

Optical Design Tolerancing

A Key to Product Cost Reduction

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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 system. Alternatively, an acceptable performance degradation may drive the tolerances. An inverse sensitivity analysis determines the set of tolerances that achieve a specific performance degradation. Both of these analyses should consider the effects of permissible compensators.

Why Is Tolerancing Important?

The simple answer is cost. A design may be very expensive to manufacture if small variations in the lens parameters result in significant performance loss even after compensation is applied. The ideal optical system design minimizes production costs and meets performance requirements using achievable component and assembly tolerances and well-chosen post-assembly adjustments. Optical design software can help to make this ideal manufactured system a reality, and the tolerancing process should be fast, flexible, and accurate.

Tolerancing With Optical Design Software

Many optical design software packages have the ability to perform a tolerance analysis; however, the algorithms used for tolerancing may differ. Ideally, a tolerancing algorithm provides a combination of speed, accuracy, and insight into which tolerances drive system performance; unfortunately, many optical design packages offer tolerancing algorithms that only provide two of these three.

CODE V is a comprehensive software package offered by Synopsys for the design, analysis, tolerancing, and fabrication support of optical systems. CODE V is used worldwide by organizations to design a wide range of optical systems for a variety of products, including digital camera equipment, medical instruments, aerospace systems, telecommunication components, microlithographic stepper systems, and many more. Many of these companies and users chose CODE V for its advanced algorithms and features related to tolerancing.

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.

With Wavefront Differential Tolerancing, You Can:

- ▶ 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

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 & Tiziani¹, King², 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.

Assumptions Of The Wavefront Differential Method

The accuracy of the Wavefront Differential method is dependent on a few assumptions. Primarily, the ray optical path differences (OPDs) due to tolerance perturbations are assumed to vary linearly with the perturbation. Typically, this assumption is valid if the perturbation is small and results in a slight degradation of the nominal performance, which is what a designer nominally tries to achieve when tolerancing a system.

Also, the Wavefront Differential method is only applicable to performance metrics that can be computed by analyzing the complex field at the exit pupil of the system. Such metrics include wavefront error, diffraction MTF, fiber coupling insertion loss, polarization-dependent insertion loss, and Zernike wavefront coefficients.

Additionally, development of the Wavefront Differential equations requires knowledge of how each tolerance affects the system; CODE V's Wavefront Differential tolerancing option (TOR) will analyze pre-programmed (i.e., built-in) tolerance types, of which there are over 60. Also, new tolerance types can be "synthesized" by combining existing tolerances (e.g., a ball lens diameter tolerance can be constructed from two radii and one thickness tolerance).

Wavefront Differential Tolerancing (continued)

- ▶ Force compensation based on field symmetry without requiring additional field points to be entered
- ▶ Assign tolerances and compensators to a specific configuration of a multi-configuration lens (i.e., a specific zoom position).
- ▶ Override tolerance limits for each supported tolerance type
- ▶ Create a new tolerance by grouping individual tolerances
- ▶ Perform accurate tolerancing of double-pass systems or systems with parametric relationships among the constructional data (such as the front and rear radii and center thickness of a ball lens)
- ▶ Predict changes in distortion (or calibrated distortion) due to tolerances
- ▶ Compensate for image quality while simultaneously correcting line-of-sight errors (i.e., boresight correction) and magnification errors, due to tolerances
- ▶ Define different tolerance probability distributions for different classes of tolerances
- ▶ Identify the best compensator set from among all possible compensators using a singular value decomposition algorithm

Finally, the tabular output for the Wavefront Differential tolerancing assumes that the overall performance probability has a Gaussian form, defined by a mean and sigma. This assumption is typically valid if each tolerance is contributing about the same to the overall performance degradation, which is what TOR's inverse sensitivity analysis tries to achieve. Otherwise, the Gaussian probability assumption tends to be conservative. It is important to understand that the Wavefront Differential method includes cross-terms; wavefront differentials are computed for each tolerance and for every pair of tolerances, so these important factors are included in the overall predicted performance for the system.

| Tolerancing Algorithm | CODE V Command | Supported Performance Metrics | Supported Tolerances | Comments |
|------------------------|------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Wavefront Differential | TOR | <ul style="list-style-type: none"> RMS Wavefront Error Diffraction MTF Fiber Coupling Efficiency Polarization Dependent Loss Zernike Coefficients-based error function | CODE V pre-programmed tolerances (e.g., radius, thickness, wedge, barrel tilt, test plate fit (in fringes), etc.) | <ul style="list-style-type: none"> Very fast Very accurate for tolerances that result in a small degradation in system performance (includes cross-terms) Provides individual tolerance sensitivities and accurate performance prediction Both inverse sensitivity and sensitivity analyses are supported Supports optional distortion analysis, boresight correction, and an SVD compensator algorithm |
| Finite Difference | TOLFDIF (macro) | Any quantity that CODE V can compute | Most CODE V preprogrammed tolerances & macro-based user-defined tolerances | <ul style="list-style-type: none"> Can be slow depending on number of tolerances, fields, zooms, and type of performance metric analyzed Provides accurate individual tolerance sensitivities, particularly for larger tolerances Performance summary is optimistic because cross-terms are not included Method assumes that the performance variation is quadratic with tolerance, which may not be valid for the requested performance metric Sensitivity analysis only |
| Monte Carlo | TOLMONTE (macro) | Any quantity that CODE V can compute | Most CODE V preprogrammed tolerances and macro-based user-defined tolerances | <ul style="list-style-type: none"> Can be slow depending on the number of trials requested and type of performance metric analyzed Provides accurate performance prediction (if many trials are requested) No information about individual tolerance sensitivities Sensitivity analysis only |

Table 1: Feature summary of CODE V's primary tolerancing methods

The fast Wavefront Differential method can be effectively used in concert with other tolerancing methods, for optical engineers who are accustomed to alternative algorithms. Designers often take advantage of the speed of the Wavefront Differential method's inverse sensitivity analysis to quickly determine appropriate tolerances and compensators. Afterward, a single Monte Carlo analysis of the resulting system (consisting of a large number of trials) can provide assurance of the accuracy of the Wavefront Differential performance prediction. After gaining experience with the Wavefront Differential method, most users find that the extra Monte Carlo analysis step is unnecessary.

CODE V fully supports the Finite Difference and Monte Carlo tolerancing methods for systems in which the Wavelength Differential method's assumptions are invalid. Table 1 lists the supported performance metrics and tolerance types for each of the three methods.

The applicability of CODE V's Wavefront Differential tolerancing method to real systems is affirmed by its successful use within Synopsys' Optical Engineering Services Group to define tolerances and analyze as-built performance for over a thousand fabricated designs. Additionally, thousands of systems have been successfully analyzed and fabricated by CODE V customers around the world; Wavefront Differential tolerancing can be a powerful feature in your optical design toolkit.

Example System: F/2.5 Double Gauss Objective

To illustrate these different tolerancing methods, consider an F/2.5, 14° half-FOV Double Gauss lens, as shown in Figure 1. The comparison uses the set of CODE V default tolerances which, for this lens system, is 52 centered tolerances (i.e., thickness, index, power, or irregularity) and 16 decentered tolerances (i.e., wedge, element tilt, or element decenter). The radial and tangential MTF at 15 cycles/mm across the field of view is used as the performance metric for the tolerance analysis. While CODE V's fast Wavefront Differential tolerancing and user-tolerancing features allow for multiple compensators, for this example the only allowed compensation is a longitudinal shift of the image plane to achieve maximum on-axis performance. This type of compensator is often called refocus.

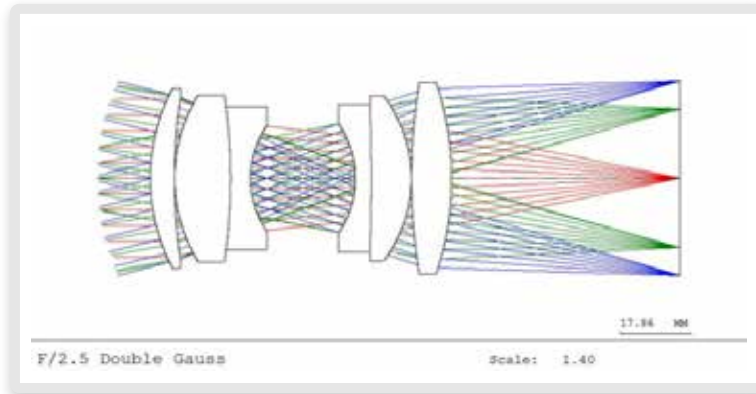


Figure 1: F/2.5 Double Gauss Lens

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.

| C E N T E R E D T O L E R A N C E S | | | | | | | | | |
|----------------------------------------|------------|------------|-----------------|-----------|---------------|-------|-----------|----------|--|
| F/2.5 Double Gauss | | | | | | | | | |
| SUR | RADIUS | RADIUS TOL | FRINGES POW/IRR | THICKNESS | THICKNESS TOL | GLASS | INDEX TOL | V-NO (%) | |
| 1 | 48.57123 | 0.0200 | 2.0/ 0.50 | 6.00000 | 0.02000 | NSSK2 | 0.00050 | 0.80 | |
| 2 | 131.57415 | 0.6000 | 2.0/ 0.50 | 0.10000 | 0.02000 | | | | |
| 3 | 39.95081 | 0.0200 | 2.0/ 0.50 | 14.00000 | 0.02000 | NSK2 | 0.00020 | 0.80 | |
| 4 | -142.35727 | 6.7000 | 12.0/ 3.00 | 5.00000 | 0.02000 | F5 | 0.00020 | 0.50 | |
| 5 | 23.51612 | 0.0200 | 2.0/ 0.50 | 4.06422 | 0.04000 | | | | |
| 6 | | | | 22.19286 | 0.04000 | | | | |
| 7 | -24.31769 | 0.0200 | 2.0/ 0.50 | 4.00000 | 0.02000 | F5 | 0.00050 | 0.30 | |
| 8 | -426.08911 | 73.0000 | 12.0/ 3.00 | 10.00000 | 0.02000 | NSK16 | 0.00050 | 0.50 | |
| 9 | -34.42842 | 0.0200 | 6.0/ 1.50 | 0.10000 | 0.10000 | | | | |
| 10 | 149.62579 | 0.5000 | 8.0/ 2.00 | 10.00000 | 0.10000 | NSK16 | 0.00150 | 0.50 | |
| 11 | -76.35573 | 0.1000 | 10.0/ 2.50 | 57.81453 | | | | | |
| 12 | | | | -0.70092 | | | | | |

| D E C E N T E R E D T O L E R A N C E S | | | | | | | | | |
|--------------------------------------------|--------------|-------------|-------------|---------------|-------------|--------------|---------|-----------------|--|
| F/2.5 Double Gauss | | | | | | | | | |
| ELEMENT NO. | FRONT RADIUS | BACK RADIUS | ELEMENT TIR | WEDGE ARC MIN | ELEMENT TIR | TILT ARC MIN | EL. TIR | DEC/ROLL(R) mm. | |
| 1 | 48.57123 | 131.57415 | 0.0040 | 0.3 | 0.0123 | 1.0 | 0.0112 | 0.0200 | |
| 2 | 39.95081 | -142.35727 | 0.0020 | 0.2 | | | 0.0231 | 0.0200 (R) | |
| 2- 3 | 39.95081 | 23.51612 | | | 0.0079 | 1.0 | 0.0029 | 0.0200 | |
| 3 | -142.35727 | 23.51612 | 0.0020 | 0.3 | | | | | |
| 4 | -24.31769 | -426.08911 | 0.0060 | 0.8 | | | 0.0211 | 0.0200 (R) | |
| 4- 5 | -24.31769 | -34.42842 | | | 0.0137 | 1.7 | 0.0001 | 0.0200 | |
| 5 | -426.08911 | -34.42842 | 0.0080 | 0.8 | | | | | |
| 6 | 149.62579 | -76.35573 | 0.0400 | 3.2 | 0.0131 | 1.0 | 0.0176 | 0.0200 | |

Table 2: Tolerance set determined with Inverse Sensitivity Tolerancing

For this analysis, all scalar and cylindrical parameters are assumed to have an equal probability of having any value within the plus and minus tolerance limits. Two-dimensional decentered tolerances use a Gaussian probability distribution. Additionally, the tolerance probability distribution can be modified in CODE V for different classes of tolerances. The system will be analyzed for the following five field positions: on-axis, +/-70% field, and +/- full field. Symmetric fields are used to access both radial and tangential MTF. If field-averaged compensation is desired, or decenter compensators are present, the off-axis fields should be duplicated for the Monte Carlo analysis. TOR can handle the field symmetric compensation algorithmically, without duplicating fields, by means of an input control.

| Tolerancing Method | Computation Time for an Intel® Core™ i7 2.7GHz CPU |
|------------------------------------|----------------------------------------------------|
| Wavefront Differential (TOR) | 2.3 seconds |
| Finite Difference (TOLFDIF) | 41 seconds (18x TOR) |
| Monte Carlo—5000 trials (TOLMONTE) | 70 minutes, 20 seconds (1835x TOR) |

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, ± 0.020mm) | | | Single Tolerance Comparison (Y Decenter of surface 3-5, ± 0.020 mm) | | |
|-----------------------------------------------------------------------|-------------------------------|-------------|----------------------------------------------------------------------------------------------|-------------------------------|-------------|
| Wavefront Differential Results | | | Wavefront Differential Results | | |
| Field | Change in MTF at 15 cycles/mm | | Field | Change in MTF at 15 cycles/mm | |
| | + Tolerance | - Tolerance | | + Tolerance | - Tolerance |
| 1 (On-axis) | +0.016 | -0.018 | 1 (On-axis) | -0.001 | -0.001 |
| 2 (+10 deg, tan) | +0.024 | -0.027 | 2 (+10 deg, tan) | +0.033 | -0.049 |
| 3 (+14 deg, tan) | -0.014 | +0.007 | 3 (+14 deg, tan) | -0.021 | +0.006 |
| 4 (-10 deg, rad) | +0.003 | -0.005 | 4 (-10 deg, rad) | +0.018 | -0.023 |
| 5 (-14 deg, rad) | -0.015 | +0.013 | 5 (-14 deg, rad) | +0.010 | -0.017 |
| Compensator (refocus) Motion for best axial focus = +0.0673 mm | | | Compensator (refocus) Motion for best axial focus = +0.0000 mm | | |
| Finite Difference Results | | | Finite Difference Results | | |
| Field | Change in MTF at 15 cycles/mm | | Field | Change in MTF at 15 cycles/mm | |
| | + Tolerance | - Tolerance | | + Tolerance | - Tolerance |
| 1 (On-axis) | +0.016 | -0.017 | 1 (On-axis) | -0.002 | -0.002 |
| 2 (+10 deg, tan) | +0.029 | -0.033 | 2 (+10 deg, tan) | +0.033 | -0.049 |
| 3 (+14 deg, tan) | -0.016 | +0.008 | 3 (+14 deg, tan) | -0.020 | +0.006 |
| 4 (-10 deg, rad) | -0.001 | -0.002 | 4 (-10 deg, rad) | +0.018 | -0.023 |
| 5 (-14 deg, rad) | -0.017 | +0.015 | 5 (-14 deg, rad) | +0.010 | -0.016 |
| Compensator (refocus) Motion for best axial focus = +0.0692 mm | | | Compensator (refocus) Motion for best axial focus = +0.0000 mm | | |
| | | | Mean+2σ Comp. Motion for all tolerances using the Wavefront Differential method = ±0.4110 mm | | |
| | | | 2σ Comp. Motion for all tolerances using the Finite Differences method = ±0.4169 mm | | |

Table 4: Single tolerance comparisons between Wavefront Differential and Finite Difference methods

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 2σ compensator motion range for all tolerances correlates very well for the two methods (within 7 μM). The predicted performance degradation due to any of the individual tolerances is similar to these representative examples.

All three methods (Wavefront Differential, Finite Difference, and Monte Carlo) predict the cumulative probability performance, when all tolerances are applied. However, the prediction from the Finite Difference method tends to be optimistic, since it does not include the impact of cross-terms (i.e., how the individual tolerances interact to impact performance). Both the Wavefront Differential and Monte Carlo methods include cross-terms.

| Performance Summary Comparison | | | | |
|------------------------------------------|---------|---------|---------|---------|
| Change in MTF at 15 cycles/mm | | | | |
| Cumulative Probability | | | | |
| Wavefront Differential Results | | | | |
| Field | 50% | 84.1% | 97.7% | 99.9% |
| 1 | -0.0135 | -0.0394 | -0.0653 | -0.0912 |
| 2 | -0.0164 | -0.0676 | -0.1189 | -0.1701 |
| 3 | -0.0186 | -0.0489 | -0.0792 | -0.1096 |
| 4 | -0.0190 | -0.0518 | -0.0846 | -0.1174 |
| 5 | -0.0164 | -0.0458 | -0.0752 | -0.1045 |
| Monte Carlo Results (5000 trials) | | | | |
| Field | 50% | 84.1% | 97.7% | 99.9% |
| 1 | -0.0115 | -0.0373 | -0.0657 | -0.0978 |
| 2 | -0.0064 | -0.0623 | -0.1311 | -0.2000 |
| 3 | -0.0145 | -0.0482 | -0.0974 | -0.1701 |
| 4 | -0.0172 | -0.0503 | -0.0887 | -0.1412 |
| 5 | -0.0121 | -0.0484 | -0.1003 | -0.1620 |

Table 5: Cumulative performance summary for three tolerancing methods

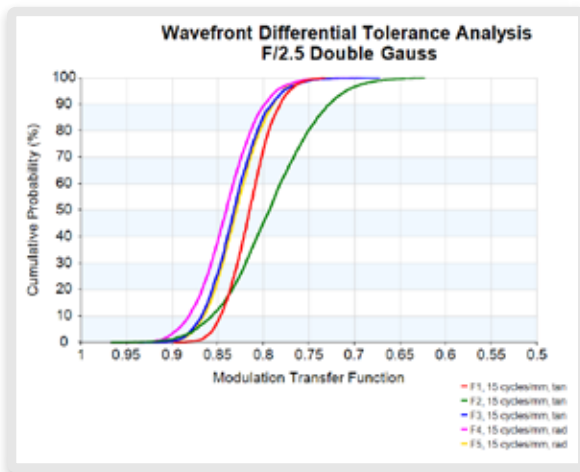


Figure 2: Wavefront Differential cumulative probability chart

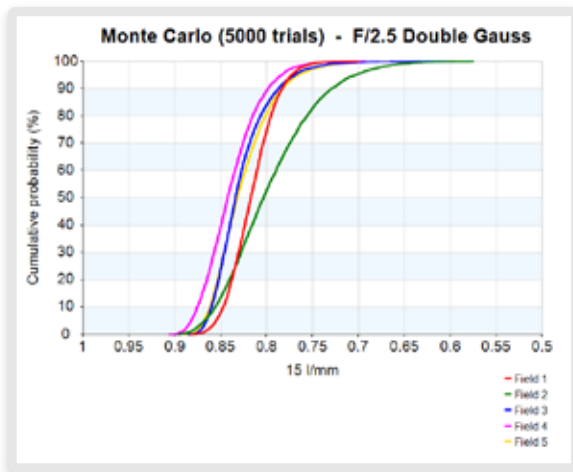


Figure 3: Monte Carlo cumulative probability chart

Table 5 compares the cumulative probability performance summary for the Wavefront Differential and Monte Carlo methods. It lists the MTF degradation at the 50% (mean), 84.1% (mean plus 1σ), 97.7% (mean+ 2σ), and 99.9% (mean+ 3σ) probability levels. The values in the table represent maximum degradation in MTF for a given field for a certain percentage of built systems, assuming a random application of tolerances within their tolerance limits on each parameter. Users can also control the distribution of the random perturbations (e.g., uniform probability

between tolerance limits, a Gaussian probability between the tolerance limits, etc.). Once again, fields 2 and 3 indicate tangential MTF performance, fields 4 and 5 the radial MTF, and compensation is for best axial focus. The results between the Wavefront Differential and Monte Carlo methods correlate well, with the predicted MTF degradation due to tolerances within 0.01 for both methods through “mean + σ ” probability (84%) for all fields, and within 0.03 for the “mean + 3σ ” probability (98%) at all the inner fields. While the Monte Carlo results become more pessimistic for the outer fields at the “mean + 3σ ” probability (i.e., difference ~ 0.06), the average difference across all listed fields and probabilities is within 0.014 in MTF.

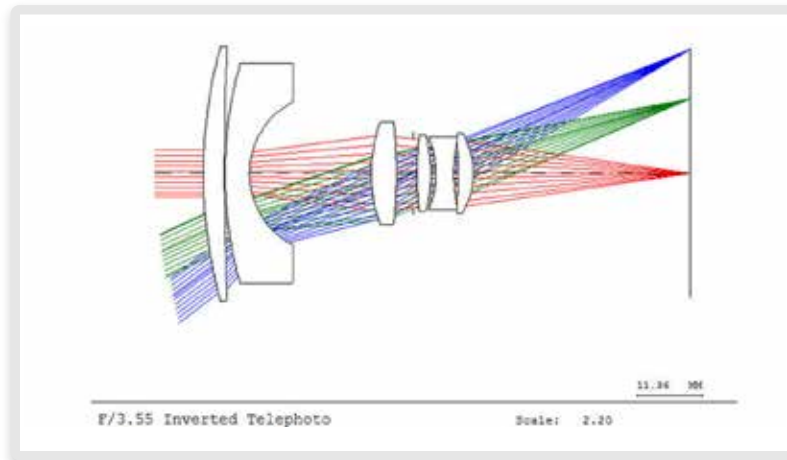


Figure 4: F/3.55 inverted telephoto before tolerance desensitization optimization

Each of the three CODE V tolerancing methods discussed in this paper will create a cumulative probability performance chart. These charts show the performance at any probability level. Figure 2 is the cumulative probability plot generated by the Wavefront Differential tolerancing method (TOR). Figure 3 is the cumulative probability chart generated by the Monte Carlo method (TOLMONTE). Like the tabular data, they compare very well.

Directly Optimizing for Tolerance Desensitization

CODE V's optimization capabilities have long been recognized as the best in the industry for achieving optimum nominal performance for systems ranging from the simple to the very complex. The speed of the Wavefront Differential tolerancing approach supports its inclusion as a separate, optional error function component in optimization (the Reduce Tolerance Sensitivity, or SAB error function). CODE V's primary optimization algorithm is based on a Damped Least Squares (DLS) method, which works best for systems with many variables and many relevant aberrations to be reduced by those variables. The Wavefront Differential tolerancing approach allows aberrations based on multivariate equations to be created for every tolerance at every field and every zoom. This is an ideal problem for DLS!

Typically, when using SAB, you choose the same tolerance values for common parameter types, often based on tolerance classes such as commercial, precision, high precision, etc. The general goal is to optimize for a design form that can meet the as-built specification with the least-expensive tolerance set. SAB is best used early in the design phase and can also be effectively used during global optimization. Some pre-SAB optimization may be required, since a system with very poor nominal performance is generally insensitive to tolerance variations. SAB should be used on systems with “reasonable” nominal performance that will show degradation with “reasonable” tolerances.

| 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 TIR | WEDGE ARC MIN | ELEMENT TIR | TILT ARC MIN | EL. TIR | 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 |

Table 6: "Select" 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 maximum improvement, an iterative approach works best. The results shown in Table 7 for the "mean + 2σ" as-built RMS wavefront 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 | DESIGN | DESIGN | DESIGN | DESIGN |
| FIELD | + TOL | | + TOL | |
| 0.00, 0.00 | 0.3497 | 0.7098 | 0.3886 | 0.6000 |
| 0.00, 0.71 | 0.6242 | 1.0293 | 0.7370 | 0.9410 |
| 0.00, 1.00 | 0.8054 | 1.3309 | 0.6493 | 0.9862 |
| Average => | 0.5931 | 1.0233 | 0.5916 | 0.8424 (18% ▼) |

Table 7: Performance comparison for lens optimized without and with the Tolerance Desensitization Error Function (SAB)

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!

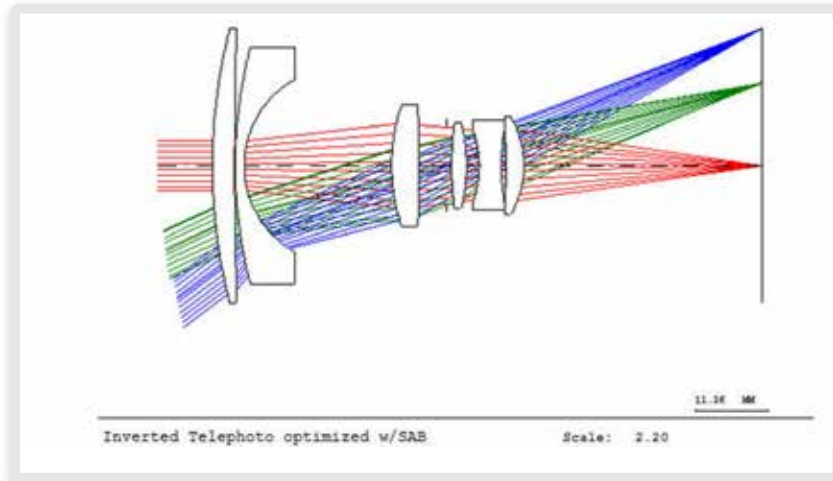


Figure 5: F/3.55 inverted telephoto after tolerance desensitization optimization

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.

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