Tolerancing in Zemax

Rachel Haynes
Opti 521
Tutorial
December 10, 2007

Introduction

Being able to design a good optical system is important as an optical engineer, but equally as important is being able to tolerance it. Without this skill it is near impossible to bring any theoretical system that you have designed to reality. For simple systems consisting of perhaps one or two lenses, this is a relatively easy task because there a limited number of degrees of freedom. Designs can get complicated very quickly though, making tolerancing by hand an extremely tedious and time consuming process. Computer programs such as Zemax can be very helpful in these situations. They save time and prevent calculation mistakes that are inherent when tabulating everything by hand. In this paper, I will go over using the tolerancing feature of Zemax. I will then do a quick demonstration using the doublet from homework 4 as an example, comparing to the results I got tolerancing the same system by hand.

Sources of Error

Once your optical system is completely designed, the first step in tolerancing is determining all your degrees of freedom. That is, where are all of the sources of error. They can come from misalignment of the optics (tilt,lateral decenter, or axial decenter), manufacturing errors of the actual elements (curvature, thickness, wedge, etc.), defects of the element material (eg, index and dispersion), surface finish, the list goes on and on. Zemax is fully capable to combining all these variables into one large tolerancing computation, however, it is often easier to break them up into groups (alignment, lenses, operational changes, etc) and allocate each group a specific error budget. You can then tolerance each group separately, making it easier to keep track of what is going on, and make sure the program is doing what you want it to. As you will see, this is what was done in the example I will show latter. I will be focusing only on the alignment tolerances of the doublet from homework 4.

The Tolerance Data Editor

Tolerance information in Zemax is inserted into the *Tolerance Data Editor* (TDE), which is very similar to the Merit Function Editor (MFE). Each line of the TDE spreadsheet is one operand that represents one degree of freedom. As with the MFE, there is often extra data to insert to specify each of these operands, such as surface number. Then, you must enter the minimum and maximum departure from nominal for this operand. For example, suppose you were specifying the tolerance on the separation of two lenses. Nominally, this distance is say 5 mm, but you are going to allow it to shift +/- 0.2 mm. In the TDE, you would have a thickness operand for the surface spanning between the two lenses, with the minimum value set at -0.2 and the maximum value set at +0.2. A list of the different operands is provided in the Zemax manual, or the Help function in Zemax.

A good starting point for a list of degrees of freedom are the default tolerances in Zemax. Especially for a beginner, it is a good way to, perhaps not catch *all* of the possible variables, but it will certainly list most of them. It is similar to the default merit function, in that is opens a window that has different fields for you to fill in. In the case of the default tolerances, it lists the alignment variables for each element, as well as for each surface. The latte is used to specify the lens itself, in that one surface can be off center or tilted wrong with respect to the other. It is the users job to simply enter minimum and maximum values for each of these, and what range of surfaces to apply them to. Then, once in the TDE, you can refine them for each specific surface.

Compensators

Often when you build a system, there is a way to compensate for errors. Probably the most common of these is focus, meaning the the position of the image plane can be adjusted to make the best image when the system is put together. In the TDE, you can add your own compensators with the operand COMP. For example, if designing a telescope, the spacing between the primary and secondary mirror can be adjusted to make the best image. In that case, you would add a compensator to that surface.

Zemax then uses the compensators in the following way. When your system is perturbed from it's nominal state by the amount you indicate in the TDE, the image quality drops. The entire purpose of tolerancing is to determine how much things are allowed to be wrong without the image degrading too much. If you were to measure the image quality strictly from the perturbations, your analysis will not be correct. You have to take into account that fact that you can “fix” or compensate for at least a little bit of the error. Thus, after perturbing the system, Zemax then looks at all the compensators you have defined (keep in mind you do not have to define any, your system might not have any.) and optimizes them to make the best image.

Tolerancing

Once your TDE is filled, the next step is to open the tolerancing window (Ctrl + T, or Tools – Tolerancing – Tolerancing...) In the tolerance window, there are 4 different tabs, I will discuss each one here.

Set-Up

Zemax supports a few different modes of tolerancing. I will discuss the most common, *Sensitivity*. In this mode, Zemax perturbs each of the specified degrees of freedom in the minimum and maximum direction and measures the change in the criterion you set (discussed below). This difference can be calculated as either a Root-Sum-Square (RSS) change or a Linear Change.

Criterion

This is where you specify what Zemax looks at when it does the tolerancing. Meaning, what the *criterion* is. The criterion can be many things, including the spot radius, wavefront error, MTF, or even your own merit function. Sampling is how many rays are traced in the tolerancing. Comp is the compensator setting, there are 3 options: Optimize All, which is just like optimizing in Zemax. Zemax uses the compensators you have set as variables and minimizes the criterion you selected. There are two different optimization choices: DLS which is Damped Least Squares, and OD, Orthogonal Decent. The third compensator setting is *paraxial focus*. If this is selected, then only the focus position is adjusted as a compensator.

Monte Carlo

The Monte Carlo Simulations are what take the most time in the Zemax tolerancing. After each sensitivity is computed and the total criterion change found, Zemax will run a user defined number of simulations. In each of the simulations, each of the degrees of freedom is perturbed a random amount between the minimum and maximum set values. The the compensators are adjusted and the criterion evaluated. You can choose what kind of statistics the Monte Carlo analysis uses. The options are Normal (Gaussian), Parabolic, or uniform distributions.

If selected, each of the trials are saved in it's own file. That way, you can go back and look at them to make sure Zemax is doing what you are expecting, and investigate in more detail any unusual or curious results.

Display

This tab lets you choose how many of the tolerance operands are displayed, whether descriptions of each operand are printed, and whether or not the compensator data is shown for each trial of the Monte Carlo Analysis.

Tolerance Results

Once all four of these tabs are filled with the appropriate information, you can press the “OK” button and let Zemax loose. When it completes the analysis, it will pop up a Text Viewer Screen with the results. The sensitivity analysis is shown first, with 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.

After the Sensitivity analysis comes the Monte Carlo Analysis for for ever many trials were selected. For each trial, the criterion and change in criterion is listed. And then a distribution of the data is computed depending on the statistical method selected previously.

Finally, the compensator statistics are are shown. This in information regarding the nominal value of the compensator variable, and its maximum, minimum, and average change.

Example

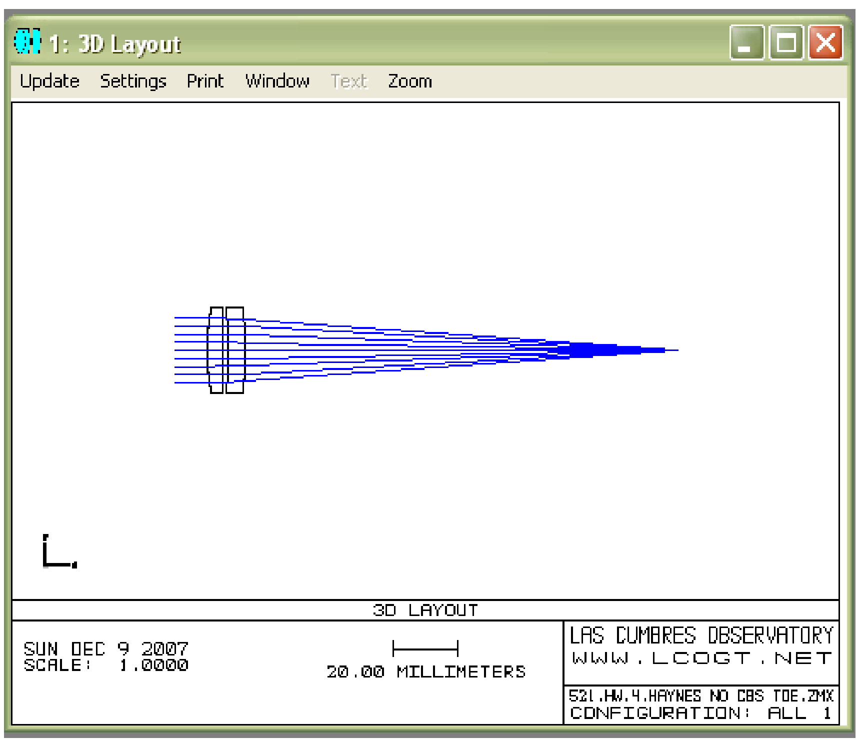
Now I will show a simple example of tolerancing, using the doublet of homework 4. Recall that this assignment was only concerned with the alignment tolerances of the lens.

First I set up the optical system, below shows the LDE and layout.

Lens Data Editor

Edit Solves View Help

Surf	Type	Comment	Radius	Thickness	Glass	Semi-Diameter	
OBJ	Standard		Infinity	Infinity		0.000000	
STO	Standard		Infinity	10.000000		10.000000	U
2*	Standard		73.070000	5.000000	BK7	13.000000	U
3*	Standard		-240.200000	1.500000		13.000000	U
4*	Standard		-103.730000	5.000000	BK7	12.000000	U
5*	Standard		-175.730000	132.814692		13.000000	U
IMA	Standard		Infinity	-		3.2154E-004	



Next, each degree of freedom was entered into the TDE as a different operand. Below shows what that looks like:

Tolerance Data Editor

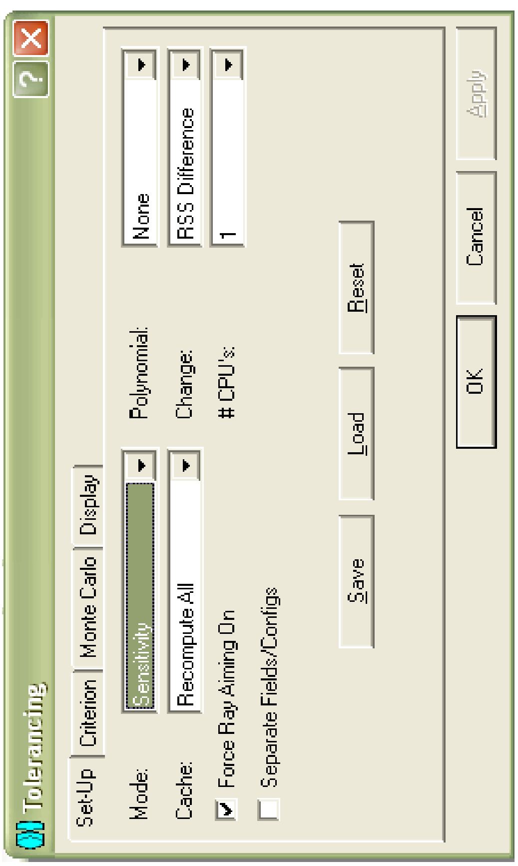
Edit Tools View Help

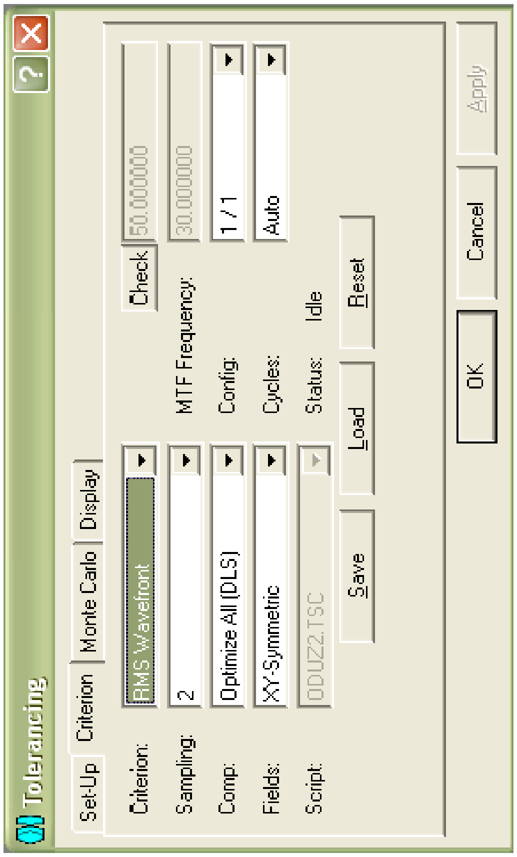
Oper #	Type	Surf	Code	-	Nominal	Min	Max	Comment
1 (COMP)	COMP	5	0	-	0.000000	-5.000000	5.000000	Default compensator on back focus.
2 (TWAV)	TWAV	-	-	-	-	0.632800	-	Default test wavelength.
3 (TTHI)	TTHI	3	5	-	1.500000	-0.200000	0.200000	
4 (TEDX)	TEDX	2	3	-	0.000000	-0.130000	0.130000	Default element dec/tilt tolerances 2-*
5 (TEDY)	TEDY	2	3	-	0.000000	-0.130000	0.130000	
6 (TETX)	TETX	2	3	-	0.000000	-0.141000	0.141000	
7 (TETY)	TETY	2	3	-	0.000000	-0.141000	0.141000	
8 (TEDX)	TEDX	4	5	-	0.000000	-0.141000	0.141000	Default element dec/tilt tolerances 4-*
9 (TEDY)	TEDY	4	5	-	0.000000	-0.141000	0.141000	
10 (TETX)	TETX	4	5	-	0.000000	-0.141000	0.141000	
11 (TETY)	TETY	4	5	-	0.000000	-0.141000	0.141000	

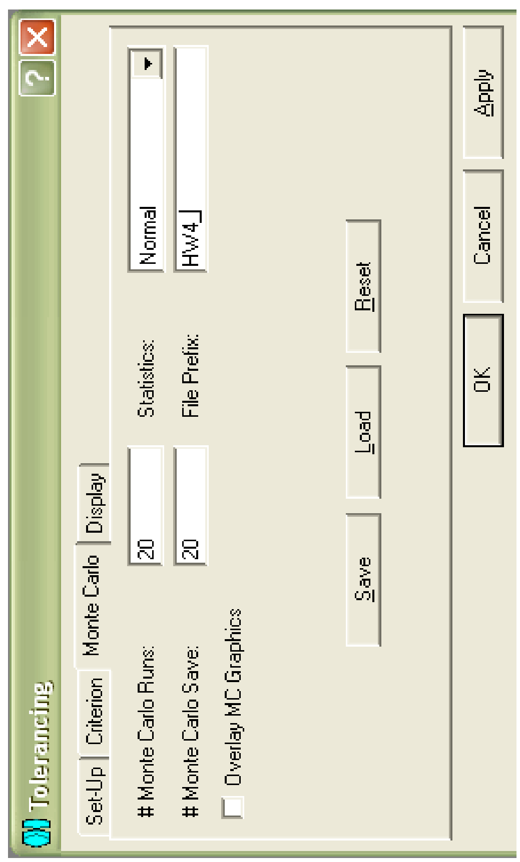
My original hand calculated tolerances are attached in the appendix, and if you have a look at that, you'll notice a decentration tolerance of 0.2mm on each lens. Above however, you don't see that. What I realized, is that decentration has no x- or y- orientation, it is just decentering. In Zemax however, you have to specify whether you are decentering in x or y and by how much. Because I wanted to be able to make a comparison between my hand calculations and the Zemax output, I had to figure out how to represent the same thing I had done by hand. What I realized is that the total decenter is just the x and y decenters summed in quadrature. Thus I set the x and y decenters equal and computed what their decenters would have to be to sum to the decenter I had originally specified. As one would expect, the result is just the total decenter divided by root two.

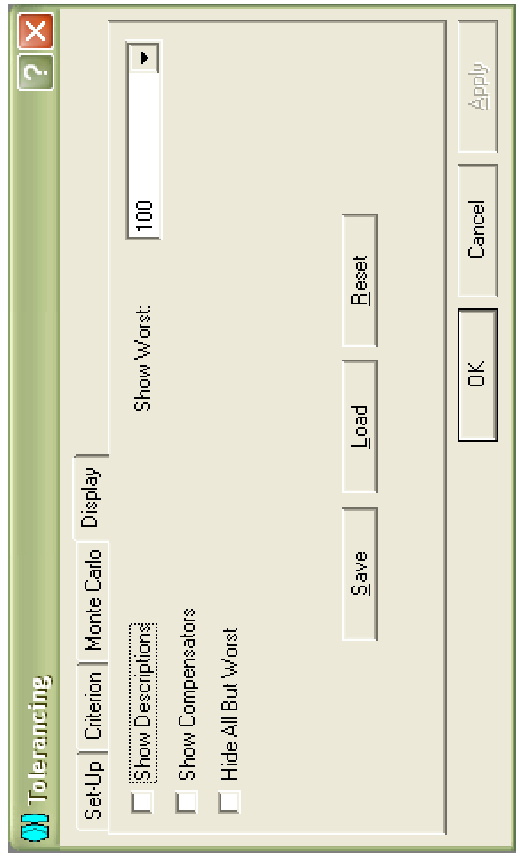
One mistake I almost made was to assume that because my system is axially symmetric, I could just use the x- or just the y- decenters in the TDE. But, because a tilt and decneter can compensate each other, not including tilt and decenter in both x- and y- does not represent the system properly, and the correct results were not obtained.

After figuring this out, I set up the tolernacing. I choose my Criterion to be the RMS wavefront error. With a self-defined compensator on the back focus of the systeml, and RSS change calculation. The next page shows each of these.


Tolerancing
Set-Up
Criterion
Monte Carlo
Display
Mode:
Sensitivity
Polynomial:
None
Cache:
Recompute All
Change:
RSS Difference
Force Ray Aiming On
CPU's:
1
Separate Fields/Configs
Save
Load
Reset
OK
Cancel
Apply


Tolerancing
Set-Up
Criterion
Monte Carlo
Display
Criterion:
RMS Wavefront
Check
50.000000
Sampling:
2
MTF Frequency:
30.000000
Comp:
Optimize All (DLS)
Config:
1 / 1
Fields:
XY-Symmetric
Cycles:
Auto
Script:
ODUZ2.TSC
Status:
Idle
Save
Load
Reset
OK
Cancel
Apply


Tolerancing
Set-Up
Criterion
Monte Carlo
Display
Monte Carlo Runs:
20
Statistics:
Normal
Monte Carlo Save:
20
File Prefix:
HW4_
Overlay MC Graphics
Save
Load
Reset
OK
Cancel
Apply


Tolerancing
Set-Up
Criterion
Monte Carlo
Display
Show Descriptions
Show Worst:
100
Show Compensators
Hide All But Worst
Save
Load
Reset
OK
Cancel
Apply

Then the tolerancing was run. The out put of the sensitivity analysis and Monte Carlo Analysis for 20 trials is shown below. As you can just barely make out in the text below, the estimated RMS Wavefront after errors is 0.0394 waves, *very* close to the 0.0398 waves I calculated by hand. This is nice reassurance that I successfully modeled in Zemax what I had previously done by hand.

Analysis of Tolerances

File : C:\Documents and Settings\rhaynes.LCO\Desktop\521.HW.4.Haynes no CBs TDE.ZMX
Title:
Date : SUN DEC 9 2007

Units are Millimeters.
All changes are computed using root-sum-square (RSS) differences.

All compensators will be optimized using Damped Least Squares.

Compensator: Thickness 5, Min = -5.0000, Max = 5.0000

Criterion : RMS Wavefront Error in waves
Mode : Sensitivities
Sampling : 2
Optimization Cycles : Automatic mode
Nominal Criterion : 0.00000000
Test Wavelength : 0.6328

Fields: XY Symmetric Real Image height in Millimeters

#	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	
TTHI 3 5	-0.20000000	4.5015E-010	-2.6145E-010	0.20000000	6.3820E-010	3.6920E-010	
TEDX 2 3	-0.13000000	0.01569342	0.01569342	0.13000000	0.01569342	0.01569342	
TEDY 2 3	-0.13000000	0.01569342	0.01569342	0.13000000	0.01569342	0.01569342	
TETX 2 3	-0.14100000	0.00776939	0.00776939	0.14100000	0.00776939	0.00776939	
TETY 2 3	-0.14100000	0.00776939	0.00776939	0.14100000	0.00776939	0.00776939	
TEDX 4 5	-0.14100000	0.01430090	0.01430090	0.14100000	0.01430090	0.01430090	
TEDY 4 5	-0.14100000	0.01430090	0.01430090	0.14100000	0.01430090	0.01430090	
TETX 4 5	-0.14100000	0.01627728	0.01627728	0.14100000	0.01627728	0.01627728	
TETY 4 5	-0.14100000	0.01627728	0.01627728	0.14100000	0.01627728	0.01627728	

Worst offenders:

Type	Value	Criterion	Change
TETX 4 5	-0.14100000	0.01627728	0.01627728
TETX 4 5	0.14100000	0.01627728	0.01627728
TETY 4 5	-0.14100000	0.01627728	0.01627728
TETY 4 5	0.14100000	0.01627728	0.01627728
TEDY 2 3	-0.13000000	0.01569342	0.01569342
TEDY 2 3	0.13000000	0.01569342	0.01569342
TEDX 2 3	-0.13000000	0.01569342	0.01569342
TEDX 2 3	0.13000000	0.01569342	0.01569342
TEDY 4 5	-0.14100000	0.01430090	0.01430090
TEDY 4 5	0.14100000	0.01430090	0.01430090
TEDX 4 5	-0.14100000	0.01430090	0.01430090
TEDX 4 5	0.14100000	0.01430090	0.01430090
TETY 2 3	-0.14100000	0.00776939	0.00776939
TETY 2 3	0.14100000	0.00776939	0.00776939
TETX 2 3	-0.14100000	0.00776939	0.00776939
TETX 2 3	0.14100000	0.00776939	0.00776939
TTHI 3 5	0.20000000	6.3820E-010	3.6920E-010
TTHI 3 5	-0.20000000	4.5015E-010	-2.6145E-010

Estimated Performance Changes based upon Root-Sum-Square method:
Nominal RMS Wavefront : 5.2057E-010
Estimated change : 0.03939828
Estimated RMS Wavefront : 0.03939828

Compensator Statistics:
Thickness Surf 5:
Nominal : 132.814692
Minimum : 132.481581
Maximum : 133.145089
Mean : 132.812931
Standard Deviation : 0.110586

The results of the Monte Carlo Analysis are below.

Monte Carlo Analysis:
Number of trials: 20

Initial Statistics: Normal Distribution

Trial	Criterion	Change
1	0.02522244	0.02522244
2	0.00555705	0.00555705
3	0.02770406	0.02770406
4	0.00489696	0.00489696
5	0.02637886	0.02637886
6	0.01255285	0.01255285
7	0.00667736	0.00667736
8	0.04547902	0.04547902
9	0.02105195	0.02105194
10	0.01260668	0.01260668
11	0.01609995	0.01609995
12	0.00620689	0.00620689
13	0.02240306	0.02240306
14	0.02533753	0.02533753
15	0.03639390	0.03639389
16	0.01557734	0.01557734
17	0.01573148	0.01573148
18	0.01160763	0.01160763
19	0.01057407	0.01057407
20	0.01334694	0.01334694

Nominal 5.2057E-010
Best 0.00489696 Trial 4
Worst 0.04547902 Trial 8
Mean 0.01807030
Std Dev 0.01043372

Compensator Statistics:
Thickness Surf 5:
Nominal : 132.814692
Minimum : 132.566202
Maximum : 133.046469
Mean : 132.793476
Standard Deviation : 0.130666

90% < 0.03204898
50% < 0.01565441
10% < 0.00588197

Conclusions

Probably the most important thing to remember when tolerancing is to set it up like you would assemble the actual system. And this goes for the entire set-up and running of the tolerances. As you define your operands in the TDE, think about how you are assembling the system, and the possible ways you could be wrong in alignment. Imagine making the optic (unless you are making it yourself), and think about all the ways you could make it wrong. Then, after assembly, how do you look at the image. Is there a focuser on the eyepiece, and adjustment of an element position? Or anything else to produce the best image possible? This is the best way to model your system as accurately as possible.

APPENDIX
HW 4 – Tolerancing by Hand

Mounting Requirements For Focusing Doublet

Rachel Haynes
OPTI 521

September 26, 2007

Introduction
This report gives the tolerance analysis for the optical alignment of a focusing doublet. The doublet is used to focus a collimated HeNe laser onto a Position Sensing Detector (PSD). It consists of a bi-convex and concave-convex lens with 26 mm diameter, and 140mm effective focal length. The complete description is provided for your reference below. It has a residual system error of <0.001λ rms. The total system is allowed 0.07λ rms of wavefront error, with the optical alignment component being budgeted 0.04λ rms. The doublet itself was allowed 5 degrees of freedom (dof) from which error could come: tilt and decenter of each element, and their relative spacing. A focus compensator was allowed during tolerancing by moving the PSD. The resolution for this adjustment is 5 MICROMETERS, thus the sixth and final dof was an assumed 2.5 MICROMETER focus error. The sensitivity analysis was done in Zemax, and then appropriate tolerance values assigned to each DOF such that the total system wavefront error was 0.04λ rms. The sensitivities, tolerance value, and corresponding error contribution for each dof is shown below in table 1. The total system error is a root-sum-square (RSS) addition of each individual term.

Element	parameter	Sensitivity	units: RMS wavefront error/	Tolerance		Error Contribution
Lens 1	Tilt	0.05999967	deg	0.2	deg	0.011999933
	Decenter	0.12099897	mm	0.18	mm	0.021779814
Lens 2	Tilt	0.11649893	deg	0.2	deg	0.023299785
	Decenter	0.10199877	mm	0.2	mm	0.020399755
Relative	Lens Spacing	0.00698212	mm	0.2	mm	0.001396424
System	Focus	0.00115931	um	2.5	um	0.002898275
RSS						0.0398

Table 1. Sensitivity and tolerance values for focusing doublet

Optical Design

Figure 1 below shows the optical design for this focusing doublet, and table 2 shows the corresponding prescription.

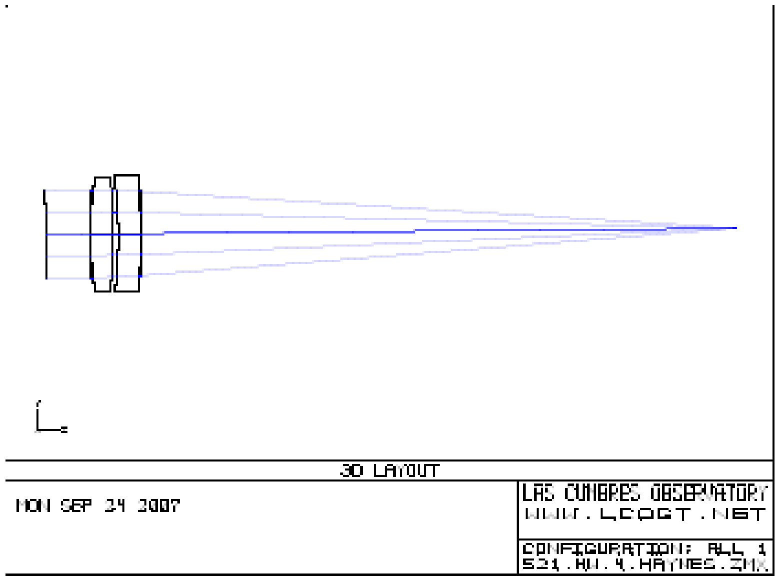


Figure 1. Focusing Doublet

System/Prescription Data

SURFACE DATA SUMMARY:

Surf	Type	Radius	Thickness	Glass	Diameter
OBJ	STANDARD	Infinity	Infinity		0
STO	STANDARD	Infinity	0		20
2	STANDARD	73.07	5	BK7	26
3	STANDARD	-240.2	1.5		26
4	STANDARD	-103.73	5	BK7	24
5	STANDARD	-175.73	132.8139		26
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
BK7 1.51508810

Table 2. Prescription Data for Focusing Doublet

Sensitivity and Tolerancing

As stated above, the tolerance sensitivities were determined using Zemax. The system was perturbed in each dof by an amount somewhat near where the final tolerance value was expected to be, and then the system was refocused by moving the image plane. At that point, the RMS wavefront error was noted. Note that only one dof was perturbed at a time. The rest of the optical assembly was left at it's nominal position, or returned there after perturbation. To find the sensitivity to a particular dof, the residual wavefront error must be removed from the total error found after each perturbation. Assuming these two errors are uncorrelated, this subtraction can be done in a RSS fashion also. For this system though, the residual error, PHI NOUGHT, was so much less than the error after perturbation, that it's contribution is negligible. Thus the perturbation error is just the total error previously noted.

The sensitivity was then found back taking the ratio of the change in wavefront error to the amount of the perturbation. In that way, if you assume a linear relationship between the perturbation amount and system error, you can determine the wavefront error for any given tolerance value. (Note that this is why I stated that the sensitivities were determined by perturbing an element by approximately the expected final tolerance amount. In that way, your assumption of a linear relationship has less error.) Then by, varying the tolerance for each dof, you can't distribute the error until you reach your allocated budget. Table 3 shows all the values thus described.

					Sensitivity	units RMS WE/	Tolerance		Error Contribution
Element	parameter, i	Δxi		ΔΦ	ΔΦ/Δxi		Δxi		Δxi(ΔΦ/Δxi)
Lens 1	Tilt	0.5	deg	0.0300	0.0600	deg	0.2	deg	0.0120
	Decenter	0.2	mm	0.0242	0.121	mm	0.18	mm	0.0218
Lens 2	Tilt	0.2	deg	0.0233	0.116	deg	0.2	deg	0.0233
	Decenter	0.2	mm	0.0204	0.102	mm	0.2	mm	0.0204
Relative	Lens Spacing	0.2	mm	0.0014	0.00698	mm	0.2	mm	0.00140
System	Focus	2.5	um	0.0029	0.00116	um	2.5	um	0.00290
RSS									**0.0398**

Table 3. Sensitivity analysis

Conclusions - The Art of Tolerancing

Assigning tolerance values to each dof is not as simple as picking numbers until you use up the error budget. If that were the case, it would be easy. You could simply pick one dof, use the appropriate tolerance to exactly meet budget, and then say all other tolerances are zero. Now this example is a little extreme, yes, but it illustrates an important point. Tolerancing is the art of balancing error and cost. A tighter tolerance is harder, which equates to more money. Thus, yo umust distribute the allowable error in a way that minimizes total system cost, but still assures you an adequate system being produced. Degrees of freedom with high sensitivites will also be ones that need stricter tolerances, because loose ones would quickly contribute much error to the system.