Institute of Applied Physics
Friedrich-Schiller-Universität Jena

Optical Design with Zemax for PhD - Advanced

Seminar 8 : Tolerancing I

2015-01-21

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Preliminary Schedule

No	Date	Subject	Detailed content
1	12.11.	Repetition	Correction, handling, multi-configuration
2	19.11.	Illumination I	Simple illumination problems
3	26.11.	Illumination II	Non-sequential raytrace
4	03.12.	Physical modeling I	Gaussian beams, physical propagation
5	10.12.	Physical modeling II	Polarization
6	07.01.	Physical modeling III	Coatings
7	14.01.	Physical modeling IV	Scattering
8	21.01.	Tolerancing I	Sensitivity, practical procedure
9	28.01.	Tolerancing II	Adjustment, thermal loading, ghosts
10	04.02.	Additional topics	Adaptive optics, stock lens matching, index fit, Macro language, coupling Zemax-Matlab

Content

- Specifications are usually defined for the as-built system

- Optical designer has to develop an error budget that cover all influences on performance degradation as
  - design imperfections
  - manufacturing imperfections
  - integration and adjustment
  - environmental influences

- No optical system can be manufactured perfectly (as designed)
  - Surface quality, scratches, digs, micro roughness
  - Surface figure (radius, asphericity, slope error, astigamtic contributions, waviness)
  - Thickness (glass thickness and air distances)
  - Refractive index (n-value, n-homogeneity, birefringence)
  - Abbe number
  - Homogeneity of material (bubbles and inclusions)
  - Centering (orientation of components, wedge of lenses, angles of prisms, position of components)
  - Size of components (diameter of lenses, length of prism sides)
  - Special: gradient media deviations, diffractive elements, segmented surfaces,...

- Tolerancing and development of alignment concepts are essential parts of the optical design process

Ref: K. Uhlendorf

Sensitivity of a System

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

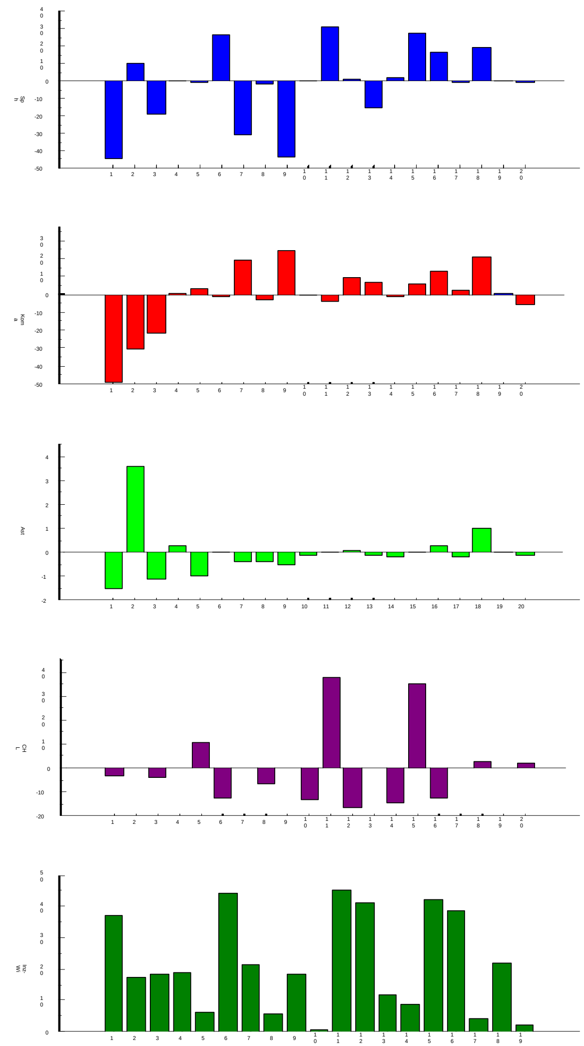
- Correctability:
  Average of all total aberration values

- Total refractive power

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

- Important weighting factor:
  ratio of marginal ray heights

$$\omega_j = \frac{h_j}{h_1}$$



Sph

Coma

Ast

CHL

incidence angle

Sensitivity of a System

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- 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

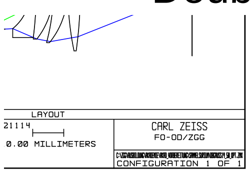
- Large sensitivities can be avoided by incorporating surface contribution of aberrations into merit function during optimization

Sensitivity of a System

Representation of wave

Seidel coefficients [λ]

Double Gauss 1.4/50



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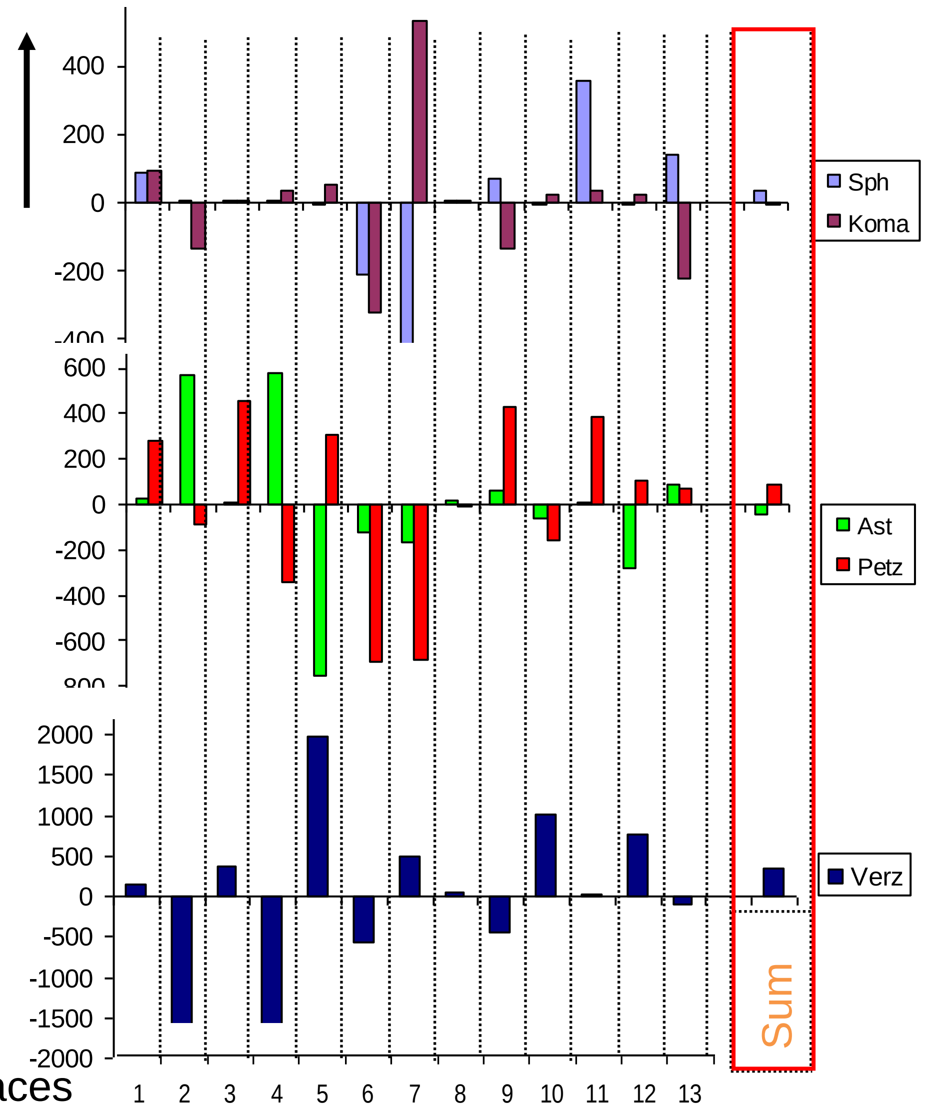


Ref: H.Zügge

Tolerances: Standards

- Standard ISO-10110

ISO 10110-2	Material imperfections – stress birefringence
ISO 10110-3	Material imperfections – bubbles and inclusions
ISO 10110-4	Material imperfections – inhomogeneity and striae
ISO 10110-5	Surface-form tolerances
ISO 10110-6	Centering tolerances
ISO 10110-7	Surface-imperfection tolerances
ISO 10110-8	Surface texture
ISO 10110-9	Surface treatment and coating

Ref.: M. Peschka

Specification of Data

- Data for mechanical design, development and manufacturing:
- Dat a sheet with standard data/numbersof system and tolerances

- Additional support data (optional) :
  1. Prisms, plano comopnents, test procedures
  2. Adjustment and system integration
  3. Centering for cementing
  4. Centering for mechanics
  5. Coatings
  6. Geometrical dimensions / folding mirrors
  7. Test procedures and necessary accuracies
  8. Auxiliary optics for testing
  9. Combination of tolerances
  10. Zoom curves and dependencies
  11. Adaptive control data
  12. Interface to connected systems

Data Sheet

ZEISS

	OBERKOCHEN: RECHNUNG VOM xxx	ABT. xxxxx
	ZEICHNUNG: Ø	KOMIKRO
DATEN: BETA =-99.6 X1 =UNENDL. F2,3=+ 4.0MM F8,9 =-35. F1-16=+ 1.66MM X16'=-8.59MM F4,5=+102.3MM F9,10=+10. O-O' =195.0MM O-S16=38.21MM F6,7=+ 17.3MM F8-10=+15.	MIKRO 63D13415 K0 HERAUSGEGEBEN AM 26.6.91	FO-EM-M/MUCH

RADIUS			PLAN	PLAN	2.0700	2.6550	3.2210	13.428	6.3100
2H			0.5	1.5	3.9	4.5	6.2	8.7	9.4
FREIER Ø			1.5	1.5	3.9	4.5	6.2	8.7	9.4

SKIZZE D TEIL NR.			0.17	0.35	2.18	0.13	1.74	0.19	2.00	0.28
Ø										
GLASART SCHMELZE			K5	IMOEL	K7		LAK11		PSK53A	
(587.6 nm) STUFE			1.52249 ±0.001 (4)	1.51500	1.51112 ±0.0003 (2)		1.65830 ±0.0005 (3)		1.62014 ±0.0005 (3)	
Vd STUFE			59.48 ±0.8 % (4)	43.45	60.41 ±0.5 % (3)		57.26 ±0.5 % (3)		63.48 ±0.3 % (2)	

TOLERANZEN: KOMBINATIONSFREIE FERTIGUNG

D			±0.04		±0.03	±0.05	±0.02	±0.01	±0.02
KITT									
0) KUEHLUNG			20		20		20		20
1) BLASEN					1X0.1		1X0.1		1X0.1
2) SCHLIEREN			-;2		-;2		-;2		-;2

3) PASSE				5.0(1.0)	2.0(0.4)	2.0(0.4)	3.0(0.6)	1.0(0.2)	1.0(0.2)
4) ZENTR.				9'	6'	8'	6'	2'	2'
5) UNSAUB.	3415			1X0.04	1X0.1	1X0.1	1X0.1	1X0.16	1X0.16

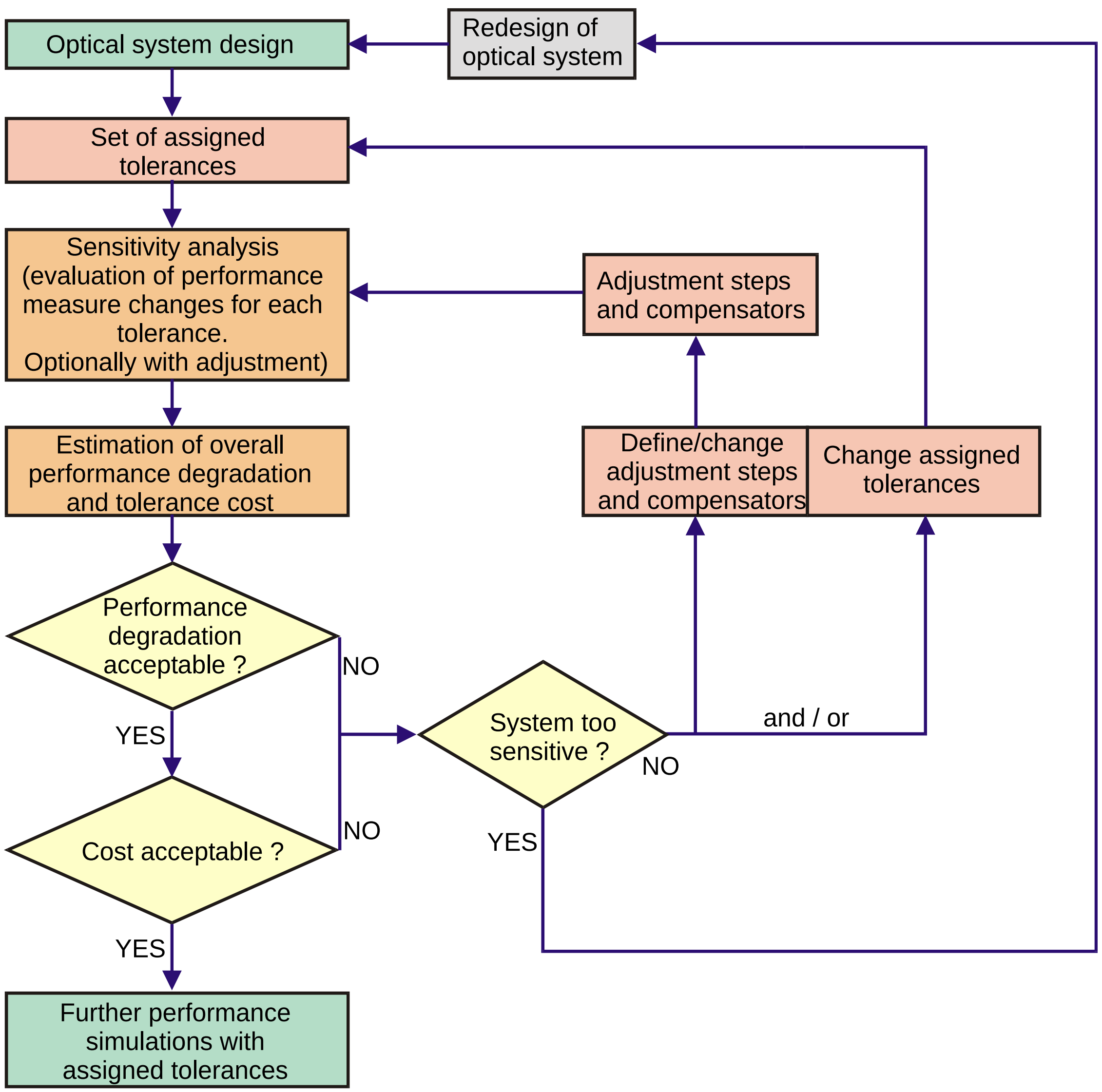
Tolerances

- Surface quality, scratches, digs, micro roughness
- Surface figure
  radius, asphericity, slope error, astigamtic contributions, waviness
- Thickness
  glass thickness and air distances
- Refractive index
  n-value, n-homogeneity, birefringence
- Abbe number
- Homogeneity of material
  bubles and inclusions
- Centering:
  orientation of components, wedge of lenses, angles of prisms, position of components
- Size of components
  diameter of lenses, length of prism sides
- Special:
  gradient media deviations, diffractive elements, segmented surfaces,...

Tolerances: Typical Values

Diameter	**Tolerance**	**Unit**	**<10 mm**	**10...20 mm**	**20...30 mm**
Center thickness		mm	0.02	0.03	0.03
Centering	Tilt angle	sek	60	60	60
	Decenter/offset	µm	15	15	15
Roughness		nm	15	10	10
Spherical/radius	spherical	rings	3	4	5
	astigmatism	rings	.5	1	1
Asphericity	Global deviation	µm	1	1.2	1.5
	Global asphericity	µm	0.25	0.45	0.60
	Local deviation	µm	0.025	0.05	0.075
	Slope error	rad	0.0005	0.0005	0.0005

- Systematic finding of tolerances



Ref.: M. Peschka

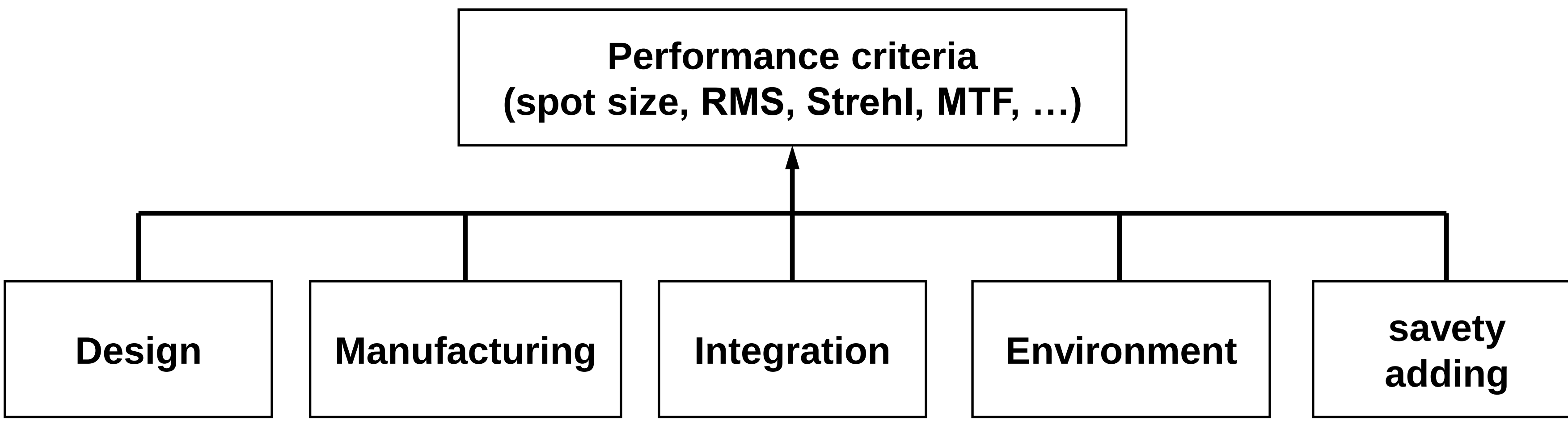
Tolerance Analysis

- Selection of the performance criterion,
  spot size, rms wavefront, MTF, Strehl,...
- Choice of the allowed degradation of performance, limiting maximum value of the criterion
- Definition of compensators for the adjustments
  image location, intermediate air distances, centering lenses, tilt mirrors,...
- Calculation of the sensitivities of all tolerances:
  influence of all tolerances on all performance numbers
- Starting the tolerance balancing with proper default values,
  alternatively inverse sensitivity: largest amount of deviation for the accepted degradation
- Tolerance balancing:
  calculating all tolerances individually to keep the overall performance with technical realistic accuracies of the parameter

Ref: C. Menke

Error Budget

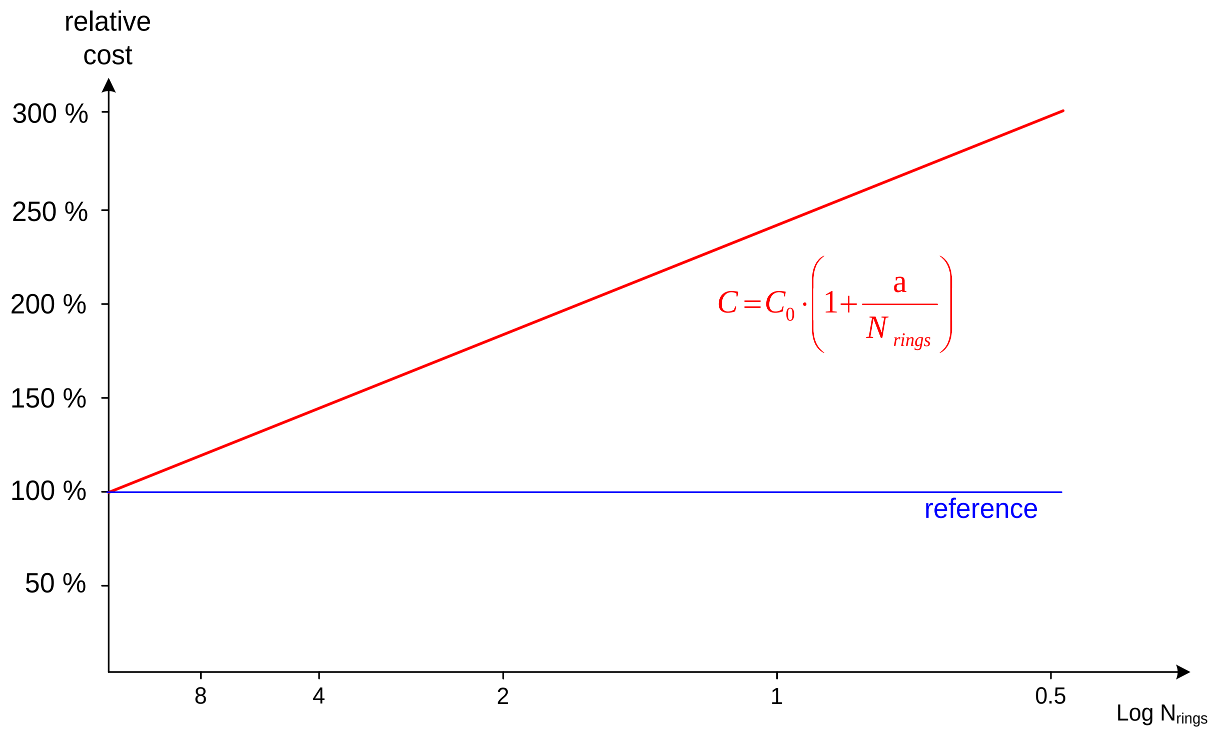
- Sources of errors:
  - materials
  - manufacturing
  - integration/adjustment/mounting
  - enviromental influences
  - residual design aberrations
- Performance evaluation:
  – selection of proper criterion
  – fixation of allowed performance level
  – calculation of sensitivity of individual tolerances and combined effects (groups, dependent errors)
  – balancing of overall tolerance limits for complete system



Ref: C. Menke

Tolerances and Cost Impact

- Typical behavior of the cost function: additive cost
- Exponential growth of cost with decreased tolerance width
- The slope and the reference value depends on type of tolerance and technology of manufacturing
- Special aspects:
  - new manufacturing technologies
  - jumps of cost



Tolerances and Additional Cost

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Diameter tolerance in mm	0.1 100 %	0.05 100 %	0.025 103 %	0.0125 115 %	0.0075 150 %	
Thickness tolerance in mm	0.2 100 %	0.1 105 %	0.05 115 %	0.025 150 %	0.0125 300 %	
Centering tolerance in minutes	6' 100 %	3' 103 %	2' 108 %	1' 115 %	30" 140 %	15" 200 %
Shape tolerance as ring number in λ	10 7 5 100 %	5 / 2 105 %	3 / 1 120 %	2 / 0.5 140 %	2 /0.25 175 %	1 /0.12 300 %
ratio diameter vs thickness	9 100 %	15 120 %	20 150 %	30 200 %	40 300 %	50 500 %
Scratches and dots (MIL-Norm)	80 / 50 100 %	60 / 40 110 %	40 / 30 125 %	20 / 10 175 %	10 7 5 350 %	
Coating	without 100 %	1 Layer 115 %	3 Layer 150 %	Multilay. < 500 %		

Models and Statistics in Tolerancing

- Evaluation of the complete system:
  additive effect of all tolerances, taking partial compensations due to sign and statistics into acount

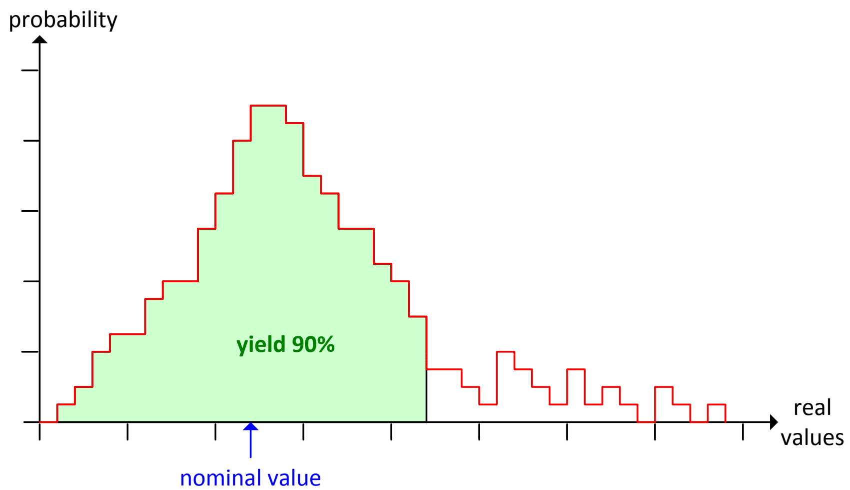
- Worst case superposition:
  - adding all absolute amounts of degradations
  - usually gives to costly and tight tolerances
  - no compensations considered, to pessimistic

$$\Delta f = \sum_j \left| \Delta f_j \right|$$

- Rms mean superposition:
  - approach with ideal statistics and quadratic summation
  - compensations are taken into account approximately
  - real world statistics is more complicated
  - deterministic effects of adjustments are not considered

$$\Delta f = \sqrt{\sum_j \left| \Delta f_j \right|^2}$$

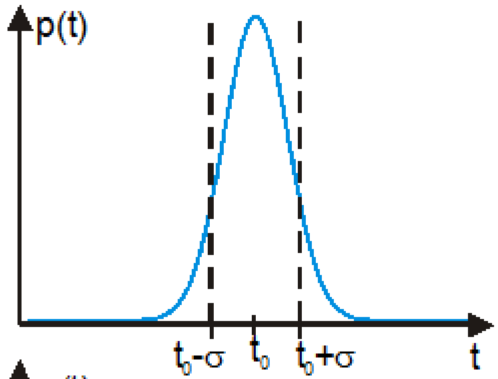
- Calculation of Monte Carlo statistics with deterministic adjustment steps
  - best practice approach
  - statistical distribution can be adapted to experience
  - problems with small number manufacturing



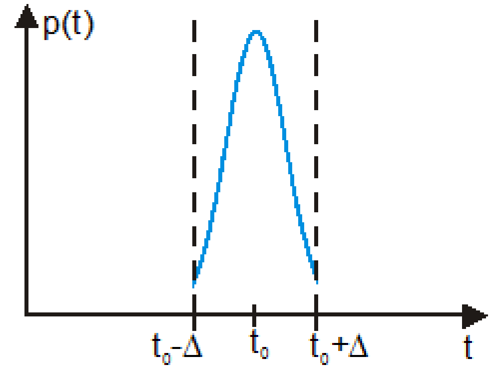
Tolerance Distributions

- Gaussian

$$p(t) = \frac{1}{\sqrt{2\pi\sigma}} e^{-\frac{(t-t_0)^2}{2\sigma^2}}$$

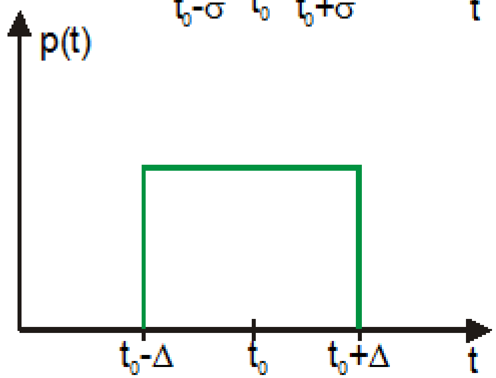


- Truncated Gaussian



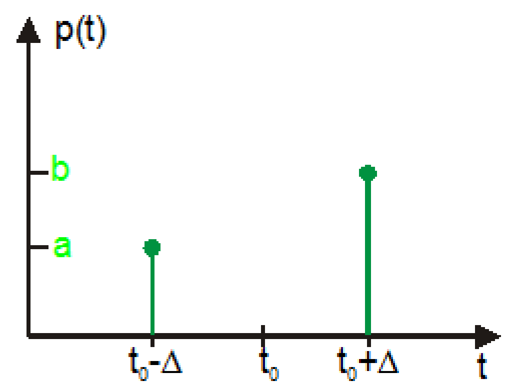
- Uniform

$$p(t) = \frac{1}{2\Delta} \quad , \quad t_0 - \Delta \le t \le t_0 + \Delta$$



- Ping-pong

$$p(t) = \frac{1}{a+b}\left[a \cdot \delta(t - t_0 + \Delta) + b \cdot \delta(t - t_0 - \Delta)\right]$$



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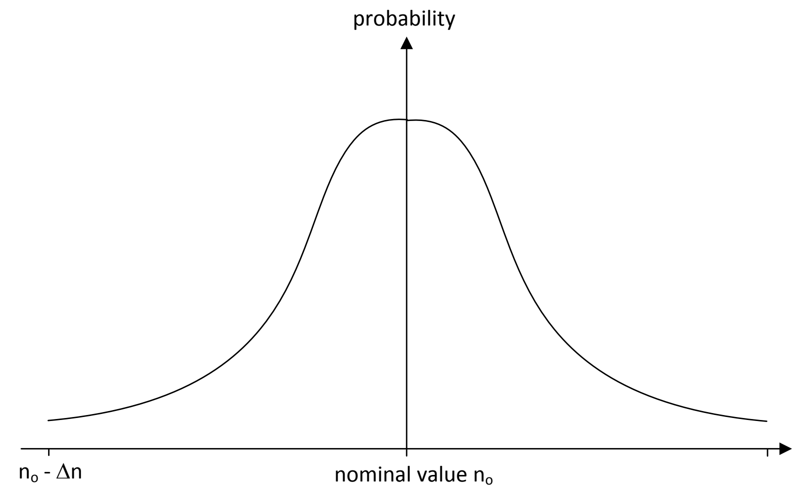
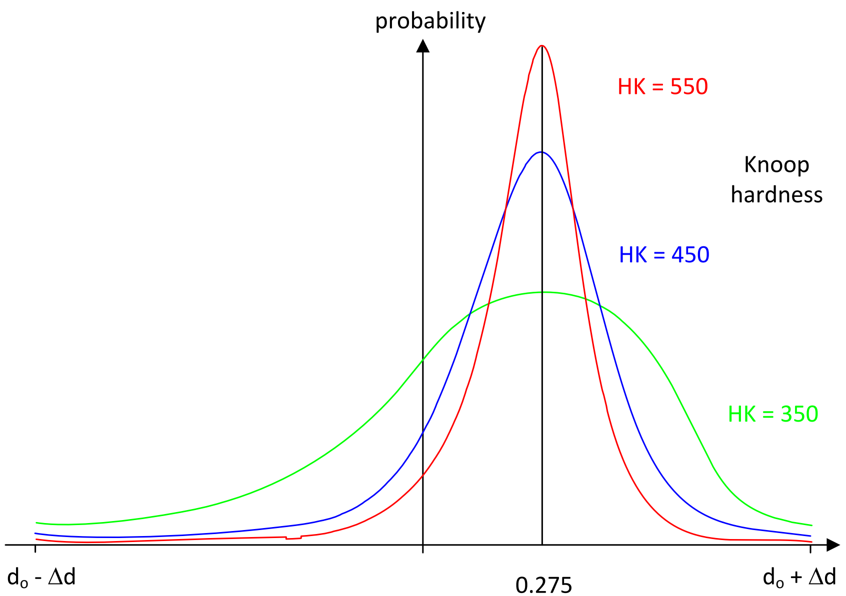
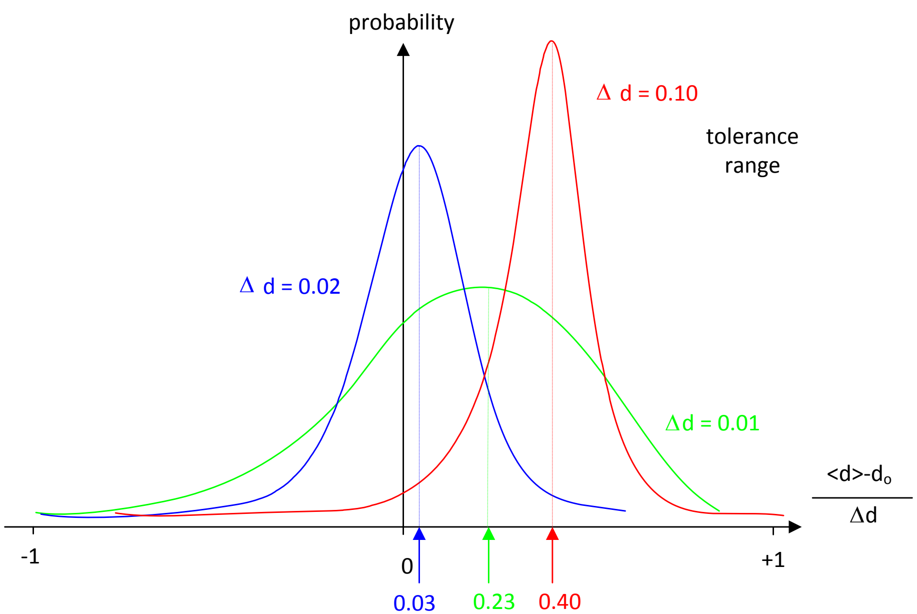
Tolerances and Statistics

- Statistics of refractive index tolerances:
  nearly normal distributed

- Tolerances of lens thickness:
  - biased statistical istribution with mean at 0.3 Δd
  - less pronounced offset for small intervals of tolerance
  - width of the distribution depends on the hardness of the material

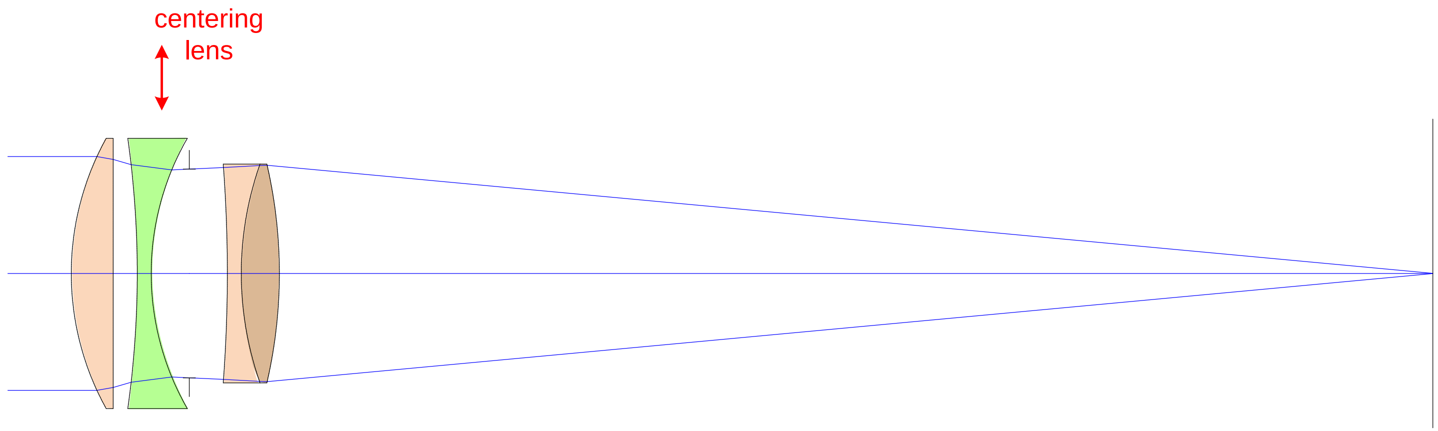






Compensators

- Compensators:
  - changeable system parameter to partly compensate the influence of tolerances
  - compensators are costly due to an adjustment step in the production
  - usually the tolerances can be enlarged, which lowers the cost of components
  - clever balance of cost and performance between tolerances and adjustment
- Adjustment steps should be modelled to lear about their benefit, observation of criterias, moving width,...
- Special case: image position
  compensates for tolerances of radii, indices, thickness
- Centeriung lenses:
  lateral shift of one lens to get a circular symmetric point spread function on axis
- Adjustment of air distances between lenses to adjust for spherical aberration, afocal image position,...



Thickness Tolerance

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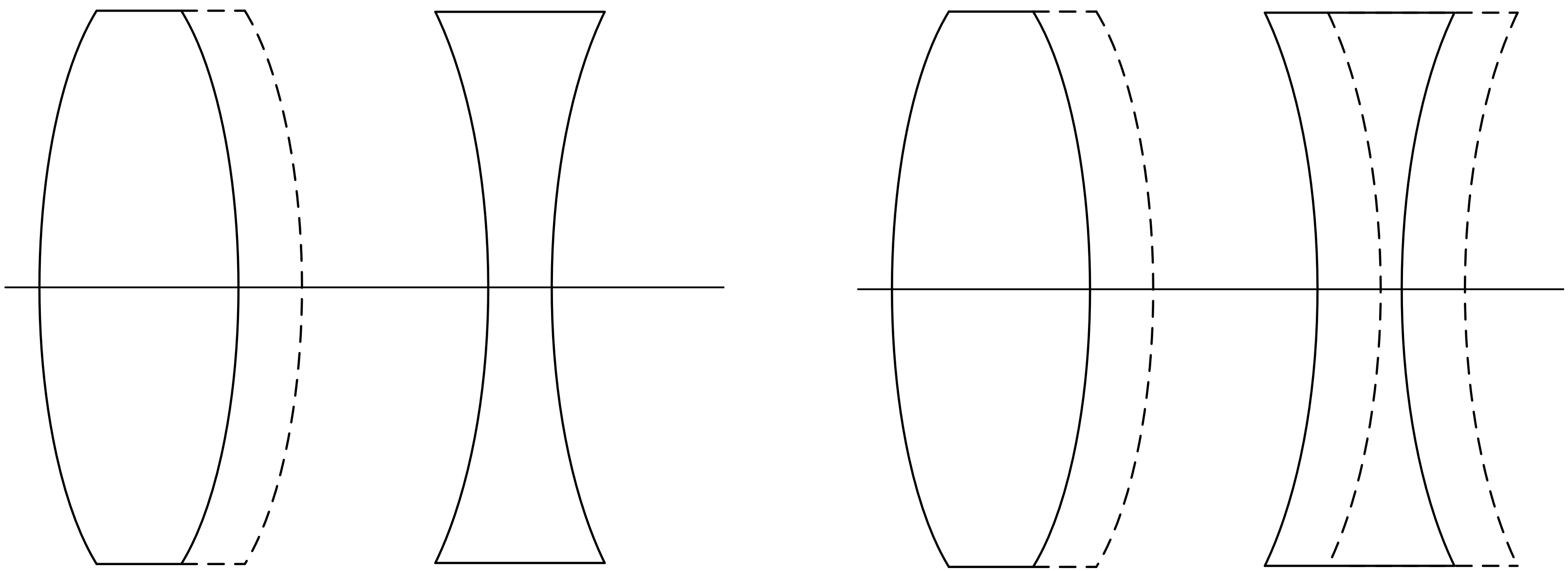
- Tolerances of thickness or distances
- in case of glass thickness: effect of tolerance depends on the mounting setup, the difference usually is added or subtracted in the neighboring air distance
- usually, the overall length of the system remains constant
- the thickness tolerance is far less sensitive as curvature errors

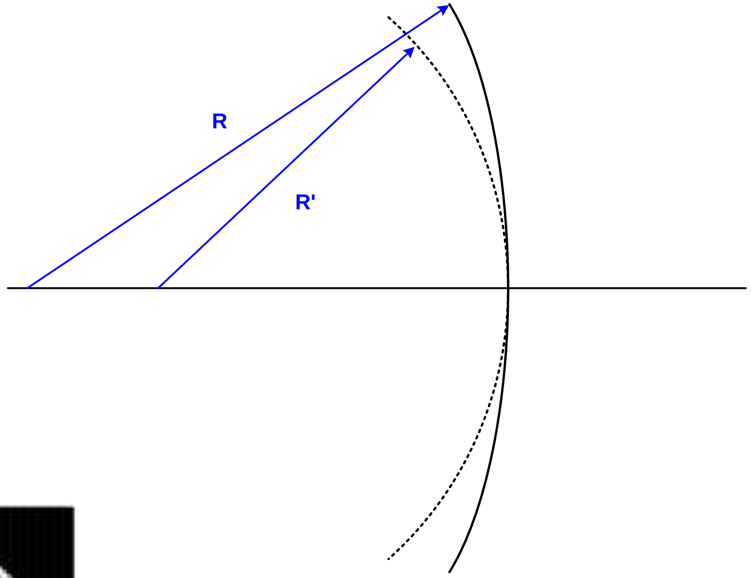


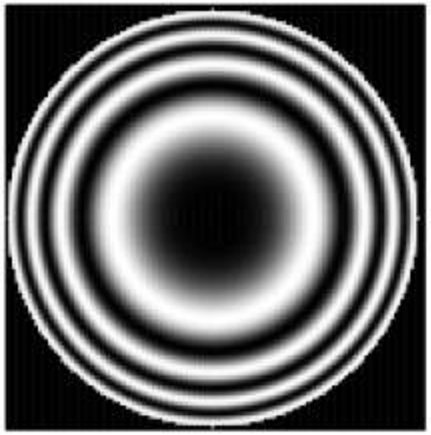
Ref: C. Menke

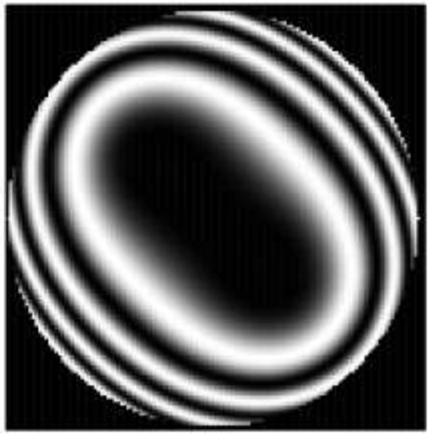
Surface Shape Tolerance

Tolerance of the surface shape:

- specification in fringes
- interferometric measurement
- irregularity: deviation from spherical shape
- typical specification:
  5(1) menas: 5 ring1 spherical deviation
  1 ring asymmetry/astigmatism







Ref: C. Menke

Tolerances of Aspheres

- Conventional tolerance:
  1. error of radii, can be compensated by defocussing
  2. irregularity, astigmatism
  3. higher order spherical errors like 4th order edge errors

- Slope errors:
  1. relevant error from viewpoint of optical influence
  2. reverence basis length necessary for specification to fix spatial frequency
  3. diversification by tolerancing different diameter ranges

- Sag error of the real surface
  1. not propriate tolerance without specification of the basis length (spatial frequency)
  2. rms number more significant than pv value

- Micro roughness:
  1. high frequent errors due to manufacturing, causes wide angle scattering
  2. specification as rms tolerance
  3. influences contrast

Tolerances of Aspheres

Typical errors of aspherical surfaces
1. long range figure errors
2. high frequency micro roughness

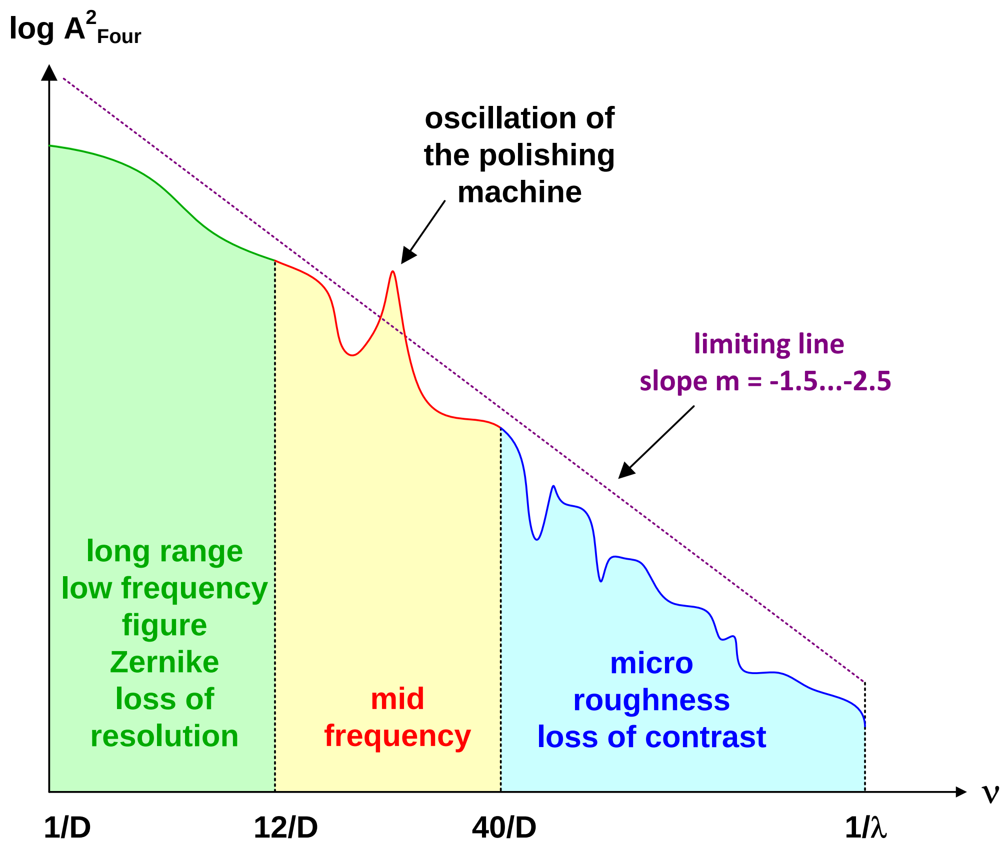
Application	Figure error Rms [nm]	Micro roughness Rms [nm]
Eye glassesr	2000	10
Illumination systems	300	2
Digital projection	300	1
Photographic lenses, cameras, comsumer	100	1
Satellite systems	20	0.5
DUV – Lithography lenses	2	0.3
EUV – Lithography lenses	0.1	0.1

Tolerancing of Free Form Surfaces

- Today there is only insufficient experience for the tolerancing of free shaped surfaces
- Specification and tolerancing are not standardized
- Possible options are:
  1. rms value
  2. global maximum deviation Δz (peak valley)
  3. Slope error, in components, in various area ranges of the surface
  4. Sinusoidal perturbations with specified intervals, amplitudes to cover the mid-frequency range
  5. Limiting straight line or accepted thresholds in a logarithmic power spetrum representation

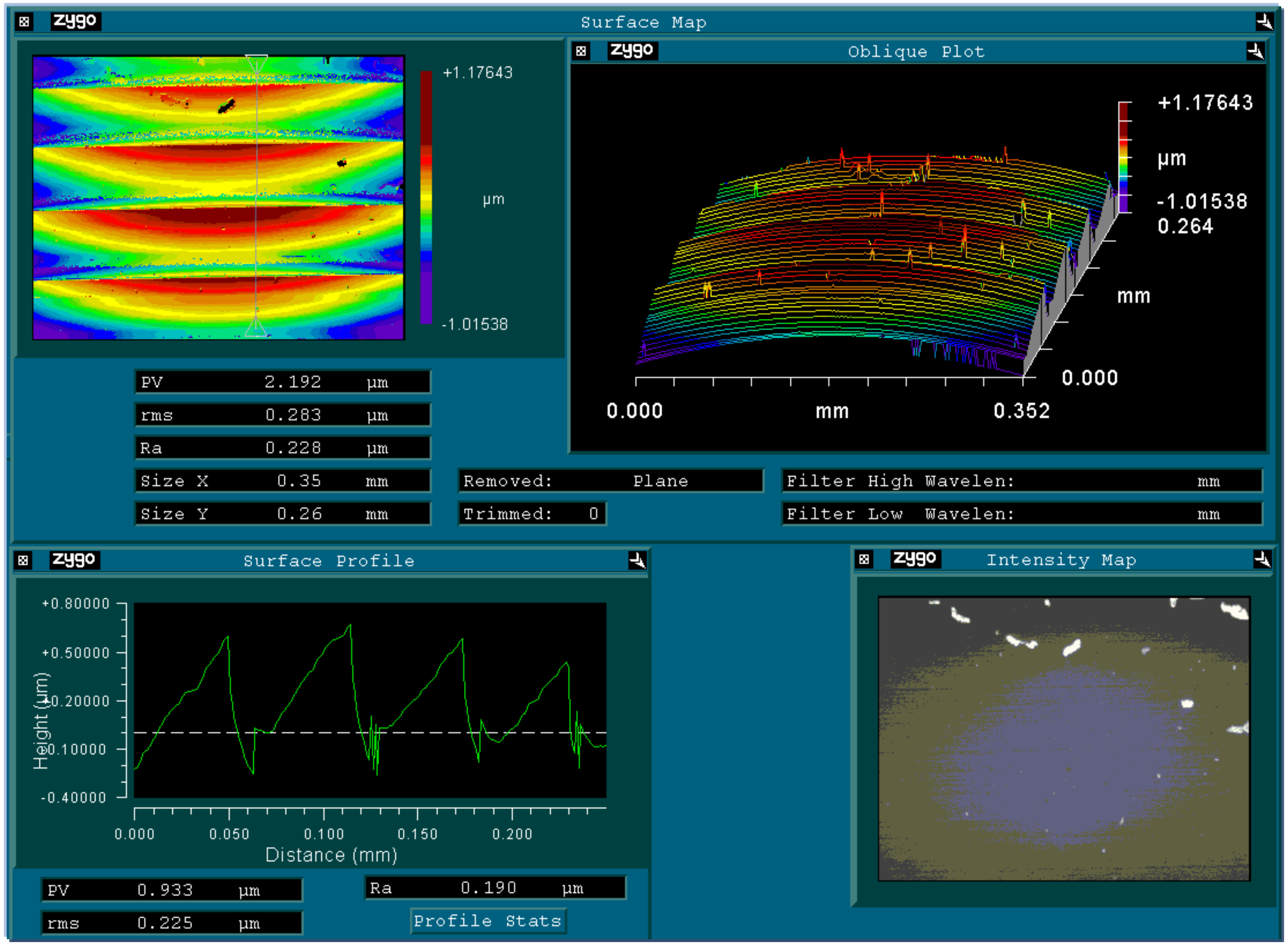
Spatial Frequency Ranges of Surface Errors

- Spatial frequency domain discussion of surface errors
- Power spectral density describes the power in the Fourier components
- Low frequency range:
  - figure error
  - loss in resolution
  - classical aberrations, description by Zernikes
  - interferometric measurement
  - spatial frequency ν < 12/D
- Midfrequency range:
  - ripple due to manufacturing
  - spatial frequency ν < 12/D ...40/D
  - reason mostly mechanical perturbations in manufacturing
- High frequency range:
  - micro roughness with high spatial frequencies
  - causes wide angle scattering and straylight
  - reasons are problems with polishing



Diamond Turning of Plastic Surfaces

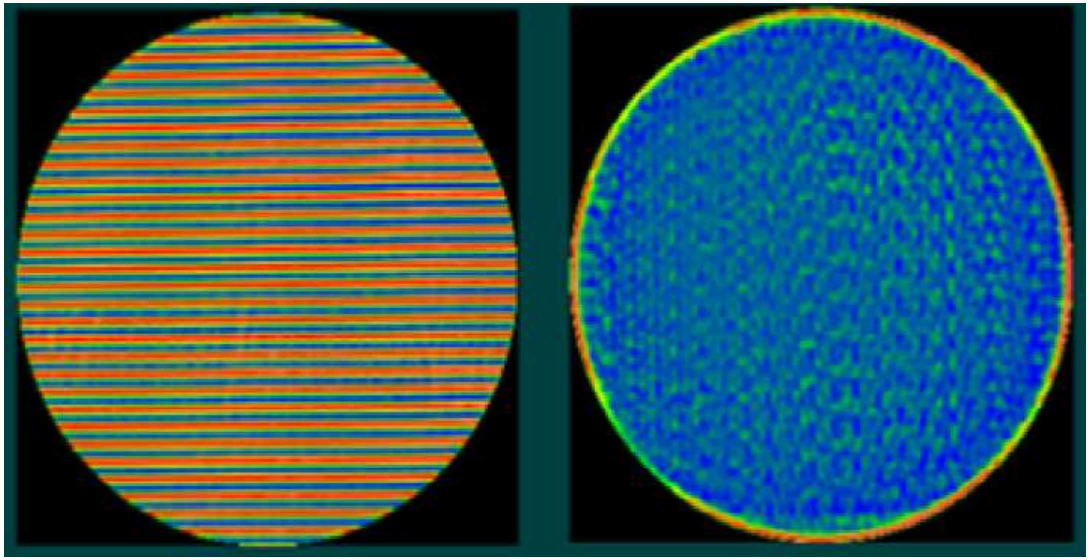
- Structured surface with ripple

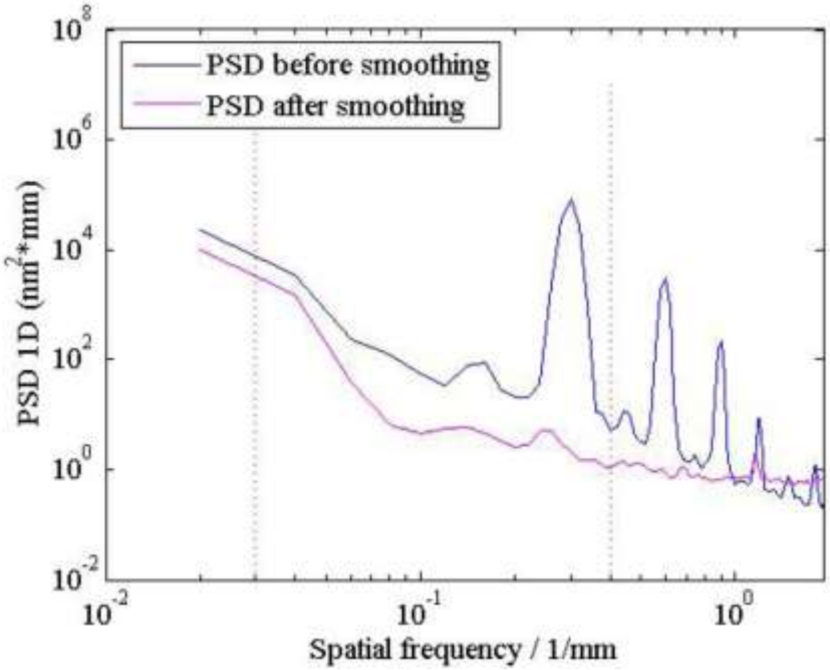


Ref: A. Rohrbach

Spatial Midfrequency Errors

- Surface with diamond turning shaping
- Surface and PSD before and after polishing

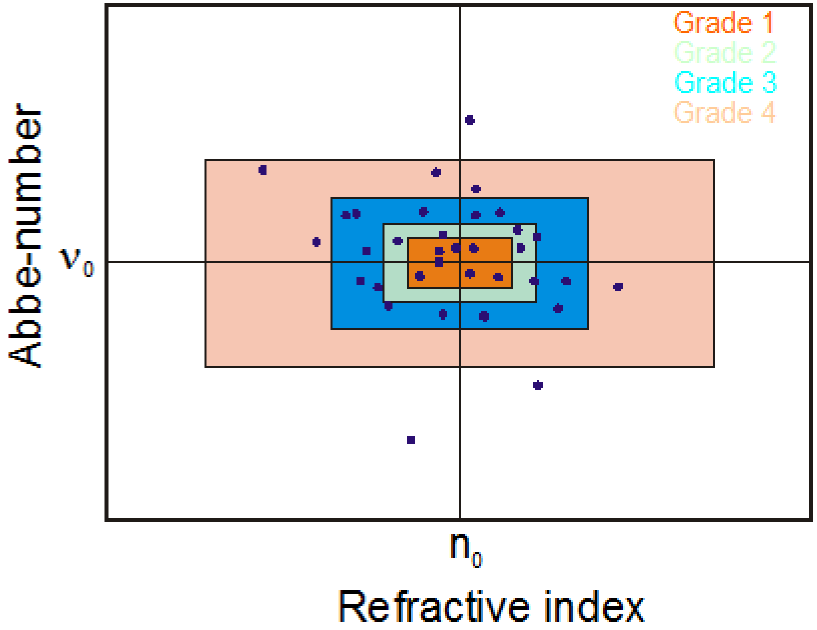




Ref.: Zhang et. al.

Tolerances of Glass

- Discrete tolerance steps
- Rectangulare tolerance areas in n-ν- plane



Grade (tolerance step)	Δn	$\Delta \nu / \nu$
1	**+/– 0.0002**	**+/– 0.2%**
2	**+/– 0.0003**	**+/– 0.3%**
3	**+/– 0.0005**	**+/–0.5%**
4	**+/– 0.001**	**+/–0.8%**

Ref.: M. Peschka

Index Homogeneity of Glasses

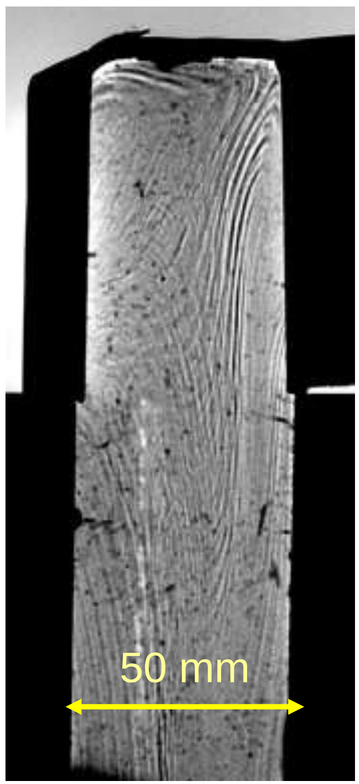
Different classes of homogeneity of glasses

Class	ISO 10110	Δn in the sample
	0	50 10^{-6}
	1	20 10^{-6}
H 2	2	5 10^{-6}
H 3	3	2 10^{-6}
H 4	4	1 10^{-6}
H 5	5	0.5 10^{-6}

Ref.: M. Peschka

Definition of Striae

- Standard not sufficient
- Appearance:
  like wood in transmission shadow image



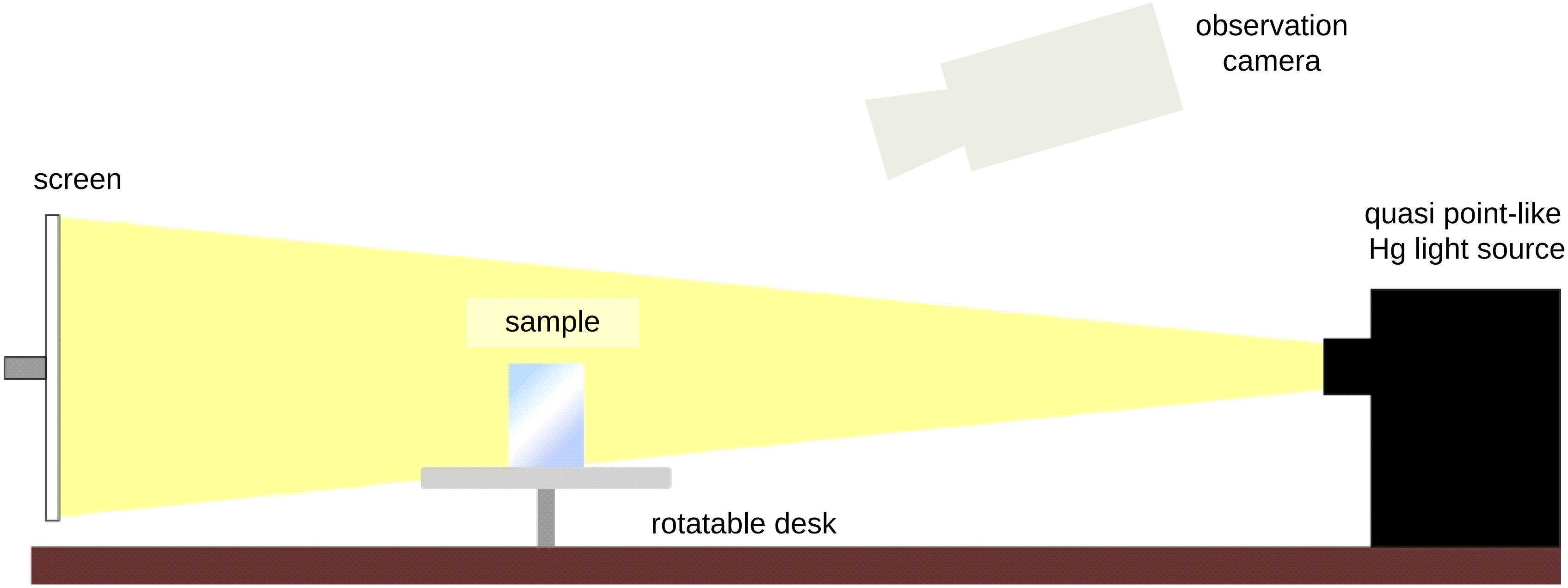
	MIL-G-174B	DIN ISO 10110-4	SCHOTT (nur intern)	SCHOTT (Katalog)
Gültig für:	**Rohglas**	**Optisches Element**	**Rohglas**	
Charakterisierung durch:	Intensität ohne Beachtung der Probendicke	Schlierendurchsetzte Fläche (Schlierendichte)	Intensität mit Beachtung der Probendicke (50 mm)	
Schlierengrade:	**D**	$\geq$30 nm **1**: $\leq$ 10% **2**: $\leq$ 5% **3**: $\leq$ 2% **4**: $\leq$ 1%	**D**: ~60 nm	
	C	**5:** sehr schwache bis keine Schlieren sichtbar	**C:** ~ 30 nm	< 30 nm: **normale** Rohglasqualität
	B		**B:** ~ 15 nm	~< 15 nm: Bearbeitetes Glas
	A		**A:** < 10 nm	
			VS: keine Schlieren sichtbar	**VS1/VS2:** Keine Schlieren in zueinander senkrechten Richtungen sichtbar

Measurement with Shadowgraphy

- Advantages:
  1. Fast, cheap
  2. Simple setup
  3. Small requirements on sample surface quality

- Disadvantage:
  1. no quantitatve calibration until now

shadow image

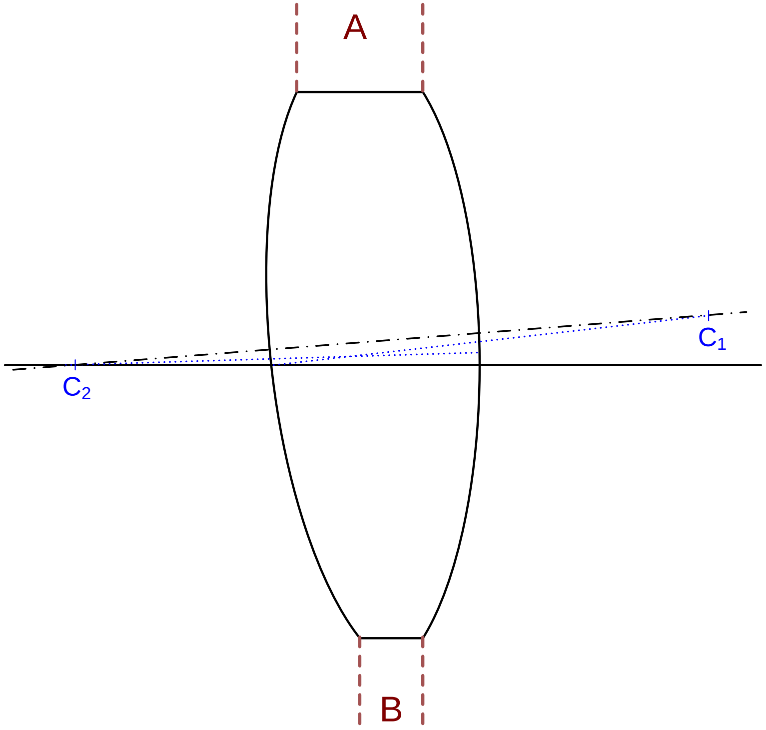


Centering Wedge Error

- Wedge error:
  - tilt of a single surface relative to the optical or mechanical axis.
  - Specification as tilt error of total indicator runout (TIR) in [mm]
  - angle value in rad: TIR / D (D diameter)

TIR = A - B

- The optical axis is the straight line through the two centers of curvature of the two spherical surfaces
- Mechanical axis:
  defined by the cylindrical boundary of the lens
- Usually the optical and the mechanical axes do no coincide
- A wedge error must be specified only for one of the surfaces



Ref: C. Menke

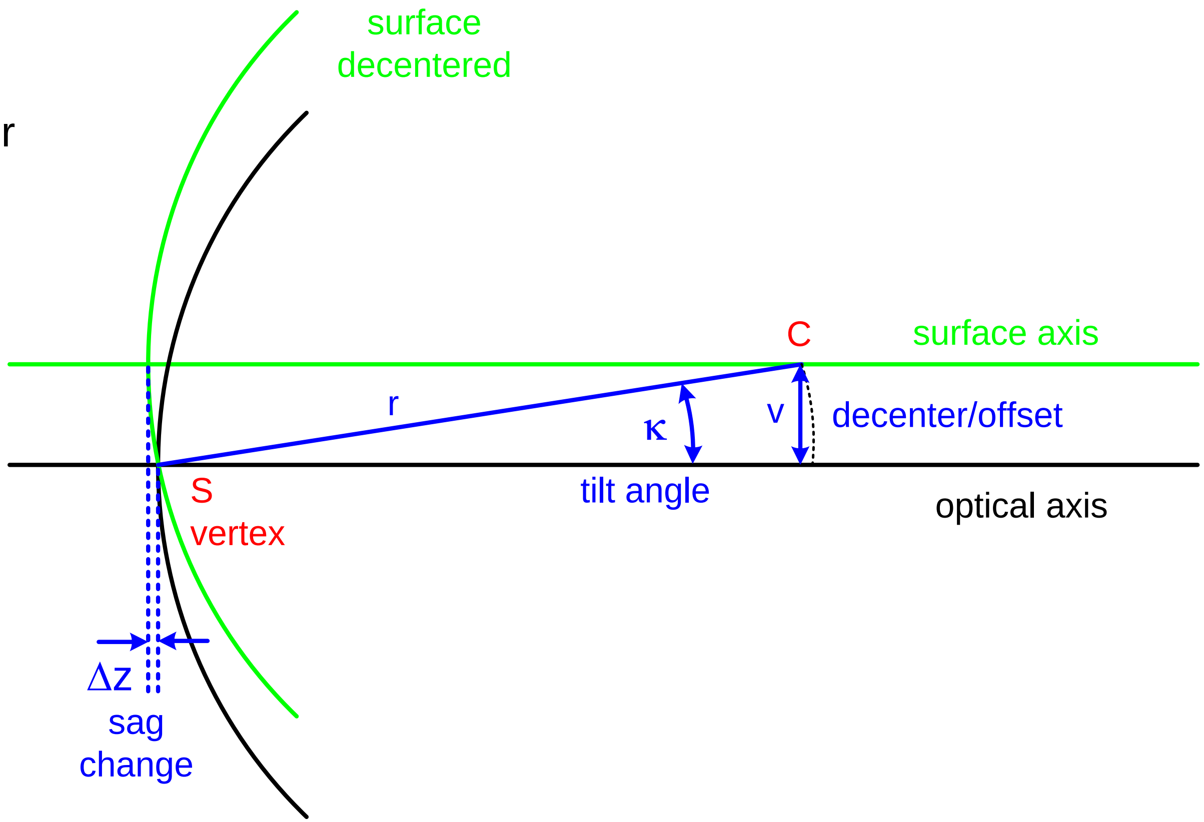
Centering of Spherical Surfaces

- Equivalence of decenter (offset) and tilt angle

$$\sin\kappa = -\frac{v}{r}$$

- Small change in sag (vertex position) in 2nd order

$$\Delta z = r \cdot (1 - \cos\kappa)$$



Rotation of a Spherical Surface

- Shift of center of rotation to D: relation

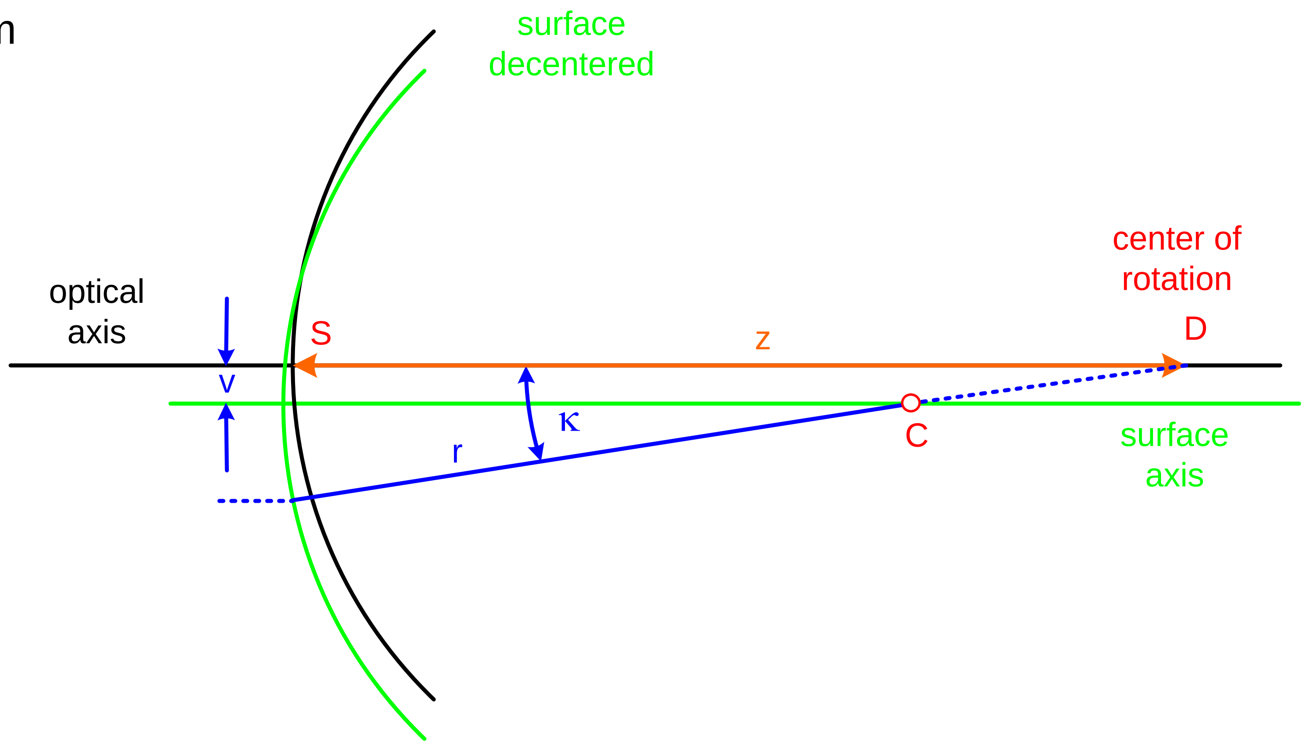
$$\sin\kappa = -\frac{v}{r-z}$$

- Conversion of units form radiant in minutes

$$k = \frac{\pi}{60\cdot 180}$$

$$= 2.9089\cdot 10^{-4}$$

$$\approx 3\cdot 10^{-4}$$

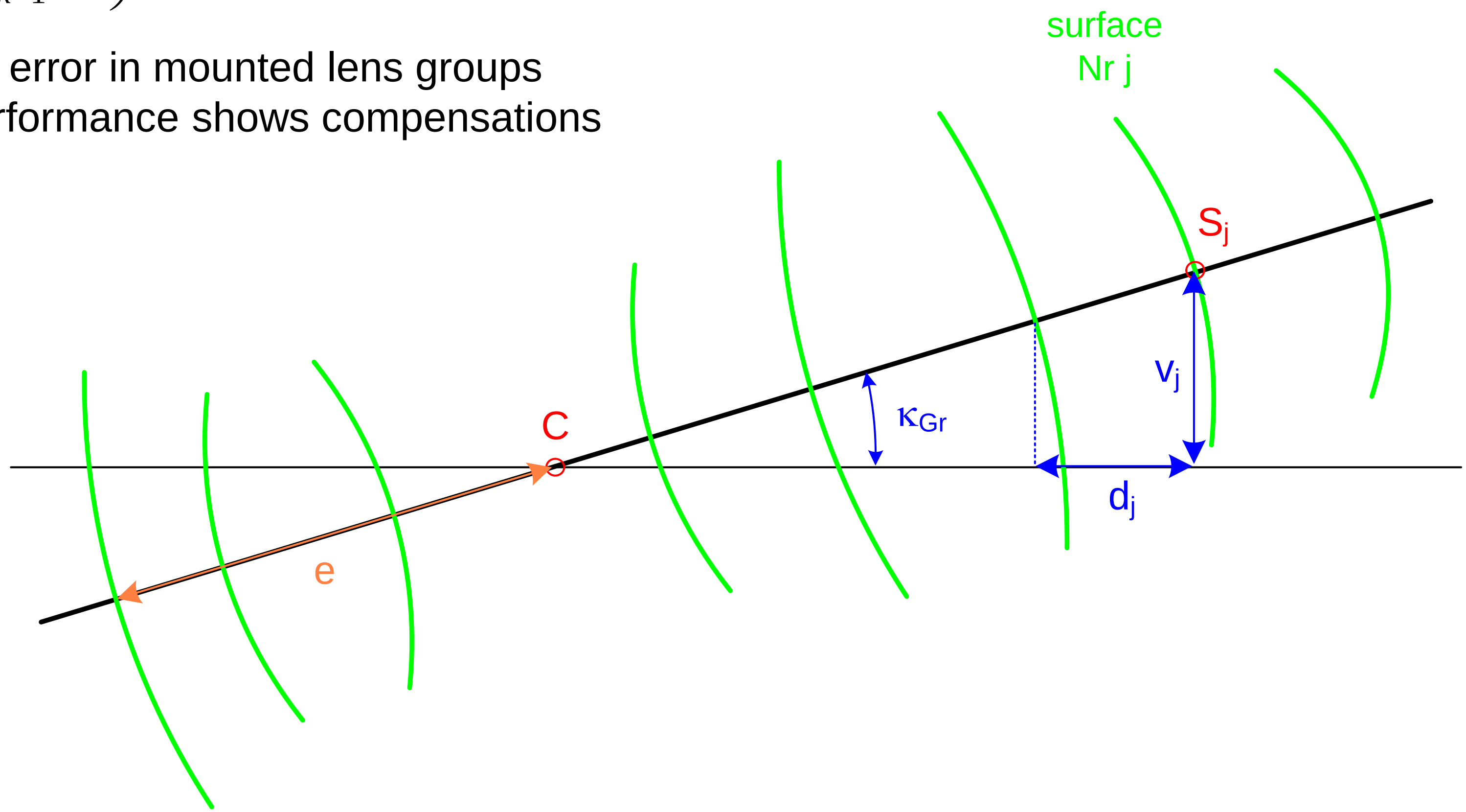


Rotation of a Group of Surfaces

- Rigid coupled sequence of surfaces
- Tilt with arbitrary location of center of rotation

$$v_j = \left(e - \sum_{k=1}^{j} d_k \right) \cdot \sin \kappa_{Gr}$$

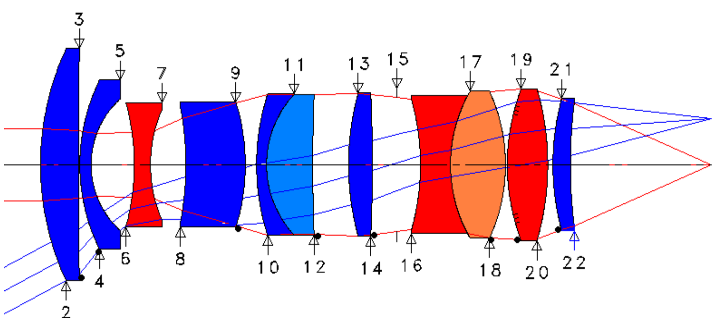
- Model for tilt error in mounted lens groups
- Effect on performance shows compensations



Centering Tolerances

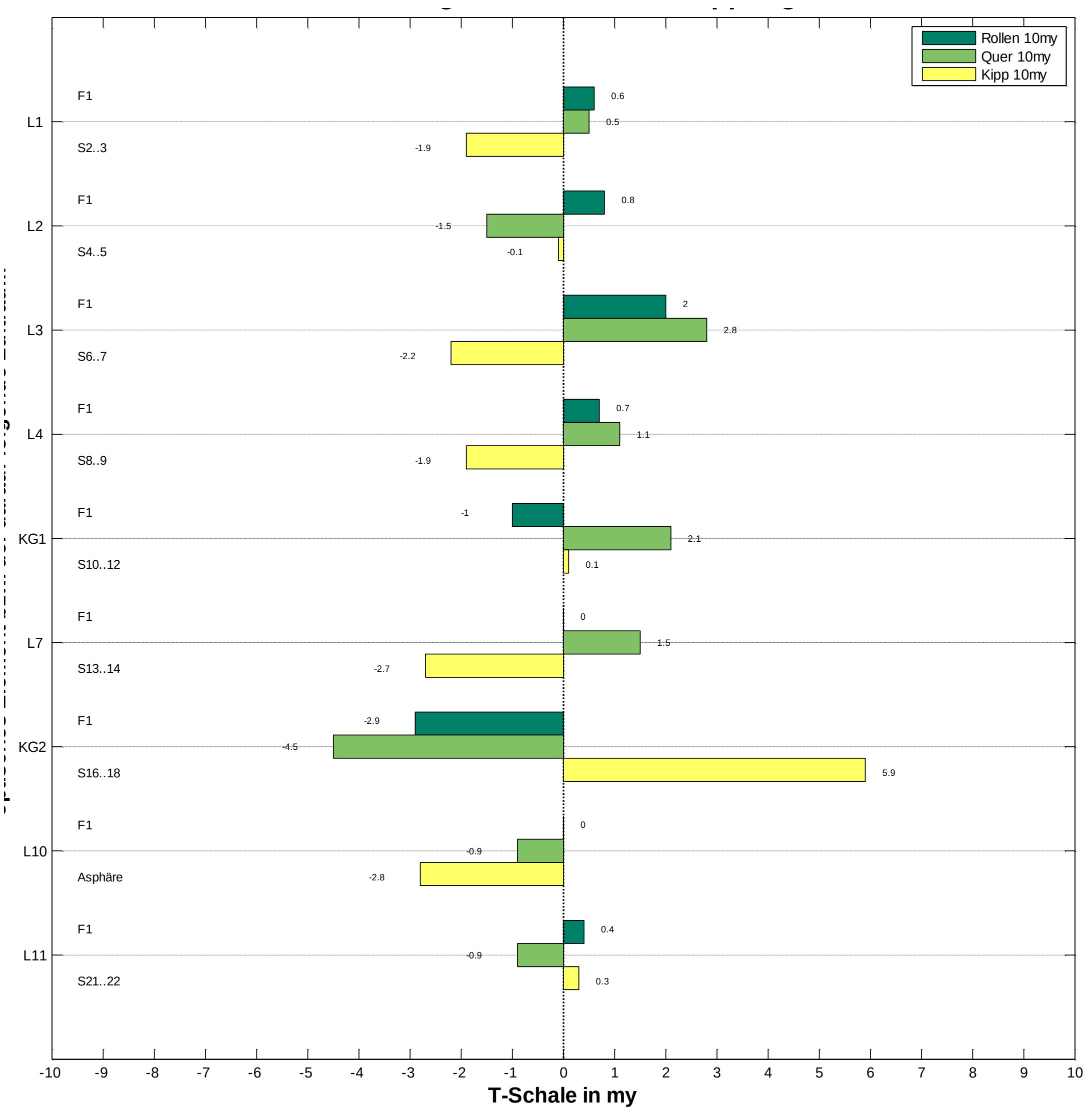
Centering tolerances in photographic lenses:

1. System layout



2. Tilt of image plane due to
    - tilt (yellow)
    - roll (green dark)
    - decenter (green bright)

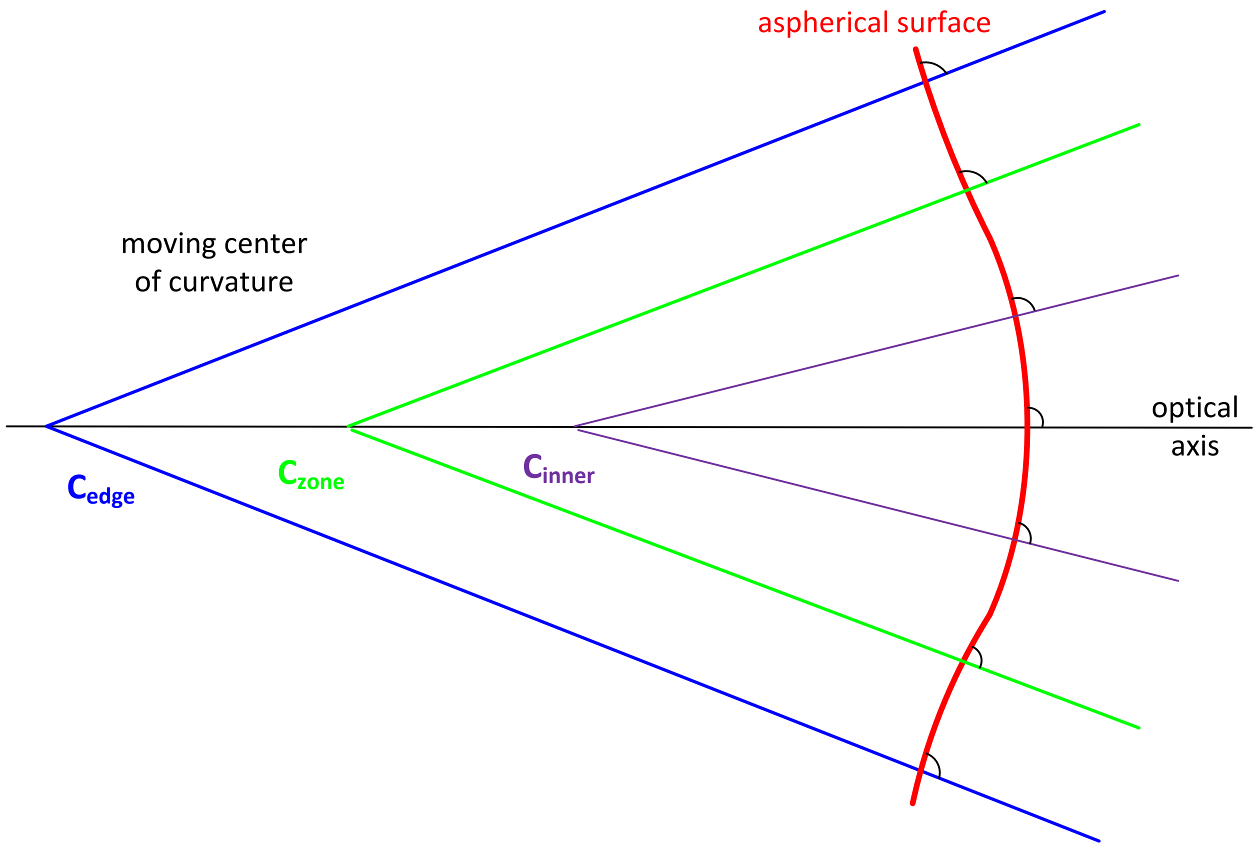
of lenses



From: D. Gängler

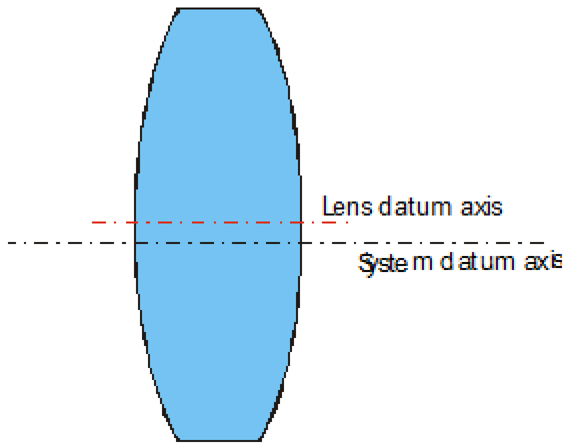
Centering of Aspheres

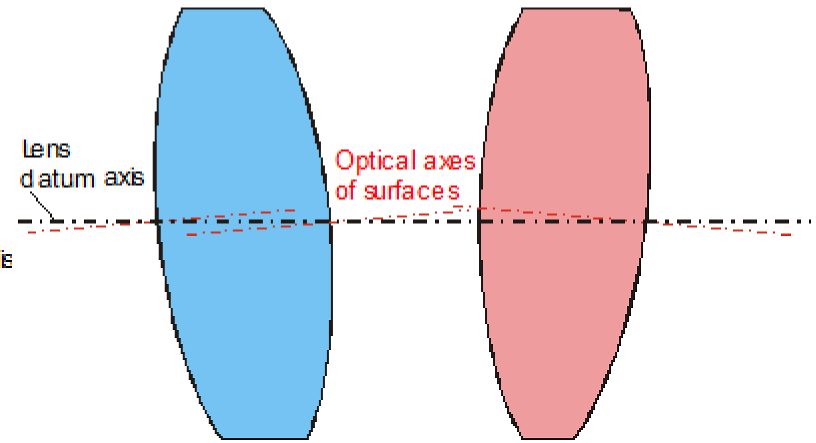
- Asphere :
  The location of the center of curvature moves with the radial surface position
- Conventional reflex light measurement in autocollimation is not possible



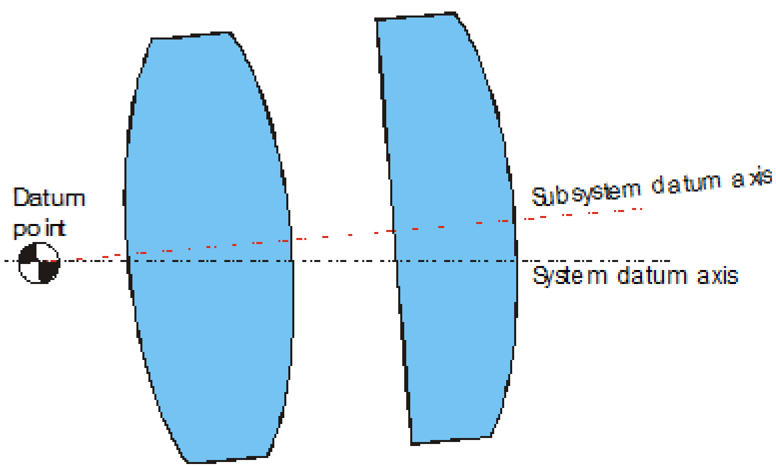
Centering Errors of Lenses

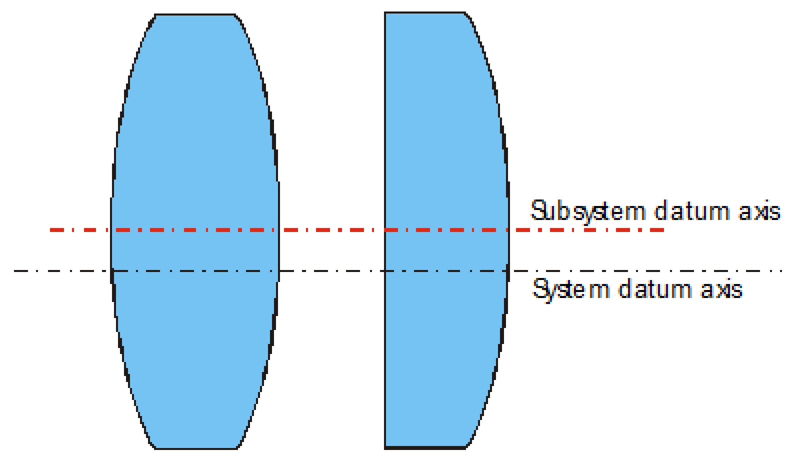
- Lens
  1. Radial offset
  2. Shearing
  3. Wedge





- Lens group
  1. Group tilt
  2. Group offset





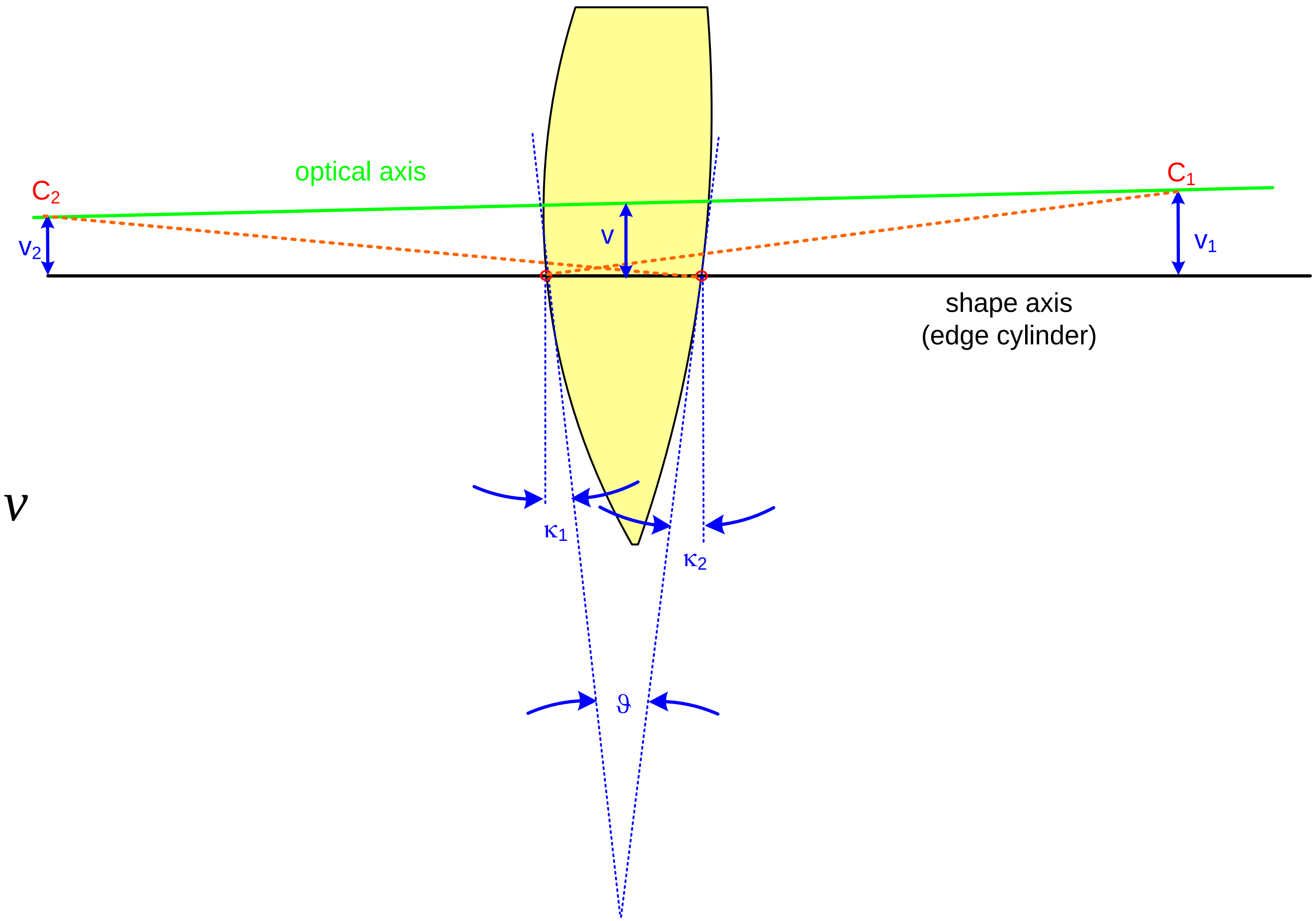
Ref.: M. Peschka

Wedge Angle of a Thin Lens

Thin lens with wedeg error

$$\vartheta = -\frac{v}{(n-1)\cdot f}$$

$$\vartheta = \kappa_1 - \kappa_2 = \left(\frac{1}{r_1} - \frac{1}{r_2}\right)\cdot v$$



Tolerances: Centering Methods

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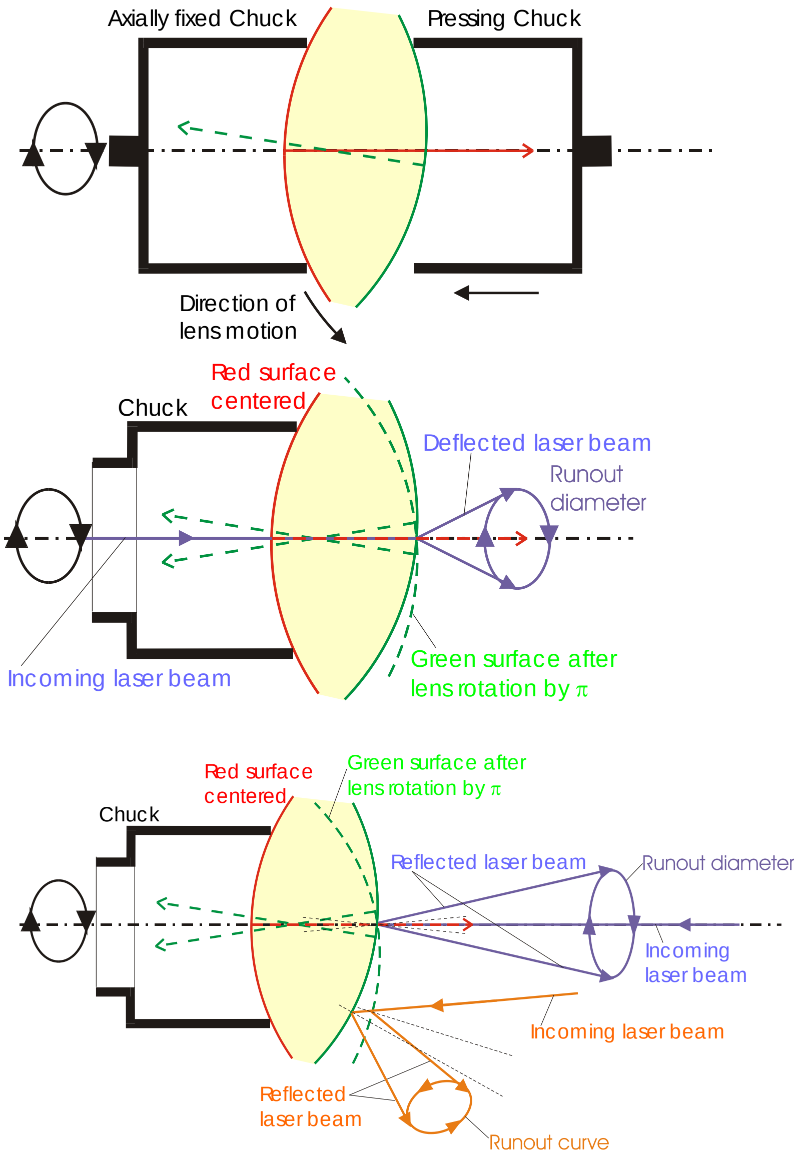
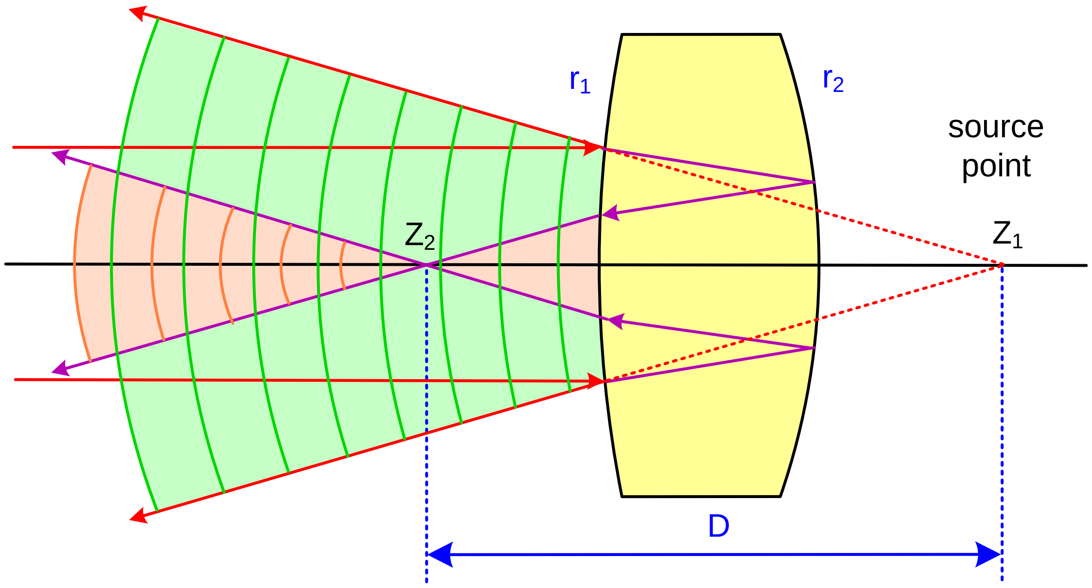
- Mechanical
- Ray in transmission
- Rays in reflection



Ref.: M. Peschka

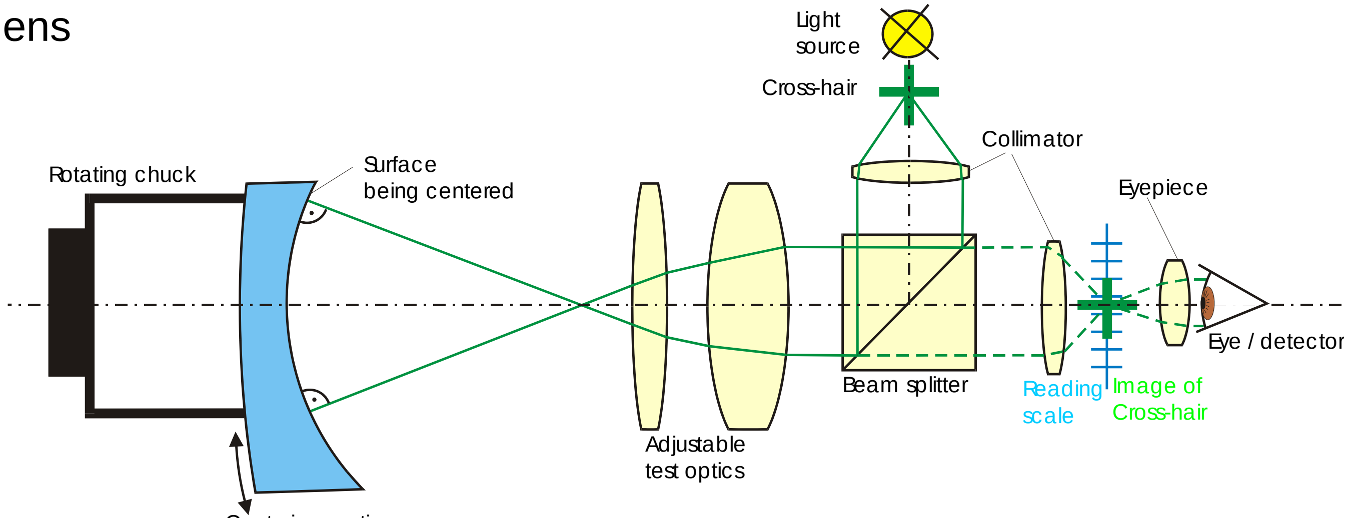
Centering of a Lens with Interferogram

- Measurement of the centering of lens by inspection of the interferogram of front and rear surface

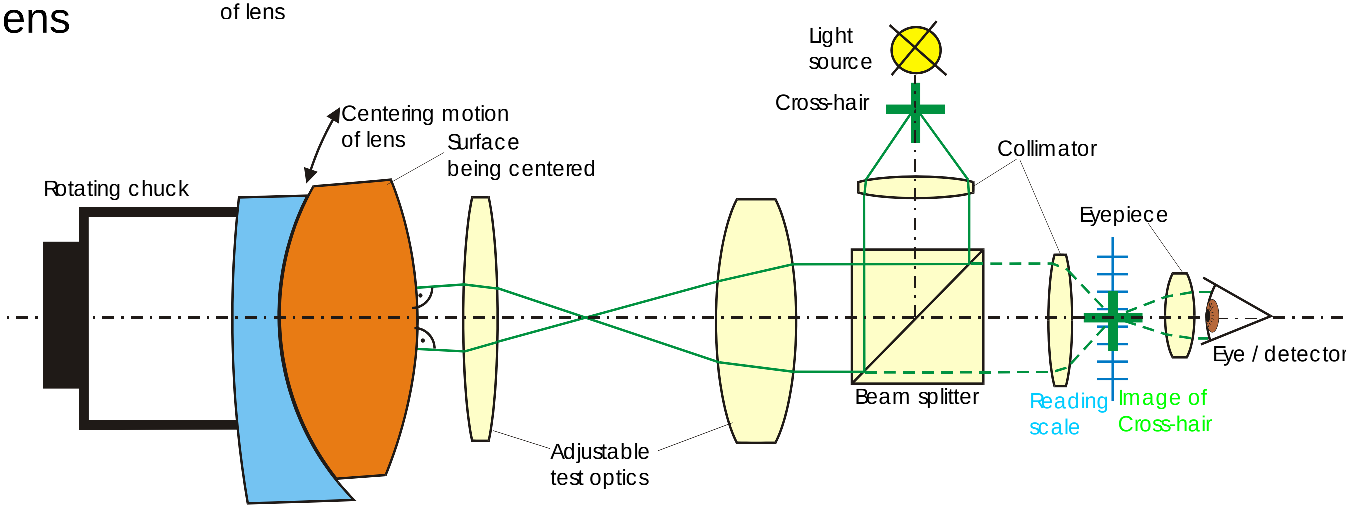


Centering in Bonding Process

- Centering carrier lens



- Adjusting second lens



Ref.: M. Peschka

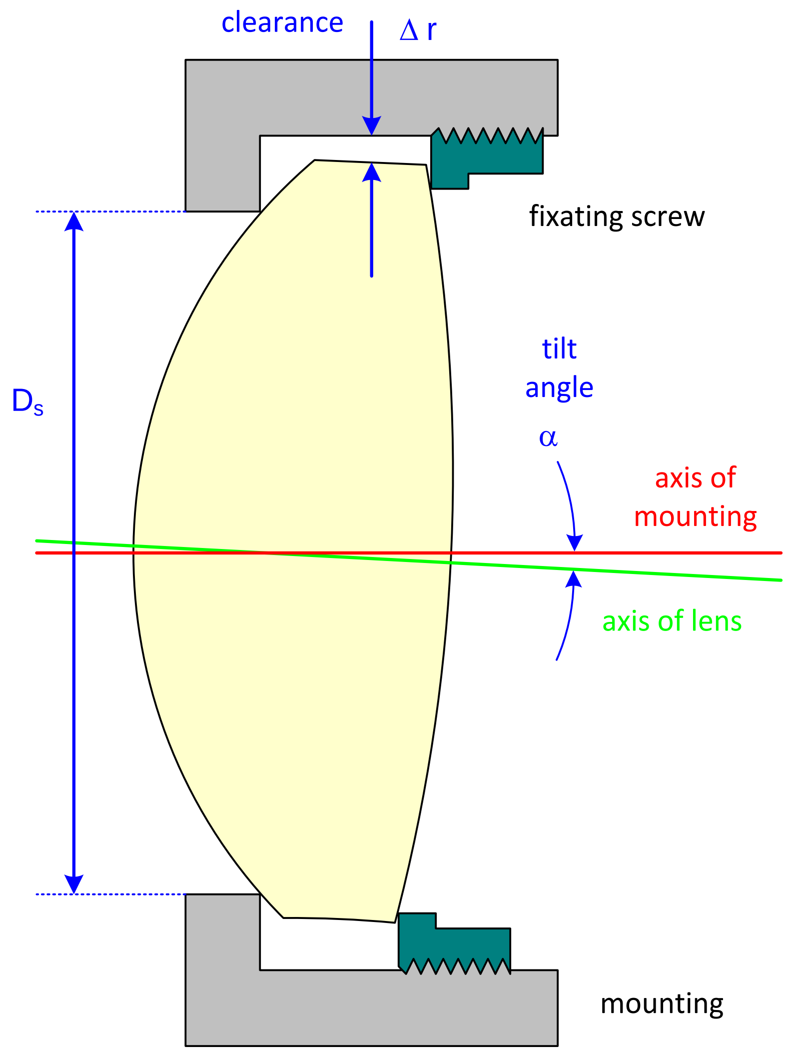
Tolerances and Mechanical Interface

- Coupling optics – mechanics
  Interface glass – metal

- Mechanical design of mountings and housing

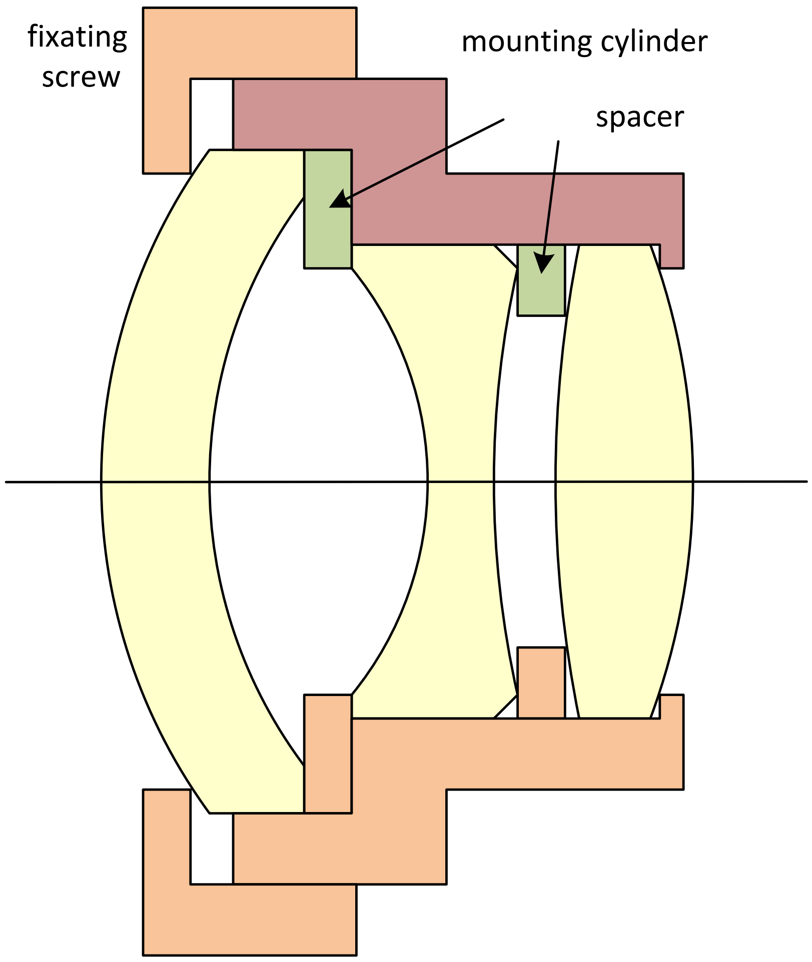
- Typical options:
  1. Filling cylinder with fixating screw
  2. Cementing, later centering
  3. Lace / bordering

- Critical:
  - Centering tolerances
  - reference surfaces
  - analysis of complete geometry (kinematic)



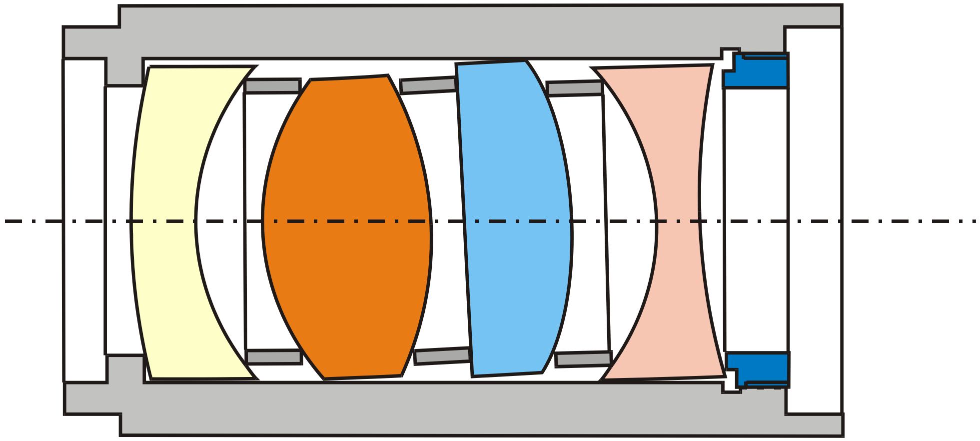
Mechanicl Mounting Geometry

- Filling of lenses into mounting cylinder with spacers
- Accumulation of centering errors by transportation of reference
- Definition of lens positions by:
  1. mechanical play inside mounting
  2. fixating ring screw
  3. planarity of spacers

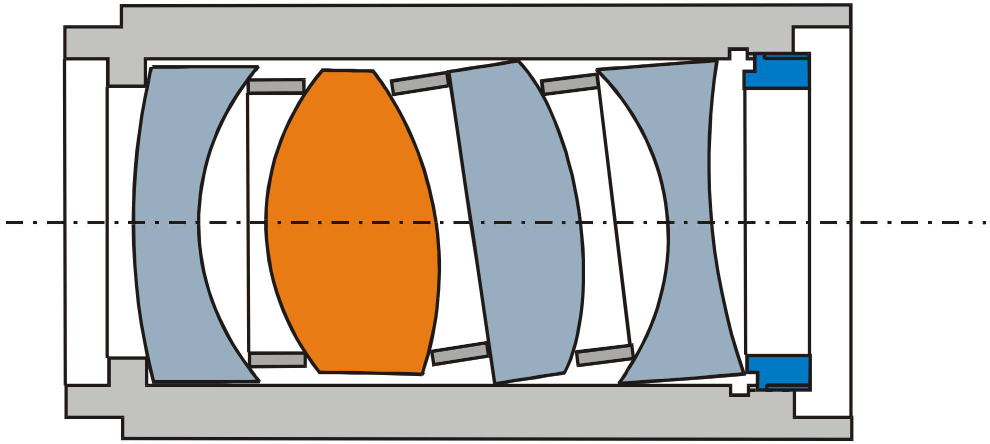


Tolerances of Mounting Assembly

- Mechanical Play



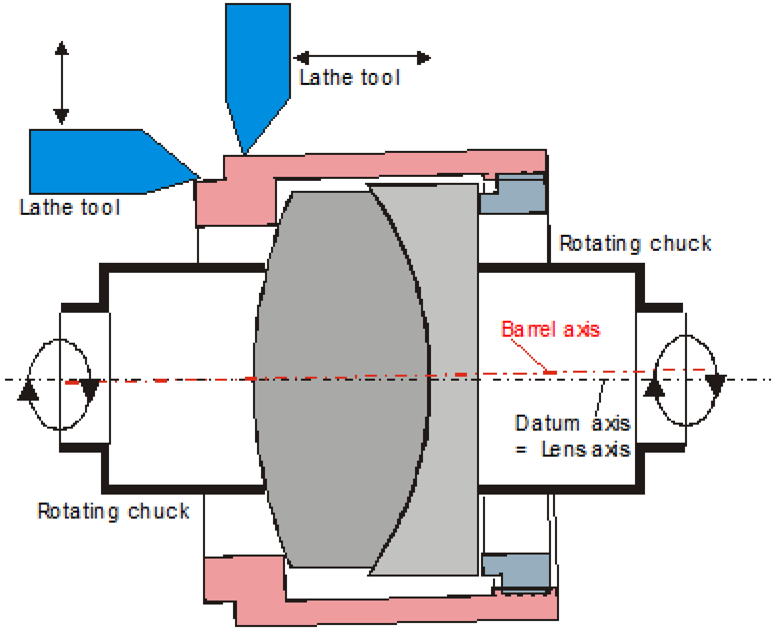
- Wedge errors



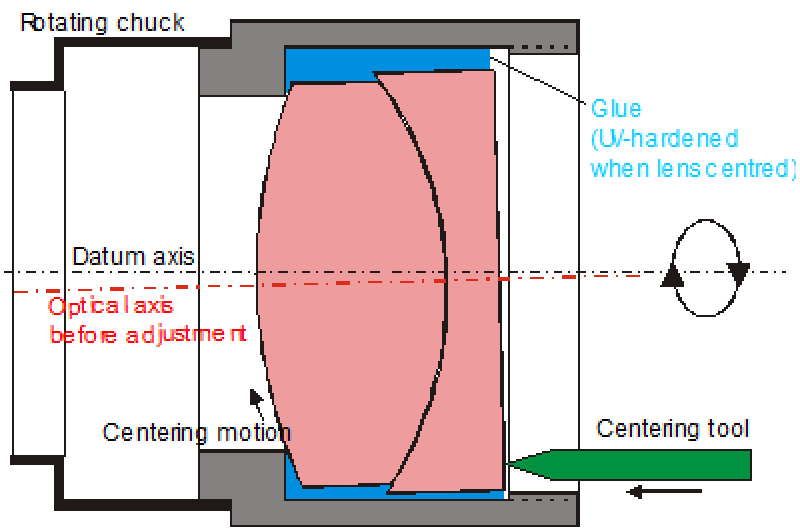
Ref.: M. Peschka

High Precision Mountings

- Adjustment turning



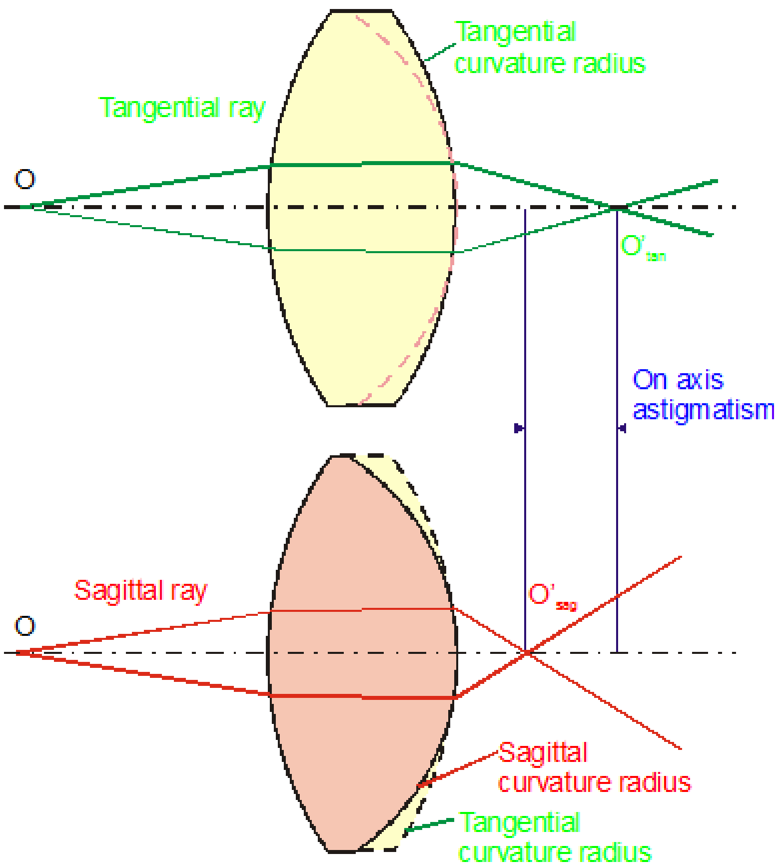
- Adjustment glueing



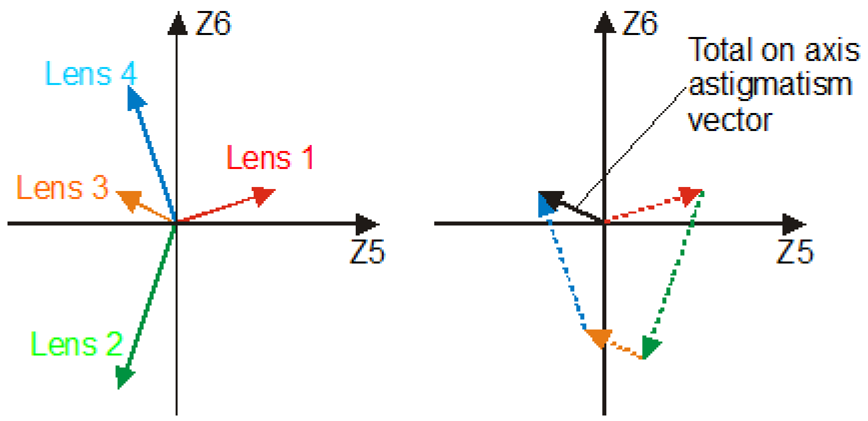
Ref.: M. Peschka

On-Axis Astigmatism

- On-axis astigmatism due to cylindrical irregularity



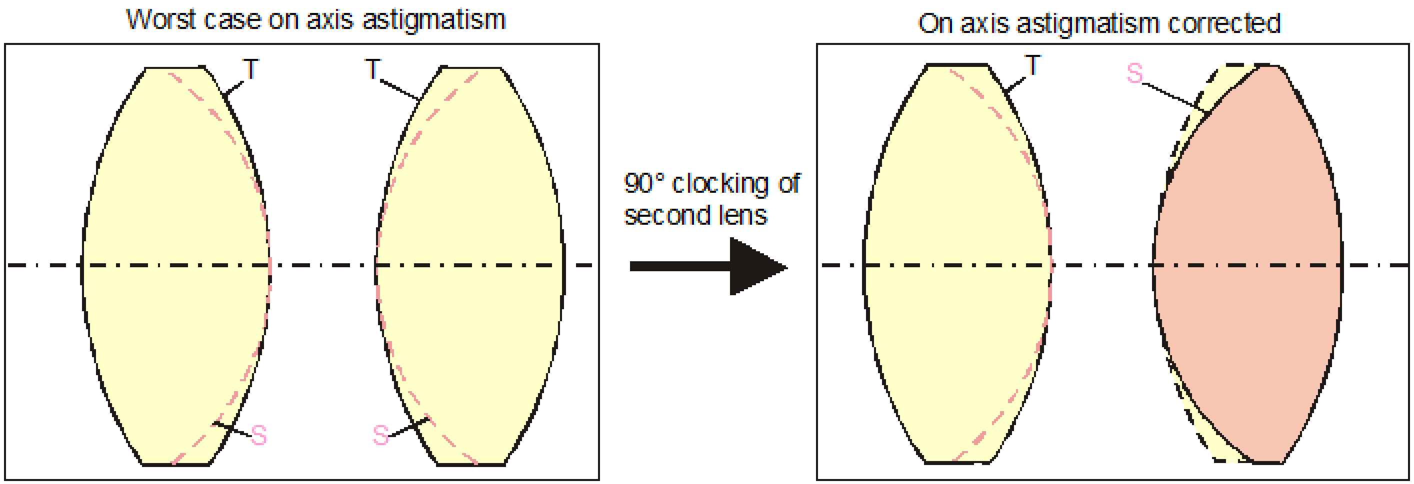
- Vectorial addition of astigmatism in systems



Ref.: M. Peschka

Correcting Astigmatism by Clocking

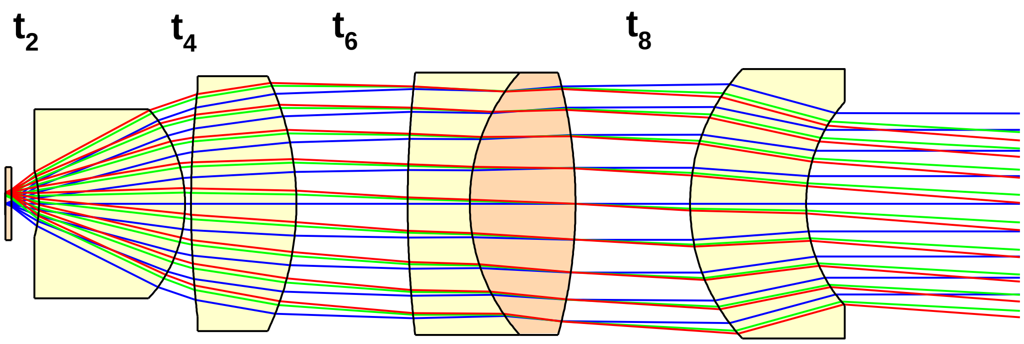
- Rotating of lenses around the optical axis
- Vectorial addition of individual astigmatism components



Ref.: M. Peschka

Adjustment of Objective Lenses

- Adjustment of air gaps to optimize spherical aberration
- Reduced optimization setup



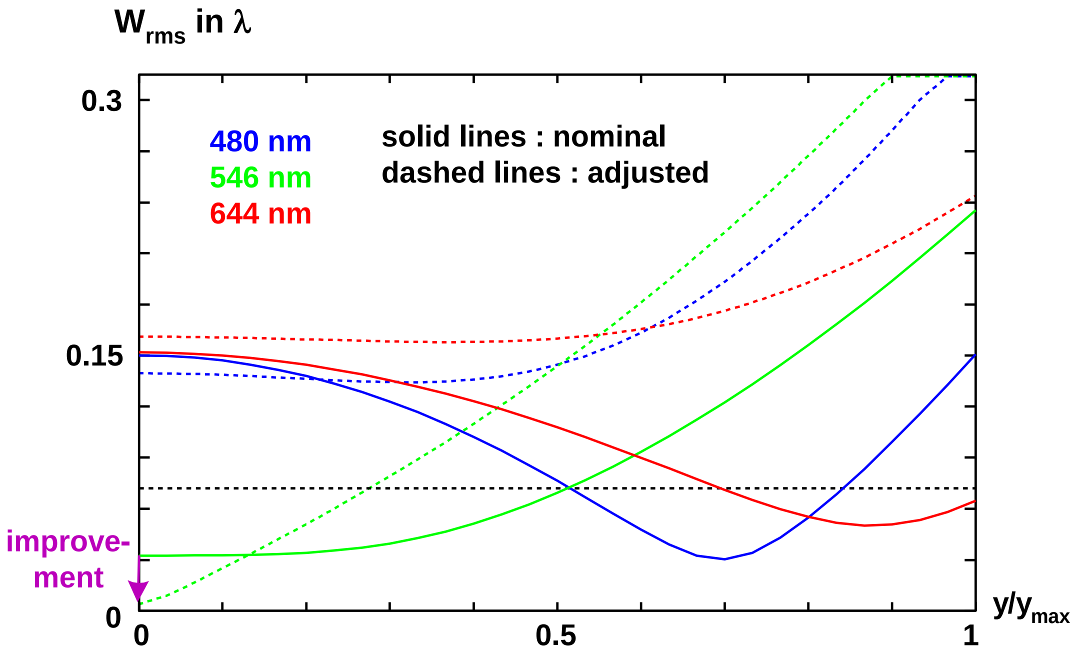
$$c_j = c_{jo} + \sum_{k=1,4} \Delta c_j \cdot \frac{\partial c_j}{\partial t_k} \quad , \; j = 2,4,6,8$$

- Compensates residual aberrations due to tolerances (radii, thicknesses, refractive indices)

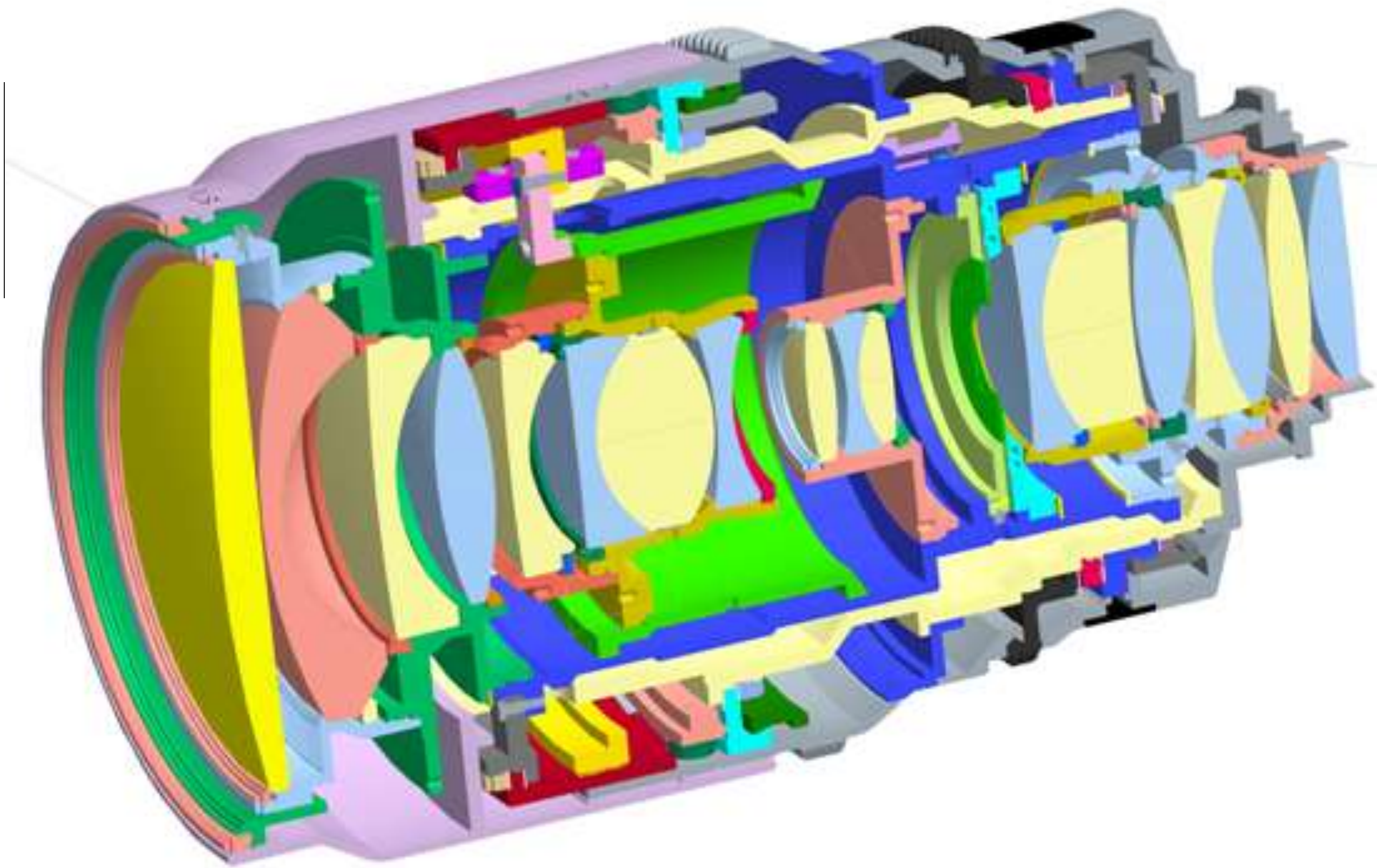
	d_2	d_4	d_6	d_8	c_{20}	c_{40}	c_{60}	c_{80}	W_{rms}
nominal	**0.77300**	**0.17000**	**3.2200**	**2.0500**	**0.00527**	**-0.0718**	**0.00232**	**0.01290**	**0.0324**
d_2 varied	0.77320	0.17000	3.2200	2.0500	0.04144	-0.07586	0.00277	0.12854	
d_4 varied	0.77300	0.17050	3.2200	2.0500	0.03003	-0.07461	0.00264	0.01286	
d_6 varied	0.77300	0.17000	3.2250	2.0500	0.00728	-0.07367	0.00275	0.01284	
d_8 varied	0.77300	0.17000	3.2200	2.0550	0.005551	-0.0717	0.00235	0.01290	
optimized	**0.77297**	**0.16942**	**3.12670**	**3.2110**	**0.000414**	**0.00046**	**0.00030**	**0.01390**	**0.00468**

Adjustment of Objective Lenses

- Significant improvement for one wavelength on axis
- Possible decreased performance in the field

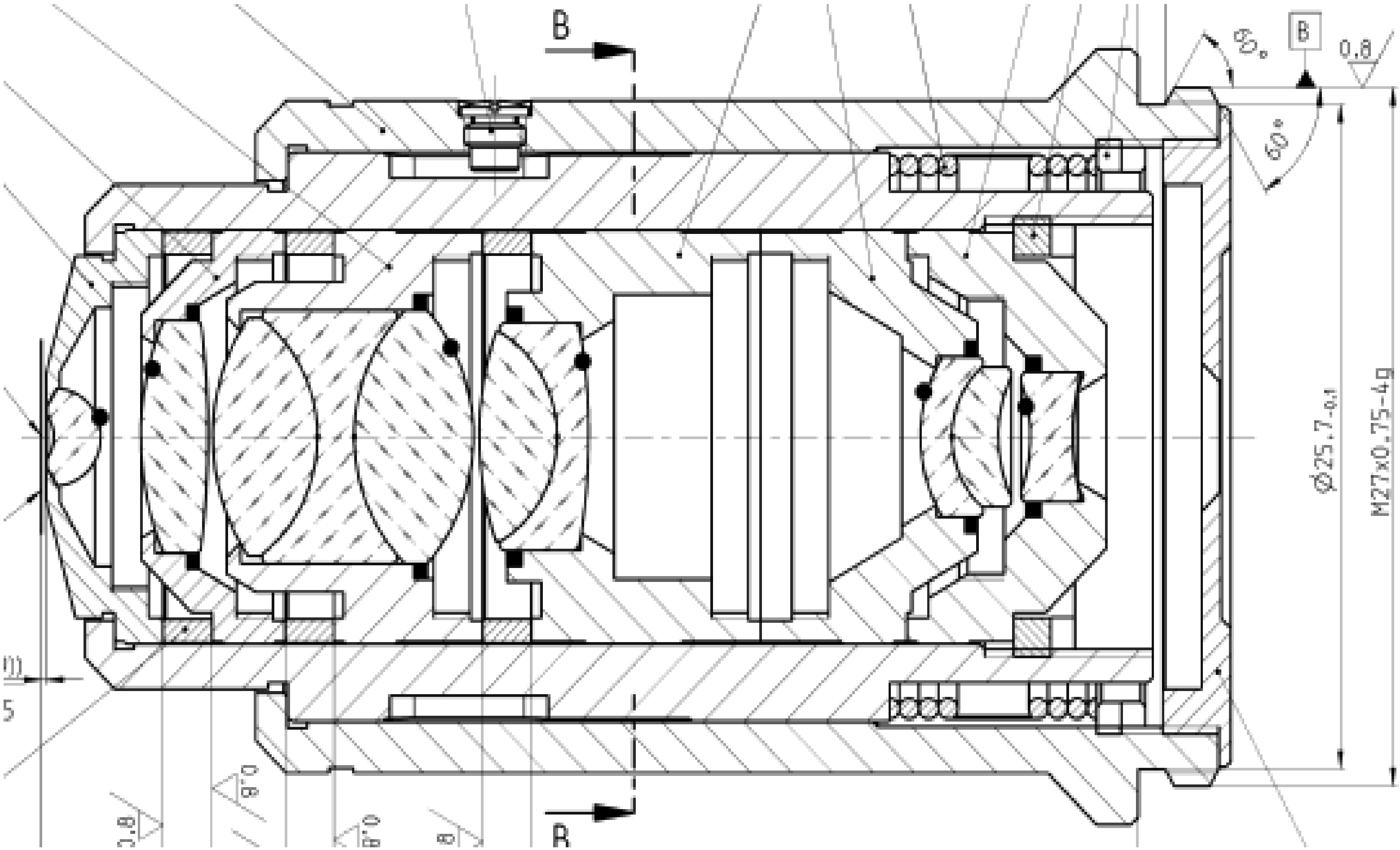


- Photographic lens: Digiprime 7



Ref.: M. Peschka

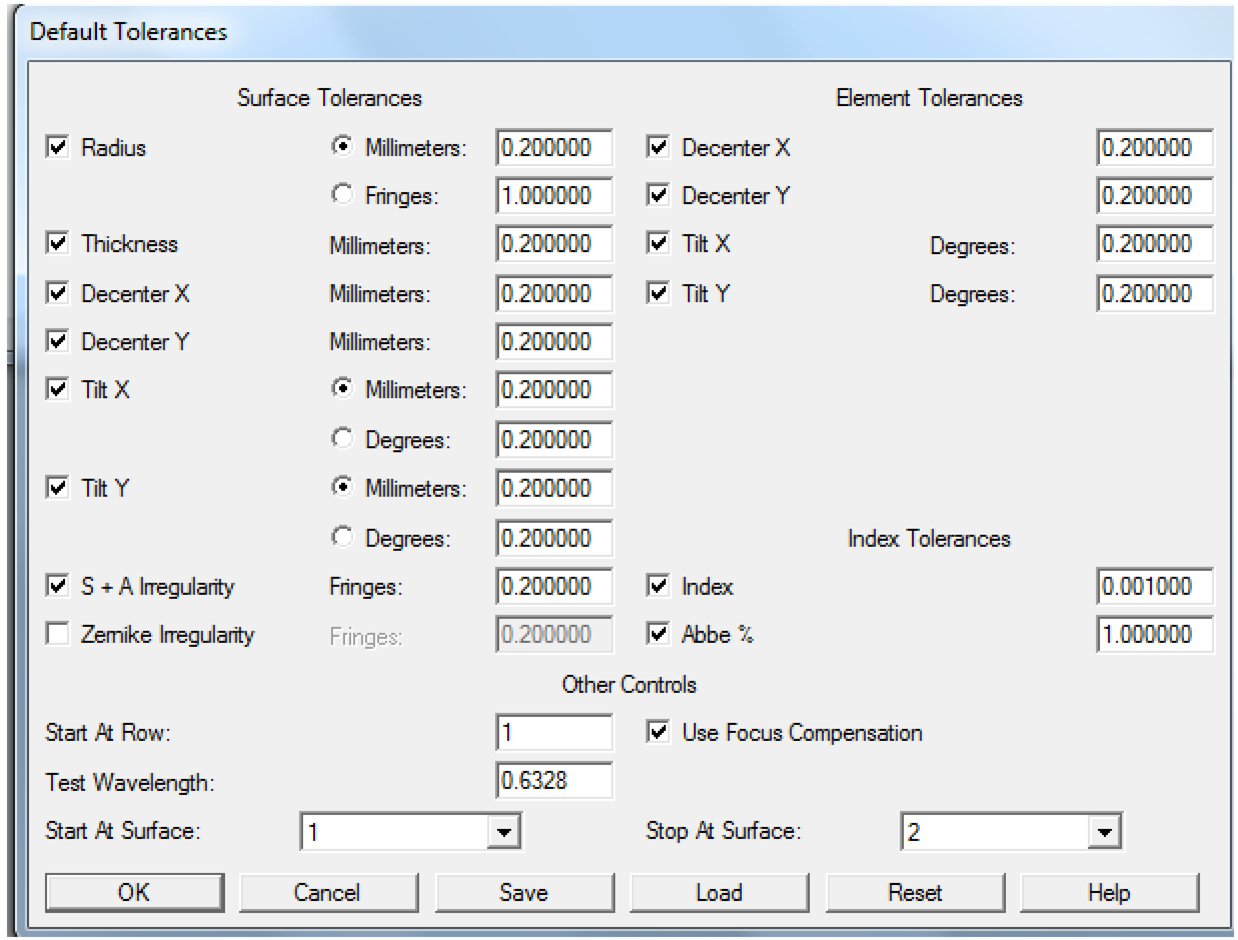
Drawing of Microscopic Lens with Housing

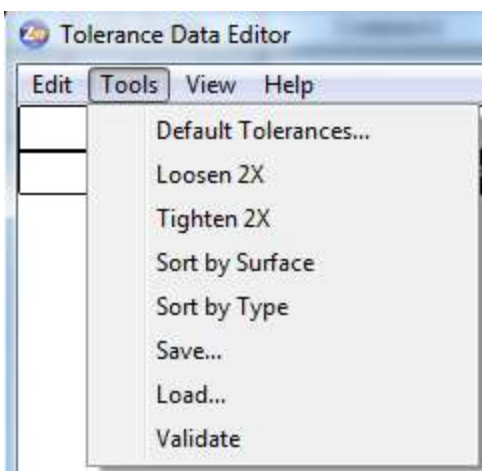


Mechanical Design of Photographic Lens

Tolerancing in Zemax

- Tolerance editor





Tolerancing in Zemax

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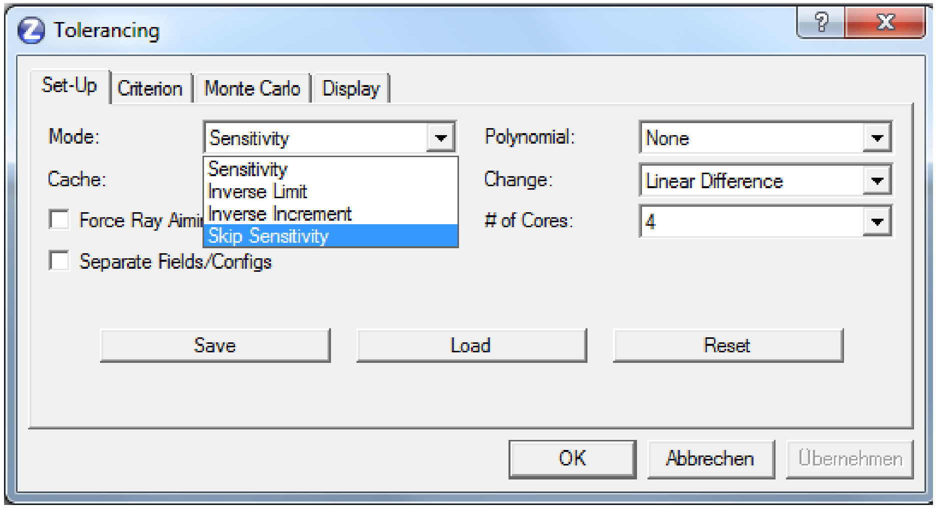
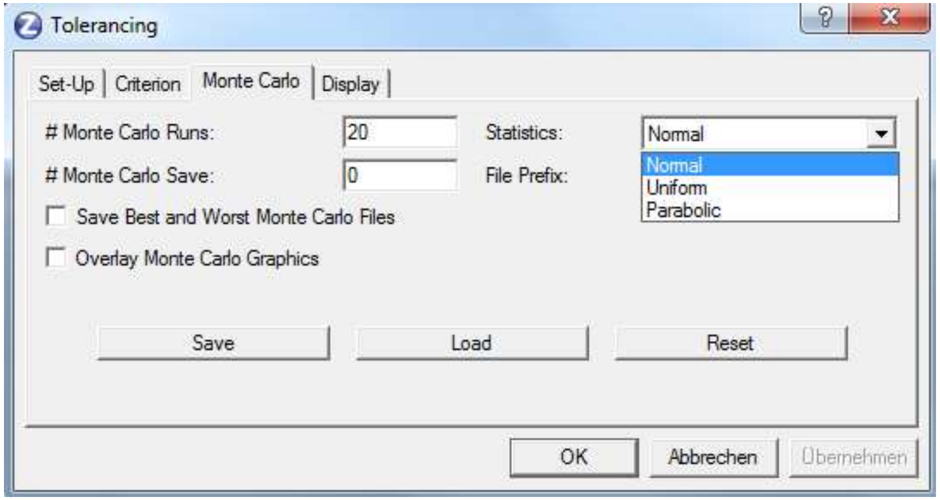
- Specification of tolerances:

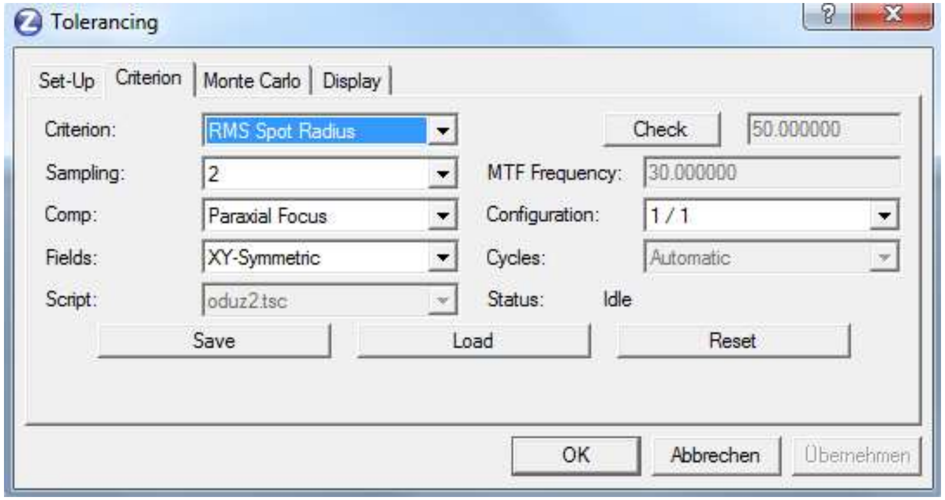
Operators :		
	TRAD	Radius
	TFRN	Number of rings
	TTHI	Thickness
	TEDX	Element decenter x
	TETX	Element tilt x
	TSDX	Flächen decenter x
	TIRX	Flächen tilt x
	TIRR	Surface irregularity
	TIND	Refractive index
	TABB	Abbe number
	....	

Tolerancing in Zemax

- Specifying options:
  - statistics
  - model mode
  - criteria
  - compensators
  - ...







- Results
- Sensitivity and total performance

1: Text Viewer

Update Settings Print Window

7	-9.800E+000	0.000E+000	1.000E+000	0.000	0.000	0.000	0.000
8	1.400E+001	0.000E+000	1.000E+000	0.000	0.000	0.000	0.000
9	-1.400E+001	0.000E+000	1.000E+000	0.000	0.000	0.000	0.000

Sensitivity Analysis:

Type			Minimum Value	Minimum Criterion	Minimum Change	Maximum Value	Maximum Criterion	Maximum Change
TRAD	1		-0.20000000	0.00849681	0.00085843	0.20000000	0.00840246	0.00076408
TRAD	2		-0.20000000	0.00765278	1.4399E-005	0.20000000	0.00764493	6.5515E-006
TRAD	3		-0.20000000	0.01007277	0.00243440	0.20000000	0.00929790	0.00165952
TFRN	4		-1.00000000	0.00763885	4.6955E-007	1.00000000	0.00763791	-4.6440E-007
TRAD	5		-0.20000000	0.01331290	0.00567453	0.20000000	0.01387767	0.00623929
TRAD	7		-0.20000000	0.01144217	0.00380380	0.20000000	0.01129590	0.00365752
TFRN	8		-1.00000000	0.00763763	-7.4458E-007	1.00000000	0.00763912	7.4594E-007
TRAD	9		-0.20000000	0.00850263	0.00086425	0.20000000	0.00910557	0.00146720
TRAD	10		-0.20000000	0.00764407	5.6948E-006	0.20000000	0.00763532	-3.0531E-006
TRAD	11		-0.20000000	0.00765819	1.9813E-005	0.20000000	0.00792170	0.00028332
TTHI	1	2	-0.20000000	0.00762323	-1.5148E-005	0.20000000	0.00768413	4.5758E-005
TTHI	2	5	-0.20000000	0.00824536	0.00060698	0.20000000	0.00817407	0.00053569
TTHI	3	5	-0.20000000	0.00993570	0.00229732	0.20000000	0.01021174	0.00257337
TTHI	4	5	-0.20000000	0.00985836	0.00221998	0.20000000	0.01016222	0.00252384
TTHI	5	6	-0.20000000	0.00757994	-5.8439E-005	0.20000000	0.00770451	6.6137E-005
TTHI	6	9	-0.20000000	0.00958733	0.00194896	0.20000000	0.00897468	0.00133631
TTHI	7	9	-0.20000000	0.00790577	0.00026739	0.20000000	0.00852506	0.00088668
TTHI	8	9	-0.20000000	0.00790654	0.00026816	0.20000000	0.00850526	0.00086688
TTHI	9	11	-0.20000000	0.00771631	7.7930E-005	0.20000000	0.00814041	0.00050203
TTHI	10	11	-0.20000000	0.00763321	-5.1669E-006	0.20000000	0.00783020	0.00019182
TEDX	1	2	-0.20000000	0.00937533	0.00173695	0.20000000	0.00937533	0.00173695
TEDY	1	2	-0.20000000	0.00937533	0.00173695	0.20000000	0.00937533	0.00173695

Worst offenders:

Type		Value	Criterion	Change
TSDX	5	-0.20000000	0.02526059	0.01762221
TSDX	5	0.20000000	0.02526059	0.01762221
TSDY	5	-0.20000000	0.02526059	0.01762221
TSDY	5	0.20000000	0.02526059	0.01762221
TSDX	7	-0.20000000	0.02437259	0.01673421
TSDX	7	0.20000000	0.02437259	0.01673421
TSDY	7	-0.20000000	0.02437259	0.01673421
TSDY	7	0.20000000	0.02437259	0.01673421
TIRX	7	-0.20000000	0.02379589	0.01615751
TIRX	7	0.20000000	0.02379589	0.01615751

```
Estimated Performance Changes based upon Root-Sum-Square method:
Nominal RMS Spot Radius     :     0.00763838
Estimated change            :     0.05195068
Estimated RMS Spot Radius   :     0.05958906

Compensator Statistics:
Change in back focus:
Minimum             :        -1.082992
Maximum             :         1.116496
Mean                :         0.000260
Standard Deviation  :         0.187537


Monte Carlo Analysis:
Number of trials: 20

Initial Statistics: Normal Distribution

  Trial      Criterion        Change
      1     0.01495279     0.00731442
      2     0.04400927     0.03637090
      3     0.03415890     0.02652053
      4     0.04071841     0.03308004
      5     0.04029339     0.03265501
      6     0.02398819     0.01634981
```

```
Number of traceable Monte Carlo files generated: 20

Nominal      0.00763838
Best         0.01495279    Trial     1
Worst        0.05384504    Trial    20
Mean         0.03581970
Std Dev      0.00958822

Compensator Statistics:
Change in back focus:
Minimum             :        -1.576642
Maximum             :         1.508236
Mean                :         0.085907
Standard Deviation  :         0.838905

90% >        0.04780477
80% >        0.04316296
50% >        0.03725716
20% >        0.02545120
10% >        0.02369940
```

Tolerancing in Zemax

- Graphical overlay of tolerance influence