

## Lesson 9: Tolerancing the Apochromatic Objective

In the previous lesson we designed an apochromatic telescope objective. In this lesson we will calculate a tolerance budget for that lens.

Before you can send drawings of the lens elements to the shop, you have to figure out how large the manufacturing errors can be and still get adequate performance. Since this example is a very well-corrected astronomical objective – the fussiest lenses you are ever likely to meet unless you design microlithography objectives – the budget will probably be very tight. That is exactly what we need for this exercise: most lenses are very easy to tolerance with SYNOPSIS, but that would not be a very interesting lesson. We will use the lens L8L2 from the previous lesson.

The on-axis image is the most important for this kind of objective, which is often used for planetary observing, and there is some field curvature (which is why we varied the image surface radius) and some astigmatism, which you cannot correct with a compact lens group at the stop.

First we will try a simple **BTOL** evaluation. BTOL has a great many options, of which we will use only a few. We have provided a menu for simple cases: **MSB**, for **M**enu, **S**imple **B**TOL. Type **MSB** in the Command Window, and then fill in the boxes as follows: (Most of them are already filled in for you; but we selected the **TOLERANCE** and **WAVE** radio buttons (instead of **DEGRADE SPOT**), and clicked the **Prepare MC** box to select that option. Everything else can be left as it is. Click the **GO** button.

Simple BTOL Dialog

This dialog contains a few of the most-often used features of the budget tolerance program BTOL. There are many more features, which you can read about by clicking the Help button. See also page 16 of the Syntax Summary.

BTOL  Enter the desired confidence level, in units of sigma. (2 or 3 sigma recommended.)

Change default ranges if desired. These define "loose" tolerances. Most users do not need to change these.

<input type="checkbox"/> RANGE RFR	<input type="text" value="5.0"/>	Radius, in fringes; default depends on radius.
<input type="checkbox"/> RANGE TH	<input type="text" value="0.005"/>	Thicknesses; default is 0.005 inches. Enter in lens units.
<input type="checkbox"/> RANGE INDEX	<input type="text" value="0.001"/>	Index; default is 0.001
<input type="checkbox"/> RANGE VNUM	<input type="text" value="1.0"/>	V-number; default is 1.0
<input type="checkbox"/> RANGE IRREG.	<input type="text" value="2.5"/>	Irregularity (cylinder); default is 2.5 fringes.
<input type="checkbox"/> RANGE REDGE.	<input type="text" value="1.0"/>	Rolled edge; default is 1.0 fringes.
<input type="checkbox"/> RANGE WEDGE	<input type="text" value="0.005"/>	Element wedge; default is 0.005 inches TIR. Enter in lens units.
<input type="checkbox"/> RANGE DECENT.	<input type="text" value="0.005"/>	Element decenter; default is 0.005 inches. Enter in lens units.
<input type="checkbox"/> RANGE TILT	<input type="text" value="0.005"/>	Element tilt; default is 0.005 inches TIR. Enter in lens units.

TPR:  None  
 All Select this if all surfaces are matched to testplates. Other tolerances will be looser.  
 Surfaces  List surfaces matched to testplates.

Adjustments and focusing:

<input type="checkbox"/> Focus at this field point.	<input type="text" value="0.0"/>	If the lens has a paraxial focus solve, this is disabled.
<input type="checkbox"/> Adjust with this thickness:	<input type="text"/>	This adjusts a TH or airspace, with no reverse.
<input type="checkbox"/> Adjust with this decenter.	<input type="text"/>	This adjusts the YDC of a single element.

Quality descriptor; choose one

<input type="radio"/> DEGRADE	<input checked="" type="radio"/> SPOT	<input type="text" value="0.2"/>	Enter the fractional degradation in the spot variance.
	<input checked="" type="radio"/> WAVE	<input type="text" value="0.2"/>	Enter the fractional degradation in the wavefront variance.
	<input type="radio"/> STREHL	<input type="text" value="0.2"/>	Enter the fractional degradation in the Strehl ratio.
	<input type="radio"/> MTF	<input type="text" value="20"/> <input type="text" value="0.20"/>	Enter the frequency and fractional degradation in the MTF.
<input checked="" type="radio"/> TOLERANCE	<input type="radio"/> SPOT	<input type="text" value="0.05"/>	Enter the value of the maximum spot variance.
	<input checked="" type="radio"/> WAVE	<input type="text" value="0.05"/>	Enter the value of the maximum wavefront variance.
	<input type="radio"/> STREHL	<input type="text" value="0.7"/>	Enter the value of the minimum Strehl ratio.
	<input type="radio"/> MTF	<input type="text" value="20"/> <input type="text" value="0.4"/>	Enter the frequency and value of the minimum MTF.

GO EVALUATE Help Cancel  Prepare MC Check this if you want to use the Monte-Carlo program.

When the calculations are finished, look up a little from the bottom line and you will see

SUMMARY OF OPTICAL PERFORMANCE		ANTICIPATED STATISTICS OF QUALITY DESCRIPTOR			
REL. Y-HEIGHT	REL. X-HEIGHT	MEAN VALUE	MULTIPLE DEV	EXPECTED ZOOM	
(HBAR)	(GBAR)				
0.000	0.000	0.03472	0.01563	0.05035	1
1.000	0.000	0.03940	0.00854	0.04794	1
0.500	0.000	0.03520	0.01482	0.05002	1

This says that the on-axis image will get a variance of 0.05, as specified, which is a rather large value. The edge of the field went almost to that value, but for this lens we don't care much about it. What does the budget look like? Scroll the display up a bit more until you come to the budget results:

BUDGET TOLERANCE ANALYSIS					-----B-----	
EL. SURF	RADIUS	RADIUS TOLERANCE	THICKNESS	THICKNESS TOL		
		(RADIUS)	(FRINGES)			
1 1	-167.68076	0.83952	4.82574	0.58188	0.00500	
1 2	-7.06479	0.00091	2.95710	0.36076	0.00157	
2 3	-6.55387	7.70586E-04	2.72673	0.26355	0.00487	
2 4	5.31383	2.93873E-04	1.62247	0.03937	4.25845E-04	
3 5	5.40837	2.91628E-04	1.57357	0.53301	0.00496	
3 6	-19.41777	0.01032	4.32489	39.42904	0.00000	
7	-11.19311	0.00000	0.00000	0.00000	0.00000	

ELE SURF	GLASS NAME	BASE INDEX	INDEX TOL	V-NUMBER	V-NUMBER TOL
1 1	N-BAK2	1.53996d	4.28482E-04	59.70771d	0.15534
2 3	N-KZFS4	1.61336d	1.68964E-04	44.49298d	0.05359
3 5	N-BAF10	1.67003d	1.92822E-04	47.11137d	0.06830

Note: The symbol "d" indicates that the quantity is estimated at 0.58756  $\mu\text{m}$ .  
The symbol "F" indicates that the quantity is taken at the primary color.

ELE SURF	WEDGE TOLERANCE	IRREG. TOL	ROLLED EDGE TOL
	(ARC MIN)	(FRINGES)	(FRINGES)
1 1	0.00000	0.37554	0.23097
1 2	0.44053	0.37277	0.22647
2 3	0.00000	0.34602	0.20629
2 4	0.23321	0.34291	0.20100
3 5	0.00000	0.32721	0.19092
3 6	0.51677	0.33277	0.19873
7	16.69273	0.00000	0.00000

ELE SURF	ELEMENT TILT TOLERANCE	Y-DECENT TOL	X-DECENT TOL
	(ARC MIN)	(TIR)	
1 1	0.53402	0.00062	0.00066
1 2	0.00000	0.00000	0.00000
2 3	0.30597	0.00035	0.00024
2 4	0.00000	0.00000	0.00000
3 5	0.24585	0.00028	0.00027
3 6	0.00000	0.00000	0.00000
7	0.00000	0.00000	0.00000

This is scary. The lens has a 0.0016 airspace tolerance between elements 1 and 2, and 0.0004 between 2 and 3. The V-number tolerance is 0.054 on the center element, and you need to hold centration of 0.00024 on that element. *Nobody* can make this lens by just following a budget.

We have to loosen these tolerances. How? Well, one reason tolerances can be tight is because the aberrations of individual elements are large. While 3<sup>rd</sup>-order aberrations are no longer as useful for the lens designer as they were a generation ago, here is a case where they actually make a difference – but we will not control them directly. Type the command **THIRD SENS**.

```
SYNOPTSYS AI>THIRD SENS
```

```
ID F10 APO
```

```
NORMALIZED 3RD-ORDER ANALYSIS OF TOLERANCE SENSITIVITY
```

```
SS OF SA3 BY SURFACE (SAT) =          8.363047
SS OF CO3 BY SURFACE (COT) =          0.018283
SS OF CO3/YDC BY SURFACE (ACD) =       0.132904
SS OF CO3/TILT BY SURFACE (ACT) =      4.158202
SS OF CO3/YDC BY ELEMENT (ECD) =       0.038108
SS OF CO3/TILT BY ELEMENT (ECT) =      1.184945
SS OF SA3 BY ELEMENT (ESA) =           0.042947
SS OF CO3 BY ELEMENT (ECO) =           0.000094
```

This listing shows the sum of the squares of the individual surface contributions to various aberrations. The idea is that if those are large, even if they are compensated by other surface contributions, the system becomes sensitive to small errors since then the cancellation will not be as good. The value of SAT, the spherical aberration contributions, is 8.363. Let us modify the merit function to bring that sum down. Here is the new MACro:

```
PANT
VLIST RAD 1 2 3 4 5 7
VLIST TH 2 4
END
AANT
AEC
ACC
M 4 1 A SAT
GSO 0 1 5 M 0 0
GNO 0 .2 4 M .75 0
GNO 0 .1 4 M 1.0 0
END
SNAP
SYNO 30
```

Here we ask for a value of 4 for the quantity SAT and also ask for a finer grid of rays. After running this, the lens is slightly changed, and SAT now has a value of 4, as requested. (L9L1.RLE)

Now we run BTOL again, changing the wavefront variance tolerance to 0.1, and specifying the adjustment of thickness 6. (The first BTOL run utilized the paraxial thickness solve on 6, but sometimes the tolerances are looser if you let the program depart slightly. The adjustment will take care of that. The **NOF** directive removes all paraxial solves.) We also specify that the index and Abbe number of the three glasses are exact, which removes them from the budget. In systems as fussy as this, one always requests melt data from the glass vendor, which give the measured index, and then one tweaks up the design with those values. So errors in those values do not have to be part of the budget anymore.

```
CHG
NOF
END
BTOL 2
```

```

EXACT INDEX 1 3 5
EXACT VNO 1 3 5

TPR ALL
TOL WAVE 0.1
ADJUST 6 TH 100 100

PREPARE MC

GO
STORE 4

```

We run this, and the tolerances are somewhat looser.

BUDGET TOLERANCE ANALYSIS

EL. SURF		RADIUS	RADIUS TOLERANCE (RADIUS)	TOLERANCE (FRINGES)	THICKNESS	THICKNESS TOL
1	1	-59.38005	0.10772	4.93291	0.58188	0.00500
1	2	-6.51230	0.00118	4.49176	0.23997	0.00305
2	3	-6.10170	0.00105	4.39207	0.26355	0.00498
2	4	6.63058	0.00107	3.91104	0.03937	0.00148
3	5	6.66960	0.00105	3.81273	0.53301	0.00498
3	6	-16.08586	0.00781	4.90457	39.98704	0.00000
	7	-13.17213	0.00000	0.00000	0.00000	0.00000

ELE SURF	GLASS NAME	BASE INDEX	INDEX TOL	V-NUMBER	V-NUMBER TOL

Note: The symbol "d" indicates that the quantity is estimated at 0.58756  $\mu\text{m}$ .  
The symbol "F" indicates that the quantity is taken at the primary color.

ELE SURF		WEDGE TOLERANCE (ARC MIN)	TOLERANCE (TIR)	IRREG. TOL (FRINGES)	ROLLED EDGE TOL (FRINGES)
1	1	0.00000	0.00000	0.99505	0.26670
1	2	0.72714	0.00085	0.98343	0.26160
2	3	0.00000	0.00000	0.90848	0.24078
2	4	0.50988	0.00059	0.89873	0.23704
3	5	0.00000	0.00000	0.85303	0.22519
3	6	0.85761	0.00100	0.87086	0.23246
	7	23.61909	0.00480	0.00000	0.00000

ELE SURF		ELEMENT TILT TOLERANCE (ARC MIN)	TOLERANCE (TIR)	Y-DECENT TOL	X-DECENT TOL
1	1	0.86414	0.00101	0.00104	0.00000
1	2	0.00000	0.00000	0.00000	0.00000
2	3	0.99650	0.00114	0.00050	0.00000
2	4	0.00000	0.00000	0.00000	0.00000
3	5	0.57610	0.00067	0.00065	0.00000
3	6	0.00000	0.00000	0.00000	0.00000
	7	0.00000	0.00000	0.00000	0.00000

Now the lens will get a variance of 0.1 everywhere in the field, at the two-sigma level. Is that too large? To find out, let us run the Monte-Carlo routine and see what the as-made lenses look like. The starting lens is now in the library at location 4, and we want a worst-case example to be placed into location 5.


Type in the CW:

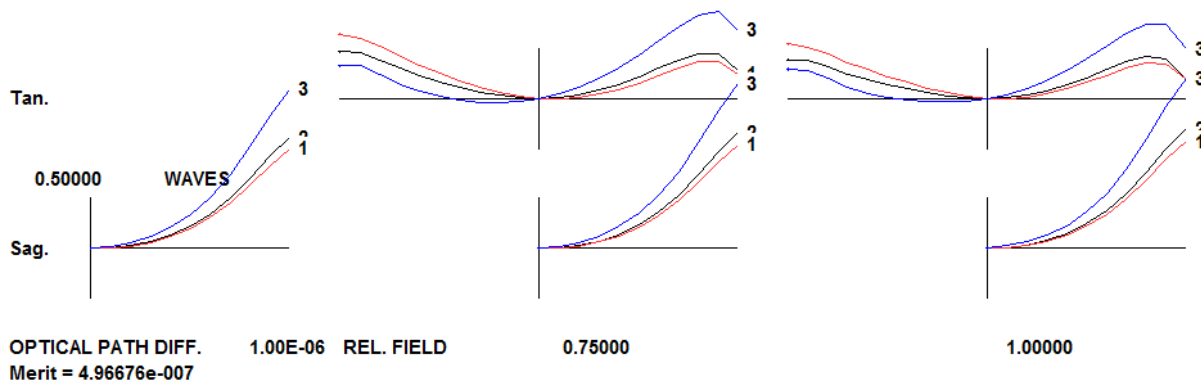
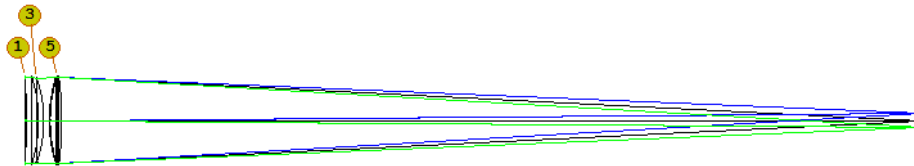
```
MC 50 4 QUIET -1 ALL 5.
```

This will run a batch of 50 lenses, made according to the budget above, compile statistics for the batch, and then save the worst-case example. If you do not know the arguments of the command, just type the letters **MC**, and

look at the tray. The format of the command is displayed for you, and if you need more information, just press the F2 key while the command is in the tray to open the Help File at that topic, or type **HELP MC**. (You have to run BTOL before MC will work, since it uses the budget from BTOL.)

```
MC [nsamples {libloc/MULTI} [QUIET] [qtol {qnum/ALL} qlib]]
```

MC runs its 50 cases and prints some statistics. You can look at a histogram of the results by typing **MC PLOT** after the run is finished. The on-axis image now has a variance of 0.1 at a two-sigma confidence. But this looks too easy. We need to examine the worst-case example. Switch to ACON 2 (type **ACON 2** or click the button ) and type **GET 5**. This is where MC put that example. Now look at the PAD display.



Here we selected the OPD Fan Plots option for the bottom display, and we see that the lens has way more than a quarter-wave of aberration at the on-axis image. We told you this would not be an easy problem! And this budget is still very tight, with centration tolerances of less than a micron.

Anyone with experience with astronomical optics could have predicted all of this, of course. One can rarely just build to print and expect such lenses to work. We have a great budget that nobody can hold, and a slightly more practical budget that makes a bad lens. What's next?

### Fabrication Adjustment

Clearly we need some fabrication adjustments. In this scenario, one makes an element, measures it, and then reoptimizes the lens again, varying the other elements. Then one makes another element to the new design, measures and adjusts all over again, continuing in this way until everything is made. At assembly one then adjusts centration and possibly tilts to get the best possible image.

One really should read about this topic in order to use it. Type **HELP FAMC**. (FAMC is Fab Adjust MC.) It's actually not too complicated. Here is our MACro:

```
FAMC 50 4 QUIET -1 ALL 5  
PASSES 20
```

```

FAORDER 5 3 1

PHASE 1
PANT
VLIST RAD 1 2 3 4 5 6
VLIST TH 2 4 6
END

AANT
GSO 0 1 5 M 0
GNO 0 1 5 M 1
END
SNAP
EVAL

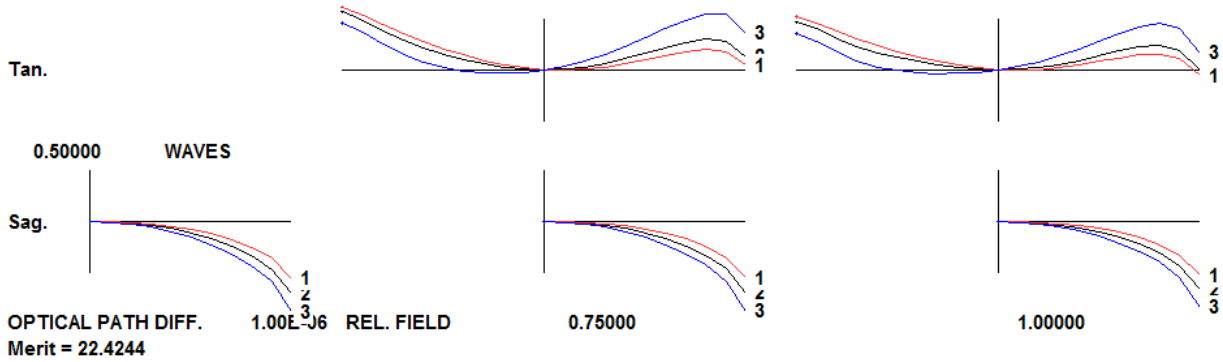
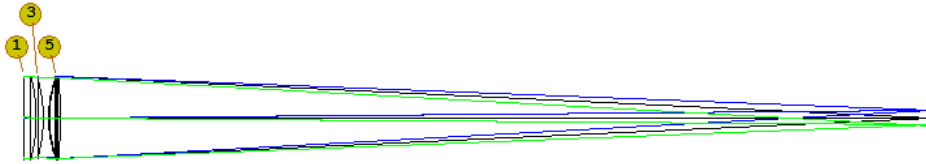
PHASE 2
PANT
VY 3 YDC 2 100 -100
VY 3 XDC 2 100 -100
VY 5 YDC 2 100 -100
VY 5 XDC 2 100 -100
VY 6 TH
END
AANT
GNO 0 1 4 M 0 0 0 F
GNO 0 1 4 M 1 0 0 F
END
SNAP
SYNO 30

PHASE 3

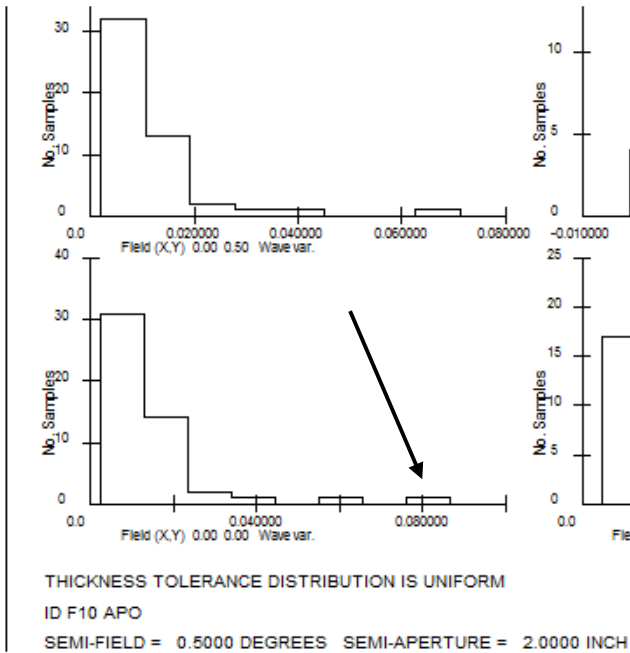
```

Here is what is going on in this MACro:

1. Request FAMC, with arguments the same as for the MC program that was run above.
2. In Phase 1, the program will alter the lenses in the order given in the **FAORDER** line, changing the parameters by a random amount within the BTOL budget. This simulates making the hardest element first, and so on. It will optimize the lens with the variables and merit function listed in the **PHASE 1** portion, as each element is manufactured, deleting those variables that apply to elements that are already finished.
3. When the lenses are all made, it simulates their mounting in the cell according to the tilt and decenter tolerances. Then it optimizes once again, varying the decenter of elements two and three in both X and Y (errors are simulated in both directions, so the compensation must be as well) in accordance with the **PHASE 2** parameters. It also varies thickness 6 once again, since a large centration change produces a small focus shift as well. The merit function also corrects rays over both halves of the pupil (the “**F**” in the GNO lines) because there is no bilateral symmetry anymore once the errors are simulated. We run this MACro and look at the worst case again.



This lens still has wavefront errors of over a quarter wave on axis – but remember this is the worst case. Most of the 50 in this batch are very much better. Type MC PLOT, and look at the portion that describes the on-axis image, in the lower left of the plot:



The worst-case example is the lonely box at the end of the bottom histogram, and it is much worse than the others. There is always a small chance of getting a lemon, after all, and this is it. Nonetheless, there is a high probability that the lens will work just fine if built according to this rather tight budget. (If you run these cases yourself, your statistics will be different, since MC introduces random errors according to the budget.)

Note that the budget itself was not altered, or recalculated, when we decided to use FAMC. What we did was to employ a budget that did not work very well and made it work much better. As a fringe benefit, we don't have

to worry about the tight centration errors anymore – which are expensive to hold – since the elements are to be adjusted at assembly anyway. So things have gotten much easier.

But there is a price to pay: you have to get melt data when the glass is delivered, tweak up the design with those data, the shop must make the elements in the order given, measure them carefully, and then send those data back to the designer, who will reoptimize everything at each step. And provision must be made for adjusting the centration of elements two and three on the test bench, and then locking everything down once the image is tuned up. But that's what precision optics is all about.

And about those adjustments: It's easier to adjust the centration of only one element, not two as in this example. What happens if you delete the adjustments on, say surface 3 and redo the whole procedure? If it works, the assembly technician will thank you. Try it and find out!



