Institute of Applied Physics
Friedrich-Schiller-Universität Jena

Optical Design with Zemax

Lecture 7: Optimization II

2012-12-18

Herbert Gross

8 Optimization II
Time schedule

1	16.10.	Introduction	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
2	23.10.	Properties of optical systems I	Diameters, stop and pupil, vignetting, Layouts, Materials, Glass catalogs, Raytrace, Ray fans and sampling, Footprints
3	30.10.	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
4	06.11.	Aberrations I	Representation of geometrical aberrations, Spot diagram, Transverse aberration diagrams, Aberration expansions, Primary aberrations,
5	13.+27.11.	Aberrations II	Wave aberrations, Zernike polynomials, Point spread function, Optical transfer function
6	04.12.	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, Multiconfiguration, Macro language, Lens catalogs
7	11.12.	Optimization I	Principles of nonlinear optimization, Optimization in optical design, Global optimization methods, Solves and pickups, variables, Sensitivity of variables in optical systems
8	18.12.	Optimization II	Systematic methods and optimization process, Starting points, Optimization in Zemax
9	08.01	Imaging	Fundamentals of Fourier optics, Physical optical image formation, Imaging in Zemax
10	15.01.	Illumination	Introduction in illumination, Simple photometry of optical systems, Non-sequential raytrace, Illumination in Zemax
11	22.01.	Correction I	Symmetry principle, Lens bending, Correcting spherical aberration, Coma, stop position, Astigmatism, Field flattening, Chromatical correction, Retrofocus and telephoto setup, Design method
12	29.01.	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
13	05.02.	Physical optical modelling	Gaussian beams, POP propagation, polarization raytrace, coatings

Contents

8 Optimization II
Correction Effectiveness

- Effectiveness of correction features on aberration types

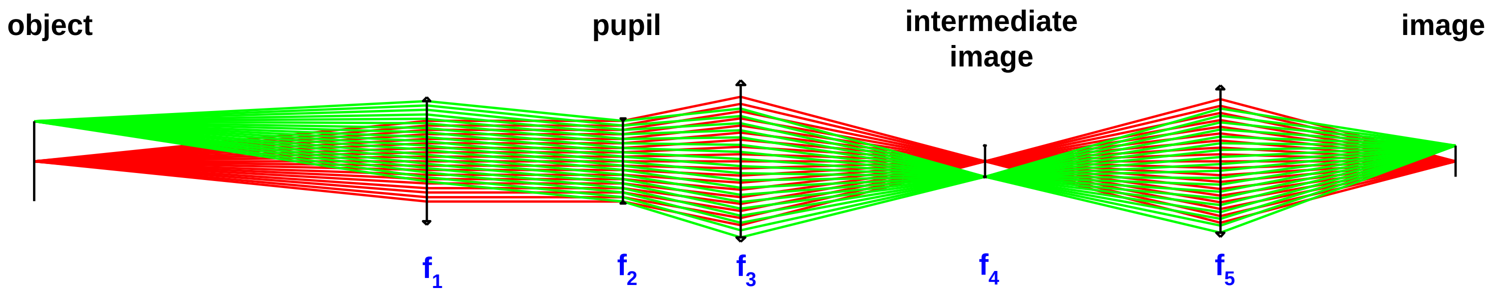
			Aberration									
			Primary Aberration					5th	Chromatic			
			Spherical Aberration	Coma	Astigmatism	Petzval Curvature	Distortion	5th Order Spherical	Axial Color	Lateral Color	Secondary Spectrum	Spherochromatism
Action	Lens Parameters	Lens Bending	(a)	(c)		e	(f)					
		Power Splitting										
		Power Combination	a	c			f		i	j		(k)
		Distances				(e)						k
		Stop Position										
	Material	Refractive Index	(b)	(d)			(g)	(h)				
		Dispersion							(i)	(j)		(l)
		Relative Partial Disp.										
		GRIN										
	Special Surfaces	Cemented Surface	b	d			g	h	i	j		l
		Aplanatic Surface										
		Aspherical Surface										
		Mirror										
		Diffractive Surface										
	Struc	Symmetry Principle										
		Field Lens										

(dark blue)	Makes a good impact.
(medium blue)	Makes a smaller impact.
(light blue)	Makes a negligible impact.
(white)	Zero influence.

Ref : H. Zügge

- 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

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

8 Optimization II
Initial Conditions

Institute of Applied Physics
Friedrich-Schiller-Universität Jena

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

$$\frac{F'}{\nu} = \sum_{m=1}^{M} \omega_m^2 \sum_{n=1}^{N} \frac{F'_{nm}}{\nu_{nm}}$$

2.2 Dichromatic correction of chief ray
achromatical lateral magnification

$$\frac{F'}{\bar{\nu}} = \sum_{m=1}^{M} \omega_m \omega_{pm} \sum_{n=1}^{N} \frac{F'_{nm}}{\nu_{nm}}$$

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

$$\frac{F' P}{\nu} = \sum_{m=1}^{M} \omega_m^2 \sum_{n=1}^{N} \frac{P_{nm} F'_{nm}}{\nu_{nm}}$$

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

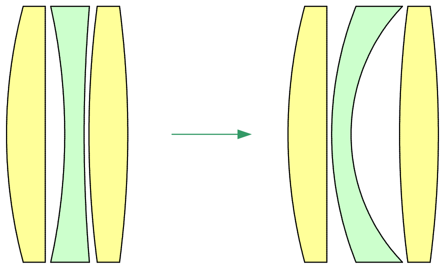
Operationen with zero changes in first approximation:

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.

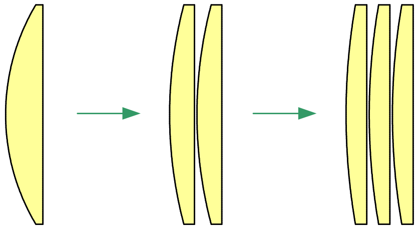
8 Optimization II
Structural Changes for Correction

Institute of Applied Physics
Friedrich-Schiller-Universität Jena

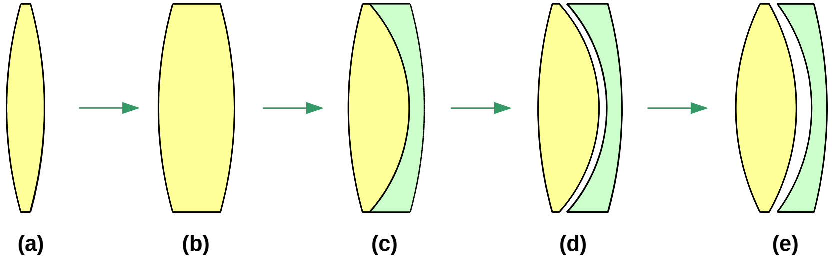
- Lens bending



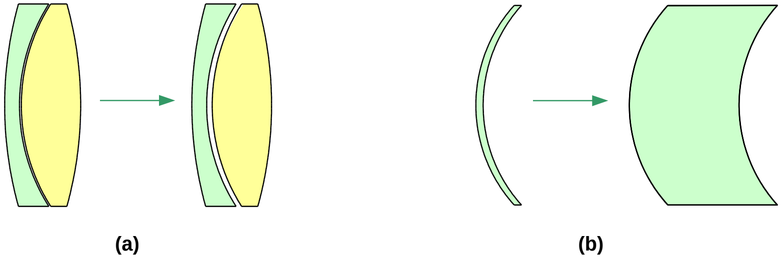
- Lens splitting



- Power combinations



- Distances



Ref : H. Zügge

8 Optimization II
Sensitivity of a System

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

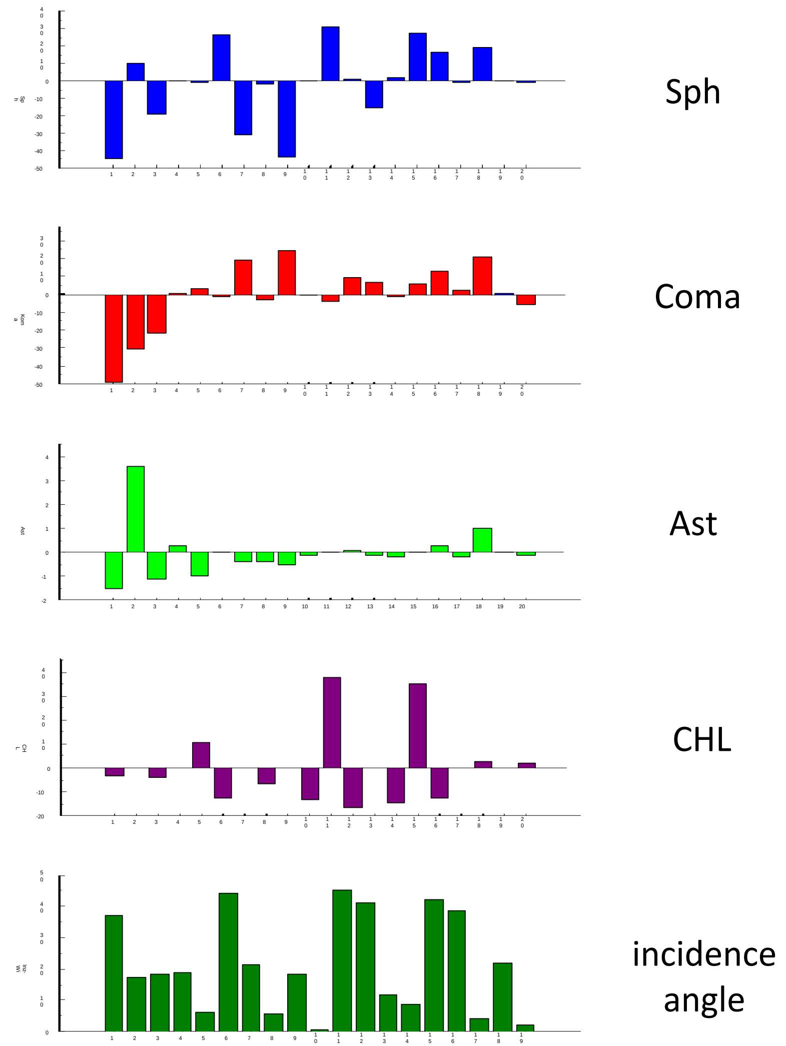
- Correctability:
  Average of all total aberration values

- 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 occurence of higher aberration orders
  5. Large sensitivity for centering

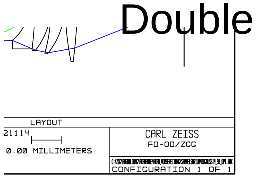
- Internal relaxation can not be easily recognized in the total performance

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

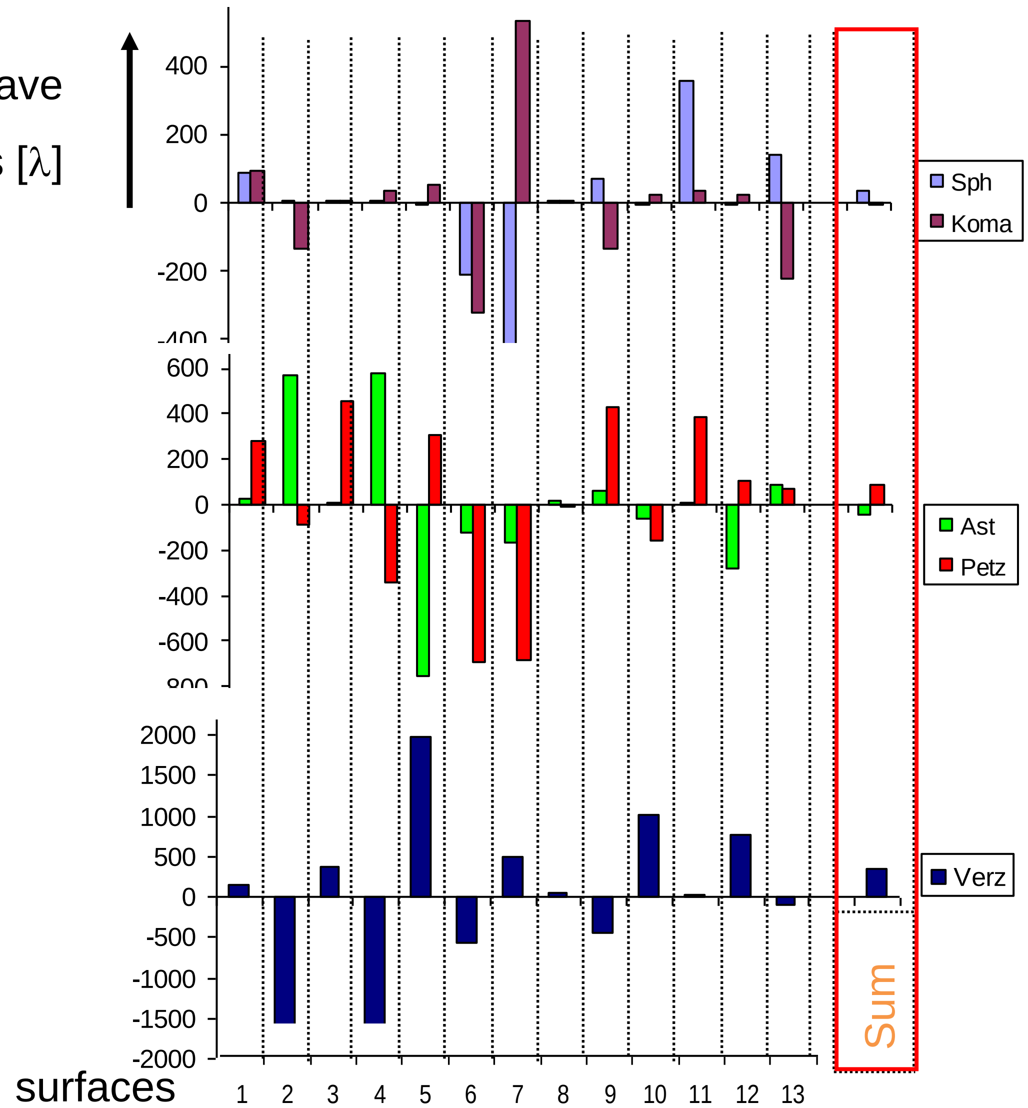
Representation of wave

Seidel coefficients [λ]

Double Gauss 1.4/50



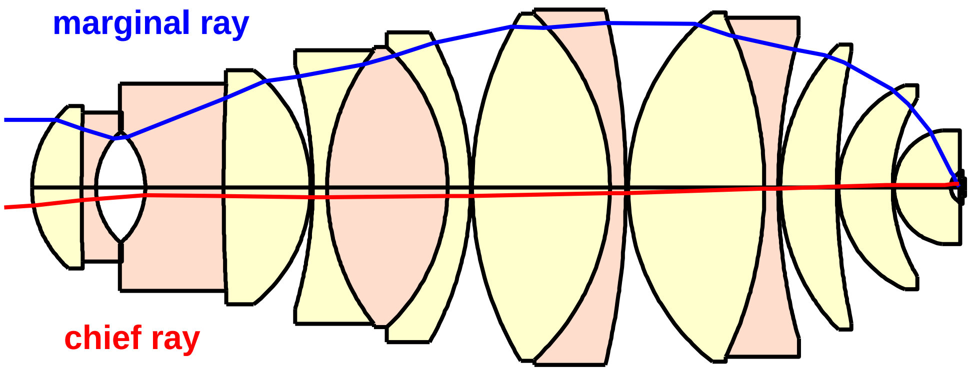
1 2 3 4 5 6 7 8 9 10 11 12 13

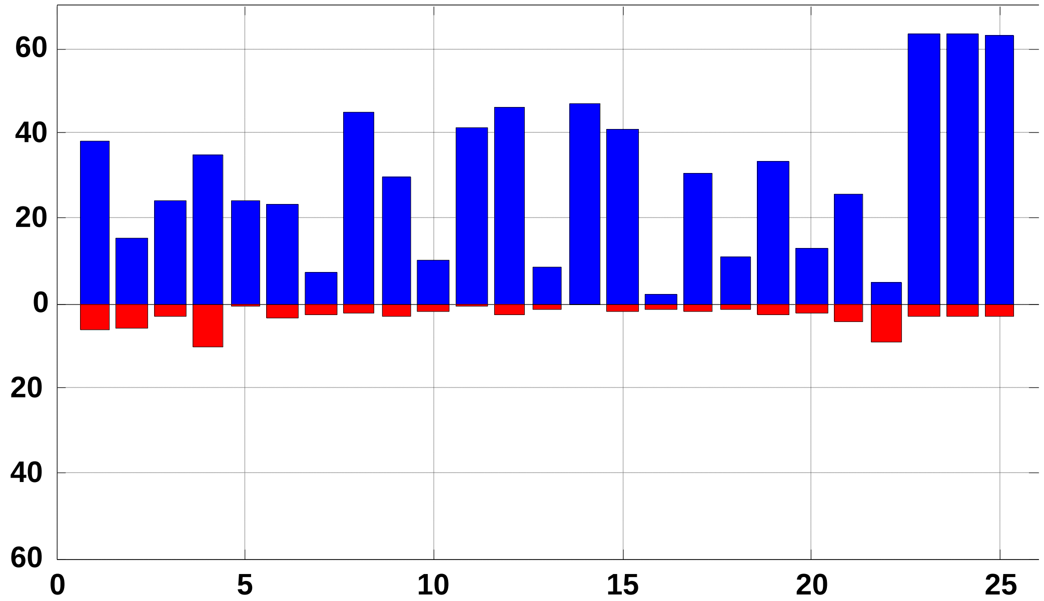


Ref: H.Zügge

8 Optimization II
Microscopic Objective Lens

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

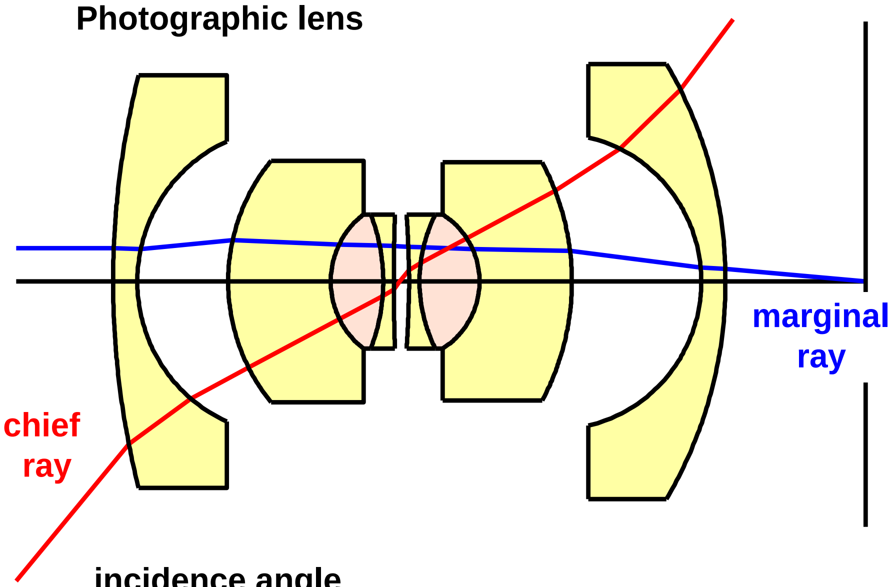


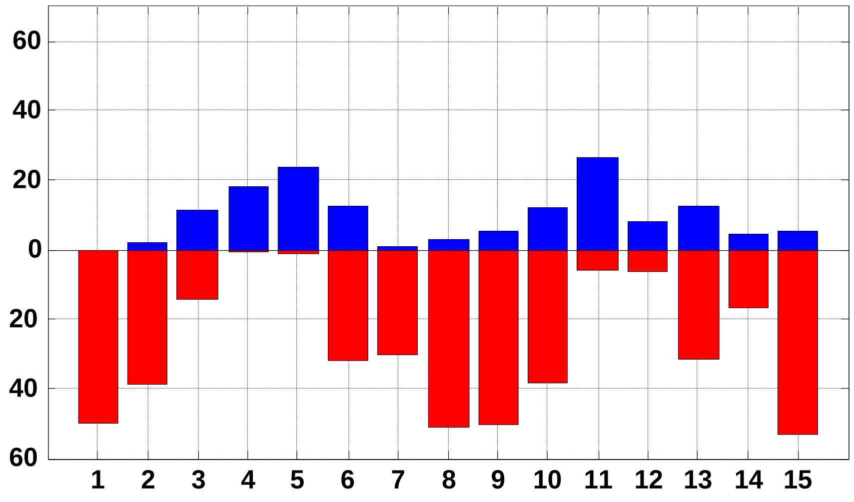


- Incidence angles for chief and marginal ray

- Field dominant system

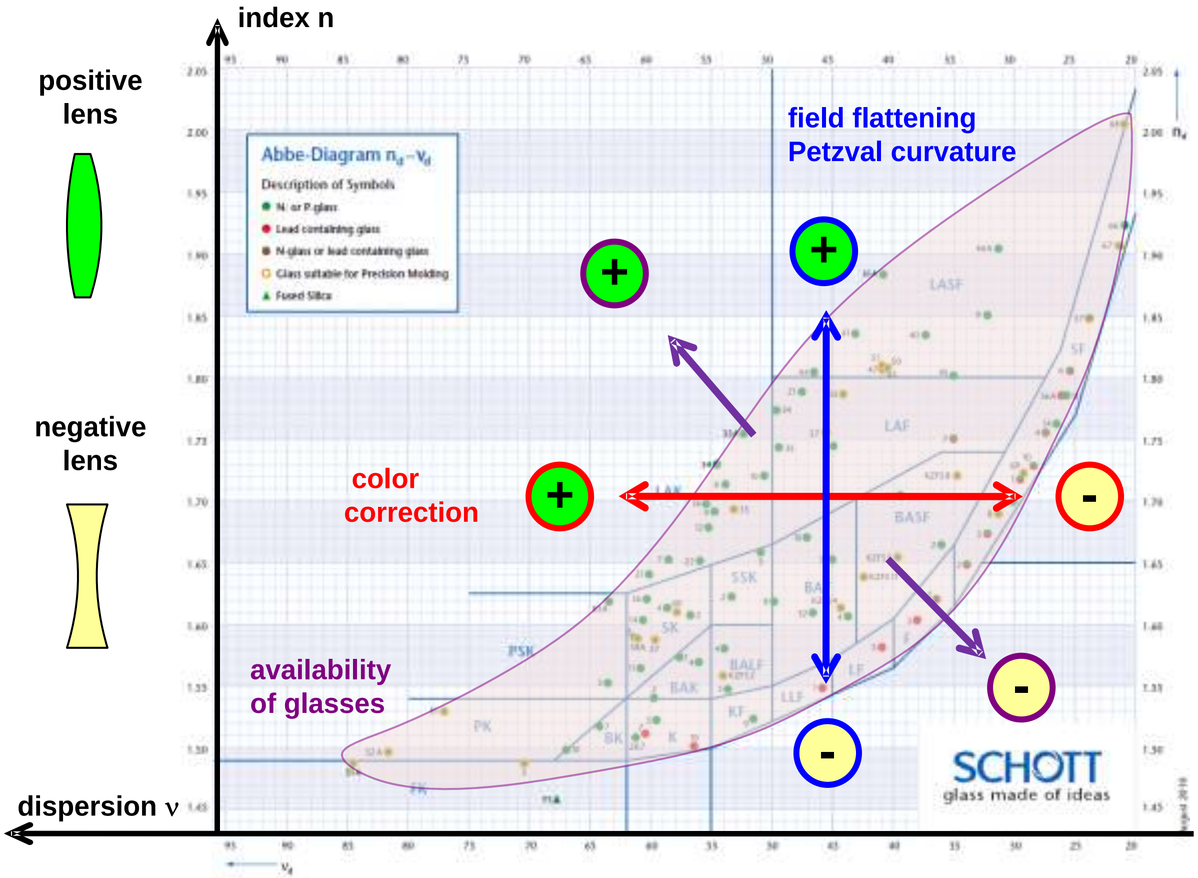
- Primary goal is to control and correct field related aberrations:
  coma, astigmatism, field curvature, lateral color





- Design Rules for glass selection

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

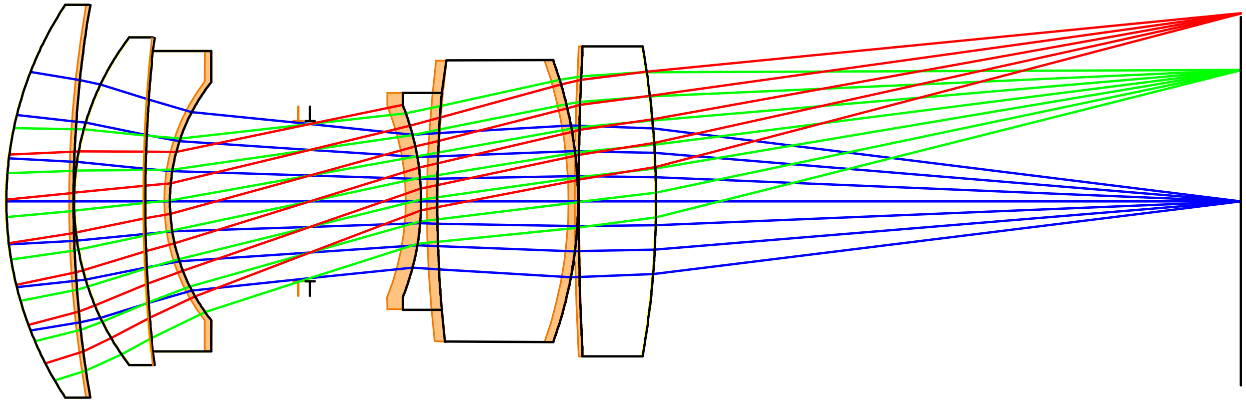


Ref : H. Zügge

8 Optimization II
Substitution of Standard Radii

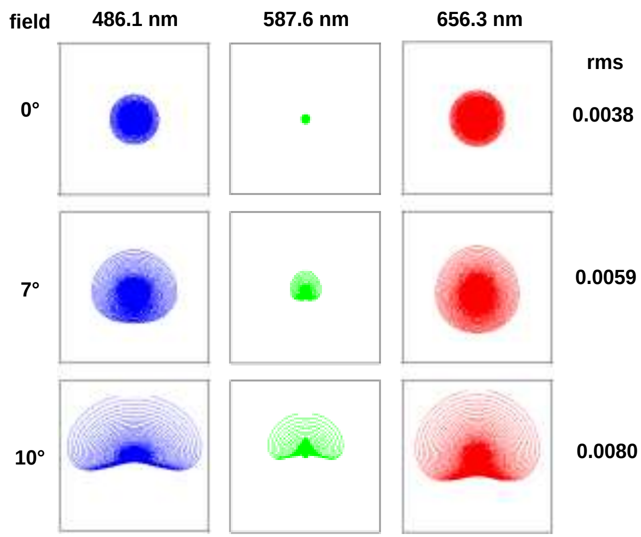
- Method:
  Insertion of nearest available radii
  Check of optimal combinations
  re-adjusting thicknessess
- In general system slightly decreased in performance

- Example : Photographic lens :
  Orange : original, black: new system

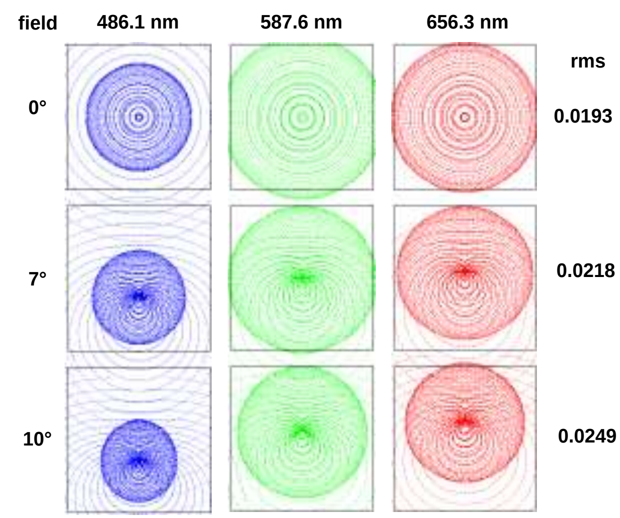


8 Optimization II
Substitution of Standard Radii

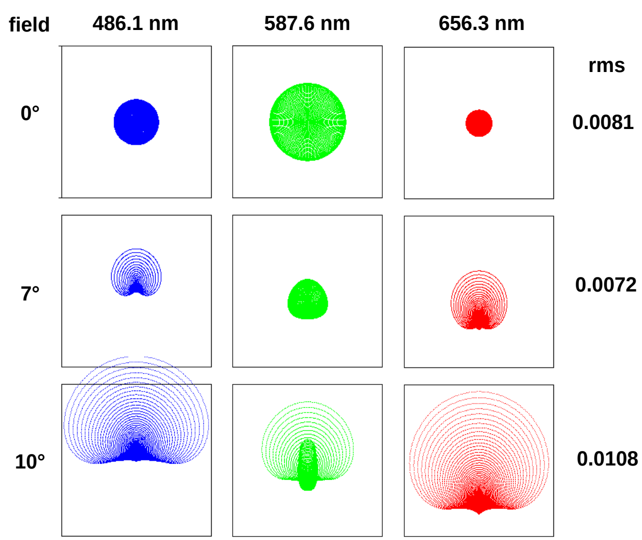
- 1. After optimization



- 2. After substitution



- 3. After re-optimization



Institute of Applied Physics
Friedrich-Schiller-Universität Jena

- Distribution of refractive power
  good: small W

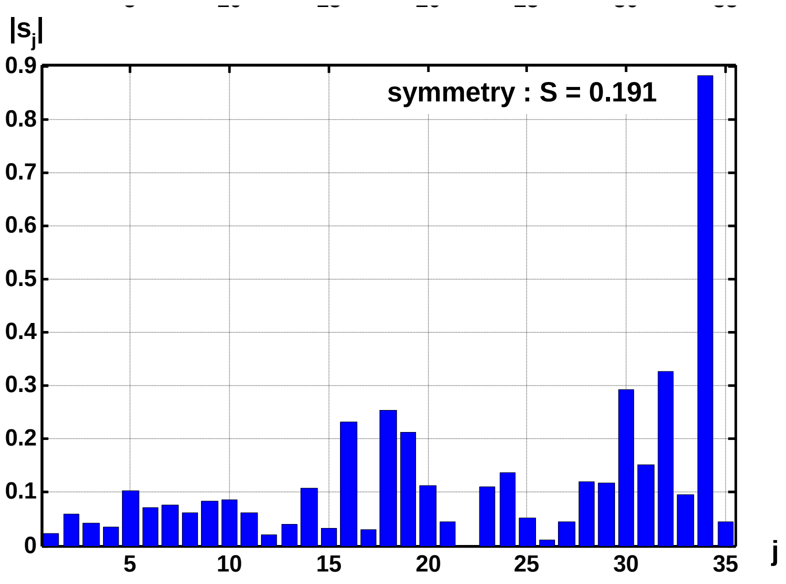
$$W = \sqrt{\frac{1}{N}\sum_{j=1}^{N} w_j^2} \qquad w_j = -\frac{n'_j - n_j}{1-m} \cdot \frac{y_j}{n_N' u'_N} \cdot \rho_j$$

- Symmetry content
  good: large S

$$S = \sqrt{\frac{1}{N}\sum_{j=1}^{N} s_j^2} \qquad s_j = \frac{1}{1-m} \cdot \frac{n_j \cdot \bar{i}_j}{n \cdot \bar{i}_{stop} \cdot n_N' u'_N} \cdot \left(\frac{u'_j}{n'_j} - \frac{u_j}{n_j} \right)$$

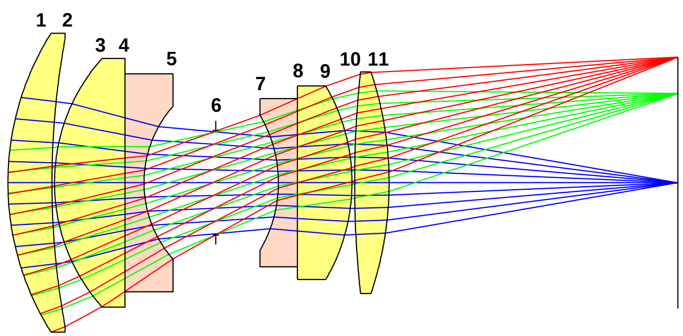
- General trend :
  Cost of small W and large S : - long systems
  - many lenses

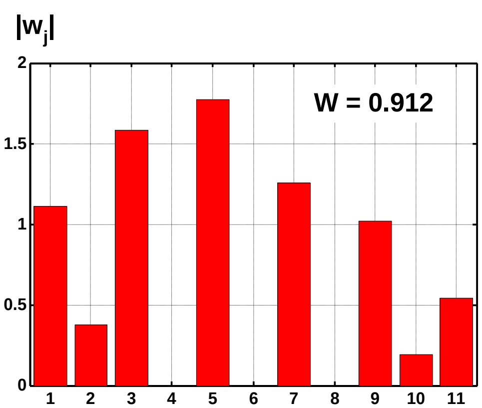
- Advantage of w_j, s_j-diagram :
  Identification of strange surfaces

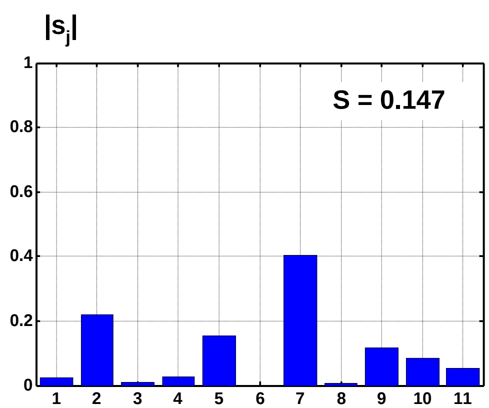


8 Optimization II
System Structure

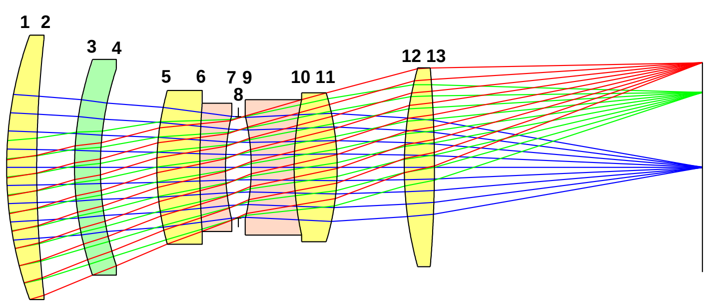
- Example:
  optimizing W and S with one additional lens
- Starting system:

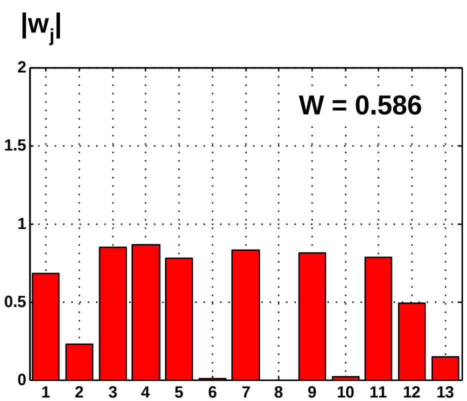


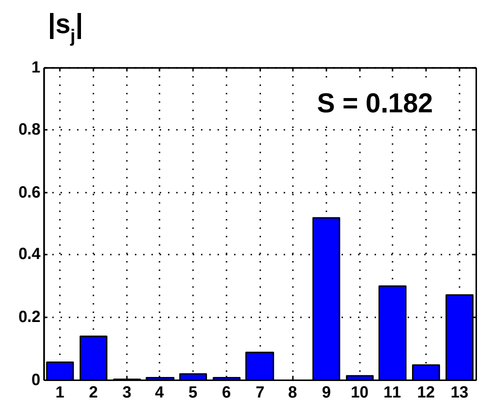




- Final design



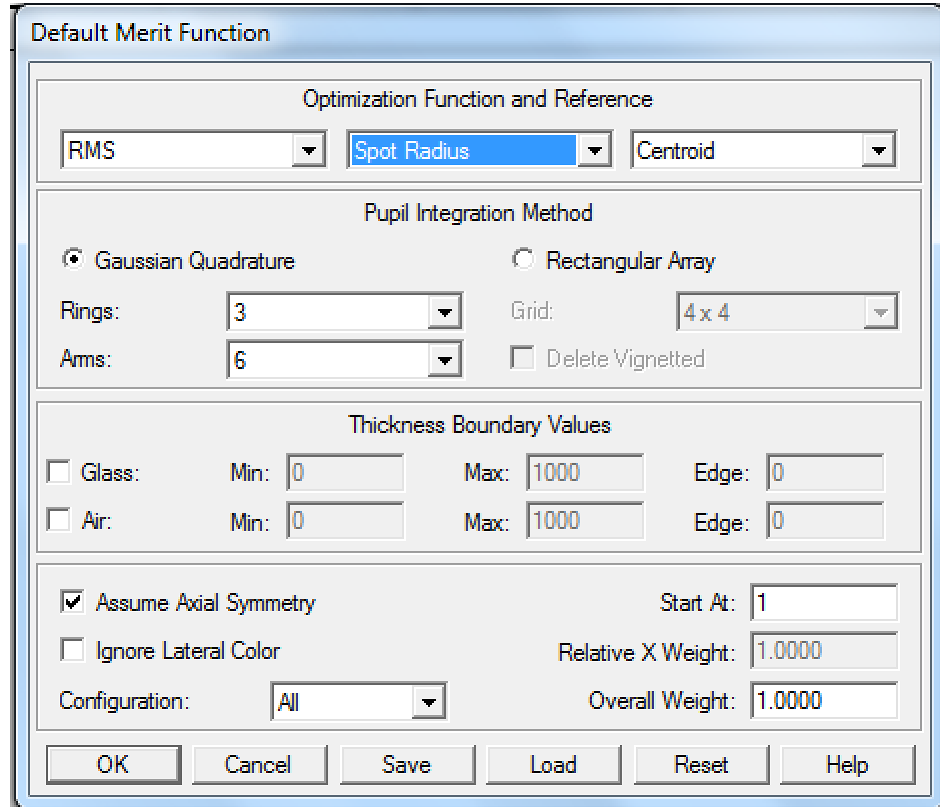


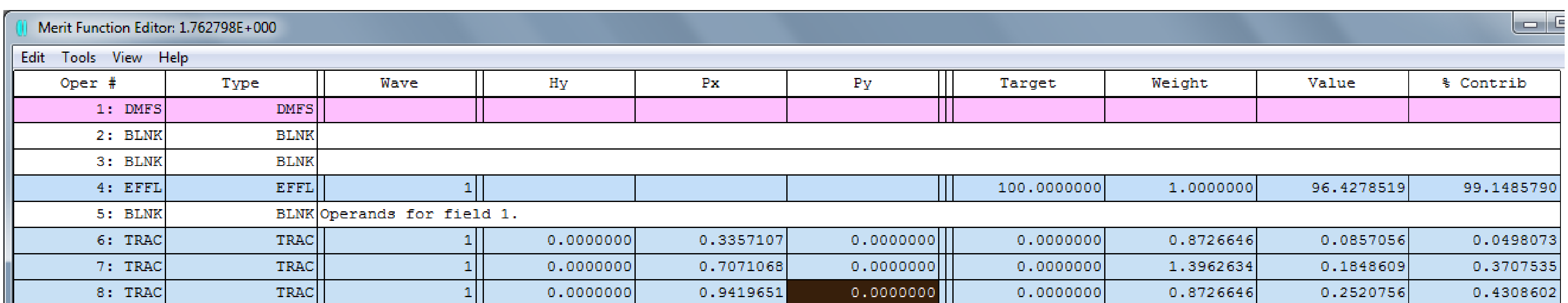


8 Optimization II
Merit Function in Zemax

Institute of Applied Physics
Friedrich-Schiller-Universität Jena

- 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





Merit Function Editor: 1.762798E+000

Edit Tools View Help

Oper #	Type	Wave	Hy	Px	Py	Target	Weight	Value	% Contrib
1: DMFS	DMFS								
2: BLNK	BLNK								
3: BLNK	BLNK								
4: EFFL	EFFL	1				100.0000000	1.0000000	96.4278519	99.1485790
5: BLNK	BLNK	Operands for field 1.							
6: TRAC	TRAC	1	0.0000000	0.3357107	0.0000000	0.0000000	0.8726646	0.0857056	0.0498073
7: TRAC	TRAC	1	0.0000000	0.7071068	0.0000000	0.0000000	1.3962634	0.1848609	0.3707535
8: TRAC	TRAC	1	0.0000000	0.9419651	0.0000000	0.0000000	0.8726646	0.2520756	0.4308602

- If the number of field points, wavelengths or configurations is changed: the merit function must be updated explicitly
- Help function in Zemax: many operands

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, ISFN, LINV, OBSN, PIMH, PMAG, POWF, POWP, POWR, SFNO, TFNO, WFNO

Aberrations:
ABCD, ANAC, ANAR, ANAX, ANAY, ANCX, ANCY, ASTI, AXCL, BIOC, BIOD, BSER, COMA, DIMX, DISA, DISC, DISG, DIST, FCGS, FCGT, FCUR, LACL, LONA, OPDC, OPDM, OPDX, OSCD, PETC, PETZ, RSCE, RSCH, RSRE, RSRH, RWCE, RWCH, RWRE, RWRH, SPCH, SPHA, TRAC, TRAD, TRAE, TRAI, TRAR, TRAX, TRAY, TRCX, TRCY, ZERN

MTF data:
GMTA, GMTS, GMTT, MSWA, MSWS, MSWT, MTFA, MTFS, MTFT, MTHA, MTHS, MTHT

PSF/Strehl Ratio Data:
STRH

Encircled energy:
DENC, DENF, ERFP, GENC, GENF, XENC, XENF

Constraints on lens data:
COGT, COLT, COVA, CTGT, CTLT, CTVA, CVGT, CVLT, CVVA, DMGT, DMLT, DMVA, ETGT, ETLT, ETVA, FTGT, FTLT, MNCA, MNCG, MNCT, MNCV, MNEA, MNEG, MNET, MNPD, MXCA, MXCG, MXCT, MXCV, MXEA, MXEG, MXET, MXPD, MNSD, MXSD, TTGT, TTHI, TTLT, TTVA, XNEA, XNET, XNEG, XXEA, XXEG, 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

- 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

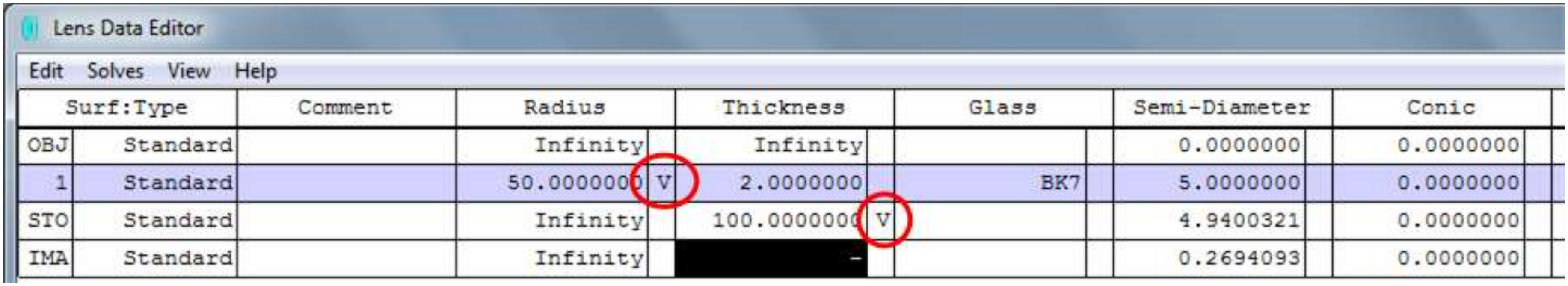
- Optimization operands with derivatives:
  building a system insensitive for small changes (wide tolerances)

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

- General outline:
  - use sinple operands in a rough optimization phase
  - use more complex, application-related operands in the final fine-tuning phase

8 Optimization II
Variables in Zemax

- Defining variables: indicated by V in lens data editor
  toggle: CNTR z or right mouse click



Lens Data Editor

Edit Solves View Help

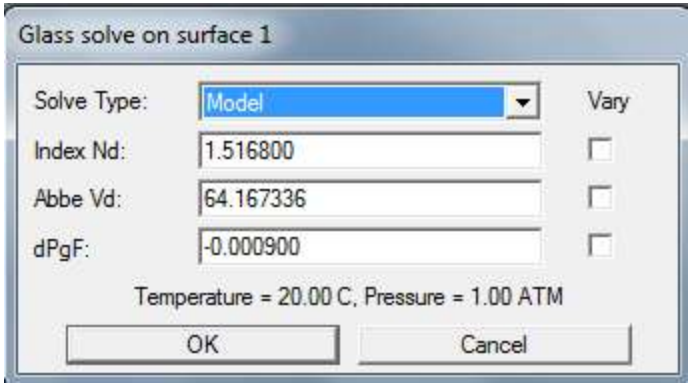
Surf	Type	Comment	Radius		Thickness		Glass	Semi-Diameter	Conic
OBJ	Standard		Infinity		Infinity			0.0000000	0.0000000
1	Standard		50.0000000	V	2.0000000		BK7	5.0000000	0.0000000
STO	Standard		Infinity		100.0000000	V		4.9400321	0.0000000
IMA	Standard		Infinity					0.2694093	0.0000000

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

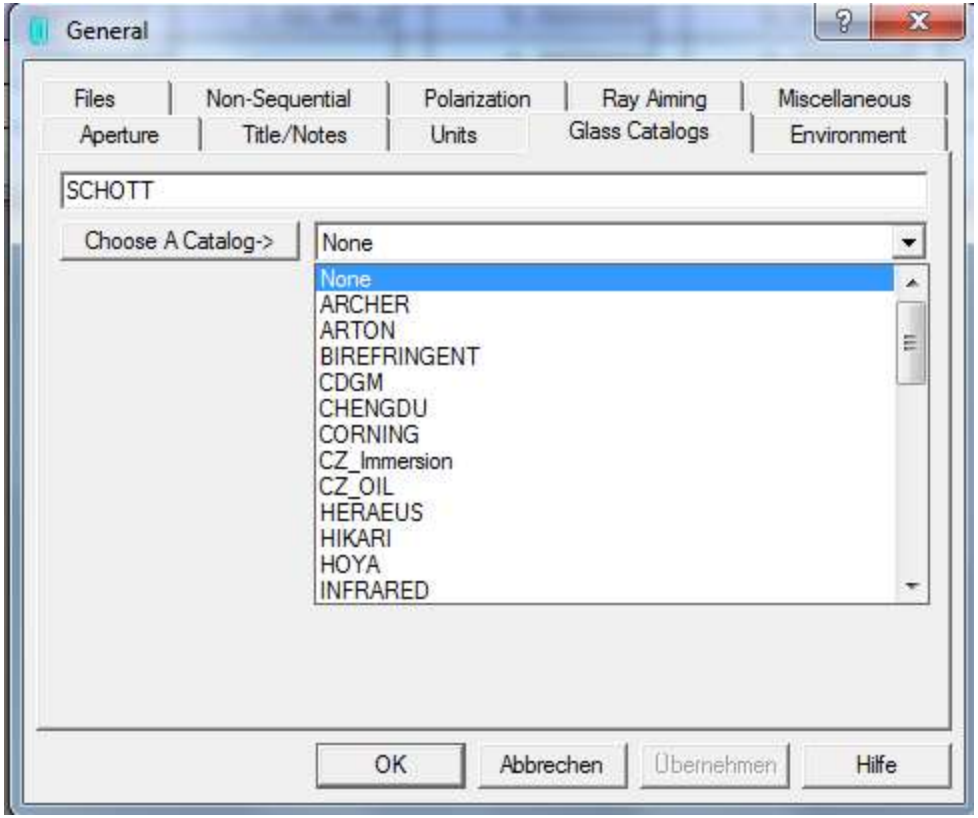
- If the initial value of a variable is quite bad and a ray failure occurs, the optimization can not run and the merit function not be computed

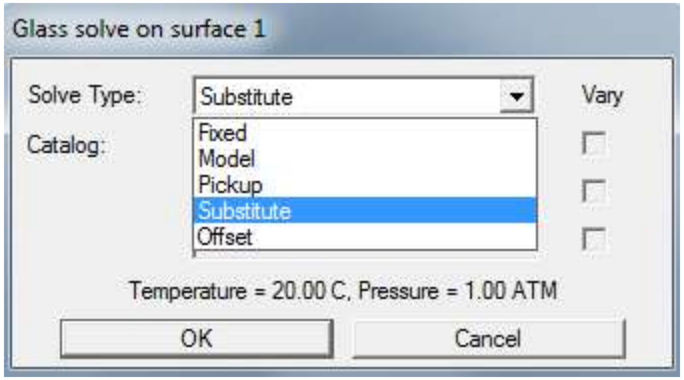
8 Optimization II
Variable Glass in Zemax

Institute of Applied Physics
Friedrich-Schiller-Universität Jena



- 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

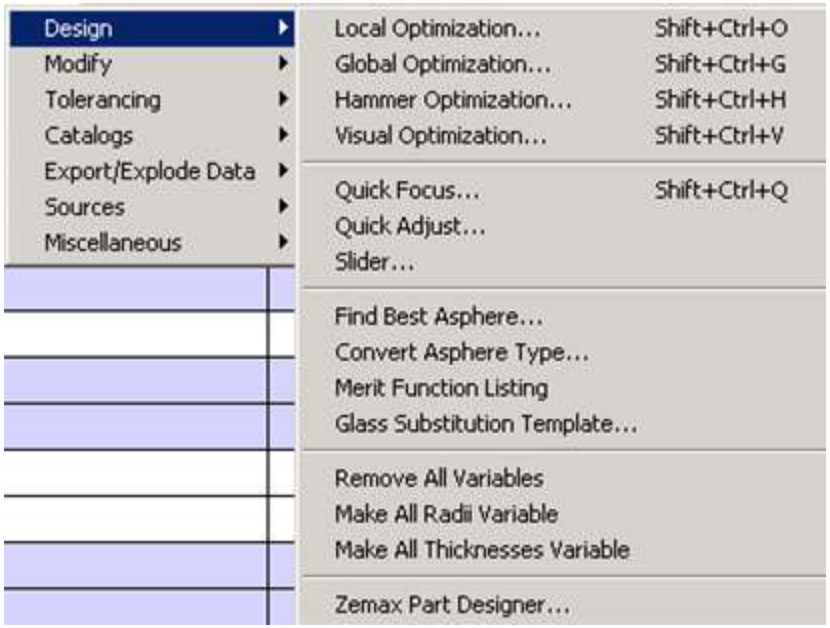




8 Optimization II
Methods Available in Zemax

Institute of Applied Physics
Friedrich-Schiller-Universität Jena

- General optimization methods
  - local
  - global
- Easy-one-dimensional optimizations
  - focus
  - adjustment
  - slider, for visual control
- Special aspects:
  - solves
  - aspheres
  - glass substitutes

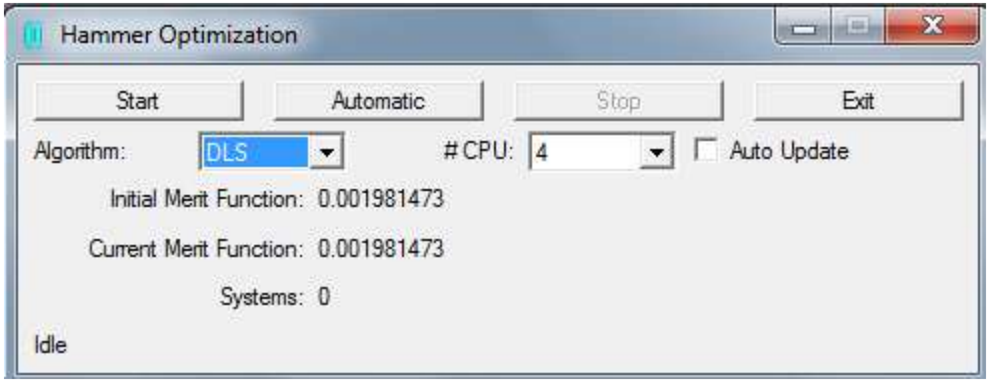


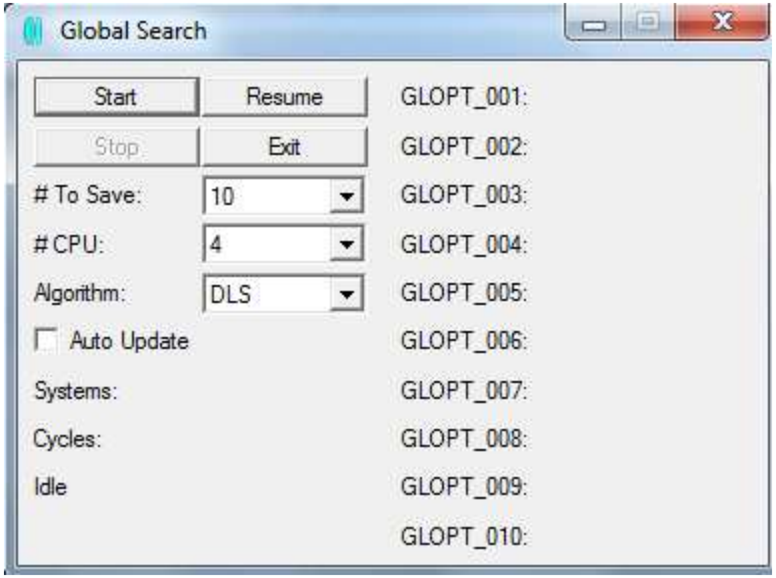
8 Optimization II
Methods Available in Zemax

- Classical local derivative:
  - DLS optimization (Marquardt)
  - orthogonal descent

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

- Global:
  - global search, followed by local optimization
  - Save of best systems
  - must be explicitely stopped





8 Optimization II
Conventional DLS-Optimization in Zemax

- 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) explictly