Optical Design with Zemax for PhD - Basics

Lecture 10: Correction
2013-07-11
Herbert Gross

Summer term 2013
## Preliminary Schedule

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<th>Detailed content</th>
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<td>1</td>
<td>02.05.</td>
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<td>Zemax interface, menus, file handling, system description, editors, preferences, updates, system reports, coordinate systems, aperture, field, wavelength, glass catalogs, layouts, raytrace, system insertion, scaling, component reversal</td>
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<tr>
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<td>16.05.</td>
<td>Fundamentals</td>
<td>Diameters, stop and pupil, pick ups, solves, variables, ray fans, quick focus, 3D geometry, ideal lenses, vignetting, footprints, afocal systems,</td>
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<td>23.05.</td>
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<td>Aspheres, gratings and diffractive surfaces, special types of surfaces, telecentricity</td>
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<td>30.05.</td>
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<td>06.06.</td>
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<td>Representations, geometrical aberrations, spot, Seidel, transverse aberration curves, Zernike wave aberrations</td>
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<td>Aberrations II</td>
<td>PSF, MTF, ESF</td>
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<td>Imaging</td>
<td>Fourier imaging, geometrical images</td>
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<td>8</td>
<td>27.06.</td>
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<td>Slider, universal plot, I/O of data, multi configurations</td>
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<td>9</td>
<td>04.07.</td>
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<td>Algorithms, merit function, methodology, correction process, examples</td>
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<td>Principles, simple systems</td>
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1. Correction methods
2. Symmetry principle
3. Correction of spherical aberration
4. Coma and astigmatism
5. Field flatness
6. Chromatical correction
7. Miscellaneous
### Correction Effectiveness

- Effectiveness of correction features on aberration types

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<tr>
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<th>Primary Aberration</th>
<th>5th Order Spherical</th>
<th>Chromatic</th>
</tr>
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<tr>
<td>Spherical Aberration</td>
<td>(a)</td>
<td>(c)</td>
<td></td>
</tr>
<tr>
<td>Coma</td>
<td>(e)</td>
<td>(f)</td>
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<td>Astigmatism</td>
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<tr>
<td>Petzval Curvature</td>
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<td>Distortion</td>
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<td>Chromatic</td>
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<tr>
<td>5th Order Spherical</td>
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<tr>
<td>Axial Color</td>
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<tr>
<td>Lateral Color</td>
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<td>Secondary Spectrum</td>
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<tr>
<td>Spherochromatism</td>
<td></td>
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</tbody>
</table>

#### Action
- Makes a good impact.
- Makes a smaller impact.
- Makes a negligible impact.
- Zero influence.

#### Lens Parameters
- Lens Bending
- Power Splitting
- Power Combination
- Distances
- Stop Position

#### Material
- Refractive Index
- Dispersion
- Relative Partial Disp.
- GRIN

#### Special Surfaces
- Cemented Surface
- Aplanatic Surface
- Aspherical Surface
- Mirror
- Diffractive Surface

#### Symmetry Principle
- Field Lens

Ref: H. Zügge
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
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.
- 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
Strategy of Correction and Optimization

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
Sensitivity of a System

Representation of wave
Seidel coefficients $[\lambda]$
Structural Changes for Correction

- Lens bending

- Lens splitting

- Power combinations

- Distances

Ref : H. Zügge
- 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
Symmetrical Systems

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
Symmetry Principle

- 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
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
Splitting of lenses and appropriate bending:
1. compensating surface contributions
2. Residual zone errors
3. More relaxed setups preferred, although the nominal error is larger

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

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
- 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

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 sagittal</td>
</tr>
<tr>
<td>Transverse Aberration:</td>
<td>$\Delta y'$ 0.5 mm</td>
</tr>
</tbody>
</table>

From: H. Zügge
- Combined effect, aspherical case prevent 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>
</tr>
</tbody>
</table>

Ref: H. Zügge
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

Ref: H. Zügge
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

- Petzval theorem for field curvature:
  1. formulation for surfaces

\[
\frac{1}{R_{ptz}} = -n'_m \sum_k \frac{n'_k - n_k}{n_k \cdot n'_k \cdot r_k}
\]

  2. formulation for thin lenses (in air)

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

- Important: no dependence on bending

- Natural behavior: image curved towards system

- Problem: collecting systems with \( f > 0 \):
  If only positive lenses:
  \( R_{ptz} \) always negative
Petzval Theorem for Field Curvature

- **Goal:** vanishing Petzval curvature

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

and positive total refractive power

\[
\frac{1}{f} = \sum_j \frac{h_j}{h_1} \cdot \frac{1}{f}
\]

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
Flattening Meniscus Lenses

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

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

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

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

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

\[r_2 = r_1 - d
\]

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

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

3. Thick meniscus without refractive power
   Relation between radii

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

\[\frac{1}{R_{ptz}} = \frac{(n-1)^2 \cdot d}{nr_1 \cdot [nr_1 - d \cdot (n-1)]} > 0
\]
Field Curvature

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

- Positive lenses: Green \( h_j \text{ large} \)
- Negative lenses: Blue \( h_j \text{ small} \)

- Correction principle: certain number of bulges

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

\[
F = \sum_j \frac{h_j}{h_1} \cdot F_j
\]
Flattening Field Lens

Effect of a field lens for flattening the image surface

1. Without field lens
   curved image surface

2. With field lens
   image plane
Microscope Objective Lens

- Possible setups for flattening the field
- Goal:
  - reduction of Petzval sum
  - keeping astigmatism corrected
Axial Colour: Achromate

- 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

\[ \begin{align*}
    \text{BK7 F2} & : n = 1.5168, \\ 
    \text{F} & = 2.31 - 1.31 \\
    \text{BK7 N-SSK8 F2} & : n = 1.5168, \\ 
    \text{F} & = 4.47 - 3.47
\end{align*} \]

Ref: H. Zügge
Achromate : Basic Formulas

- **Idea:**
  1. Two thin lenses close together with different materials
  2. Total power

\[ F = F_1 + F_2 \]

- **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
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 \( n_{\text{neg}} > n_{\text{pos}} \)

- 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
Achromatic solutions in the Glass Diagram

Abbe-Diagramm

Zeichenerklärung

Po/As-frei.................................. N-Typ......
Po/As-frei und alter Typ..........................
Alter Typ..........................................
Zirkon.......................................... N-ZK......
Kurzflintsondergläser......KzFS............

Achromat

Crown positive lens

Flint negative lens
Achromate

- Achromate
- Longitudinal aberration
- Transverse aberration
- Spot diagram

![Achromatic Optical System](image.png)

- Spot diagrams for different wavelengths:
  - 486 nm
  - 587 nm
  - 656 nm

- Parameters:
  - \( r_p \)
  - \( \Delta s' \) [mm]
  - \( \lambda = 486 \text{ nm} \)
  - \( \lambda = 587 \text{ nm} \)
  - \( \lambda = 656 \text{ nm} \)

- Angular deviations:
  - 1.4°
  - 2°
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
Axial Colour: Apochromate

Anormal partial dispersion and normal line

\[ P_{g,F} \]

0.6500
0.6125
0.5750
0.5375
0.5000

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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<tbody>
<tr>
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<td>49.24</td>
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</tbody>
</table>
Principles of Glass Selection in Optimization

- Design Rules for glass selection

- Different design goals:
  1. Color correction:
     - large dispersion difference desired
  2. Field flattening:
     - large index difference desired

Ref: H. Zügge
Field Lenses

- Field lens: in or near image planes
- Influences only the chief ray: pupil shifted
- Critical: conjugation to image plane, surface errors sharply seen
Field Lens im Endoscope

without field lenses

with 1 field lens

with 2 field lenses

Ref : H. Zügge
Influence of Stop Position on Performance

- Ray path of chief ray depends on stop position
Effect of Stop Position

- Example photographic lens
- Small axial shift of stop changes transverse aberrations
- In particular coma is strongly influenced

Ref: H. Zügge
Higher Order Aberrations: Achromate, Aspheres

- Splitted achromate

- Aspherical surface

Ref: H. Zügge
Aspherical Surfaces

- Additional degrees of freedom for correction
- Exact correction of spherical aberration for a finite number of aperture rays
- Strong asphere: many coefficients with high orders, large oscillative residual deviations in zones
- Location of aspherical surfaces:
  1. spherical aberration: near pupil
  2. distortion and astigmatism: near image plane
- Use of more than 1 asphere: critical, interaction and correlation of higher orders
Aspherical Expansion Order

- Improvement by higher orders
- Generation of high gradients

![Graph showing the relationship between order and rms deviation](Diagram)
Aspheres: Correction of Higher Order

- Correction at discrete sampling
- Large deviations between sampling points
- Larger oscillations for higher orders
- Better description: slope, defines ray bending

\[ y' = c \frac{dz_A}{dy} \]

\[
\text{Corrected points with } y' = 0
\]

\[
\text{paraxial range}
\]

\[
\text{residual spherical transverse aberrations}
\]

\[
\text{perfect correcting surface}
\]

\[
\text{points with maximal angle error}
\]

\[
\text{corrected points residual angle deviation}
\]

\[
\text{real asphere with oscillations}
\]
Lenses with diffractive structured surfaces: hybrid lenses

Refractive lens: dispersion with Abbe number $\nu = 25...90$

Diffractive lens: equivalent Abbe number

$$\nu_d = \frac{\lambda_d}{\lambda_f - \lambda_c} = -3.453$$

Combination of refractive and diffractive surfaces: achromatic correction for compensated dispersion

Usually remains a residual high secondary spectrum

Broadband color correction is possible but complicated
Diffractive Optics: Dispersion

- Dispersion by grating diffraction:
  Abbe number

Relative partial dispersion

Consequence:
Large secondary spectrum

- \(\nu\)-P-diagram

\[
\nu_e = \frac{\lambda_e}{\lambda_F - \lambda_C} = -3.330
\]

\[
P_{g,F'} = \frac{\lambda_g - \lambda_{F'}}{\lambda_{F'} - \lambda_C} = 0.2695
\]
- Combination of DOE and aspherical carrier
Data:
- $\lambda = 193 \text{ nm}$
- $NA = 0.65$
- $\beta = 50$
- $s_{\text{free}} = 7.8 \text{ mm}$

Properties:
- short total track
- extreme large free working distance
- few lenses
1. Step:
Generation of high-NA on axis

- a) without meniscus lens
- b) 1 a-c meniscus lens
- c) 2 a-c meniscus lenses
- d) 3 a-c meniscus lenses
- e) 3 a-c meniscus lenses and 1 c-c meniscus lens

Numerical aperture:
- NA = 0.119
- NA = 0.214
- NA = 0.371
- NA = 0.589
Development of Microscopic Lens

- 2. Step:
  - Optimization on axis
  - Correcting thickness
  - Introducing free working distance
  - Inserting finite field

1. version:
- 2. and 4. lens to thin,
- field 20 μm

2. version:
- Free working distance to short,
- field 50 μm

3. version:
- Field 100 μm
3. Step:
- Improvements
- Additional degrees of freedom
- Material changes
- Avoiding strong bendings
- Optimization of lens-thickness
- Comparison of variants
- Fine-tuning
Development of Microscopic Lens

- Overview of the steps of development

1. Correction on axis, quality good
2. Correction with field, compact, quality not sufficient
3. Correction with triplet, some surfaces obsolet, quality not sufficient
4. Correction with one doublet and larger air distances, quality not sufficient
5. Correction with two doublets, quality nearly good enough
6. Further optimization with glass choices, better field uniformity
7. with working distance and telecentricity