Introduction

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

In addition to traditional algorithms for calculating tolerance sensitivity, CODE V also includes the Wavefront Differential tolerancing method that is extremely fast and accurate. The speed of this method enables tolerancing to be performed frequently throughout the design process, not just as an end-of-the-project analysis. The Wavefront Differential tolerancing algorithm can even be invoked during optimization itself, allowing direct optimization for tolerance desensitization, including the impact of realistic compensation.

Two Traditional Approaches to Tolerancing

Finite Difference and Monte Carlo are two common tolerancing algorithms. The Finite Difference approach individually varies each parameter within its tolerance range and analyzes the resulting system performance for each tolerance. These individual results are statistically combined to yield a total system performance prediction. This method predicts performance sensitivity for each tolerance, which helps to identify the individual parameters that are “performance drivers.” To keep unnecessary cost out of a design, it is important to have tight tolerances only on those parameters that cause the greatest performance degradation for small changes. Only the most sensitive components should warrant the extra cost associated with tight tolerances.

The Finite Difference method does not consider how simultaneous changes in multiple parameters interact; its prediction of overall performance is typically optimistic. The effects of multiple tolerance interactions on the system performance are known as cross-terms. The Finite Difference method also suffers from numerical precision issues when a tolerance change causes a small difference between two very large numbers.

The Monte Carlo approach varies all of the fabrication parameters by random amounts within each tolerance range and typically uses optimization to compensate (i.e., refocus) the system. This simulates the performance of a single production unit chosen at random. The analysis of this random unit constitutes a single Monte Carlo trial. This process is repeated many times with different random perturbations. An accurate statistical prediction of the probability of achieving a particular performance level is generated if many trials (typically 100 to 1000) are run. Because all of the parameters are being varied at the same time, the Monte Carlo method accurately accounts for cross-terms. However, no information can be obtained from the Monte Carlo analysis about individual tolerance sensitivities. As such, you can accurately predict a system's as-built performance, but you cannot determine the specific tolerances that are driving the performance, and therefore cannot select the best set of tolerances to minimize cost.

Both the Finite Difference and Monte Carlo tolerancing methods are computationally intensive, which can be slow. With the Finite Difference method, a system’s performance must be analyzed twice for each tolerance parameter (to consider the impact for both the plus and minus perturbation), and additionally this is done for every field and lens configuration (zoom). Thus, more complex systems will take longer for a tolerance analysis than simpler systems. For example, a triplet typically has over 50 tolerances and perhaps 3 fields resulting in over 300 required simulations.

Some optical design software packages utilize polynomial curve-fitting routines during the initial Finite Difference tolerance analysis to decrease the computational time required for subsequent tolerance analyses. In this case, the effect of changing a tolerance value can be quickly analyzed using the polynomial coefficients. However, this approach is useful only if tolerancing is the last step of the design; otherwise, the polynomials will need to be recalculated every time the design changes, adding to the overall time required for both design and tolerancing.

In the Monte Carlo approach, the system must be analyzed for every trial. System complexity is less of an issue, but many trials are required to achieve an accurate performance prediction. Analyzing a complex system to a reasonable level of accuracy using either the Finite Difference or the Monte Carlo method may require many hours (or even days) of analysis time.

Wavefront Differential Tolerancing

The Wavefront Differential algorithm is very fast and combines the best attributes of both the Finite Difference and Monte Carlo methods. The Wavefront Differential method provides information about individual tolerance sensitivities (like the Finite Difference method) and a more accurate performance prediction, including the effect of cross-terms (like the Monte Carlo method).

The speed of the Wavefront Differential approach is derived from the design of the algorithm. All of the information needed for the initial and all subsequent tolerance analyses is obtained from the nominal system by tracing a single group of rays. This single-pass approach is extremely fast, even when compared to curve-fitting routines.

The algorithmic foundation for the Wavefront Differential analysis method is based on the work of Hopkins & Tiziani [1], King [2], and Matthew Rimmer [3], [4]. The advanced algorithms developed by Mr. Rimmer used in CODE V’s tolerancing feature (TOR) were first implemented in CODE V in 1978, decades prior to any other commercial implementation. The CODE V Wavefront Differential algorithms have been continually enhanced since they were first introduced, and include many proprietary features and advanced capabilities not found in any other software package.

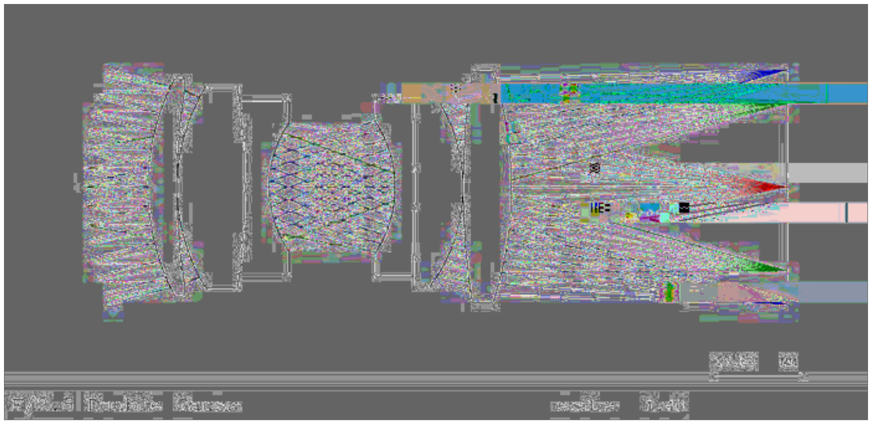
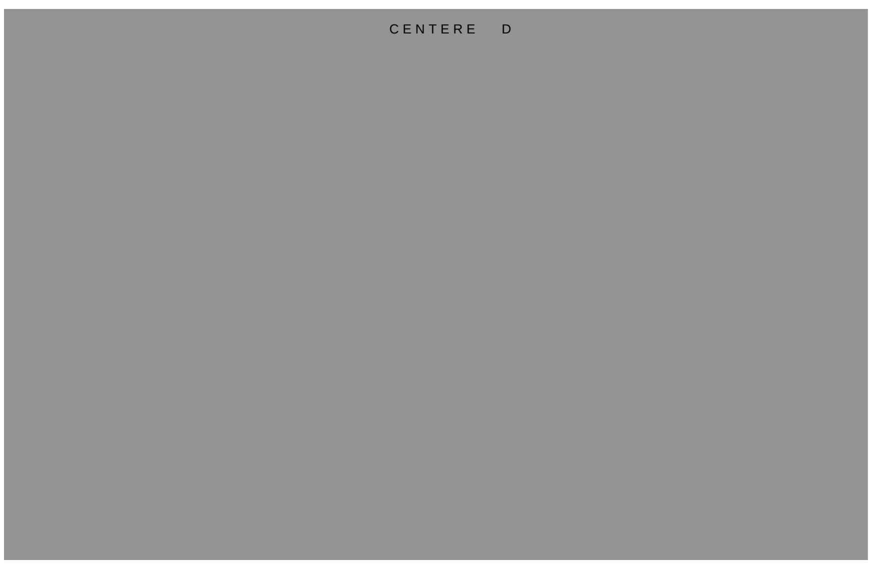


Figure 1: F/2.5 Double Gauss Lens

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
	2 seconds

Table 3: Speed comparison of tolerancing methods

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, ± 0.02 0mm)

Wavefront Differential Results

Field	Change in MTF at 15 cycles/mm	
	+ Tolerance	- Tolerance
1 (On - axis)	+0.01 6	- 0.01 8
2 (+10 deg , tan)	+0.0 24	- 0.0 27
3 (+14 deg , tan)	- 0.0 14	+0.0 07
4 (- 10 deg , rad)	+0.0 03	- 0.0 05
5 (- 14 deg , rad)	- 0.015	+0.0 13
Compensator (refocus) Motion	for best 0. 9T 5.9243 0 4 418.	

Notice that the difference in the predicted MTF degradation across field for the two methods is within 0.006 MTF for the compensated tolerance. This small difference is not unexpected, since the compensation solution will be slightly different between the two approaches. The predicted performance degradation matches almost exactly (within 0.001 MTF) for the uncompensated, decenter tolerance. The predicted refocus for the radius tolerance is within 2 µM for the two methods. Also, the predicted mean plus 1Ă bn l odmr`snq l nshnm q`mfd enq `kk snkdq`mbdr bnqqdk`sdr udqx vdkk enq sgd svn ldsgncr 'vhsghm 6 ²L(- Sgd oqdchbsdc odqenql`mbd degradation due to any of the individual tolerances is similar to these representative examples.

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	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

Table 6: “Select [5] Tolerance set

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.

We will apply the “Select” class of tolerances which are achievable by a large number of optical fabrication vendors5 and also include a defocus compensator. The tolerance values are shown in Table 6.

The SAB optimization results are sensitive to the weight chosen for the SAB component. In general, the use of SAB with any weight will improve the as-built performance compared to the pre-SAB result; however, to find the weight that provides the l `wh l t l h l oqnud l dms+ `m hsdq`shud `ooqn`bg vnqjr adrs- Sgd qdrtksr rgnvm hm S`akd 6 enq sgd ?l d`m * 1Ă? `r,atkks QLR v`udeqnms performance are based on using a macro to perform several optimizations (each using a different SAB component weight for all fields) and then to select the best result. The nominal (design) performance for the post-SAB result is typically degraded compared to the pre-SAB nominal performance; however, in this case, the nominal performance is essentially the same (on average) for both designs. The best solution reduced the as-built RMS wavefront error by 18% compared to optimizing without SAB.

RMS Wavefront Error (waves @550 nm)

Pre - SAB Result Post - SAB Result

RELATIVE DESIGNsLATIVE DESIGNsLATIVE DESIGNsLATIVE 2L4 9>18.7 <0036004A004700030054>9.1 <0047005507y<7Tw -706GNs

The final lens form, shown in Figure 5, is only slightly different than the system optimized without SAB (Figure 4), but much less sensitive to same set of manufacturing and assembly errors!

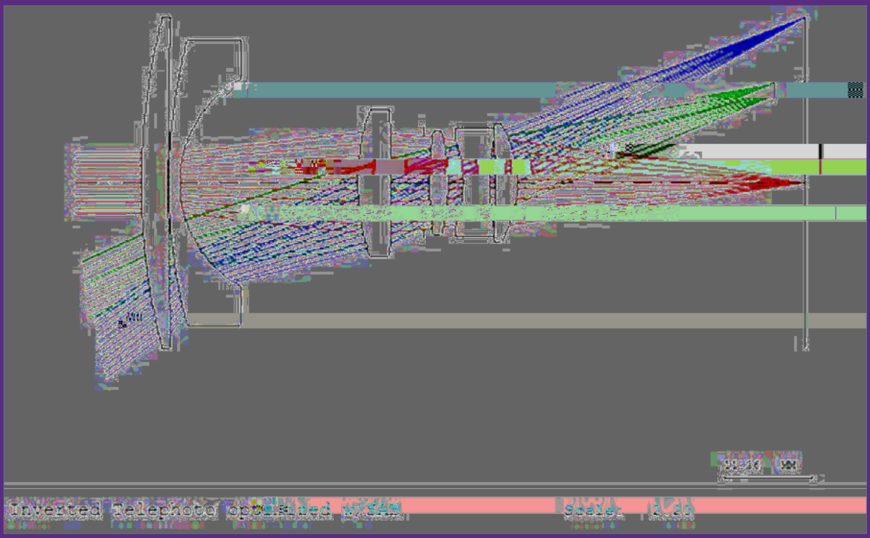


Figure 5: F/3.5 inverted telephoto after tolerance desensitization optimization

This paper demonstrates how CODE V's advanced tolerancing features provide outstanding speed, accuracy, and flexibility, which ultimately help to maintain optical system performance while reducing costs during product development and throughout the product life cycle.

[1] H.H. Hopkins and H.J. Tiziani. "A theoretical and experimental study of lens centring errors and their influence on optical image quality." Brit. J. Appl. Phys. Vol. 17. 33 (1966).

[2] W. B. King. "Use of the Modulation-Transfer Function (MTF) as an Aberration-Balancing Merit Function in Automatic Lens Design." JOSA. Vol 59. 1155 (1969).

[3] M. Rimmer. "Analysis of Perturbed Lens Systems." Appl. Opt., Vol 9, 533 (1970).

[4] M. Rimmer. "A Tolerancing Procedure Based on Modulation Transfer Function (MTF)." SPIE. Vol. 147, 66 (1978).

[5] K. Thompson and L. Hoyle. "Key to Cost Effective Optical Systems: Maximize the Number of Qualified Fabricators." OSA Vol. 22 (IODC Proceedings), 208 (1994)