Optical Design with Zemax

Lecture 7: Optimization II
2012-12-18
Herbert Gross
## 8 Optimization II

### Time schedule

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<th>Week</th>
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<th>Topic</th>
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**Introduction**: Zemax interface, Menues, File handling, Preferences, Editors, Updates, Windows, Coordinate systems and notations, System description, Component reversal, System insertion, Scaling, 3D geometry, Aperture, Field, Wavelength

**Properties of optical systems I**: Diameters, Stop and pupil, Vignetting, Layouts, Materials, Glass catalogs, Raytrace, Ray fans and sampling, Footprints

**Properties of optical systems II**: Types of surfaces, Aspheres, Gratings and diffractive surfaces, Gradient media, Cardinal elements, Lens properties, Imaging, Magnification, Paraxial approximation and modelling

**Aberrations I**: Representation of geometrical aberrations, Spot diagram, Transverse aberration diagrams, Aberration expansions, Primary aberrations

**Aberrations II**: Wave aberrations, Zernike polynomials, Point spread function, Optical transfer function

**Advanced handling**: Telecentricity, Infinity object distance and afocal image, Local/global coordinates, Add fold mirror, Vignetting, Diameter types, Ray aiming, Material index fit, Universal plot, Slider, IO of data, Multi-configuration, Macro language, Lens catalogs

**Optimization I**: Principles of nonlinear optimization, Optimization in optical design, Global optimization methods, Solves and pickups, Variables, Sensitivity of variables in optical systems

**Optimization II**: Systematic methods and optimization process, Starting points, Optimization in Zemax

**Imaging**: Fundamentals of Fourier optics, Physical optical image formation, Imaging in Zemax

**Illumination**: Introduction in illumination, Simple photometry of optical systems, Non-sequential raytrace, Illumination in Zemax

**Correction I**: Symmetry principle, Lens bending, Correcting spherical aberration, Coma, Stop position, Astigmatism, Field flattening, Chromatical correction, Retrofocus and telephoto setup, Design method

**Correction II**: Field lenses, Stop position influence, Aspheres and higher orders, Principles of glass selection, Sensitivity of a system correction, Microscopic objective lens, Zoom system

**Physical optical modelling**: Gaussian beams, POP propagation, Polarization raytrace, Coatings
1. Principles of nonlinear optimization
2. Optimization in optical design
3. Global optimization methods
4. Sensitivity of variables in optical systems
5. Systematic methods and optimization process
6. Optimization in Zemax
### Effectiveness of correction features on aberration types

- **Primary Aberration**
  - Spherical Aberration
  - Coma
  - Astigmatism
  - Petzval Curvature
  - Distortion

- **Chromatic**
  - 5th Order Spherical Aberration
  - Axial Color
  - Lateral Color
  - Secondary Spectrum
  - Spherochromatism

#### Action

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<tr>
<th>Lens Bending</th>
<th>Power Splitting</th>
<th>Power Combination</th>
<th>Distances</th>
<th>Stop Position</th>
<th>Refractive Index</th>
<th>Dispersion</th>
<th>Relative Partial Disp.</th>
<th>Material</th>
<th>Special Surfaces</th>
<th>Symmetry Principle</th>
<th>Field Lens</th>
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<tr>
<td>a</td>
<td>c</td>
<td>f</td>
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<td>i</td>
<td>j</td>
<td>(b)</td>
<td>(d)</td>
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<td>(h)</td>
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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
8 Optimization II
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
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

\[ \frac{F'}{V} = \sum_{m=1}^{M} \omega_m^2 \sum_{n=1}^{N} \frac{F'_{nm}}{V_{nm}} \]

2.2 Dichromatic correction of chief ray

achromatical lateral magnification

\[ \frac{F'}{\bar{V}} = \sum_{m=1}^{M} \omega_m \omega_{pm} \sum_{n=1}^{N} \frac{F'_{nm}}{V_{nm}} \]

2.3 Field flattening

Petzval

\[ \frac{F'}{n} = \sum_{m=1}^{M} \sum_{n=1}^{N} \frac{F'_{nm}}{n_{nm}} \]

2.4 Distortion correction according
to Berek

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

3. Tri-chromatical correction

Secondary spectrum

\[ \frac{F' P}{V} = \sum_{m=1}^{M} \omega_m^2 \sum_{n=1}^{N} \frac{P_{nm} F'_{nm}}{V_{nm}} \]
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
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.
8 Optimization II
Structural Changes for Correction

- Lens bending

- Lens splitting

- Power combinations

- Distances

Ref: H. Zügge
8 Optimization II
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

\[ \omega_j = \frac{h_j}{h_1} \]
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
8 Optimization II
Sensitivity of a System

Representation of wave
Seidel coefficients $[\lambda]$

Double Gauss 1.4/50

Ref: H. Zügge
- Incidence angles for chief and marginal ray

- Aperture dominant system

- Primary problem is to correct spherical aberration
8 Optimization II
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
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
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Substitution of Standard Radii

- Method:
  - Insertion of nearest available radii
  - Check of optimal combinations
  - re-adjusting thicknesses
- In general system slightly decreased in performance

- Example: Photographic lens:
  Orange: original, black: new system
1. After optimization

2. After substitution

3. After re-optimization
Distribution of refractive power
- good: small W

Symmetry content
- good: large S

General trend:
- Cost of small W and large S: long systems, many lenses

Advantage of $w_j$, $s_j$-diagram:
- Identification of strange surfaces

$$W = \sqrt{\frac{1}{N} \sum_{j=1}^{N} w_j^2}$$

$$w_j = -\frac{n_j' - n_j}{1-m} \cdot \frac{y_j}{n_N' u_N'} \cdot \rho_j$$

$$S = \sqrt{\frac{1}{N} \sum_{j=1}^{N} s_j^2}$$

$$s_j = \frac{1}{1-m} \cdot \frac{n_j \cdot i_j}{n \cdot i_{\text{stop}} \cdot n_N' u_N'} \cdot \left(\frac{u_j' - u_j}{n_j'} - \frac{u_j}{n_j}\right)$$
Example:
optimizing W and S with one additional lens

Starting system:

Final design:
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Merit Function in Zemax

- Default merit function
  1.Criterion
  2. Ray sampling (high NA, aspheres,...)
  3. Boundary values on thickness of center and edge for glass / air
  4. Special options
     ▪ Add individual operands
     ▪ Editor: settings, weight, target actual value relative contribution to sum of squares
     ▪ Several wavelengths, field points, aperture points, configurations: many requirements
     ▪ Sorted result: merit function listing
If the number of field points, wavelengths or configurations is changed:
the merit function must be updated explicitly

Help function in Zemax: many operands

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**Optimization Operand Definitions**

ZEMAX supports optimization operands which are used to define the merit function. Each operand may be assigned a weight which indicates the relative importance of that operand, as well as a target, which is the desired value for that operand.

**First-order optical properties:**
AMAG, ENPP, EFFL, EFLX, EFLY, EPDI, EXPD, EXPP, ISEN, UNIV, OBSN, PIMH, PMAG, POWE, POWP, POWR, SFNO, TENO, WENO

**Aberrations:**
ABCD, ANAC, ANAR, ANAX, ANAY, ANCX, ANCY, ASTI, AXCL, BIOC, BIOD, BSER, COMA, DIXM, DISA, DISC, DISG, DIST, ECAS, FCCT, FCUR, ICUL, LONA, ODP, ODPD, OPDM, OPDX, OSCP, PEC, PET, PER, RESC, RESH, RRSE, RSRH, RWSF, RWCE, RWCH, RWRE, RWRH, SCOH, SPHA, TRAC, TRAD, TRAE, TRAI, TRAR, TRAX, TRAY, TRCX, TRCY, ZERN

**MTF data:**
GMAT, GMATS, GMTT, MSWA, MSWS, MSWT, MTF, MTFD, MTHA, MTHS, MTHT

**PSF/Strehl Ratio Data:**
STRH

**Encircled energy:**
DEN, DENS, EFRF, GEPC, GENC, GENE, XENC, XENE

**Constraints on lens data:**
CGNT, COLT, COVA, CTGT, CTLT, CTVA, CVGT, CVLT, CVVA, DMGT, DMLT, DMVA, ETGT, ETLT, ETVA, FGT, FTLT, MNCA, MNCV, MNCZ, MNEA, MNEB, MNFT, MNPD, MXCA, MXCG, MXGT, MXCV, MXFA, MXEG, MXET, MXPD, MNSD, MXSO, TTGT, TTHI, TILT, TVA, XNEA, XNET, XNEG, XXFA, XXEC, ZTHI

**Constraints on lens properties:**
CVOL, MNDT, MXDT, SAGX, SAGY, SSAG, STHI, TMAS, TOTR, VOLU, NORX, NORY, NORZ, NORD

**Constraints on parameter data:**
PMGT, PMLT, PMVA
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Merit Function in Zemax

- Classical definition of the merit function in Zemax:

\[ MF^2 = \frac{\sum W_i (V_i - T_i)^2}{\sum W_i} \]

- Special merit function options: individual operands can be composed:
  - sum, diff, prod, divi,... of lines, which have a zero weight itself
  - mathematical functions sin, sqrt, max ....
  - less than, larger than (one-sided intervals as targets)

- Negative weights:
  requirement is considered as a Lagrange multiplier and is fulfilled exact

- Optimization operands with derivatives:
  building a system insensitive for small changes (wide tolerances)

- Further possibilities for user-defined operands:
  construction with macro language (ZPLM)

- General outline:
  - use simple operands in a rough optimization phase
  - use more complex, application-related operands in the final fine-tuning phase
Defining variables: indicated by \( V \) in lens data editor
toggle: CNTR z or right mouse click

Auxiliary command: remove all variables, all radii variable, all distances variable

If the initial value of a variable is quite bad and a ray failure occurs, the optimization can not run and the merit function not be computed.
Modell glass:
characterized by index, Abbe number and relative dispersion

- Individual choice of variables
- Glass moves in Glass map
- Restriction of useful area in glass map is desirable (RGLA = regular glass area)
- Re-substitution of real glass: next neighbor in n-n-diagram
- Choice of allowed glass catalogs can be controlled in General-menu
- Other possibility to reset real glasses: direct substitution
8 Optimization II
Methods Available in Zemax

- General optimization methods
  - local
  - global
- Easy-one-dimensional optimizations
  - focus
  - adjustment
  - slider, for visual control
- Special aspects:
  - solves
  - aspheres
  - glass substitutes
- Classical local derivative:
  - DLS optimization (Marquardt)
  - orthogonal descent

- Hammer:
  - Algorithm not known
  - Useful after convergence
  - needs long time
  - must be explicitly stopped

- Global:
  - global search, followed by local optimization
  - Save of best systems
  - must be explicitly stopped
- Optimization window:
  - Choice of number of steps / cycles
- Automatic update of all windows possible for every cycle (run time slows down)
- After run: change of merit function is seen
- Changes only in higher decimals: stagnation
- Window must be closed (exit) explicitly