Lens Design I

Lecture 10: Optimization II
2019-06-20
Herbert Gross
<table>
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<tr>
<th>Week</th>
<th>Date</th>
<th>Topic</th>
<th>Content</th>
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<tbody>
<tr>
<td>1</td>
<td>11.04</td>
<td>Basics</td>
<td>Introduction, Zemax interface, menus, file handling, preferences, Editors, updates, windows, coordinates, System description, 3D geometry, aperture, field, wavelength</td>
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<tr>
<td>2</td>
<td>18.04</td>
<td>Properties of optical systems I</td>
<td>Diameters, stop and pupil, vignetting, layouts, materials, glass catalogs, raytrace, ray fans and sampling, footprints</td>
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<tr>
<td>3</td>
<td>25.04</td>
<td>Properties of optical systems II</td>
<td>Types of surfaces, cardinal elements, lens properties, Imaging, magnification, paraxial approximation and modelling, telecentricity, infinity object distance and afocal image, local/global coordinates</td>
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<td>4</td>
<td>02.05</td>
<td>Properties of optical systems III</td>
<td>Component reversal, system insertion, scaling of systems, aspheres, gratings and diffractive surfaces, gradient media, solves</td>
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<tr>
<td>5</td>
<td>09.05</td>
<td>Advanced handling I</td>
<td>Miscellaneous, fold mirror, universal plot, slider, multiconfiguration, lens catalogs</td>
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<td>6</td>
<td>16.05</td>
<td>Aberrations I</td>
<td>Representation of geometrical aberrations, spot diagram, transverse aberration diagrams, aberration expansions, primary aberrations</td>
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<td>7</td>
<td>23.05</td>
<td>Aberrations II</td>
<td>Wave aberrations, Zernike polynomials, measurement of quality</td>
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<td>8</td>
<td>06.06</td>
<td>Aberrations III</td>
<td>Point spread function, optical transfer function</td>
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<td>9</td>
<td>13.06</td>
<td>Optimization I</td>
<td>Principles of nonlinear optimization, optimization in optical design, general process, optimization in Zemax</td>
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<td>10</td>
<td>20.06</td>
<td>Optimization II</td>
<td>Initial systems, special issues, sensitivity of variables in optical systems, global optimization methods</td>
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<tr>
<td>11</td>
<td>27.06</td>
<td>Advanced handling II</td>
<td>System merging, ray aiming, moving stop, double pass, IO of data, stock lens matching</td>
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<tr>
<td>12</td>
<td>04.07</td>
<td>Correction I</td>
<td>Symmetry principle, lens bending, correcting spherical aberration, coma, astigmatism, field curvature, chromatical correction</td>
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<tr>
<td>13</td>
<td>11.07</td>
<td>Correction II</td>
<td>Field lenses, stop position influence, retrofocus and telephoto setup, aspheres and higher orders, freeform systems, miscellaneous</td>
</tr>
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</table>
1. Initial systems
2. Special issues
3. Sensitivity of variables in optical systems
4. Global methods
- 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
Optimization and Starting Point

- The initial starting point determines the final result
- Only the next located solution without hill-climbing is found
Initial System Influence

- Simple system of two lenses
- Criterion: spot on axis, one wavelength
- Starting with different radii of curvature: completely different solutions
- Large aperture: start with corrected marginal ray
- Large filed: start with corrected chief ray
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.
Structural Changes for Correction

- Lens bending

- Lens splitting

- Power combinations

- Distances

Ref: H. Zügge
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
- Special problem in glass optimization: finite area of definition with discrete parameters $n, \nu$

- Restricted permitted area as one possible constraint

- Model glass with continuous values of $n, \nu$ in a pre-phase of glass selection, freezing to the next adjacent glass
Sensitivity by large Incidence

- Small incidence angle of a ray: small impact of centering error
- Large incidence angle of a ray:
  - strong non-linearity range of \( \sin(i) \)
  - large impact of decenter on ray angle

Ref: H. Sun
Sensitivity and Relaxation

- Reality:
  - as-designed performance: not reached in reality
  - as-built-performance: more relevant

- Possible criteria:
  1. Incidence angles of refraction
  2. Squared incidence angles
  3. Surface powers
  4. Seidel surface contributions
  5. Permissible tolerances

- Special aspects:
  - relaxed systems does not contain higher order aberrations
  - special issue: thick meniscus lenses
Sensitivity of a System

- Quantitative measure for relaxation

\[ A_j = \omega_j \cdot \frac{F_j}{F} = \frac{h_j \cdot F_j}{h_1 \cdot F} \]

with normalization

\[ \sum_{j=1}^{k} A_j = 1 \]

- Non-relaxed surfaces:
  1. Large incidence angles
  2. Large ray bending
  3. Large surface contributions of aberrations
  4. Significant occurrence of higher aberration orders
  5. Large sensitivity for centering

- Internal relaxation can not be easily recognized in the total performance

- Large sensitivities can be avoided by incorporating surface contribution of aberrations into merit function during optimization
Sensitivity of a System

- Sensitivity/relaxation:
  Average of weighted surface contributions of all aberrations

- Correctability:
  Average of all total aberration values

- Total refractive power

  \[ F = F_1 + \sum_{j=2}^{k} \omega_j F_j \]

- Important weighting factor:
  ratio of marginal ray heights

  \[ \omega_j = \frac{h_j}{h_1} \]
### Design Solutions and Sensitivity

- **Focussing**: 3 lens with NA = 0.335
- **Spherical correction** with/without compensation
- **Red surface**: main correcting surface
- **Counterbending**: every lens in one direction

<table>
<thead>
<tr>
<th>counterbending</th>
<th>Dspot</th>
<th>SPH-min</th>
<th>SPH-max</th>
</tr>
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<tbody>
<tr>
<td>no</td>
<td>10.9</td>
<td>0.63</td>
<td>3.7</td>
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<tr>
<td>L1 +</td>
<td>0.38</td>
<td>4</td>
<td>151</td>
</tr>
<tr>
<td>L1 -</td>
<td>0.28</td>
<td>12</td>
<td>105</td>
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<tr>
<td>L2 -</td>
<td>0.19</td>
<td>14</td>
<td>95</td>
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<tr>
<td>L2 +</td>
<td>0.65</td>
<td>4</td>
<td>292</td>
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<tr>
<td>L3 -</td>
<td>0.18</td>
<td>5</td>
<td>151</td>
</tr>
<tr>
<td>L3 +</td>
<td>0.50</td>
<td>5</td>
<td>151</td>
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Relaxed Design

- Photographic lens comparison
- Data:
  - F# = 2.0
  - f = 50 mm
  - Field 20°
- Same size and quality
- Considerably tighter tolerances in the first solution

Ref: D. Shafer
Microscopic Objective Lens

- Incidence angles for chief and marginal ray
- Aperture dominant system
- Primary problem is to correct spherical aberration
Photographic lens

- Incidence angles for chief and marginal ray
- Field dominant system
- Primary goal is to control and correct field related aberrations: coma, astigmatism, field curvature, lateral color
**Effectiveness of correction features on aberration types**

<table>
<thead>
<tr>
<th>Action</th>
<th>Lens Parameters</th>
<th>Material</th>
<th>Special Surfaces</th>
<th>Structure</th>
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<tbody>
<tr>
<td></td>
<td>Lens Bending</td>
<td>(a)</td>
<td>(c)</td>
<td>(e)</td>
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<tr>
<td></td>
<td>Power Splitting</td>
<td>(b)</td>
<td>(d)</td>
<td>(f)</td>
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<tr>
<td></td>
<td>Power Combination</td>
<td>a</td>
<td>c</td>
<td>f</td>
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<td></td>
<td>Distances</td>
<td>(g)</td>
<td>(h)</td>
<td></td>
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<tr>
<td></td>
<td>Stop Position</td>
<td>(i)</td>
<td>(j)</td>
<td>(k)</td>
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<tr>
<td></td>
<td>Refractive Index</td>
<td>(l)</td>
<td></td>
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<td></td>
<td>Dispersion</td>
<td>(m)</td>
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<td></td>
<td>Relative Partial Disp.</td>
<td>(n)</td>
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<td></td>
<td>GRIN</td>
<td>(o)</td>
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<td>Cemented Surface</td>
<td>(p)</td>
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<td>Aplanatic Surface</td>
<td>(q)</td>
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<td>Aspherical Surface</td>
<td>(r)</td>
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<td></td>
<td>Mirror</td>
<td>(s)</td>
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<td></td>
<td>Diffractive Surface</td>
<td>(t)</td>
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<td>Symmetry Principle</td>
<td>(u)</td>
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<tr>
<td></td>
<td>Field Lens</td>
<td>(v)</td>
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**Aberration**

<table>
<thead>
<tr>
<th>Aberration</th>
<th>Primary Aberration</th>
<th>5th Aberration</th>
<th>Chromatic Aberration</th>
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<tbody>
<tr>
<td>Spherical</td>
<td>(a)</td>
<td>(c)</td>
<td>(e)</td>
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<tr>
<td>Coma</td>
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<td>Astigmatism</td>
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<td>Petzval Curvature</td>
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<tr>
<td>Distortion</td>
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<tr>
<td>5th Order Spherical</td>
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<td>Axial Color</td>
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<td>Lateral Color</td>
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<td>Secondary Spectrum</td>
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<td>Spherochromatism</td>
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Makes a good impact.
Makes a smaller impact.
Makes a negligible impact.
Zero influence.

Ref: H. Zügge
Number of Lenses

- Approximate number of spots over the field as a function of the number of lenses. Linear for small number of lenses. Depends on mono-/polychromatic design and aspherics.

- Diffraction limited systems with different field size and aperture.
- Simulated Annealing: temporarily added term to overcome local minimum

\[ \Delta F_{esc}(\bar{x}) = \Delta F_0 \cdot e^{-\beta \cdot (F(\bar{x}) - F_0)^2} \]

- Optimization and adaptation of annealing parameters
Global Optimization

- No unique solution
- Constraints not sufficient
  fixed:
  unwanted lens shapes
- Many local minima with
  nearly the same
  performance
- Saddel points in the merit function topology
- Systematic search of adjacent local minima is possible
- Exploration of the complete network of local minima via saddelpoints
Saddel Point Method

- Example Double Gauss lens of system network with saddelpoints