Optical Design with Zemax for PhD - Basics

Lecture 1: Introduction
2018-10-17
Herbert Gross
Overview

- Time: Wednesday, 14.00 – 17.00
- Location: Computerpool, ACP
- Web page on IAP homepage under 'learning/materials' provides slides and exercises Zemax files
- Contents (type of the seminar):
  - Not: pure Zemax handling
  - But: - optical design with Zemax as tool
    - hands on training
    - understanding of simulation opportunities and limits
    - learning by doing
    - mix of theory/principles, presented examples and own exercises
    - questions and dialog welcome
- The content is adapted and is changed depending on progress
- Seminar: Exercises and solution of given problems integrated in the lecture
- Lecturers:
  - Yi Zhong / IAP
  - Uwe Lippmann / IOF
  - Herbert Gross / IAP+IOF
<table>
<thead>
<tr>
<th>No</th>
<th>Date</th>
<th>Subject</th>
<th>Detailed content</th>
<th>Lecturer</th>
<th>Assistant</th>
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<tbody>
<tr>
<td>1</td>
<td>17.10.</td>
<td>Introduction</td>
<td>Zemax interface, menus, file handling, system description, editors, preferences, updates, system reports, coordinate systems, aperture, field, wavelength, layouts, diameters, stop and pupil, solves</td>
<td>Yi</td>
<td>Uwe Uwe</td>
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<td>24.10.</td>
<td>Basic Zemax handling</td>
<td>Raytrace, ray fans, paraxial optics, surface types, quick focus, catalogs, vignetting, footprints, system insertion, scaling, component reversal</td>
<td>x</td>
<td>Ziyao</td>
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<td>07.11.</td>
<td>Properties of optical systems</td>
<td>aspheres, gradient media, gratings and diffractive surfaces, special types of surfaces, telecentricity, ray aiming, afocal systems</td>
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<td>14.11.</td>
<td>Aberrations I</td>
<td>representations, spot, Seidel, transverse aberration curves, Zernike wave aberrations</td>
<td>x</td>
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<td>Aberrations II</td>
<td>Point spread function and transfer function</td>
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<td>Advanced handling</td>
<td>slider, universal plot, I/O of data, material index fit, multi configuration, macro language</td>
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<td>Fourier imaging, geometrical images</td>
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<td>Adaptive optics, stock lens matching, index fit, Macro language, coupling Zemax-Matlab / Python</td>
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<td>W. Smith, Modern lens design, McGraw Hill, 2005</td>
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<td>Geary, Lens Design with practical Examples, Willmann-Bell, 2002</td>
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<td>G. Smith, Practical computer-aided lens design, Willman Bell, 1998</td>
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<td>H. Sun, Lens Design, CRC Press 2017</td>
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</table>
Content

1. Introduction
2. Zemax interface, menues, file handling, preferences
3. Editors, updates, windows, preferences
4. Coordinate systems and notations
5. System description, reports
6. Component reversal, system insertion, scaling
7. Solves and pickups, variables
8. 3D geometry
9. Aperture, field, wavelength
10. Glass catalogs
11. Raytrace
12. Layouts
Modelling of Optical Systems

- Principal purpose of calculations:

1. Solving the direct problem of understanding the properties: analysis

2. Solving the inverse problem: Finding the concrete system data for a required functionality: synthesis

Ref: W. Richter
Approximation of Optical Models

- Imaging model with levels of refinement

- Paraxial model (focal length, magnification, aperture,..)
  - linear approximation
  - Geometrical optics
    - Analytical approximation (3rd order aberrations,..)
      - exact geometry
  - approximation $\lambda \to 0$
    - Wave optics
      - Scalar approximation Helmholtz equation (PSF, OTF,..)
        - no time dependence
        - Maxwell equations
          - no description of small structures and polarization effects
            - no description of short pulses
              - exact

- no aberrations
- no higher order aberrations
- no diffraction
- no description of small structures and polarization effects
- no description of short pulses
- exact
- Different levels of modelling in optical propagation
- Schematical illustration (not to scale)

Ref: A. Herkommer
Five levels of modelling:

1. Geometrical raytrace with analysis
2. Equivalent geometrical quantities, classification
3. Physical model: complex pupil function
4. Primary physical quantities
5. Secondary physical quantities

Blue arrows: conversion of quantities
Settings and Environment

- The settings can be customized in the preferences
- All the settings can be saved
- Important:
  - data file folders
  - graphics parameters
  - editor cell size and Text font
  - preferred fast button functions
  - colors
  - language (don't use German !)
Zemax interface

- Helpful shortcuts:
  1. F3 undo
  2. F2 edit a cell in the editor
  3. cntr A multiconfiguration toggle
  4. cntr V variable toggle
  5. F6 merit function editor
  6. cntr U update
  7. shift cntr Q quick focus

- Window options:
  1. several export options:
     - save clipboard - save as BMP/JPEG/PNG
  2. fixed aspect ratios
  3. clone
  4. adding comments or graphics
Description of optical systems

- Interface surfaces
  - mathematical modelled surfaces
  - planes, spheres, aspheres, conics, free shaped surfaces,…

- Size of components
  - thickness and distances along the axis
  - transversal size, circular diameter, complicated contours

- Geometry of the setup
  - special case: rotational symmetry
  - general case: 3D, tilt angles, offsets and decentrations, needs vectorial approach

- Materials
  - refractive indices for all used wavelengths
  - other properties: absorption, birefringence, nonlinear coefficients, index gradients,…

- Special surfaces
  - gratings, diffractive elements
  - arrays, scattering surfaces
3D Geometry

- Auxiliary menus:
  1. Tilt/Decenter element
  2. Scale lens
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

- 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
Menu:
reports / prescription data
**SURFACE DATA SUMMARY:**

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<th>Radius</th>
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<th>Glass</th>
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**INDEX OF REFRACTION DATA:**

System Temperature: 20,0000 Celsius  
System Pressure: 1,0000 Atmospheres  
Absolute air index: 1,000273 at wavelength 0.546074 µm  
Index data is relative to air at the system temperature and pressure.  
Wavelengths are measured in air at the system temperature and pressure.

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Important Surface Types

- Standard spherical and conic sections
- Even asphere classical asphere
- Paraxial ideal lens
- Paraxial XY ideal toric lens
- Coordinate break change of coordinate system
- Diffraction grating line grating
- Gradient 1 gradient medium
- Toroidal cylindrical lens
- Zernike Fringe sag surface as superposition of Zernike functions
- Extended polynomial generalized asphere
- Black Box Lens hidden system, from vendors
- ABCD paraxial segment
Selection of Wavelengths

- Setting of wavelengths:
  - maximum of 24 values
  - weighting factors allow for spectral modelling
  - unit is always µm
  - selection of primary wavelength: paraxial data are based on it
System changes

- Useful commands for system changes:
  1. Make double pass
  2. Scale to focal length
  3. Reverse element
  4. Add / delete folding mirror
  5. Tilt/decenter elements
     (see next page)

2. Insert system with other system file
Coordinate Systems and Sign of Quantities

- Coordinate systems
  2D sections: y-z shown

- Sign of lengths, radii, angles:
  - s
    - negative: to the left
    - positive: + R to the right
  + s
  - R
    - negative: C to the left
    - positive: C to the right
  + j
    - reference angle positive: counterclockwise
- Single step:
  - surface and transition
  - parameters: radius, diameter, thickness, refractive index, aspherical constants, conic parameter, decenter, tilt,

- Complete system:
  - sequence of surfaces
  - object has index 0
  - image has index N
  - $t_N$ does not exist

- Ray path has fixed sequence
  0-1-2-...-(N-1)-N
Necessary data for system calculation:
1. system surfaces with parameters (radius)
2. distances with parameters (length, material)
3. stop surface
4. wavelength(s)
5. aperture
6. field point(s)

Optional inputs:
1. finite diameters
2. vignetting factors
3. decenter and tilt
4. coordinate reference
5. weighting factors
6. multi configurations
7. ...
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
Pupil stop defines:
1. chief ray angle \( w \)
2. aperture cone angle \( u \)

The chief ray gives the center line of the oblique ray cone of an off-axis object point
The coma rays limit the off-axis ray cone
The marginal rays limit the axial ray cone
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
Properties of the pupil

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

- Entrance pupil
- Exit pupil
- Upper marginal ray
- Chief ray
- Lower coma ray
- Upper coma ray
- Lower marginal ray
- Outer field point of object
- Field point of image
- On axis point of object

Symbols:
- U
- U'
- W
- Generalization of paraxial picture: Principal surface works as effective location of ray bending
- Paraxial approximation: plane
- Real systems with corrected sine-condition (aplanatic): principal pupil sphere
Pupil sphere: equidistant sine-sampling
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
- 3D-effects due to vignetting
- Truncation of the at different surfaces for the upper and the lower part of the cone

![Diagram](image-url)
- 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
Diameters and stop sizes

1. Determination of one surface as system stop:
   - Fixes the chief ray intersection point with axis
   - can be set in surface properties menu
   - indicated by STO in lens data editor
   - determines the aperture for the option 'float by stop size'

2. Diameters in lens data editor
   - indicated U for user defined
   - only circular shape
   - effects drawing
   - effects ray vignetting
   - can be used to draw 'nice lenses' with overflow of diameter

3. Diameters as surface properties:
   - effects on rays in drawing (vignetting)
   - no effect on lens shapes in drawing
   - also complicated shapes and decenter possible
   - indicated in lens data editor by a star
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
Important types of optical materials:
1. Glasses
2. Crystals
3. Liquids
4. Plastics, cement
5. Gases
6. Metals

Optical parameters for characterization of materials
1. Refractive index, spectral resolved $n(\lambda)$
2. Spectral transmission $T(\lambda)$
3. Reflectivity $R$
4. Absorption
5. Anisotropy, index gradient, eigenfluorescence,…

Important non-optical parameters
1. Thermal expansion coefficient
2. Hardness
3. Chemical properties (resistence,…)

### Test wavelengths

<table>
<thead>
<tr>
<th>$\lambda$ in [nm]</th>
<th>Name</th>
<th>Color</th>
<th>Element</th>
</tr>
</thead>
<tbody>
<tr>
<td>248.3</td>
<td>UV</td>
<td>Hg</td>
<td></td>
</tr>
<tr>
<td>280.4</td>
<td>UV</td>
<td>Hg</td>
<td></td>
</tr>
<tr>
<td>296.7278</td>
<td>UV</td>
<td>Hg</td>
<td></td>
</tr>
<tr>
<td>312.5663</td>
<td>UV</td>
<td>Hg</td>
<td></td>
</tr>
<tr>
<td>334.1478</td>
<td>UV</td>
<td>Hg</td>
<td></td>
</tr>
<tr>
<td>365.0146</td>
<td>i</td>
<td>UV</td>
<td>Hg</td>
</tr>
<tr>
<td>404.6561</td>
<td>h</td>
<td>violett</td>
<td>Hg</td>
</tr>
<tr>
<td>435.8343</td>
<td>g</td>
<td>blau</td>
<td>Hg</td>
</tr>
<tr>
<td>479.9914</td>
<td>F'</td>
<td>blau</td>
<td>Cd</td>
</tr>
<tr>
<td>486.1327</td>
<td>F</td>
<td>blau</td>
<td>H</td>
</tr>
<tr>
<td>546.0740</td>
<td>e</td>
<td>grün</td>
<td>Hg</td>
</tr>
<tr>
<td>587.5618</td>
<td>d</td>
<td>gelb</td>
<td>He</td>
</tr>
<tr>
<td>589.2938</td>
<td>D</td>
<td>gelb</td>
<td>Na</td>
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<tr>
<td>632.8</td>
<td></td>
<td></td>
<td>HeNe-Laser</td>
</tr>
<tr>
<td>643.8469</td>
<td>C'</td>
<td>rot</td>
<td>Cd</td>
</tr>
<tr>
<td>656.2725</td>
<td>C</td>
<td>rot</td>
<td>H</td>
</tr>
<tr>
<td>706.5188</td>
<td>r</td>
<td>rot</td>
<td>He</td>
</tr>
<tr>
<td>852.11</td>
<td>s</td>
<td>IR</td>
<td>Cä</td>
</tr>
<tr>
<td>1013.98</td>
<td>t</td>
<td>IR</td>
<td>Hg</td>
</tr>
<tr>
<td>1060.0</td>
<td></td>
<td></td>
<td>Nd:YAG-Laser</td>
</tr>
</tbody>
</table>
Dispersion and Abbe number

- Description of dispersion:

  Abbe number \( \nu(\lambda) = \frac{n(\lambda) - 1}{n_F - n_C} \)

- Visual range of wavelengths:

  \( \nu_e = \frac{n_e - 1}{n_{F'} - n_{C'}} \)

- Typical range of glasses
  \( \nu_e = 20 \ldots 120 \)

- Two fundamental types of glass:
  Crone glasses:
  \( n \) small, \( \nu \) large
  Flint glasses:
  \( n \) large, \( \nu \) small

\[
\nu = \frac{n_e - 1}{n_{F'} - n_{C'}}
\]
Material with different dispersion values:
- Different slope and curvature of the dispersion curve
- Stronger change of index over wavelength for large dispersion
- Inversion of index sequence at the boundaries of the spectrum possible

![Dispersion Diagram](image)
Dispersion formulas

- **Schott formula**
  empirical

- **Sellmeier**
  Based on oscillator model

- **Bausch-Lomb**
  empirical

- **Herzberger**
  Based on oscillator model

- **Hartmann**
  Based on oscillator model

\[ n = \sqrt{a_o + a_1 \lambda^2 + a_2 \lambda^{-2} + a_3 \lambda^{-4} + a_4 \lambda^{-6} + a_5 \lambda^{-8}} \]

\[ n(\lambda) = \sqrt{A + B \frac{\lambda^2}{\lambda^2 - \lambda_1^2} + C \frac{\lambda^2}{\lambda^2 - \lambda_2^2}} \]

\[ n(\lambda) = \sqrt{A + B \lambda^2 + C \lambda^4 + D \frac{\lambda^2}{\lambda^2} + \frac{E \lambda^2}{(\lambda^2 - \lambda_o^2) + \frac{F \lambda^2}{\lambda^2 - \lambda_o^2}}} \]

\[ n(\lambda) = a_o + a_1 \lambda^2 + \frac{a_2}{\lambda^2 - \lambda_o^2} + \frac{a_3}{(\lambda^2 - \lambda_o^2)^2} \]

*mit* \( \lambda_o = 0.168 \, \mu m \)

\[ n(\lambda) = a_o + \frac{a_1}{\lambda - a_3} + \frac{a_4}{\lambda - a_5} \]
Relative partial dispersion

- Relative partial dispersion: Change of dispersion slope with $\lambda$.
- Definition of local slope for selected wavelengths relative to secondary colors

$$P_{\lambda_1\lambda_2} = \frac{n(\lambda_1) - n(\lambda_2)}{n_{F'} - n_{C'}}$$

- Special selections for characteristic ranges of the visible spectrum

$\lambda = 656 / 1014$ nm far IR
$\lambda = 656 / 852$ nm near IR
$\lambda = 486 / 546$ nm blue edge of VIS
$\lambda = 435 / 486$ nm near UV
$\lambda = 365 / 435$ nm far UV
Glass diagram

- Usual representation of glasses: diagram of refractive index vs dispersion $n(\nu)$
- Left to right: Increasing dispersion decreasing Abbe number
Glasses in Zemax

- Selection of glass catalogs in GENERAL / GLASS CATALOGS
- Viewing of dispersion curves ANALYSIS / GLASS AND GRADIENT
- Viewing of glass map
Glasses in Zemax

- Viewing of transmission curves also for several glasses in comparison

ANALYSIS / GLASS AND GRADIENT

- Definition of a glass as a variable point in the map (model glass)
Scheme of raytrace

- Ray: straight line between two intersection points
- System: sequence of spherical surfaces
- Data: - radii, curvature $c=1/r$
  - vertex distances
  - refractive indices
  - transverse diameter
- Surfaces of 2nd order:
  Calculation of intersection points
  analytically possible: fast computation

Ray: straight line between two intersection points
System: sequence of spherical surfaces
Data: - radii, curvature $c=1/r$
  - vertex distances
  - refractive indices
  - transverse diameter
Surfaces of 2nd order:
Calculation of intersection points
analytically possible: fast computation
• General 3D geometry
• Tilt and decenter of surfaces
• General shaped free form surfaces
• Full description with 3 components
• Global and local coordinate systems
- Vignetting/truncation of ray at finite sized diameter: can or can not considered (optional)
- No physical intersection point of ray with surface
- Total internal reflection
- Negative edge thickness of lenses
- Negative thickness without mirror-reflection
- Diffraction at boundaries
Definition of a single ray by two points

- First point in object plane:
  relative normalized coordinates: $H_x$, $H_y$

- Second point in entrance pupil plane:
  relative normalized coordinates $P_x$, $P_y$
- **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
- 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
Ray fan selection for transverse aberrations plots

- Transverse aberrations:
  Ray deviation from 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 of pupil sampling

- 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
- Selection of 2 points on the ray on object and entrance pupil plane
- Real and paraxial rays are tabulated
- Coordinate reference can be selected to be local or global
Graphical control of system and ray path

Principal options in Zemax:
1. 2D section for circular symmetry
2. 3D general drawing

Several options in settings
Zooming with mouse
- Different options for 3D case
- Multiconfiguration plot possible
- Rayfan can be chosen
Layout options

- Professional graphic
- Many layout options
- Rotation with mouse or arrow buttons
Looking for the ray bundle cross sections