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Realistic Optical System Tolerancing: A Practical Example

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Introduction

Ruda-Cardinal's optical designers use experience, research, and careful iteration to take a set of desired specifications and encompass them within an elegant lens design. While such a design may nominally meet or even exceed those specifications, the lens is only useful if each of its component elements can be fabricated and assembled with enough fidelity to the nominal design to maintain performance. Tolerancing is the practice of determining how closely the as-built lens must match the nominal design in order to meet performance specifications. The tolerancing process is just as critical as the design process. As design methods advance and optical manufacturing technology matures, tolerancing must logically follow suit. While lens design software has long had the capability to assist with the task of tolerancing, complex and/or critical optical systems require the user to push beyond the software's basic functionality. At Ruda-Cardinal, Inc. (RCI) we seek to represent tolerancing of optical systems as close to reality as possible by utilizing the most advanced tolerancing tools both built into lens design software and of our own creation. We are constantly working to maintain a feedback loop of experience and manufacturing insight into our future tolerancing endeavors. This paper touches on the basics of our approach to tolerancing using a sample optical system and discussing model setup, sensitivity and Monte Carlo analysis, and results interpretation.

Sample Lens

Our sample lens is an F/3 double Gauss lens with a 100 mm effective focal length, a 486-656 nm wavelength range, and a ±14° field of view as shown in Figure 1. The lens consists of two singlets and two bonded doublets.

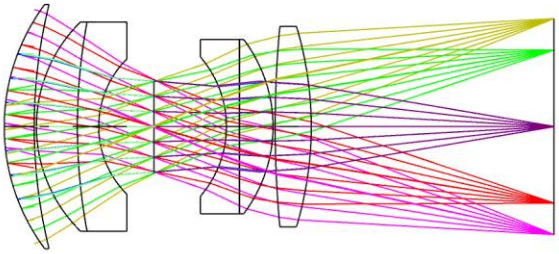

Figure 1: 2D layout of the sample double Gauss lens. F/3, EFL = 100 mm, 486-656 nm, ±14° FOV.

The important performance metrics for evaluating this sample lens are the image space modulation transfer function (MTF) at 40 lp/mm, the maximum distortion at full field, and the root-mean-square (RMS) spot radius. RMS spot radius and MTF are largely synonymous for this non-diffraction-limited lens, however observing both provides a good example when results interpretation is discussed later.

Tolerancing Model Setup

Most optical design software includes the capability to apply tolerancing in the forms of sensitivity analyses and Monte Carlo simulations. For the sake of this example, we used Zemax OpticStudio to perform tolerancing actions. For simple cases, OpticStudio can provide the user with a semi-automated tolerance model in which a set of default tolerance operands and their perturbation ranges are applied to surfaces and elements within the model. These include basic operands, such as TETX/TETY, which apply a tilt perturbation through coordinate transformations without user defined coordinate breaks. The downside to automated model is that the user relinquishes control of fine details, such as the location about which the tilt is applied.

For more sophisticated designs, the optical designer often has preconceived notions of how individual elements or element groups will be mounted and secured and, therefore, manual setup of the tolerancing model allows for a closer match between the model and reality. This detailed manual setup requires the liberal use of coordinate breaks, dummy surfaces, and careful control of coordinate transformation order, which can quickly transform the nominal design lens data into a significantly more complicated and convoluted file. In the case of our sample lens, the nominal design only has 12 surfaces in the Zemax lens data editor and the full manual tolerance model has 46 surfaces. As an example, the first doublet in the sample lens (Element 2D with sub-elements 2D_A and 2D_B) is represented by the surface data shown in Figure 2. Coordinate breaks and dummy surfaces are used to apply element tilt and decenter, sub-element wedge, and sub-element roll of 2D_A. We apply the perturbations for these actions using manual variants of the tolerance operands such as TUTX and TUTY which apply perturbations to their respective tilt parameters in a user-defined coordinate break.

8		Standard ▾	To 2D_B_S2	Infinity		14.31000		
9		Coordinate Break ▾	2D Tilt/Dec			-4.90000		-
10		Coordinate Break ▾	2D_B Wedge			-1.00000E-02		-
11		Standard ▾	to 2S_A_S2 CofC	Infinity		130.30000		
12		Coordinate Break ▾	2D_A Roll			-130.30000		-
13		Standard ▾	Ret to 2D_A_S1	Infinity		-9.40000		
14		Coordinate Break ▾	2D_A Wedge			0.00000		-
15	(aper)	Standard ▾	2D_A_S1	33.49000		0.00000		S-FPM2
16		Coordinate Break ▾	2D_A Wedge Ret			9.40000	P	-
17	(aper)	Standard ▾	2D_A_S2	130.30000		130.30000	T	NOA61
18		Coordinate Break ▾	2D_A Roll Ret			-130.30000	T	-
19		Coordinate Break ▾	Glue Gap			1.00000E-02	P	-
20	(aper)	Standard ▾	2D_B_S1	130.30000		0.00000		S-NBH8
21		Coordinate Break ▾	2D_B Wedge Ret			4.90000	P	-
22		Standard ▾	2D_B_S2	21.84000		0.00000		
23		Coordinate Break ▾	2D Tilt/Dec Ret			12.71455		-

Figure 2: The Zemax OpticStudio lens data editor representation of the fully manual optical tolerance model for the first doublet element in the sample double Gauss lens.

Aside from the mechanical positioning tolerances (tilt, decenter, wedge, and roll), Zemax applies the remaining tolerances on its own from the tolerance data editor. Index, abbe number, and surface power are all relatively straightforward in most cases. Thickness tolerance – on both glass thicknesses and air spaces – requires some consideration of how lenses might be held to apply realistic relationships between a perturbed thickness and any dependent thicknesses. Finally, surface details like irregularity, or other form error, require especially careful consideration that we will not discuss in detail here.

Deciding where to start can be challenging when it comes to tolerance ranges. For element level tolerances, fabrication shops like Optimax and Lacroix often provide generic tolerance charts which categorize tolerances into tiers of cost or difficulty. For positioning tolerances, starting values are more abstract. The values used here are mostly based on experience in iteration between an optical designer and an opto-mechanical engineer where an achievable and cost-effective solution is converged upon.

Tolerance Run Parameters

Once the tolerance model and the associated list of tolerance operands are defined in the lens design software, the user must still set up the simulation parameters. As previously mentioned, lens design software generally has the functionality to run both sensitivity analysis and Monte Carlo simulation. We can approach sensitivity analysis in two primary ways: direct or inverse.

A merit function or a basic default criterion, such as spot size or wavefront error, guides inverse sensitivity analysis. The user sets an acceptable threshold for that criteria and the analysis reports the range of each tolerance such that the system performance remains within the threshold. This method can be helpful if the user has little knowledge of where to start with the range on each tolerance or if we can effectively evaluate the system performance by a single basic parameter, like spot size. Unfortunately, for a complex system, having many complicated performance metrics that need to be balanced, inverse sensitivity becomes less helpful. If we use a user merit function as the criteria, a seemingly arbitrary threshold must be set for the merit function value which may allow too much or too little perturbation of each tolerance.

Direct sensitivity analysis is more straightforward in its operation as it simply applies the maximum and minimum user defined perturbation for each tolerance and evaluates and reports performance. At surface level this is not much more useful than inverse sensitivity analysis if the reported performance value is still a default criterion or the merit function value because the nuance of balancing multiple performance metrics is lost. This is where the use of tolerance scripts becomes paramount.

Tolerance scripts serve as a custom set of criteria that allows for sensitivity to be evaluated for multiple parameters simultaneously while keeping the results decoupled. Scripts also allow the user to control physical compensators more finely by toggling them on and off for multiple stages of optimization. Using direct sensitivity analysis in tandem with a tolerance script allows for targeted tuning of the tolerance ranges to meet performance while not being overly tight.

Finally, tolerance runs can also include a Monte Carlo simulation, in which the full set of tolerances are applied simultaneously at random values according to a chosen distribution and the performance is evaluated. We can use the data generated from a Monte Carlo simulation to predict the yield or success rate of an actual build of the system to provide confidence.

Sample System Tolerance Report

Using the philosophy outlined in the previous two sections, we performed a tolerance analysis for the sample double Gauss lens described above. The model included element tilts, decenters, wedges, and rolls all defined in manual fashion to represent the lens assembly procedure most accurately. We also included other standard tolerances such as index, abbe number, surface power, surface irregularity, and thicknesses. The tolerance analysis includes three iterations where the tolerances were modified and, ultimately, we added a decenter compensator to achieve a desirable yield for an MTF spec of 40% at 40 lp/mm across the field. A back focal distance compensator is active in all three runs. As previously mentioned, we also monitored distortion at max field and RMS spot radius, but they were not considered as a performance requirement for this example. The sample report below is mostly graphical in nature, using plots generated by a proprietary RCI visualization and analysis software.

Figure 3 exhibits the sensitivity analysis for the MTF performance at 40 lp/mm from the first tolerance run. The plot shows that the worst offending tolerances in terms of MTF impact are the decenter of the 1S, 2D, and 3D lenses followed by the roll of the front element in 2D. This graphic provides clear guidance that, if possible, these tolerances should be tightened to improve as-built performance, if necessary.

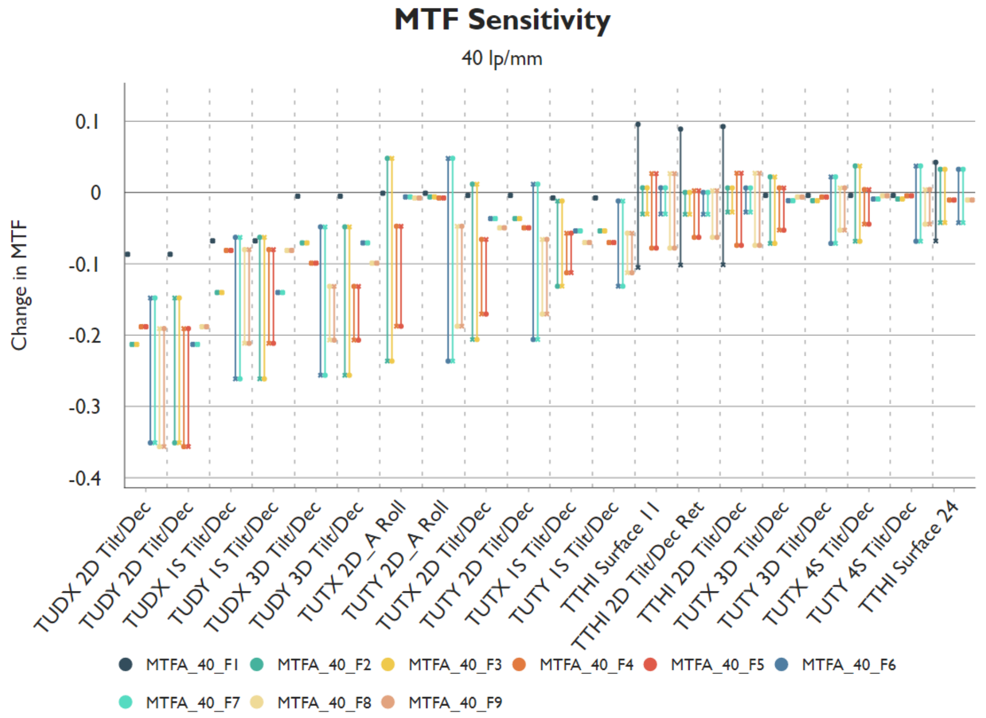

Figure 3: Sensitivity plot for the first iteration of tolerance analysis. The x-axis shows individual tolerances, the y-axis shows changes to the fractional MTF from nominal performance, and the colored bars represent the MTF as evaluated at each specific field in the model. The 20 worst offending tolerances are shown in decreasing order from left to right. The two connected points for each field and tolerance operand represent the impact of the max and min perturbations to that tolerance.

The Monte Carlo simulation results for the same tolerance run for MTF performance at 40 lp/mm are shown in Figure 4. We ran 100 trials and plotted the worst performing field for each trial. A specification line for the desired 40% MTF makes it quite clear that the majority of trials do not meet the spec. As a result, we targeted the worst offenders in the sensitivity plot above for tightening and initiated the run.

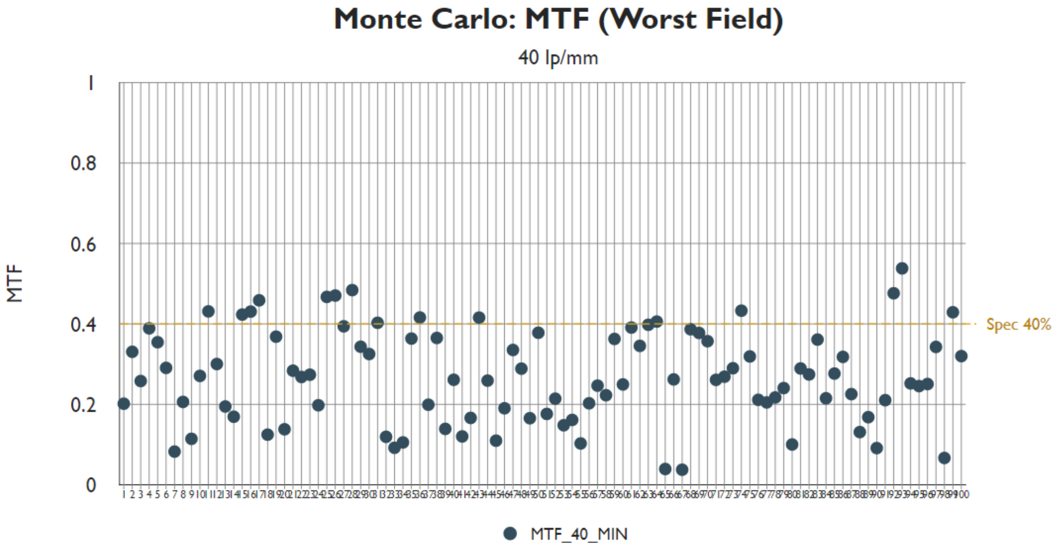

Figure 4: First run Monte Carlo trial results for MTF performance at 40 lp/mm are plotted. We extracted and displayed the worst performing field. Most trials do not show passing MTF across the full field, which indicates a need for tightened tolerances.

We continued the tolerance analysis with tightened decenter tolerances for 1S, 2D, and 3D. The second tolerance run continued to show a low passing rate for MTF across the field with only marginal improvement of yield. The final iteration of tolerancing, the third run, included the addition of a decenter compensator to the 2D element as well as a tightening of the roll tolerance on 2D. We show the updated sensitivity and Monte Carlo plots for the final tolerance run in Figures 5 and 6. The sensitivity results shifted through the iterations due to tightening of decenter and roll tolerances as well as the addition of the decenter compensator for 2D in the final iteration.

The Monte Carlo simulations now show that, for most systems, the MTF is better than the 40% spec at 40 lp/mm across the field. From the first tolerance run to the final run, the yield is dramatically improved from 15% to 95%. We demonstrated the yield in a yield curve extrapolated from the Monte Carlo data. The yield curves for all three tolerance runs are overlayed in figure 7. There is a clear progression of improved yield from Run 1 to Run 3.

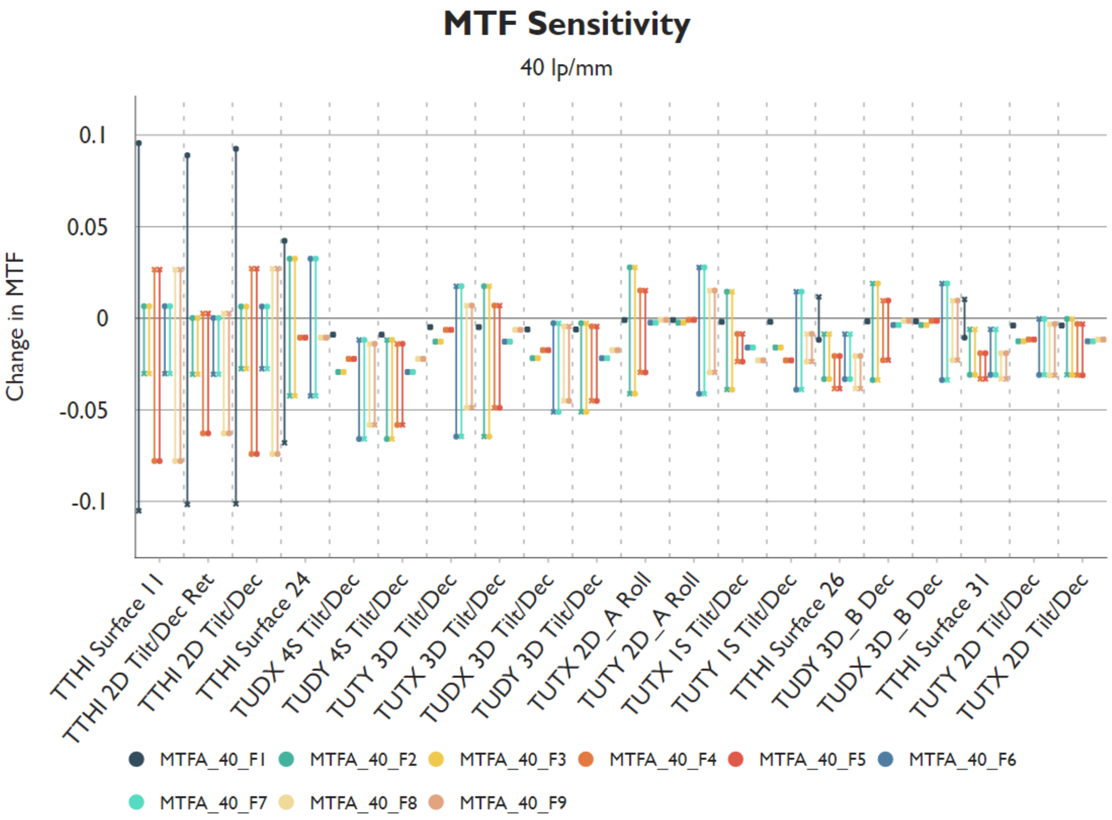

Figure 5: The sensitivity analysis for the third and final tolerance run. The worst offenders changed as decenter and roll tolerances were tightened, and a decenter compensator now influences sensitivity results.

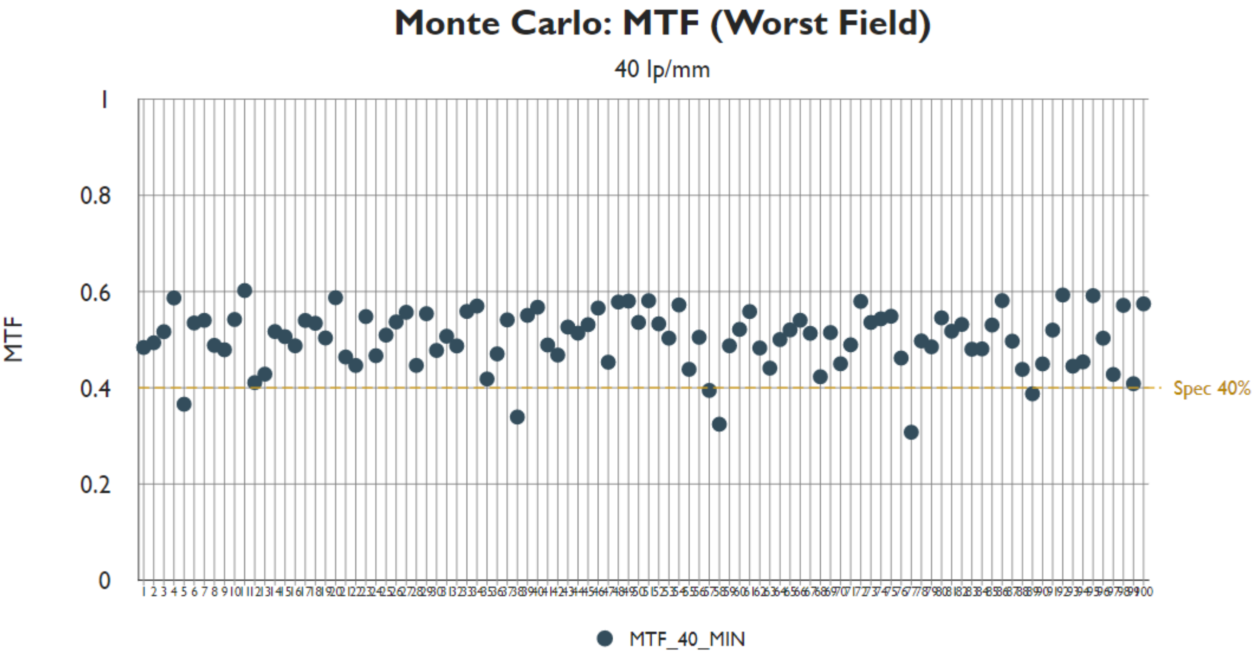

Figure 6: Monte Carlo trial results for the third tolerance run with the worst field extracted from each trial. The passing rate is dramatically improved for the 40% spec at 40 lp/mm.

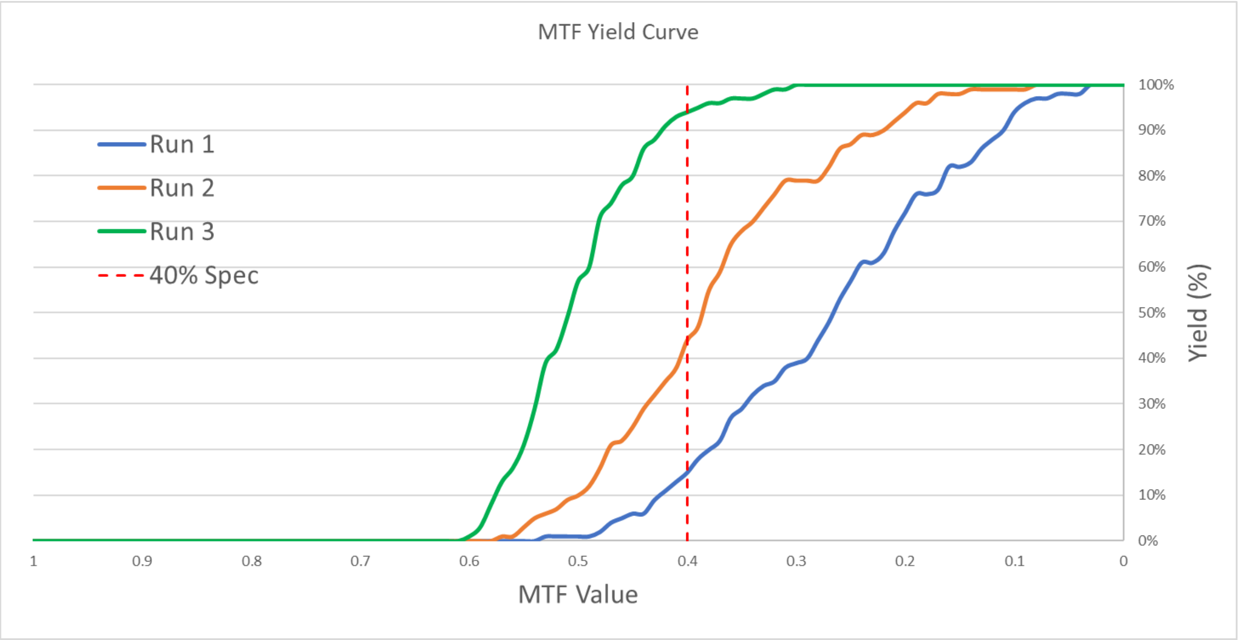

Figure 7: MTF yield curve derived from Monte Carlo simulations for all three tolerance runs. The x-axis shows MTF values and the y-axis shows the cumulative percentage of the 100 Monte Carlo trials meet or exceed the corresponding MTF value. At the 40% spec for MTF at 40 lp/mm, a clear improvement process can be seen from Run 1 to Run 2 to Run 3.

While not observed as specifications, we also reported the distortion percentage at maximum field and the RMS spot radius from the tolerance script and Monte Carlo simulation results, which are shown in Figures 8 and 9. While the lens had significant variation in MTF, the changes to distortion at max field were insignificant. The RMS spot radius could be considered synonymous with MTF to some extent, but it still serves as an inverted case for the Monte Carlo plot where a larger value is undesired as opposed to MTF where the opposite is true.

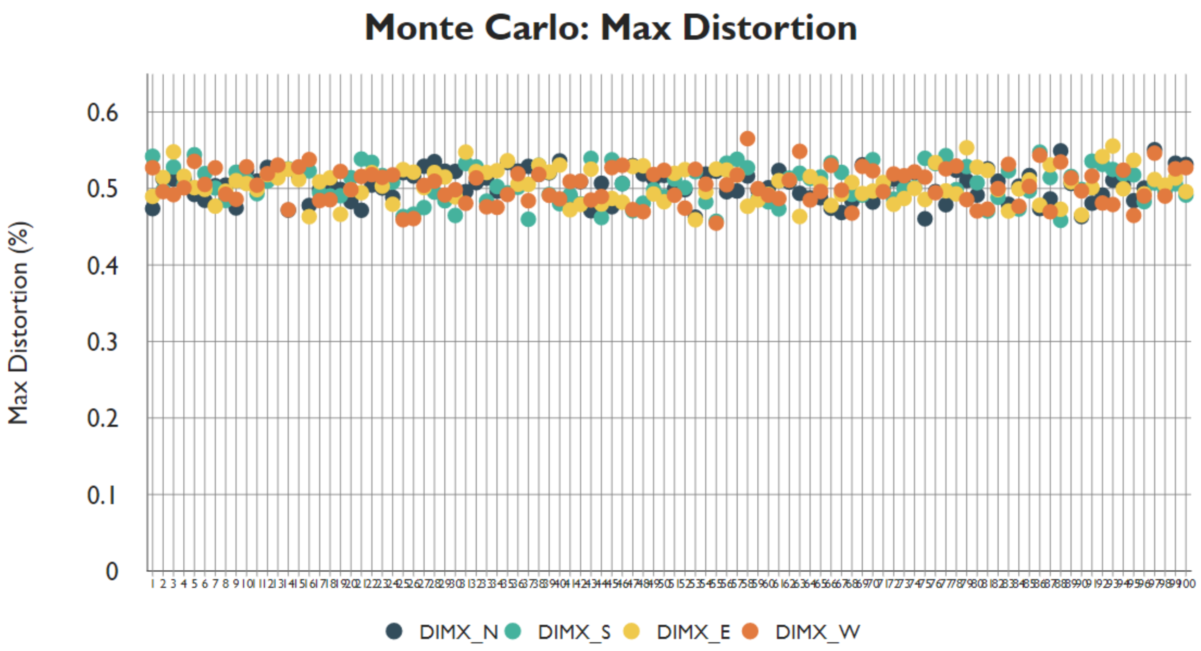

Figure 8: Monte Carlo simulation results for tolerance Run 3 of maximum distortion at maximum field. The colors represent different maximum fields in the X and Y directions. The tight groupings demonstrate acceptable variance in distortion.

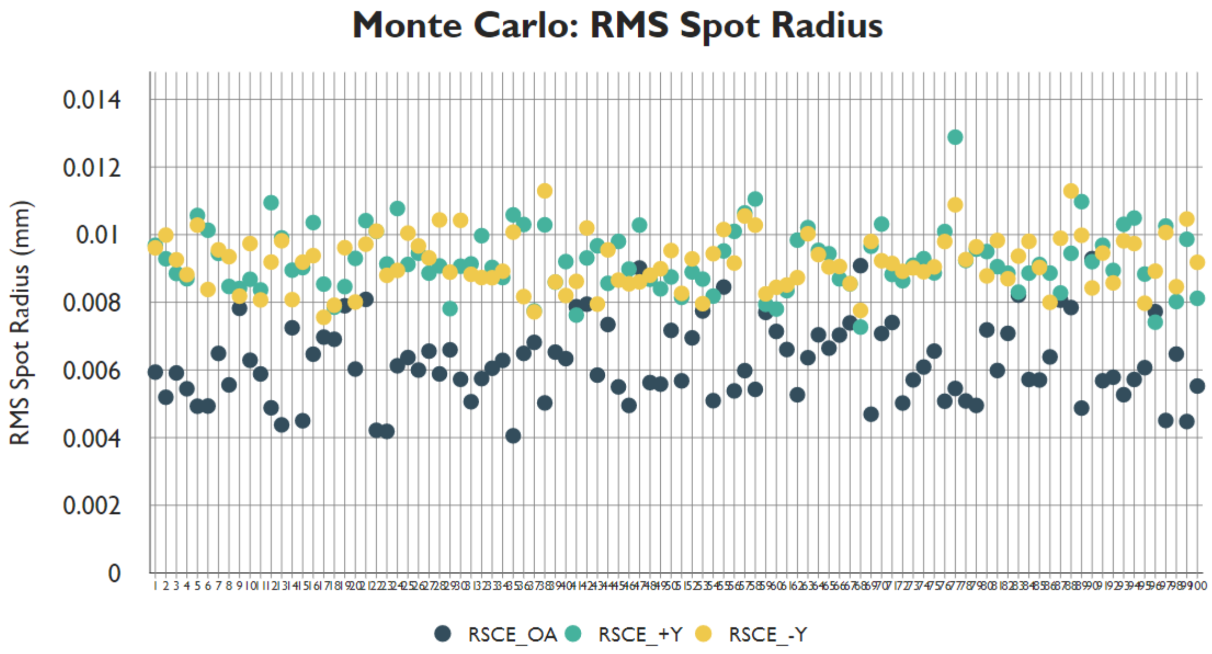

Figure 9: Monte Carlo simulation results for tolerance Run 3 of the RMS spot radius for the on-axis spot and the ±Y maximum fields. This provides an alternative analytical view to MTF and clearly shows the general relationship between the opposing fields whereas the field improves on one side, the opposing side generally suffers.

Finally, the motion of the compensators during each Monte Carlo trial can be reported from the script and reviewed to ensure that such a compensator is realistic. We would supply this data to the opto-mechanical engineers as specification for the hardware to be designed. The Monte Carlo data for the decenter of 2D in x and y is shown in Figure 10.

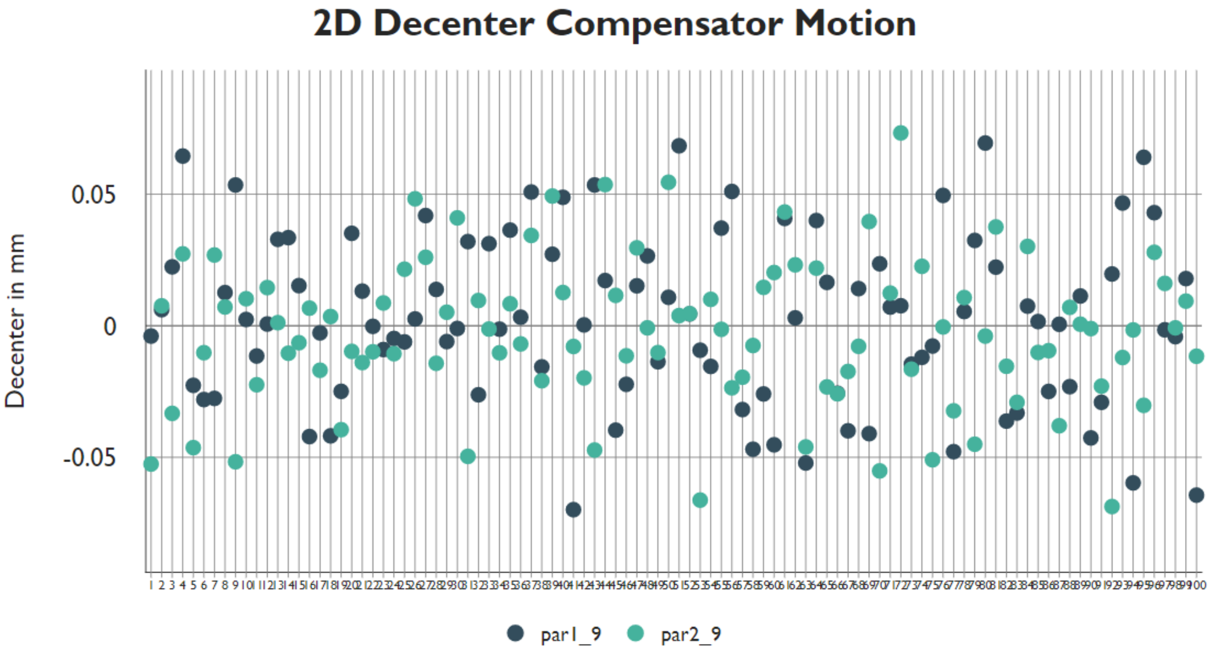

Figure 10: Monte Carlo trial data from run 3 for the decenter compensator motion.

Conclusion:

While tolerancing can often consume more time and effort than the nominal optical design, the importance of that effort is critical. While tolerancing functionality is built into lens design software packages such as Zemax OpticStudio, the construction of a tolerance model presents a high skill ceiling when trying to replicate the reality of the build and alignment process for a complex optical system. The benefits of investing the time into a realistic tolerance model are realized at the opto-mechanical design phase when the engineer allocates a tolerance budget to parts and at the successful completion of a system build.

We showed a sample tolerance study, including three iterative tolerance runs, as an example using a wide field double Gaussian lens. The sample tolerance report demonstrated the iterative decision-making process for tightening tolerances and adding compensators to improve yield. At Ruda-Cardinal we strive to utilize our best ability to create such realistic models and present the resulting tolerance analysis data both internally and externally to allow for informed decision-making and provide ultimate confidence that an as-built optical system will perform as desired.