Tolerance on material inhomogenity and surface irregularity

Opti 521
Wenrui Cai

Abstract
In this tutorial, a case study on tolerance for a focusing doublet is performed by using ZEMAX. First, how to perform a general tolerance analysis is briefly introduced and compared with results from manual calculation. Then methods to tolerance the material inhomogenity and surface irregularity in ZEMAX are discussed. And method to understand the results of the tolerance analysis is introduced.

Introduction to ZEMAX tolerance
Tolerance analysis is an important step in optical system design, since all the optical elements cannot be made perfectly. Tolerancing provides information about the sensitivity of an optical system to typical fabrication and mounting errors. Tolerancing can also help determine which design to make if you have a selection of lens designs to choose from, as well as determine the manufacturing tolerances you need to maintain to achieve a particular level of performance.

Criterions
In ZEMAX, tolerances may be evaluated by several different criterions:

RMS spot radius	for low quality optics
RMS wavefront error	for superb quality optics
MTF	for photographic or moderate quality optics
Merit function	for custom requirements

Analysis options
Tolerances may be computed and analyzed three ways in ZEMAX:

Sensitivity	Used to determine the change in performance for a given set of tolerances individually.
Inverse Sensitivity	Used to reduce individual tolerances to meet a maximum allowable change in performance.
Monte Carlo	Used to determine the change in performance when all tolerances are combined together randomly. The statistical distribution may be Normal (Gaussian), Uniform, or Parabolic.

Tolerancing procedure

The procedure of tolerancing usually consists of the following steps.

1) Define an appropriate set of tolerances for the lens. The default tolerance is usually a good place to start, or you can use the different tolerance levels given in appendix table a1.

2) Modify the default tolerances or add new ones to suit the system requirements.

3) Add compensators and set allowable ranges for the compensators. The default compensator is

the back focal distance, which controls the position of the image plane. Other compensators, such as image surface tilt and decenter, may be defined.

4) Select appropriate criteria, such as RMS spot radius, wavefront error, MTF or boresight error. More complex criteria may be defined using a user defined merit function.

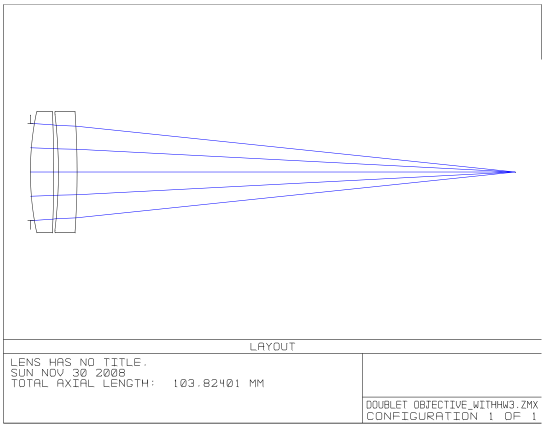
5) Select the desired mode, either sensitivity or inverse sensitivity. For inverse sensitivity, choose criteria limits or increments, and whether to use averages or computer each field individually.

6) Perform an analysis of the tolerances.

7) Review the data generated by the tolerance analysis, and consider the budgeting of tolerances. If required, modify the tolerances and repeat the analysis.

<u>Case study</u>

From here an example of focusing doublet in Opti 521 HW4 part3 will be used to perform a tolerance analysis, especially tolerancing on inhomogenity and surface irregularity.



Surf	Type	Radius	Thickness	Glass	Diameter
OBJ	STANDARD	Infinity	Infinity		0
STO	STANDARD	Infinity	0		20
2	STANDARD	58.6	5.0	N-SK15	25
3	STANDARD	-277.0	1.0		25
4	STANDARD	-97.0	4.0	N-SK15	24
5	STANDARD	-174.0	93.824		25
IMA	STANDARD	Infinity			

INDEX OF REFRACTION DATA:
Index data is relative to air at the system temperature and pressure.
Index of refraction at 632.8 nm
N-SK15 1.620702

Fig 1 Focusing Doublet layout and surface summary

Lens errors include: radii of curvature, lens thickness, Wedge, surface irregularity, index error, and inhomogenity, decenter, tilt, and lens spacing.

Use built-in tolerance operand

There are many fabrication and mounting errors to consider when tolerancing an optical system. ZEMAX's tolerancing capabilities can model a number of different tolerances, including tolerance on radius, thickness, tilts and decenters of surfaces or elements, surface irregularity, and much more. Each of these is supported via their own tolerance operand in ZEMAX.

Tolerance information in Zemax is inserted into the *Tolerance Data Editor* (TDE) (Editors -> tolerance data, Shift + F2). Each line of the TDE spreadsheet is one operand that represents one degree of freedom. In the case of the default tolerances (TDE window -> Tools -> default tolerances), it lists the alignment variables for each element, as well as for each surface.

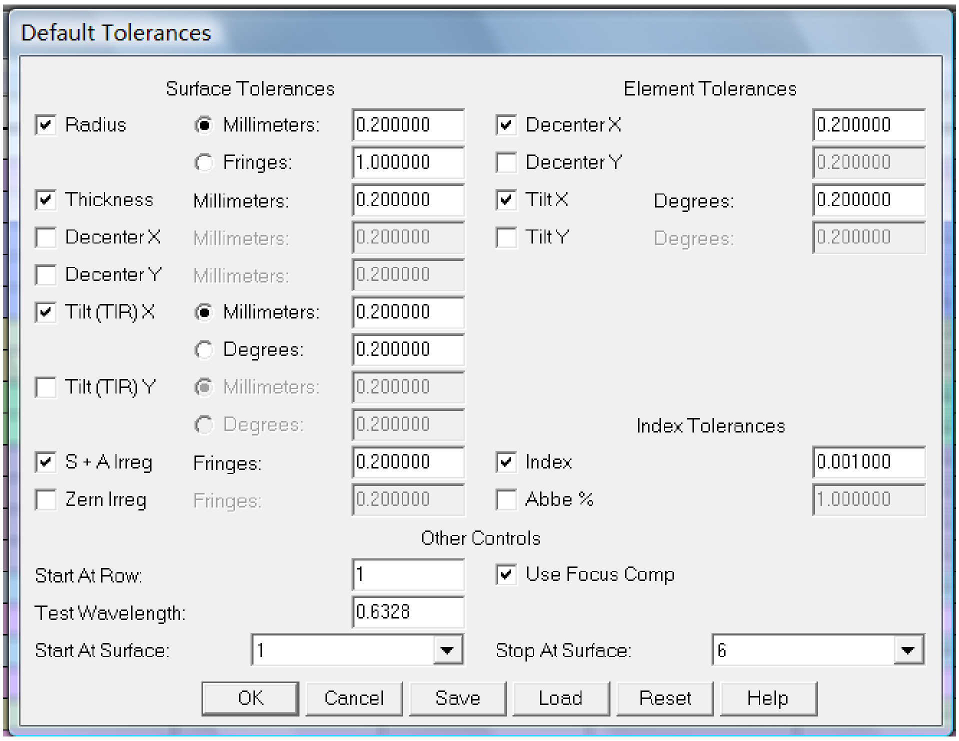


Fig 2 default tolerances

Since this system is rotationally symmetric, tilts and decenters in the x and y directions turn out to be the same. It is proper to delete all of the y direction entries.

Then According to different tolerance levels, specifically refine minimum and maximum values for every surfaces or elements surface in TDE. Or you can type in different operand from the TDE. Each tolerance operand has a four letter mnemonic.

Next step is to go to button 'TOL' or to the "Tools" drop down window and choose "Tolerancing" and then "Tolerancing…"

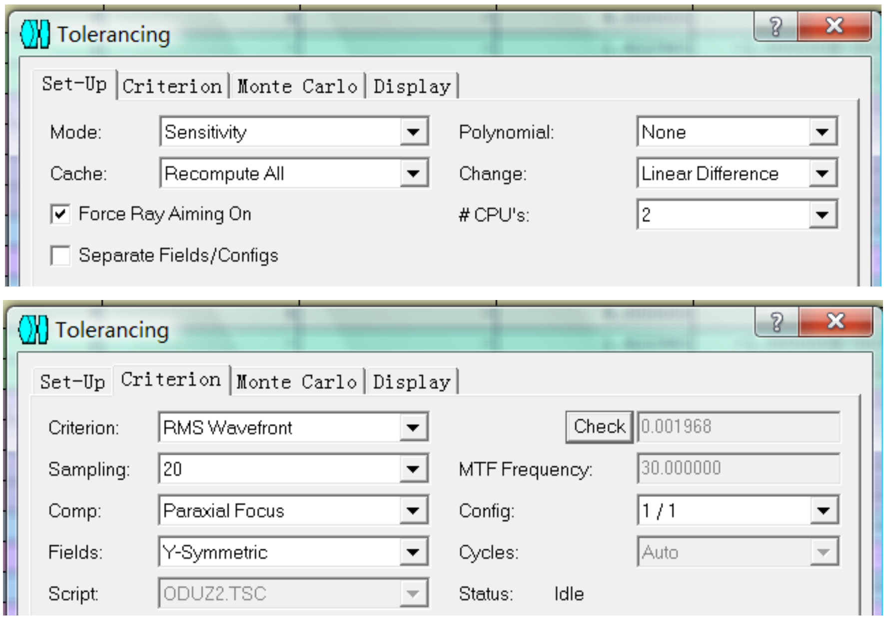


Fig 3 tolerancing

Adjust the parameters in the Tolerancing window (shown in Figure 3).
①Choose mode: sensitivity.
②Check "Force Ray Aiming On" (which makes it more accurate, but slower).
③Choose the Criteria: (RMS Spot Radius, RMS Wavefront, Merit Function, Boresight Error, MTF and more). We need to select RMS Wavefront.
④Choose the Compensator: (Paraxial focus, Optimize All, None). We want the paraxial focus to be the compensator, which is already the default.
Show Compensators (for example to see how much focus changes for example).

At last, a results window will open, showing many results (shown in appendix). Depending on the results, one may wish to loosen or tighten the tolerances. Each tolerance operand listed with the change in criterion for its maximum and minimum values. These are then ordered in a list called "Worst Offenders," which lists the operands from most to least effect on the criterion. A statistical analysis is then performed on the data, estimating the change in criterion using a Root Sum Square calculation.

Now we can compare the result with the manual calculation in HW4

Table 1

	ZEMAX Operand	**Sensitivities (hand calculation)**	**Sensitivities (ZEMAX tolerance)**	**Compare (%)**
Lens1				
Decenter (mm)	TEDX/TEDY	0.18794	0.18909	-0.6
Tilt (deg)	TETX/TETY	0.10817	0.10883	-0.6
R1 (mm)	TRAD	0.007355	0.007225	2
R2 (mm)	TRAD	0.003618	0.001411	156
Thickness (mm)	TTHI	0.007355	0.031276	-76
Index	TIND	0.723633	0.63448	14
Wedge 1 (deg)	TSTX/TSTY	0.138611	0.105868	31
Wedge 2 (deg)	TSTX/TSTY	0.251231	0.216540	16
Irregularity 1 (waves)	TIRR	0.15574	0.020707	652
Irregularity 2 (waves)	TIRR	0.15574	0.019762	688
Inhomogenity	no	3950.695	-	-
Lens2				
Decenter (mm)	TEDX/TEDY	0.18794	0.19034	-1
Tilt (deg)	TETX/TETY	0.19799	0.19999	-1
R1 (mm)	TRAD	0.009853	0.010132	-3
R2 (mm)	TRAD	0.003618	0.007447	-51
Thickness (mm)	TTHI	0.003618	0.000277	29
Index	TIND	0.723633	0.93317	-22
Wedge 1 (deg)	TSTX/TSTY	0.479597	0.44684	7
Wedge 2 (deg)	TSTX/TSTY	0.291537	0.254682	14
Irregularity 1 (waves)	TIRR	0.15574	0.021213	634
Irregularity 2 (waves)	TIRR	0.15574	0.018617	737
Inhomogenity	no	3160.556	-	-

We can see in the table above, sensitivities of most lens error are within one order of magnitude using two different methods. However the operand for surface irregularity (TIRR) obviously fails to analysis the sensitivity correctly. And there is no as-built operand to calculate the tolerance of material inhomogenity.

Tolerance on surface irregularity using different methods

Modeling irregularity is somewhat more problematic than other types of tolerances. This is primarily because irregularity by nature is random, and not deterministic such as a change in radius. Therefore, some assumptions about the nature of the irregularity need to be made in order to perform the analysis.

Use rule of thumb

Change in RMS wavefront error (WFE) due to P-V surface irregularity on one surface is

$$\Delta W_{RMS} \simeq 0.25 \times \alpha \cdot \Delta S_{P-V}(n-1) \cdot \cos\Phi$$

Where：α is the ratio of beam foot print to the surface diameter.

Φ is the beam incidence angle.

Lens diameter is 25mm and stop diameter is 20mm, so assume α = 1 and normal incidence here, given 1 wave P-V surface irregularity (0.1582umrms),

$$\Delta W_{rms} \approx 0.25 \times 1 \times \Delta S_{pv}(n-1) = 0.25 \times 1 \times 1 \times (1.62296-1) = 0.15574(wave)$$

Use operand TIRR (S+A Irreg)

TIRR is used to analyze irregularity of a Standard surface. Surface irregularity can be defined as a sum of spherical and astigmatism (which is usually what is done when test-plate interferograms are 'eyeballed'). The assumption ZEMAX makes when using TIRR is that the irregularity is half spherical aberration, and half astigmatism. This is less restrictive model than assuming 100% astigmatism, because astigmatism cannot be compensated by focus, and is therefore a more serious defect in the lens.

The min and max values are the irregularity in units of fringes measured at the maximum radial aperture of the surface where the maximum radial aperture is defined by the semi-diameter of the surface. More detail information can be found in ‘ZEMAX User’s Guide’ p502.

Use operand TEXI

TEXI is used to analyze random irregular deviations of small amplitude on a surface that is either a Standard, Even Aspheric, or Zernike Fringe Sag surface. TEXI uses the Zernike Fringe Sag surface (see ‘ZEMAX User’s Guide’ p319) to model the irregularity rather than using the third order aberration formulas used by TIRR.

Table 2 Extra data definitions for Zernike fringe sag surfaces

Extra Data Number	Description
1	Number of terms.
2	Normalization radius. Coordinates are normalized by this value.
3 - 39	Coefficients on Zernike polynomials 1 - 37, respectively, in lens units.
40 and above	Not used.

When using TEXI, the min and max tolerance values are interpreted to be the *approximate* magnitude of the zero to peak error of the surface in double-pass fringes at the test wavelength.

The zero to peak is only a very rough measure of the irregularity. Whether the zero to peak and peak to valley are the same depends upon the particular Zernike term used.

The "Number of terms" is used to specify the maximum Zernike polynomial term to be used in calculating the surface sag. This number is provided to speed the ray tracing calculation; terms beyond this number are ignored.

Generally speaking, if lower order terms are used, the irregularity will be of low frequency, with fewer "bumps" across the surface. If higher order terms are used, there will be higher frequency irregularity, with more "bumps" across the surface. (see table 3)

For example, let's use surface 2 of the system to illustrate the difference of two methods. In the 'Tolerance Data Editor', insert a SAVE tolerance control operand under the operand you want to deal with. Here is TEXI of Surf.#2. If we want to see the RMS wave front error due to 1 wave P-V Surface irregularity, we need to enter **2 fringes**. (it is wrong to enter 1 fringe to represent 1 wave p-v in table 1, but the result will still off two orders of magnitude) And we can use different Zernike polynomial terms to represent different kinds of surface irregularity. (see fig 4)

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The SAVE command allows you to save the previous tolerance to a ZEMAX Lens File with the specified "File #." A file will be saved for both the maximum and minimum tolerance. The file names will be TSAV_MIN_xxxx.ZMX and TSAV_MAX_xxxx.ZMX for the min and max tolerance analysis, respectively, where xxxx is the integer number specified in the Int1 column. In this case, the integer number is 1, so the maximum tolerance file will be TSAV_Max_0001.ZMX.

Oper #	Type	File#	-	-	Nominal	-	-
1 (COMP)	COMP	5	0	-	93.824011	-5.000000	5.000000
2 (TWAV)	TWAV	-	-	-	-	0.632800	-
3 (TEXI)	TEXI	2	8	2	0.000000	-2.000000	2.000000
4 (SAVE)	SAVE	1	-	-	-	-	-
5 (TEXI)	TEXI	3	8	2	0.000000	-2.000000	2.000000
6 (TEXI)	TEXI	4	8	2	0.000000	-2.000000	2.000000
7 (TEXI)	TEXI	5	8	2	0.000000	-2.000000	2.000000

Fig 4 Save a tolerance situation

Much like the SAVE tolerance control operand (which is useful for evaluating one tolerance at a time), you may also save each individual Monte Carlo file generated during the tolerance analysis. This option exists in the Tolerancing dialog.(shown in fig 5)

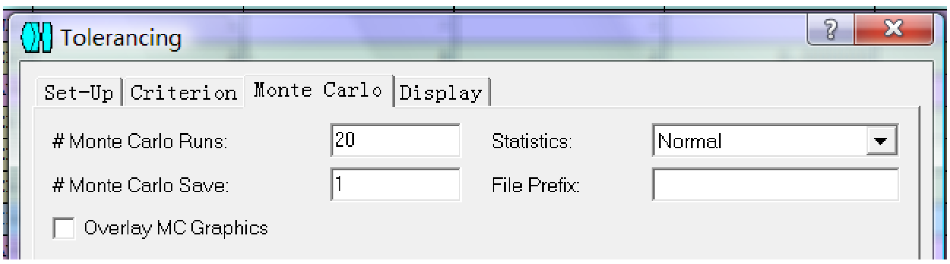
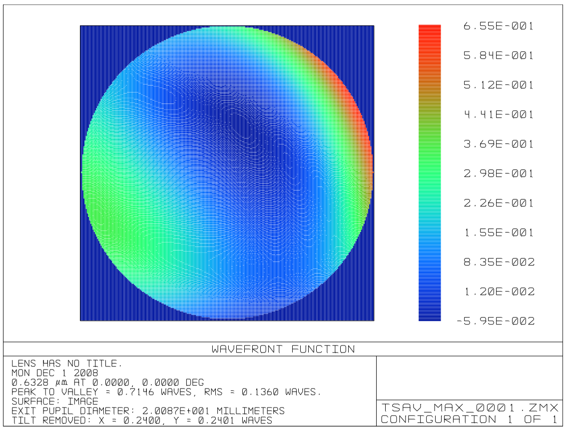


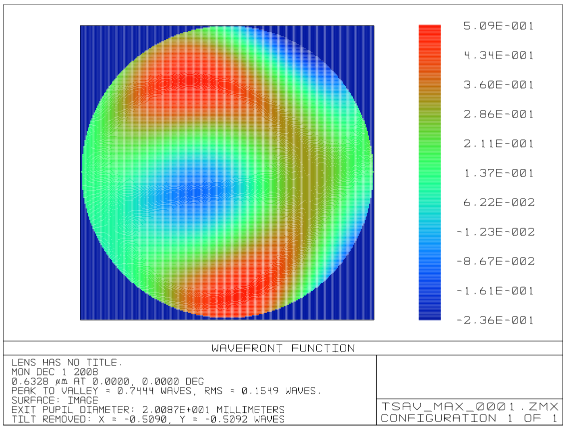
Fig 5 Saving Monte Carlo Tolerance Files

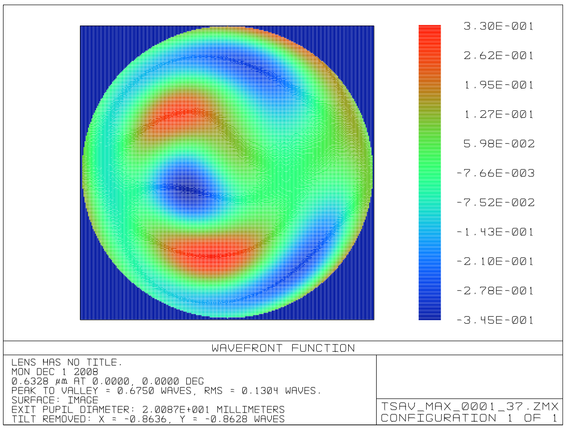
With this capability, we can clearly review what ZEMAX has done to ensure any given tolerance is performed the way we expect. Most importantly, we can thoroughly investigate any tolerance which we find to produce curious results.

Table 3 different kinds of surface irregularity

<table>
<tr><th>Zernike polynomial terms</th><th>Wavefront Map</th><th>RMS WFE (wave)</th></tr>
<tr><td>Term #2-#8

Irregularity of low spatial frequencies</td><td>
</td><td>0.1361</td></tr>
<tr><td>Term #10-#18

Irregularity of medium spatial frequencies</td><td>
</td><td>0.1548</td></tr>
<tr><td>Term #37-#30

Irregularity of high spatial frequencies</td><td>
</td><td>0.1305</td></tr>
</table>

Now we can see that. The optical performance of a surface depends not only on the RMS amplitude of the irregularity but also on the frequency of those peaks and valleys, because **it is the**

slope of the surface that bends rays. As we polish a surface from l/5 wave to l/10 wave to l/20 wave to l/50 wave, the spatial frequency of the irregularity increases. Surfaces polished to say l/5 are often quite "slow" in terms of the spatial frequency of the irregularity, whereas super-polished surfaces often have a very high spatial freqeuncy of irregularity.

To illustrate this, we use the example from ZEMAX's knowledge base online. (see fig 6) The surface #2 type is Periodic with a periodic structure in Y direction only. The 3D layout shows the difference in the ray trace results when the frequency of the periodic structure is increased while keeping the amplitude constant.

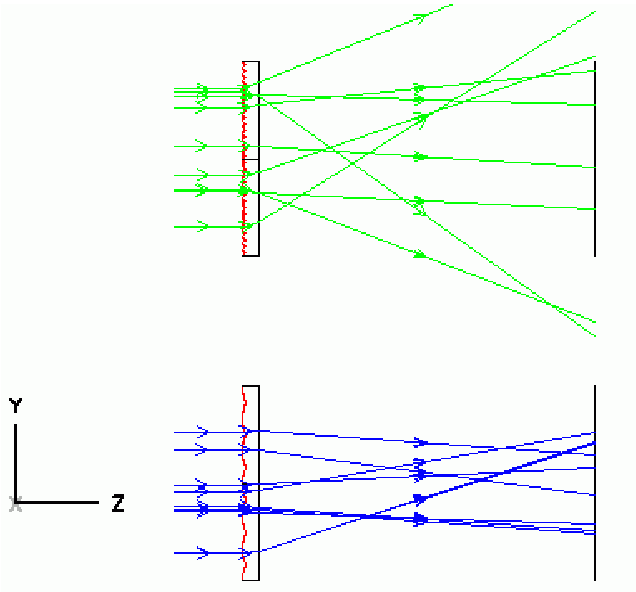


Fig 6

Zernike polynomials tend to diverge quite rapidly beyond the normalization radius, and so care should be taken that rays do not strike the surface beyond this radius. Although the ray tracing algorithm may work, the data may be inaccurate. The extrapolate flag may be set to zero to ignore the Zernike terms for rays that land outside the normalization radius.

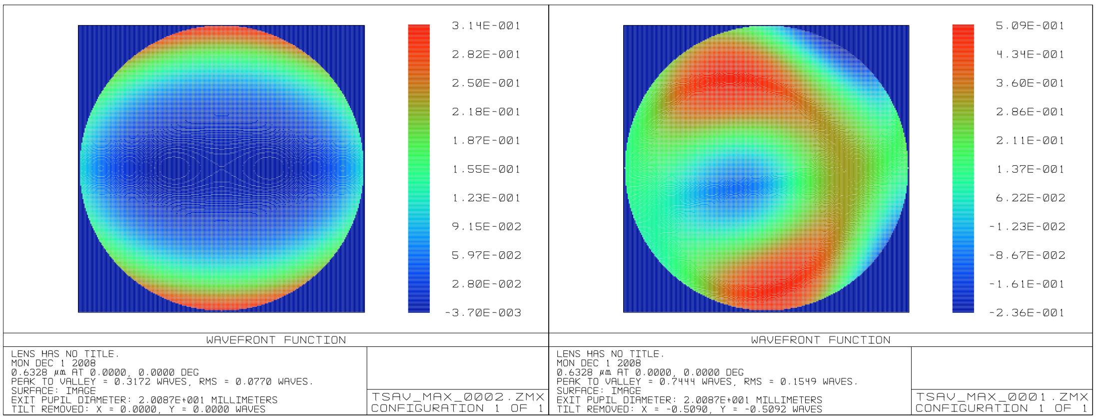
<u>Compare TIRR with TEXI</u>

Now compare the result of the sensitivity calculated in ZEMAX using different operand. Use Zernike polynomial terms #10-#18 for example.

Table 4 comparison between TIRR & TEXI

Surface Irregularity	ZEMAX Operand	Sensitivities (hand calculation)	Sensitivities (ZEMAX tolerance)	Compare (%)
Surf 2	TIRR	0.15574	0.07518	107.2
	TEXI	0.15574	0.15286	1.9
Surf 3	TIRR	0.15574	0.07034	121.4
	TEXI	0.15574	0.15236	2.2
Surf 4	TIRR	0.15574	0.07727	101.6
	TEXI	0.15574	0.15459	0.7
Surf 5	TIRR	0.15574	0.06489	140.0
	TEXI	0.15574	0.15011	3.7

The TIRR irregularity operand models the lowest frequency form of irregularity, with just a quadratic and quartic deviation across the surface. TEXI can model much more irregular surfaces, and with 30 or more terms used, about 5-15 "bumps" will typically be seen over the surface. So we can model the surface irregularity that more close to the RMS wavefront error the rule of thumb predicted.



Irregularity generated by TIRR Irregularity generated by TEXI

Fig 7

Tolerance on inhomogenity

Given a single number or value representing the inhomogeneity of a material, it is impossible to exactly predict the index profile of the glass. Therefore, the most accurate and superior approach to modeling the inhomogeneity of a material can be performed via the statistical results of Monte Carlo Tolerance Analysis using tolerances on surface irregularity.

For example, the TEZI tolerance operand in ZEMAX is used to analyze random irregular deviations of small amplitude on a surface. Within the Monte Carlo Analysis, the specified surface is converted to a Zernike Standard Sag surface, and each polynomial term is assigned a coefficient randomly chosen between zero and one. The resulting coefficients are normalized to yield the exact specified RMS tolerance.

Assume we have a perturbation of refractive index as +/-1e-4：

Lens1: $\Delta W_{rms} \approx 0.25 \times \Delta n \times t / \lambda = 0.25 \times 2 \times 1e - 5 \times 5mm / 0.6328 \mu m = 0.0395(wave)$

Lens2: $\Delta W_{rms} \approx 0.25 \times \Delta n \times t / \lambda = 0.25 \times 2 \times 1e - 5 \times 4mm / 0.6328 \mu m = 0.0316(wave)$

According to the article “How to tolerance for material inhomogeneity”, we first calculate:

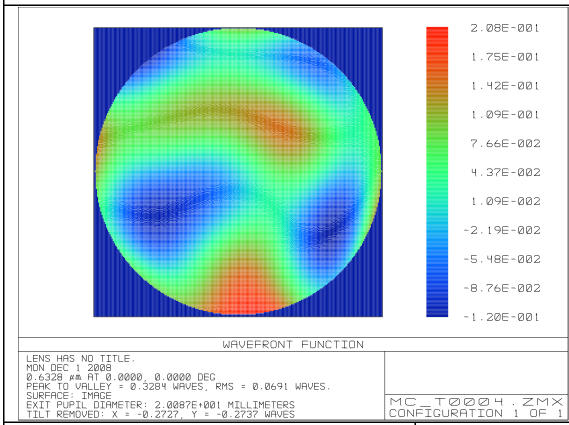
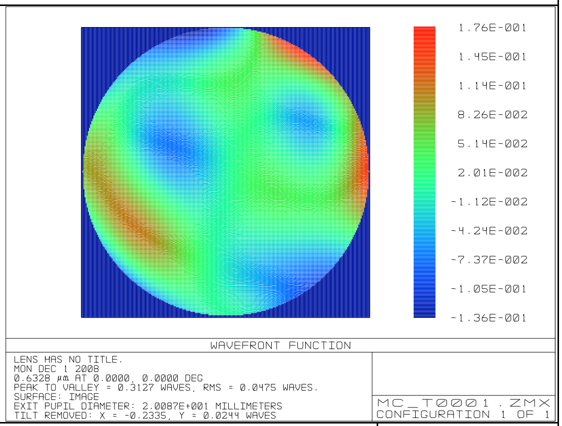
At lens 1, $\Delta OPL_1 = t \times \Delta n = 5mm \times 2 \times 1e - 5 = 1E - 4mm$,

At lens 2, $\Delta OPL_2 = t \times \Delta n = 4mm \times 2 \times 1e - 5 = 8E - 5mm$.

Then we use TEZI tolerance operand in the tolerance data editor.

The number of Zernike terms used for the analysis may be between 0 and 231. Generally speaking, if fewer terms are used, the irregularity will be of low frequency, with fewer "bumps" across the surface. The maximum number of terms should be chosen accordingly. Here we use set Max# of Zernike terms is set as 37, Min# 2.

Table 5 Use Monte Carl Analysis model inhomogenity

<table>
<tr><td colspan="3">LENS 1</td><td colspan="3">LENS 2</td></tr>
<tr><td colspan="3">
</td><td colspan="3">
</td></tr>
<tr><td colspan="2">Sensitivity</td><td rowspan="2">Difference (%)</td><td colspan="2">Sensitivity</td><td rowspan="2">Difference (%)</td></tr>
<tr><td>Rule of thumb</td><td>Monte Carl</td><td>Rule of thumb</td><td>Monte Carl</td></tr>
<tr><td>3950</td><td>7127</td><td>-45</td><td>3161</td><td>5777</td><td>-45</td></tr>
</table>

We can see that the difference between rule of thumb and Monte Carl analysis is within one order of magnitude. Either the rule of thumb is too general for this specific case or we can manipulate the result of MC analysis by changing the number of Zernike terms.

Each Monte Carlo trial will have a slightly different representation of the inhomogeneity of your glass. Therefore, a statistical listing of the entire Monte Carlo set is essential for estimating the probable effects the inhomogeneity has on your system performance. In a number of Monte Carlo Runs, we can gather a significant amount of statistical data relating to the change in RMS Wavefront Error due to the inhomogeneity of the glass. The more Monte Carlo tolerance runs that are performed, the better the statistical average of performance degradation (change in criteria) will be.(details are shown in appendix)

Conclusion

In this paper, we first went over the general tolerance procedure in ZEMAX. And mainly focus on the issue of surface irregularity and inhomogenity. The Zernike polynominal is used in both cases. In the tolerance of surface irregularity, the spatial frequency of the irregularity as well as its RMS amplitude must be modeled. In the tolerance of inhomogenity, the Monte Carlo tolerance analysis is used to randomize the irregularity (inhomogeneity) and provide with accurate, statistical results of how this irregularity is affecting the performance of the whole system.

Reference:

1, Zemax Users' Knowledge Base--- http://www.zemax.com/kb
2, Zemax Users' Guide
3, Pingzhou, Tutorial of Tolerancing Analysis Using Commercial Optical Software
4, Stacie Hvisc, Tolerancing in ZEMAX, OPTI 521 – Tutorial
5, OPTI 521 class notes

Appendix

Optical element tolerances

Table a1 Optical element tolerances

Parameter	**Base**	**Precision**	**High precision**
Lens thickness	200 µm	50 µm	10 µm
Radius of curvature sag Value of R	20 µm 1%	1.3 µm 0.1%	0.5 µm 0.02%
Wedge (light deviation)	6 arc min (0.1 deg)	1 arc min	15 arc sec
Surface irregularity	1 wave	λ /4	λ /20
Refractive index departure fromnominal	± 0.001 (Standard)	±0.0005 (Grade 3)	±0.0002 (Grade 1)
Refractive index homogeneity	± 1 x 10-4 (Standard)	± 5 x 10-6 (H2)	± 1 x 10-6 (H4)

Base: Typical, no cost impact for reducing tolerances beyond this.
Precision: Requires special attention, but easily achievable, may cost 25% more
High precision: Requires special equipment or personnel, may cost 100% more

Rules of thumb for lenses

Refractive index inhomogeneity happens on a larger scale. The wavefront errors from an optic with thickness *t* and index variation Δn are

$$\Delta W = t * \Delta n$$

Define α_i = ratio of beam footprint from single field point to the diameter of optic = B/D

For spherical surfaces like lenses, wavefront errors for each field point will fall off roughly with α, so surface *i* would contribute a wavefront error of

$$\Delta W_i \approx \alpha_i \Delta S_i (n-1)\cos(\phi)$$

Calculate sensitivities

the contribution from a tolerance σ_i on parameter x_i is

$$\Delta\Phi_i = \frac{\Delta\Phi}{\Delta x_i}\sigma_i \qquad \text{= (sensitivity) * (tolerance)}$$

Calculate system merit function by scaling from the sensitivities, and use RSS

$$\Phi = \sqrt{\Phi_0^2 + \left(\frac{\partial\Phi}{\partial x_1}\cdot\sigma_1\right)^2 + \left(\frac{\partial\Phi}{\partial x_2}\cdot\sigma_2\right)^2 + \ldots}$$

Result of tolerance analysis

Analysis of Tolerances
Units are Millimeters.
All changes are computed using linear differences.

Paraxial Focus compensation only.

Criterion : RMS Wavefront Error in waves
Mode : Sensitivities
Sampling : 20
Nominal Criterion : 0.00196760
Test Wavelength : 0.6328

Fields: Y Symmetric Angle in degrees

#	X-Field	Y-Field	Weight	VDX	VDY	VCX	VCY
1	0.000E+000	0.000E+000	1.000E+000	0.000	0.000	0.000	0.000

Sensitivity Analysis:

	Minimum			Maximum		
Type	Value	Criterion	Change	Value	Criterion	Change
TRAD 2	-0.10000000	0.00456249	0.00259489	0.10000000	0.00445741	0.00248982
TRAD 3	-1.00000000	0.00329200	0.00132440	1.00000000	0.00337889	0.00141130
TRAD 4	-0.20000000	0.00974232	0.00777472	0.20000000	0.00971565	0.00774805
TRAD 5	-1.00000000	0.00918457	0.00721698	1.00000000	0.00941515	0.00744756
TTHI 2 3	-0.10000000	0.00516165	0.00319406	0.10000000	0.00509519	0.00312759
TTHI 4 5	-0.10000000	0.00228409	0.00031649	0.10000000	0.00224497	0.00027737
TIND 2	-0.00100000	0.00253376	0.00056617	0.00100000	0.00260210	0.00063450
TIND 4	-0.00100000	0.00295857	0.00099097	0.00100000	0.00290074	0.00093314
TSTX 2	-0.05000000	0.00726102	0.00529342	0.05000000	0.00726102	0.00529342
TSTX 3	-0.05000000	0.01279461	0.01082701	0.05000000	0.01279461	0.01082701
TSTX 4	-0.05000000	0.02430970	0.02234211	0.05000000	0.02430970	0.02234211
TSTX 5	-0.05000000	0.01470170	0.01273410	0.05000000	0.01470170	0.01273410
TEZI 2	-0.00010000	0.02868832	0.02672073	0.00010000	0.02967379	0.02770619
TEZI 4	-8.0000E-005	0.02318843	0.02122083	8.0000E-005	0.02417917	0.02221157
TEXI 2	-0.50000000	0.02658429	0.02461669	0.50000000	0.02670688	0.02473929
TEXI 3	-0.50000000	0.02534865	0.02338105	0.50000000	0.02524477	0.02327717
TEXI 4	-0.50000000	0.02715985	0.02519226	0.50000000	0.02726088	0.02529329
TEXI 5	-0.50000000	0.02394458	0.02197698	0.50000000	0.02384895	0.02188135
TEDX 2 3	-0.10000000	0.01901183	0.01704423	0.10000000	0.01901183	0.01704423
TEDX 4 5	-0.10000000	0.01913553	0.01716794	0.10000000	0.01913553	0.01716794
TETX 2 3	-0.10000000	0.01105947	0.00909187	0.10000000	0.01105947	0.00909187
TETX 4 5	-0.10000000	0.02009618	0.01812859	0.10000000	0.02009618	0.01812859
TTHI 3 4	-0.10000000	0.00810477	0.00613718	0.10000000	0.00815976	0.00619216

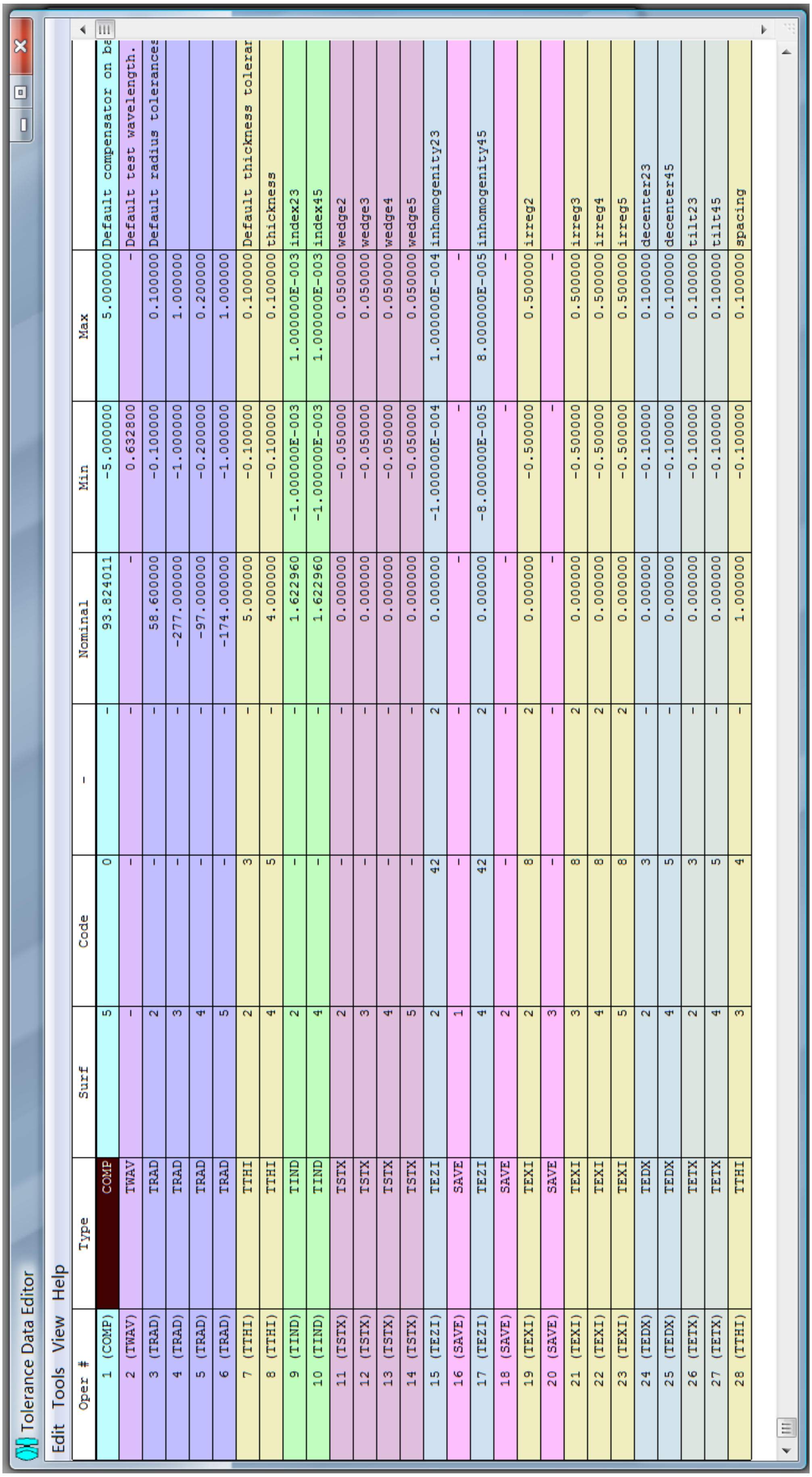
Worst offenders:

Type	Value	Criterion	Change
TEZI 2	0.00010000	0.02967379	0.02770619
TEZI 2	-0.00010000	0.02868832	0.02672073
TEXI 4	0.50000000	0.02726088	0.02529329
TEXI 4	-0.50000000	0.02715985	0.02519226
TEXI 2	0.50000000	0.02670688	0.02473929
TEXI 2	-0.50000000	0.02658429	0.02461669
TEXI 3	-0.50000000	0.02534865	0.02338105
TEXI 3	0.50000000	0.02524477	0.02327717
TSTX 4	-0.05000000	0.02430970	0.02234211
TSTX 4	0.05000000	0.02430970	0.02234211

Estimated Performance Changes based upon Root-Sum-Square method:
Nominal RMS Wavefront : 0.00196760
Estimated change : 0.07388404
Estimated RMS Wavefront : 0.07585164

Compensator Statistics:
Change in back focus:
Minimum : -0.201220
Maximum : 0.202049
Mean : 0.000002
Standard Deviation : 0.083533

Tolerance Data Editors



Tolerance Data Editor

Edit Tools View Help

Oper #	Type	Surf	Code	-	Nominal	Min	Max	
1 (COMP)	COMP	5	0	-	93.824011	-5.000000	5.000000	Default compensator on ba
2 (TWAV)	TWAV	-	-	-	-	0.632800	-	Default test wavelength.
3 (TRAD)	TRAD	2	-	-	58.600000	-0.100000	0.100000	Default radius tolerances
4 (TRAD)	TRAD	3	-	-	-277.000000	-1.000000	1.000000	
5 (TRAD)	TRAD	4	-	-	-97.000000	-0.200000	0.200000	
6 (TRAD)	TRAD	5	-	-	-174.000000	-1.000000	1.000000	
7 (TTHI)	TTHI	2	3	-	5.000000	-0.100000	0.100000	Default thickness tolerar
8 (TTHI)	TTHI	4	5	-	4.000000	-0.100000	0.100000	thickness
9 (TIND)	TIND	2	-	-	1.622960	-1.000000E-003	1.000000E-003	index23
10 (TIND)	TIND	4	-	-	1.622960	-1.000000E-003	1.000000E-003	index45
11 (TSTX)	TSTX	2	-	-	0.000000	-0.050000	0.050000	wedge2
12 (TSTX)	TSTX	3	-	-	0.000000	-0.050000	0.050000	wedge3
13 (TSTX)	TSTX	4	-	-	0.000000	-0.050000	0.050000	wedge4
14 (TSTX)	TSTX	5	-	-	0.000000	-0.050000	0.050000	wedge5
15 (TEZI)	TEZI	2	42	2	0.000000	-1.000000E-004	1.000000E-004	inhomogenity23
16 (SAVE)	SAVE	1	-	-	-	-	-	
17 (TEZI)	TEZI	4	42	2	0.000000	-8.000000E-005	8.000000E-005	inhomogenity45
18 (SAVE)	SAVE	2	-	-	-	-	-	
19 (TEXI)	TEXI	2	8	2	0.000000	-0.500000	0.500000	irreg2
20 (SAVE)	SAVE	3	-	-	-	-	-	
21 (TEXI)	TEXI	3	8	2	0.000000	-0.500000	0.500000	irreg3
22 (TEXI)	TEXI	4	8	2	0.000000	-0.500000	0.500000	irreg4
23 (TEXI)	TEXI	5	8	2	0.000000	-0.500000	0.500000	irreg5
24 (TEDX)	TEDX	2	3	-	0.000000	-0.100000	0.100000	decenter23
25 (TEDX)	TEDX	4	5	-	0.000000	-0.100000	0.100000	decenter45
26 (TETX)	TETX	2	3	-	0.000000	-0.100000	0.100000	tilt23
27 (TETX)	TETX	4	5	-	0.000000	-0.100000	0.100000	tilt45
28 (TTHI)	TTHI	3	4	-	1.000000	-0.100000	0.100000	spacing

Result of inhomogenity using Monte Carlo Analysis

Surface 2

Monte Carlo Analysis:

Number of trials: 50

Initial Statistics: Normal Distribution

Trial	Criterion	Change
1	0.06522942	0.06326183
2	0.07225432	0.07028672
3	0.09318801	0.09122041
4	0.05367260	0.05170500
5	0.07076307	0.06879548
6	0.08075363	0.07878603
7	0.07533238	0.07336478
8	0.09213563	0.09016804
9	0.06924572	0.06727812
10	0.07211866	0.07015106
11	0.05847875	0.05651116
12	0.05351484	0.05154725
13	0.07308790	0.07112031
14	0.07230065	0.07033305
15	0.07918595	0.07721836
16	0.06899019	0.06702259
17	0.05778052	0.05581293
18	0.06062229	0.05865469
19	0.06975438	0.06778679
20	0.06901097	0.06704337
21	0.07657252	0.07460492
22	0.08264812	0.08068052
23	0.06276381	0.06079621
24	0.07910809	0.07714049
25	0.06688549	0.06491789
26	0.06361334	0.06164574
27	0.07984098	0.07787338
28	0.07883145	0.07686386
29	0.06765781	0.06569022
30	0.07835047	0.07638287
31	0.07694001	0.07497242
32	0.07693093	0.07496334
33	0.08177981	0.07981222
34	0.07103722	0.06906963
35	0.06637245	0.06440486
36	0.06981339	0.06784579
37	0.07652053	0.07455294
38	0.06754082	0.06557322
39	0.08223271	0.08026511
40	0.06553477	0.06356717
41	0.08144231	0.07947472
42	0.06274237	0.06077477
43	0.07643439	0.07446680
44	0.05919572	0.05722813
45	0.05638980	0.05442220
46	0.06362478	0.06165719
47	0.06683497	0.06486737
48	0.06897937	0.06701177
49	0.07616049	0.07419289
50	0.07336144	0.07139384

Number of traceable Monte Carlo files generated: 50

Nominal	0.00196760		
Best	0.05351484	Trial	12
Worst	0.09318801	Trial	3
Mean	**0.07127120**		
Std Dev	0.00879588		

90% <	0.08161106
50% <	0.07090015
10% <	0.05883724

Surface 4:

Analysis of Tolerances

Monte Carlo Analysis:
Number of trials: 50

Initial Statistics: Normal Distribution

Trial	Criterion	Change
1	0.04753389	0.04556630
2	0.05881069	0.05684310
3	0.05831567	0.05634807
4	0.04646614	0.04449854
5	0.06130289	0.05933529
6	0.06533279	0.06336519
7	0.06569923	0.06373164
8	0.05549546	0.05352786
9	0.05356110	0.05159350
10	0.05556977	0.05360217
11	0.06265096	0.06068336
12	0.06784088	0.06587328
13	0.05869546	0.05672786
14	0.04789488	0.04592728
15	0.05153086	0.04956326
16	0.06416051	0.06219292
17	0.07077192	0.06880432
18	0.05013013	0.04816253
19	0.05375728	0.05178968
20	0.05662734	0.05465975
21	0.05750364	0.05553604
22	0.05070616	0.04873857
23	0.05335878	0.05139119
24	0.05522122	0.05325362
25	0.06430335	0.06233576
26	0.06214731	0.06017971
27	0.05766259	0.05569500
28	0.05150732	0.04953973
29	0.06066803	0.05870043
30	0.07173467	0.06976707
31	0.06036958	0.05840199
32	0.06378870	0.06182110
33	0.04738594	0.04541834
34	0.05813946	0.05617186
35	0.05273932	0.05077172
36	0.05561456	0.05364696
37	0.06011750	0.05814991
38	0.06198762	0.06002002
39	0.05932531	0.05735771
40	0.04760936	0.04564176
41	0.05648141	0.05451381
42	0.05584632	0.05387872
43	0.04717017	0.04520258
44	0.06551341	0.06354581
45	0.05949195	0.05752436
46	0.06442356	0.06245597
47	0.06656734	0.06459974
48	0.05333903	0.05137143
49	0.05406516	0.05209756
50	0.06140796	0.05944037

Number of traceable Monte Carlo files generated: 50

Nominal	0.00196760		
Best	0.04646614	Trial	4
Worst	0.07173467	Trial	30
Mean	**0.05776689**		
Std Dev	0.00629539		

90% <	0.06560632
50% <	0.05790103
10% <	0.04775212