Institute of
Applied Physics
Friedrich-Schiller-Universität Jena

Optical Design with Zemax

Lecture 10: Illumination

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www.iap.uni-jena.de

10 Illumination
Time schedule

1	16.10.	Introduction	Introduction, Zemax interface, menues, file handling, preferences, Editors, updates, windows, Coordinate systems and notations, System description, Component reversal, system insertion, scaling, 3D geometry, aperture, field, wavelength
2	23.10.	Properties of optical systems I	Diameters, stop and pupil, vignetting, Layouts, Materials, Glass catalogs, Raytrace, Ray fans and sampling, Footprints
3	30.10.	Properties of optical systems II	Types of surfaces, Aspheres, Gratings and diffractive surfaces, Gradient media, Cardinal elements, Lens properties, Imaging, magnification, paraxial approximation and modelling
4	06.11.	Aberrations I	Representation of geometrical aberrations, Spot diagram, Transverse aberration diagrams, Aberration expansions, Primary aberrations,
5	13.+27.11.	Aberrations II	Wave aberrations, Zernike polynomials, Point spread function, Optical transfer function
6	04.12.	Advanced handling	Telecentricity, infinity object distance and afocal image, Local/global coordinates, Add fold mirror, Vignetting, Diameter types, Ray aiming, Material index fit, Universal plot, Slider,IO of data, Multiconfiguration, Macro language, Lens catalogs
7	11.12.	Optimization I	Principles of nonlinear optimization, Optimization in optical design, Global optimization methods, Solves and pickups, variables, Sensitivity of variables in optical systems
8	18.12.	Optimization II	Systematic methods and optimization process, Starting points, Optimization in Zemax
9	08.01	Imaging	Fundamentals of Fourier optics, Physical optical image formation, Imaging in Zemax
10	15.01.	Illumination	Introduction in illumination, Simple photometry of optical systems, Non-sequential raytrace, Illumination in Zemax
11	22.01.	Correction I	Symmetry principle, Lens bending, Correcting spherical aberration, Coma, stop position, Astigmatism, Field flattening, Chromatical correction, Retrofocus and telephoto setup, Design method
12	29.01.	Correction II	Field lenses, Stop position influence, Aspheres and higher orders, Principles of glass selection, Sensitivity of a system correction, Microscopic objective lens, Zoom system
13	05.02.	Physical optical modelling	Gaussian beams, POP propagation, polarization raytrace, coatings

10 Illumination
Contents

1. Photometry
2. Energy transport in optical systems
3. Vignetting
4. Non-sequential raytrace
5. Illumination in Zemax

Illumination

Illumination systems:

- Different requirements: energy transfer efficiency, uniformity
- Performnace requirements usually relaxed
- Very often complicated structures components
- Problem with raytracing: a ray corresponds to a plane wave with infinity extend
- Usual method: Monte-Carlo raytrace
  Problems: statistics and noise
- Illumination systems and strange components needs often a strong link to CAD data
- There are several special software tools, which are optimized for (incoherent) illumination:
  - LightTools
  - ASAP
  - FRED

10 Illumination
Radiometric vs Photometric Units

Quantity	Formula	Radiometric		Photometric	
		Term	Unit	Term	Unit
Energy		Energy	Ws	Luminous Energy	Lm s
Power Radiation flux	Φ		W	Luminous Flux	Lumen Lm
Power per area and solid angle	$L=\frac{d^2\Phi}{\cos\theta d\Omega dA}$	Radiance	W / sr / m^2	Luminance	cd / m^2 Stilb
Power per solid angle	$I=\frac{d\Phi}{d\Omega}=\int L\, dA_\perp$	Radiant Intensity	W / sr	Luminous Intensity	Lm / sr, cd
Emitted power per area	$E=\frac{d\Phi}{dA}=\int L\cdot\cos\theta\, d\Omega$	Radiant Excitance	W / m^2	Luminous Excitance	Lm / m^2
Incident power per area	$E=\frac{d\Phi}{dA}=\int L\cdot\cos\theta\, d\Omega$	Irradiance	W / m^2	Illuminance	Lux = Lm / m^2
Time integral of the power per area	$H=\int E\, dt$	Radiant Exposure	Ws / m^2	Light Exposure	Lux s

10 Illumination
Photometric Quantities

- Radiometric quantities:
  Physical MKSA units, independent of receiver

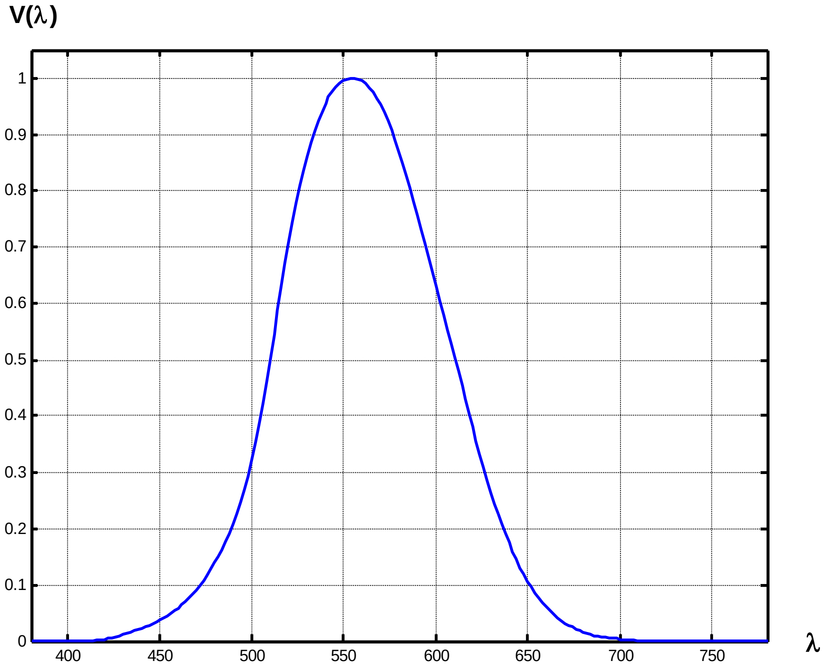
- Photometric quantities:
  Referenced on the human eye as receiver
  Conversion by a factor K_m

- Sensitivity of the human eye V(λ)
  for photopic vision (daylight)

$$\Phi_{V\lambda} = K_m \cdot V(\lambda) \cdot \Phi_\lambda$$

$$K_m = 673 \frac{Lm}{W}$$

Illuminance	description
1 Lux	just visible
50 - 100 Lux	coarse work
100 Lux	projection onto screen
100 - 300 Lux	fine work
1000 Lux	finest work
100000 Lux	sunlight on paper



10 Illumination
Solid Angle

- 2D extension of the definition of an angle:
  area perpendicular to the direction over square of distance

- Area element dA in the distance r with inclination θ

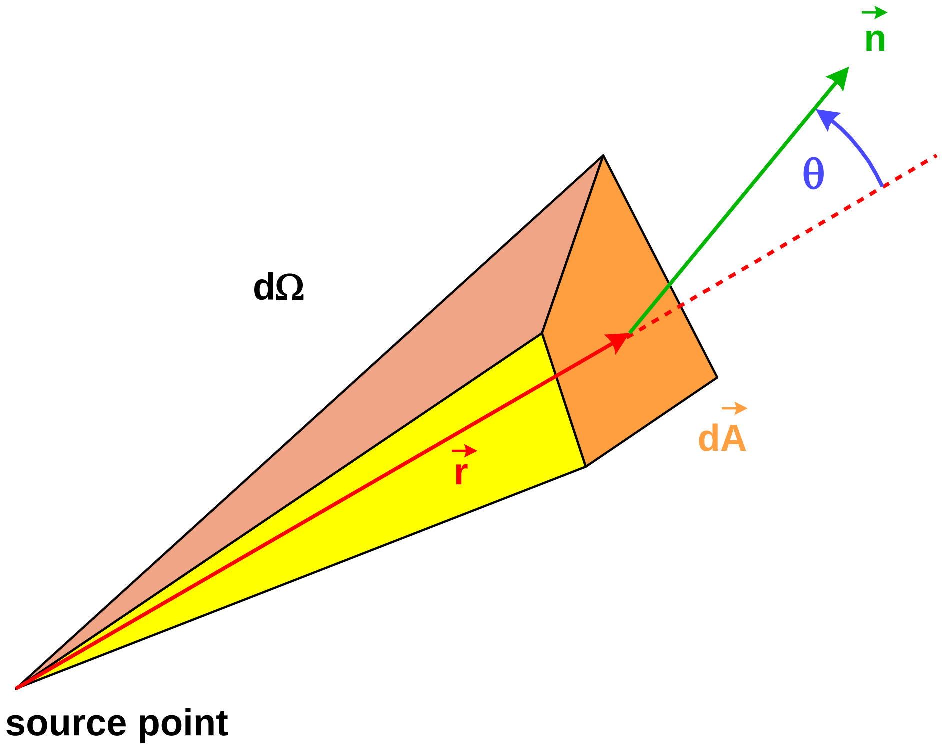
$$d\Omega = \frac{\cos\theta \cdot dA}{r^2} = \frac{dA_\perp}{r^2}$$

- Units: steradiant sr

- Full space: $\Omega = 4\pi$
  half space: $\Omega = 2\pi$

- Definition can be considered as
  cartesian product of conventional angles

$$d\Omega = \frac{dA}{r^2} = \frac{dx}{r} \cdot \frac{dy}{r} = \alpha_x \cdot \alpha_y$$



10 Illumination
Irradiance

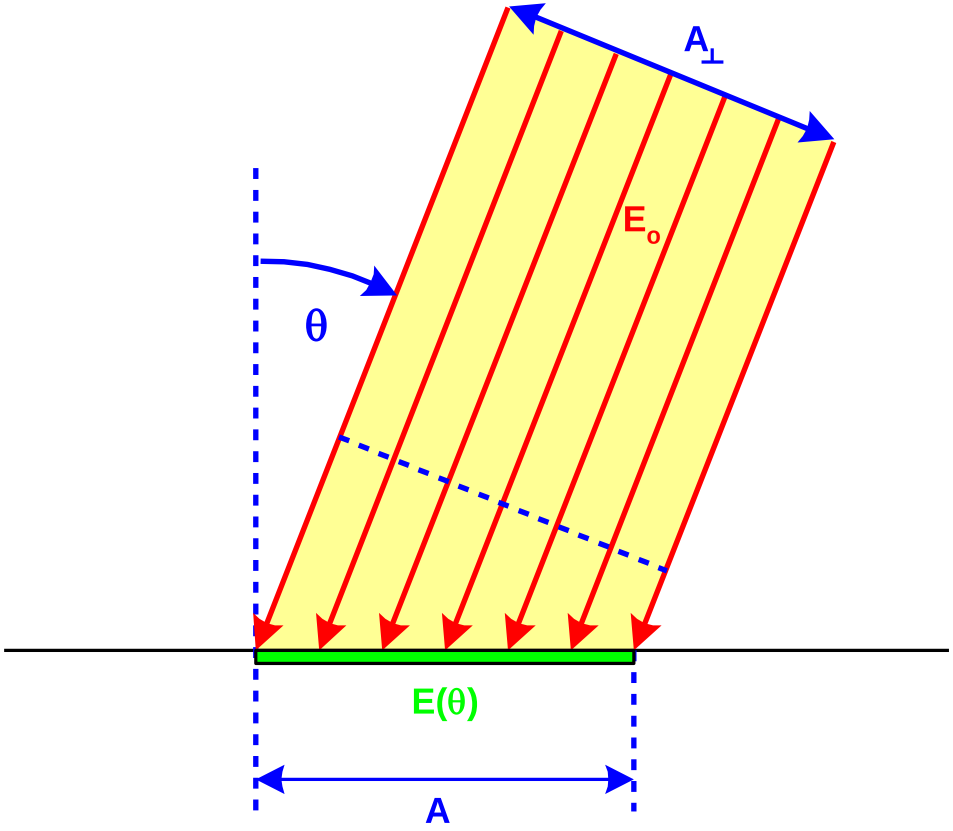
- Irradiance: power density on a surface
  Conventional notation: intensity
  Unit: watt/m^2

$$E = \frac{d\Phi}{dA} = \int L \cdot \cos\theta \, d\Omega$$

- Integration over all incident directions

- Only the projection of a collimated beam perpendicular to the surface is effective

$$E(\theta) = E_0 \cdot \cos\theta$$

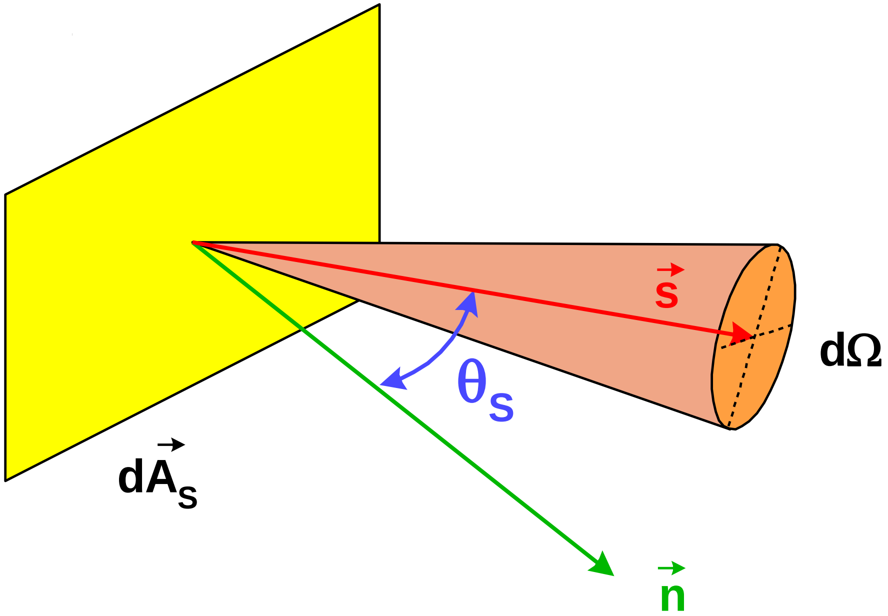


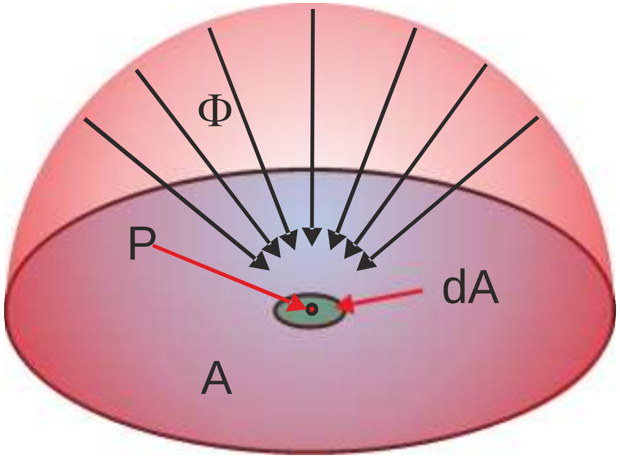
10 Illumination
Differential Flux

- Differential flux of power from a small area element dAs with normal direction n in a small solid angle dΩ along the direction s of detection

$$d^2\Phi = L\cdot d\Omega\cdot dA_{S\perp}$$
$$= L\cdot\cos\theta_S\cdot d\Omega\cdot dA_S$$
$$= L\cdot d\Omega\cdot\left(\vec{s}\, d\vec{A}_S\right)$$

- Integration of the radiance over the area and the solid angle gives a power





10 Illumination
Lambertian Source

- Radiance independent of space coordinate and angle

$$L(\vec{r},\vec{s})=L=const$$

- The irradiance varies with the cosine of the incidence angle

$$E(\theta)=L\cdot A\cdot\cos\theta=E_o\cdot\cos\theta$$

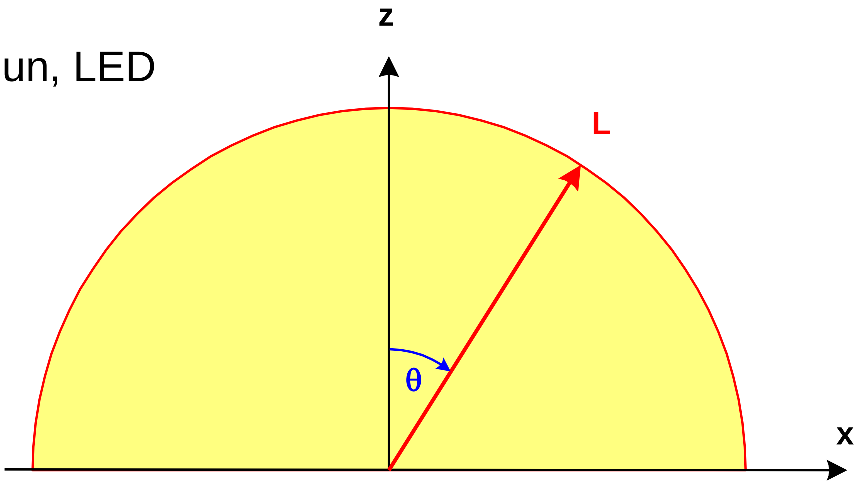
- Integration over half space

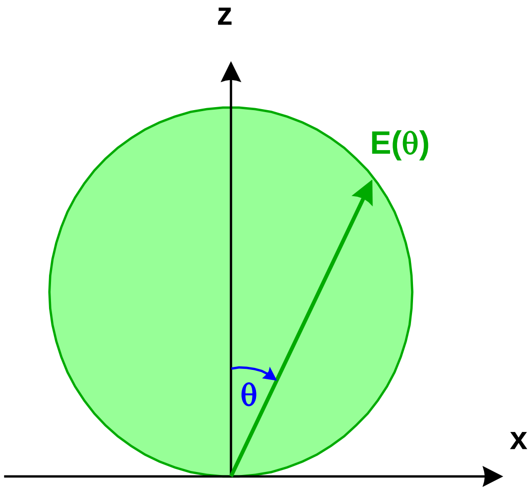
$$\Phi_{Lam}^{HR}=\int E(\theta)\cdot d\Omega=\pi\cdot A\cdot L$$

- Integration of cone

$$\Phi_{Lam}(\varphi)=\pi AL\cdot\sin^2\varphi$$

- Real sources with Lambertian behavior:
  black body, sun, LED





10 Illumination
Fundamental Law of Radiometry

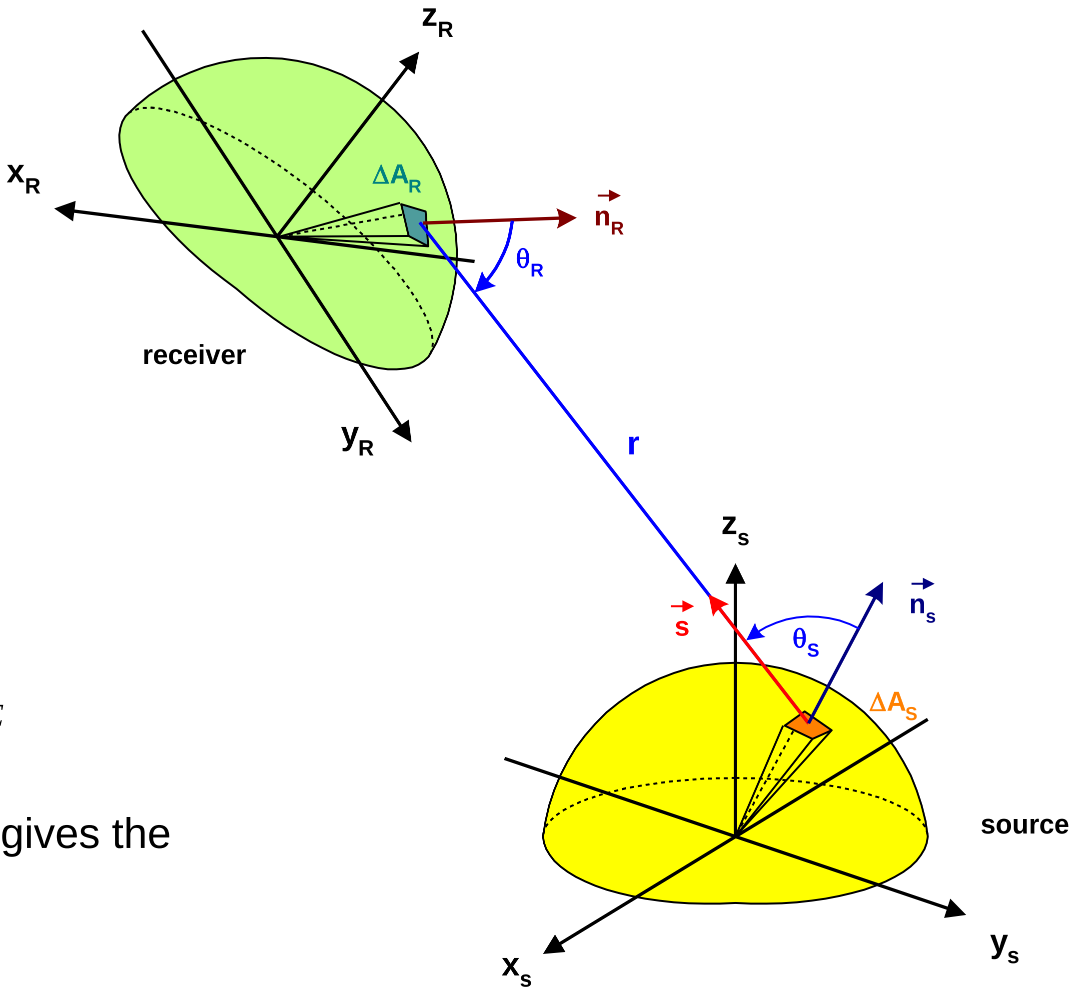
- Differential flux of power from a small area element dA_S on a small receiver area dA_R in the distance r,
  the inclination angles of the two area elements are θ_S and θ_R respectively

  Fundamental law of radiometric energy transfer

$$d^2\Phi = \frac{L}{r^2} \cdot dA_{S\perp} dA_{E\perp}$$

$$= \frac{L}{r^2} \cdot \cos\theta_S \cos\theta_E \, dA_S \, dA_E$$

- The integration over the geometry gives the total flux



10 Illumination
Radiation Transfer

- Basic task of radiation transfer problems:
  integration of the differential flux transfer law

$$d^2\Phi = \frac{L}{r^2} \cdot dA_{S\perp} dA_{E\perp} = \frac{L}{r^2} \cdot \cos\theta_S \cos\theta_E \, dA_S \, dA_E$$

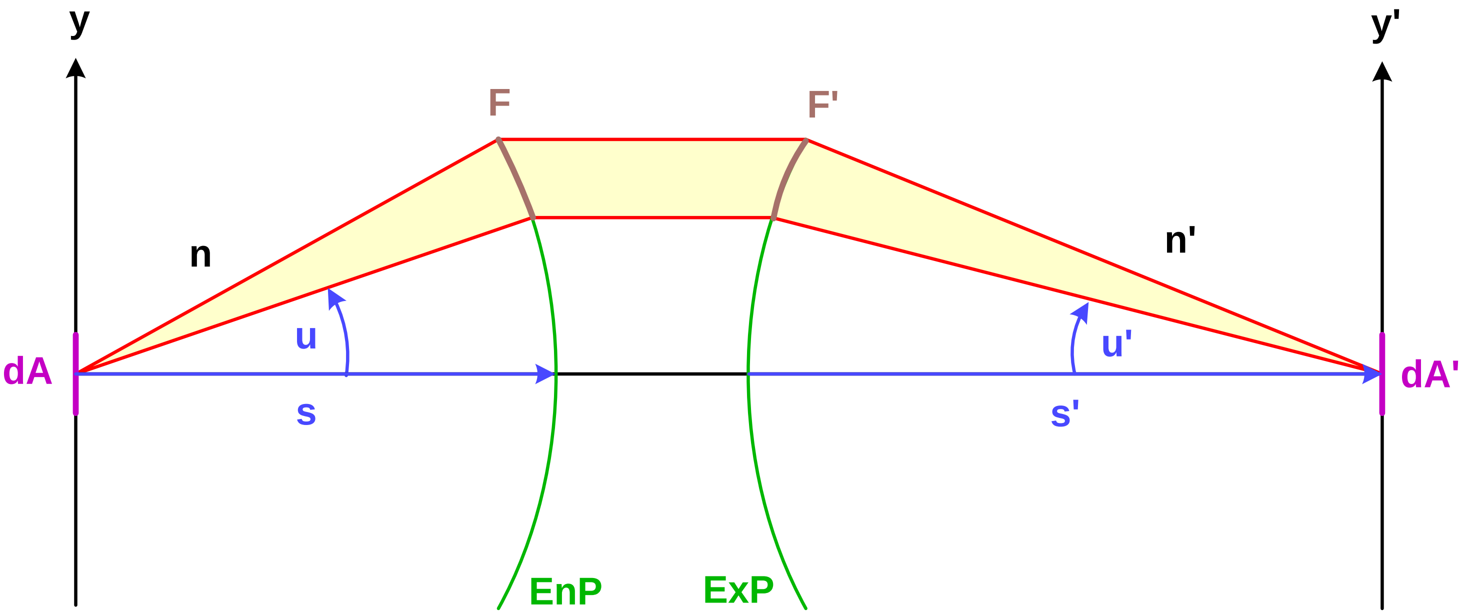
- Two classes of problems:
  1. Constant radiance, the integration is a purely geometrical task
  2. Arbitrary radiance, a density function has to be integrated over the geometrical light tube

- Special cases:
  Simple geometries, mostly high symmetric , analytical formulas

- General cases: numerical solutions
  - Integration of the geometry by raytracing
  - Considering physical-optical effects in the raytracing:
    1. absorption
    2. reflection
    3. scattering

10 Illumination
Transfer of Energy in Optical Systems

- Conservation of energy $d^2\Phi = d^2\Phi'$
- Differential flux $d^2\Phi = L \cdot \sin u \cdot \cos u \cdot dA \cdot du\, d\varphi$
- No absorption $T = 1$
- Sine condition fulfilled $n y \cdot \sin u = n' y' \cdot \sin u'$



10 Illumination
Transfer of Energy in Optical Systems

- Aplanatic systems:
  sine condition fulfilled

  consequence: constant radiance

$$n\,x\sin\theta = n'\,x'\sin\theta'$$

$$\frac{L}{n^2} = \frac{L'}{n'^2}$$

- Irradiance

  Irradiance in afocal systems

$$E = \pi L \cdot \sin^2\theta$$

$$E_\infty' = \left(\frac{n'}{n}\right)^2 \cdot \frac{\pi \cdot L}{4 \cdot F^2}$$

- Irradiance changes with the square of the numerical aperture

- Optical systems with finite image location:
  m: magnification
  m_P: magnification of pupil imaging

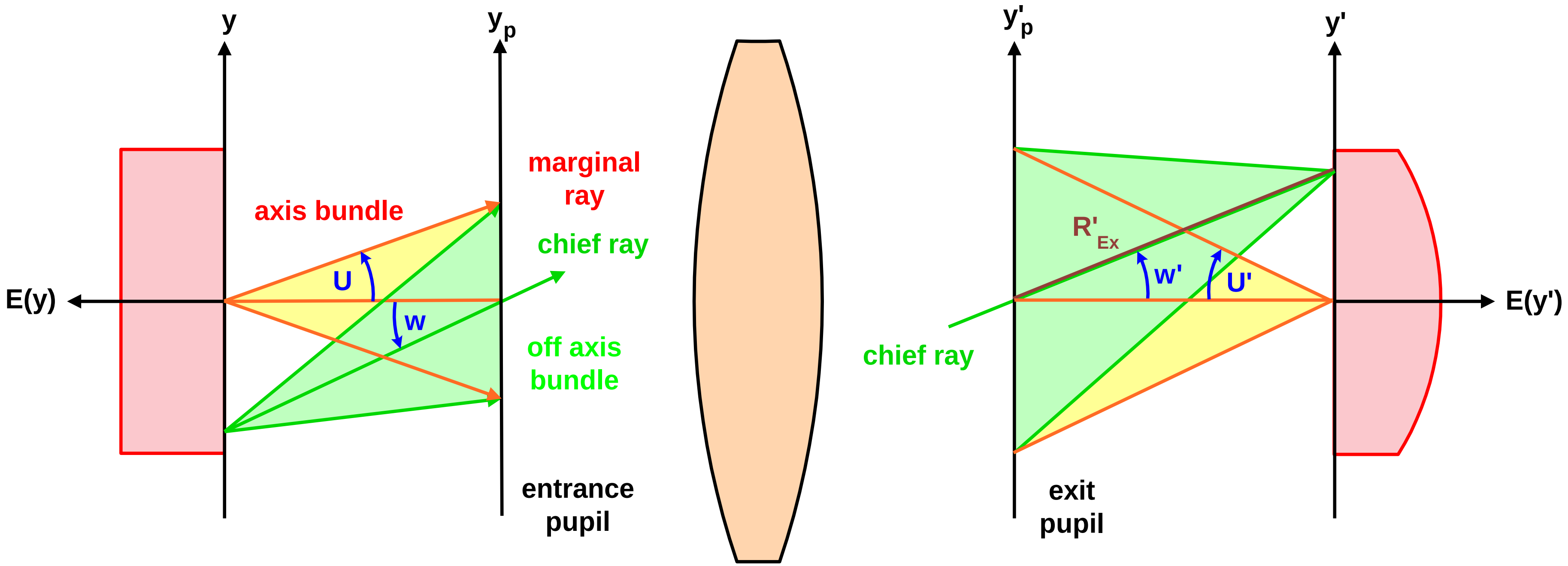
$$\sin u' = \frac{D_{AP}}{2f' \cdot (m + m_P)} = \frac{1}{2F \cdot \left(1 + \frac{m}{m_P}\right)}$$

Approximation $m_p = 1$:

$$E'(m) = \left(\frac{n'}{n}\right)^2 \cdot \frac{\pi \cdot L}{4 \cdot F^2 \cdot (1+m)^2} = \frac{E'_\infty}{(1+m)^2}$$

10 Illumination
Illumination Fall-off

- Irradiance decreases in the image field
- Two reasons:
  1. projection due to oblique ray bundles
  2. enlarged distances along oblique chief rays
- Natural vignetting: smooth function
  depends on: 1. stop location
  2. distortion correction



10 Illumination
Natural Vignetting: Setup with Rear Stop

- Stop behind system:
  exact integration possible

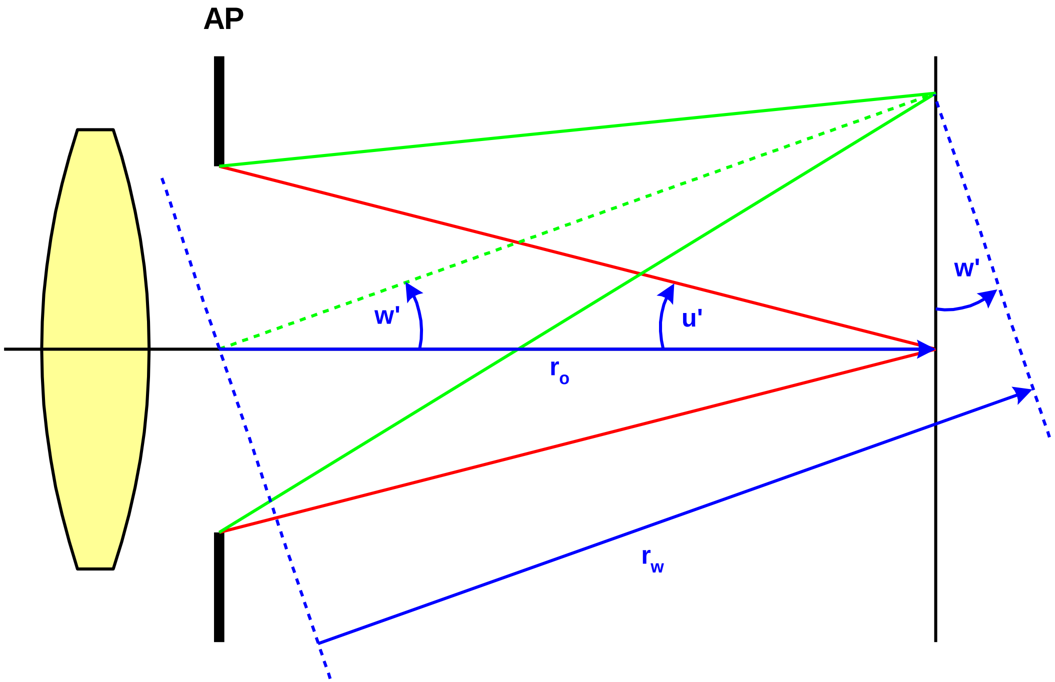
$$E(w') = \frac{\pi \cdot L}{2} \cdot \left(\frac{n'}{n}\right)^2 \cdot \left[1 - \left(1 + \frac{4\cos^2 w' \cdot \tan^2 u'}{\left(1 - \cos^2 w' \cdot \tan^2 u'\right)^2}\right)^{-1/2}\right]$$

- Special case on axis

$$E'(0) = \pi L' \sin^2 u' = \left(\frac{n'}{n}\right)^2 \cdot \pi \cdot L \sin^2 u'$$

- Approximation small aperture:
  Classical cos-to-the-fourth-law

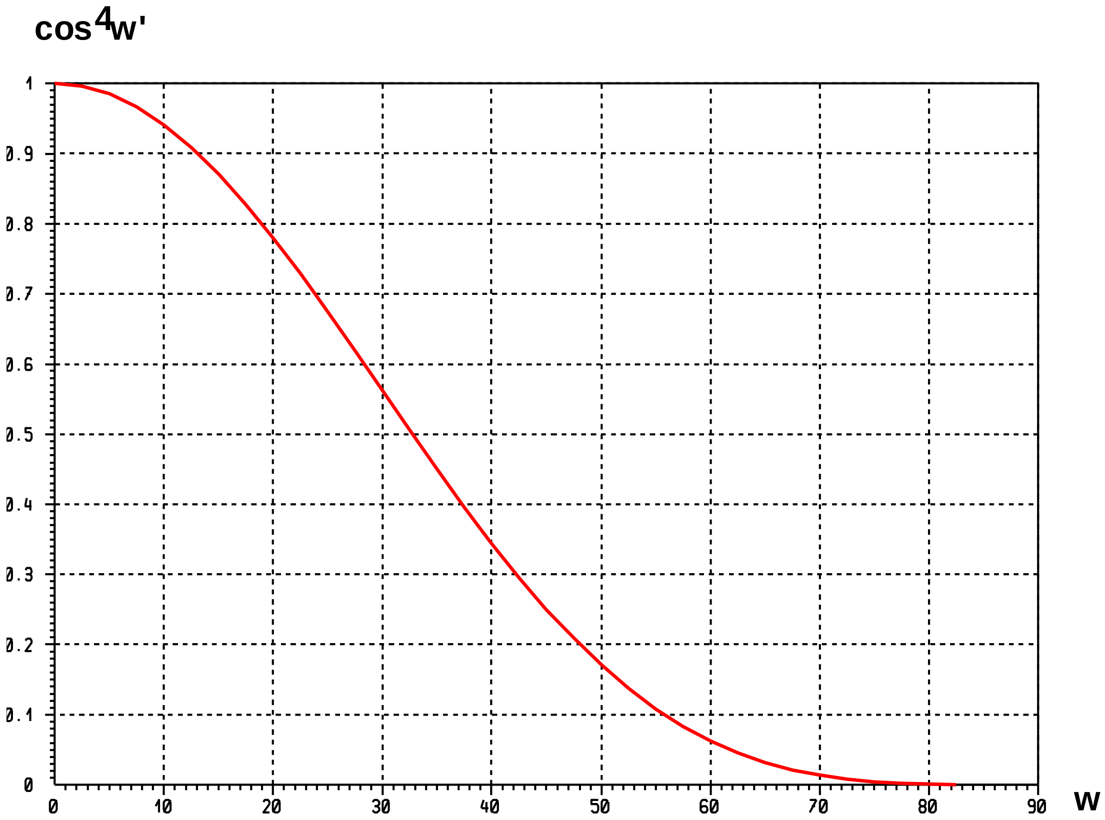
$$E(w') = E(0) \cdot \cos^4 w'$$



10 Illumination
Illumination Fall-off due to Natural Vignetting

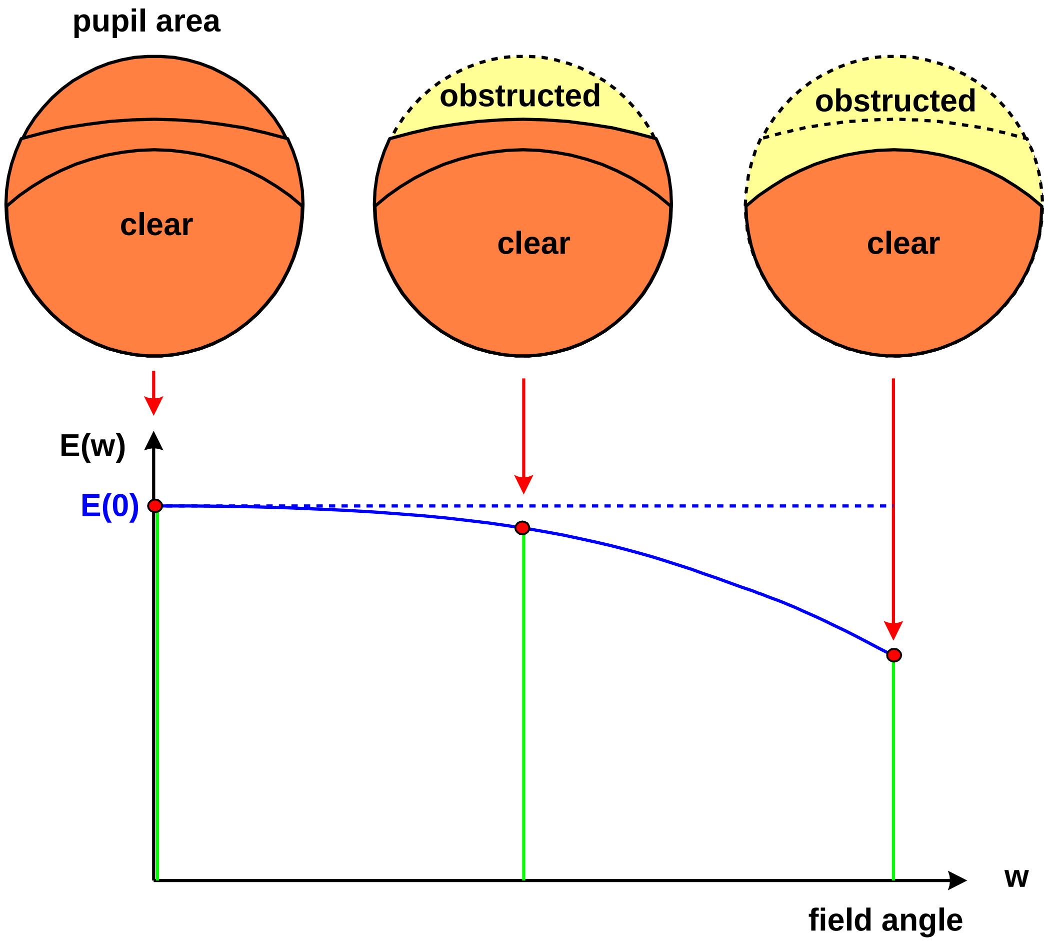
Relative decrease of irradiance towards the rim of the field

w	$\cos^4 w$
0	1
10°	0.94
20°	0.78
30°	0.56



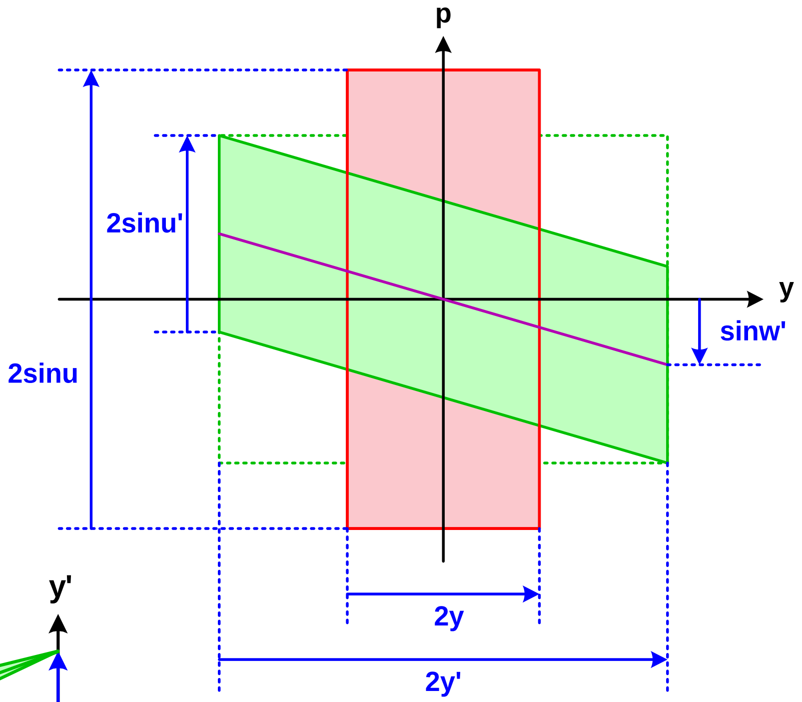
10 Illumination
Real Systems: Vignetting

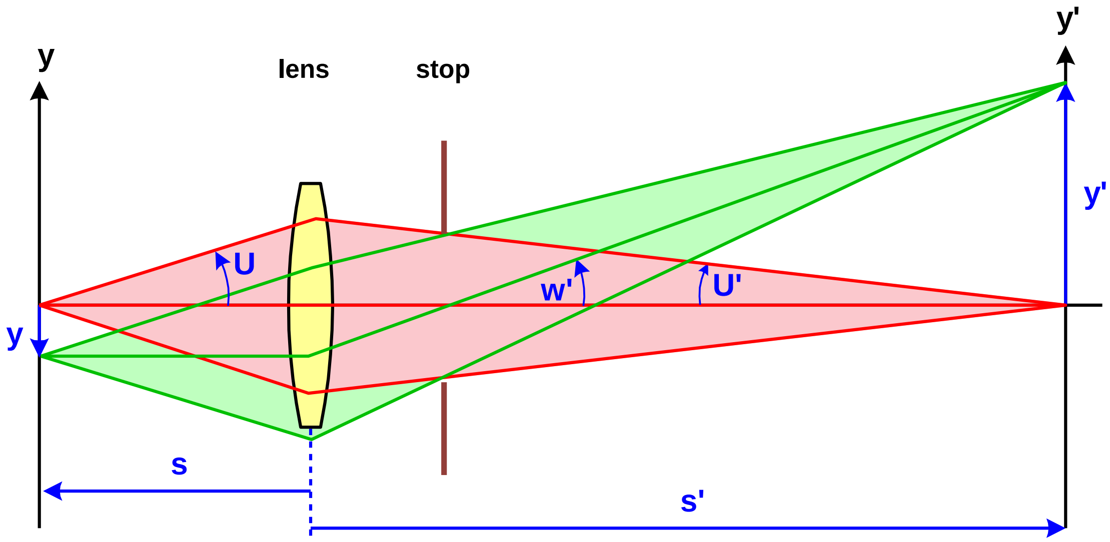
- Artificial vignetting by truncation of rays
- Change of usable pupil area due to lens diameters, stops,...
- Approximation for uniform illuminated pupils:
  irradiance decreases proportional to effective pupil area



10 Illumination
Photometry in Phase Space

- Radiation transport in optical systems
- Phase space area changes its shape
- Finite chief ray angle:
  parallelogram geometry





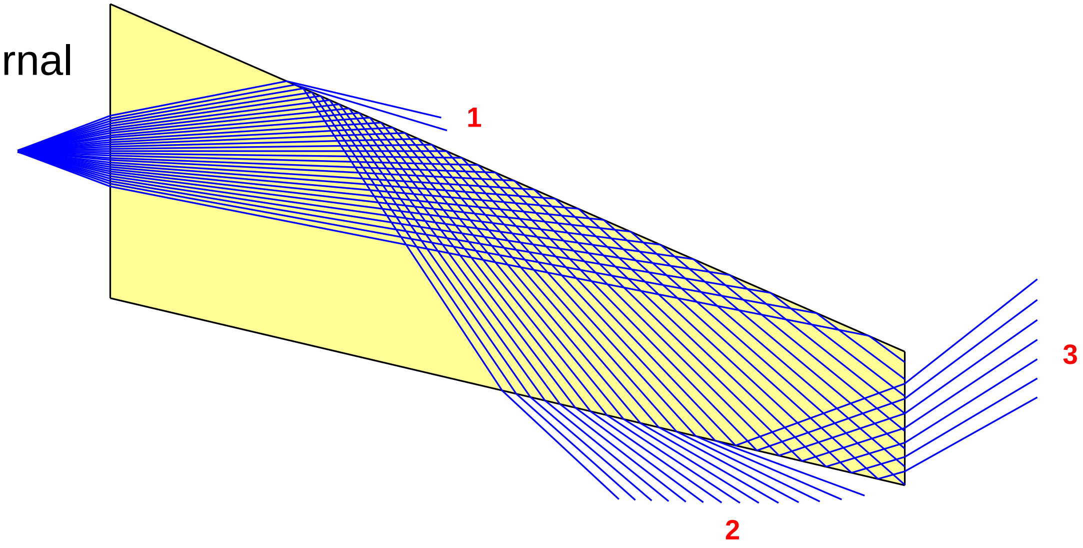
10 Illumination
Non-sequential raytrace

- Conventional raytrace:
  - the sequence of surface hits of a ray is pre-given and is defined by the index vector
  - simple and fast programming of the surface-loop of the raytrace
- Non-sequential raytrace:
  - the sequence of surface hits is not fixed
  - every ray gets ist individual path
  - the logic of the raytrace algorithm determines the next surface hit at run-time
  - surface with several new directions of the ray are allowed:
    1. partial reflection, especially Fresnel-formulas
    2. statistical scattering surfaces
    3. diffraction with several grating orders or ranges of deviation angles
- Many generalizations possible:

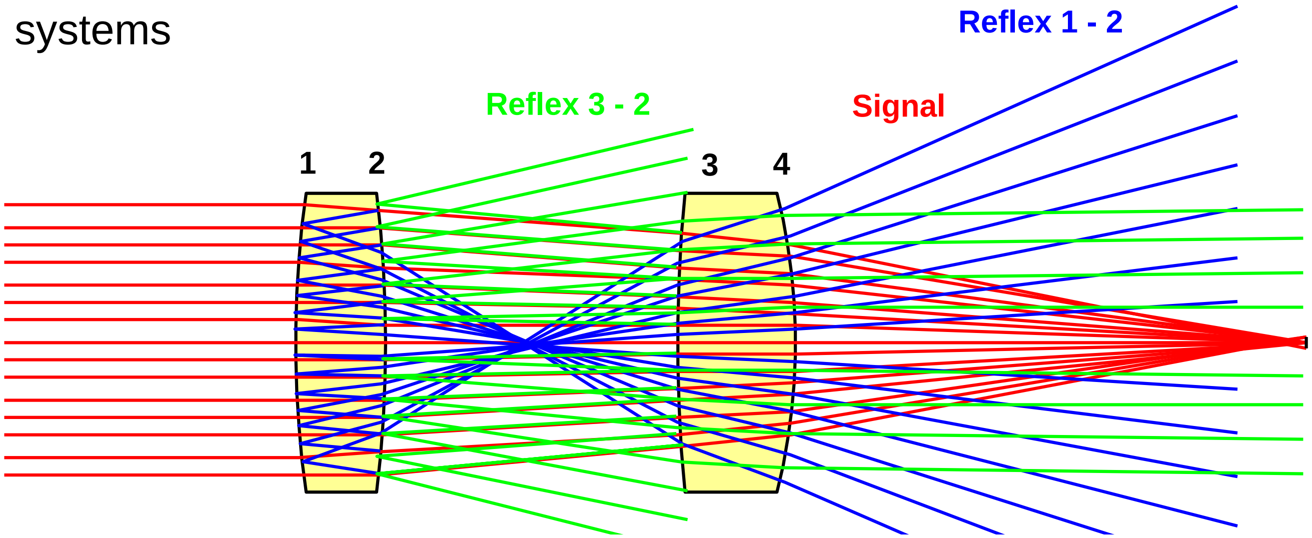
  several light sources, segmented surfaces, absorption, …
- Applications:
  1. illumination modelling
  2. statistical components (scatter plates)
  3. straylight calculation

10 Illumination
Non-sequential raytrace

1. Prism with total internal reflection



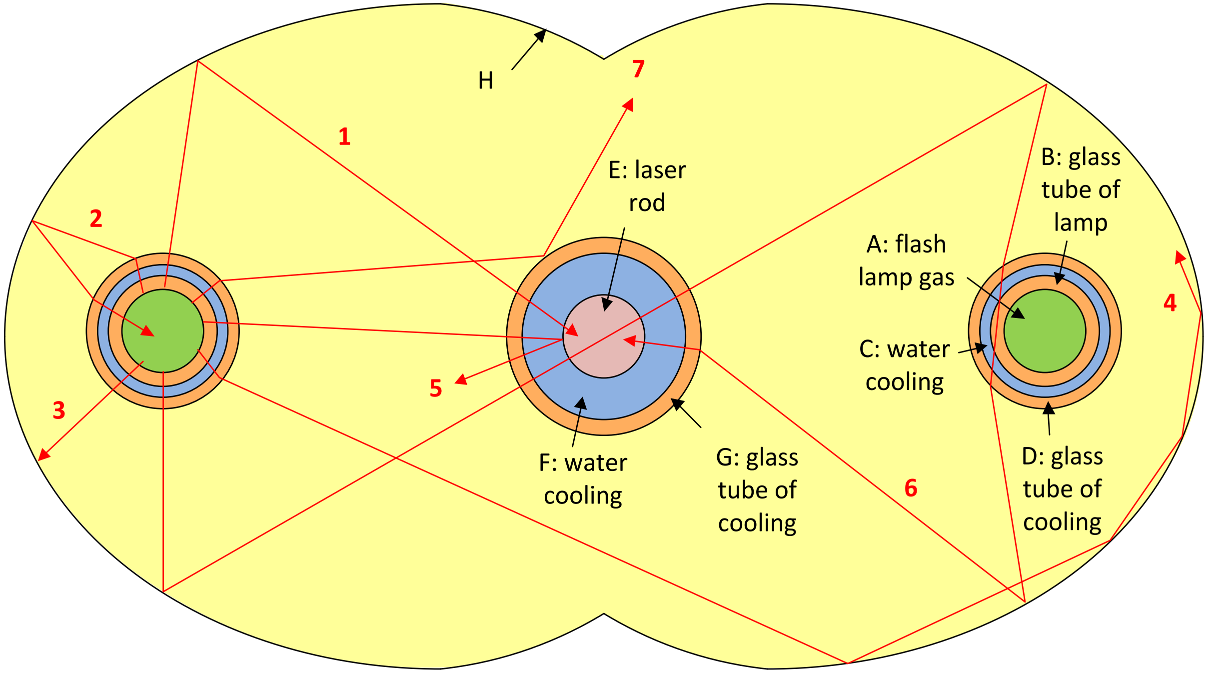
2. Ghost images in optical systems with imperfect coatings



10 Illumination
Non-sequential raytrace

3. Illumination systems, here:
   - cylindrical pump-tube of a solid state laser
   - two flash lamps (A, B) with cooling flow tubes (C, D)
   - laser rod (E) with flow tube (F, G)
   - double-elliptical mirror
     for refocussing (H)

   Different ray paths
   possible



10 Illumination
Illumination in Zemax

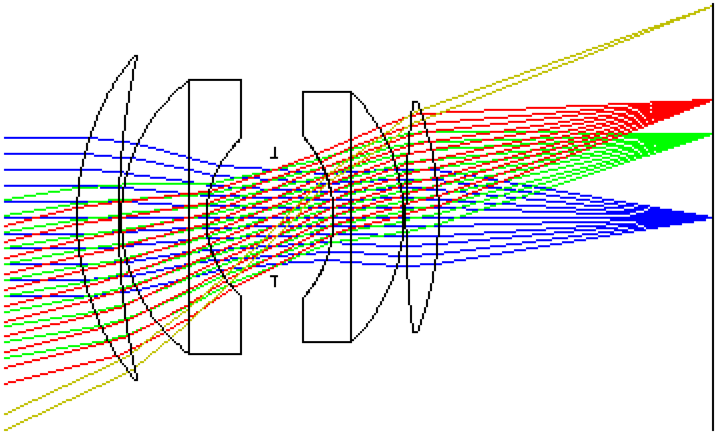
- Simple options:
  Relative illumination / vignetting for systems with rotational symmetry

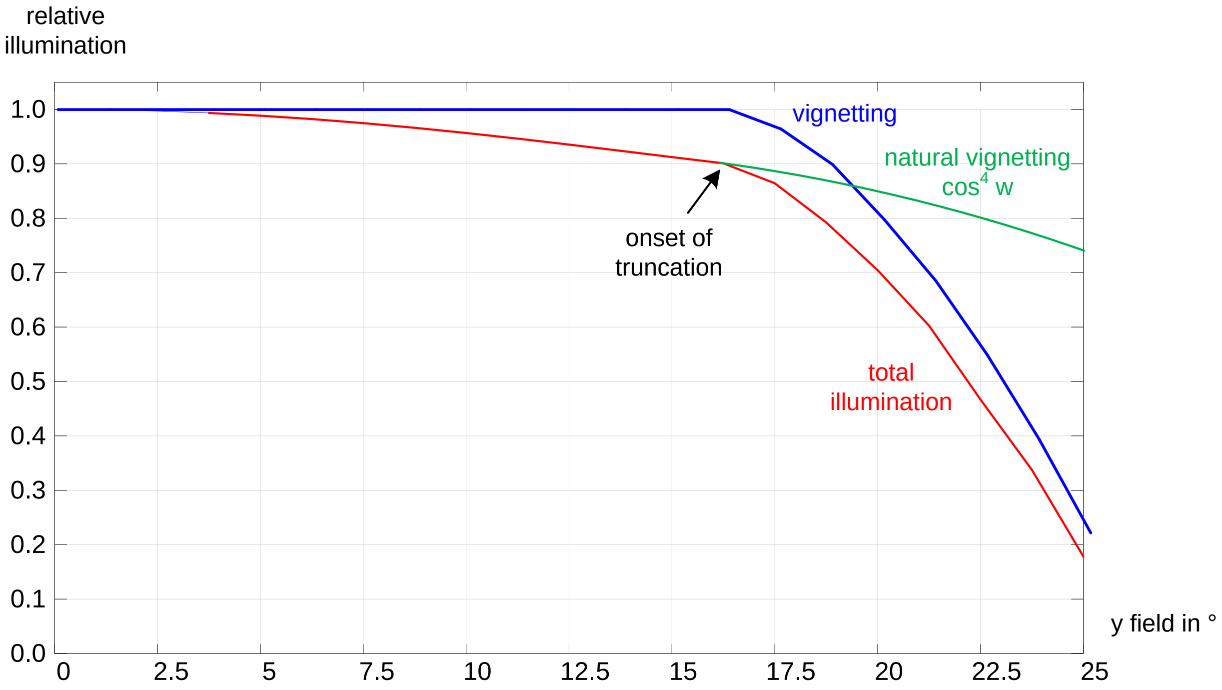
- Advanced possibility:
  - non-sequential component
  - embedded into sequential optical systems
  - examples: lightguide, arrays together with focussing optics, beam guiding,...

- General illumination calculation:
  - non-sequential raytrace with complete different philosophy of handling
  - object oriented handling: definition of source, components and detectors

10 Illumination
Relative Illumination

- Relative illumination or vignetting plot
- Transmission as a function of the field size
- Natural and arteficial vignetting are seen





10 Illumination
Illumination in Zemax

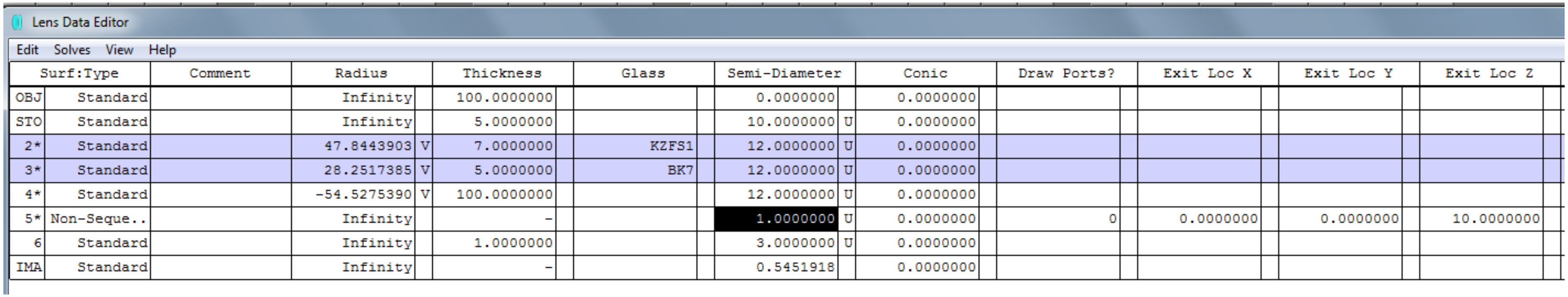
Partly non-sequential raytrace:

- Choice of surface type ‚non-sequential‘
- Non-sequential component editor with many control parameters is used to describe the element:
  - type of component
  - reference position
  - material
  - geometrical parameters
- Some parameters are used from the lens data editor too:
  entrance/exit ports as interface planes to the sequential system parts

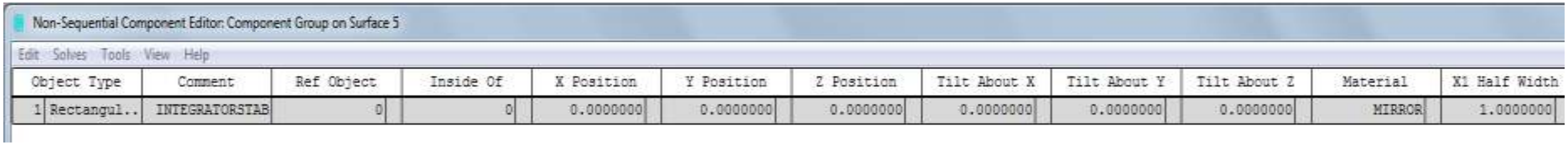
10 Illumination
Illumination in Zemax

Example:

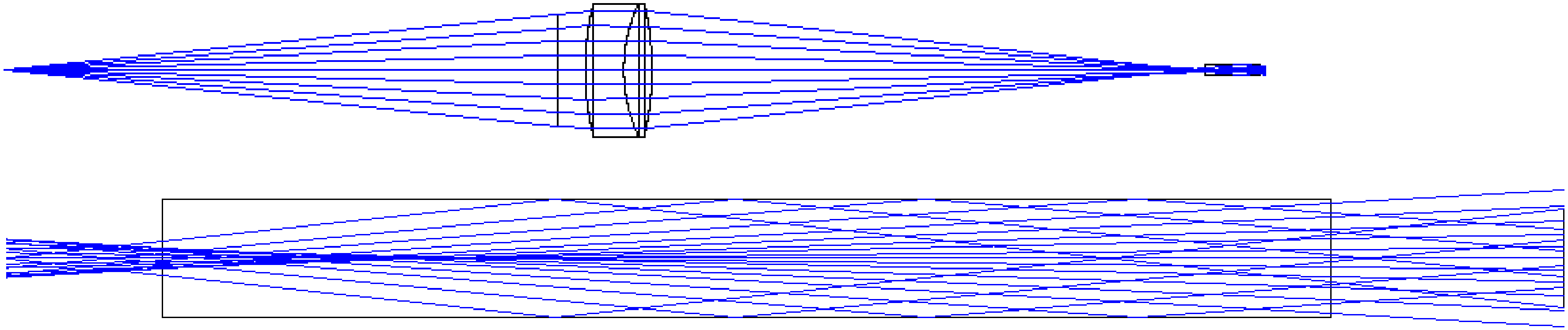
Lens focusses into a rectangular lightpipe



Surf:Type		Comment	Radius		Thickness	Glass	Semi-Diameter		Conic	Draw Ports?	Exit Loc X	Exit Loc Y	Exit Loc Z
OBJ	Standard		Infinity		100.0000000		0.0000000		0.0000000				
STO	Standard		Infinity		5.0000000		10.0000000	U	0.0000000				
2*	Standard		47.8443903	V	7.0000000	KZFS1	12.0000000	U	0.0000000				
3*	Standard		28.2517385	V	5.0000000	BK7	12.0000000	U	0.0000000				
4*	Standard		-54.5275390	V	100.0000000		12.0000000	U	0.0000000				
5*	Non-Seque..		Infinity		-		1.0000000	U	0.0000000	0	0.0000000	0.0000000	10.0000000
6	Standard		Infinity		1.0000000		3.0000000	U	0.0000000				
IMA	Standard		Infinity		-		0.5451918		0.0000000				



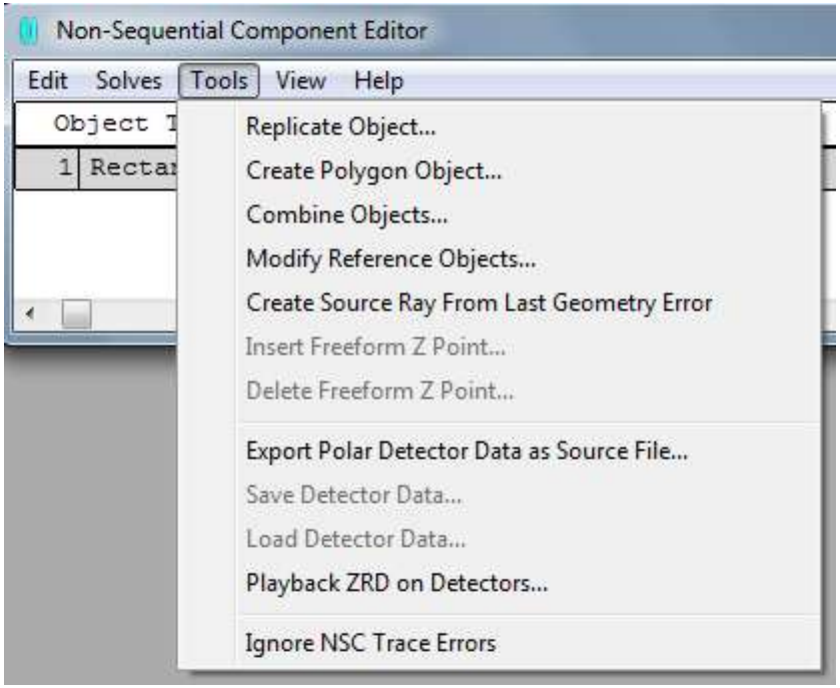
	Object Type	Comment	Ref Object	Inside Of	X Position	Y Position	Z Position	Tilt About X	Tilt About Y	Tilt About Z	Material	X1 Half Width
1	Rectangul..	INTEGRATORSTAB	0	0	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	MIRROR	1.0000000

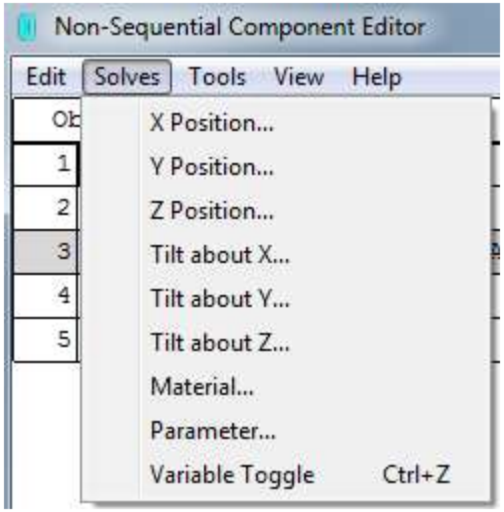


10 Illumination
Illumination in Zemax

Complete non-sequential raytrace

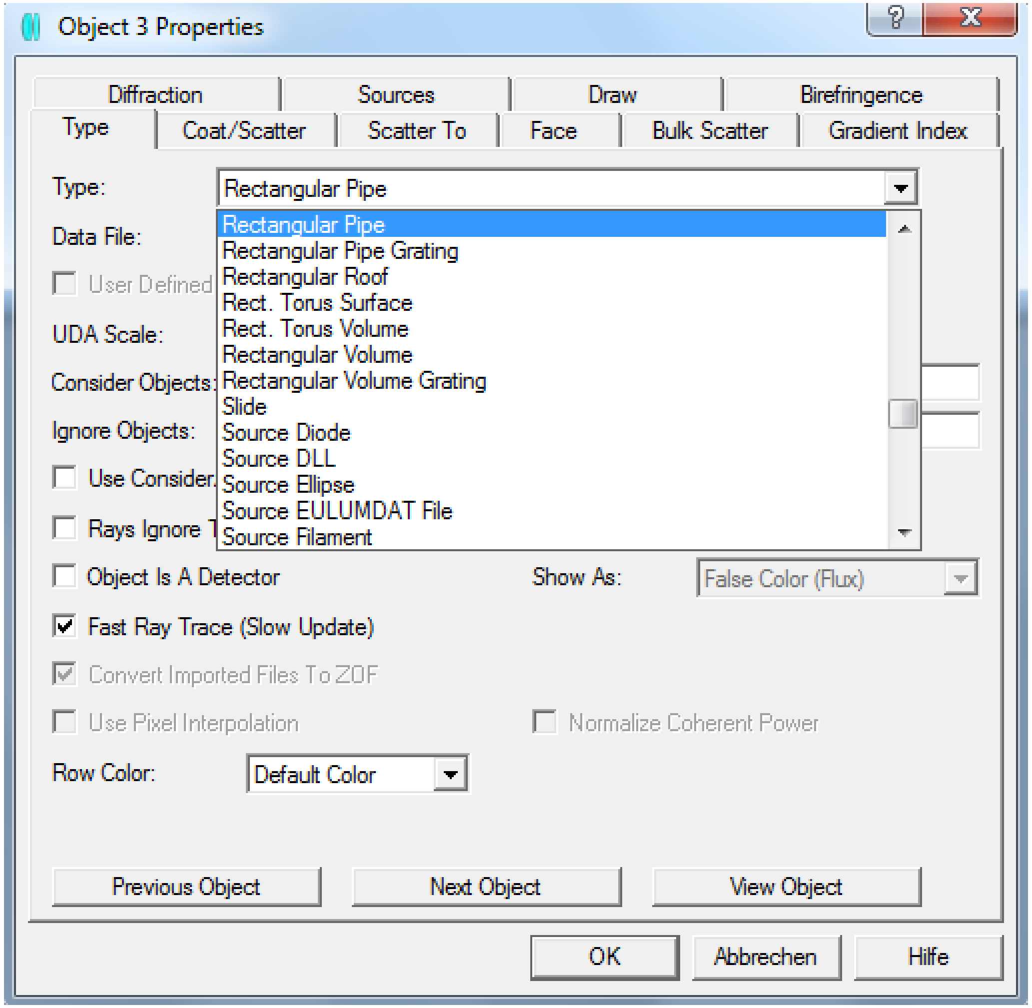
- Switch into a different control mode in File-menue
- Defining the system in the non-sequential editor, separated into
  1. sources
  2. light guiding components
  3. detectors
- Various help function are available to constitue the system
- It is a object (component) oriented philosophy
- Due to the variety of permutations, the raytrace is slow !





10 Illumination
Illumination in Zemax

- Many types of components and options are available
- For every component, several parameters can be fixed:
  - drawing options
  - coating, scatter surface
  - diffraction
  - ray splitting
  - ...



Object 3 Properties

Type: Rectangular Pipe

Rectangular Pipe
Rectangular Pipe Grating
Rectangular Roof
Rect. Torus Surface
Rect. Torus Volume
Rectangular Volume
Rectangular Volume Grating
Slide
Source Diode
Source DLL
Source Ellipse
Source EULUMDAT File
Source Filament

Data File:

☐ User Defined

UDA Scale:

Consider Objects:

Ignore Objects:

☐ Use Consider

☐ Rays Ignore T

☐ Object Is A Detector

Show As: False Color (Flux)

☑ Fast Ray Trace (Slow Update)

☑ Convert Imported Files To ZOF

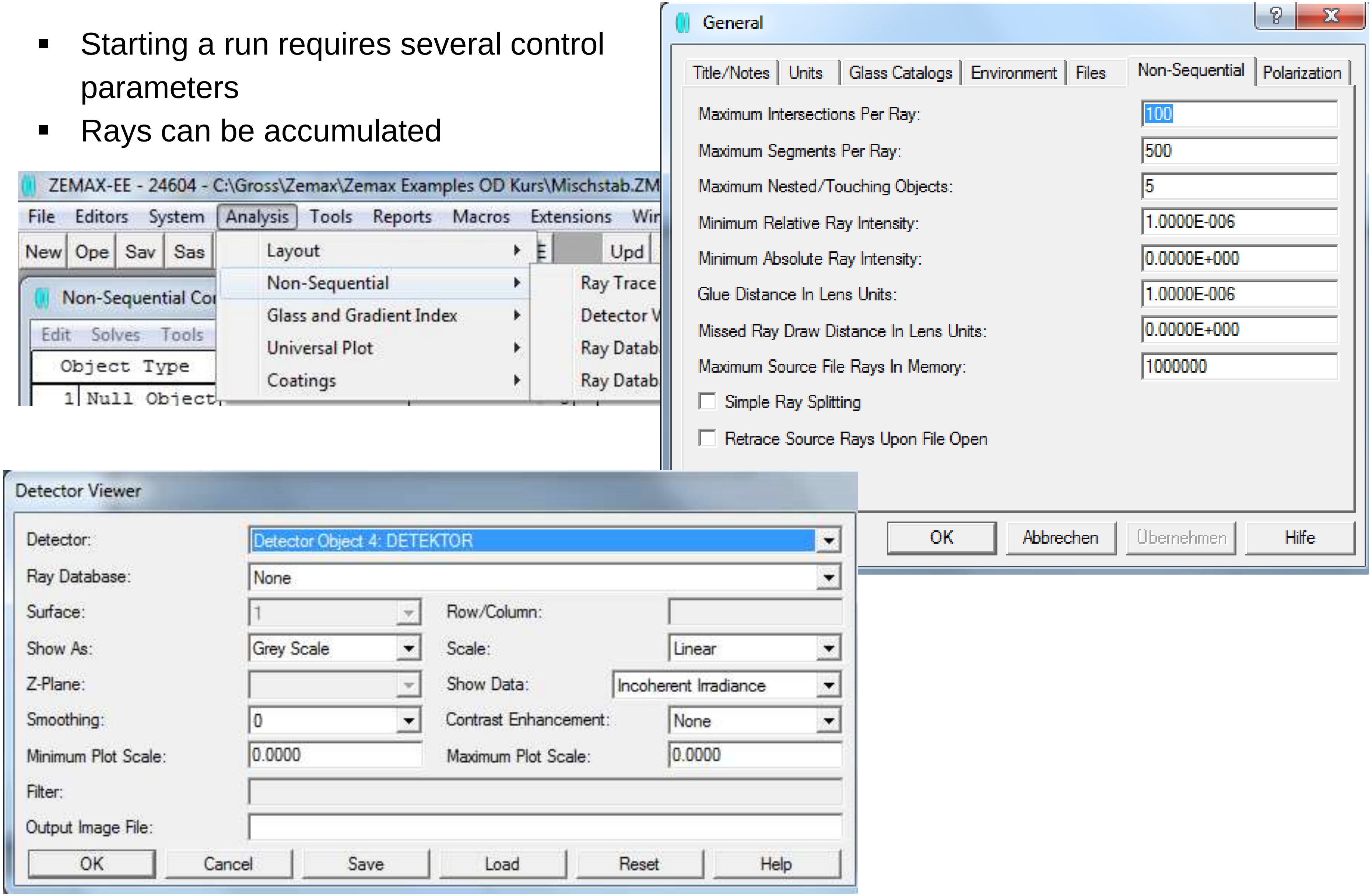
☐ Use Pixel Interpolation

☐ Normalize Coherent Power

Row Color: Default Color

10 Illumination
Illumination in Zemax

- Starting a run requires several control parameters
- Rays can be accumulated



General – Non-Sequential

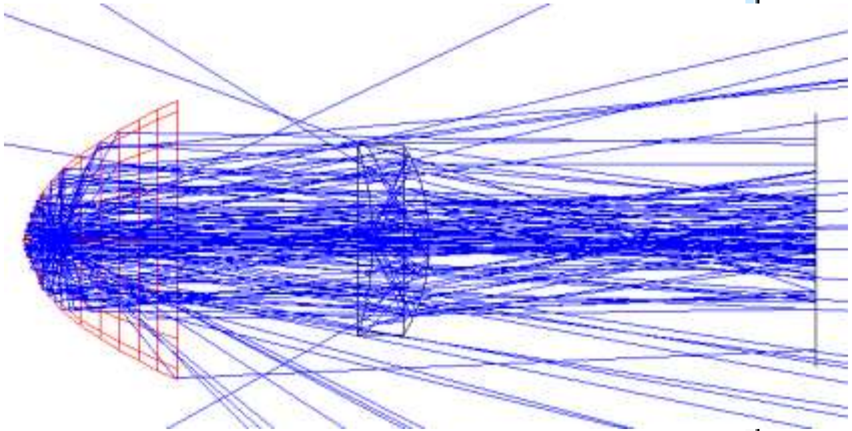
Maximum Intersections Per Ray: 100
Maximum Segments Per Ray: 500
Maximum Nested/Touching Objects: 5
Minimum Relative Ray Intensity: 1.0000E-006
Minimum Absolute Ray Intensity: 0.0000E+000
Glue Distance In Lens Units: 1.0000E-006
Missed Ray Draw Distance In Lens Units: 0.0000E+000
Maximum Source File Rays In Memory: 1000000
☐ Simple Ray Splitting
☐ Retrace Source Rays Upon File Open

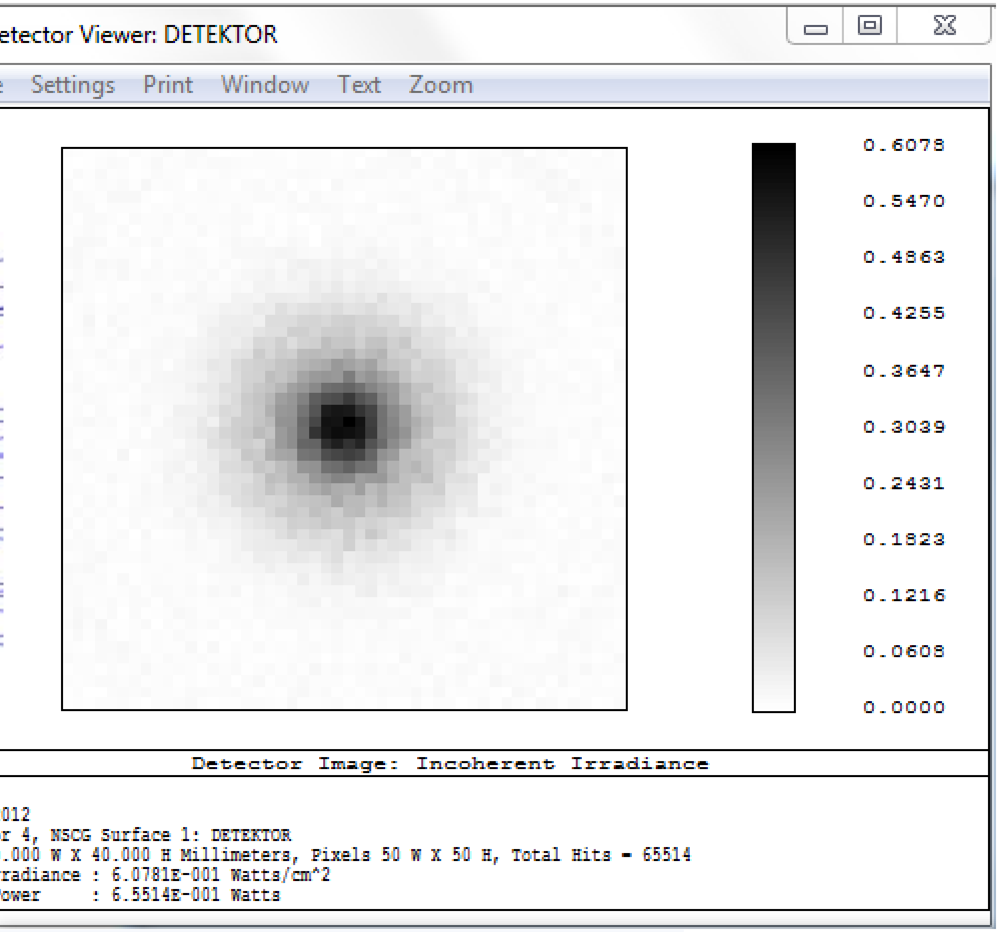
Detector Viewer

Detector: Detector Object 4: DETEKTOR
Ray Database: None
Surface: 1
Row/Column:
Show As: Grey Scale
Scale: Linear
Z-Plane:
Show Data: Incoherent Irradiance
Smoothing: 0
Contrast Enhancement: None
Minimum Plot Scale: 0.0000
Maximum Plot Scale: 0.0000
Filter:
Output Image File:

10 Illumination
Illumination in Zemax

Typical output of a run:

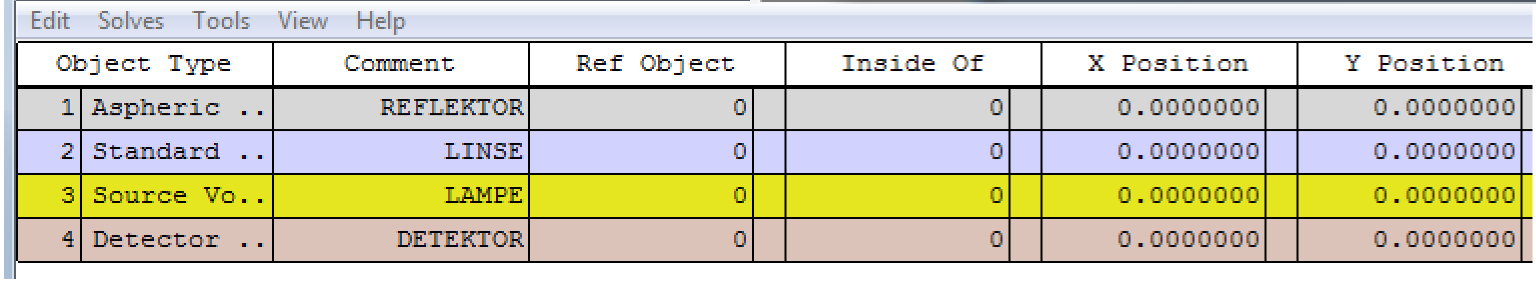




Detector Image: Incoherent Irradiance

```
Lampe
06.09.2012
Detector 4, NSCG Surface 1: DETEKTOR
Size 40.000 W X 40.000 H Millimeters, Pixels 50 W X 50 H, Total Hits = 65514
Peak Irradiance : 6.0781E-001 Watts/cm^2
Total Power     : 6.5514E-001 Watts
```

Non-Sequential Component Editor



	Object Type	Comment	Ref Object	Inside Of	X Position	Y Position
1	Aspheric ..	REFLEKTOR	0	0	0.0000000	0.0000000
2	Standard ..	LINSE	0	0	0.0000000	0.0000000
3	Source Vo..	LAMPE	0	0	0.0000000	0.0000000
4	Detector ..	DETEKTOR	0	0	0.0000000	0.0000000