During the design of any optical system destined to be manufactured, it is critical to define a fabrication and assembly budget. This budget must consider any potential compensation that will be used during the manufacturing process to mitigate the performance degradation introduced by fabrication variations. It is important to specify the best set of tolerances and compensators, as these will significantly impact the manufacturing costs. The complex process of defining system tolerances and compensators is often simply called, tolerancing.

Some minimum tolerances are dictated by the manufacturing process. It is important to perform a sensitivity analysis on these tolerances to determine the as-built performance of the

- Utilize the following performance metrics: RMS wavefront error, diffraction MTF, single mode fiber insertion loss or polarization-dependent loss, and Zernike wavefront coefficients
- Perform a sensitivity analysis to the current tolerance set
- Use the Inverse Sensitivity mode to automatically determine each tolerance within user-defined tolerance limits such that it contributes about equally to a specific system performance degradation for the worst case field and zoom position. A subset of tolerances can be frozen so that their values remain fixed
- Use the Interactive Tolerancing mode to make changes to individual tolerance values and instantly see the performance impact
- List tolerance sensitivities and performance predictions for every field and zoom position, with either common or independent compensation across field and zoom position
- Assign specific compensators to specific tolerances by using tolerance and compensator labels
- Force compensation based on field symmetry without requiring additional field pointsensatLang tkS.25 Tm(•)Tj/Span<ActualText<EF

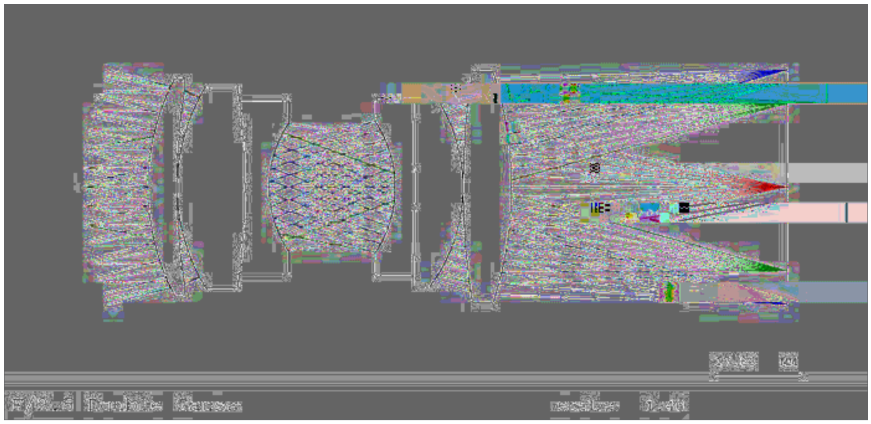

Table 2 shows the tolerance set, based on first running the Wavefront Differential tolerancing method in inverse sensitivity mode.In this mode, TOR tries to set the tolerance values so that each results in identical performance degradation at the worst case field and zoom, after compensation. More sensitive parameters are assigned tighter tolerances, and less sensitive ones, looser tolerances. However, the tolerance values must remain between realistic default or user-specified tolerance limits.

Tolerancing Method	Computation Time for an Intel® Core™ i7 2.7GHz CPU

Using these settings, three tolerance analyses were performed using the described algorithms. Table 3 compares the relative speed of the tolerancing methods, and is based on execution for a single processor with the same number of rays in the ray grid for each analysis.

The Wavefront Differential and Finite Difference tolerancing methods provide information about individual tolerance sensitivities. This information allows the designer to determine the tolerance drivers for the system. As an example, Table 4 shows the change in performance resulting from a perturbation of a symmetrical tolerance that can be compensated with refocus (i.e., the radius of surface 7) and a decenter tolerance that cannot be compensated with refocus, for both methods. The compensation motion is analytically calculated with the Wavefront Differential method and determined by optimization in the Finite Difference method. Both selected tolerances are among the top 5 most significant tolerances for this system (out of 68 total).

Single Tolerance Comparison

(Delta Radius of surface 7, ± 0.020mm)

Wavefront Differential Results

Field	Change in MTF at 15 cycles/mm	
	+ Tolerance	**- Tolerance**
1 (On-axis)	+0.016	-0.018
2 (+10 deg, tan)	+0.024	-0.027
3 (+14 deg, tan)	-0.014	+0.007
4 (-10 deg, rad)	+0.003	-0.005
5 (-14 deg, rad)	-0.015	+0.013

Compensator (refocus) Motion for best axial focus = +0.0673 mm

Finite Difference Results

Field	Change in MTF at 15 cycles/mm	
	+ Tolerance	**- Tolerance**
1 (On-axis)	+0.016	-0.017
2 (+10 deg, tan)	+0.029	-0.033
3 (+14 deg, tan)	-0.016	+0.008
4 (-10 deg, rad)	-0.001	-0.002
5 (-14 deg, rad)	-0.017	+0.015

Compensator (refocus) Motion for best axial focus = +0.0692 mm

Table 5 compares the cumulative probability performance summary for the Wavefront Differential and Monte Carlo methods. It

C E N T E R E D
T O L E R A N C E S

F/3.55 Inverted Telephoto

SUR	RADIUS	RADIUS TOL	FRINGES POW/IRR	THICKNESS	THICKNESS TOL	GLASS	INDEX TOL	V-NO (%)
1	82.52700	0.0417	1.0/ 0.25	3.62536	0.05000	627.586	0.00050	0.50
2	552.75182	2.0127	1.0/ 0.25	0.10000	0.05000			
3	70.28017	0.0412	1.0/ 0.25	4.24208	0.05000	669.523	0.00050	0.50
4	14.03202	0.0036	1.0/ 0.25	20.96646	0.05000			
5	25.18458	0.0262	1.0/ 0.25	4.32311	0.05000	680.339	0.00050	0.50
6	-92.32481	0.4040	1.0/ 0.25	2.91221	0.05000			
7				0.67259	0.05000			
8	53.77045	0.2177	1.0/ 0.25	2.39888	0.05000	646.556	0.00050	0.50
9	-23.74002	0.0446	1.0/ 0.25	0.89584	0.05000			
10	-15.73622	0.0212	1.0/ 0.25	3.03014	0.05000	755.275	0.00050	0.50
11	28.32816	0.0670	1.0/ 0.25	0.78824	0.05000			
12	-67.78803	0.3832	1.0/ 0.25	2.57758	0.05000	692.496	0.00050	0.50
13	-13.97934	0.0133	1.0/ 0.25	37.99347				
14				-0.49333				

D E C E N T E R E D
T O L E R A N C E S

F/3.55 Inverted Telephoto

ELEMENT NO.	FRONT RADIUS	BACK RADIUS	ELEMENT WEDGE TIR	ELEMENT WEDGE ARC MIN	ELEMENT TILT TIR	ELEMENT TILT ARC MIN	EL. DEC/ROLL(R) TIR	EL. DEC/ROLL(R) mm.
1	82.52700	552.75182	0.0130	1.1	0.0040	0.3	0.0107	0.0250
2	70.28017	14.03202	0.0130	1.9	0.0024	0.3	0.0299	0.0250
3	25.18458	-92.32481	0.0130	3.0	0.0015	0.3	0.0198	0.0250
4	53.77045	-23.74002	0.0130	3.9	0.0011	0.3	0.0175	0.0250
5	-15.73622	28.32816	0.0130	4.1	0.0011	0.3	0.0274	0.0250
6	-67.78803	-13.97934	0.0130	4.0	0.0011	0.3	0.0180	0.0250

To illustrate the improvement possible using SAB, we will compare the final as-built performance for an inverted telephoto lens optimized without and with SAB. Figure 4 shows the best optimized result, without using SAB.