Optical Design with Zemax

Lecture 7: Correction I
2012-10-09
Herbert Gross
## Preliminary time schedule

<table>
<thead>
<tr>
<th>No.</th>
<th>Date</th>
<th>Session</th>
<th>Topics</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>17.07.</td>
<td>Introduction</td>
<td>Zemax interface, menus, file handling, system description, editors, preferences, updates, 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>
</tr>
<tr>
<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>
</tr>
<tr>
<td>3</td>
<td>14.08.</td>
<td>Aberrations</td>
<td>Representations, spot, Seidel, transverse aberration curves, Zernike wave aberrations. PSF, MTF, ESF.</td>
</tr>
<tr>
<td>4</td>
<td>28.08.</td>
<td>Optimization</td>
<td>Algorithms, merit function, methodology, correction process, first examples.</td>
</tr>
<tr>
<td>5</td>
<td>11.09.</td>
<td>Imaging and illumination</td>
<td>Fourier imaging, geometrical images, non-sequential option.</td>
</tr>
<tr>
<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>
</tr>
<tr>
<td>7</td>
<td>09.10.</td>
<td>Correction I</td>
<td>Simple systems, systems with medium complexity.</td>
</tr>
<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>
</tr>
<tr>
<td>9</td>
<td>06.11.</td>
<td>Physical optical modelling I</td>
<td>Gaussian beams, POP propagation, polarization raytrace, transmission, aberrations.</td>
</tr>
<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>
</tr>
</tbody>
</table>
1. Symmetry principle
2. Lens bending
3. Correcting spherical aberration
4. Coma, stop position
5. Astigmatism
6. Field flattening
7. Chromatical correction
8. Retrofocus and telephoto setup
9. Design method
10. Starting points
7 Correction I
Principle of Symmetry

- Perfect symmetrical system: magnification $m = -1$
- Stop in centre of symmetry
- Symmetrical contributions of wave aberrations are doubled (spherical)
- Asymmetrical contributions of wave aberration vanishes $W(-x) = -W(x)$
- Easy correction of:
  - coma, distortion, chromatical change of magnification
Ideal symmetrical systems:
- Vanishing coma, distortion, lateral color aberration
- Remaining residual aberrations:
  1. spherical aberration
  2. astigmatism
  3. field curvature
  4. axial chromatical aberration
  5. skew spherical aberration
- Application of symmetry principle: photographic lenses
- Especially field dominant aberrations can be corrected
- Also approximate fulfillment of symmetry condition helps significantly: quasi symmetry
- Realization of quasi-symmetric setups in nearly all photographic systems

Ref: H. Zügge
Effect of bending a lens on spherical aberration

Optimal bending:
  Minimize spherical aberration

Dashed: thin lens theory
  Solid: think real lenses

Vanishing SPH for n=1.5
  only for virtual imaging

Correction of spherical aberration possible for:
  1. Larger values of the magnification parameter |M|
  2. Higher refractive indices
7 Correction I
Correcting Spherical Aberration: Lens Splitting

- Correction of spherical aberration: Splitting of lenses

- Distribution of ray bending on several surfaces:
  - smaller incidence angles reduces the effect of nonlinearity
  - decreasing of contributions at every surface, but same sign

- Last example (e): one surface with compensating effect

Ref: H. Zügge
Correcting spherical aberration by cemented doublet:

- Strong bended inner surface compensates
- Solid state setups reduces problems of centering sensitivity
- In total 4 possible configurations:
  1. Flint in front / crown in front
  2. bi-convex outer surfaces / meniscus shape
- Residual zone error, spherical aberration corrected for outer marginal ray

<table>
<thead>
<tr>
<th>Crown in front</th>
<th>Flint in front</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) 1.0 mm</td>
<td>(b) 0.25 mm</td>
</tr>
<tr>
<td>(c) 0.25 mm</td>
<td>(d) 0.25 mm</td>
</tr>
</tbody>
</table>

Ref: H. Zügge
Better correction for higher index

- Shape of lens / best bending changes from
  1. nearly plane convex for \( n = 1.5 \)
  2. meniscus shape for \( n > 2 \)

Ref: H. Zügge
Better correction for high index also for multiple lens systems

Example: 3-lens setup with one surface for compensation
Residual aberrations is quite better for higher index

Ref: H. Zügge
Perfect coma correction in the case of symmetry
But magnification $m = -1$ not useful in most practical cases

<table>
<thead>
<tr>
<th>Symmetry principle</th>
<th>Image height: $y' = 19$ mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pupil section:</td>
<td>meridional</td>
</tr>
<tr>
<td>Transverse Aberration:</td>
<td>$\Delta y'$</td>
</tr>
<tr>
<td></td>
<td>0.5 mm</td>
</tr>
</tbody>
</table>

From: H. Zügge
- Combined effect, aspherical case prevents correction.

<table>
<thead>
<tr>
<th>Plano-convex element exhibits spherical aberration</th>
<th>Sagittal coma $\Delta y$' 0.5 mm</th>
<th>Spherical aberration corrected with aspheric surface</th>
<th>Sagittal coma $\Delta y$' 0.5 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Diagram" /></td>
<td><img src="image2.png" alt="Diagram" /></td>
<td><img src="image3.png" alt="Diagram" /></td>
<td><img src="image4.png" alt="Diagram" /></td>
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<tr>
<td><img src="image5.png" alt="Diagram" /></td>
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<td><img src="image7.png" alt="Diagram" /></td>
<td><img src="image8.png" alt="Diagram" /></td>
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<td><img src="image9.png" alt="Diagram" /></td>
<td><img src="image10.png" alt="Diagram" /></td>
<td><img src="image11.png" alt="Diagram" /></td>
<td><img src="image12.png" alt="Diagram" /></td>
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</tbody>
</table>

Ref: H. Zügge
7 Correction I
Distortion and Stop Position

- Sign of distortion for single lens: depends on stop position and sign of focal power
- Ray bending of chief ray defines distortion
- Stop position changes chief ray height at the lens

<table>
<thead>
<tr>
<th>Lens</th>
<th>Stop location</th>
<th>Distortion</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>positive</td>
<td>rear</td>
<td>$V &gt; 0$</td>
<td>tele photo lens</td>
</tr>
<tr>
<td>negative</td>
<td>in front</td>
<td>$V &gt; 0$</td>
<td>loupe</td>
</tr>
<tr>
<td>positive</td>
<td>in front</td>
<td>$V &lt; 0$</td>
<td>retrofocus lens</td>
</tr>
<tr>
<td>negative</td>
<td>rear</td>
<td>$V &lt; 0$</td>
<td>reversed binocular</td>
</tr>
</tbody>
</table>

Ref: H. Zügge
Bending effects astigmatism
For a single lens 2 bending with zero astigmatism, but remaining field curvature

Ref: H. Zügge
Petzval theorem for field curvature:

1. formulation for surfaces

\[ \frac{1}{R_{\text{ptz}}} = -n_m \sum_k \frac{n_k'n_k - n_k}{n_k \cdot n_k'r_k} \]

2. formulation for thin lenses (in air)

\[ \frac{1}{R_{\text{ptz}}} = -\sum_j \frac{1}{n_j \cdot f_j} \]

- Important: no dependence on bending

- Natural behavior: image curved towards system

- Problem: collecting systems with \( f > 0 \):
  If only positive lenses: \( R_{\text{ptz}} \) always negative
Goal: vanishing Petzval curvature

\[
\frac{1}{R_{ptz}} = - \sum_j \frac{1}{n_j \cdot f_j}
\]

and positive total refractive power

\[
\frac{1}{f} = \sum_j \frac{h_j}{h_i} \cdot \frac{1}{f}
\]

for multi-component systems

Solution:

General principle for correction of curvature of image field:

1. Positive lenses with:
   - high refractive index
   - large marginal ray heights
   - gives large contribution to power and low weighting in Petzval sum

2. Negative lenses with:
   - low refractive index
   - small marginal ray heights
   - gives small negative contribution to power and high weighting in Petzval sum
### 7 Correction I

**Flattening Meniscus Lenses**

- Possible lenses / lens groups for correcting field curvature
- Interesting candidates: thick meniscus shaped lenses

\[
\frac{1}{R_{ptz}} = -\sum_k \frac{n_k' - n_k}{n_k \cdot n_k' \cdot r_k} = -\frac{1}{n \cdot f} + \left(\frac{n-1}{n}\right)^2 \cdot \frac{d}{r_1 r_2}
\]

1. **Hoeghs mensicus: identical radii**
   - Petzval sum zero
   - remaining positive refractive power

\[
F' = \frac{(n-1)^2 d}{n \cdot r^2}
\]

2. **Concentric meniscus,**
   - Petzval sum negative
   - weak negative focal length
   - refractive power for thickness \(d\):

\[
\frac{1}{R_{ptz}} = \frac{(n-1) \cdot d}{n r_1 \cdot (r_1 - d)}
\]

\[
F' = -\frac{(n-1)d}{nr_1(r_1 - d)}
\]

3. **Thick meniscus without refractive power**
   Relation between radii

\[
r_2 = r_1 - d \cdot \frac{n-1}{n}
\]

\[
\frac{1}{R_{ptz}} = \frac{(n-1)^2 \cdot d}{n r_1 \cdot [nr_1 - d \cdot (n-1)]} > 0
\]
7 Correction I
Correcting Petzval Curvature

- Group of meniscus lenses

- Effect of distance and refractive indices

From: H. Zügge
7 Correction I
Field Curvature

- Correction of Petzval field curvature in lithographic lens for flat wafer

- Positive lenses: Green $h_j$ large
- Negative lenses: Blue $h_j$ small

- Correction principle: certain number of bulges

\[ \frac{1}{R} = - \sum_j \frac{F_j}{n_j} \]

\[ F = \sum_j \frac{h_j}{h_1} \cdot F_j \]
Effect of a field lens for flattening the image surface

1. Without field lens
   curved image surface

2. With field lens
   image plane
- Compensation of axial colour by appropriate glass choice

- Chromatical variation of the spherical aberrations: spherochromatism (Gaussian aberration)

- Therefore perfect axial color correction (on axis) are often not feasible
- **Achromate:**
  - Axial colour correction by cementing two different glasses
  - Bending: correction of spherical aberration at the full aperture
  - Aplanatic coma correction possible be clever choice of materials
- **Four possible solutions:**
  - Crown in front, two different bendings
  - Flint in front, two different bendings
- **Typical:**
  - Correction for object in infinity
  - Spherical correction at center wavelength with zone
  - Diffraction limited for NA < 0.1
  - Only very small field corrected
- **Advantage of cementing:**
  solid state setup is stable at sensitive middle surface with large curvature

- **Disadvantage:**
  loss of one degree of freedom

- **Different possible realization forms in practice**

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**Diagram:**

- a) flint in front
  - edge contact
  - cemented

- b) crown in front
  - edge contact
  - cemented
  - contact on axis
  - broken, Gaussian setup
7 Correction I
Achromate : Basic Formulas

- Idea:
  1. Two thin lenses close together with different materials
  2. Total power
     \[ F = F_1 + F_2 \]
  3. Achromatic correction condition
     \[ \frac{F_1}{v_1} + \frac{F_2}{v_2} = 0 \]

- Individual power values
  \[ F_1 = \frac{1}{1 - \frac{v_2}{v_1}} \cdot F \]
  \[ F_2 = \frac{1}{1 - \frac{v_1}{v_2}} \cdot F \]

- Properties:
  1. One positive and one negative lens necessary
  2. Two different sequences of plus (crown) / minus (flint)
  3. Large \( v \)-difference relaxes the bendings
  4. Achromatic correction independent from bending
  5. Bending corrects spherical aberration at the margin
  6. Aplanatic coma correction for special glass choices
  7. Further optimization of materials reduces the spherical zonal aberration
7 Correction I
Achromate: Correction

- Cemented achromate:
  6 degrees of freedom:
  3 radii, 2 indices, ratio $\nu_1/\nu_2$

- Correction of spherical aberration:
  diverging cemented surface with positive
  spherical contribution for $n_{neg} > n_{pos}$

- Choice of glass: possible goals
  1. aplanatic coma correction
  2. minimization of spherochromatism
  3. minimization of secondary spectrum

- Bending has no impact on chromatical correction:
  is used to correct spherical aberration at the edge

- Three solution regions for bending
  1. no spherical correction
  2. two equivalent solutions
  3. one aplanatic solution, very stable
7 Correction I
Achromatic solutions in the Glass Diagram

Abbe-Diagramm
Zeichenerklärung
- Pb/As-frei: N-Typ
- Pb/As-frei und alter Typ
- Alter Typ
- Zinkkronen: N-ZK
- Kurzflintsondergläser: KzFS

Crown positive lens
Flint negative lens
Achromat
Achromate

- Longitudinal aberration
- Transverse aberration
- Spot diagram
Bending of an achromate
- optimal choice: small residual spherical aberration
- remaining coma for finite field size

Splitting achromate:
- additional degree of freedom:
  - better total correction possible
  - high sensitivity of thin air space

Aplanatic glass choice:
- vanishing coma

Cases:
- a) simple achromate, sph corrected, with coma
- b) simple achromate, coma corrected by bending, with sph
- c) other glass choice: sph better, coma reversed
- d) splitted achromate: all corrected
- e) aplanatic glass choice: all corrected

Ref: H. Zügge
Residual aberrations of an achromate
Cleary seen:
1. Distortion
2. Chromatical magnification
3. Astigmatism
Residual spherochromatism of an achromate
- Representation as function of aperture or wavelength

- Longitudinal aberration
- Defocus variation

Pupil height:
- $r_p = 1$
- $r_p = 0.707$
- $r_p = 0.4$
- $r_p = 0$

Wavelengths:
- 486 nm
- 587 nm
- 656 nm
Effect of different materials
Axial chromatical aberration changes with wavelength
Different levels of correction:
1. No correction: lens, one zero crossing point
2. Achromatic correction:
   - coincidence of outer colors
   - remaining error for center wavelength
   - two zero crossing points
3. Apochromatic correction:
   - coincidence of at least three colors
   - small residual aberrations
   - at least 3 zero crossing points
   - special choice of glass types with anomalous partial dispersion necessary
Anormal partial dispersion and normal line
- Choice of at least one special glass
- Correction of secondary spectrum: anomalous partial dispersion
- At least one glass should deviate significantly from the normal glass line
- Cemented surface with perfect refractive index match
- No impact on monochromatic aberrations
- Only influence on chromatical aberrations
- Especially 3-fold cemented components are advantages
- Can serve as a starting setup for chromatical correction with fulfilled monochromatic correction
- Special glass combinations with nearly perfect parameters

<table>
<thead>
<tr>
<th>Nr</th>
<th>Glas</th>
<th>$n_d$</th>
<th>$\Delta n_d$</th>
<th>$\nu_d$</th>
<th>$\Delta \nu_d$</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>SK16</td>
<td>1.62031</td>
<td>0.00001</td>
<td>60.28</td>
<td>22.32</td>
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<tr>
<td></td>
<td>F9</td>
<td>1.62030</td>
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<td></td>
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</tr>
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<td>4</td>
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<td>1.60720</td>
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<td>BaF5</td>
<td>1.60718</td>
<td></td>
<td></td>
<td></td>
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</table>
8 Correction II
Telephoto Systems

- Combination of a positiv and a negative lens:
  Shift of the first principal plane in front of the system
- The intersection length is smaller than the focal length: reduction factor $k$
- Typical values: $k = 0.6...0.9$
- Focal lengths:

$$f_a = \frac{f' \cdot d}{f' \cdot (1 - k) + d}$$
$$f_b = \frac{(f_a - d)(kf' - d)}{f_a - kf'}$$

- Overall length

$$L = k \cdot f'$$

- Free intersection length

$$s_f = k \cdot f' - d$$
8 Correction II  
Retrofocal System

- Combination of a negative and a positive lens:
  - Shift of the second principal plane behind the system
- The intersection length is larger than the focal length
- Application: systems for large free working distance
- Corresponds to an inverse telephoto system
Retrofocus system results form a telephoto system by inversion.

A diagram illustrating the principle of telephoto and inverse telephoto systems, showing the relationship between the focal length and the principal plane $P'$, image plane, and telephoto system.
7 Correction I
System Design Phases

1. Paraxial layout:
   - specification data, magnification, aperture, pupil position, image location
   - distribution of refractive powers
   - locations of components
   - system size diameter / length
   - mechanical constraints
   - choice of materials for correcting color and field curvature

2. Correction/consideration of Seidel primary aberrations of 3rd order for ideal thin lenses,
   fixation of number of lenses

3. Insertion of finite thickness of components with remaining ray directions

4. Check of higher order aberrations

5. Final correction, fine tuning of compromise

6. Tolerancing, manufactability, cost, sensitivity, adjustment concepts
- Existing solution modified
- Literature and patent collections
- Principal layout with ideal lenses
  successive insertion of thin lenses and equivalent thick lenses with correction control

- Approach of Shafer
  AC-surfaces, monochromatic, buried surfaces, aspherics
- Expert system
- Experience and genius
7 Correction I
Initial Conditions

Valid for object in infinity:

\[ s_1 = -\infty \]

1. Total refractive power
\[ F' = \sum_{m=1}^{M} \omega_m \sum_{n=1}^{N} F'_{nm} \]

2. Correction of Seidel aberrations
2.1 Dichromatic correction of marginal ray
axial achromatical
\[ F' = \sum_{m=1}^{M} \omega_m^2 \sum_{n=1}^{N} F'_{nm} \quad \frac{V'}{V} = \sum_{m=1}^{M} \omega_m \omega_{pm} \sum_{n=1}^{N} \frac{F'_{nm}}{V_{nm}} \]

2.2 Dichromatic correction of chief ray
achromatical lateral magnification
\[ F' = \sum_{m=1}^{M} \omega_m \sum_{n=1}^{N} \frac{F'_{nm}}{V_{nm}} \quad \frac{n'}{n} = \sum_{m=1}^{M} \sum_{n=1}^{N} \frac{F'_{nm}}{n_{nm}} \]

2.3 Field flattening
Petzval
\[ 0 = \sum_{m=1}^{M} \omega_{pm} \sum_{n=1}^{N} F'_{nm} \]

2.4 Distortion correction according
to Berek
\[ \frac{F' P}{V} = \sum_{m=1}^{M} \omega_m^2 \sum_{n=1}^{N} \frac{P_{nm} F'_{nm}}{V_{nm}} \]

3. Tri-chromatical correction
Secondary spectrum
Usefull options for accelerating a stagnated optimization:

- split a lens
- increase refractive index of positive lenses
- lower refractive index of negative lenses
- make surface with large spherical surface contribution aspherical
- break cemented components
- use glasses with anomalous partial dispersion
7 Correction I
Correction Methods

- Lens bending
- Lens splitting
- Power combinations
- Distances

Ref: H. Zügge
Operationen with zero changes in first approximation:

1. Bending a lens.
2. Flipping a lens into reverse orientation.
3. Flipping a lens group into reverse order.
4. Adding a field lens near the image plane.
5. Inserting a powerless thin or thick meniscus lens.
6. Introducing a thin aspheric plate.
7. Making a surface aspheric with negligible expansion constants.
8. Moving the stop position.
9. Inserting a buried surface for color correction, which does not affect the main wavelength.
10. Removing a lens without refractive power.
11. Splitting an element into two lenses which are very close together but with the same total refractive power.
12. Replacing a thick lens by two thin lenses, which have the same power as the two refracting surfaces.
13. Cementing two lenses a very small distance apart and with nearly equal radii.