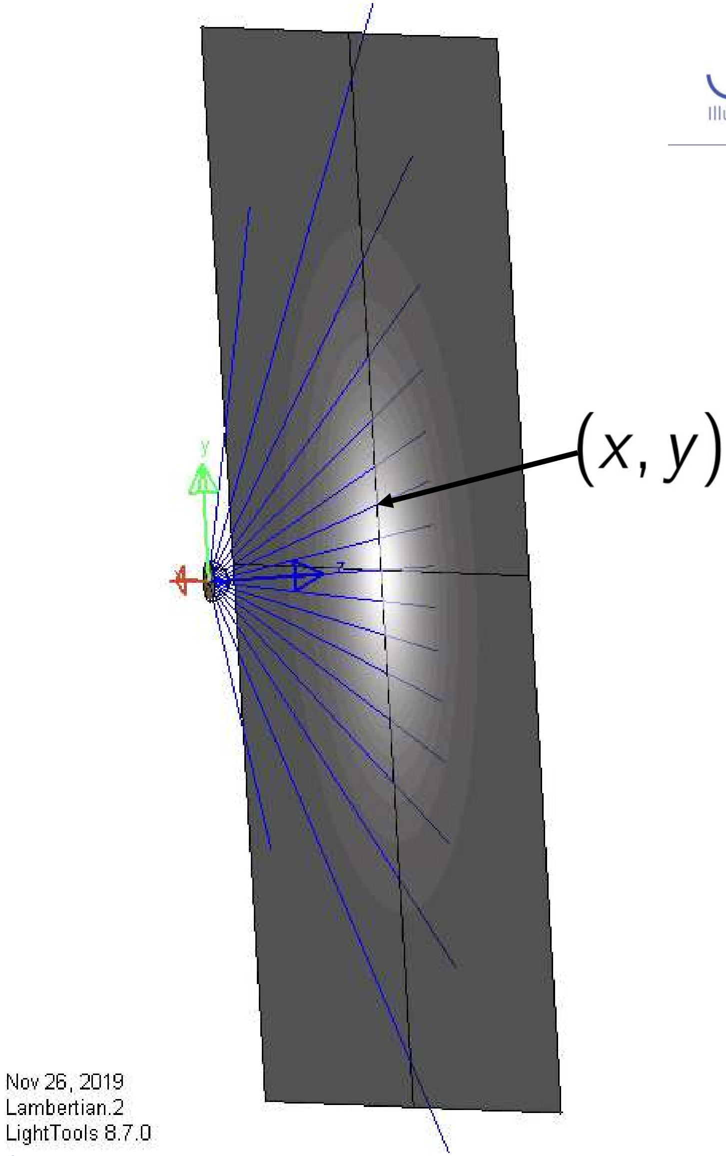
Irradiance E:

Choose location (x, y)

Consider tiny area element dA there

Determine flux dΦ into dA

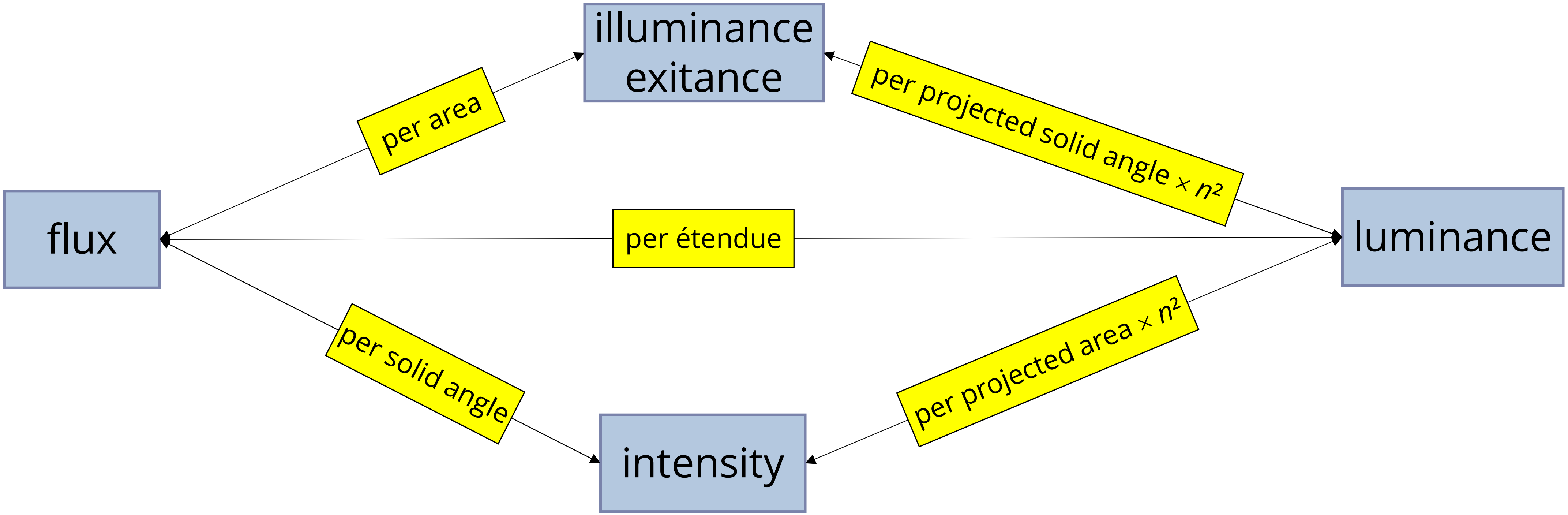
$$E = E(x, y) = \mathrm{d}\Phi / \mathrm{d}A$$



A word on radiometric vs. photometric quantities

	Overall a number	Per solid angle function of θ, φ	Per area function of *x*, *y*	Per phase space volume Per proj. solid angle, area, n² function of *x*, *y*, θ, φ
Photometric	Luminous flux	Luminous intensity	Illuminance Luminous exitance	Luminance
	Lumen (lm)	Candela (cd = lm/sr)	Lux (lx = lm/m²)	nit (cd/m² = lx/sr = lm/(m² sr)
	Φ_v	I_v	E_v	L_v
Radiometric	Radiant flux	Radiant intensity	Irradiance Radiant exitance	Radiance
	Watt (W)	W/sr	W/m²	W/(m² sr)
	Φ (Φ_E, P)	I	E	L

The diamond

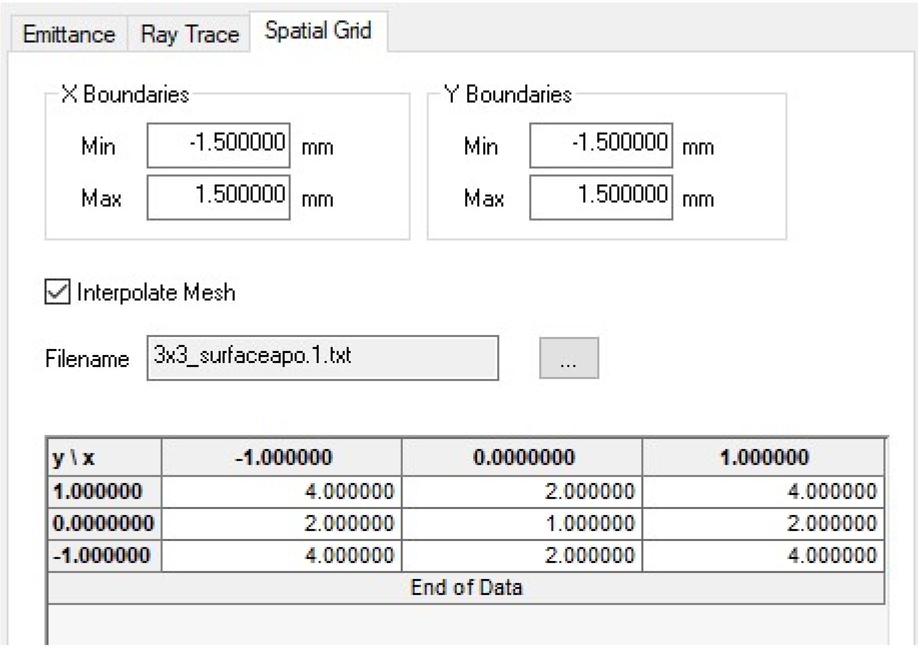


For more on this, see my previous webinar on étendue at
https://www.osa.org/en-us/meetings/webinar/2019/what_is_etendue_and_why_is_it_important/

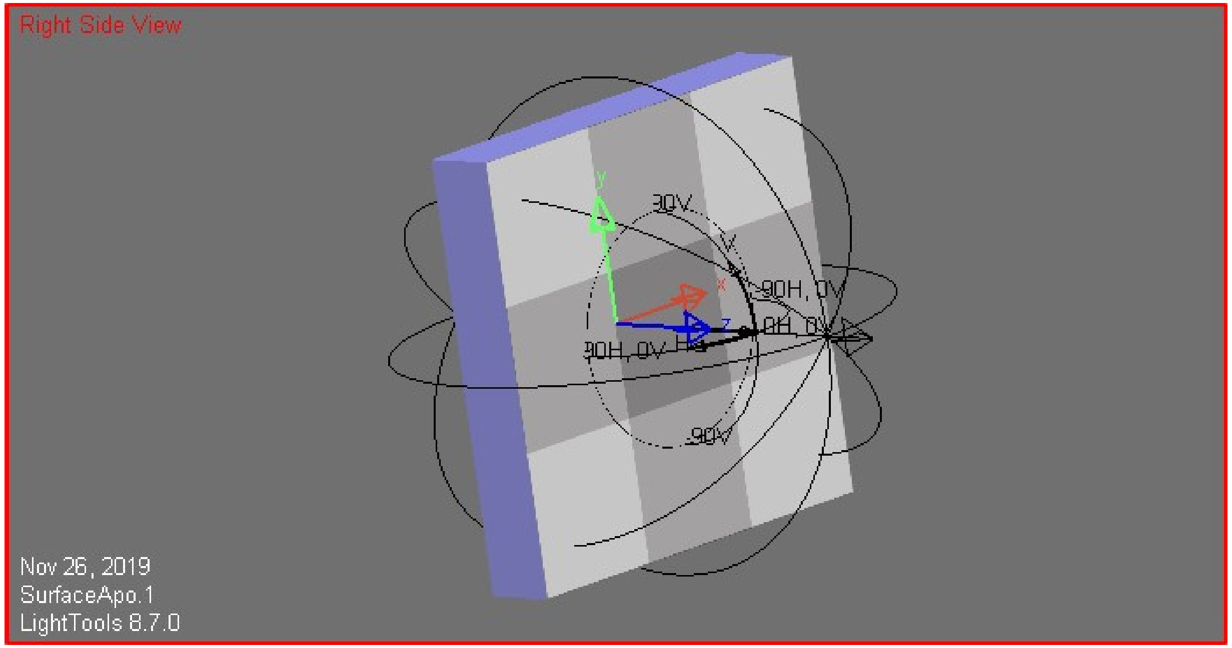
Varying exitance: surface apodization

In general, exitance (flux per area as function of location) varies

Assign tabulated values to your emitting surface:



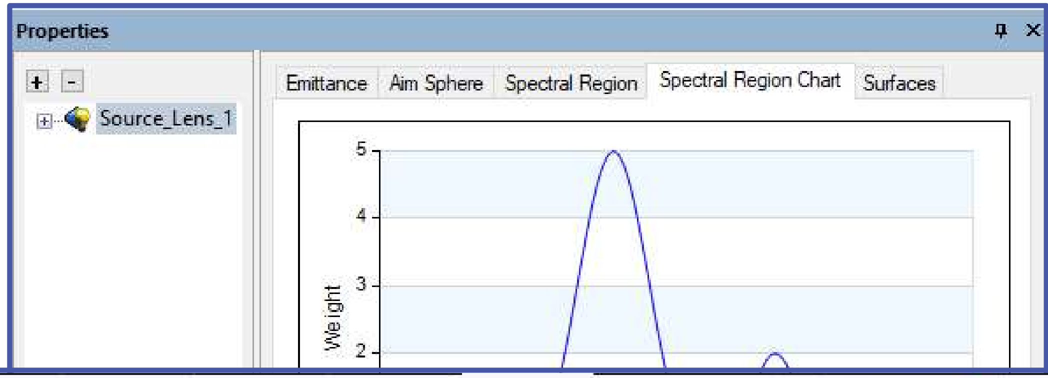
y \ x	-1.000000	0.0000000	1.000000
1.000000	4.000000	2.000000	4.000000
0.0000000	2.000000	1.000000	2.000000
-1.000000	4.000000	2.000000	4.000000
End of Data			

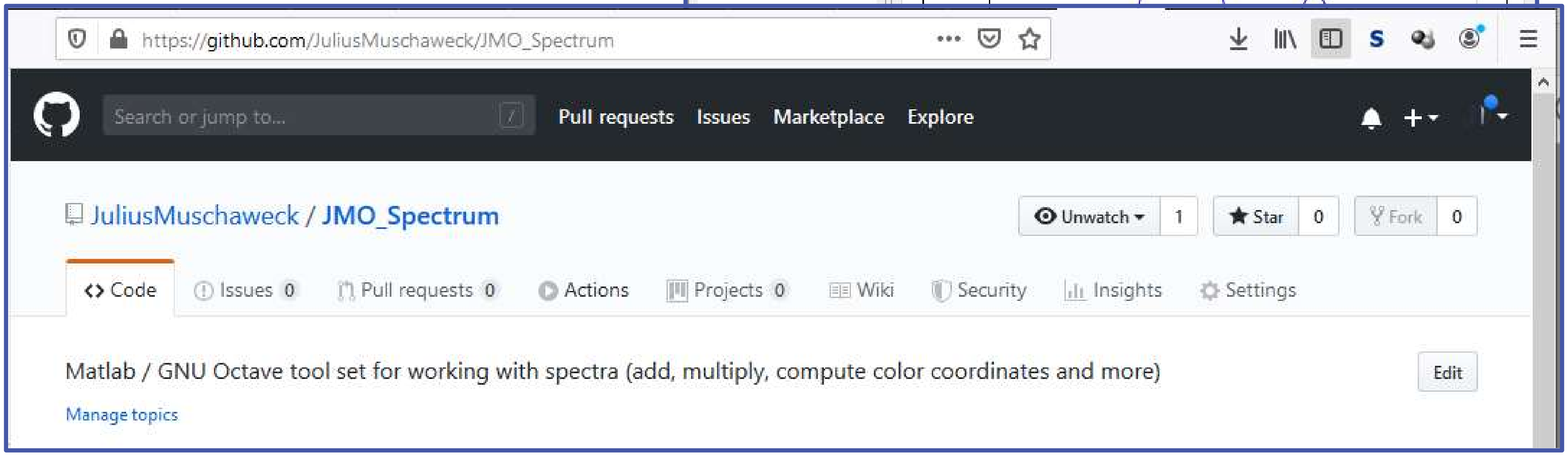


Spectral modeling

Assign any spectrum

to the whole source





Spatial / angular apodization and spectrum

Spatial, angular and spectral dependence separate:

$$L_\lambda(x, y, \theta, \varphi, \lambda) = C_0 \times f_1(x, y) \times f_2(\theta, \varphi) \times f_3(\lambda)$$

C_0: Normalization factor for correct overall flux

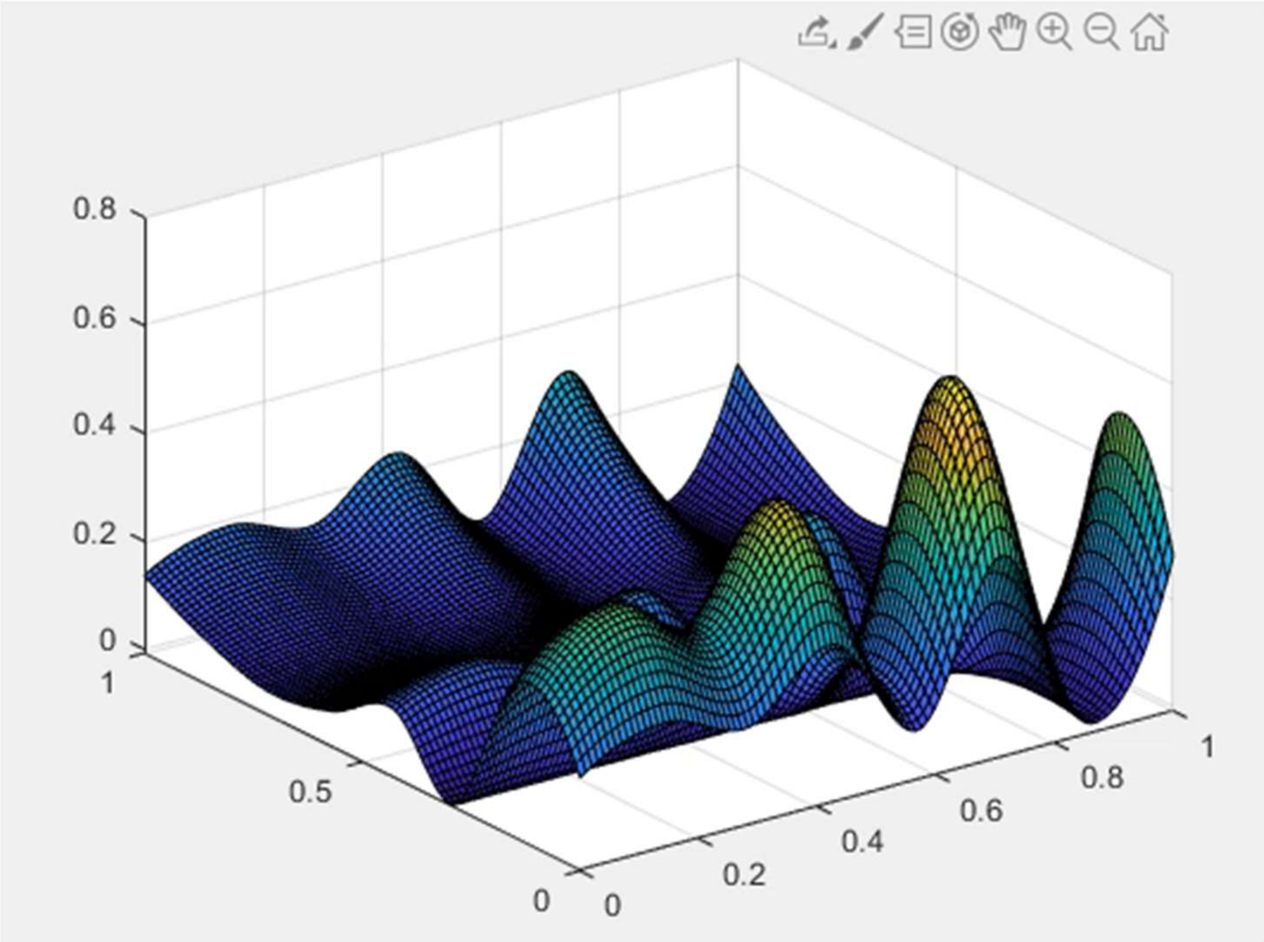
f_1: Spatial apodization

f_2: Angular apodization

f_3: Spectrum

Much less general than the full model – but **very** useful in practice

Visualizing variable separation



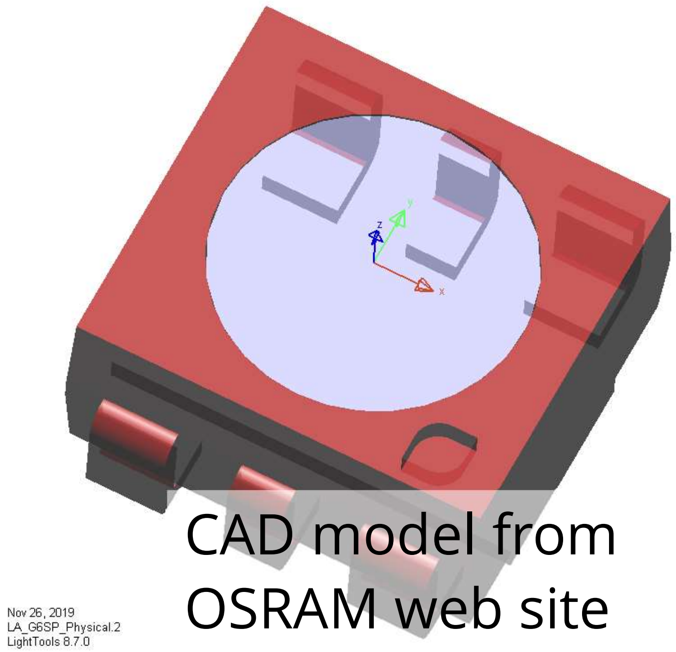
- From wherever you look, the source surface has the same apodization pattern
- Wherever you place a pinhole on the source, the far field looks the same
- Each point on the source sends the same spectrum into each direction
- What if that‘s not sufficient?

Physical modeling

Build a detailed physical model of the source in software

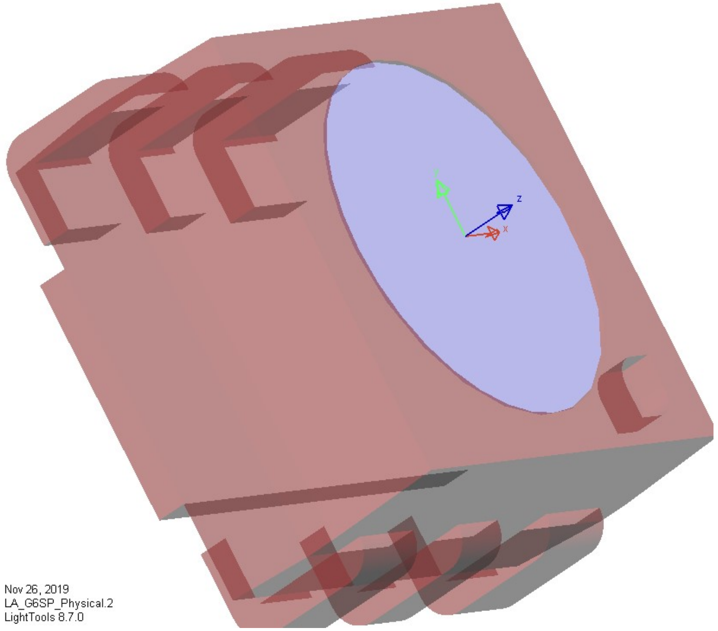
Assign all relevant optical and emission properties

OSRAM Advanced Power TopLED, LA G6SP

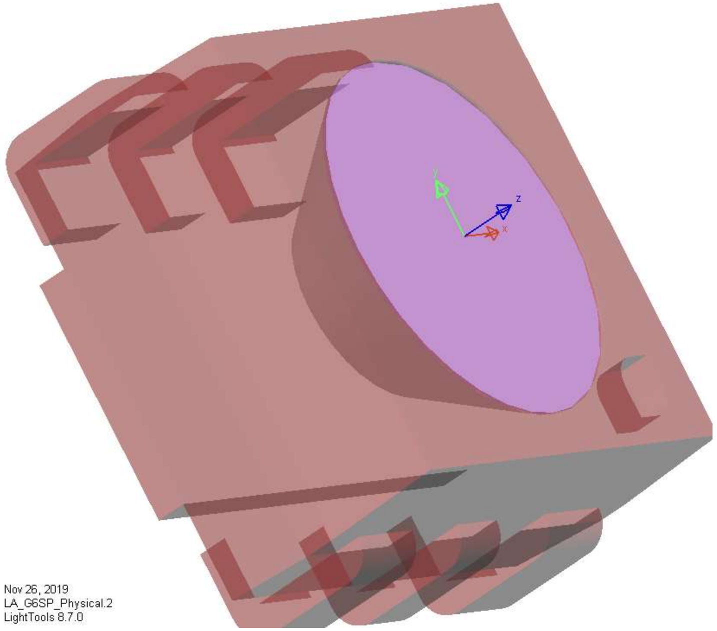


CAD model from OSRAM web site

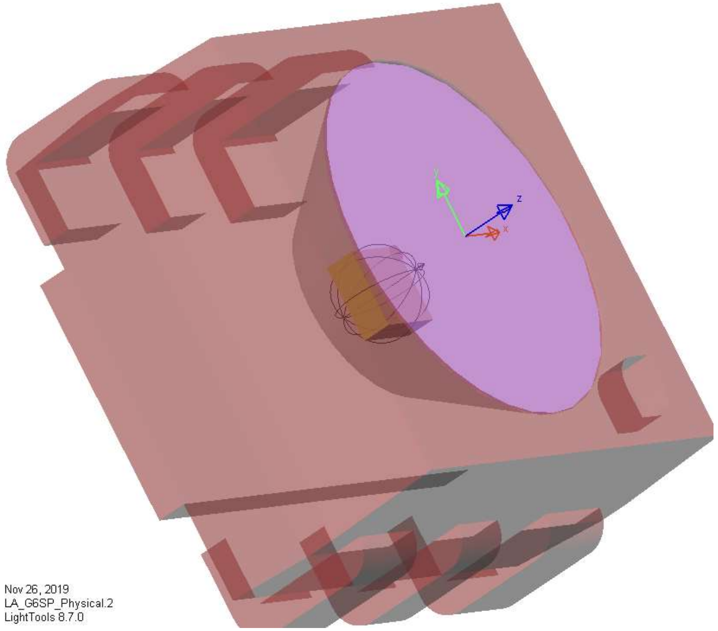
Physical modeling steps



start with „empty“ CAD



immerse silicone cup
assign refractive index
make inner surfaces 90% scatter
exit surface refracts, Fresnel split



Immerse LED chip
make top surface emitting
make surfaces absorbing
add wirebond pad

Physical modeling

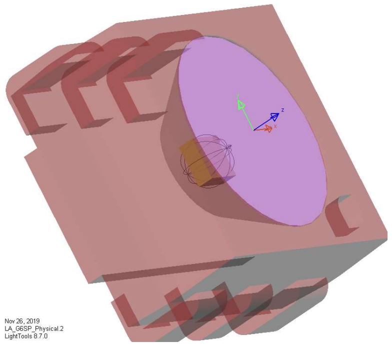
Build a detailed physical model of the source in software

Assign all relevant optical and emission properties

Sounds like „the way to go“, but not in practice: Lack of information

If you choose this approach, then validate. And validate again.

Against anything you know: Far field intensity, near field data from ray files, photographs..



Ray files

JMO
Illumination Optics

Monte Carlo sampling of $L_\lambda(x, y, \theta, \varphi, \lambda)$: Millions of rays, like single photon counting

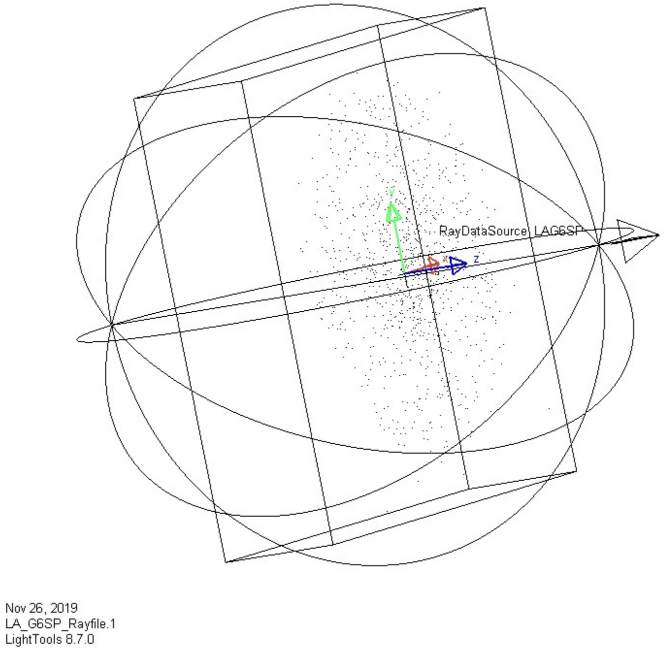
Just download ray file from vendor‘s web site, insert and run … or so you thought …

OSRAM
Opto Semiconductors

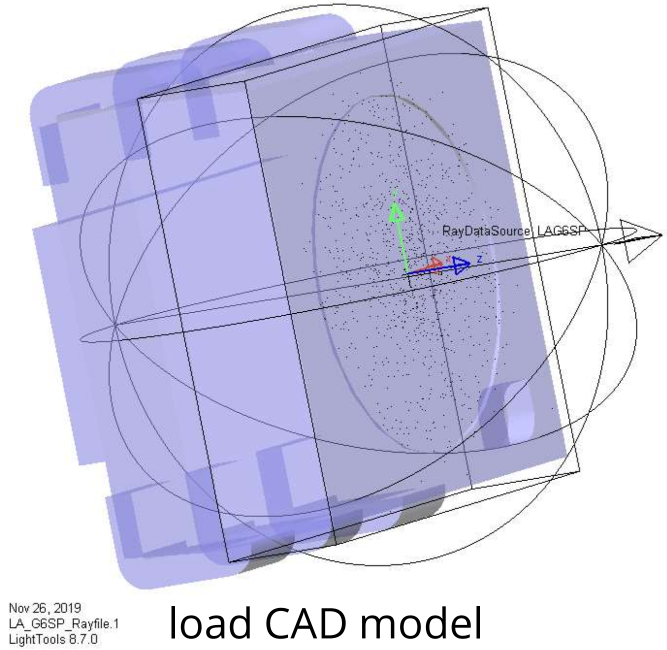
Filename	Size	Date
CAD_LA_G6SP_20190425.zip	199 KB	25.4.2019
rayfile_LA_G6SP_20190425_ASAP.zip	109.3 MB	25.4.2019
rayfile_LA_G6SP_20190425_ASCII.zip	125.8 MB	25.4.2019
rayfile_LA_G6SP_20190425_EULUMDAT.zip	228 KB	25.4.2019
rayfile_LA_G6SP_20190425_IES.zip	228 KB	25.4.2019
rayfile_LA_G6SP_20190425_IES_TM25.zip	498.3 MB	25.4.2019
rayfile_LA_G6SP_20190425_LightTools.zip	109.3 MB	25.4.2019
rayfile_LA_G6SP_20190425_Lucidshape.zip	109.3 MB	25.4.2019
rayfile_LA_G6SP_20190425_OSRAM.zip	110.8 MB	25.4.2019
rayfile_LA_G6SP_20190425_Photopia.zip	109.3 MB	25.4.2019
rayfile_LA_G6SP_20190425_Simulux.zip	109.3 MB	25.4.2019
rayfile_LA_G6SP_20190425_Speos.zip	126.5 MB	25.4.2019
rayfile_LA_G6SP_20190425_TraceProBinary.zip	109.3 MB	25.4.2019
rayfile_LA_G6SP_20190425_TraceProText.zip	125.8 MB	25.4.2019
rayfile_LA_G6SP_20190425_TTR.zip	819.2 MB	25.4.2019
rayfile_LA_G6SP_20190425_Zemax.zip	109.3 MB	25.4.2019

rayfile_LA_G6SP_20190425_LightTools.zip 109.3 MB

Ray file workflow



load ray file

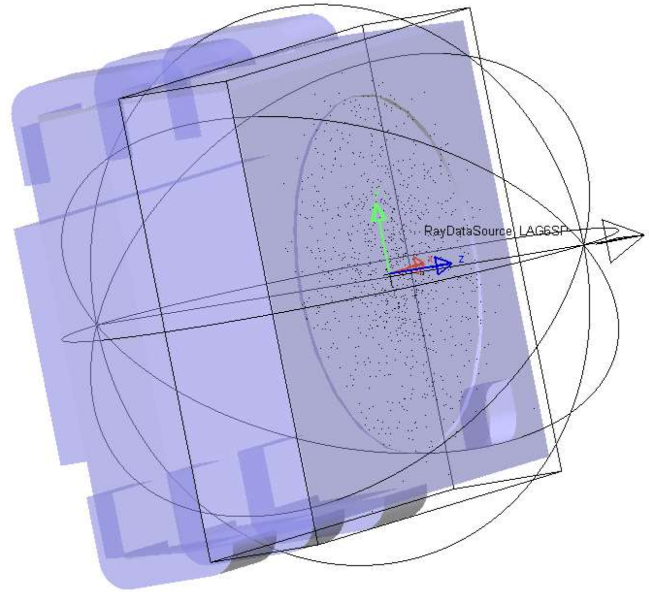


load CAD model

make sure they are properly aligned

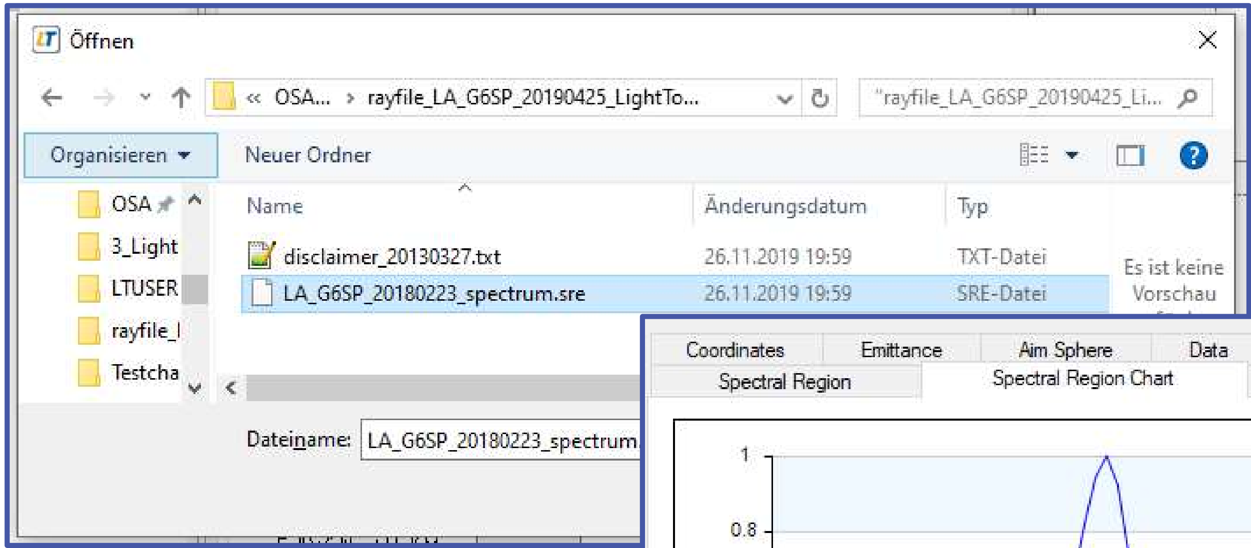
group for easy, safe move/rotate

Ray file workflow



CAD data must be made non-raytraceable

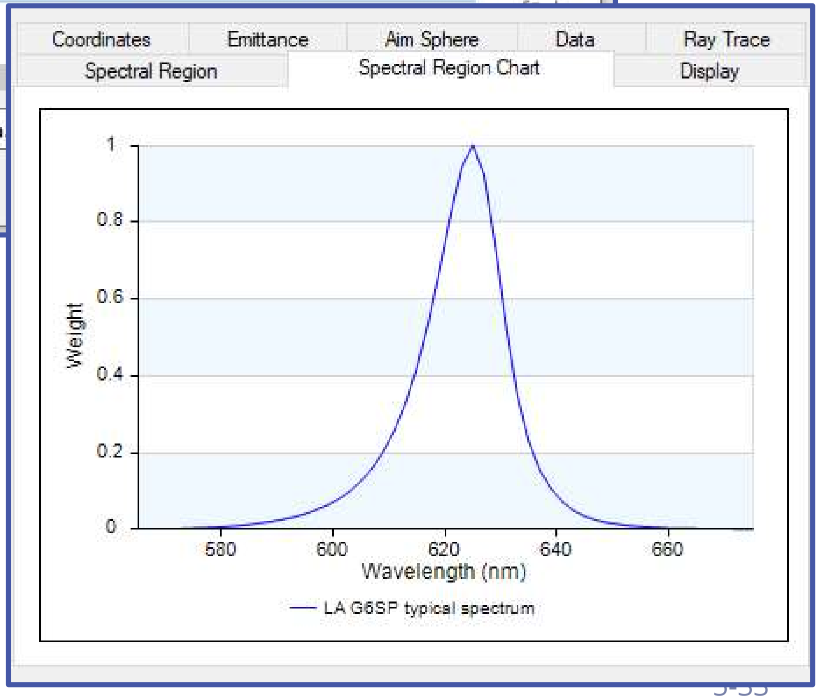
rays have „seen“ the package already



assign correct spectrum

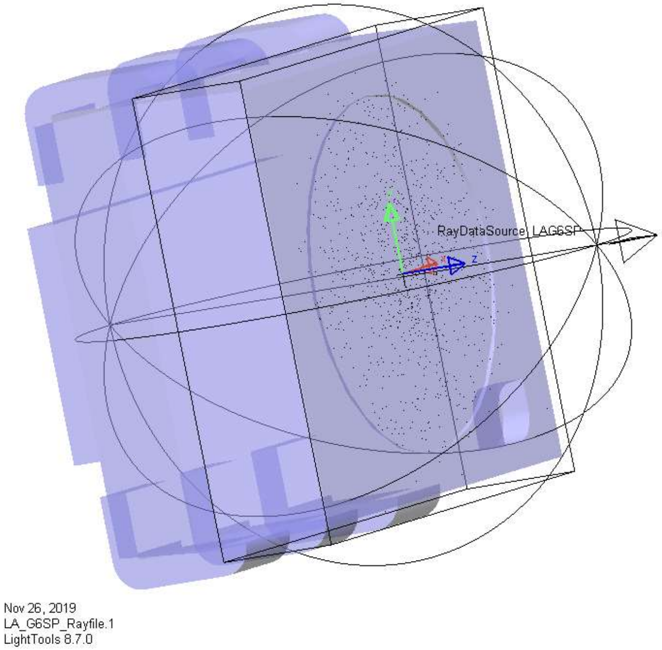
from vendor web site

or by „digitizing“ the data sheet



Ray file workflow

Illumination Optics



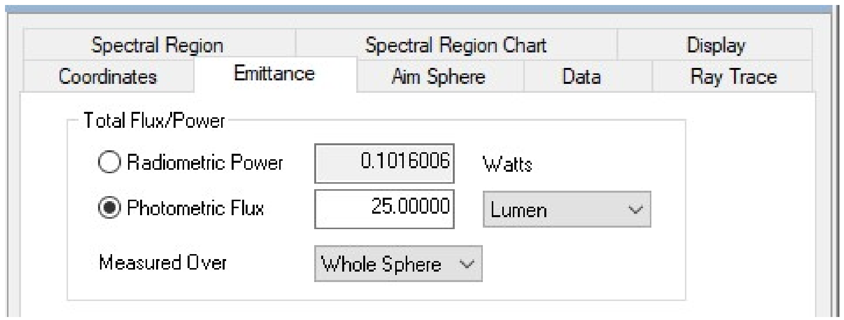
LA G6SP

Brightness Groups

Group	Luminous Intensity [1] I_F = 140 mA min. I_v	Luminous Intensity. [1] I_F = 140 mA max. I_v	Luminous Flux [8] I_F = 140 mA typ. Φ_v
DA	4.5 cd	5.6 cd	15.1 lm
DB	5.6 cd	7.1 cd	19.0 lm
EA	7.1 cd	9.0 cd	24.2 lm
EB	9.0 cd	11.2 cd	30.3 lm
FA	11.2 cd	14.0 cd	37.8 lm

assign correct flux

from data sheet



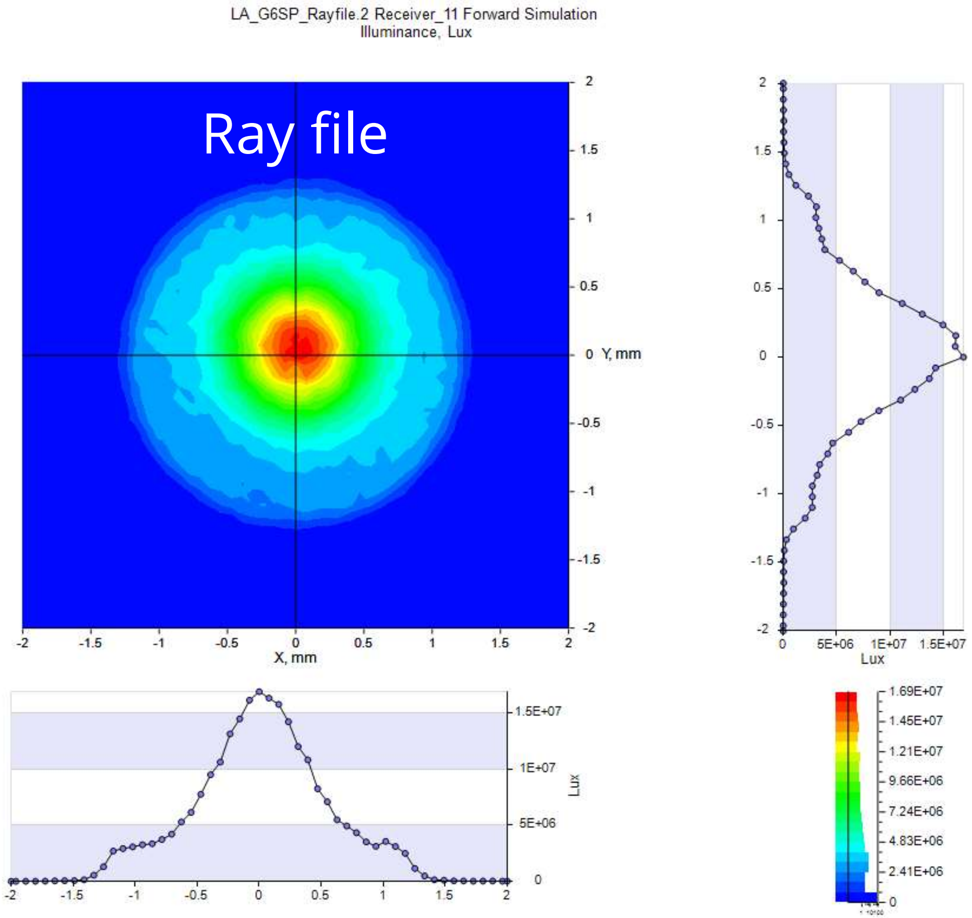
VALIDATE!

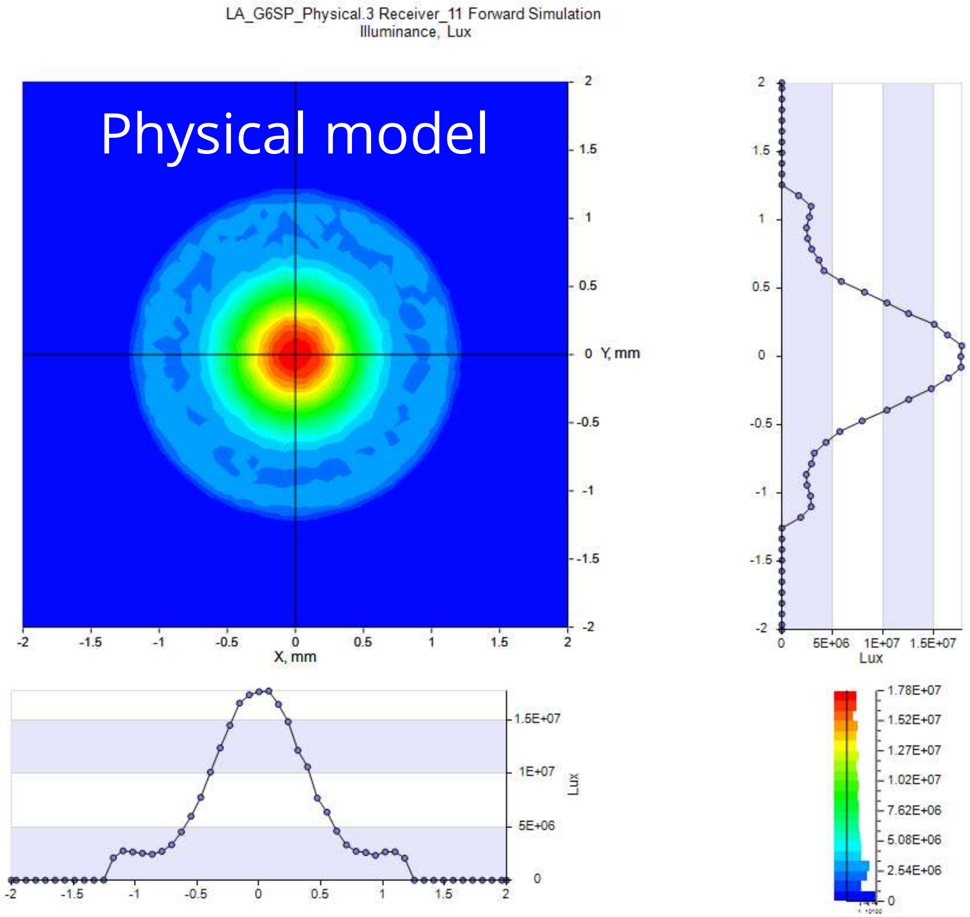
Ray file workflow

- Import ray data
- Import source CAD model, make non raytraceable, ensure proper alignment
- Assign correct spectrum
- Assign correct flux. Highly nontrivial for white or multi LEDs
- Group
- If you are lucky (e.g. OSRAM), you can use predefined library elements

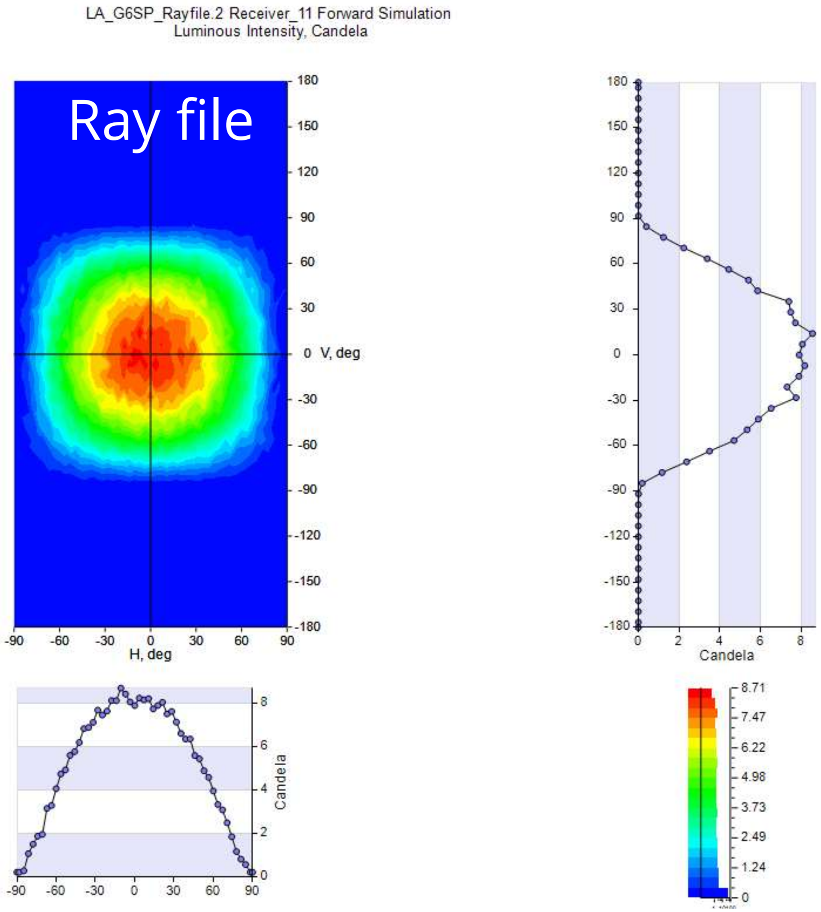
LA_G6SP_20180223_spectrum.sre	26.11.2019 19:59	SRE-Datei	2 KB
LA_G6SP_20190425_info.pdf	26.11.2019 19:59	Adobe Acrobat D...	189 KB
LA_G6SP_20190425_sample_Lighttools.ent	26.11.2019 19:59	ENT-Datei	527 KB
rayfile_LA_G6SP_5M_20190425_LightTools_7_Binary.RAY	26.11.2019 19:59	RAY-Datei	136,719 KB
rayfile_LA_G6SP_100k_20190425_LightTools_7_Binary.RAY	26.11.2019 19:59	RAY-Datei	2,735 KB

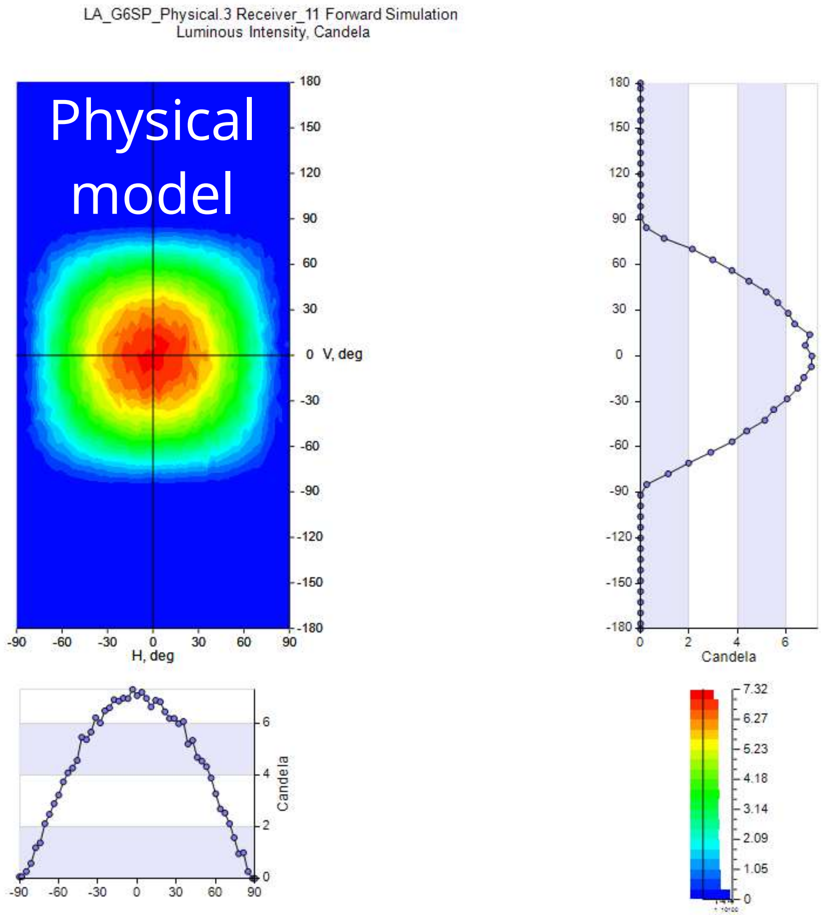
Validating: luminous exitance





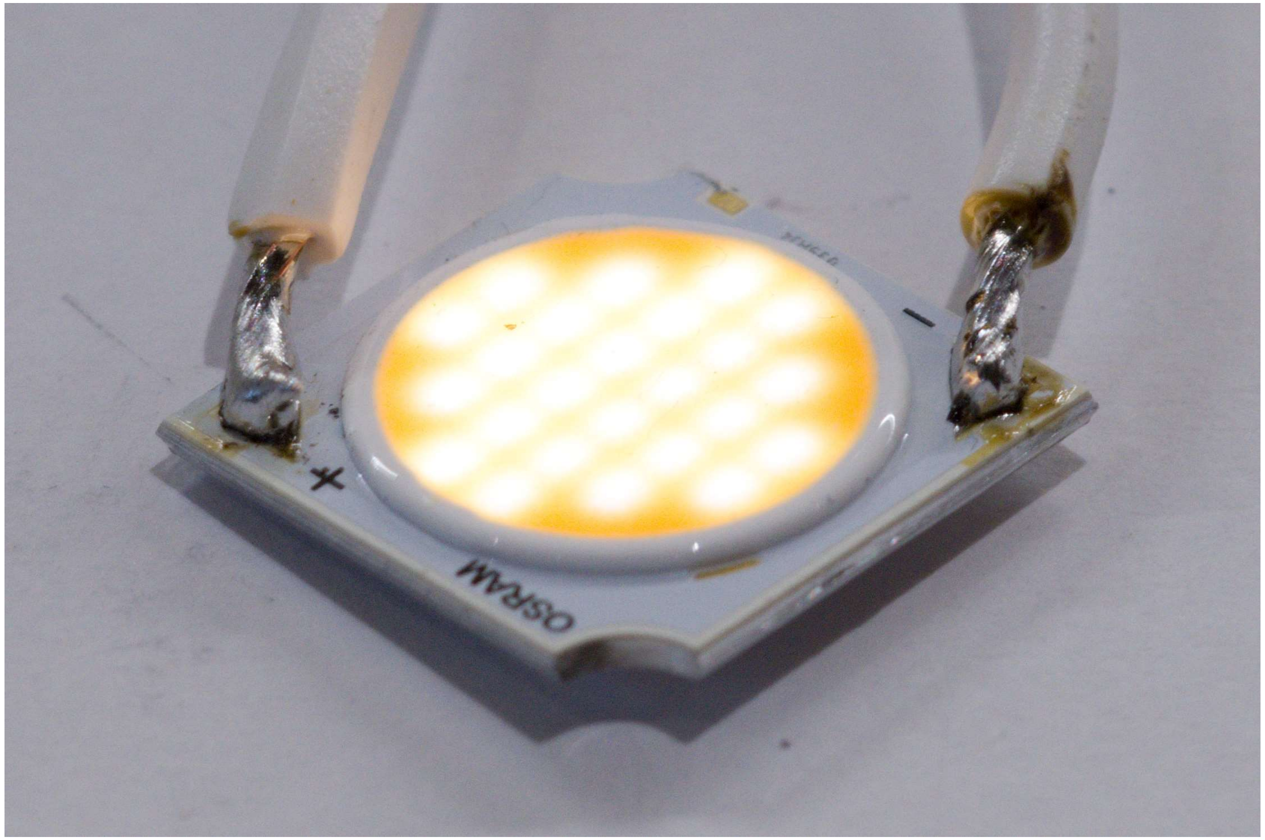
Validating: luminous intensity





Modeling white LEDs from ray files: Blue + phosphor

- Chips emit blue light
- Blue light:
  Partially scattered
  Partially converted to yellow
- Spatial blue/yellow separation
  - Depending on LED construction
  - Here: „white pearls in yellow soup“
- Angular blue/yellow separation
  - „Color over angle“
  - If you don‘t know any better:
    Play with $\cos^{0.8}$ for yellow, $\cos^{1.4}$ for blue angular apodization
    Details would be a separate talk…



Vendor support

- OSRAM: Separate blue and yellow ray files, separate spectra, complete library elements

Various CAD formats

Separate blue/yellow spectra for various color bins

Info file with alignment and more

Blue ray files up to 5 Mio rays

Complete library element

Yellow ray files up to 5 Mio rays

LCW_CQ7Pcc_160511_geometry.IGS	29.11.2018 09:02	IGS-Datei	238 KB
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Conclusion

- Source modeling in illumination optics: highly nontrivial
- Skillful simplification is key
- Default: Ray files with painstakingly accurate workflow to obtain complete model
- When available, use vendor‘s predefined library elements / scripts with care
- Use simplified physical models, validated against ray files, for huge ray numbers
- Use even more simplified heuristic models (Lambertian, apodized) for quick work
- Always validate
- In the (distant) future: IES TM25 ray file format is capable of including ALL such features


ThankYou
Gracias
Danke
Dankie
Efharisto
Arigato
Mahalo
Grazie
Спасибо
Благодаря
Merci
Obrigado