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Powerful standalone application for realistic optical tolerancing

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ABSTRACT

An innovative software application for a more realistic tolerance analysis has been developed recently by INO. The application is using optical and mechanical manufacturing databases as well as several equations to translate realistic manufacturing tolerances, optomechanical mounting interfaces, and centering methods into tilts and decenters perturbations, easily transferable to Zemax OpticStudio.

The standalone application can be used by the optical designer to quickly verify the feasibility of a mounting and alignment technique according to the specific sensibilities of the current design. The optomechanical engineer can also easily validate or choose a better centering method as well as update the mechanical tolerance parameters. Once the parameter is fixed, the optical designer can export the new parameters into a Zemax OpticStudio file, updating Lens Data Editor and Tolerance Data Editor. Communication between both optical and optomechanical specialists is straightforward with this powerful tool, making the design process easier, quicker, and more accurate.

This paper presents how INO is using its standalone application for tolerance analysis to overcome the complex simulation of various centering techniques. Through real examples, it will show how realistic tolerancing simulations impact the choice of appropriate centering method for the lens assembly.

Keywords: Tolerance analysis, optical design, tolerancing, simulation, integrated model, error budget, lens mounting, optomechanics, centering, alignment, standalone application, software

1. INTRODUCTION

Optical designers and optomechanical engineers are working together to design optics giving a good compromise between best performances and low manufacturing cost. Tolerance analysis is required to estimate the system expected performances according to manufacturing tolerances and find the best design option. As presented in [1] paper, default tolerancing parameters in optical design software does not represent real lens mounting behaviors. Programming lenses tilts and decenters for each optical mount is a long and tedious task, requiring an extensive knowledge of the interaction between lens and mount theory as well as several calculations from the optomechanical designer [2], [3]. As projects often go fast, designers may use estimated perturbations for the tolerance analysis or will wait the final design to consider them appropriately. To facilitate the design process, an integrated optical-optomechanical tolerancing application has been developed.

This paper presents how INO is using a Matlab standalone application with Zemax OpticStudio to overcome the complex simulation of various centering techniques. The *Comet* application software provides an integrated model where the optomechanical tolerance analysis is linked to the optical model. Currently, there is no software on the market specialized for optomechanical tolerance analysis. This novel application helps optical designers to simulate lenses position errors with realistic optomechanical mounts and according to its centering method. *Comet* summarizes the optomechanical theory of the interaction between lenses and mounts, in a convenient interface software, guiding step by step both optical and optomechanical designers to prepare tolerance analysis.

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2. COMET AS AN INTEGRATED OPTICAL-OPTOMECHANICAL TOLERANCE SOFTWARE

Comet is a Matlab standalone application using the Application Programming Interface for Zemax OpticStudio. It reads the full optical design prescription on an OpticStudio file, including the Lens Data Editor and Tolerance Data Editor. With a few simple steps, it computes and creates all required modifications to the lens file for a realistic tolerance analysis and exports the results to a new updated OpticStudio file. This section explains the workflow using *Comet* as well as the application capabilities of its easy-to-use interface.

2.1 *Comet* workflow

When optical design seems good enough for manufacturing, it is time to verify if the optical system will keep acceptable performances with an affordable centration method. As a first try, the optical designer could verify the feasibility of its design using *Comet* instead of OpticStudio Tolerancing Wizard. This section is showing how simple it is to prepare tolerance analysis files with more realistic optomechanical perturbations.

Comet workflow is quite simple and is illustrated in Figure 1. The imported file comes from OpticStudio at the beginning of the project or it could come from *Comet* to start with previously set parameters (.comet file). Either the optical designer or the mechanical engineer can prepare the element settings. It is possible to set the element configuration separately for each lens or to set the same configuration for all lenses together with an “Apply to all” button. Steps are:

- Selecting the centering method (rim-contact, centration machine, ...) and the mounting surface (surface 1 or surface 2 for a singlet)
- Filling the optomechanical tolerance input table. Presets similar to the OpticStudio’s tolerance wizard are available, but each parameter is editable for more accurate estimation of the perturbation.
- Setting axial perturbations. There are presets for these tolerances too, and they can be edited separately if required.

Sometimes, lenses are into a cell or are separated into several barrels. For those cases, it is possible to create lenses groups and set special perturbations to those groups. This step is optional.

When these simple steps are done, it is possible to export the file into OpticStudio format or *Comet* format. The optical designer is then ready to start tolerancing.

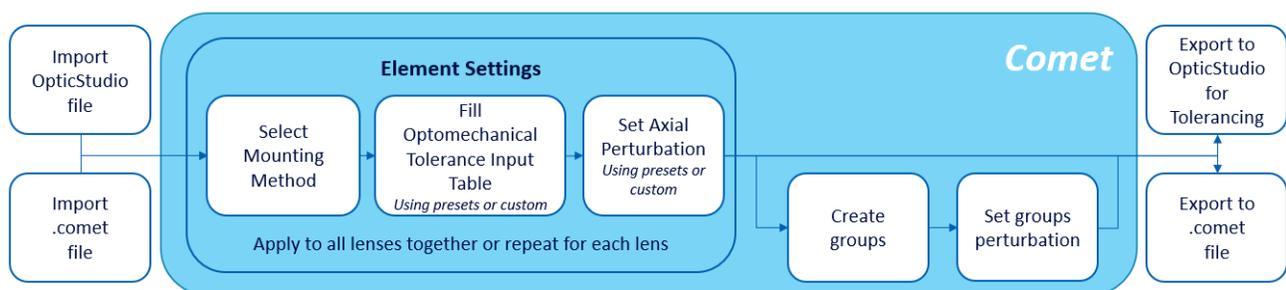


Figure 1. *Comet* application workflow.

2.2 Element Configuration tab

Figure 2 illustrates *Comet* main interface with the Element Configuration tab, where the user can set the information for each lens. It includes selecting its mounting surface, the centering method, and the centering surface in the case of a doublet element.

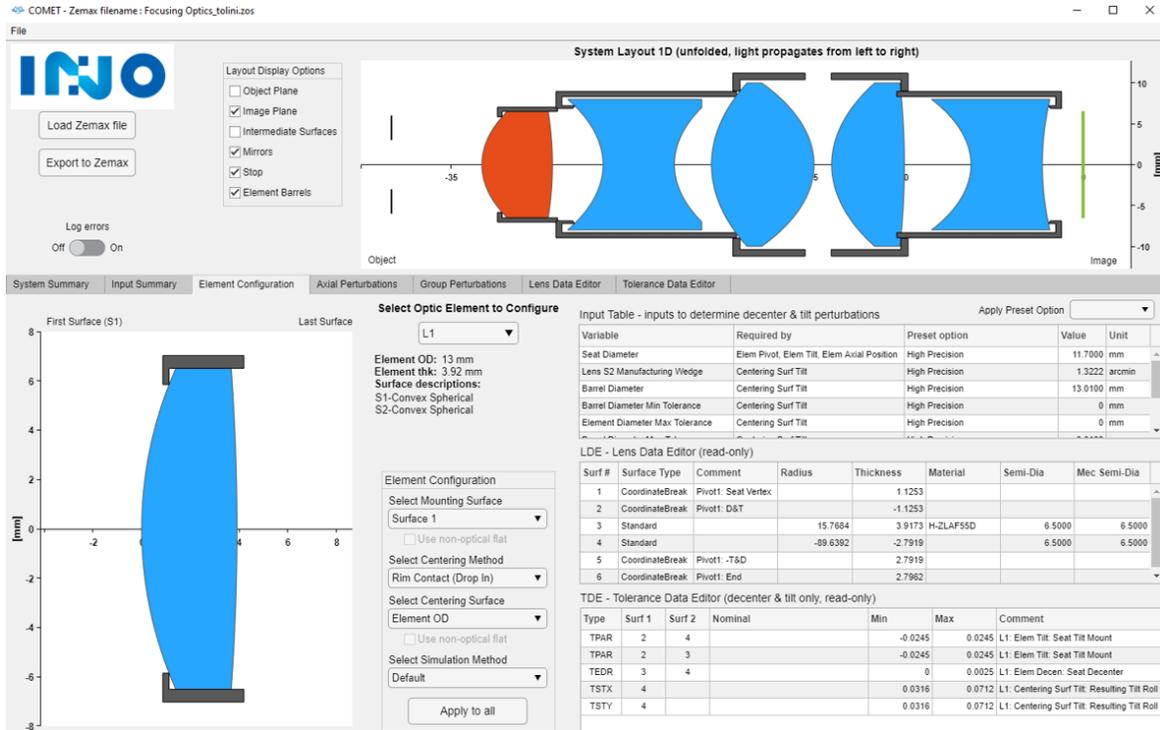


Figure 2. Comet application interface for element configuration.

Centering methods available are the most common methods used by INO. It includes the widely used lens drop-in, surface-contact standard ring, and a manual alignment with a centering machine. It also includes INO's patented (proprietary) alignment methods such as the QuickCTR-edge, QuickCTR-thread and centration with our passive centering machine.

The QuickCTR-edge method uses a standard threaded ring in contact with the lens edge, at the intersection of the cylindrical and optical surface of the lens (Figure 3). The QuickCTR-thread auto-centering refers to the adjustment of the thread angle of the retaining ring as per the lens radius of curvature to provide an improved centering of the lens. INO's passive centering machine allows to bond lenses in optical barrels using the surface-contact principle for lens centering. These later methods are detailed in reference [4], [5].

Surface-contact centering methods require a minimum clamping angle to ensure that the radial force resulting from the surface-contact mounting will be large enough to overcome the friction forces in the lens assembly. This allows the lens to roll or translate, constrained by the bell mechanical interfaces. Comet automatically computes the clamping angle when required and informs the user if the clamping angle is not sufficient to ensure a good centering with surface-contact mounting. The element configuration can be set for each lens independently or for all lenses together by clicking on the "Apply to all" button.

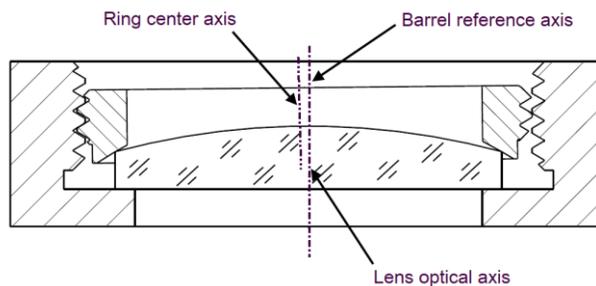


Figure 3. QuickCTR-edge lens centering.

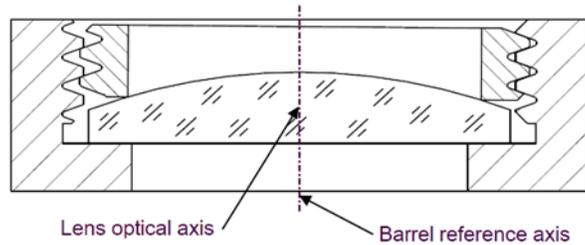


Figure 4. QuickCTR-thread lens centering.

When the element configuration is set, some information appears on the three tables on the right side of the interface (refer to Figure 2): the Input Table, the Lens Data Editor and the Tolerance Data Editor. The Input Table lists predetermined inputs required to compute decenter and tilts perturbations. Variables in the Input Table depend on the lens type (spherical, aspherical, singlet, doublet, triplet), its mounting surface and its centering method. Each value of this table can be computed automatically by *Comet* using the tolerance presets or it can be edited individually. The Input Table is the only editable table. Presets include commercial, precision and high precision settings, similar to the Zemax tolerance wizard. When known, the mechanical engineer can add some details on the barrel manufacturing method for more accurate perturbation settings. For example, it is possible to select the manufacturing method such as Computer Numerical Control (CNC) lathe or CNC milling, as well as the number of machining setup to have more exact tolerance preset values.

According to the Element Configuration and Input Data settings, *Comet* automatically computes tilts and decenters for surfaces and elements. Updated Lens Data Editor and the Tolerance Data Editor are illustrated in the two read-only tables. The Lens Data Editor includes the nominal surfaces of the selected lens, but also new Coordinate Breaks surfaces required when tilt is not according to the vertex of the first surface. The pivot position included in the partial Lens Data Editor is automatically computed according to the real optomechanical mounting and centering. Tolerance Data Editor lists all the tolerance contributors for the current lens that will be later exported to Zemax OpticStudio.

2.3 Axial Perturbations tab

Comet has a special tab for Axial Perturbations (Figure 5). Each lens has an editable Input Table for axial perturbations and a list of operands for the Tolerance Data Editor. Tolerances illustrated on this tab are the element thicknesses and element axial positions. The adjusting surface of the axial perturbation is automatically chosen according to the lens mounting surface set on the Element Configuration tab. The element axial perturbation often comes from several contributors such as the seat position tolerance, the lens center thickness tolerance, the seat diameter tolerance, and the lens mounting surface radius of curvature tolerance. The probability density and cumulative distribution function are automatically computed statistically using Monte Carlo simulation.

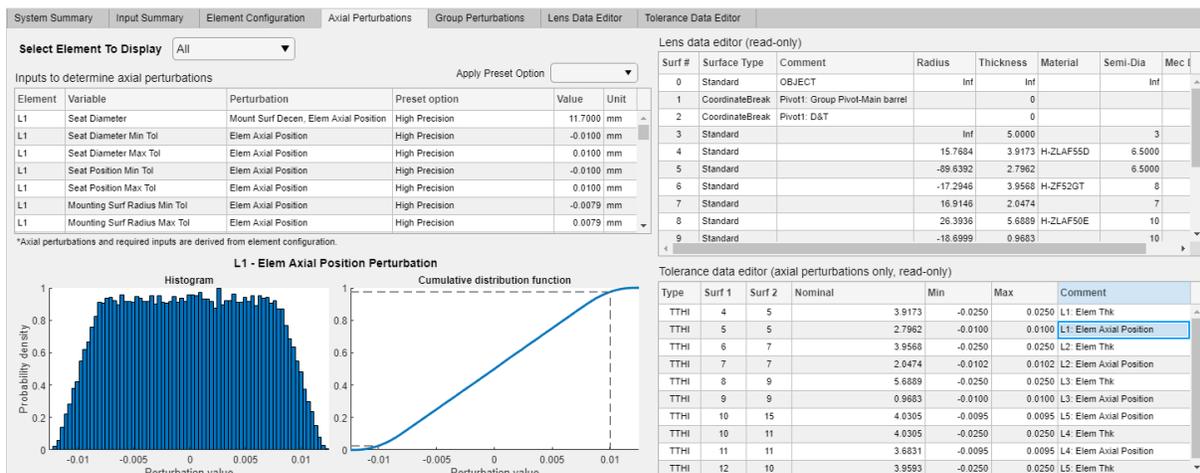


Figure 5. *Comet* application interface for axial perturbations.

2.4 Group Perturbations tab

Comet more advanced feature includes groups creation (Figure 6). Groups can be for a single lens if a lens is into a cell, or a group can include several lenses. Adding groups to a lens system is a manual operation because each system is unique. Users can add several perturbation contributors with their distribution type (uniform or normal) and its minimum and maximum limits. Contributors include axial displacements, decenters (X, Y or radial) and tilts (X, Y or radial). It is also possible to move pivot position anywhere in space, meaning that it does not have to be into the optical axis. *Comet* considers each perturbation contributor to update the Lens Data Editor with the required Coordinate Breaks surfaces and to update the Tolerance Data Editor with associated operands.

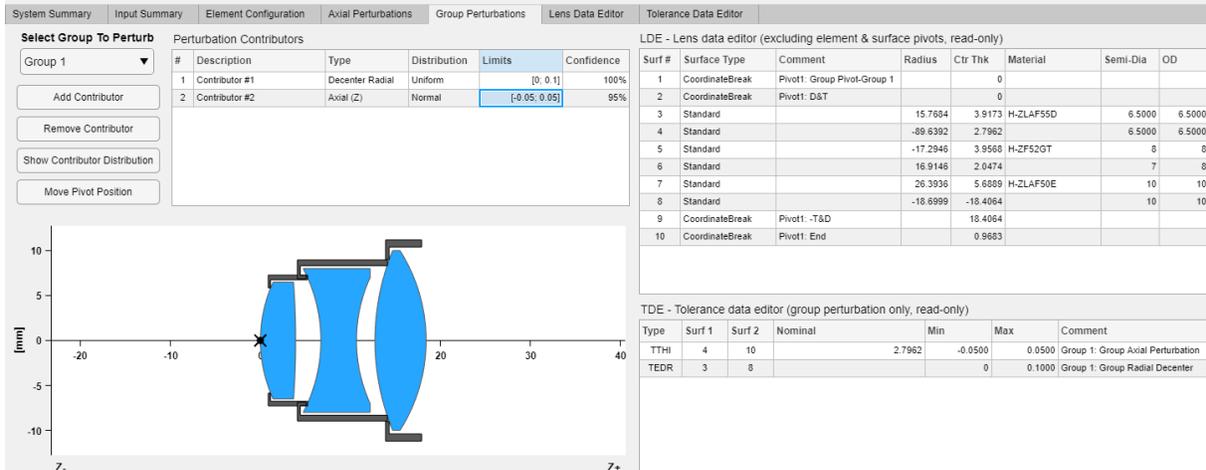


Figure 6. *Comet* application interface for group perturbations.

When a Tolerance Data Editor operand value comes from several perturbation contributors, a Monte Carlo simulation is done to set the minimum and maximum value. The probability density graph of each operand is available for an in-depth tolerance analysis with several distributions.

2.5 Summary tabs

Once Element Configuration, Axial Perturbations and Groupe Perturbations are set, it is possible to have an overview of the settings on the System Summary tab (Figure 7). Overall system data details are on the Input Summary tab (Figure 8), Lens Data Editor tab (not shown) and Tolerance Data Editor tab (not shown).

When the file is ready to be exported into a Zemax OpticStudio file, the user clicks on the “Export to Zemax” button to create a new OpticStudio file with updated Lens Data Editor and Tolerance Data Editor. Then, the optical designer is ready to start its tolerances analysis.

Comet has also its own file format that can be saved. When a “.comet” file is saved, the complete system can be later uploaded in *Comet* application. This feature is useful to remember configuration details, but also to customize parameters or share data between optical designers and optomechanical engineers.

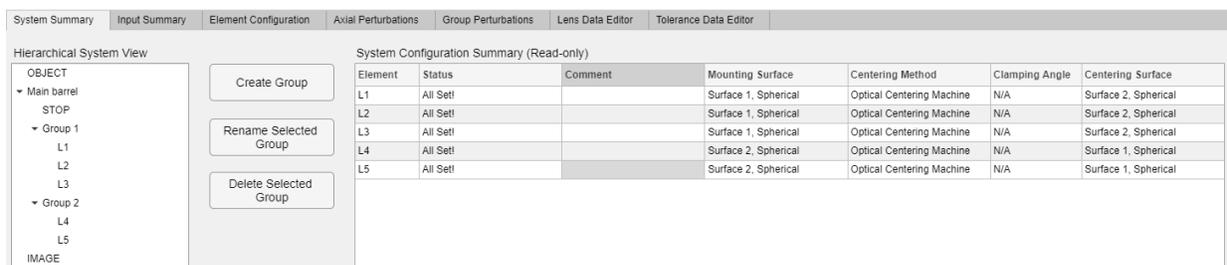


Figure 7. *Comet* application interface for system summary.

System Summary	Input Summary	Element Configuration	Axial Perturbations	Group Perturbations	Lens Data Editor	Tolerance Data Editor
Summary of all input variables used to determine all perturbations						
Optic Element	Variable	Required by	Preset option	Value	Unit	
L1	Seat Diameter	Mount Surf Decen, Elem Axial Position	High Precision	11.7000	mm	
L1	Seat Tilt Geometrical Tolerance	Mount Surf Decen	High Precision	0.0050	mm	
L1	Seat Concentricity Tolerance	Mount Surf Decen	High Precision	0.0050	mm	
L1	Surf Align Error From Active Alignment	Centering Surf Tilt	High Precision	0.0025	mm	
L1	Seat Diameter Min Tol	Elem Axial Position	High Precision	-0.0100	mm	
L1	Seat Diameter Max Tol	Elem Axial Position	High Precision	0.0100	mm	
L1	Seat Position Min Tol	Elem Axial Position	High Precision	-0.0100	mm	
L1	Seat Position Max Tol	Elem Axial Position	High Precision	0.0100	mm	
L1	Mounting Surf Radius Min Tol	Elem Axial Position	High Precision	-0.0079	mm	
L1	Mounting Surf Radius Max Tol	Elem Axial Position	High Precision	0.0079	mm	
L1	Lens Center Thk Min Tolerance	Elem Thk	High Precision	-0.0250	mm	
L1	Lens Center Thk Max Tolerance	Elem Thk	High Precision	0.0250	mm	
L2	Seat Diameter	Mount Surf Decen, Elem Axial Position	High Precision	14.4000	mm	

Figure 8. *Comet* application interface for input summary.

3. FOCUSING OPTICS EXAMPLE #1

3.1 Focusing optics design and nominal performances

The design presented here is a focusing optics for a hyperspectral camera in the visible range. Layouts and performances are illustrated in Figure 9. The F/4 optics has a $\pm 18^\circ$ field of view and is designed for a 5-megapixel camera with $5\mu\text{m}$ pixel pitch. System performance requirement is to have an average MTF better than 30% at 100 lines pairs per millimeter all over the field of view, with a goal to have better than 40%. The nominal design has a minimum average MTF of 51% at 100 lines pairs per mm. Let see which mounting method meet the requirement.

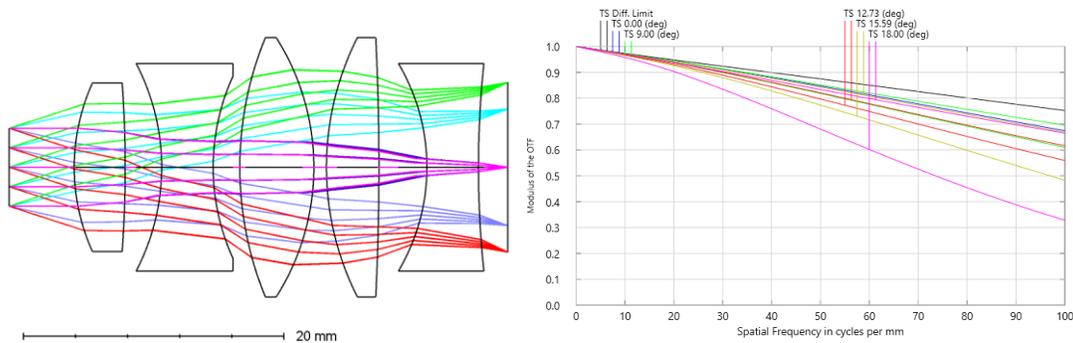


Figure 9. Example #1: focusing optics layout and its nominal performances.

3.2 Tolerancing

Before the importation into *Comet* application, it is more convenient to prepare in advance the OpticStudio file's Tolerance Data Editor for parameters without influences on the optomechanical tolerancing: surfaces power and irregularity as well as glass parameters (indexes and Abbe number). In this example, precision tolerances are used for those parameters.

With *Comet* opened and OpticStudio's file loaded, it is quite fast to create several mounting scenarios to later tolerance them separately. This section presents the tolerance analysis results for five mounting scenarios:

- 1- Drop-in assembly with rim-contact centration. Optomechanical tolerances grade is high precision.
- 2- INO's QuickCTR-edge centration using precision tolerancing.
- 3- INO's QuickCTR-edge centration using high precision tolerancing.
- 4- Centering machine with precision grade optomechanical tolerances.
- 5- Centering machine with high precision grade optomechanical tolerances.

Each mounting scenario has been evaluated according to the design criteria, which is the minimum MTF average at 100 line pairs per millimeter. A tolerancing script is required to extract the data. 100 Monte Carlo cases are generated with normal distribution.

Figure 10 illustrates the cumulative probability of the minimum MTF average at 100 line pairs per millimeter for each mounting scenario. The drop-in solution is the less expensive but only 50% of the cases meet the 30% minimum MTF average. On the other side, the most accurate and expensive method is the high precision option using the centering machine. Centering machine is quite expensive for production because of the required human precaution and curing time for the adhesive on each lens, but this mounting configuration meet the 40% minimum MTF average for 98% of the cases.

INO's QuickCTR-edge mounting seems the best compromise between performances and manufacturing cost: all Monte Carlo cases are over the 30% requirements, for either precision or high precision optomechanical tolerances. With high precision, 85% of the cases are over 40%.

Comet made it easy to compare the centering methods. In this example, one could see on Figure 10 that the precision grade QuickCTR-edge is similar to the precision grade centering machine. It is quite interesting since the centering machine is way more expensive to align than the QuickCTR-edge method.

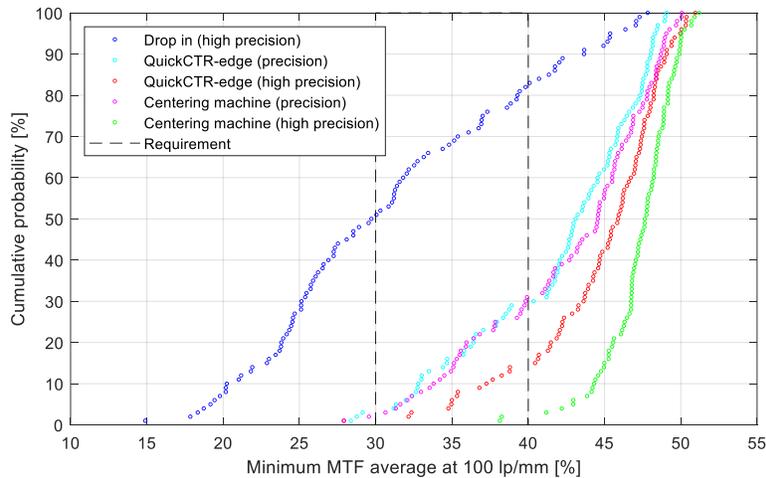


Figure 10. Cumulative probability of the minimum MTF average at 100 line pairs per millimeter for few mounting configurations on design example #1.

4. FOCUSING OPTICS EXAMPLE #2

4.1 Focusing optics design and nominal performances

Focusing optics design example #2 is similar to example #1 but its second lens is a doublet instead of a singlet. It has the same characteristics and requirements: F/4, $\pm 18^\circ$ field of view and a requirement to have the MTF average better than 30% at 100 line pairs per millimeter (goal: better than 40%) all over the field of view.

The nominal minimum average MTF of this design is 53% at 100 line pairs per millimeter, which is similar to the example #1 nominal performances. Lens layout and MTF are illustrated in Figure 11.

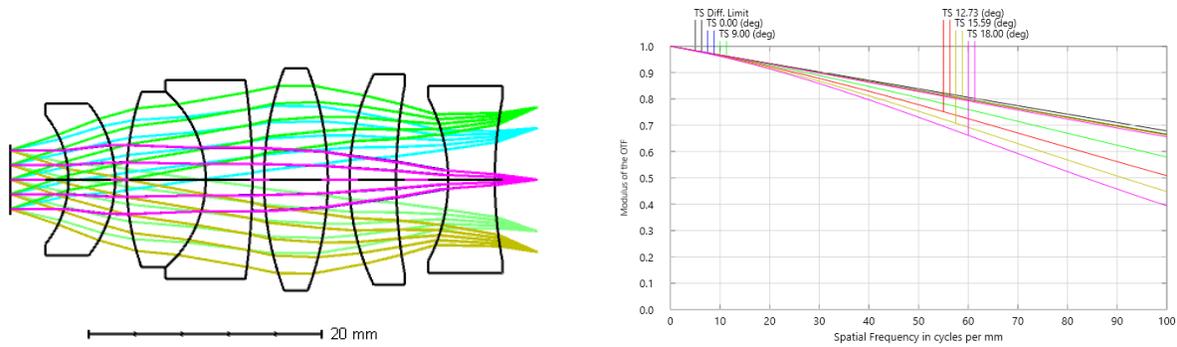


Figure 11. Example #2: focusing optics layout and its nominal performances.

4.2 Tolerancing Example #2

As the requirement is the same as example #1, the same tolerance analysis script is used to compute the minimum average MTF of each Monte Carlo case. The OpticStudio's file is similarly prepared with precision optics perturbations on surface powers, irregularities, and glass parameters.

Evaluated mounting scenarios for this example are:

- 1- Drop-in assembly with rim-contact centration. Optomechanical tolerances grade is precision.
- 2- Drop-in assembly with rim-contact centration. Optomechanical tolerances grade is high precision.
- 3- INO's QuickCTR-edge centration using precision tolerancing
- 4- INO's QuickCTR-edge centration using high precision tolerancing
- 5- INO's QuickCTR-thread centration using high precision tolerancing
- 6- Centering machine with high precision grade optomechanical tolerances

100 Monte Carlo cases are generated with normal distribution for each mounting scenario. Figure 12 illustrates cumulative probability of the minimum MTF average at 100 line pairs per millimeter for each mounting scenario.

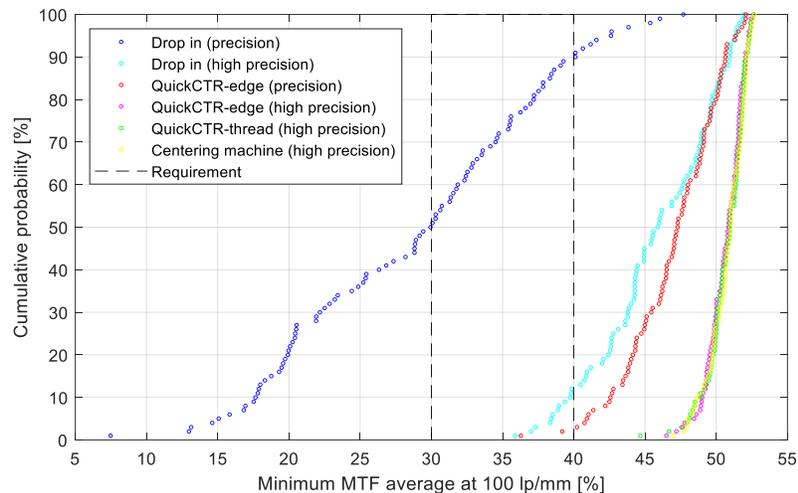


Figure 12. Cumulative probability of the minimum MTF average at 100 line pairs per millimeter for few mounting configurations on design example #2.

The example #2 design tolerance analysis gives interesting results. The minimum MTF average for drop-in precision assembly is similar to the drop-in high precision in example #1 and does not meet the performance requirement. Cumulative probabilities on drop-in high precision and QuickCTR-edge precision gives a minimum MTF average better than 40% for most of the Monte Carlo cases. Both centration methods are good options, but it turns out that the QuickCTR-edge precision manufacturability is easier thus cheaper than the drop-in using high precision tolerances. QuickCTR-edge precision will be preferred as the centration method giving the best performances compared to the goal requirement.

The most accurate centration methods on Figure 12 are high precision QuickCTR-edge, QuickCTR-thread and centering machine. They give similar cumulative probability because worst offenders are lens thicknesses and axial positions, which is not related to lenses centration.

5. EXAMPLES COMPARISON

Design #1 and Design #2 have the same requirements and similar nominal results, but Design #2 is less sensitive to centration. The expected minimum MTF is described as the minimum MTF average at 100 line pairs per millimeters over the entire field of view for 95% of the Monte Carlo cases. Main requirement is to have a minimum MTF higher than 30% and the goal requirement is to have higher than 40%. Table 1 compares the expected minimum MTF of both designs according to various centration technique and precision.

Design #1 can meet the 30% minimum requirement with a QuickCTR-edge centering technique precision manufacturing and the 40% goal requirement with a high precision alignment with the centering machine. On the other hand, Design #2 can meet the 30% minimum requirement with a drop-in assembly and high precision manufacturing, and it can achieve the goal requirement with the easy-to-do QuickCTR-edge centering technique and precision manufacturing.

It takes only a few minutes to create OpticStudio ready-to-tolerance files. Examples presented used presets, but better trade-off can be achieved with a mix of centration methods and manufacturing precisions. The process can be further streamlined by using a previously saved Comet file as a starting point. When the design is final, all manufacturing tolerances data are in the *Comet* Input Summary tab for an easy access when preparing detailed part drawings.

Table 1. Design #1 and #2 minimum MTF average comparison at 100 line pairs per millimeter for 95% of the Monte Carlo cases (2 sigmas).

Centering technique and precision	Design #1 Expected minimum MTF <i>Nominal value: 51%</i>	Design #2 Expected minimum MTF <i>Nominal value: 53%</i>
Drop-in – precision	-	15%
Drop-in – high precision	19%	38%
QuickCTR-edge precision	31%	41%
QuickCTR-edge high precision	35%	48%
QuickCTR-thread high precision	-	48%
Centering machine – precision	32%	-
Centering machine – high precision	43%	48%

6. CONCLUSION

The novel software application presented in this article can easily and quickly perform realistic tolerance analysis, even at an early stage of the design. It provides a more accurate tolerancing model, avoiding the simulation of unrealistic cases, and helping the designer to choose the best lenses centering method quickly. It improves confidence on perturbation simulations, minimizes overdesign and reduces cost on design, manufacturing, and alignment. The application is helpful for both optical designers and optomechanical engineers, giving a communication standardization between disciplines. It obviously reduces the risk of errors and misunderstanding, but also helps to understand and use appropriately optomechanical manufacturing international standards such as ISO 10110-6 and ASME Y14.5 GD&T.

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