reTORT Optical Design Software:
Instructions for Setting Up a Tolerance Analysis

1 Introduction

Tolerance analysis is an important part of any lens design to ensure it's ready for manufacturing. This document will walk you through how to configure a tolerance analysis in reTORT. The tolerancing wizard makes setup fast and easy by automatically parameterizing common lens system properties for tolerancing, and generating a tolerance analysis object. Custom modifications can be made to the generated analysis in order to tolerance additional lens properties or change other settings, if desired.

For additional details on the tolerancing features available in reTORT/GEMSIF, refer to the "Tolerancing Wizard" and "Tolerance Analysis" sections of the user manual. You can also view the documentation in reTORT via the **Help** → **Context Help** menu option. The context documentation contains the same information as the user manual, but displays the relevant documentation for objects/properties as you click on them.

2 Using the Tolerancing Wizard

First, we will demonstrate how to configure a tolerance analysis using the Tolerancing Wizard. The tolerancing wizard can help automate the process of parameterizing system properties and configuring results, and will generate a tolerance analysis using those parameters. Instructions for creating a tolerance analysis from scratch or making custom modifications to the generated analysis are given in Section 4. Additional information on the tolerancing wizard can be found in the "Tolerancing Wizard" section of the user manual.

To open the tolerancing wizard, you can click the tolerancing wizard button in the toolbar, or select **Tools** → **reTORT** → **Tolerancing Wizard** from the menu bar. You can also right-click the reTORT simulation and select **Tools** → **Tolerancing Wizard**. Upon starting the wizard, an **AutoToleranceAnalysis** object will be automatically generated.

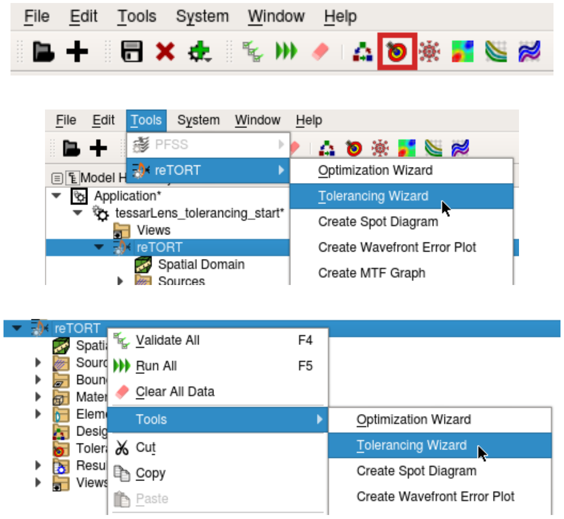


Figure 1: Ways to start the Tolerancing Wizard.

2.1 Tolerancing Wizard Parameters

The **Parameters** tab of the tolerancing wizard contains a list of system properties commonly used during an optimization or tolerance analysis. The dropdown menu in the leftmost column determines whether each parameter is toleranced (“TOL”), compensated (“CMP”), or ignored (empty). Toleranced parameters will be perturbed throughout the tolerance analysis. Compensated parameters will be optimized to minimize any performance changes as a result of the perturbations. And any ignored parameters will not be used during the analysis. Mark appropriately any system properties you want to tolerance or compensate. At least one toleranced parameter is required to run a tolerance analysis. If the properties you wish to tolerance are not listed in the wizard, you can read more about configuring your own parameters in Section 4.3.

For any toleranced parameters, a gear button will also appear. Clicking this button will reveal distribution settings for the parameter, which control the probability distribution used during a Monte Carlo analysis. More information about these settings can be found in the “Tolerancing Wizard” section of the user manual, under “Advanced Distribution Settings.” Default distribution settings can be found in the Settings tab (Section 2.2).

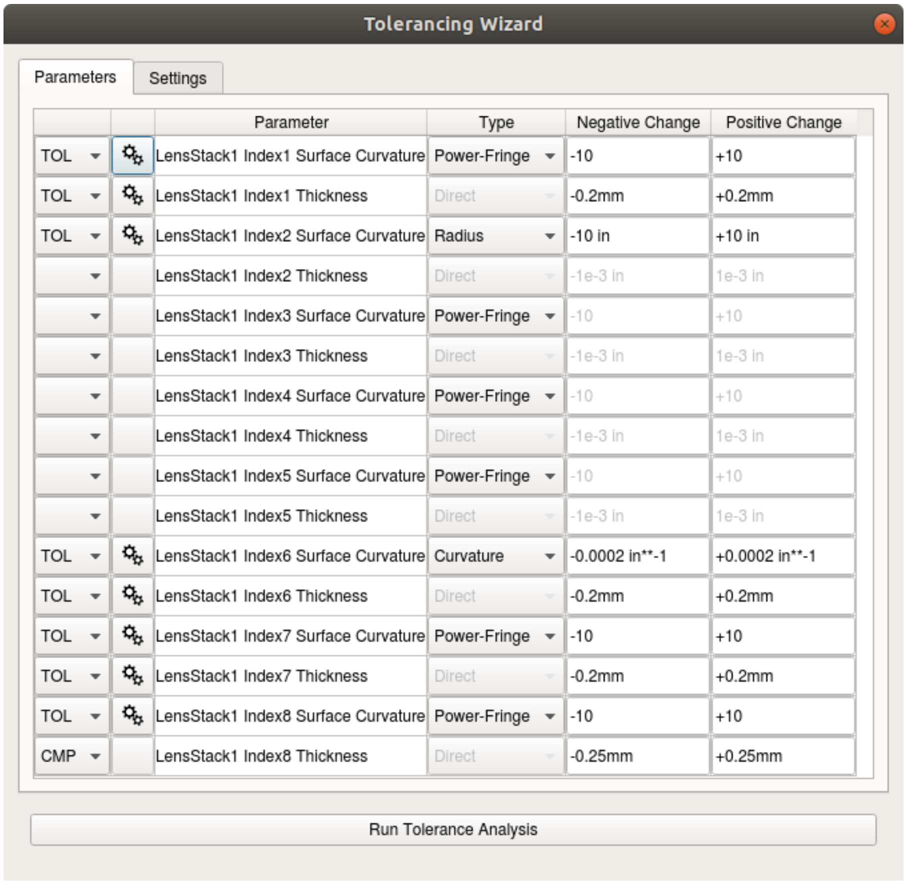
The **Negative** and **Positive Change** columns determine the maximum amount of deviation for each parameter. These properties represent the maximum changes in the parameter, not the min and max parameter values themselves. For toleranced parameters, they indicate the limits of the tolerance range. For compensated parameters, they define the optimization range for the parameter during compensation. The **Type** column controls how these ranges are defined. Most property tolerances are defined as direct changes to the parameter value (“Direct”). In this case, the tolerance range must have units compatible with the parameter value. However, surface curvatures can have their tolerances defined in terms of Power-Fringe, Radius, or Curvature. If a surface curvature is compensated instead of toleranced, then “Curvature” is the only available option. Changing the selected Type will automatically convert the current Negative/Positive Changes into the appropriate units.

Power-Fringe tolerances are specified in numbers of fringes when compared with a test surface of the nominal curvature. A single fringe is equivalent to a $\frac{\lambda}{2}$ change in the sag of the surface, where λ is the test wavelength, and the sag is calculated at the test diameter. The test wavelength and test surface diameter are defined in the Settings tab (Section 2.2). A positive fringe deviation moves the sag towards the back of the lens, which will make positive curvatures more extreme, and will make negative curvatures flatter.

Radius tolerances are defined as a change in radius of curvature (units of length). A positive radius deviation indicates an increase from the nominal radius of curvature, which will flatten a surface with a positive radius, and will sharpen the curve of a negative radius.

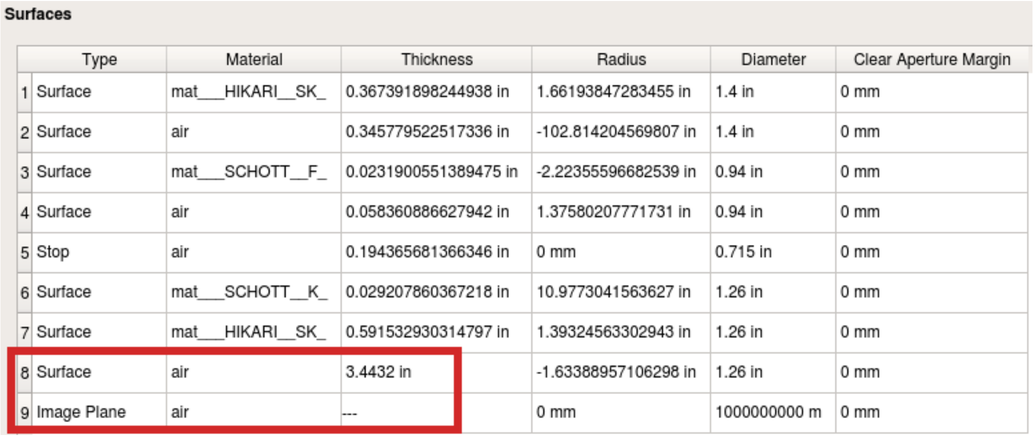
Curvature tolerances specify a tolerance range in terms of change in curvature (units of inverse-length). The positive deviation for such a curvature tolerance will sharpen the curve of a positive curvature, and will flatten a negative curvature.

In Figure 2, we marked some thicknesses and surface curvatures to be toleranced. We also marked the last thickness (the working distance to the image plane surface in the lens stack) to be compensated to counteract any performance changes. The Negative/Positive Change columns were set to the desired tolerance and compensator-optimization ranges.



		Parameter	Type	Negative Change	Positive Change
TOL	⚙	LensStack1 Index1 Surface Curvature	Power-Fringe	-10	+10
TOL	⚙	LensStack1 Index1 Thickness	Direct	-0.2mm	+0.2mm
TOL	⚙	LensStack1 Index2 Surface Curvature	Radius	-10 in	+10 in
		LensStack1 Index2 Thickness	Direct	-1e-3 in	1e-3 in
		LensStack1 Index3 Surface Curvature	Power-Fringe	-10	+10
		LensStack1 Index3 Thickness	Direct	-1e-3 in	1e-3 in
		LensStack1 Index4 Surface Curvature	Power-Fringe	-10	+10
		LensStack1 Index4 Thickness	Direct	-1e-3 in	1e-3 in
		LensStack1 Index5 Surface Curvature	Power-Fringe	-10	+10
		LensStack1 Index5 Thickness	Direct	-1e-3 in	1e-3 in
TOL	⚙	LensStack1 Index6 Surface Curvature	Curvature	-0.0002 in**-1	+0.0002 in**-1
TOL	⚙	LensStack1 Index6 Thickness	Direct	-0.2mm	+0.2mm
TOL	⚙	LensStack1 Index7 Surface Curvature	Power-Fringe	-10	+10
TOL	⚙	LensStack1 Index7 Thickness	Direct	-0.2mm	+0.2mm
TOL	⚙	LensStack1 Index8 Surface Curvature	Power-Fringe	-10	+10
CMP		LensStack1 Index8 Thickness	Direct	-0.25mm	+0.25mm

Figure 2: Tolerancing wizard parameters with various tolerances and a compensated working distance.


Surfaces

	Type	Material	Thickness	Radius	Diameter	Clear Aperture Margin
1	Surface	mat___HIKARI__SK_	0.367391898244938 in	1.66193847283455 in	1.4 in	0 mm
2	Surface	air	0.345779522517336 in	-102.814204569807 in	1.4 in	0 mm
3	Surface	mat___SCHOTT__F_	0.0231900551389475 in	-2.22355596682539 in	0.94 in	0 mm
4	Surface	air	0.058360886627942 in	1.37580207771731 in	0.94 in	0 mm
5	Stop	air	0.194365681366346 in	0 mm	0.715 in	0 mm
6	Surface	mat___SCHOTT__K_	0.029207860367218 in	10.9773041563627 in	1.26 in	0 mm
7	Surface	mat___HIKARI__SK_	0.591532930314797 in	1.39324563302943 in	1.26 in	0 mm
8	Surface	air	3.4432 in	-1.63388957106298 in	1.26 in	0 mm
9	Image Plane	air	---	0 mm	1000000000 m	0 mm

Figure 3: Lens stack surfaces showing working distance to image plane.

2.2 Tolerancing Wizard Settings

The **Settings** tab configures general tolerance analysis settings. Most importantly, it selects which analysis type to run, which metric to measure during the analysis, and whether compensation optimizations are performed.

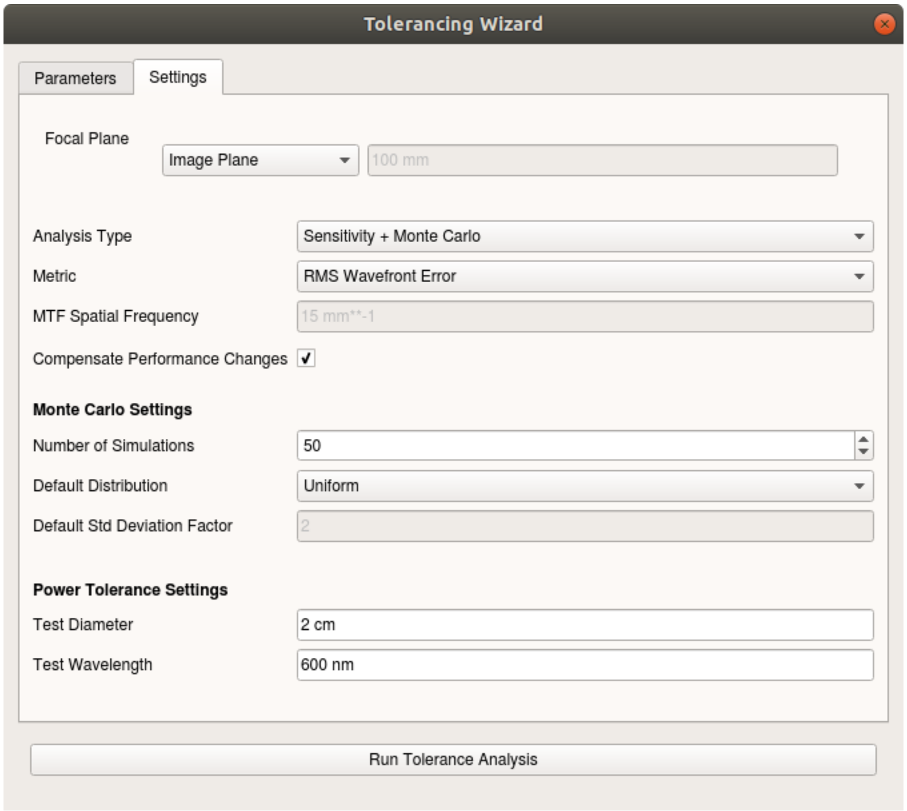
The **Analysis Type** setting allows one or both of the Direct Sensitivity and Monte Carlo analysis types to be selected. A Direct Sensitivity analysis helps identify the most sensitive tolerances by individually perturbing each of the toleranced parameters to their most extreme values. In contrast, a Monte Carlo analysis randomly perturbs all toleranced parameters at once, providing insight on a design's expected as-built performance and manufacturing yield.

The metric used during tolerancing can be set to spot size, wavefront error, or MTF via the **Metric** setting. There are also settings to control the focal plane used to compute the metric. If the tolerancing metric is set to MTF, the **MTF Spatial Frequency** can also be specified. Note that tolerancing MTF will take much longer than tolerancing wavefront error or spot size, due to the computational intensity of the result. This is especially true when compensations are enabled, because the MTF must be computed multiple times for each perturbed simulation. Whichever metric is selected, the resulting performance cost is the sum of that result across all wavelengths and incident angles. If you wish to use a different metric or adjust how the performance costs are computed, see Section 4.2.

If the **Compensate Performance Changes** setting is checked, then any compensated parameters (rows set to "CMP" in the Parameters tab) will be optimized to minimize changes in the performance metric. Note that these compensator optimizations will minimize the change in the tolerance metric compared to the nominal simulation, but will not minimize the metric itself. Additional settings for these optimizations are available in the analysis object's advanced properties (see the "Tolerance Analysis" section of the user manual).

If a Monte Carlo analysis is selected, then the number of perturbed simulations that will be generated is controlled by the **Number of Simulations** setting. In addition, the default probability distribution used to generate the random perturbations is set via the **Default Distribution** setting. Distributions can be set to "Uniform" (all values are equally likely within the negative/positive tolerance range), "End-Point" (only the most extreme negative and positive changes are possible), and "Truncated Gaussian" (a normal/Gaussian probability distribution truncated within the negative/positive tolerance range). The **Default Std Deviation Factor** setting controls the spread of the truncated Gaussian distribution, with a higher factor creating a greater concentration around the midpoint of the distribution. Additional distribution options can be set for individual parameters by clicking the gear button in the Parameters tab (see Section 2.1).

And finally, **Test Diameter** and **Test Wavelength** settings are available at the bottom of the tab. These settings are used when defining surface curvature tolerances in terms of a fringe count. See Section 2.1 or the "Deviated Tolerance Parameters for reTORT" section of the user manual for more information on fringes and power tolerances.



Tolerancing Wizard

Parameters | Settings

Focal Plane: Image Plane, 100 mm

Analysis Type	Sensitivity + Monte Carlo
Metric	RMS Wavefront Error
MTF Spatial Frequency	15 mm**-1
Compensate Performance Changes	☑

Monte Carlo Settings

Number of Simulations	50
Default Distribution	Uniform
Default Std Deviation Factor	2

Power Tolerance Settings

Test Diameter	2 cm
Test Wavelength	600 nm

Run Tolerance Analysis

Figure 4: Tolerancing wizard settings with wavefront error selected.

3 Running a Tolerance Analysis and Viewing Results

After configuring the settings in the tolerancing wizard, we are ready to run the tolerance analysis. Clicking the **Run Tolerance Analysis** button at the bottom of the tolerancing wizard will run the generated AutoTolerance-Analysis object. Alternatively, right-click the tolerance analysis object you wish to run in the model hierarchy, and select the **Run** option. Messages in the status dock and the progress bar in the lower-right corner will display information on the analysis progress. The analysis can be ended prematurely by clicking the stop button next to the progress bar, or clicking the **Stop Tolerance Analysis** button at the bottom of the wizard.

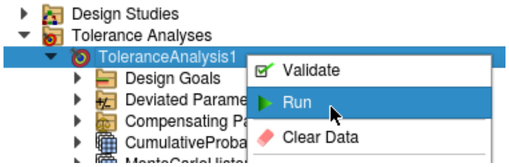
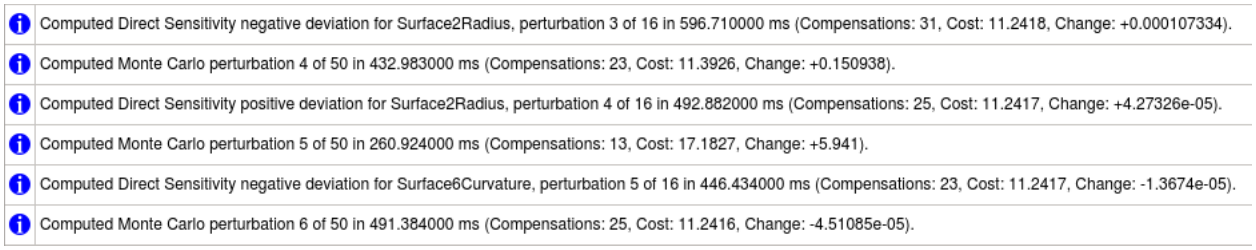


Figure 5: Running a tolerance analysis.



```
Computed Direct Sensitivity negative deviation for Surface2Radius, perturbation 3 of 16 in 596.710000 ms (Compensations: 31, Cost: 11.2418, Change: +0.000107334).
Computed Monte Carlo perturbation 4 of 50 in 432.983000 ms (Compensations: 23, Cost: 11.3926, Change: +0.150938).
Computed Direct Sensitivity positive deviation for Surface2Radius, perturbation 4 of 16 in 492.882000 ms (Compensations: 25, Cost: 11.2417, Change: +4.27326e-05).
Computed Monte Carlo perturbation 5 of 50 in 260.924000 ms (Compensations: 13, Cost: 17.1827, Change: +5.941).
Computed Direct Sensitivity negative deviation for Surface6Curvature, perturbation 5 of 16 in 446.434000 ms (Compensations: 23, Cost: 11.2417, Change: -1.3674e-05).
Computed Monte Carlo perturbation 6 of 50 in 491.384000 ms (Compensations: 25, Cost: 11.2416, Change: -4.51085e-05).
```

Figure 6: Status messages while running a tolerance analysis.

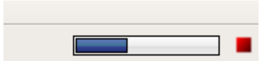


Figure 7: Progress bar during tolerancing.

To view the analysis results, right-click on the result you wish to view in the model hierarchy, and select **Show Table**. Each analysis type will have its own history and summary results. The history tables display information about the nominal simulation performance, and about every perturbed simulation that was examined during the analysis. History tables also include the parameter values used for each perturbed simulation, as well as the optimized values of any compensating parameters. The summary tables contain overall statistics about the information shown in the history table, such as estimated cost and mean performance/cost change. For a Monte Carlo analysis, the **CumulativeProbability** table lists the perturbed simulations in order of their performance, as well as the probabilities of an as-built system having that performance or better. See the “Direct Sensitivity Tolerance Analysis” and “Monte Carlo Tolerance Analysis” sections of the user manual for more information on the data in each table.

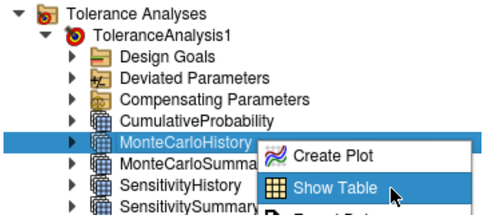
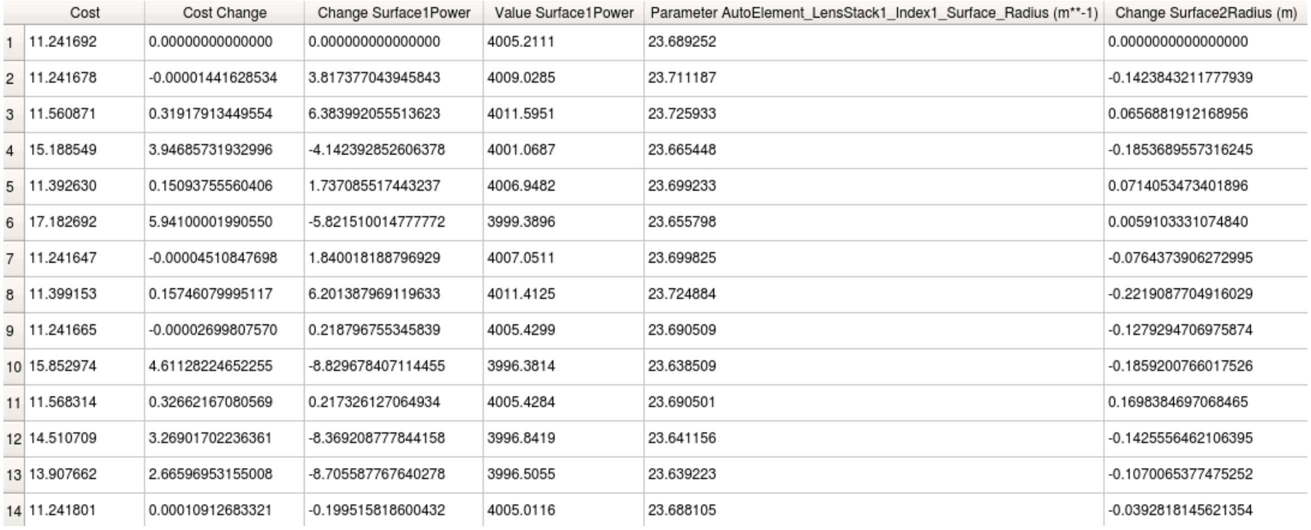
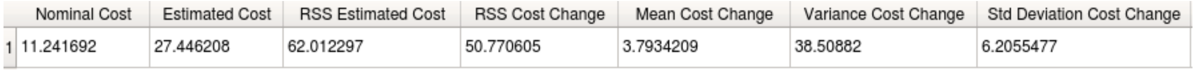


Figure 8: Viewing a table of results.



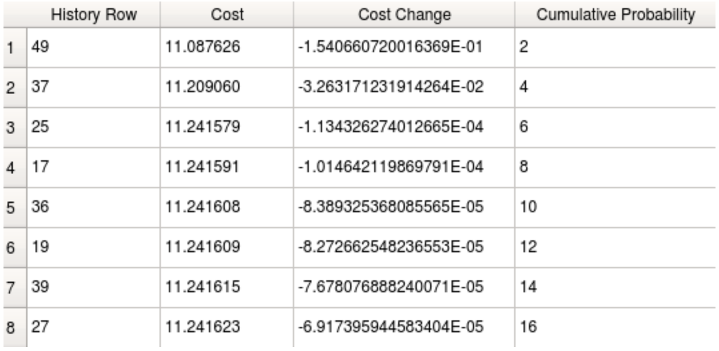
	Cost	Cost Change	Change Surface1Power	Value Surface1Power	Parameter AutoElement_LensStack1_Index1_Surface_Radius (m**-1)	Change Surface2Radius (m)
1	11.241692	0.00000000000000	0.000000000000000	4005.2111	23.689252	0.0000000000000000
2	11.241678	-0.00001441628534	3.817377043945843	4009.0285	23.711187	-0.1423843211777939
3	11.560871	0.31917913449554	6.383992055513623	4011.5951	23.725933	0.0656881912168956
4	15.188549	3.94685731932996	-4.142392852606378	4001.0687	23.665448	-0.1853689557316245
5	11.392630	0.15093755560406	1.737085517443237	4006.9482	23.699233	0.0714053473401896
6	17.182692	5.94100001990550	-5.821510014777772	3999.3896	23.655798	0.0059103331074840
7	11.241647	-0.00004510847698	1.840018188796929	4007.0511	23.699825	-0.0764373906272995
8	11.399153	0.15746079995117	6.201387969119633	4011.4125	23.724884	-0.2219087704916029
9	11.241665	-0.00002699807570	0.218796755345839	4005.4299	23.690509	-0.1279294706975874
10	15.852974	4.61128224652255	-8.829678407114455	3996.3814	23.638509	-0.1859200766017526
11	11.568314	0.32662167080569	0.217326127064934	4005.4284	23.690501	0.1698384697068465
12	14.510709	3.26901702236361	-8.369208777844158	3996.8419	23.641156	-0.1425556462106395
13	13.907662	2.66596953155008	-8.705587767640278	3996.5055	23.639223	-0.1070065377475252
14	11.241801	0.00010912683321	-0.199515818600432	4005.0116	23.688105	-0.0392818145621354

Figure 9: Partial example of a tolerance analysis history table.



	Nominal Cost	Estimated Cost	RSS Estimated Cost	RSS Cost Change	Mean Cost Change	Variance Cost Change	Std Deviation Cost Change
1	11.241692	27.446208	62.012297	50.770605	3.7934209	38.50882	6.2055477

Figure 10: Partial example of a tolerance analysis summary table.



	History Row	Cost	Cost Change	Cumulative Probability
1	49	11.087626	-1.540660720016369E-01	2
2	37	11.209060	-3.263171231914264E-02	4
3	25	11.241579	-1.134326274012665E-04	6
4	17	11.241591	-1.014642119869791E-04	8
5	36	11.241608	-8.389325368085565E-05	10
6	19	11.241609	-8.272662548236553E-05	12
7	39	11.241615	-7.678076888240071E-05	14
8	27	11.241623	-6.917395944583404E-05	16

Figure 11: Partial example of a Monte Carlo cumulative probability table.

3.1 Plotting Cumulative Probability

The **CumulativeProbability** result, enabled during a Monte Carlo analysis, contains the information required to generate a cumulative probability plot. To create the plot, right-click on the **Views** folder under the reTORT simulation in the model hierarchy, and select **New 2D Plot**. Then right-click the **Traces** folder under the plot and add a **New Trace**.

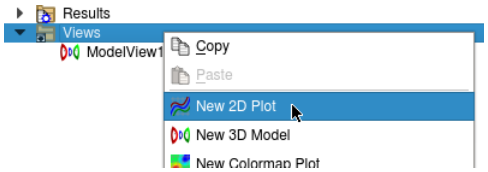


Figure 12: Creating a new 2D plot.

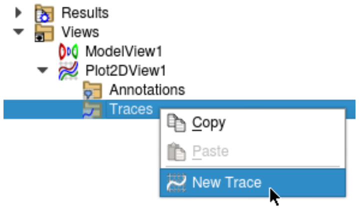
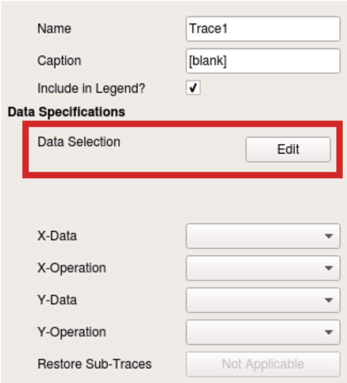


Figure 13: Creating a new plot trace.

In the trace's properties, click the **Edit** button next to **Data Selection**. Select the **CumulativeProbability** result under the tolerance analysis from the popup window, and click OK. Then set the **X-Data** property to "Cost", and **Y-Data** to "Cumulative Probability". If the tolerance analysis was run recently and the CumulativeProbability result has data, the plot should appear. If not, run the analysis now to compute the results.



Name: Trace1

Caption: [blank]

Include in Legend? ☑

Data Specifications

Data Selection

X-Data

X-Operation

Y-Data

Y-Operation

Restore Sub-Traces: Not Applicable

Figure 14: Data "Edit" button on a plot trace.

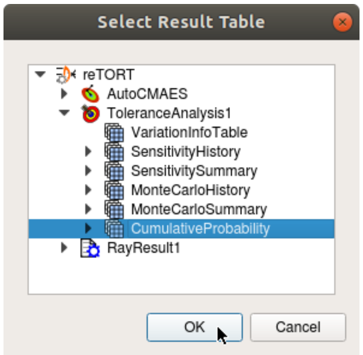
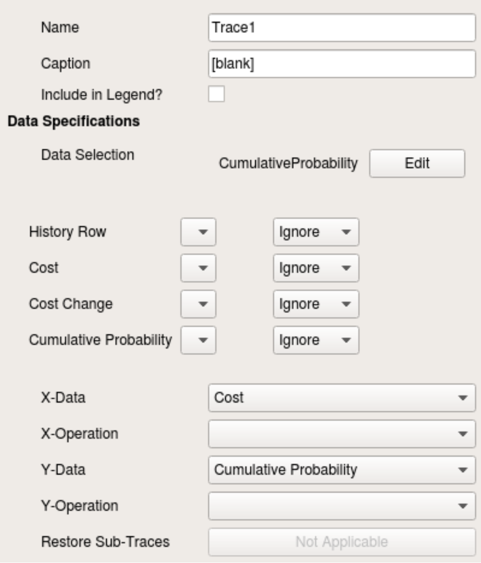


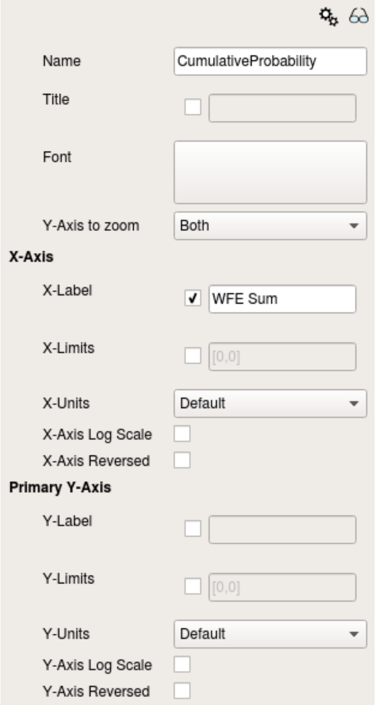
Figure 15: Selecting cumulative probability result for trace data.



Name	Trace1	
Caption	[blank]	
Include in Legend?	□	
Data Specifications		
Data Selection	CumulativeProbability	Edit
History Row	▾	Ignore ▾
Cost	▾	Ignore ▾
Cost Change	▾	Ignore ▾
Cumulative Probability	▾	Ignore ▾
X-Data	Cost ▾	
X-Operation	▾	
Y-Data	Cumulative Probability ▾	
Y-Operation	▾	
Restore Sub-Traces	Not Applicable	

Figure 16: Trace properties for cumulative probability.

To label the cost axis with the name of the result being toleranced, instead of the default “Cost”, check the **X-Label** property in the Plot2DView’s property editor, and enter the desired axis name.



Name	CumulativeProbability
Title	□
Font	
Y-Axis to zoom	Both ▾
X-Axis	
X-Label	☑ WFE Sum
X-Limits	□ [0,0]
X-Units	Default ▾
X-Axis Log Scale	□
X-Axis Reversed	□
Primary Y-Axis	
Y-Label	□
Y-Limits	□ [0,0]
Y-Units	Default ▾
Y-Axis Log Scale	□
Y-Axis Reversed	□

Figure 17: Plot properties for cumulative probability.

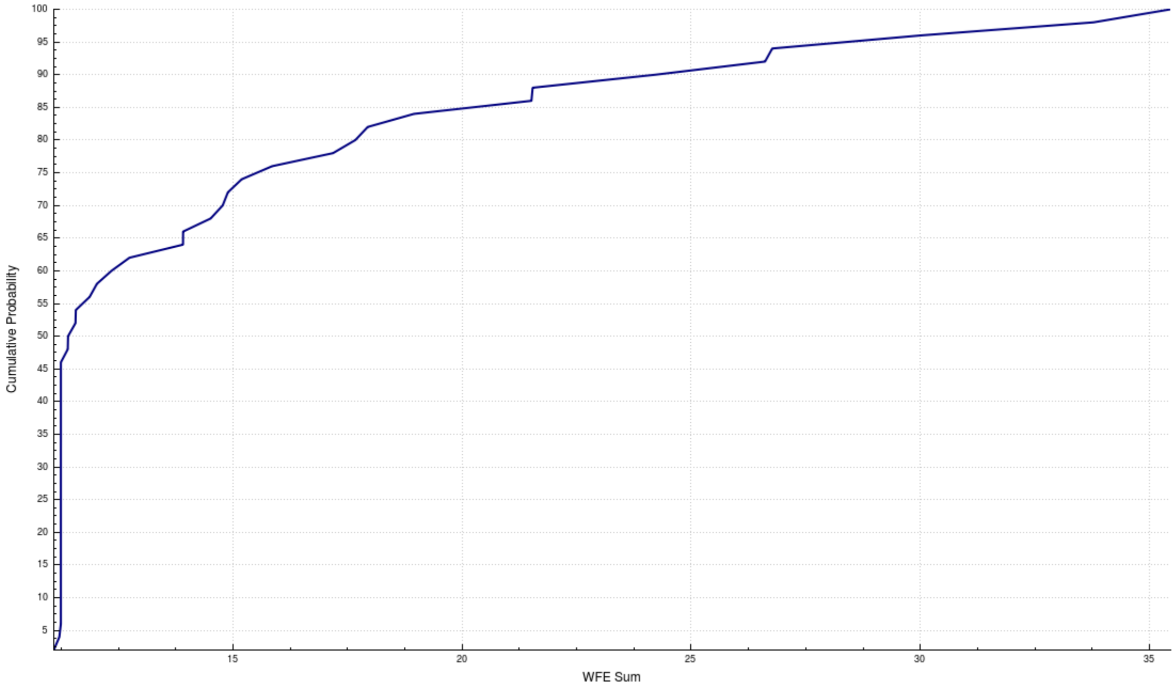
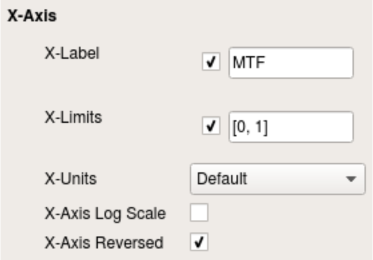


Figure 18: Example of a cumulative probability plot.

By default, the cost axis is displayed with the lowest cost on the left, and the highest cost on the right. For metrics such as MTF where the tolerance analysis **Cost Direction** property is set to “Maximize”, it might be desirable to flip the cumulative probability plot so that higher values are on the left. To do this, check the **X-Axis Reversed** property in the Plot2DView properties to invert the cost axis. We can also restrict the plot to only display MTF values between 0 and 1, by checking the **X-Limits** option and setting the limits to “[0, 1]”. Figure 20 shows an MTF cumulative probability plot with these options enabled.



X-Axis

X-Label ☑ MTF

X-Limits ☑ [0, 1]

X-Units Default

X-Axis Log Scale ☐

X-Axis Reversed ☑

Figure 19: X-axis plot properties for MTF cumulative probability.

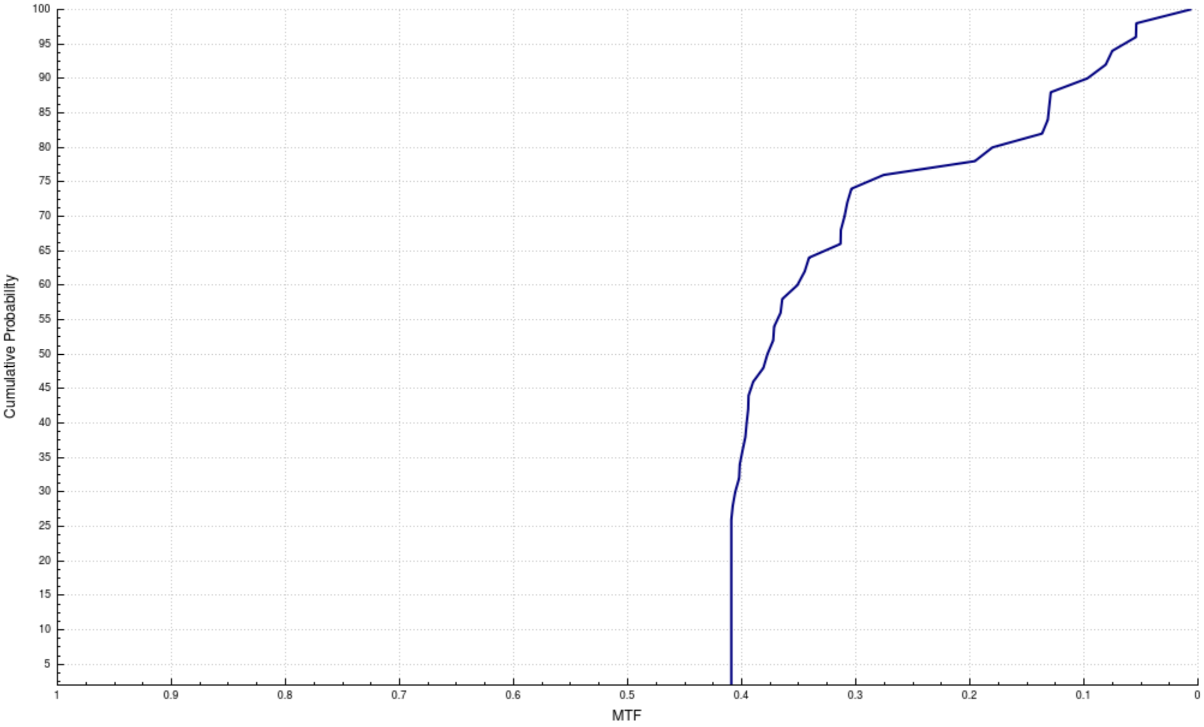


Figure 20: Example of an MTF cumulative probability plot.

4 Custom Tolerance Analysis Setup

The tolerancing wizard makes it easy to generate a tolerance analysis, but sometimes additional features are required, such as tolerancing a custom metric, or compensating with lens properties not listed in the wizard. This section describes how to set up a tolerance analysis by hand in order to configure those features.

Often, it's easiest to run the tolerancing wizard to configure the initial analysis, and make any custom modifications afterwards, rather than creating the analysis from scratch. However, running the wizard a second time may cause some custom modifications to be overwritten. Thus, it is recommended to either copy-paste or rename the generated **AutoToleranceAnalysis** object, so the wizard will ignore it. The renamed tolerance analysis can then be modified without interference from the wizard.

4.1 Creating the Tolerance Analysis

Tolerance Analysis objects can be created by right-clicking the **Tolerance Analyses** folder in the Model Hierarchy dock underneath the reTORT simulation, and selecting **New Tolerance Analysis**. One or both of the Direct Sensitivity and Monte Carlo analysis types may be selected. A Direct Sensitivity analysis helps identify the most sensitive tolerances by individually perturbing each of the toleranced parameters to their most extreme values. In contrast, a Monte Carlo analysis randomly perturbs all toleranced parameters at once, providing insight on a design's expected as-built performance and manufacturing yield.

For each perturbed simulation in either a sensitivity or Monte Carlo analysis, additional parameter values can be optimized to compensate for the change in performance. These compensator optimizations will minimize the change in the tolerance metric compared to the nominal simulation (not the metric itself). Whether or not these compensations are performed is controlled by the **Compensate Performance Changes** property, and additional optimization settings are available in the advanced properties.

Tolerance analyses also offer a **Cost Direction** property, which controls whether the tolerance metric is higher or lower for better systems. This setting affects as-built cost estimations and the computation of cumulative probability. Because many tolerancing results, such as wavefront error and spot size, use lower values to indicate better performance, the cost direction can normally be left at “Minimize”. For results such as MTF, where higher values indicate better performance, it should be set to “Maximize”. For more information on the available Tolerance Analysis settings and how the analysis types behave, see the “Tolerance Analysis” section of the user manual.

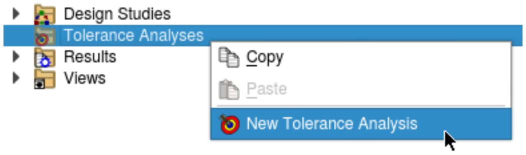
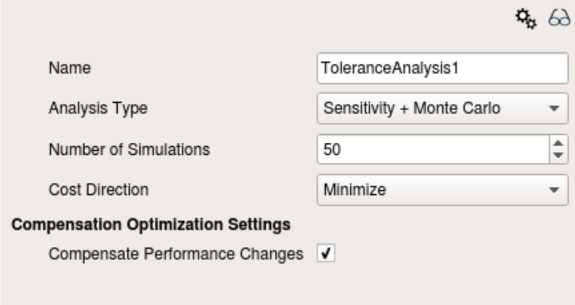


Figure 21: Creating a new tolerance analysis.



Name	ToleranceAnalysis1
Analysis Type	Sensitivity + Monte Carlo
Number of Simulations	50
Cost Direction	Minimize
Compensation Optimization Settings	
Compensate Performance Changes	☑

Figure 22: Tolerance analysis properties.

4.2 Configuring Results and Goals

A Tolerance Analysis object also requires a **Goal** object, which represents the metric/cost being toleranced. Tolerancing requires exactly one goal, and if that goal refers to a result with multiple rows, it must use an appropriate **Cost Aggregation Function** to combine the rows into a single cost. If multiple goals are desired, they must be combined under a group goal, and the group must have an aggregation function to combine the costs of the subgoals. We will show how to tolerance MTF as an example. Although the MTF metric is already offered as an option in the tolerancing wizard, it still provides a good example of how to configure custom goals.

Before creating the goal, first configure the relevant results to which the goal will refer. Most lens results in a reTORT simulation are generated by an Optical Output object, which can be created in the folder located at **reTORT** → **Results** → **RayResult** → **Outputs** in the model hierarchy. While it tends to be safe to enable extra results in the **AutoOpticalOutput** created by the optimization and tolerancing wizards, some kinds of manual changes may be overwritten by or interfere with the wizards. Thus, although we could reuse the AutoOpticalOutput for this MTF example, we will illustrate how to create a new Optical Output for reference.

First, right-click on the Outputs folder underneath the RayResult, and add a **New Optical Output**. By default, the optical output computes its results at the location of the Image Plane surface in the lens stack. However, results can also be computed at other focal plane locations, such as the minimum RMS spot size, or the location of a lens stack surface other than the image plane. We can also configure how centroids are used when computing results, by adjusting the **Use Centroids for Spot Size Calculation** and **Enable Lateral Color Correction** properties. See the “Optical Output” section of the user manual for more information on the available output configuration options.

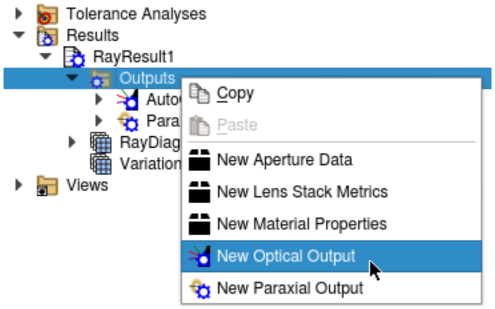
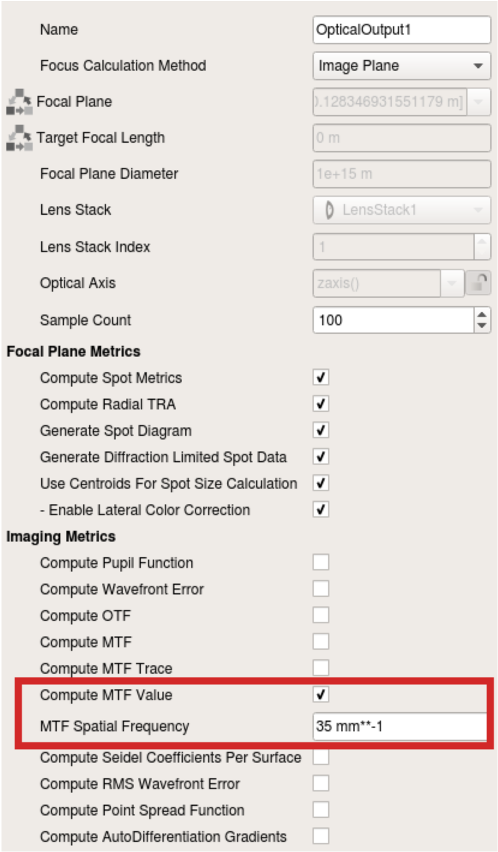


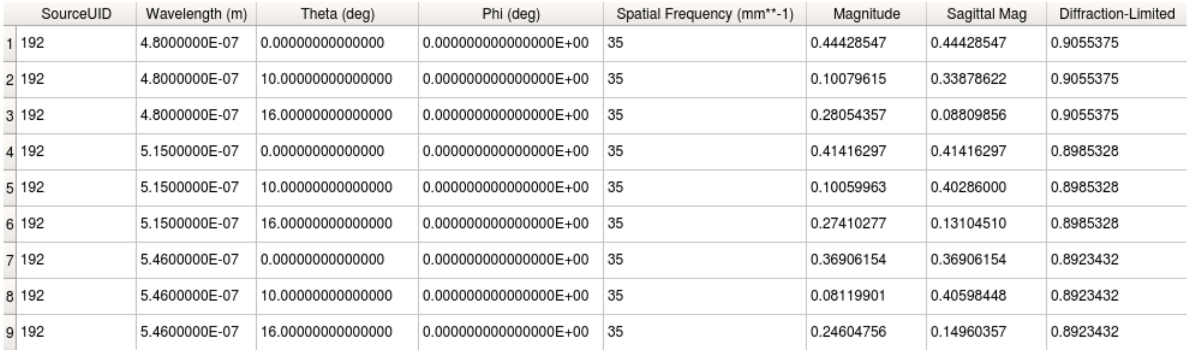
Figure 23: Creating a new optical output.

To compute the MTF metric we will use for tolerancing, check the **Compute MTF Value** option under the “Imaging Metrics” section in the optical output properties. Then set the desired spatial frequency in the **MTF Spatial Frequency** field just below it. This will add the **MTFValue** result table under the optical output in the model hierarchy. The MTFValue table contains one row for every ray bundle in the simulation (each wavelength and incident angle), and computes the MTF values by performing a linear interpolation of the MTF trace for each bundle. (To view the MTF trace for a system, use the MTF plotting wizard by selecting **Tools** → **reTORT** → **Create MTF Graph** from the menu bar.)



Name	OpticalOutput1
Focus Calculation Method	Image Plane
Focal Plane	).128346931551179 m]
Target Focal Length	0 m
Focal Plane Diameter	1e+15 m
Lens Stack	LensStack1
Lens Stack Index	1
Optical Axis	zaxis()
Sample Count	100
Focal Plane Metrics	
Compute Spot Metrics	☑
Compute Radial TRA	☑
Generate Spot Diagram	☑
Generate Diffraction Limited Spot Data	☑
Use Centroids For Spot Size Calculation	☑
- Enable Lateral Color Correction	☑
Imaging Metrics	
Compute Pupil Function	□
Compute Wavefront Error	□
Compute OTF	□
Compute MTF	□
Compute MTF Trace	□
Compute MTF Value	☑
MTF Spatial Frequency	35 mm**-1
Compute Seidel Coefficients Per Surface	□
Compute RMS Wavefront Error	□
Compute Point Spread Function	□
Compute AutoDifferentiation Gradients	□

Figure 24: Optical output properties with MTF value enabled.



	SourceUID	Wavelength (m)	Theta (deg)	Phi (deg)	Spatial Frequency (mm**-1)	Magnitude	Sagittal Mag	Diffraction-Limited
1	192	4.8000000E-07	0.00000000000000	0.000000000000000E+00	35	0.44428547	0.44428547	0.9055375
2	192	4.8000000E-07	10.00000000000000	0.000000000000000E+00	35	0.10079615	0.33878622	0.9055375
3	192	4.8000000E-07	16.00000000000000	0.000000000000000E+00	35	0.28054357	0.08809856	0.9055375
4	192	5.1500000E-07	0.00000000000000	0.000000000000000E+00	35	0.41416297	0.41416297	0.8985328
5	192	5.1500000E-07	10.00000000000000	0.000000000000000E+00	35	0.10059963	0.40286000	0.8985328
6	192	5.1500000E-07	16.00000000000000	0.000000000000000E+00	35	0.27410277	0.13104510	0.8985328
7	192	5.4600000E-07	0.00000000000000	0.000000000000000E+00	35	0.36906154	0.36906154	0.8923432
8	192	5.4600000E-07	10.00000000000000	0.000000000000000E+00	35	0.08119901	0.40598448	0.8923432
9	192	5.4600000E-07	16.00000000000000	0.000000000000000E+00	35	0.24604756	0.14960357	0.8923432

Figure 25: Example of an MTF value table.

Next, we configure the MTF goal. Right-click the **Design Goals** folder under the tolerance analysis in the model hierarchy, and add a **New Goal**. Delete any pre-existing goals in the same folder. In the goal's properties, click the **Edit** button next to **Data Selection**. Select the MTFValue result with your optical output's name under the RayResult item in the popup window, and click OK. Then set the **Data** property to "Magnitude". We will also change the **Comparison** from "minimize" to "none", since we want to tolerance the MTF values as they stand. (Although "minimize" and "none" are functionally equivalent, the other comparison methods may alter the result values for optimization purposes.)

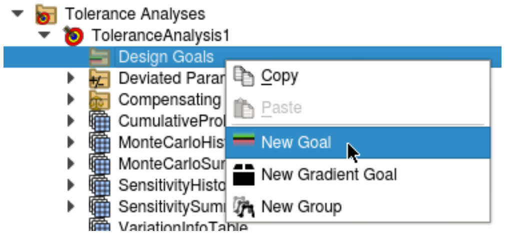
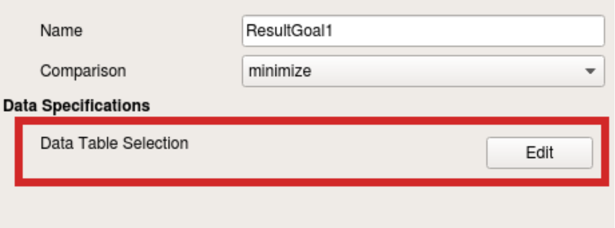


Figure 26: Creating a new goal.



Name: ResultGoal1

Comparison: minimize

Data Specifications

Data Table Selection

Figure 27: Data "Edit" button on a goal.

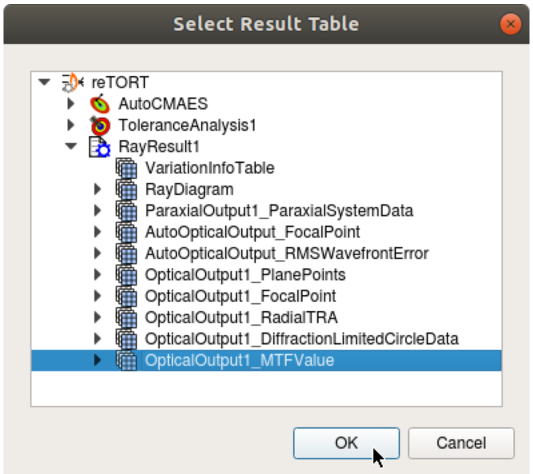
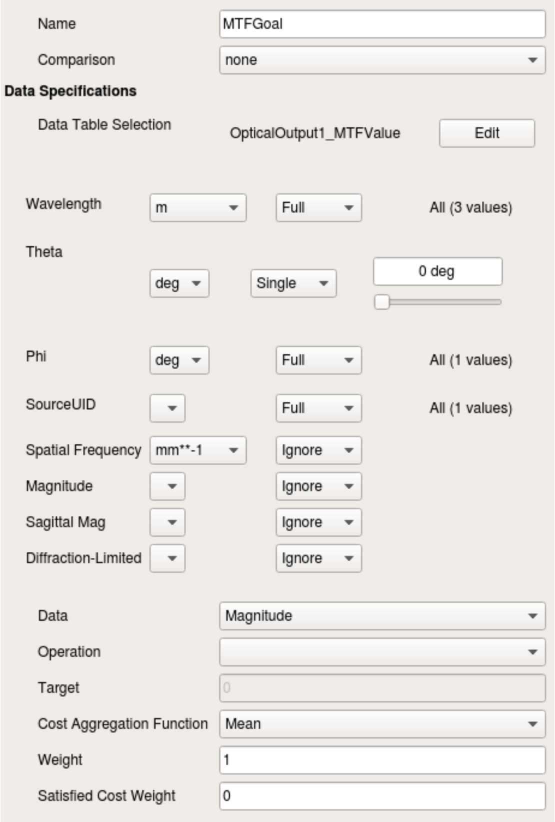

Select Result Table
reTORT
AutoCMAES
ToleranceAnalysis1
RayResult1
VariationInfoTable
RayDiagram
ParaxialOutput1_ParaxialSystemData
AutoOpticalOutput_FocalPoint
AutoOpticalOutput_RMSWavefrontError
OpticalOutput1_PlanePoints
OpticalOutput1_FocalPoint
OpticalOutput1_RadialTRA
OpticalOutput1_DiffractionLimitedCircleData
OpticalOutput1_MTFValue
OK
Cancel

Figure 28: Selecting MTF value result for goal data.

Once we select a result table using the Edit button, a list of column names with dropdown menus should appear. Optionally, we can filter which rows of the MTF table we want to tolerance by changing one or more of these options from “Full” to “Single”, and specifying the value we wish to include. For instance, to only tolerance the on-axis MTF, we could change the **Theta** item from “Full” to “Single”, and use the slider to select “0 deg”. (These filtering options work best if the result they reference has already been computed. Run the simulation if necessary, and if the filters still don’t contain the expected raybundle values, refresh the property editor by selecting a different object in the model hierarchy, and re-selecting the goal.) These filtering options are the same ones that appear for a table view when you right-click a result and select **Show Table**; applying the same filtering options to such a table view can help visualize how the goal will behave.

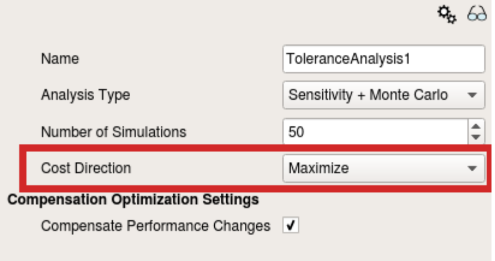


Name	MTFGoal		
Comparison	none		
Data Specifications			
Data Table Selection	OpticalOutput1_MTFValue	Edit	
Wavelength	m	Full	All (3 values)
Theta	deg	Single	0 deg
Phi	deg	Full	All (1 values)
SourceUID		Full	All (1 values)
Spatial Frequency	mm**-1	Ignore	
Magnitude		Ignore	
Sagittal Mag		Ignore	
Diffraction-Limited		Ignore	
Data	Magnitude		
Operation			
Target	0		
Cost Aggregation Function	Mean		
Weight	1		
Satisfied Cost Weight	0		

Figure 29: MTF goal properties.

To combine multiple MTF values from the result into a single cost, set the **Cost Aggregation Function** property to an appropriate operation. This property controls how the values in each row are combined into a single metric. In Figure 29, the cost aggregation is set to "Mean", and the theta filter is set to only allow on-axis ray bundles, so this goal will compute the average MTF over all wavelengths for the on-axis field.

If desired, a weight could be applied to the goal as well, or multiple goals could be collected under a single **Group Goal**. For instance, if the metric we wanted to tolerance was a weighted combination of the on-axis and off-axis MTF values, we could assign a higher weight to the on-axis MTF goal, and create a second goal with a lower weight that filtered for an off-axis theta value. Both goals could be collected under a group goal, with an appropriate aggregation function set for the group. However, weighting and grouping multiple tolerance goals can make the relationship between the tolerance cost and the performance of a system more complicated and less intuitive. Thus, we will only tolerance the on-axis MTF for the example shown here. See the "Goals" section of the user manual for more information on goals and their properties.



Name	ToleranceAnalysis1
Analysis Type	Sensitivity + Monte Carlo
Number of Simulations	50
Cost Direction	Maximize
Compensation Optimization Settings	
Compensate Performance Changes	☑

Figure 30: Tolerance analysis properties with cost direction set to "Maximize".

Because a higher MTF value indicates better performance, we also need to set the **Cost Direction** property on the Tolerance Analysis object to “Maximize”. (Note that you should not set the goal’s comparison to “maximize” to accomplish this, because that would alter the MTF values for optimization purposes; we want to tolerance the unaltered MTF values.)

Once the result, goal, and cost direction have been configured, we can move on to tolerances and compensating parameters.

4.3 Configuring Tolerances and Compensators

To finish configuring the Tolerance Analysis object, we must also create any desired **Deviated Parameters** (the properties we will tolerance), and **Compensating Parameters** (any properties that can be adjusted during compensation) in the folders underneath the analysis. The deviation and compensation objects will refer to **Parameter** objects that can be created manually or through the tolerancing and optimization wizards.

4.3.1 Using Wizard-Generated Parameters

The optimization and tolerancing wizards can be used to automatically parameterize a variety of system properties. Those parameters can be reused when configuring the tolerance ranges and compensator optimization ranges for the tolerance analysis.

To open the optimization wizard, you can click the optimization wizard button in the toolbar, or select **Tools** → **reTORT** → **Optimization Wizard** from the menu bar. You can also right-click the reTORT simulation and select **Tools** → **Optimization Wizard**. If this is the first time running the optimization wizard for this file, select an optimization type and click **OK** in the popup dialog. Otherwise, open the **Parameters** tab and click the checkbox next to any system properties you want to tolerance or use for compensation.

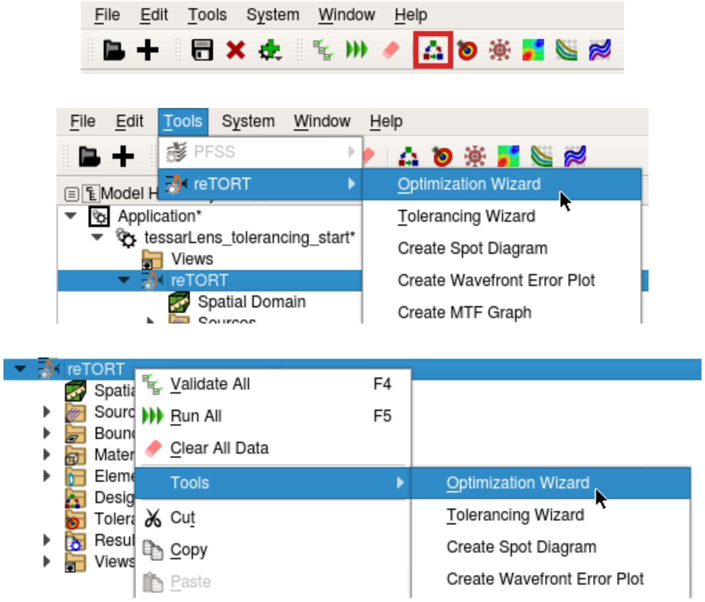
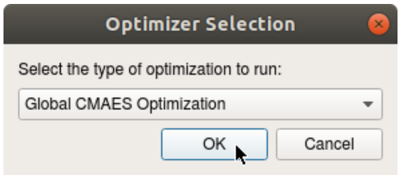


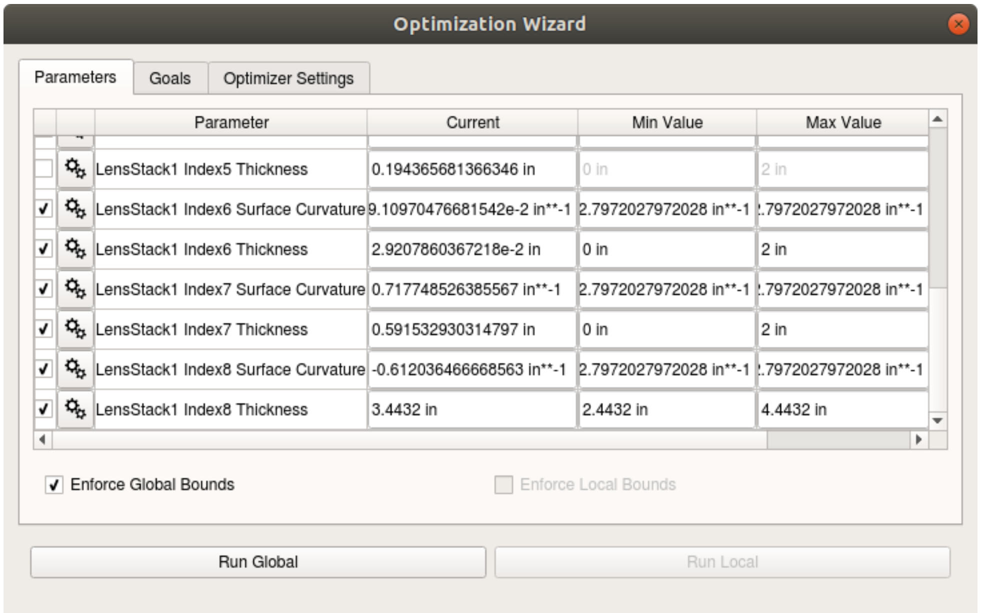
Figure 31: Ways to start the Optimization Wizard.



Select the type of optimization to run:

Global CMAES Optimization

Figure 32: First-time optimizer selection dialog.



		Parameter	Current	Min Value	Max Value
□		LensStack1 Index5 Thickness	0.194365681366346 in	0 in	2 in
☑		LensStack1 Index6 Surface Curvature	9.10970476681542e-2 in**-1	2.7972027972028 in**-1	.7972027972028 in**-1
☑		LensStack1 Index6 Thickness	2.9207860367218e-2 in	0 in	2 in
☑		LensStack1 Index7 Surface Curvature	0.717748526385567 in**-1	2.7972027972028 in**-1	.7972027972028 in**-1
☑		LensStack1 Index7 Thickness	0.591532930314797 in	0 in	2 in
☑		LensStack1 Index8 Surface Curvature	-0.612036466668563 in**-1	2.7972027972028 in**-1	.7972027972028 in**-1
☑		LensStack1 Index8 Thickness	3.4432 in	2.4432 in	4.4432 in

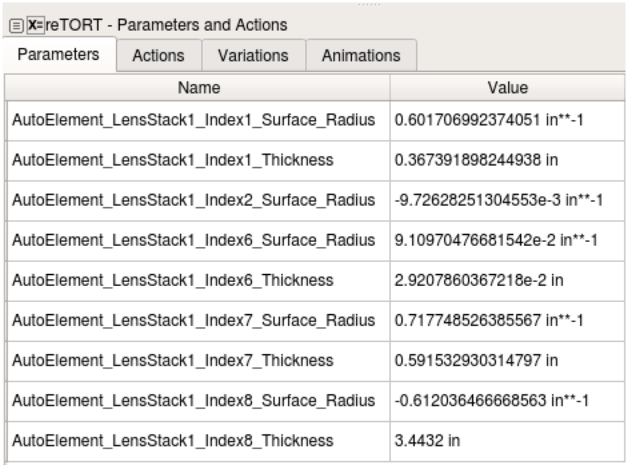
☑ Enforce Global Bounds

□ Enforce Local Bounds

Figure 33: Optimization wizard parameters with working distance and others selected.

To parameterize properties using the tolerancing wizard instead, run the wizard like in Section 2. In the **Parameters** tab, set the relevant system properties to be either toleranced or compensated as desired ("TOL" or "CMP" in the dropdown menu on the left). If desired, the deviated and compensated parameter objects created underneath the auto-generated tolerance analysis could be copied into your manually-configured analysis. Otherwise, the tolerances and compensators can be defined manually, as described in Section 4.3.3 and Section 4.3.4.

Both wizards will create parameters for any selected properties (visible in the **Parameters and Actions** dock), and will automatically modify the simulation to use those parameters in the corresponding properties. This is especially helpful for parameterizing surface curvatures, because the wizard will automatically parameterize a surface's radius-of-curvature with a curvature parameter value, which is what we need for tolerancing. If the properties you wish to tolerance are not listed in the wizard, you can read more about configuring your own parameters in Section 4.3.2.

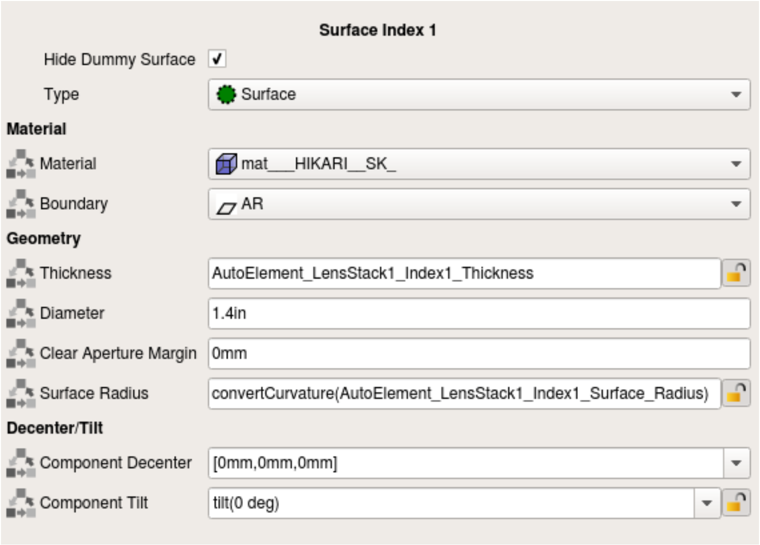


reTORT - Parameters and Actions

Parameters | Actions | Variations | Animations

Name	Value
AutoElement_LensStack1_Index1_Surface_Radius	0.601706992374051 in**-1
AutoElement_LensStack1_Index1_Thickness	0.367391898244938 in
AutoElement_LensStack1_Index2_Surface_Radius	-9.72628251304553e-3 in**-1
AutoElement_LensStack1_Index6_Surface_Radius	9.10970476681542e-2 in**-1
AutoElement_LensStack1_Index6_Thickness	2.9207860367218e-2 in
AutoElement_LensStack1_Index7_Surface_Radius	0.717748526385567 in**-1
AutoElement_LensStack1_Index7_Thickness	0.591532930314797 in
AutoElement_LensStack1_Index8_Surface_Radius	-0.612036466668563 in**-1
AutoElement_LensStack1_Index8_Thickness	3.4432 in

Figure 34: Parameters generated by the wizards.



Surface Index 1

Hide Dummy Surface ☑

Type: Surface

Material

Material: mat___HIKARI__SK_

Boundary: AR

Geometry

Thickness: AutoElement_LensStack1_Index1_Thickness

Diameter: 1.4in

Clear Aperture Margin: 0mm

Surface Radius: convertCurvature(AutoElement_LensStack1_Index1_Surface_Radius)

Decenter/Tilt

Component Decenter: [0mm,0mm,0mm]

Component Tilt: tilt(0 deg)

Figure 35: Lens stack surface parameterized by the wizards.

4.3.2 Creating Custom Parameters

Sometimes, it may be necessary to tolerance properties that are not listed in the wizards, or to optimize such properties during compensation. To do this, we can create and apply our own **Parameter** objects, and refer to them in the deviation and compensation objects, just like we would use wizard-generated parameters. To illustrate, we will create a parameter for the effective focal length.

To create a new parameter, right-click in the **Parameters** tab of the **Parameters and Actions** dock, and select **New Parameter**. Double-click the **Name** column to rename the parameter. Then double-click the **Value** column to enter a value. To use the parameter, simply enter the name of the parameter in any property where you could use the parameter's value. Parameters can also be used in place of a quantity as part of an expression.

Figure 37 and Figure 38 show a parameter being used for an optical output's effective focal length (distance from the back principal point to the optical output's measurement plane). This parameter is used by a custom compensator object in Section 4.3.4 in order to optimize the effective focal length to compensate for any performance changes. However, custom parameters can also be used in tolerance ranges, as described in Section 4.3.3.

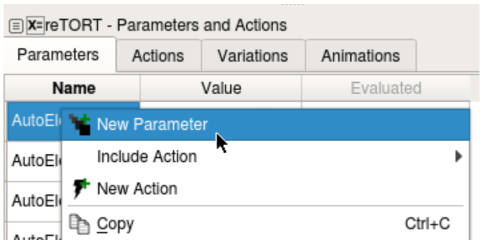
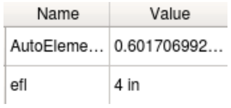
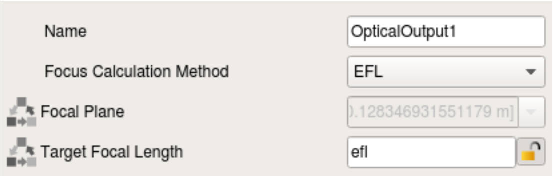


Figure 36: Creating a new parameter.



Name	Value
AutoEleme…	0.601706992…
efl	4 in

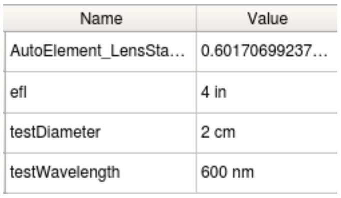
Figure 37: Parameter for compensating effective focal length.



Name	OpticalOutput1
Focus Calculation Method	EFL
Focal Plane	).128346931551179 m]
Target Focal Length	efl

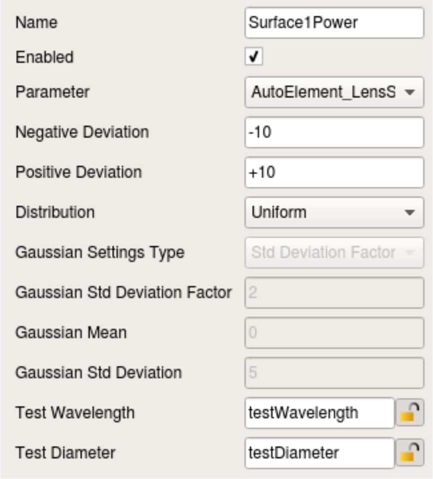
Figure 38: Optical output using EFL parameter for focal plane position.

Parameters can also be used to make tolerance configuration easier. For instance, parameters could be used to set the test wavelength and surface diameter for power-fringe tolerances. Any changes made to the test wavelength/diameter will then only need to be made to the parameter, instead of updating each deviation individually. The tolerancing wizard makes use of this by creating “AutoTolerance_TestDiameter” and “AutoTolerance_TestWavelength” parameters, which it uses in its auto-generated tolerance ranges.



Name	Value
AutoElement_LensSta…	0.60170699237…
efl	4 in
testDiameter	2 cm
testWavelength	600 nm

Figure 39: Custom parameters for test wavelength/diameter values.



Name	Surface1Power
Enabled	☑
Parameter	AutoElement_LensS
Negative Deviation	-10
Positive Deviation	+10
Distribution	Uniform
Gaussian Settings Type	Std Deviation Factor
Gaussian Std Deviation Factor	2
Gaussian Mean	0
Gaussian Std Deviation	5
Test Wavelength	testWavelength
Test Diameter	testDiameter

Figure 40: Power tolerance using custom test wavelength/diameter parameters.

4.3.3 Configuring Tolerances

To configure the tolerance ranges for the parameters that will be perturbed during the analysis, create a deviation object for every parameter. Each deviation will be associated with a parameter, and defines the upper and lower tolerance ranges to be used for that parameter (the maximum deviations that may be applied to the parameter during analysis). If a Monte Carlo analysis is being performed, the random distribution used to perturb the parameter can also be set. Right-clicking on the **Deviated Parameters** collection under the tolerance analysis in the Model Hierarchy will display the types of deviations available.

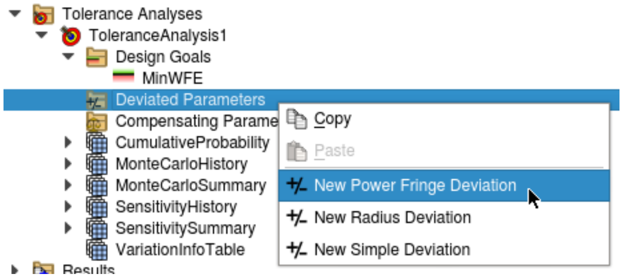
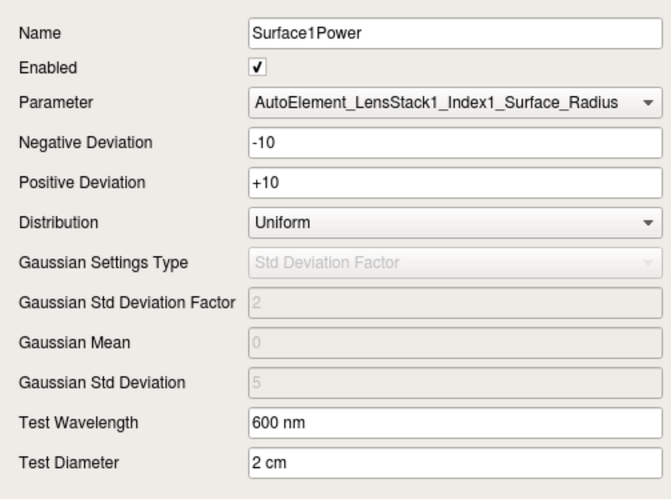


Figure 41: Creating a new deviated parameter.

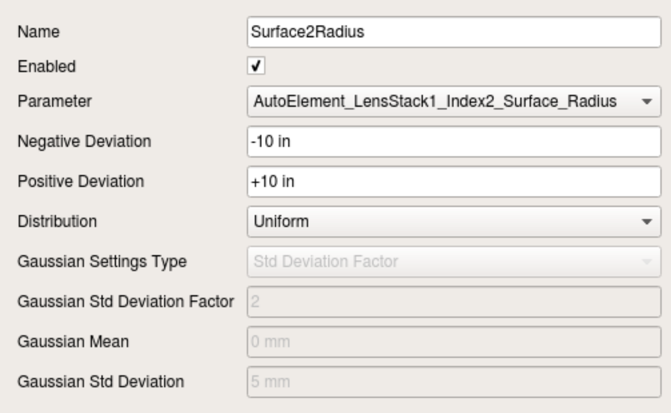
Power Fringe Deviations are used for surface curvatures. Their corresponding parameters must be curvatures (with units of inverse-length), and their tolerance ranges are specified in numbers of fringes when compared with a test surface of the nominal curvature. In addition to the normal tolerance range properties, power-fringe deviations also require the diameter of the test surface and a test wavelength. A single fringe is equivalent to a $\frac{\lambda}{2}$ change in the sag of the surface, where λ is the test wavelength, and the sag is calculated at the test diameter. A positive fringe deviation moves the sag towards the back of the lens, which will make positive curvatures more extreme, and will make negative curvatures flatter.



Name	Surface1Power
Enabled	☑
Parameter	AutoElement_LensStack1_Index1_Surface_Radius
Negative Deviation	-10
Positive Deviation	+10
Distribution	Uniform
Gaussian Settings Type	Std Deviation Factor
Gaussian Std Deviation Factor	2
Gaussian Mean	0
Gaussian Std Deviation	5
Test Wavelength	600 nm
Test Diameter	2 cm

Figure 42: Power deviation properties.

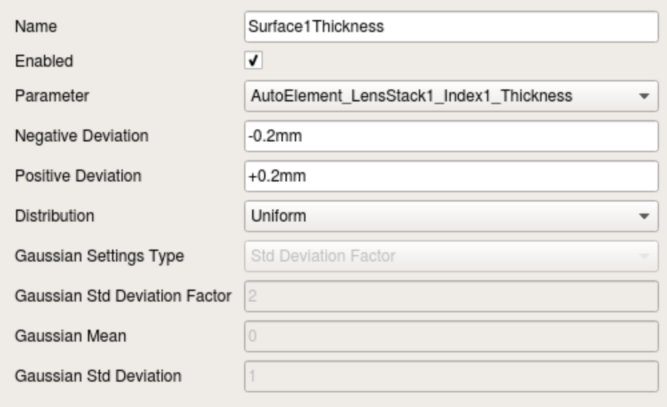
Radius Deviations are also used for surface curvatures. However, instead of fringes, they specify their tolerance ranges in terms of a change in radius of curvature (units of length). Like power deviations, they also require curvature parameters with units of inverse length. A positive radius deviation indicates an increase from the nominal radius of curvature, which will flatten a surface with a positive radius, and will sharpen the curve of a negative radius.



Name	Surface2Radius
Enabled	☑
Parameter	AutoElement_LensStack1_Index2_Surface_Radius
Negative Deviation	-10 in
Positive Deviation	+10 in
Distribution	Uniform
Gaussian Settings Type	Std Deviation Factor
Gaussian Std Deviation Factor	2
Gaussian Mean	0 mm
Gaussian Std Deviation	5 mm

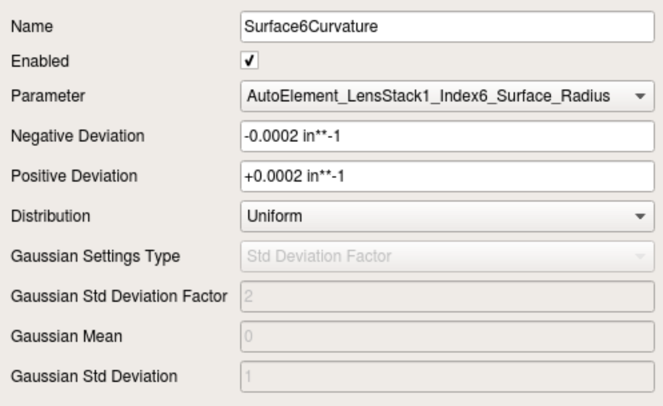
Figure 43: Radius deviation properties.

Simple Deviations are used for other toleranced properties, such as thicknesses and material coefficients. They can be used with parameters with any units, and specify their tolerance ranges in the same units as the parameter. When used with surface curvature parameters, they specify a tolerance range directly in terms of a change in curvature, rather than converting it to fringes or a change in radius. The positive deviation for such a curvature tolerance will sharpen the curve of a positive curvature, and will flatten a negative curvature.



Name	Surface1Thickness
Enabled	☑
Parameter	AutoElement_LensStack1_Index1_Thickness
Negative Deviation	-0.2mm
Positive Deviation	+0.2mm
Distribution	Uniform
Gaussian Settings Type	Std Deviation Factor
Gaussian Std Deviation Factor	2
Gaussian Mean	0
Gaussian Std Deviation	1

Figure 44: Simple thickness deviation properties.



Name	Surface6Curvature
Enabled	☑
Parameter	AutoElement_LensStack1_Index6_Surface_Radius
Negative Deviation	-0.0002 in**-1
Positive Deviation	+0.0002 in**-1
Distribution	Uniform
Gaussian Settings Type	Std Deviation Factor
Gaussian Std Deviation Factor	2
Gaussian Mean	0
Gaussian Std Deviation	1

Figure 45: Simple curvature deviation properties.

After creating the relevant deviation, select the corresponding parameter from the **Parameter** dropdown in the deviation's properties. Then set the tolerance ranges in the **Negative** and **Positive Deviation** properties; these properties represent the maximum changes in the parameter, not the min and max parameter values themselves. When using a power-fringe tolerance, you will also need to set the test diameter and test wavelength. Finally, the distribution used to generate random perturbations should also be configured when running a Monte Carlo analysis.

See the "Deviated Tolerance Parameters" and "Deviated Tolerance Parameters for reTORT" sections of the user manual for more information on deviated/toleranced parameters.

4.3.4 Configuring Compensators

Compensated parameters are used to configure which property values can be optimized to minimize any performance changes during a tolerance analysis. Compensation is not required for an analysis, so these can be skipped if desired. Just like with deviations, right-click on the **Compensating Parameters** folder to create a compensation object for every parameter you wish to optimize.

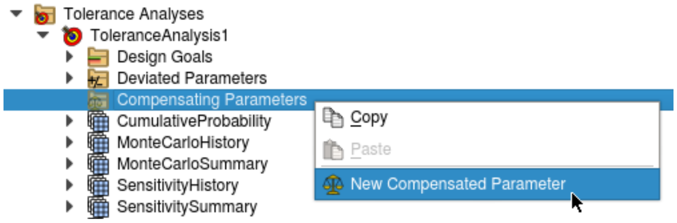
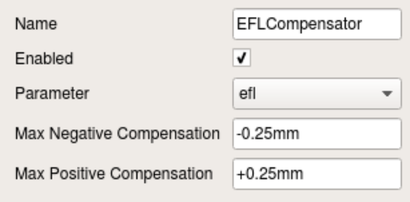


Figure 46: Creating a new compensated parameter.

After creating a compensation object, select the corresponding parameter from the **Parameter** dropdown in the object properties. Then set the max positive/negative changes allowed via the **Max Positive/Negative Compensation** properties (these represent maximum changes in the parameter, not the min/max values themselves). Like with simple deviations, the changes must have the same units as the parameter value.

Figure 47 shows a compensator object for optimizing the effective focal length parameter created in Section 4.3.2. Once any desired tolerances and compensators have been configured for the tolerance analysis, it can be run by right-clicking the analysis in the model hierarchy and selecting the **Run** option as described in Section 3.



Name	EFLCompensator
Enabled	☑
Parameter	efl
Max Negative Compensation	-0.25mm
Max Positive Compensation	+0.25mm

Figure 47: EFL compensator properties.