Optical Design with Zemax for PhD - Basics

Lecture 2: Fundamentals
2013-05-16
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1. Diameters
2. stop and pupil
3. Vignetting
4. Solves
5. Ray fans
6. 3D geometry
7. Afocal constellations
8. Miscellaneous
Definition of aperture and field

- Imaging on axis: circular / rotational symmetry
  Only spherical aberration and chromatical aberrations

- Finite field size, object point off-axis:
  - chief ray as reference
  - skew ray bundles: coma and distortion
  - Vignetting, cone of ray bundle not circular symmetric
  - to distinguish: tangential and sagittal plane
Quantitative measures of relative opening / size of accepted light cone

- Numerical aperture
  \[ NA = n \cdot \sin u' \]

- F-number
  \[ F\# = \frac{f'}{D_{EX}} \]

- Approximation for small apertures:
  \[ F\# = \frac{1}{2 \cdot NA} \]
The physical stop defines the aperture cone angle $u$

The real system may be complex

The entrance pupil fixes the acceptance cone in the object space

The exit pupil fixes the acceptance cone in the image space

Ref: Julie Bentley
Relevance of the system pupil:

- Brightness of the image
  Transfer of energy

- Resolution of details
  Information transfer

- Image quality
  Aberrations due to aperture

- Image perspective
  Perception of depth

- Compound systems:
  matching of pupils is necessary, location and size
Entrance and exit pupil

object point on axis

upper marginal ray

lower marginal ray

upper coma ray

lower coma ray

chief ray

outer field point of object

exit pupil

on axis point of image

stop

field point of image

entrance pupil

U

U'

W
Optical Image formation:

- Sequence of pupil and image planes
- Matching of location and size of image planes necessary (trivial)
- Matching of location and size of pupils necessary for invariance of energy density
- In microscopy known as Köhler illumination
Pupil Mismatch

- Telescopic observation with different f-numbers
- Bad match of pupil location: key hole effect

\[ F# = 2.8 \quad F# = 8 \quad F# = 22 \]

a) pupil adapted

b) pupil location mismatch

Ref: H. Schlemmer
Vignetting

- Artificial vignetting: Truncation of the free area of the aperture light cone

- Natural Vignetting: Decrease of brightness according to \( \cos \theta^4 \) due to oblique projection of areas and changed photometric distances
Vignetting

- Illumination fall off in the image due to vignetting at the field boundary
- Truncation of the light cone with asymmetric ray path for off-axis field points
- Intensity decrease towards the edge of the image
- Definition of the chief ray: ray through energetic centroid
- Vignetting can be used to avoid uncorrectable coma aberrations in the outer field
- Effective free area with extrem aspect ratio: anamorphic resolution
Different possible options for specification of the aperture in Zemax:
1. Entrance pupil diameter
2. Image space F#
3. Object space NA
4. Paraxial working F#
5. Object cone angle
6. Floating by stop size

Stop location:
1. Fixes the chief ray intersection point
2. input not necessary for telecentric object space
3. is used for aperture determination in case of aiming

Special cases:
1. Object in infinity (NA, cone angle input impossible)
2. Image in infinity (afocal)
3. Object space telecentric
There are several different types of diameters in Zemax:

1. Surface stop
   - defines the axis intersection of the chief ray
   - usually no influence on aperture size
   - only one stop in the system
   - is indicated in the Lens Data Editor by **STO**
   - if the initial aperture is defined, the size of the stop semi-diameter is determined by marginal raytrace
Diameters in Zemax

2. Userdefined diameter at a surface in the Lens Data Editor (U)
   - serves also as drawing size in the layout (for nice layouts)
   - if at least one diameter is fixed, the initial aperture can be computed automatically by
     General / Aperture Type / Float by Stop Size
     This corresponds to a ray aiming

3. Individual diameter of perhaps complicated shape at every surface (‘apertures‘)
   - no impact on the drawing
   - is indicated in the Lens Data Editor by a star
   - the drawing of vignetted rays can by switched on/off
4. Individual aperture sizes for every field point can be set by the vignetting factors of the Field menu.
- real diameters at surfaces must be set
- reduces light cones are drawn in the layout
VDX, VDY: relative decenter of light cone in x, y
VCX, VCY: compression factors in x, y
VAN: azimuthal rotation angle of light cone
- If limiting diameters are set in the system, the corresponding factors can be calculated by the Set Vig command
In the Tools-menu, the diameters and apertures can be converted automatically.
- Value of the parameter depends on other requirement
- Pickup of radius/thickness: linear dependence on other system parameter
- Determined to have fixed:
  - marginal ray height
  - chief ray angle
  - marginal ray normal
  - chief ray normal
  - aplanatic surface
  - element power
  - concentric surface
  - concentric radius
  - F number
  - marginal ray height
  - chief ray height
  - edge thickness
  - optical path difference
  - position
  - compensator
  - center of curvature
  - pupil position
Solves

- Examples for solves:
  1. last radius forces given image aperture
  2. get symmetry of system parts
  3. multiple used system parts
  4. moving lenses with constant system length
  5. bending of a lens with constant focal length
  6. non-negative edge thickness of a lens
  7. bending angle of a mirror (i′=i)
  8. decenter/tilt of a component with return
- Open different menus with a right-mouse-click in the corresponding editor cell
- Solves can be chosen individually
- Individual data for every surface in this menu
3D geometry

- General input of tilt and decenter:
  Coordinate break surface
- Change of coordinate system with lateral translation and 3 rotations angles
- Direct listing in lens editor
- Not shown in layout drawing
3D geometry

- Auxiliary menus:
  1. Tilt/Decenter element
  2. Folding mirror
3D geometry

- Local tilt and decenter of a surface
  1. no direct visibility in lens editor
     only + near surface index
  2. input in surface properties
  3. with effect on following system surfaces
- **Meridional rays:** in main cross section plane
- **Sagittal rays:** perpendicular to main cross section plane
- **Coma rays:** Going through field point and edge of pupil
- **Oblique rays:** without symmetry
Ray fans and ray cones

- Ray fan: 2-dimensional plane set of rays
- Ray cone: 3-dimensional filled ray cone
Off-axis object point:
1. Meridional plane / tangential plane / main cross section plane contains object point and optical axis
2. Sagittal plane: perpendicular to meridional plane through object point
- **Transverse aberrations:**
  Ray deviation form ideal image point in meridional and sagittal plane respectively

- The sampling of the pupil is only filled in two perpendicular directions along the axes

- No information on the performance of rays in the quadrants of the pupil
- Pupil sampling for calculation of transverse aberrations: all rays from one object point to all pupil points on x- and y-axis

- Two planes with 1-dimensional ray fans

- No complete information: no skew rays
- Pupil sampling in 3D for spot diagram: all rays from one object point through all pupil points in 2D

- Light cone completely filled with rays
Different types of sampling with pro and con's:
1. Polar grid: not isoenergetic
2. Cartesian: good for FFT, boundary discretization bad
3. Isoenergetic circular: good
4. Hexagonal: good
5. Statistical: good non-regularity, holes?
Artefacts due to regular gridding of the pupil of the spot in the image plane

In reality a smooth density of the spot is true

The line structures are discretization effects of the sampling
- Definition of a single ray by two points
- First point in object plane: relative normalized coordinates: Hx, Hy
- Second point in entrance pupil plane: relative normalized coordinates Px, Py
Cardinal Elements in Zemax

- Cardinal elements of a selected index range (lens or group)

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Cardinal Point Data Summary

File: C:\Users\Gross\Documents\ZEMAX\Samples\Sequential\Objective
Title: DOUBLE GAUSS
Date: 04.05.2013

Starting surface: 10
Ending surface: 11
Wavelength: 0.587600
Orientation: Y-Z
Lens units: Millimeters

Object space positions are measured with respect to surface 10. Image space positions are measured with respect to surface 11. The index in both the object space and image space is considered.

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<tr>
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<th>Object Space</th>
<th>Image Space</th>
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<tr>
<td>Focal Length</td>
<td>-81.469210</td>
<td>81.469210</td>
</tr>
<tr>
<td>Focal Planes</td>
<td>-78.283364</td>
<td>80.380092</td>
</tr>
<tr>
<td>Principal Planes</td>
<td>3.185847</td>
<td>-1.089119</td>
</tr>
<tr>
<td>Anti-Principal Planes</td>
<td>-159.752574</td>
<td>161.849302</td>
</tr>
<tr>
<td>Nodal Planes</td>
<td>3.185847</td>
<td>-1.089119</td>
</tr>
<tr>
<td>Anti-Nodal Planes</td>
<td>-159.752574</td>
<td>161.849302</td>
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Footprints

- Looking for the ray bundle cross sections
Object or field at infinity

- Image in infinity:
  - collimated exit ray bundle
  - realized in binoculars

- Object in infinity
  - input ray bundle collimated
  - realized in telescopes
  - aperture defined by diameter, not by angle
Basic Refractive Telescopes

- **Kepler typ:**
  - internal focus
  - longer total track
  - \( \Gamma > 0 \)

- **Galilei typ:**
  - no internal focus
  - shorter total track
  - \( \Gamma < 0 \)
• **Special stop positions:**
  1. stop in back focal plane: object sided telecentricity
  2. stop in front focal plane: image sided telecentricity
  3. stop in intermediate focal plane: both-sided telecentricity

• **Telecentricity:**
  1. pupil in infinity
  2. chief ray parallel to the optical axis
- Double telecentric system: stop in intermediate focus
- Realization in lithographic projection systems
Ideal lens
- one principal plane

Aplanatic lens
- principal surfaces are spheres
- the marginal ray heights in the vortex plane are different for larger angles
- inconsistencies in the layout drawings