Optical Design with Zemax

Lecture 5: Imaging and illumination
2012-09-11
Herbert Gross
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<td>1</td>
<td>17.07</td>
<td>Introduction</td>
<td>Zemax interface, menus, file handling, system description, editors, preferences, updates, system reports, coordinate systems, aperture, field, wavelength, glass catalogs, layouts, raytrace, diameters, stop and pupil, pick ups, solves, variables, ray fans, quick focus, 3D geometry, ideal lenses, vignetting, footprints, system insertion, scaling, component reversal</td>
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<td>2</td>
<td>24.07</td>
<td>Properties of optical systems</td>
<td>aspheres, gradient media, gratings and diffractive surfaces, special types of surfaces, telecentricity, ray aiming, afocal systems, Delano diagram, lens catalogs</td>
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<td>3</td>
<td>14.08</td>
<td>Aberrations</td>
<td>representations, spot, Seidel, transverse aberration curves, Zernike wave aberrations, PSF, MTF, ESF</td>
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<td>4</td>
<td>28.08</td>
<td>Optimization</td>
<td>algorithms, merit function, methodology, correction process, first examples</td>
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<td>5</td>
<td>11.09</td>
<td>Imaging and illumination</td>
<td>Fourier imaging, geometrical images, non-sequential option</td>
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<td>6</td>
<td>25.09</td>
<td>Advanced handling</td>
<td>slider, universal plot, I/O of data, material index fit, multi configuration, macro language, link of DLLs, MDD Matlab coupling</td>
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<tr>
<td>7</td>
<td>09.10</td>
<td>Correction I</td>
<td>simple systems, systems with medium complexity</td>
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<tr>
<td>8</td>
<td>23.10</td>
<td>Correction II</td>
<td>layout and correction of a microscopic objective lens, design and correction of a zoom system</td>
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<tr>
<td>9</td>
<td>06.11</td>
<td>Physical optical modelling I</td>
<td>Gaussian beams, POP propagation, polarization raytrace, transmission, aberrations</td>
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<tr>
<td>10</td>
<td>20.11</td>
<td>Physical optical modelling II</td>
<td>coatings, representations, transmission and phase effects, Ghost imaging, general straylight with BRDF</td>
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## Contents

1. Fundamentals of Fourier optics  
2. Physical optical image formation  
3. Imaging in Zemax  
4. Introduction in illumination  
5. Simple photometry of optical systems  
6. Non-sequential raytrace  
7. Illumination in Zemax
Phase space with spatial coordinate $x$ and
1. angle $\theta$
2. spatial frequency $\nu$ in mm$^{-1}$
3. transverse wavenumber $k_x$

$$\theta_x = \lambda \cdot \nu = \frac{k_x}{k_0}$$

$$k = 2\pi \nu$$

- Fourier spectrum $A(\nu_x, \nu_y) = \hat{F}[E(x, y)]$

  corresponds to a plane wave expansion

  $$A(k_x, k_y, z) = \int \int E(x, y, z) e^{-i(xk_x + yk_y)} \, dx \, dy$$

- Diffraction at a grating with period $g$:
  deviation angle of first diffraction order varies linear with $\nu = 1/g$

$$\sin \theta = \lambda \cdot \frac{1}{g} = \lambda \cdot \nu$$
- Arbitrary object expanded into a spatial frequency spectrum by Fourier transform
- Every frequency component is considered separately
- To resolve a spatial detail, at least two orders must be supported by the system

Ref: M. Kempe
- A structure of the object is resolved, if the first diffraction order is propagated through the optical imaging system.

- The fidelity of the image increases with the number of propagated diffracted orders.
Helmholtz wave equation:
Propagation with Green's function $g$, Amplitude transfer function, impulse response

For shift-invariance: convolution

Green's function of a spherical wave
Fresnel approximation

Calculation in frequency space: product

Optical systems:
Impulse response $g(x,y)$ is coherent transfer function, point spread function (PSF). $G(v_x, v_y)$ corresponds to the complex pupil function

Fourier transform: corresponds to a plane wave expansion

$$E(x', y', z) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} g(x', y', x, y) \cdot E(x, y) \, dx \, dy$$

$$E(x', y', z) = g(x - x', y - y', z) \ast E(x, y)$$

$$g(\vec{r}, \vec{r}') = \frac{1}{4\pi|\vec{r} - \vec{r}'|} e^{-ik|\vec{r} - \vec{r}'|}$$

$$g(x, y, z) = \frac{i}{\lambda z} e^{-ikz} e^{-\frac{i\pi}{\lambda z}(x^2 + y^2)}$$

$$E(v_x, v_y, z) = G(v_x, v_y, z) \cdot E(v_x, v_y)$$

$$G(v_x, v_y, z) = e^{-ikz + i\pi\lambda z(v_x^2 + v_y^2)}$$
- Self luminous points: emission of spherical waves
- Optical system: only a limited solid angle is propagated, the truncation of the spherical wave results in a finite angle light cone
- In the image space: uncomplete constructive interference of partial waves, the image point is spreaded
- The optical systems works as a low pass filter
5 Imaging and illumination
Optical Transfer Function: Definition

- Normalized optical transfer function (OTF) in frequency space
  \[ H_{OTF}(v_x, v_y) = \frac{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \left| g(x_p, y_p) \right|^2 \cdot e^{-2\pi i (x_p v_x + y_p v_y)} \, dx_p \, dy_p}{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \left| g(x_p, y_p) \right|^2 \, dx_p \, dy_p} \]

- Fourier transform of the Psf-intensity
  \[ H_{OTF}(v_x, v_y) = \hat{F}[I_{PSF}(x, y)] \]

- OTF: Autocorrelation of shifted pupil function, Duffieux-integral
  \[ H_{OTF}(v_x, v_y) = \frac{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \left| P(x_p + \frac{\lambda f v_x}{2}, y_p + \frac{\lambda f v_y}{2}) \cdot P^*(x_p - \frac{\lambda f v_x}{2}, y_p - \frac{\lambda f v_y}{2}) \right| \, dx_p \, dy_p}{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \left| P(x_p, y_p) \right|^2 \, dx_p \, dy_p} \]

- Absolute value of OTF: modulation transfer function (MTF)

- MTF is numerically identical to contrast of the image of a sine grating at the corresponding spatial frequency
- Optical system with magnification $m$
  Pupil function $P$,
  Pupil coordinates $x_p, y_p$
  
  \[
g_{psf}(x, y, x', y') = N \cdot \int \int P(x_p, y_p) \cdot e^{-\frac{ik}{z} \left[ x_p (x' - mx) + y_p (y' - my) \right]} \, dx_p \, dy_p
  \]

- PSF is Fourier transform of the pupil function (scaled coordinates)

\[
g_{psf}(x, y) = N \cdot \hat{F}[P(x_p, y_p)]
\]
Transfer of an extended object distribution $I(x,y)$

In the case of shift invariance (isoplanasie): coherent convolution of fields

Complex fields are additive

\[
E(x', y') = \int g_{psf}(x, y, x', y') \cdot E(x, y) \, dx \, dy
\]

\[
E(x', y') = \int g_{psf}(x - x', y - y') \cdot E(x, y) \, dx \, dy
\]

\[
E(x', y') = g_{psf}(x, y) \ast E(x, y)
\]
5 Imaging and illumination
Fourier Theory of Coherent Image Formation

- Object amplitude: $U(x,y)$
  - Fourier transform
  - Convolution
  - Result
  - PSF amplitude-response: $H_{psf}(x_p,y_p)$
    - Fourier transform
  - Coherent transfer function: $h_{CTF}(v_x,v_y)$
    - Product
    - Result
  - Image amplitude: $U'(x',y')$
    - Fourier transform

Transfer of an extended object distribution \( I(x,y) \)

In the case of shift invariance (isoplanasie): incoherent convolution

Intensities are additive

\[
I_{inc}(x', y') = \int \int \left| g_{psf}(x', x, y', y) \right|^2 \cdot I(x, y) dx dy
\]

\[
I_{inc}(x', y') = \int \int \left| g_{psf}(x'-x, y'-y) \right|^2 \cdot I(x, y) dx dy
\]

\[
I_{image}(x', y') = I_{psf}(x, y) * I_{obj}(x, y)
\]
Imaging and illumination
Fourier Theory of Incoherent Image Formation

- Object intensity $I(x,y)$
- Squared PSF, intensity-response $I_{\text{psf}}(x_p,y_p)$
- Image intensity $I'(x',y')$

Fourier transform

- Convolution

- Result

- Optical transfer function $H_{\text{OTF}}(v_x,v_y)$
- Image intensity spectrum $I'(v_x',v_y')$
Incoherent illumination:
No correlation between neighbouring object points
Superposition of intensity in the image

\[ I_{inc}(x', y') = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} g_{psf}(x', x, y', y) \cdot I(x, y) dx \, dy \]

In the case of shift invariance (isoplanasie):
Incoherent imaging with convolution

\[ I_{inc}(x', y') = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} g_{psf}(x'-x, y'-y) \cdot I(x, y) dx \, dy \]

\[ I_{image}(x', y') = I_{psf}(x, y) \ast I_{obj}(x, y) \]

In frequency space:
Product of spectra, linear transfer theory
The spectrum of the psf works as low pass filter onto the object spectrum
Optical transfer function

\[ H_{otf}(v_x, v_y) = FT[I_{PSF}(x, y)] \]

\[ I_{image}(v_x, v_y) = H_{otf}(v_x, v_y) \cdot I_{obj}(v_x, v_y) \]
5 Imaging and illumination
Incoherent Image of a Circular Disc

- Circular disc with diameter
  \[ D = d \times D_{\text{airy}} \]
- Small \( d \ll 1 \): Airy disc
- Increasing \( d \):
  Diffraction ripple disappear

<table>
<thead>
<tr>
<th>( d )</th>
<th>Image</th>
</tr>
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<tbody>
<tr>
<td>0.1</td>
<td><img src="image" alt="d=0.1" /></td>
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<tr>
<td>0.2</td>
<td><img src="image" alt="d=0.2" /></td>
</tr>
<tr>
<td>0.5</td>
<td><img src="image" alt="d=0.5" /></td>
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<tr>
<td>1.0</td>
<td><img src="image" alt="d=1.0" /></td>
</tr>
<tr>
<td>1.5</td>
<td><img src="image" alt="d=1.5" /></td>
</tr>
<tr>
<td>2.0</td>
<td><img src="image" alt="d=2.0" /></td>
</tr>
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</table>
Possible options in Zemax:

- Convolution of image with Psf
  1. geometrical
  2. with diffraction
- Geometrical raytrace analysis
  1. simple geometrical shapes (IMA-files)
  2. bitmaps
- Diffraction imaging:
  1. partial coherent
  2. extended with variable PSF
- Structure of options in Zemax not clear
- Redundance
- Field definition and size scaling not good
- Numerical conditions and algorithms partially not stable
Field height: location of object in the specific coordinates of the system
- zero padding included (not: size = diameter)
- image size shown is product of pixel number x pixel size
- can be full field or centre of local extracted part of the field

PSF-X/Y points: number of field points to incorporate the changes of the PSF, interpolation between this coarse grid

Object: bitmap
PSF: geometrical or diffraction
- Total field size: defined by system
- Field height/size: reduced field corresponding to the structure as considered in the imaging calculation
- Field position: reference point of the considered reduced field (center) in the total field
- Image size: size of the represented field size, should be a little larger as field size to clearly see the boundary

In some tools calculated as product of pixel number and pixel size
Geometrical imaging by raytrace

- Binary IMA-files with geometrical shapes
- Choice of:
  - field size
  - image size,
  - wavelengths
  - number of rays
- Interpolation possible
Geometrical imaging by raytrace of bitmaps

- Extension of 1st option: can be calculated at any surface
- If full field is used, this corresponds to a footprint with all rays
- Example: light distribution in pupil, at last surface, in image
Different types of partial coherent model algorithms possible
Only IMA-Files can be used as objects
\( \alpha \) describes the coherence factor (relative pupil filling)
Control and algorithms not clear, not stable
- Classical convolution of psf with pixels of IMA-File
- Coherent and incoherent model possible
- PSF may vary over field position
Illumination systems:

- Different requirements: energy transfer efficiency, uniformity
- Performance 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
## Imaging and illumination

### Radiometric vs Photometric Units

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<th>Quantity</th>
<th>Formula</th>
<th>Radiometric</th>
<th>Photometric</th>
</tr>
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<tbody>
<tr>
<td><strong>Energy</strong></td>
<td>Energy</td>
<td>Ws</td>
<td>Luminous Energy</td>
</tr>
<tr>
<td><strong>Power Radiation flux</strong></td>
<td>$\Phi$</td>
<td>W</td>
<td>Luminous Flux</td>
</tr>
<tr>
<td><strong>Power per area and solid angle</strong></td>
<td>$L = \frac{d^2\Phi}{\cos \theta d\Omega dA}$</td>
<td>Radiance</td>
<td>W / sr / m²</td>
</tr>
<tr>
<td><strong>Power per solid angle</strong></td>
<td>$I = \frac{d\Phi}{d\Omega} = \int L dA_\perp$</td>
<td>Radiant Intensity</td>
<td>W / sr</td>
</tr>
<tr>
<td><strong>Emitted power per area</strong></td>
<td>$E = \frac{d\Phi}{dA} = \int L \cos \theta d\Omega$</td>
<td>Radiant Excitance</td>
<td>W / m²</td>
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<tr>
<td><strong>Incident power per area</strong></td>
<td>$E = \frac{d\Phi}{dA} = \int L \cos \theta d\Omega$</td>
<td>Irradiance</td>
<td>W / m²</td>
</tr>
<tr>
<td><strong>Time integral of the power per area</strong></td>
<td>$H = \int E dt$</td>
<td>Radiant Exposure</td>
<td>Ws / m²</td>
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Imaging and 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 $V(\lambda)$ for photopic vision (daylight)

\[
\Phi_{\lambda} = K_m \cdot V(\lambda) \cdot \Phi_{\lambda}
\]

\[
K_m = 673 \frac{Lm}{W}
\]

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<tr>
<th>Illuminance</th>
<th>description</th>
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<tr>
<td>1 Lux</td>
<td>just visible</td>
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<tr>
<td>50 - 100 Lux</td>
<td>coarse work</td>
</tr>
<tr>
<td>100 Lux</td>
<td>projection onto screen</td>
</tr>
<tr>
<td>100 - 300 Lux</td>
<td>fine work</td>
</tr>
<tr>
<td>1000 Lux</td>
<td>finest work</td>
</tr>
<tr>
<td>100000 Lux</td>
<td>sunlight on paper</td>
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</table>
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 $\theta$

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

- Units: steradian $\text{sr}$
- Full space: $\Omega = 4\pi$
  half space: $\Omega = 2\pi$
- Definition can be considered as cartesian product of conventional angles

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

\[ E(\theta) = E_0 \cdot \cos \theta \]
5 Imaging and illumination

Differential Flux

- Differential flux of power from a small area element $dA_s$ with normal direction $n$ in a small solid angle $d\Omega$ along the direction $s$ of detection

$$d^2\Phi = L \cdot d\Omega \cdot dA_s$$

$$= L \cdot \cos \theta_s \cdot d\Omega \cdot dA_s$$

$$= L \cdot d\Omega \left( \vec{s} \cdot d\vec{A}_s \right)$$

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

$$\Phi$$

$$dA$$

$$A$$

$$P$$

$$\Phi$$
Radiance independent of space coordinate and angle

- The irradiance varies with the cosine of the incidence angle

- Integration over half space

- Integration of cone

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

\[ L(\bar{r}, \bar{s}) = L = \text{const} \]

\[ E(\theta) = L \cdot A \cdot \cos \theta = E_o \cdot \cos \theta \]

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

\[ \Phi_{Lam}(\varphi) = \pi AL \cdot \sin^2 \varphi \]
Imaging and 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 \( \theta_S \) and \( \theta_R \) 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.
Basic task of radiation transfer problems: 
integration of the differential flux transfer law

\[ d^2 \Phi = \frac{L}{r^2} \cdot dA_s \cdot dA_e = \frac{L}{r^2} \cdot \cos \theta_s \cdot \cos \theta_e \cdot dA_s \cdot dA_e \]

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
- Conservation of energy
- Differential flux
- No absorption
- Sine condition fulfilled

\[ d^2 \Phi = d^2 \Phi' \]

\[ d^2 \Phi = L \cdot \sin u \cdot \cos u \cdot dA \cdot du \cdot d\phi \]

\[ T = 1 \]

\[ ny \cdot \sin u = n' y' \cdot \sin u' \]
• Aplanatic systems:
sine condition fulfilled
consequence: constant radiance

• Irradiance
Irradiance in afocal systems

• Irradiance changes with the square of the numerical aperture

• Optical systems with finite image location:
m: magnification
mp: magnification of pupil imaging

Approximation mp = 1:

\[ n \times \sin \theta = n' \times \sin \theta' \]

\[ \frac{L}{n^2} = \frac{L'}{n'^2} \]

\[ E = \pi L \sin^2 \theta \]

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

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

\[ E'(m) = \left( \frac{n'}{n} \right)^2 \cdot \frac{\pi \cdot L}{4 \cdot F^2 \cdot (1 + m)^2} = \frac{E'_\infty}{(1 + m)^2} \]
- 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
5 Imaging and illumination
Natural Vignetting: Setup with Rear Stop

- Stop behind system: exact integration possible
  \[ E(w') = \frac{\pi \cdot L}{2} \cdot \left(\frac{n'}{n}\right)^2 \cdot \left[1 - \left(1 + \frac{4 \cos^2 w' \cdot \tan^2 u'}{(1 - \cos^2 w' \cdot \tan^2 u')^2}\right)^{-1/2}\right] \]

- Special case on axis
  \[ E'(0) = \pi L \cdot \sin^2 u' = \left(\frac{n'}{n}\right)^2 \cdot \pi \cdot L \cdot \sin^2 u' \]

- Approximation small aperture: Classical cos-to-the-fourth-law
  \[ E(w') = E(0) \cdot \cos^4 w' \]
Relative decrease of irradiance towards the rim of the field

<table>
<thead>
<tr>
<th>( w )</th>
<th>( \cos^4w )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>10°</td>
<td>0.94</td>
</tr>
<tr>
<td>20°</td>
<td>0.78</td>
</tr>
<tr>
<td>30°</td>
<td>0.56</td>
</tr>
</tbody>
</table>
- 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
- Radiation transport in optical systems
- Phase space area changes its shape
- Finite chief ray angle: parallelogram geometry
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 its 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
5 Imaging and illumination
Non-sequential raytrace

1. Prism with total internal reflection

2. Ghost images in optical systems with imperfect coatings
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
5 Imaging and 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
5 Imaging and illumination

Relative Illumination

- Relative illumination or vignetting plot
- Transmission as a function of the field size
- Natural and artificial vignetting are seen
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
Example:
Lens focusses into a rectangular lightpipe
Complete non-sequential raytrace

- Switch into a different control mode in File-menu
- Defining the system in the non-sequential editor, separated into
  1. sources
  2. light guiding components
  3. detectors
- Various help function are available to constitute the system
- It is a object (component) oriented philosophy
- Due to the variety of permutations, the raytrace is slow!
Many types of components and options are available
For every component, several parameters can be fixed:
- drawing options
- coating, scatter surface
- diffraction
- ray splitting
- ...
Starting a run requires several control parameters
Rays can be accumulated
Typical output of a run: