Optical Design with Zemax for PhD

Lecture 11: Correction II

2016-02-17

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<table>
<thead>
<tr>
<th>No</th>
<th>Date</th>
<th>Subject</th>
<th>Detailed content</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11.11</td>
<td>Introduction</td>
<td>Zemax interface, menus, file handling, system description, editors, preferences,</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>updates, system reports, coordinate systems, aperture, field, wavelength, layouts,</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>raytrace, diameters, stop and pupil, solves, ray fans, paraxial optics</td>
</tr>
<tr>
<td>2</td>
<td>02.12</td>
<td>Basic Zemax handling</td>
<td>surface types, quick focus, catalogs, vignetting, footprints, system insertion, scaling, component reversal</td>
</tr>
<tr>
<td>3</td>
<td>09.12</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>
</tr>
<tr>
<td>4</td>
<td>16.12</td>
<td>Aberrations I</td>
<td>representations, spot, Seidel, transverse aberration curves, Zernike wave aberrations</td>
</tr>
<tr>
<td>5</td>
<td>06.01</td>
<td>Aberrations II</td>
<td>PSF, MTF, ESF</td>
</tr>
<tr>
<td>6</td>
<td>13.01</td>
<td>Optimization I</td>
<td>algorithms, merit function, variables, pick up’s</td>
</tr>
<tr>
<td>7</td>
<td>20.01</td>
<td>Optimization II</td>
<td>methodology, correction process, special requirements, examples</td>
</tr>
<tr>
<td>8</td>
<td>27.01</td>
<td>Advanced handling</td>
<td>slider, universal plot, I/O of data, material index fit, multi configuration, macro language</td>
</tr>
<tr>
<td>9</td>
<td>03.02</td>
<td>Imaging</td>
<td>Fourier imaging, geometrical images</td>
</tr>
<tr>
<td>10</td>
<td>10.02</td>
<td>Correction I</td>
<td>simple and medium examples</td>
</tr>
<tr>
<td>11</td>
<td>17.02</td>
<td>Correction II</td>
<td>advanced examples</td>
</tr>
<tr>
<td>12</td>
<td>24.02</td>
<td>Illumination</td>
<td>simple illumination calculations, non-sequential option</td>
</tr>
<tr>
<td>13</td>
<td>02.03</td>
<td>Physical optical modelling</td>
<td>Gaussian beams, POP propagation</td>
</tr>
<tr>
<td>14</td>
<td>07.03</td>
<td>Tolerancing</td>
<td>Sensitivities, Tolerancing, Adjustment</td>
</tr>
</tbody>
</table>
1. Higher order aberrations
2. Aspheres
3. Freeform surfaces
4. Miscellaneous
Higher Order Aberrations: Achromate, Aspheres

- Splitter achromate

- Aspherical surface

Ref: H. Zügge
Merte Surface

- Small difference in refractive index
- Growing higher order contributions
Merte surface:
- low index step
- strong bending
- mainly higher aberrations generated

From: H. Zügge
Basic form of a conic section superimposed by a Taylor expansion of $z$

$$z(h) = \frac{\rho h^2}{1 + \sqrt{1 - (1 + c)\rho^2 h^2}} + \sum_{m=0}^{M} a_m h^{2m+4}$$

$h$ ... Radial distance to optical axis
$\rho$ ... Curvature
$c$ ... Conic constant
$a_m$ ... Apherical coefficients

Ref: K. Uhlendorf
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 aspherical expansion orders and their associated Δy(r) values.](image)
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

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

Corrected points with \( y' = 0 \)

Residual spherical transverse aberrations

Paraxial range

Points with maximal angle error

Corrected points residual angle deviation

Real asphere with oscillations
New orthogonalization and normalization using Jacobi-polynomials $Q_m$

$$z(h) = \frac{\rho h^2}{1 + \sqrt{1 - (1 + c)\rho^2 h^2}} + \left(\frac{h}{h_{\text{max}}}\right)^4 \sum_{m=0}^{M} a_m Q_m \left(\frac{h}{h_{\text{max}}}^2\right)$$

requires normalization radius $h_{\text{max}}$
(1:1 conversion to standard aspheres possible)

Mean square slope

$$\sum_{m=0}^{M} a_m / (m + 5)$$

Ref: K. Uhlendorf
Limit gradients by special choice of the scalar product

\[ z(h) = \frac{\rho_0 h^2}{1 + \sqrt{1 - \rho_0^2 h^2}} + \frac{u(1-u)}{\sqrt{1 - \rho_0^2 h^2}} \sum_{m=0}^{M} a_m B_m(u) \quad \text{mit} \quad u := \left( \frac{h}{h_{\text{max}}} \right)^2 \]

(1:1 conversion to standard aspheres not possible)

Mean square slope

\[ \left( \frac{1}{h_{\text{max}}} \right)^2 \sum_{m=0}^{M} a_m^2 \]
Reducing the Number of Lenses with Aspheres

- Example photographic zoom lens
- Equivalent performance
- 9 lenses reduced to 6 lenses
- Overall length reduced

Photographic lens $f = 53\, \text{mm}$, $F\# = 6.5$

a) all spherical, 9 lenses

b) 3 aspheres, 6 lenses, shorter, better performance

Ref: H. Zügge
Lithographic Projection: Improvement by Aspheres

- Considerable reduction of length and diameter by aspherical surfaces
- Performance equivalent
- 2 lenses removable

a) NA = 0.8 spherical

b) NA = 0.8, 8 aspherical surfaces

Ref: W. Ulrich
Aspherization of a Camera Lens

- Selection of one aspherical surface in a photographic lens
Extended polynomials
  classical non-orthogonal monomial representation

Zernike surface
  Only useful for circular pupils and low orders

Splines
  Localized description, hard to optimize, good for manufacturing characterization

Generalized Forbes polynomials
  Promising new approach, two types, strong relation to tolerancing

Radial basis functions
  Non-orthogonal local description approach, good for local effect description

Wavelets
  Not preferred for smooth surfaces, only feasible for tolerancing

Fourier representation
  Classical description without assumptions, but not adapted to aberrations

Smooth vs segmented, faceted, steps, non-Fermat surfaces
  Real world is still more complicated
Freeform Systems: Equations of Description

- Extended polynomials in x,y:

\[ z(x, y) = \frac{c_x x^2 + c_y y^2}{1 + \sqrt{1 - (1 - \kappa_x)c_x^2 x^2 - (1 - \kappa_y)c_y^2 y^2}} + \sum_{n,m=2} a_{n,m} \cdot x^n y^m \]

- Zernike expansion

\[ z(x, y) = \frac{c_x x^2 + c_y y^2}{1 + \sqrt{1 - (1 - \kappa_x)c_x^2 x^2 - (1 - \kappa_y)c_y^2 y^2}} + \sum_{j=0} c_j \cdot Z_j(x, y) \]

- Extended Forbes asphere

\[ z(x, y) = \frac{c r^2}{1 + \sqrt{1 - c^2 r^2}} + \frac{r^2}{a^2} \cdot \left(1 - \frac{r^2}{a^2}\right) \cdot \sum_{n=0} a_n^0 Q^0_n \left(\frac{r^2}{a^2}\right) \]

\[ + \sum_{m=1} \left(\frac{r}{a}\right)^m \sum_{n=0} \left[ a_n^m \cos(m\theta) + b_n^m \sin(m\theta) \right] \cdot Q^m_n \left(\frac{r^2}{a^2}\right) \]

- Fourier expansion

\[ z(x, y) = \frac{c_x x^2 + c_y y^2}{1 + \sqrt{1 - (1 + \kappa_x)c_x^2 x^2 - (1 + \kappa_y)c_y^2 y^2}} + \sum_{n,m} B_{nm} \cdot \text{Re}\left[ e^{-ik_{nx}x - ik_{ny}y} \right] \]

- Expansion into non-orthogonal local shifted Gaussian functions (RBF)

\[ z(x, y) = \frac{c_x x^2 + c_y y^2}{1 + \sqrt{1 - (1 + \kappa_x)c_x^2 x^2 - (1 + \kappa_y)c_y^2 y^2}} + \sum_{n,m} a_{nm} \cdot e^{-\left(\frac{x-x_n}{w_x}\right)^2 - \left(\frac{y-y_n}{w_y}\right)^2} \]

- Cubic spline, locally in patch j,k defined as polynomials of order 3

\[ z_{j,k}(x, y) = \sum_{m=0}^3 \sum_{n=0}^3 a_{jkmn} \cdot (x - x_j)^m \cdot (y - y_k)^n \]
Freeform Systems: Forbes Surfaces

- Generalized approach for orthogonal surface decomposition
- Slope orthogonality is guaranteed and is related to tolerancing

\[
z(x, y) = \frac{cr^2}{1 + \sqrt{1 - c^2r^2}} + \frac{r^2 \left(1 - \frac{r^2}{a^2}\right)}{\sqrt{1 - c^2r^2}} \cdot \sum_{n=0}^{\infty} a_n^0 Q_n^0 \left(\frac{r^2}{a^2}\right)
\]

\[
+ \sum_{m=1}^{\infty} \left(\frac{r}{a}\right)^m \sum_{n=0}^{\infty} \left[a_n^m \cos(m\theta) + b_n^m \sin(m\theta)\right] \cdot Q_n^m \left(\frac{r^2}{a^2}\right)
\]

Freeform Systems: Exact Tailoring

- **History:**
  - exact solutions of Fermat-principle for one wavelength and only a few field points corresponding to the number of surfaces
  - development of algorithms for illumination tailoring
  - mostly methods are applicable for illumination and imaging

- **Dimension:**
  - 2D is much easier / 3D is complicated and often not unique

- **SMS-method of Minano**
  - construction of the surfaces ray by ray with simple procedure
  - approved method in illumination and imaging

- **Ries tailoring**
  - method used since longer time
  - exact algorithm not known

- **Oliker-Method for illumination**
  - approximation of smooth surface by sequence of parabolic arcs

- **Reality:**
  - due to finite size of source and broadband applications tailored methods are only useful for finding a good starting system for optimization
Freeform Systems: Optimization

- Optimization of systems with freeform surfaces:
  - huge number of degrees of freedom
  - large differences in convergence according to surface representation
  - local vs global influence functions
  - definition of performance and formulation of merit function is complicated and cumbersome

- Classical system matrix for local defined splines is ill conditioned

- Starting systems:
  - still more important as in conventional optics
  - only a few well known systems published
  - larger archive for starting systems not available until now
  - own experience usually is poor

- Best location of FFF surfaces inside the system:
  - still more important as in the case of circular symmetric aspheres
  - no criteria known until now
Freeform Systems: Applications

- **General purpose:**
  - Freeform surfaces are useful for compact systems with small size
  - Due to high performance requirements in imaging systems and limited technological accuracy most of the applications are in illumination systems
  - Mirror systems are developed first in astronomical systems with complicated symmetry-free geometry to avoid central obscuration

- **HMD**
  Head mounted device with extreme size constraints

- **HUD**
  Head up display, only few surfaces allowed

- **Schiefspiegler**
  - Astronomical systems without central obscuration
  - EUV mirror systems for next generation lithography systems

- **Illumination systems**
  Various applications, smooth and segmented
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
- Relative position of stop inside system
- Quantitative measure: Parameter of excentricity
  \( \chi = \frac{h_{CR} - h_{MR}}{h_{CR} + h_{MR}} \)
- Special cases:
  \( \chi = 1 \)  image plane
  \( \chi = -1 \)  pupil plane
  \( \chi = 0 \)  same effective distance from image and pupil
Parameter of Excentricity

- Example: excentricity for all surfaces
- Change: $\chi = +1 \ldots -1 \ldots +1$
Astigmatism of Oblique Mirrors

- Mirror with finite incidence angle: effective focal lengths

\[
\begin{align*}
    f_{\text{tan}} &= \frac{R \cdot \cos i}{2} \\
    f_{\text{sag}} &= \frac{R}{2 \cos i}
\end{align*}
\]

- Mirror introduces astigmatism

\[
\Delta s'_{\text{ast}} = \frac{s^2 \cdot R \cdot \sin^2 i}{2 \cos i \cdot \left( s - \frac{R \cos i}{2} \right) \cdot \left( s - \frac{R}{2 \cos i} \right)}
\]

- Parametric behavior of scales astigmatism
- Telescopes with tilted elements
- Anastigmatic solution for two mirrors

\[ \frac{\theta_2}{\theta_2} = \sqrt{r_1 \cdot r_2} \quad \frac{r_1 - 2d}{r_1} \]
Mangin Mirror

- **Principle:**
  Backside mirror, catadioptric lens

- **Advantages:**
  Mirror can be made spherical
  Refractive surface corrects spherical
  System can be made nearly aplanatic
- Seidel surface contributions of a real lens:
  - Spherical correction perfect
  - Residual axial chromatic unavoidable
Aberrations Limited by Vignetting

- Clipping of outer coma rays by vignetting
- Consequences:
  - reduced brightness
  - anisotropic resolution

Ref: H. Zügge
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:
  \[
  f_a = \frac{f' \cdot d}{f'(1 - k) + d}
  \]
  \[
  f_b = \frac{(f_a - d)(kf' - d)}{f_a - kf'}
  \]

- Overall length
  \[
  L = k \cdot f'
  \]
- Free intersection length
  \[
  s_f = k \cdot f' - d
  \]
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.