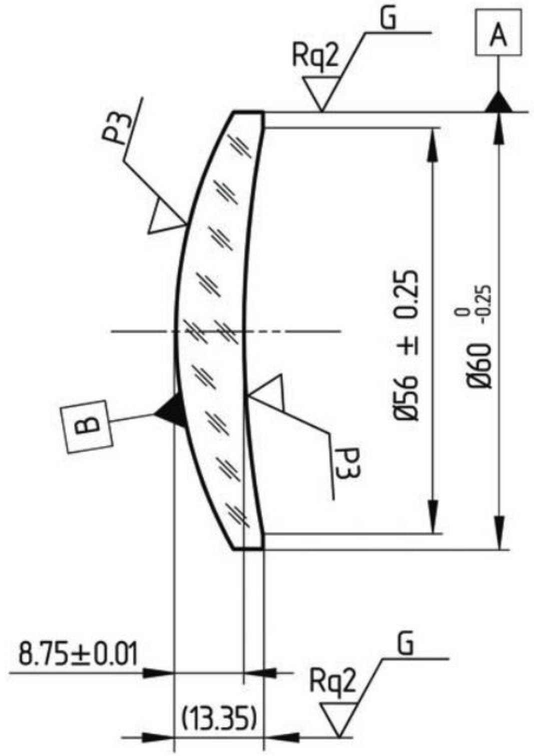
Lectures Notes on Optical Design using Zemax OpticStudio

Lecture 18

Tolerancing Analysis



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Content

1. **Introduction**
2. **Tolerancing**
3. **ISO 10110 Drawings**

For more details you can read the following reference book:
Field Guide to Lens Design. J Bentley and C. Olson.

What is Tolerancing?

- Nothing is perfect in the world!
- A real lens element fabricated is more or less different from the designed element in terms of
  - surface radius and surface smoothness,
  - central thickness,
  - parallelism between the two surfaces,
  - and glass index and Abbe number.
- In addition, an element will not be perfectly mounted; there is always a centering error, a position error and a tilting error.
- Because of all these errors, the performance of a real lens will be more or less lower than the design performance.
- Tolerance analysis is meant to set the maximum acceptable range for every error so that the lens can still perform to the specifications.
- *For more information see addidional lecture notes on the webpage.*

Optics Manufacturing Tolerances for Glass

Attribute	Commercial	Precision	High Precision
Glass Material (n_d, v_d)	±0.001, ±0.8%	±0.0005, ±0.5%	Melt Rebalanced & Controlled
Diameter (mm)	+0.000/-0.100	+0.000/-0.025	+0.000/-0.010
Center Thickness (mm)	±0.150	±0.050	±0.020
Sag (mm)	±0.050	±0.025	±0.010
Clear Aperture	80%	90%	90%
Radius (larger of two)	±0.2% or 5 fr	±0.1% or 3 fr	±0.025% or 1 fr
Irregularity - Interferometer (waves, PV)	1	0.25	0.05
Irregularity - Profilometer (microns, PV)	±2	±0.5	N/A
Irregularity - CMM (microns, PV)	±5	±1	N/A
Wedge Lens (ETD, mm)	0.050	0.010	0.005
Scratch Dig (ISO 10110-7:2017)*	80-50	60-40	10-5
Surface Roughness (Å RMS)	20	10	5
AR Coating (R_{Ave})	MgF_2 R < 1.5%	V-coat R < 0.2%	Custom Design

Compansators

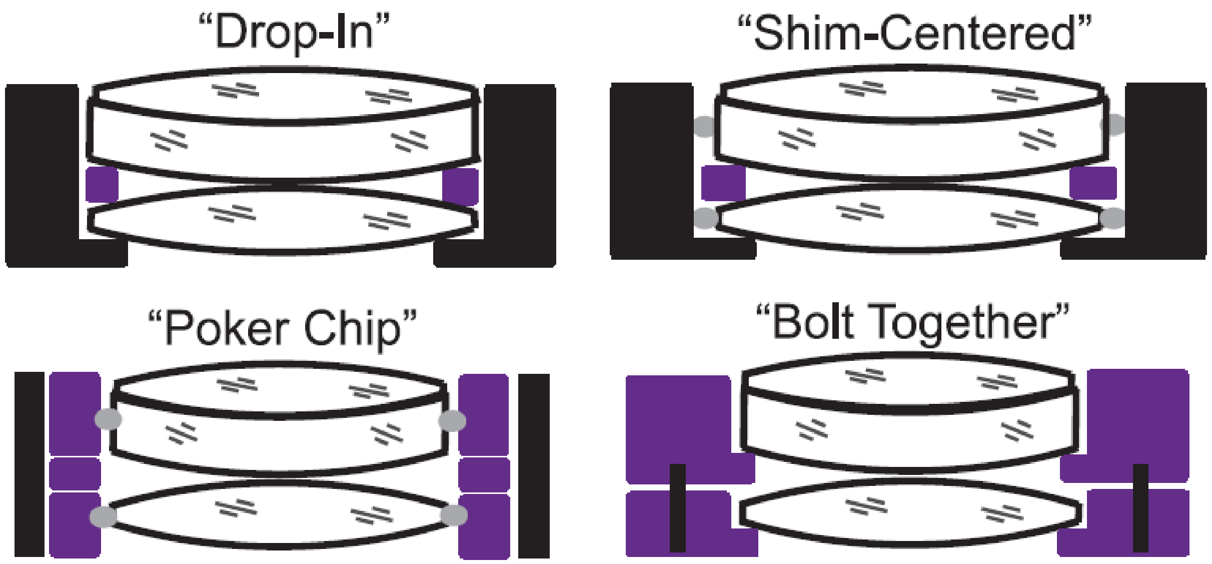
- Tolerances include both optical print values
  (e.g., radius of curvature, center thickness, index variation, wedge)
  and
- mechanical print and assembly values
  (e.g., tilt, decenter, axial spacing, subassembly alignment).

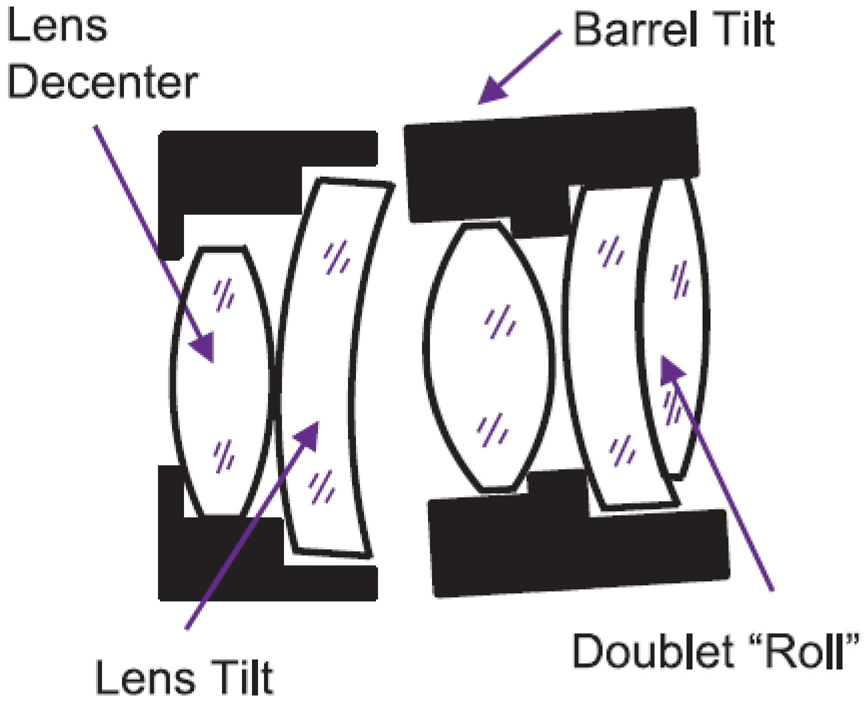
Compensators are parameters that can be adjusted during the lens build
(e.g., focus, airspace changes, active element centering)
to recover performance losses caused by other tolerances.

Lens Assembly Methods and Tolerances

To properly tolerance a lens assembly, it is important to anticipate how the lens elements will be mounted and aligned.

Assembly tolerances (such as decenter, tilt, roll, and axial spacing) represent positioning errors of optical surfaces in a lens system.





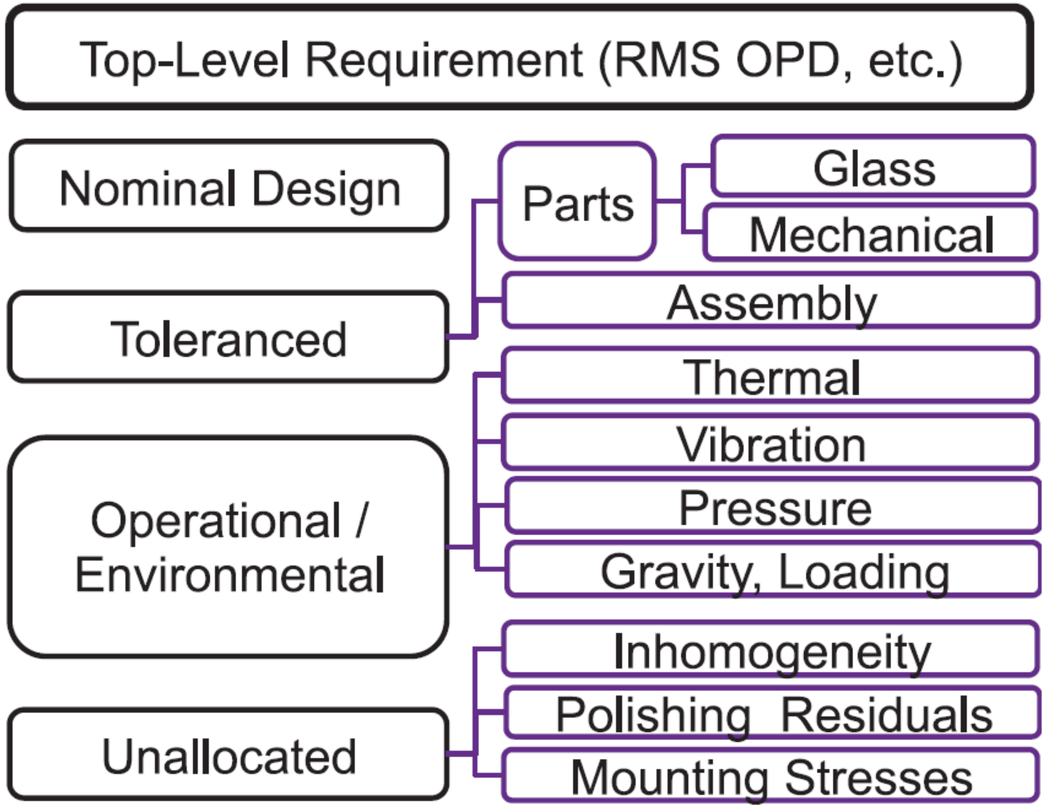
Procedure for Tolerancing

1. Choose initial tolerance values for all parameters.
2. Define the performance metrics (e.g., MTF, RMS spot size, …) and the requirements.
3. Run a sensitivity analysis to determine the impact on performance from each tolerance, and identify sensitive and cost-driving tolerances.
4. Define compensators and their allowable ranges.
5. Run appropriate statistical analyses (e.g., Monte Carlo analysis) and evaluate the expected as-built performance and manufacturing yield.
6. Adjust tolerances and compensators until cost and performance goals are met, or a redesign is needed.

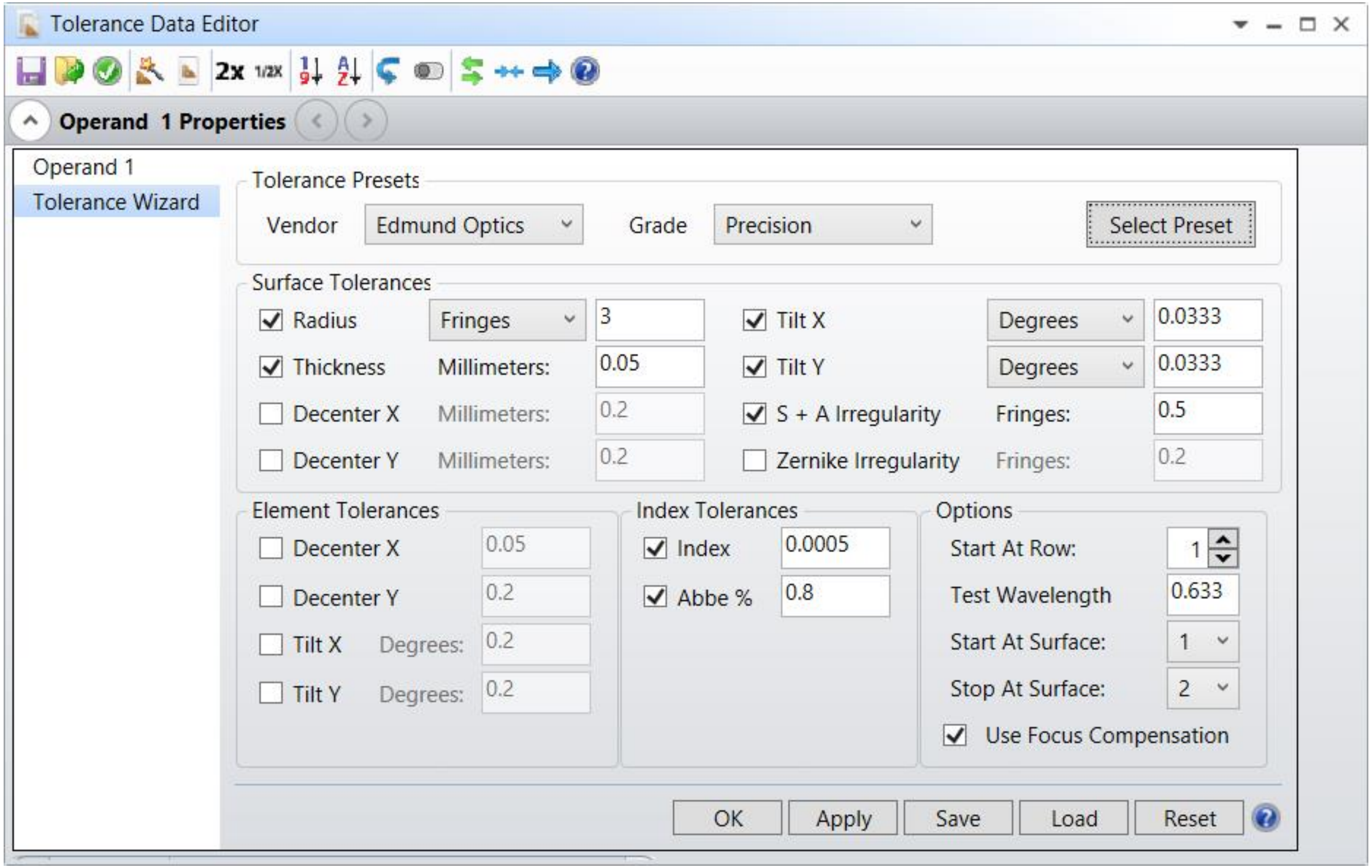
Design Margins

Design margin is the difference between the required as-built performance and the nominal design performance.

In addition to tolerancing, the performance budget values are used for design targets.



Tolerance Wizard

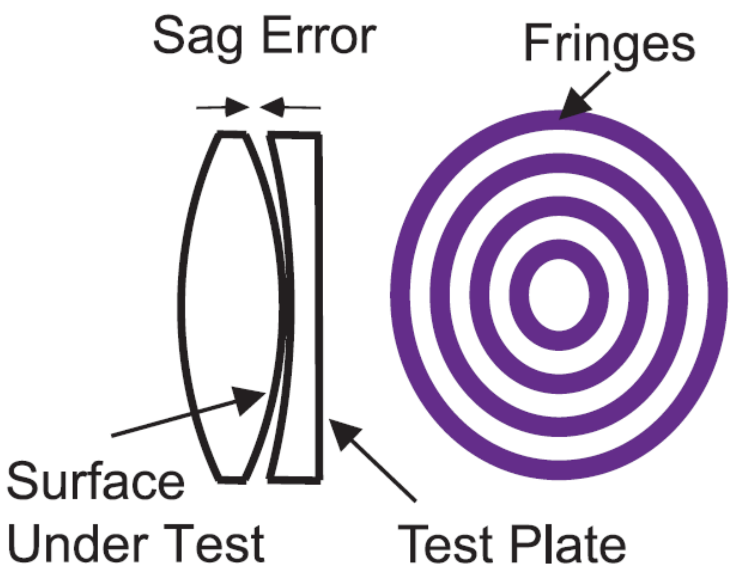


Surface Tolerances

Radius

We can select either tolerance with unit Millimeters, Fringes or Percent.

$$\text{Fringe} = \frac{\Delta sag}{\lambda/2} = \frac{1}{8(\lambda/2)}\frac{D^2}{R}\frac{\Delta R}{R}$$



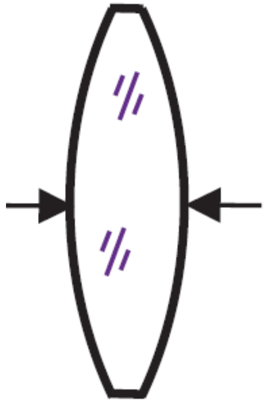
*Radius tolerances refer to the change in vertex curvature of a surface and are specified differently depending on how the lens is to be measured. One can measure Radius of Curvature (ROC) directly using **spherometer**, **profilometer**, or **distance measuring interferometer**.*
*Other designs use **test plate** fringes indirectly measure ROC.*

Thickness.

A center thickness (ct) tolerance specifies the allowable error in the vertex thickness of an element (±0.05 mm tolerance is common).

Lenses with diameter-to-ct ratio 10:1 to 5:1 are cheap and easy to fabricate.

But, thin lenses with diameter-to-ct ratios greater than about 15:1 typically require special handling during fabrication, increasing their manufacturing cost.

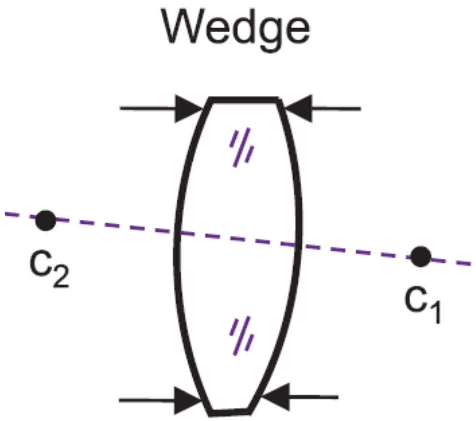


Decenter X and Decenter Y

The lens surface decenter is equivalent to the surface tilt (wedge).

Use either tilt or decenter.

Surface decenter is more difficult to measure than surface tilt.



S + A Irregularity.

Irregularity refers to any measured deviation of an optical surface from its intended shape.

0.5 wave = 1 fringe (peak-to-valley) is common for lens surface irregularity.

During a standard polishing process, irregularity is monitored with a test plate by assessing the number of fringes and/or their irregularity

Zernike Irregularity.

More-complex tolerance models use a combination of Zernike polynomials.

It’s redundant if you selected S + A Irregularity.

Element and Index Tolerances

Decenter X and Decenter Y and **Tilt X and Tilt Y.**

The decenter and tilt of lens mounting are two different issues.

We need to specify both the tolerances. Mounting tolerance of the lens can vary highly, based on lens housing the structure and the mounting technique used.

Index tolerance of 0.001is typical

Abbe number tolerance of 1% is typical.

Options

Start at Row. Select 1 if there is no other content in the Tolerance Data Editor box.

Test Wavelength. He–Ne laser is commonly used to test lenses, and the wavelength is 0.6328 μm.

Start At Surface and **Stop At Surface.** Select the range of surface in the Lens Data Editor box to perform the tolerance analysis. If nothing special is going on, the range should cover all the elements.

We should check the **Use Focus Compensation** box so that Zemax will move the image plane back and forth during the tolerance analysis process for the best focusing.

Tolerance Data Editor (TDE) in Zemax

If you click on OK button in Wizard you may see operands in TDE as follows:

Tolerance Data Editor

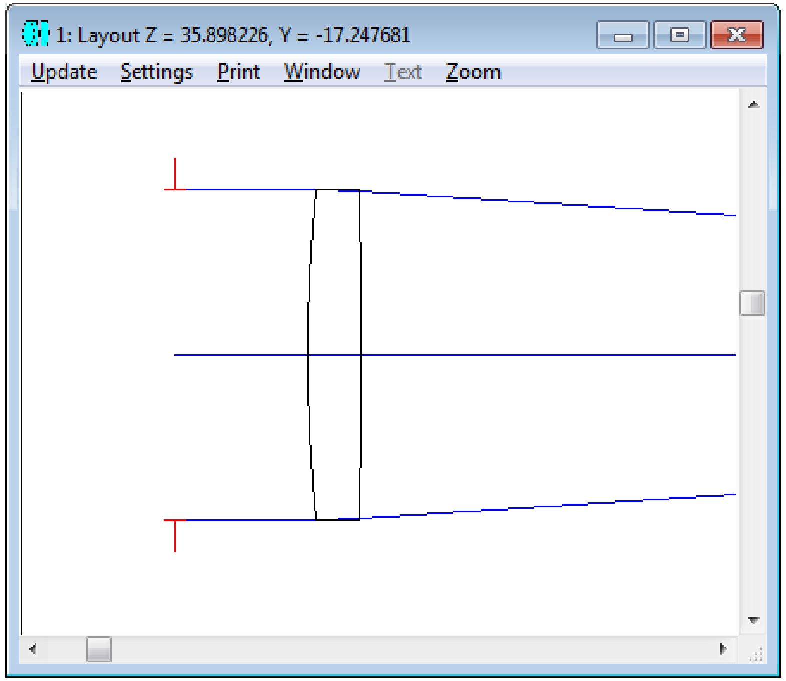
Operand 1 Properties

	Type	Surf	Code	Nominal	Min	Max	Comment
1	COMP	3	0	0.000	-2.000	2.000	Default compensator on bac
2	TWAV				0.633		Default test wavelength.
3	TRAD	2	0	100.000	-1.000	1.000	Default radius tolerances.
4	TTHI	1	3	0.000	-0.050	0.050	Default thickness toleranc...
5	TTHI	2	3	6.000	-0.050	0.050	
6	TSTX	2		0.000	-0.033	0.033	Default surface dec/tilt tol...
7	TSTY	2		0.000	-0.033	0.033	
8	TIRR	2		0.000	-1.000	1.000	Default irregularity tolera...
9	TIND	2		1.517	-5.000E-04	5.000E-04	Default index tolerances.
10	TABB	2		64.167	-0.449	0.449	Default Abbe tolerances.

Example 1

Singlet Designing and Tolerancing

- Glass = N-BK7
- ct = 4 mm
- EnP = 25 mm
- EFFL = +200 mm
- Object is at infinity
- Radius of curvatures:
  R_1 = +117.960 mm
  R_2 = −753.890 mm
- Image plane is placed a position where we get the smallest RMS spot radius



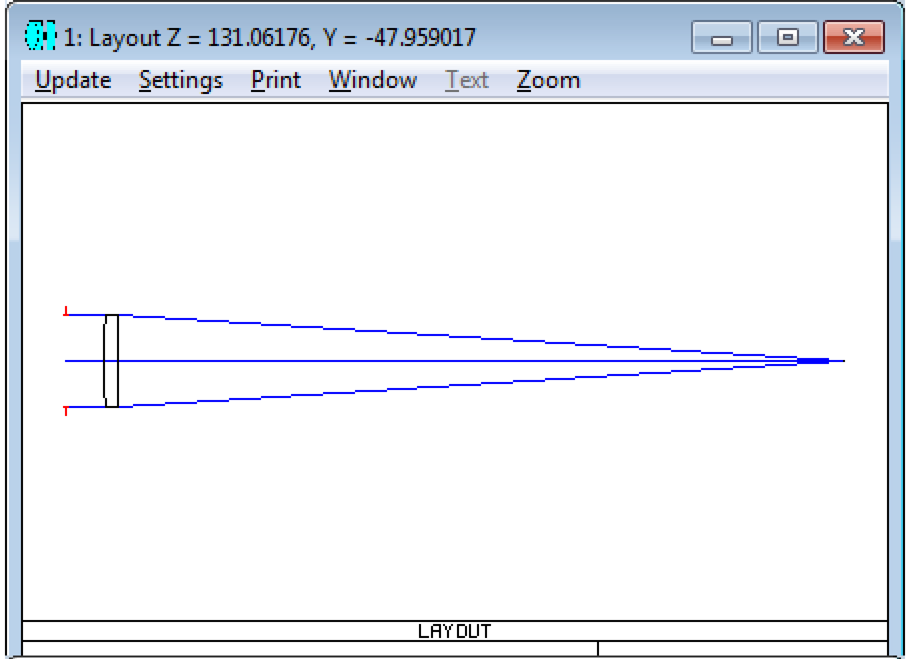
Lens Data

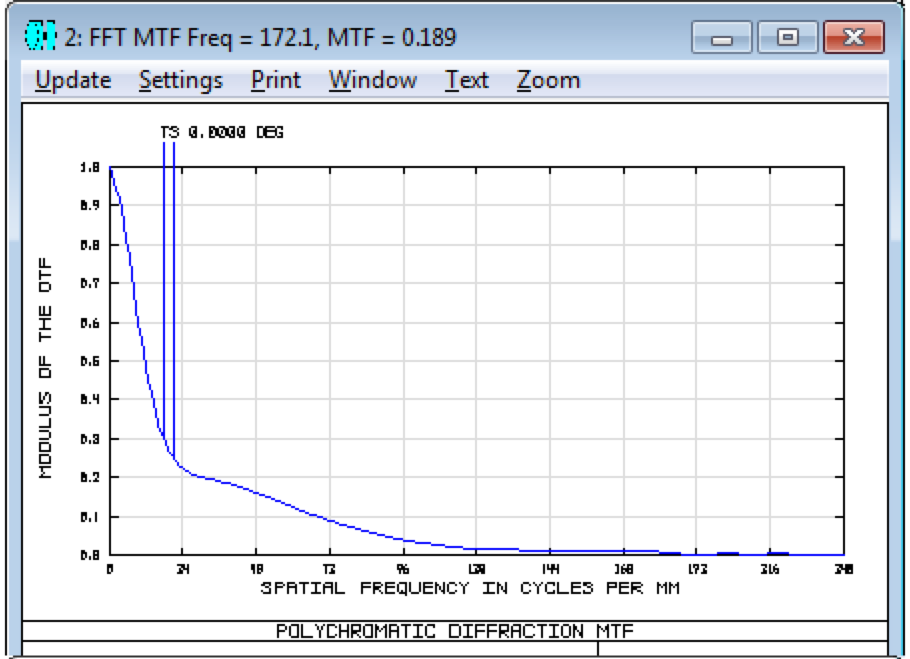
Update: All Windows

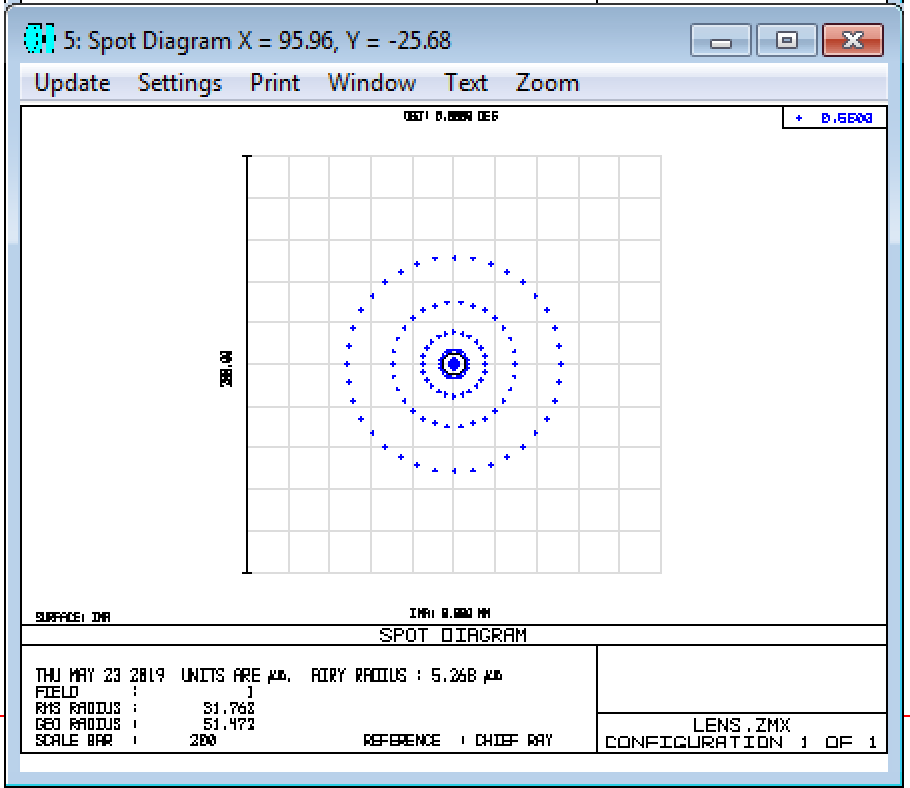
Surface 4 Properties   Configuration 1/1

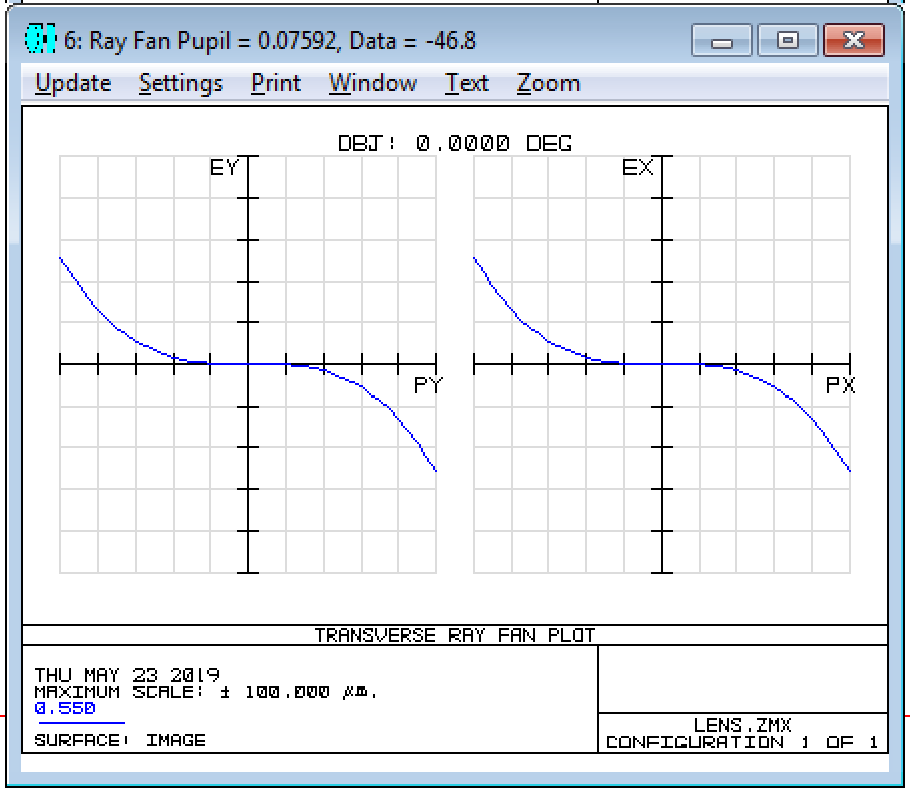
	Surface Type		Commen	Radius	Thickness	Material	Co	Clear Semi-Di		Chi
0	OBJECT	Standard		Infinity	Infinity			0.000		0.0..
1	STOP	Standard		Infinity	10.000			12.500	U	0.0..
2	(aper)	Standard		117.960	4.000	N-BK7		12.500	U	0.0..
3	(aper)	Standard		-753.890	195.509			12.383	U	0.0..
4	IMAGE	Standard		Infinity	-	[redacted]		0.017		0.0..

Exam


1: Layout Z = 131.06176, Y = -47.959017
Update Settings Print Window Text Zoom
LAYOUT

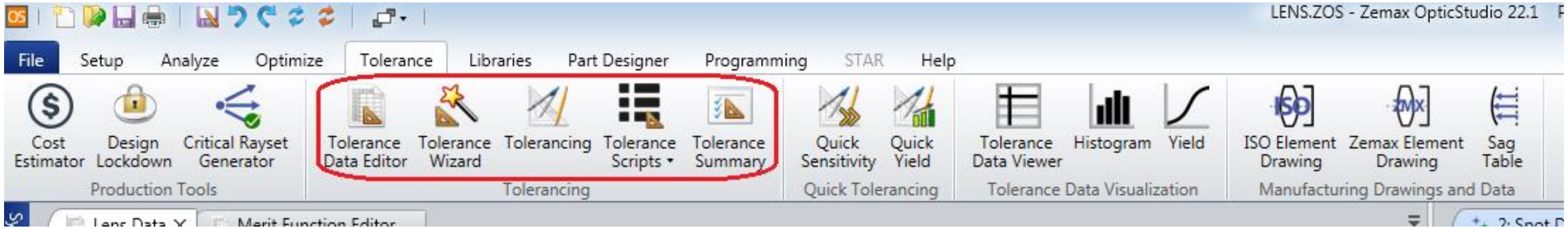

2: FFT MTF Freq = 172.1, MTF = 0.189
Update Settings Print Window Text Zoom
TS 0.0000 DEG
MODULUS OF THE OTF
SPATIAL FREQUENCY IN CYCLES PER MM
POLYCHROMATIC DIFFRACTION MTF

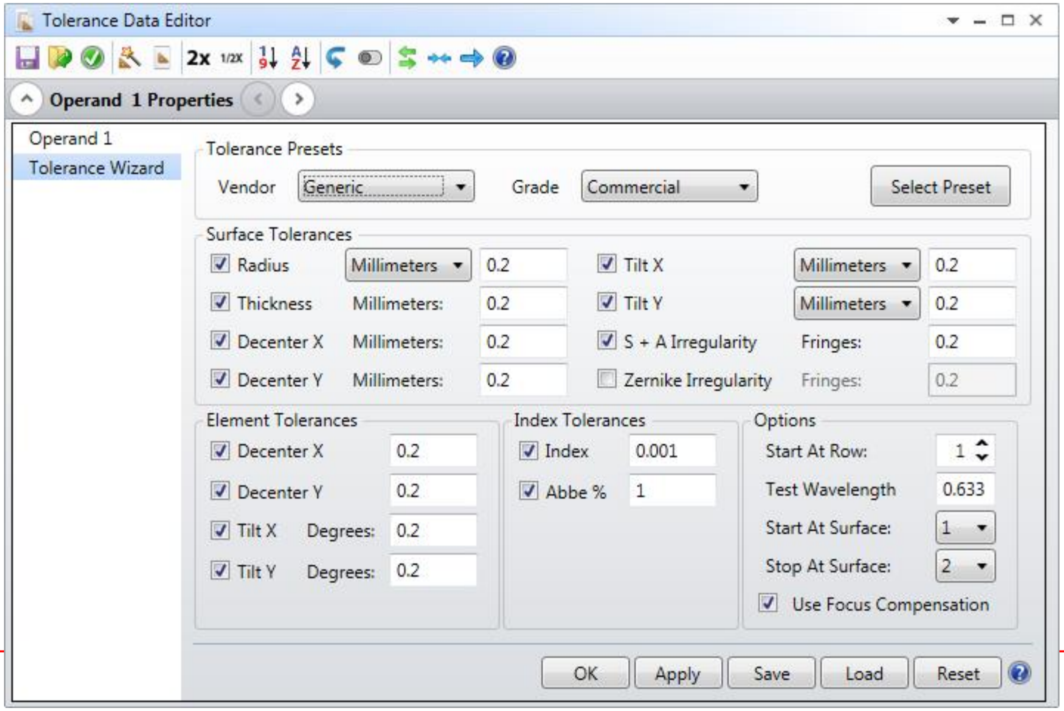

5: Spot Diagram X = 95.96, Y = -25.68
Update Settings Print Window Text Zoom
SPOT DIAGRAM
THU MAY 23 2019 UNITS ARE µm. AIRY RADIUS : 5.268 µm
FIELD : 1
RMS RADIUS : 31.762
GEO RADIUS : 51.473
SCALE BAR : 200
REFERENCE : CHIEF RAY
LENS.ZMX
CONFIGURATION 1 OF 1


6: Ray Fan Pupil = 0.07592, Data = -46.8
Update Settings Print Window Text Zoom
OBJ: 0.0000 DEG
EY
PY
EX
PX
TRANSVERSE RAY FAN PLOT
THU MAY 23 2019
MAXIMUM SCALE: ± 100.000 µm.
0.550
SURFACE: IMAGE
LENS.ZMX
CONFIGURATION 1 OF 1

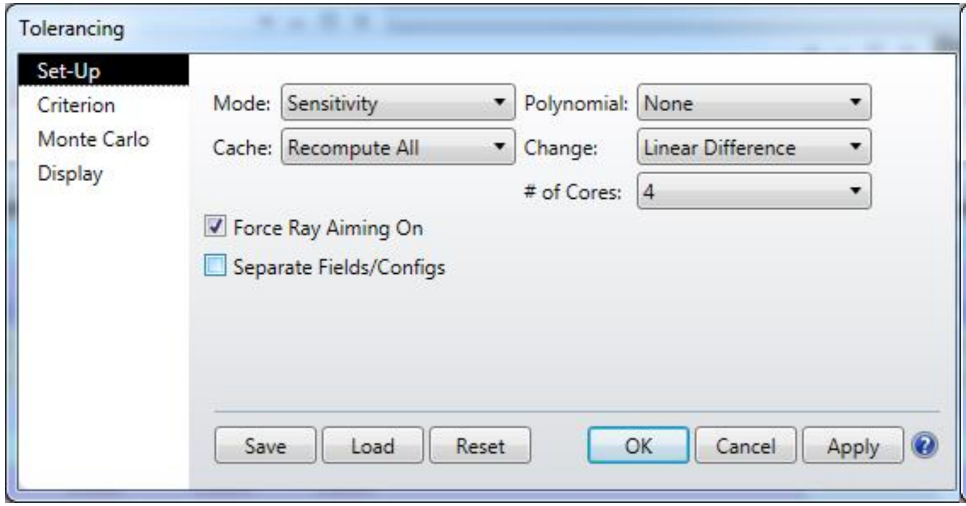
Procedure for Tolerancing in Zemax

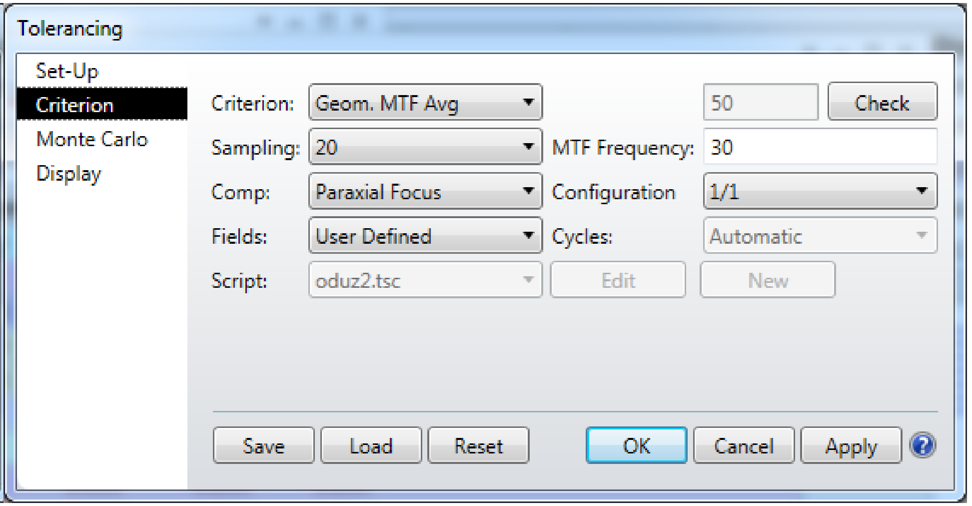
1. Go to **Tolerance** Tab
2. Click on **Tolerance Wizard**
3. Click on **Tolerancing**

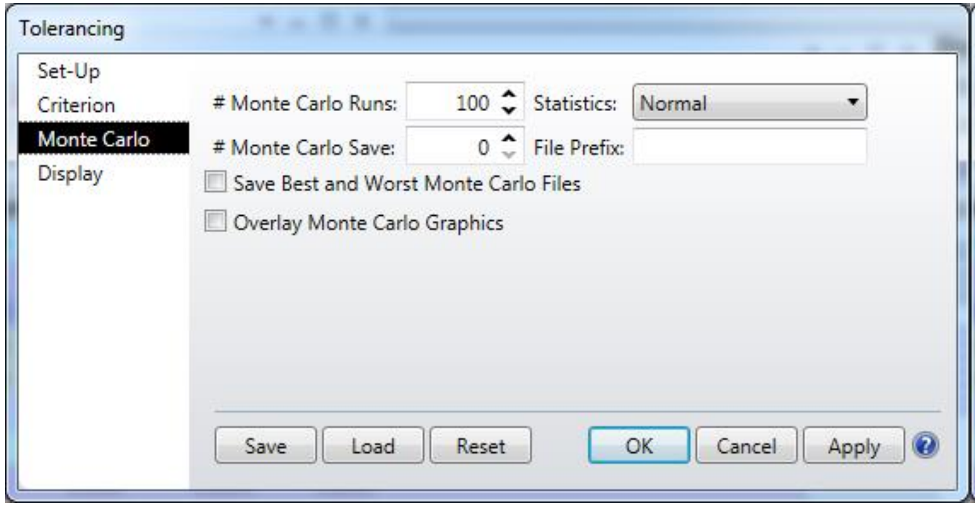


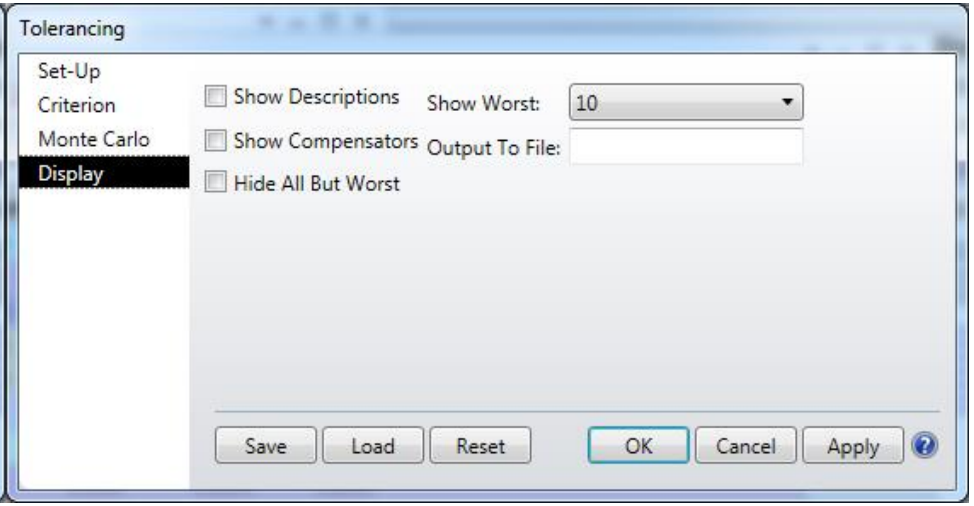


Tolerance Settings



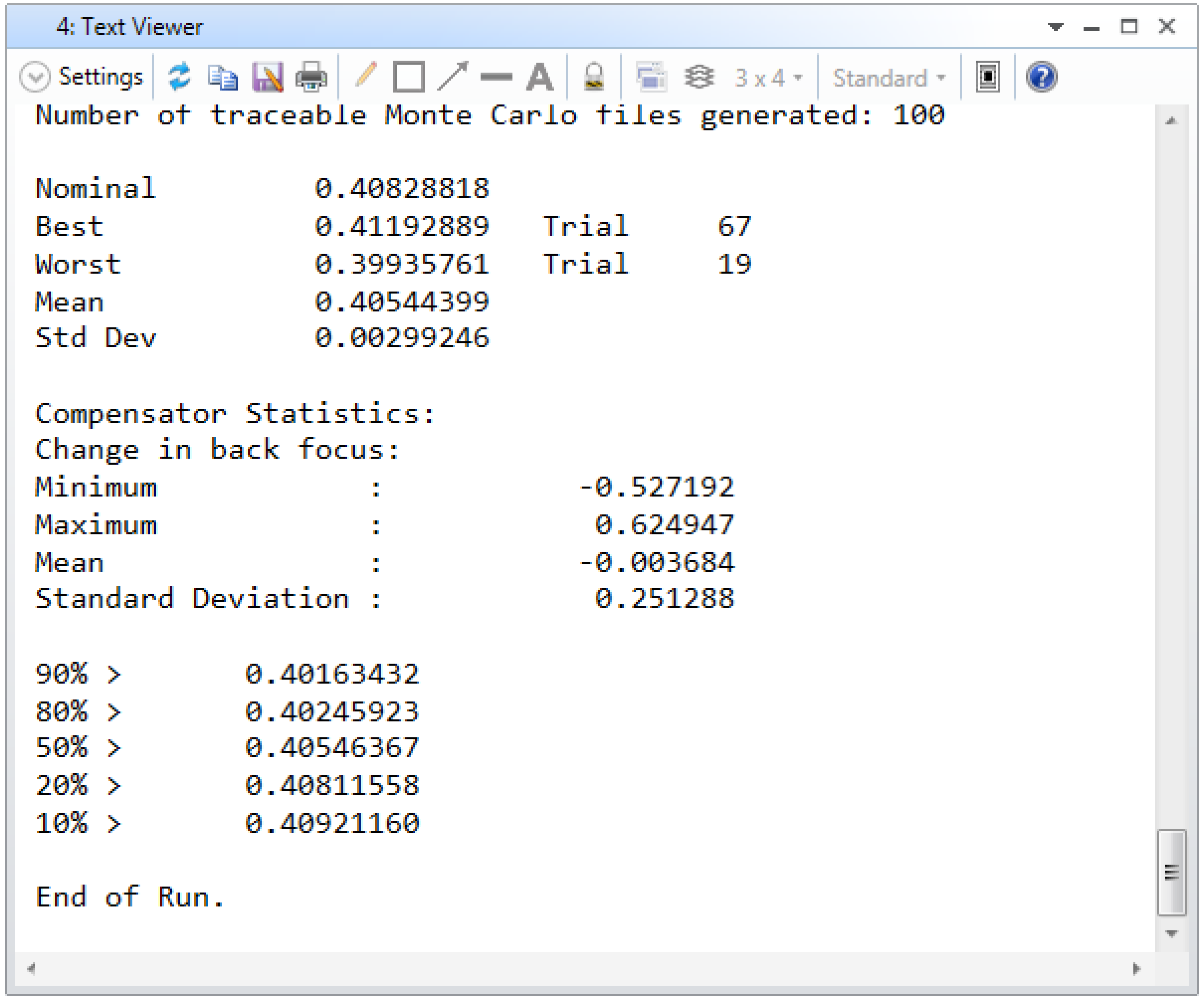






If you click OK.

You will see a report of 100 MC simulations

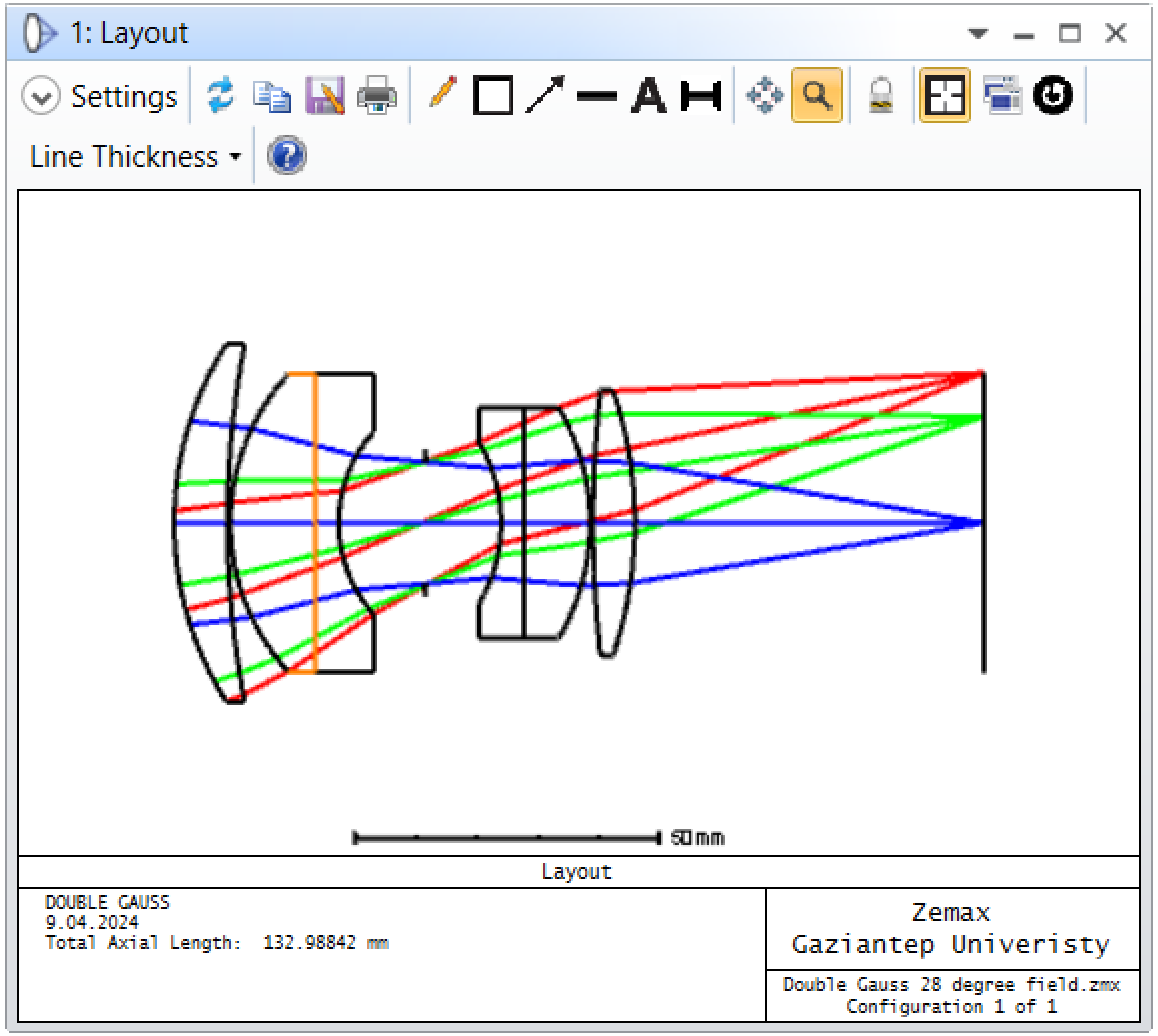



```
Number of traceable Monte Carlo files generated: 100

Nominal          0.40828818
Best             0.41192889    Trial     67
Worst            0.39935761    Trial     19
Mean             0.40544399
Std Dev          0.00299246

Compensator Statistics:
Change in back focus:
Minimum            :           -0.527192
Maximum            :            0.624947
Mean               :           -0.003684
Standard Deviation :            0.251288

90% >       0.40163432
80% >       0.40245923
50% >       0.40546367
20% >       0.40811558
10% >       0.40921160

End of Run.
```

Example 2

Perform tolerancing analysis of objective at:

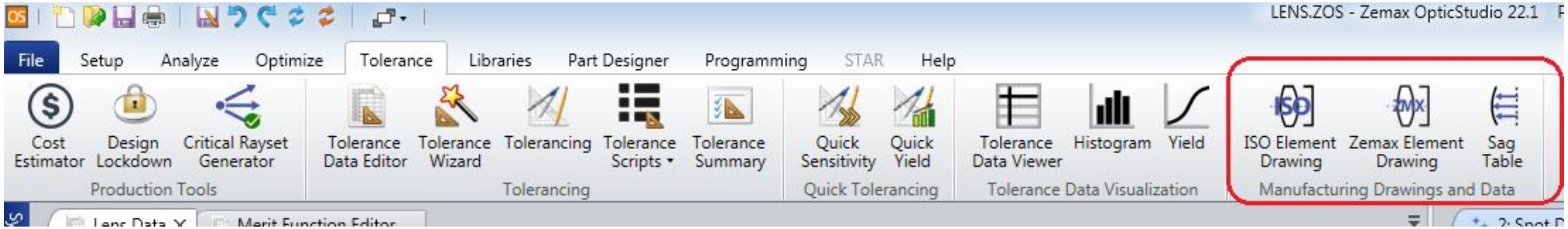
C:\<Zemax>\Samples\Sequential\Objectives\Double Gauss 28 degree field



ISO 10110 Drawings

The ISO 10110 standard is an optical drawing standard used to explicitly describe an optical part based on the principle of geometric dimensioning and tolerancing.

In Zemax, **ISO Element Drawing** can be opened from **Tolerance Tab**.



Structure of the ISO 10110 standard

Part	Title	Indication
ISO 10110-1	General	N/A
ISO 10110-2	Material imperfections – stress birefringence	0/
ISO 10110-3	Material imperfections – bubbles and inclusions	1/
ISO 10110-4	Material imperfections – inhomogeneity and striae	2/
ISO 10110-5	Surface form tolerances	3/
ISO 10110-6	Centering tolerances	4/
ISO 10110-7	Surface imperfection tolerances	5/ and 15/
ISO 10110-8	Surface texture	$\sqrt{\ }$
ISO 10110-9	Surface treatment and coating	(λ)
ISO 10110-10	Table representing data of a lens element	N/A
ISO 10110-11	Nontolerance data	N/A
ISO 10110-12	Aspheric surfaces	N/A
ISO 10110-17	Laser irradiation damage threshold	6/

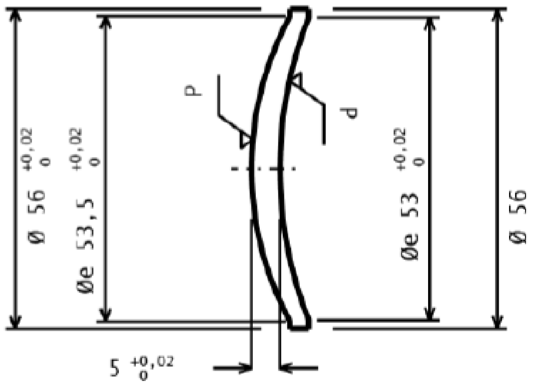
ISO 10110 standard

Examples of low-quality, typical, and high-quality ISO 10110 indications

Parameter	Indication	Low quality	Typical	High quality
Stress birefringence	0/A	20 nm/cm	10 nm/cm	4 nm/cm
Bubbles/Inclusions	1/N×A	1/10×0.3	1/4×0.1	1/2×0.075
Inhomogeneity/Striae	2/A;B	2/1;2	2/3;3	2/5;5
Surface irregularity (for spherical surfaces)	3/A(B)	3/-(2) (radius tolerance is a dimension)	3/3(0.5)	3/1(0.2)
Centering tolerances (wedge, arc minutes)	4/σ	4/5′	4/2′	4/0.6′
Surface imperfection (scratch and dig per MIL-PRF-13830 in the USA)	5/N×A; 5/LN″ ×A″; 5/EA‴	5/5×0.5; 5/L1×0.008; 5/E1.0 (80–50 in the USA)	5/5×0.4; 5/L1×0.006; 5/E0.5 (60–40 in the USA)	5/5×0.05; 5/L1×0.001; 5/E0.5 (10–5 in the USA)
Laser irradiation damage threshold	6/H_{TH}; λ; pdg	6/10; 1064; 2 (group 2 per ISO 11254-1)	6/20; 1064; 2 (group 2 per ISO 11254-1)	6/40; 1064; 2 (group 2 per ISO 11254-1)

See ISO-GUDE shown in course web page!

Example Lens Drawing in Zemax OpticStudio

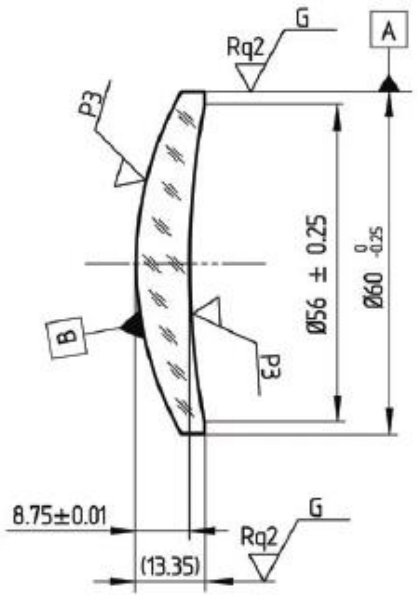


Dimensions in Millimeters

Left Surface	Material	Right Surface
R 56,1272 +0,001 0 CX	GLASS: GERMANIUM	R 71,7485 +0,001 0 CC
Øe 53,5 +0,02 0	N(8 µm) = 4,006687 +0,001 +0,001	Øe 53 +0,02 0
⊗ AR+DLC	V -	⊗
3/ - RMSi < 0,5000	0/ 10	3/ -(-/()) RMSi < 0,5000
4/ -	1/ 1x0,025	4/ -
5/ 3x0,63;C2x1,6;L2x0,01;E0,1	2/ 3;2	5/ 3x0,63;C2x1,6;L2x0,01;E0,1
6/ -		6/ -

ISO Element Drawing Indications According to ISO 10110

DATE	SCALE	DRAWN	APPRV	
17.02.2020	0,7600:1	FERHAT BÖLÜKBAŞ		69.12 mm LWIR OBJECTIVE
PROJECT/TITLE 69mmOBJ				
PART/DRAWING L1		REVISION 1.1		LWIR__69mm-DES_VER_18h1__Ge_Ge_ZnS_Final_OS_SON++Ready _For_Tolerancing - Kopya1.ZMX Configuration 4 of 8



Left surface			Material specification		Right surface		
R	55.1±0.1	CX	Schott SK2		R	152.5±0,03	CC
$Ø_e$	$56^{+0.025}_{0}$				$Ø_e$	$52^{+0.025}_{0}$	
Prot. chamfer	0.1–0.3		n_d	1.607381	Prot. chamfer	0.1–0.3	
(λ)	AR @0.5876 µm BBAR AVG T>98%		ν_d	56.65	(λ)	AR @0.5876 µm BBAR AVG T>98%	
3/	3 (0.5)		0/	10	3/	3 (0.5)	
4/	2'		1/	4 x 0.1	4/	2'	
5/	5 x 0.4; L1 x 0.006; E0.5		2/	3; 3	5/	5 x 0.4; L1 x 0.006; E0.5	
6/	20 J/cm^2; 1064 nm; 2 ns				6/	20 J/cm^2; 1064 nm; 2 ns	

Responsible dept.	Technical reference	Created by	Approved by	Indications according to ISO 10110
Optical Systems Engineering	Jason Lane	Michael Pfeffer	Thomas Spagele	

Hochschule Ravensburg-Weingarten
University of Applied Sciences

Document type	Document status
ISO 10110 Tutorial example	Released

Title, Supplementary title

SK2 Singlet

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Rev.	Date of issue.	Lang.	Sheet
A	2012-09-24	en	1/1