QUICK START GUIDE 4.1
Guide to Wavefront Matching with E x H reTORT Ray Tracer
Estimated Time to Invest: 15 minutes

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1.0 Introduction

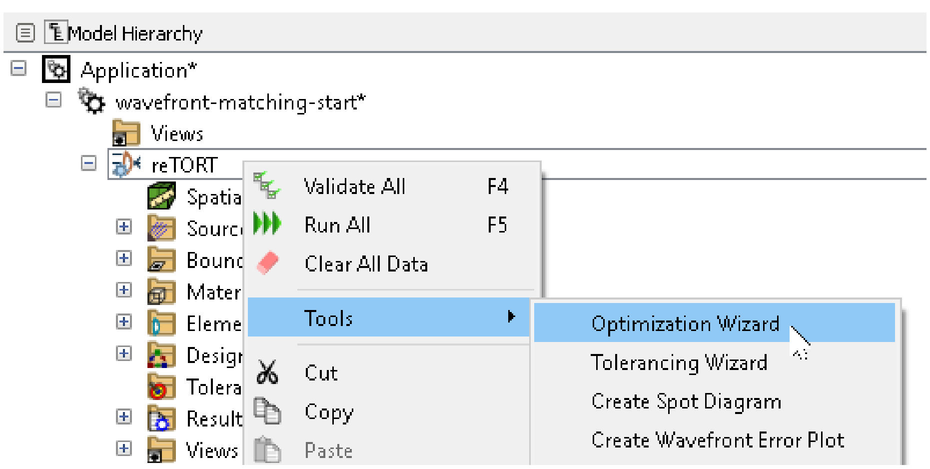
Wavefront matching is a useful technique in lens design. In particular, it can make replacing homogeneous lenses with a GRIN lens during a SWaP reduction much easier. Rather than optimizing a lens for its best standalone performance, wavefront-matching can optimize a GRIN lens to match the performance of the lenses it is replacing.

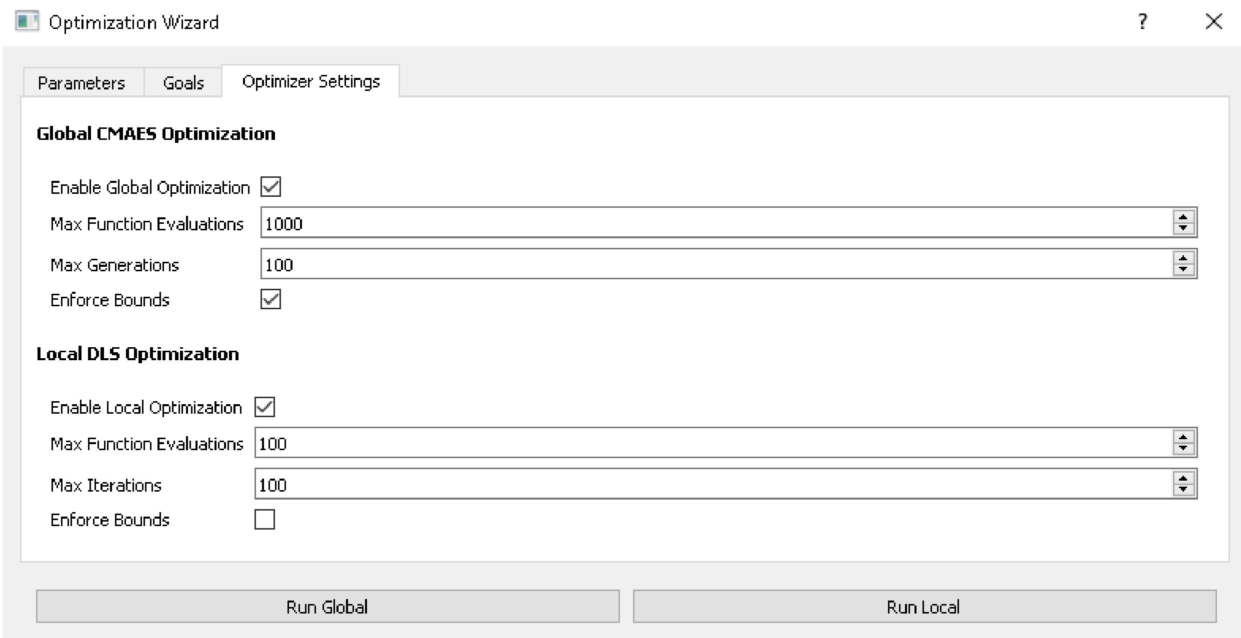
In reTORT, wavefront matching is implemented by matching spot diagrams. Thus, the terms “wavefront matching” and “spot diagram matching” are used interchangeably. This document will show how to use wavefront matching in a reTORT optimization by saving the spot diagram/wavefront profile, enabling the spot diagram matching result, and using that result in an optimization.

2.0 Preparing the Lens System and Optimization

For this guide, we will start with the GRIN lens system that was created as part of the SWaP reduction tutorial. That file has been included with this guide as “wavefront-matching-start.gemsif”.

In addition to the DLS optimization that was created during the tutorial, we will also add a global CMAES optimization. The optimization wizard can be run by right-clicking the reTORT simulation in the Model Hierarchy and selecting Tools > Optimization Wizard, or by clicking the Optimization Wizard icon in the toolbar. If the Optimization Wizard icon is not shown in the toolbar, make sure that “reTORT” is selected in the Model Hierarchy dock. The CMAES optimization can be enabled by checking the Enable Global Optimization option in the Optimizer Settings tab of the wizard. You may also wish to disable the local DLS optimization, so its finite-difference calculations do not interfere with CMAES. However, we will include it in the guide for now for the sake of completeness.

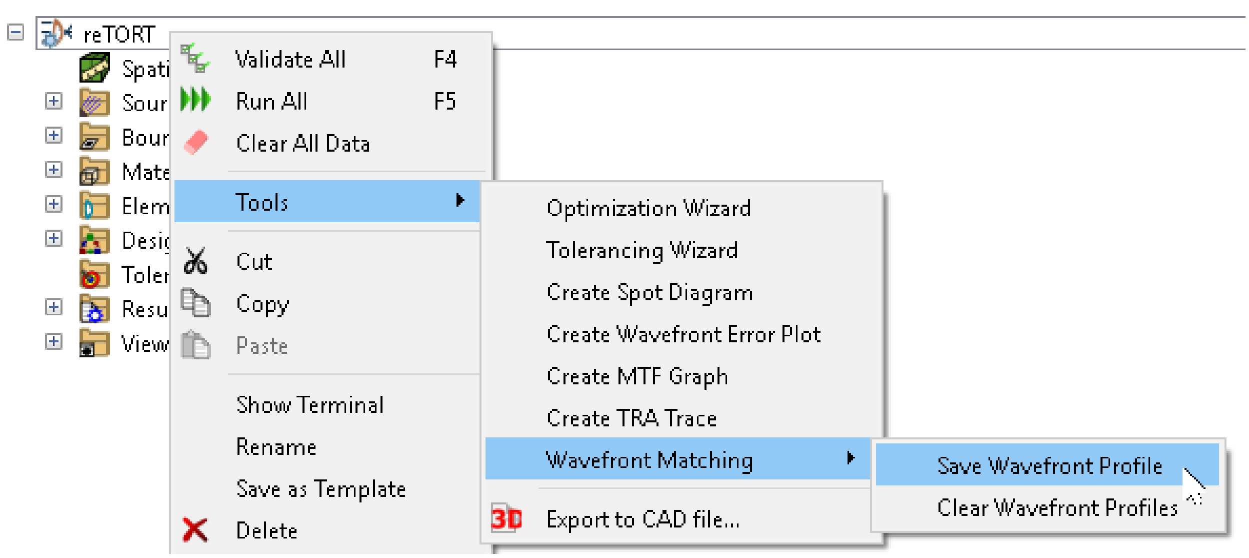




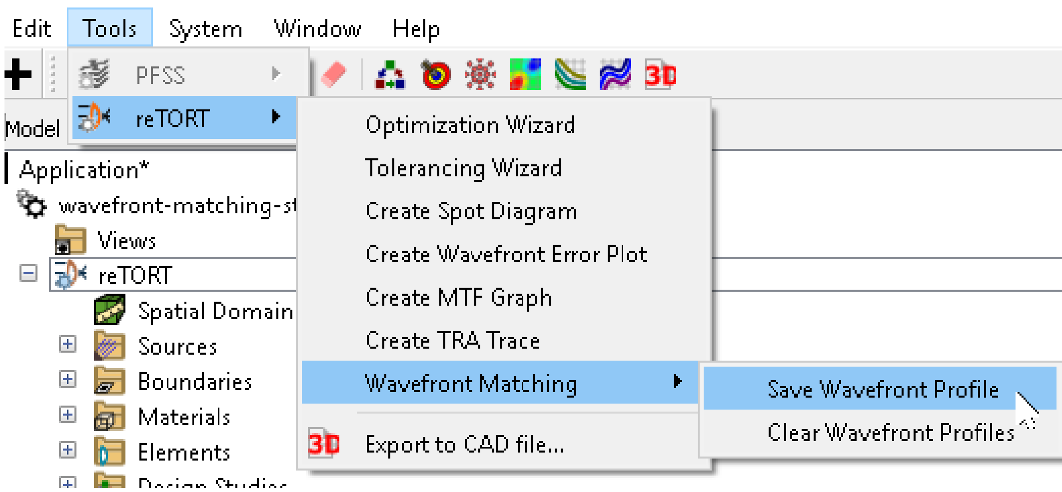
3.0 Saving the Current Wavefront Profile

Before modifying the optimization for wavefront matching, we need to save the wavefront we're going to match.

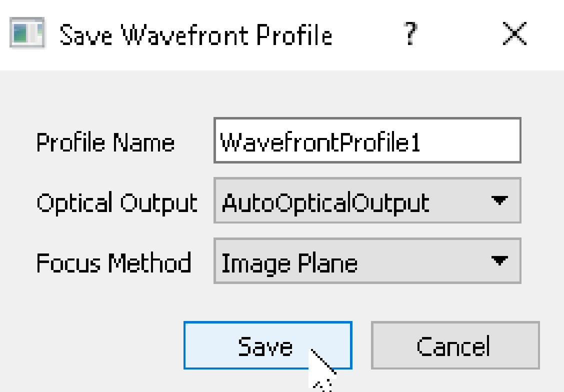
To save the current wavefront profile/spot diagram, right-click the reTORT simulation in the Model Hierarchy dock, and select Tools > Wavefront Matching > Save Wavefront Profile.



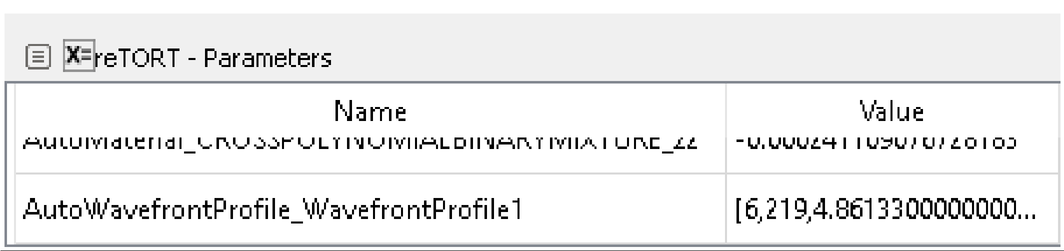
The same option can be found in the menu bar, by selecting Tools > reTORT > Wavefront Matching > Save Wavefront Profile. If the reTORT menu option is not enabled, be sure that “reTORT” is selected in the Model Hierarchy dock.



In the dialog that appears, enter the desired name for the profile. Make sure the optical output to be used for wavefront matching is selected, along with the desired focus method. A new optical output can be created, if desired, by selecting New Optical Output. For this guide, we will match the wavefront at the image plane using the AutoOpticalOutput that was created by the optimization wizard. Click the Save button to save the wavefront.



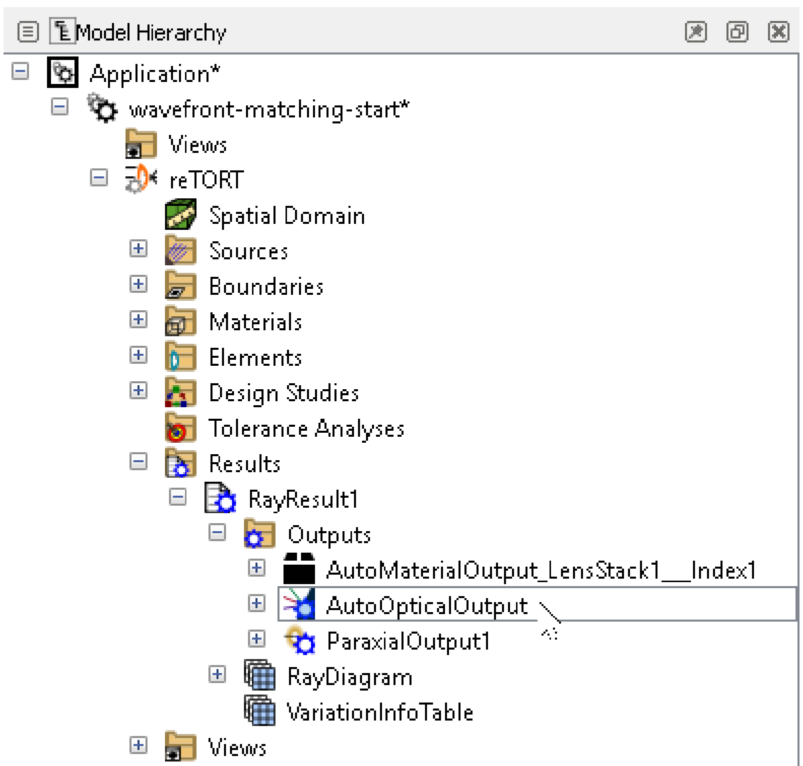
In the Parameters dock, a new parameter has been created at the end of the parameter list with the name AutoWavefrontProfile_WavefrontProfile1, based on the name provided in the popup dialog. This parameter contains the spot diagram information for the current system using the optical output selected earlier, and is what the spot-matching results will be based on.

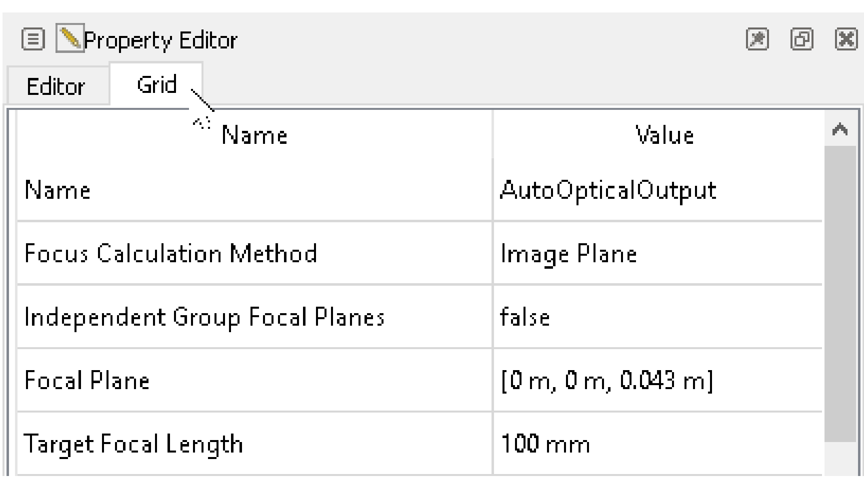


4.0 Configuring the Spot-Matching Result

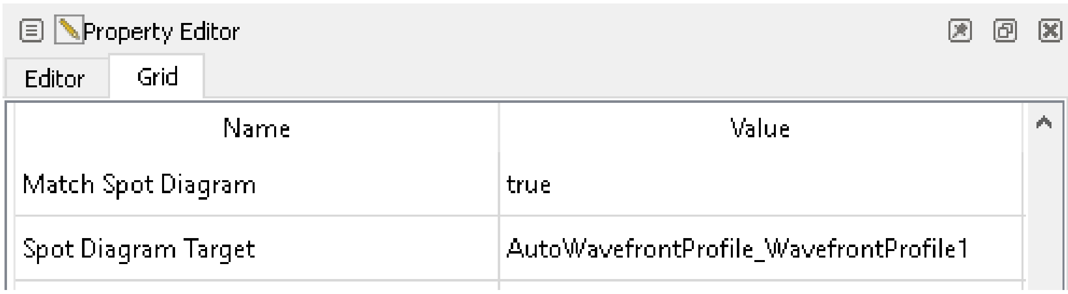
Next, we will use the saved wavefront profile to configure the spot-diagram matching result.

Expand the “Results” sub-menu in the Model Hierarchy as shown below, and select the optical output that was used to save the wavefront, AutoOpticalOutput in this case. Then in the Property Editor dock, select the Grid tab to view the output’s properties in a table. The Grid editor is an advanced method of editing properties, and contains properties hidden more deeply than even the advanced properties revealed by clicking the gear icon in the Property Editor.

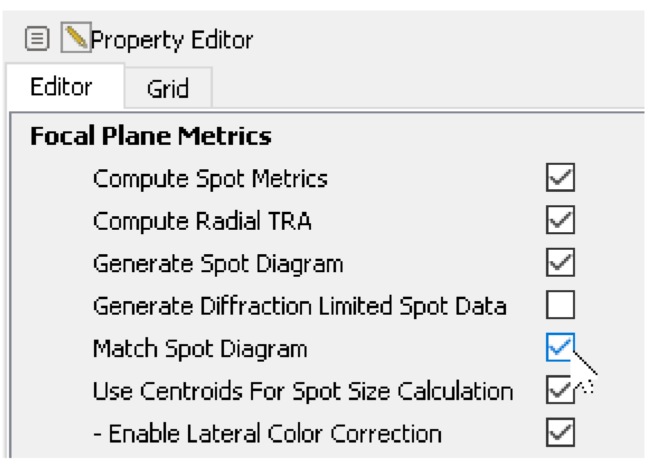




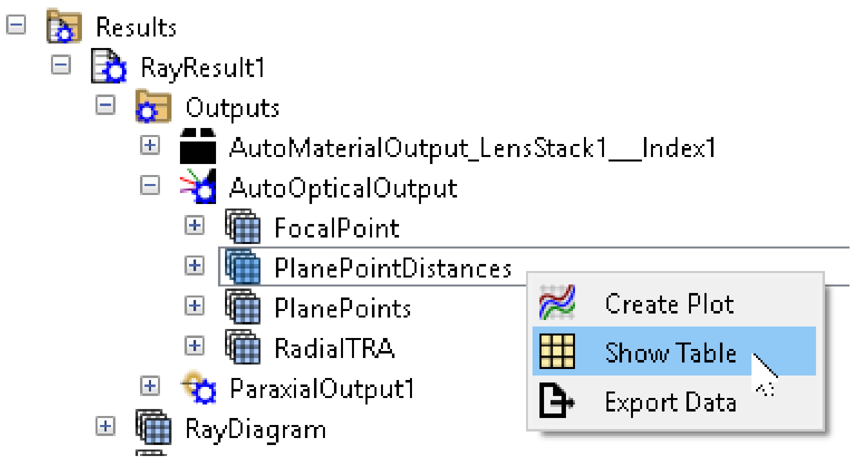
In this case, the Grid editor is necessary to access the Spot Diagram Target property. Double-click the Value column of the row labeled “Spot Diagram Target”, and enter the name of the wavefront profile parameter: AutoWavefrontProfile_WavefrontProfile1.



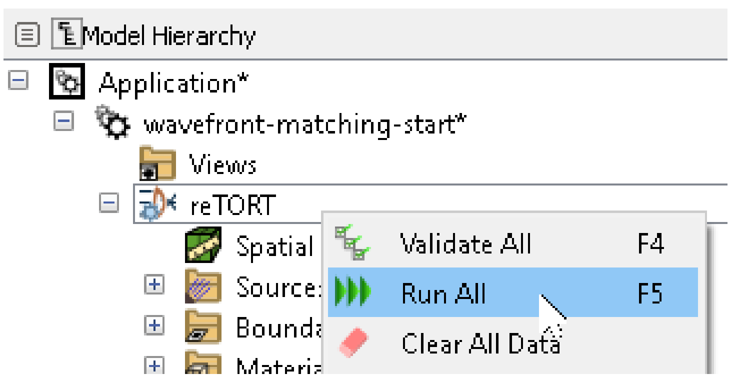
Then, double-click the Value column of the row labeled “Match Spot Diagram”, and change its value to “true”. This property can also be set without the Grid editor, by going back to the Editor tab and clicking the gear icon to show the output’s advanced properties. We’ve already enabled it in the Grid editor, so there’s no need to do it again, this is just an alternative input method.



Enabling the Match Spot Diagram property adds a PlanePointDistances table under AutoOpticalOutput in the Model Hierarchy dock. We can view this table by right-clicking it and selecting Show Table.



If the table is empty, run the simulation to generate the results. The simulation can be run by right-clicking the reTORT simulation in the Model Hierarchy and selecting Run All, or by clicking the Run All icon in the toolbar. If there are issues running the simulation due to pre-existing data, click the eraser icon to clear the data before trying again. Like the other toolbar icons, if the Run All icon is not available, make sure that reTORT is selected in the Model Hierarchy.



The PlanePointDistances table contains a row for each ray bundle (wavelength and incident angle) with information about how well the current spot diagram matches the saved profile. The Total Distance column is the sum of the distance of each ray from its location in the saved wavefront profile. The RMS Distance column is the root-mean-square of the distances, and the Max Distance is the distance of the ray that is furthest from its profile location.

	SourceUID	Wavelength (m)	Theta (deg)	Phi (deg)	Total Distance (m)	RMS Distance (m)	Max Distance (m)
1	219	4.8613E-07	0.00000000000...	0.00000000...	0.000000000000000E+00	0.000000000000000E+00	0.000000000000000E+00
2	219	4.8613E-07	2.00000000000...	0.00000000...	0.000000000000000E+00	0.000000000000000E+00	0.000000000000000E+00
3	219	5.8756E-07	0.00000000000...	0.00000000...	0.000000000000000E+00	0.000000000000000E+00	0.000000000000000E+00
4	219	5.8756E-07	2.00000000000...	0.00000000...	0.000000000000000E+00	0.000000000000000E+00	0.000000000000000E+00
5	219	6.5627E-07	0.00000000000...	0.00000000...	0.000000000000000E+00	0.000000000000000E+00	0.000000000000000E+00
6	219	6.5627E-07	2.00000000000...	0.00000000...	0.000000000000000E+00	0.000000000000000E+00	0.000000000000000E+00

Note that all distances are currently zero, because the system has not been changed since the wavefront profile was saved. For purposes of this guide, some arbitrary changes will be made to the GRIN material coefficients to alter the system. These changes are highlighted in the following screenshot of the Parameters dock. After making the changes and re-running the simulation, the distances are now non-zero.

reTORT - Parameters

Name	Value
AutoElement_LensStack1_Index1_Surface_Radius	0.0441267697380291 mm**-1
AutoElement_LensStack1_Index2_Surface_Radius	-0.0117097368151663 mm**-1
AutoMaterial_CROSSPOLYNOMIALBINARYMIXTURE_n0	0.97
AutoMaterial_CROSSPOLYNOMIALBINARYMIXTURE_r2	0
AutoMaterial_CROSSPOLYNOMIALBINARYMIXTURE_r4	-5.96750289823282e-05

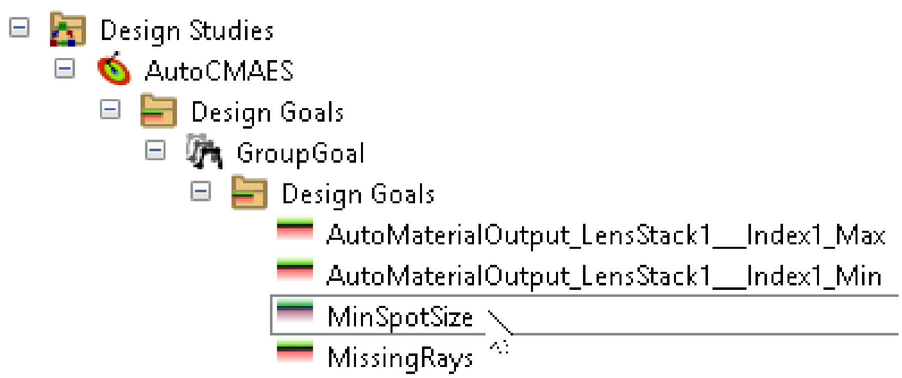
	SourceUID	Wavelength (m)	Theta (deg)	Phi (deg)	Total Distance (m)	RMS Distance (m)	Max Distance (m)
1	219	4.8613E-07	0.000000000...	0.00000000...	0.013489473	4.3957511E-04	6.1146334E-04
2	219	4.8613E-07	2.000000000...	0.00000000...	0.013488627	4.4009495E-04	6.2476977E-04
3	219	5.8756E-07	0.000000000...	0.00000000...	0.012731428	4.1487074E-04	5.7709249E-04
4	219	5.8756E-07	2.000000000...	0.00000000...	0.012738594	4.1547085E-04	5.8963091E-04
5	219	6.5627E-07	0.000000000...	0.00000000...	0.012436154	4.0525028E-04	5.6371593E-04
6	219	6.5627E-07	2.000000000...	0.00000000...	0.012446304	4.0587567E-04	5.7595123E-04

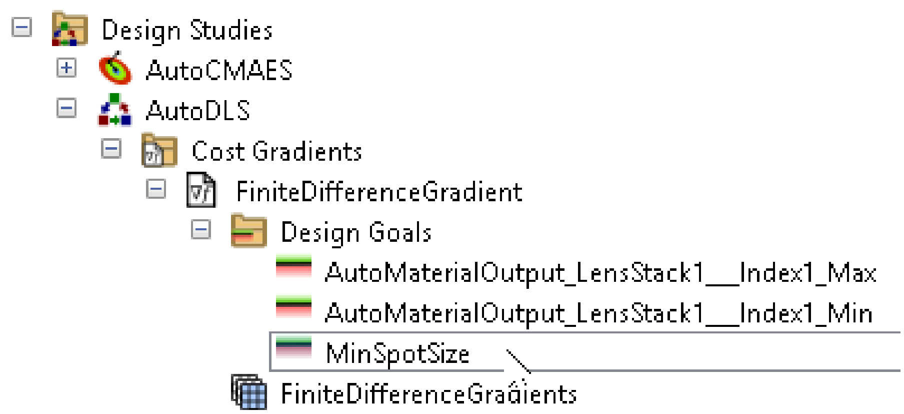
For the accuracy of the spot-diagram matching results, it's important that the source's wavelength, incident angle, ray distribution, and ray density settings remain unchanged from when the wavefront profile was saved. If the number of rays in the simulation changes, then some of the distances will be given very large values, indicating the wavefront cannot be compared to the saved profile.

5.0 Configuring the Spot-Matching Optimization Goal

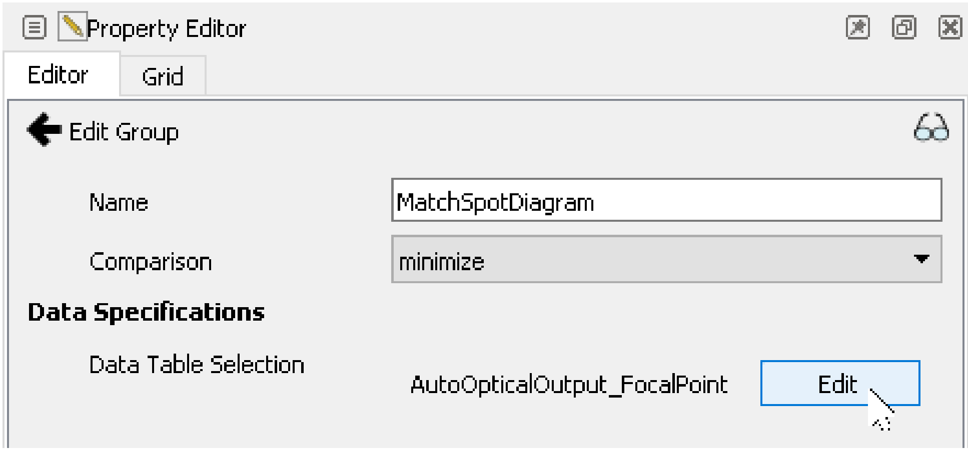
After creating the spot-diagram/wavefront matching result and setting it to the saved wavefront profile, the next step is to use that result in an optimization. For this guide, we will modify the MinSpotSize goals in the optimizations that were created by the optimization wizard, rather than creating the goal from scratch.

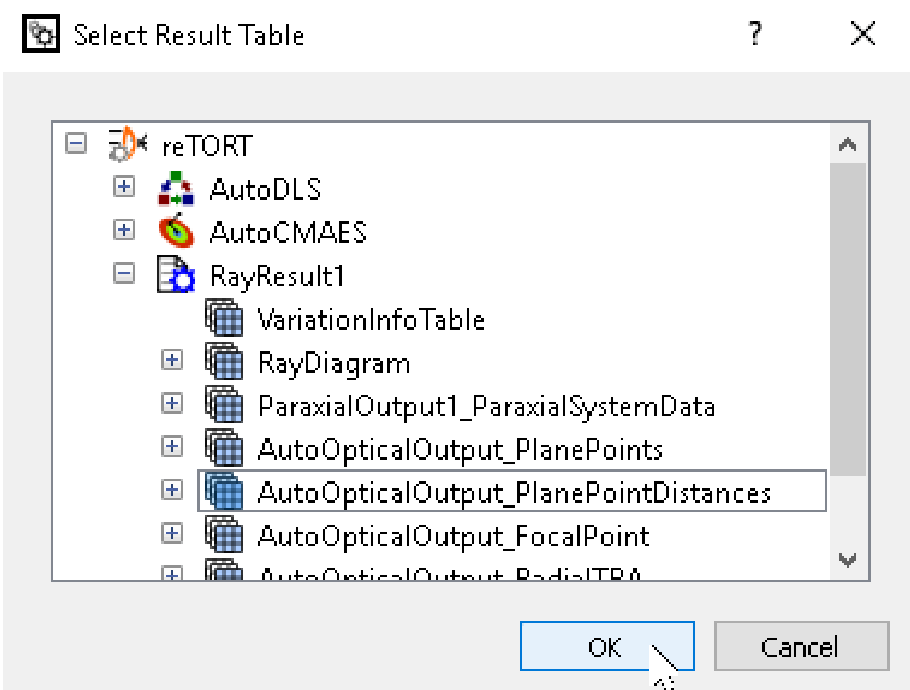
For CMAES optimizations, the spot size goal is located under Design Studies > AutoCMAES > Design Goals > GroupGoal > Design Goals > MinSpotSize in the Model Hierarchy dock. For DLS optimizations, the spot size goal is located at Design Studies > AutoDLS > Cost Gradients > FiniteDifferenceGradient > Design Goals > MinSpotSize. This guide will use the CMAES optimization, because it is the best at matching wavefronts in our experience. Select the goal in the Model Hierarchy to open its Property Editor.



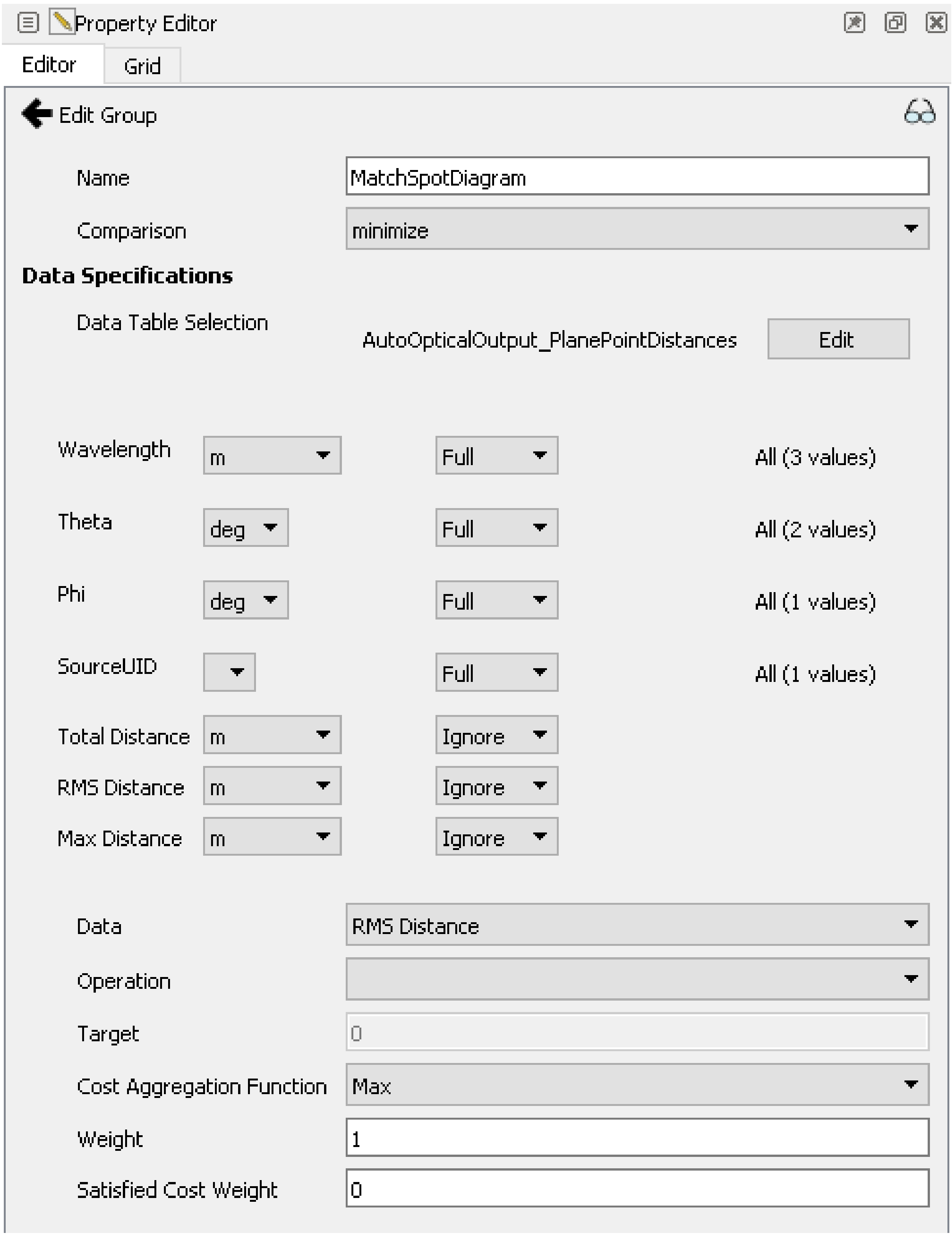


In the goal's property editor, we'll rename the goal to MatchSpotDiagram, make sure the Comparison property is set to "minimize", then click the Edit button next to "Data Table Selection" to change the result the goal refers to. In the dialog that appears, expand reTORT and RayResult1, and select the AutoOpticalOutput_PlanePointDistances item, then click OK.





To select which distance to use during the optimization, select the desired column name from the Data dropdown. For this guide, we will optimize on the RMS Distance.


Property Editor
Editor
Grid
Edit Group
Name
MatchSpotDiagram
Comparison
minimize
Data Specifications
Data Table Selection
AutoOpticalOutput_PlanePointDistances
Edit
Wavelength
m
Full
All (3 values)
Theta
deg
Full
All (2 values)
Phi
deg
Full
All (1 values)
SourceUID
Full
All (1 values)
Total Distance
m
Ignore
RMS Distance
m
Ignore
Max Distance
m
Ignore
Data
RMS Distance
Operation
Target
0
Cost Aggregation Function
Max
Weight
1
Satisfied Cost Weight
0

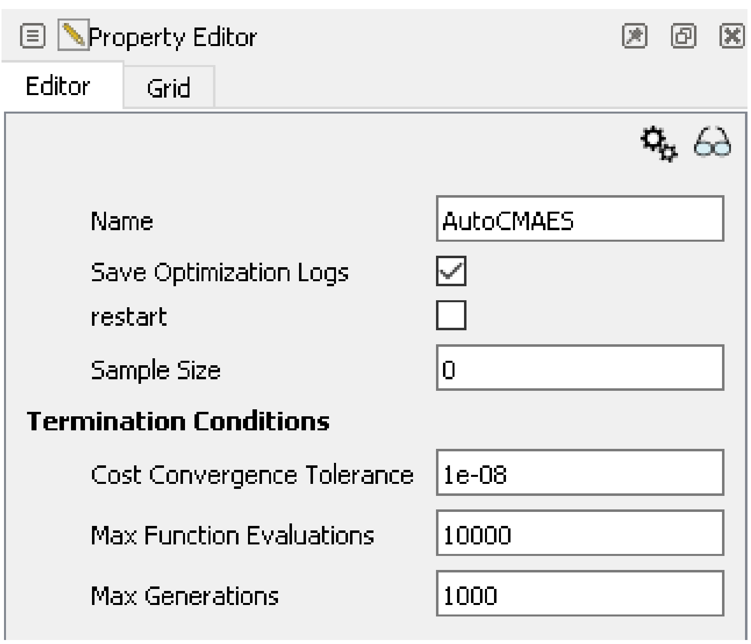
The Cost Aggregation Function determines how each row in the PlanePointDistances table will be combined into a single cost. For DLS optimizations, it's normally better to set this to None, so the optimization can use each row as a separate data point during the optimization. However, CMAES optimizations require a single cost. Setting this to Max will use the maximum RMS Distance across all rows in the table as the cost. We are using CMAES, and so will make sure the aggregation is set to Max.

We've already set the Comparison property is set to "minimize". Now set a weight if desired. For instance, to optimize the distances in microns instead of the default meters, set the weight to 1e6. However, note that changing this weight will not affect the distances when clicking Show Table on the PlanePointDistances result; those distances will still be in meters. We'll leave the weight at 1.

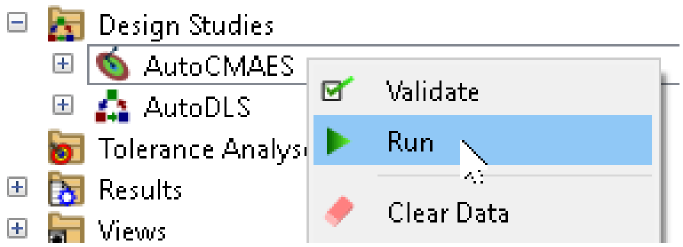
6.0 Running the Optimization

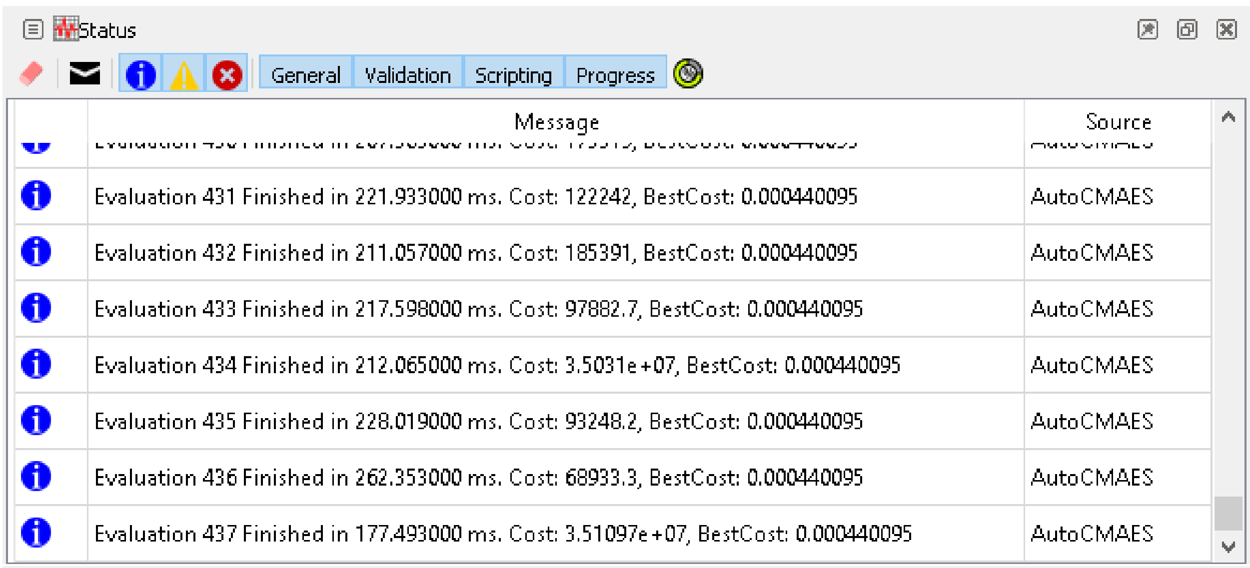
After configuring the goals to use the spot-diagram matching result, it's time to run the optimization. This guide will use CMAES to perform the wavefront matching.

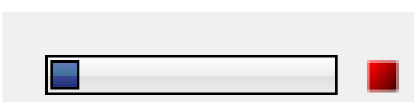
First, select AutoCMAES in the Model Hierarchy, and set the Max Function Evaluations and Max Generations properties in its Property Editor to your desired values. For this guide, we'll be using 10000 and 1000 respectively, although you may need to adjust this to fit your needs.



Then run the optimization by right-clicking AutoCMAES in the Model Hierarchy and selecting "Run". The optimization's progress will be shown in the Status dock and in the progress bar in the lower-right corner of the window.







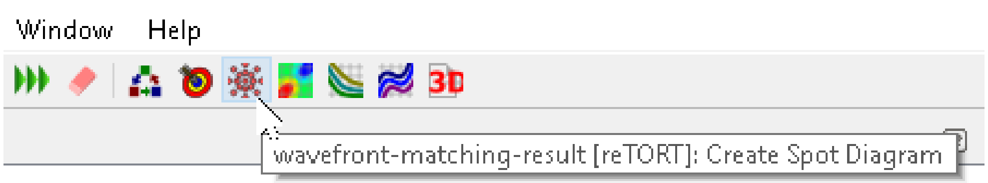
Due to the stochastic nature of CMAES, it may take more than one attempt to perform the optimization successfully. For example, the optimization may get stuck re-sampling bounds, in which case you can stop the optimization by clicking the stop button next to the progress bar. If you haven't already disabled the local DLS optimization in the optimization wizard from Section 2.0, you should delete the unused DLS optimization now, because the finite-difference calculations can sometimes interfere with CMAES.

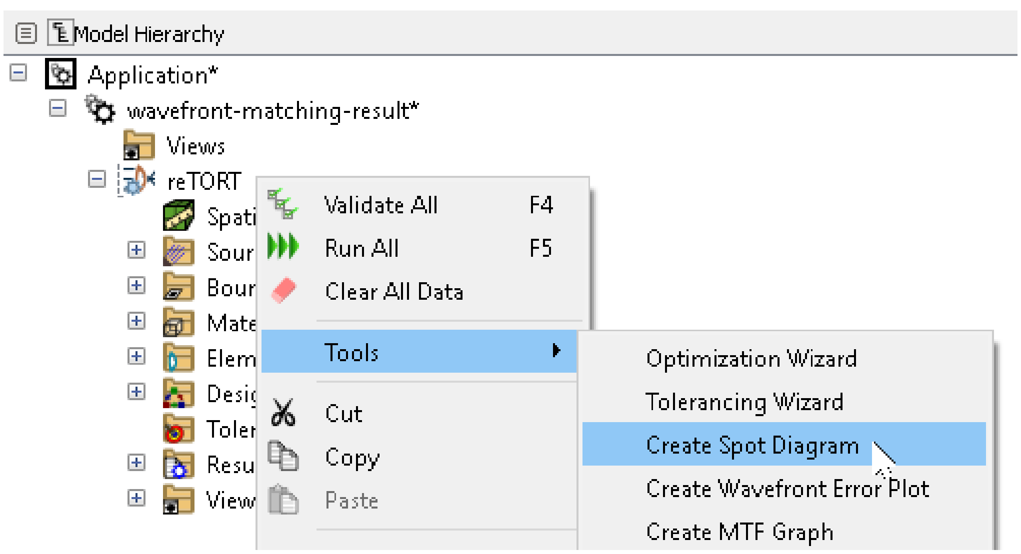
7.0 Analyzing Results

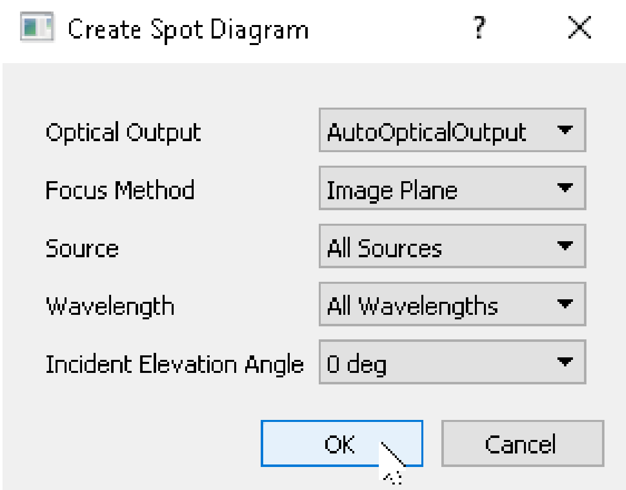
After the optimization, we can open the PlanePointDistances table again to see that the distances are very low. We can also view other metrics to see how well the wavefront was matched to the original design.

	SourceUID	Wavelength (m)	Theta (deg)	Phi (deg)	Total Distance (m)	RMS Distance (m)	Max Distance (m)
1	219	4.8613E-07	0.00000000...	0.0000000...	1.3231621E-05	6.6260131E-07	1.3208778E-06
2	219	4.8613E-07	2.00000000...	0.0000000...	4.4838193E-05	1.6254935E-06	3.1163808E-06
3	219	5.8756E-07	0.00000000...	0.0000000...	2.0296892E-05	9.6405442E-07	1.9153487E-06
4	219	5.8756E-07	2.00000000...	0.0000000...	4.3285484E-05	1.5515691E-06	2.6192644E-06
5	219	6.5627E-07	0.00000000...	0.0000000...	2.4552210E-05	1.0881152E-06	2.1323811E-06
6	219	6.5627E-07	2.00000000...	0.0000000...	4.5087610E-05	1.6233085E-06	2.8388913E-06

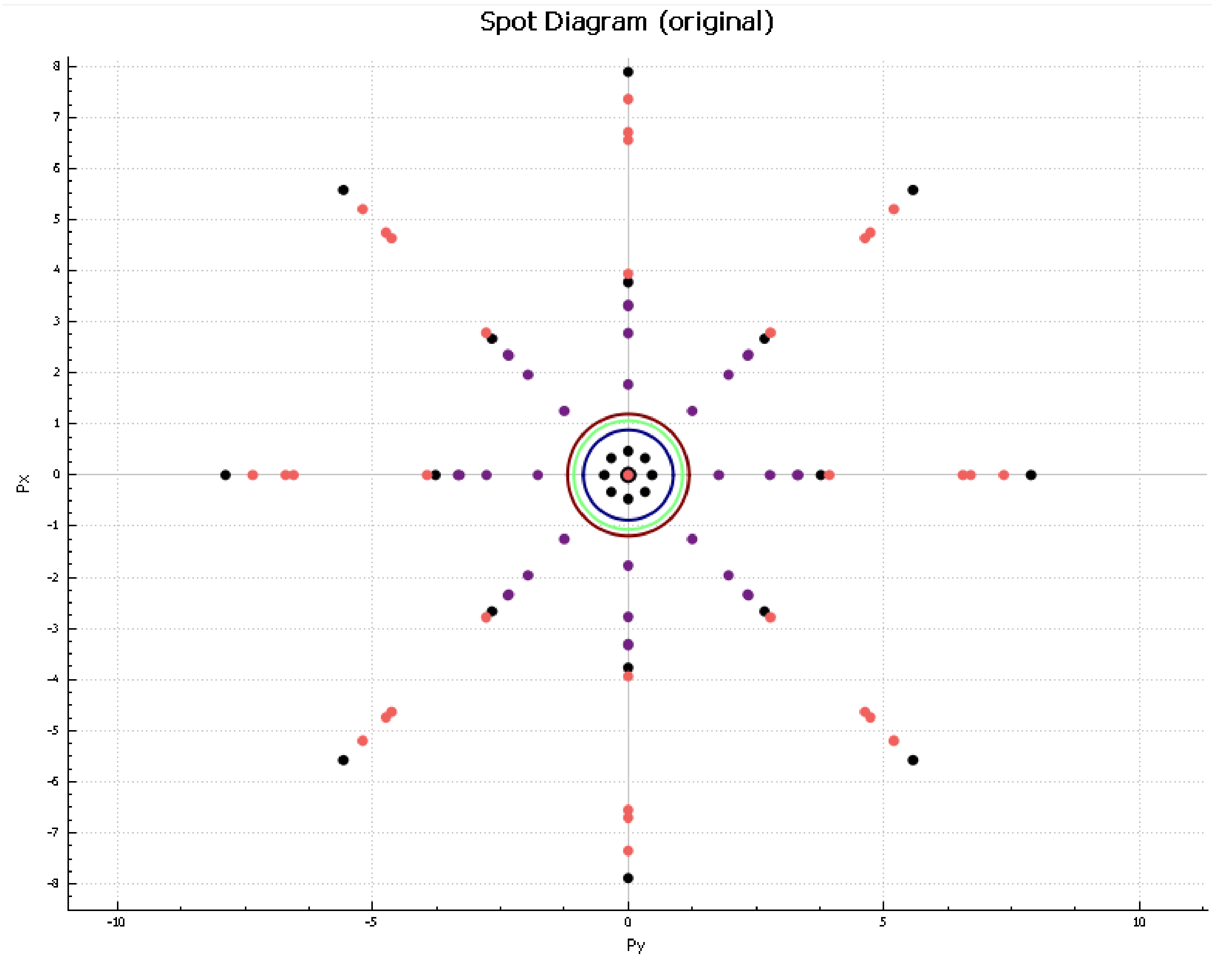
To view the spot diagram, click on the spot diagram icon in the toolbar, or right-click the reTORT simulation in the Model Hierarchy and select Tools > Create Spot Diagram. Make sure the Optical Output is set to AutoOpticalOutput, and select the desired wavelengths and incident angles, then click OK.

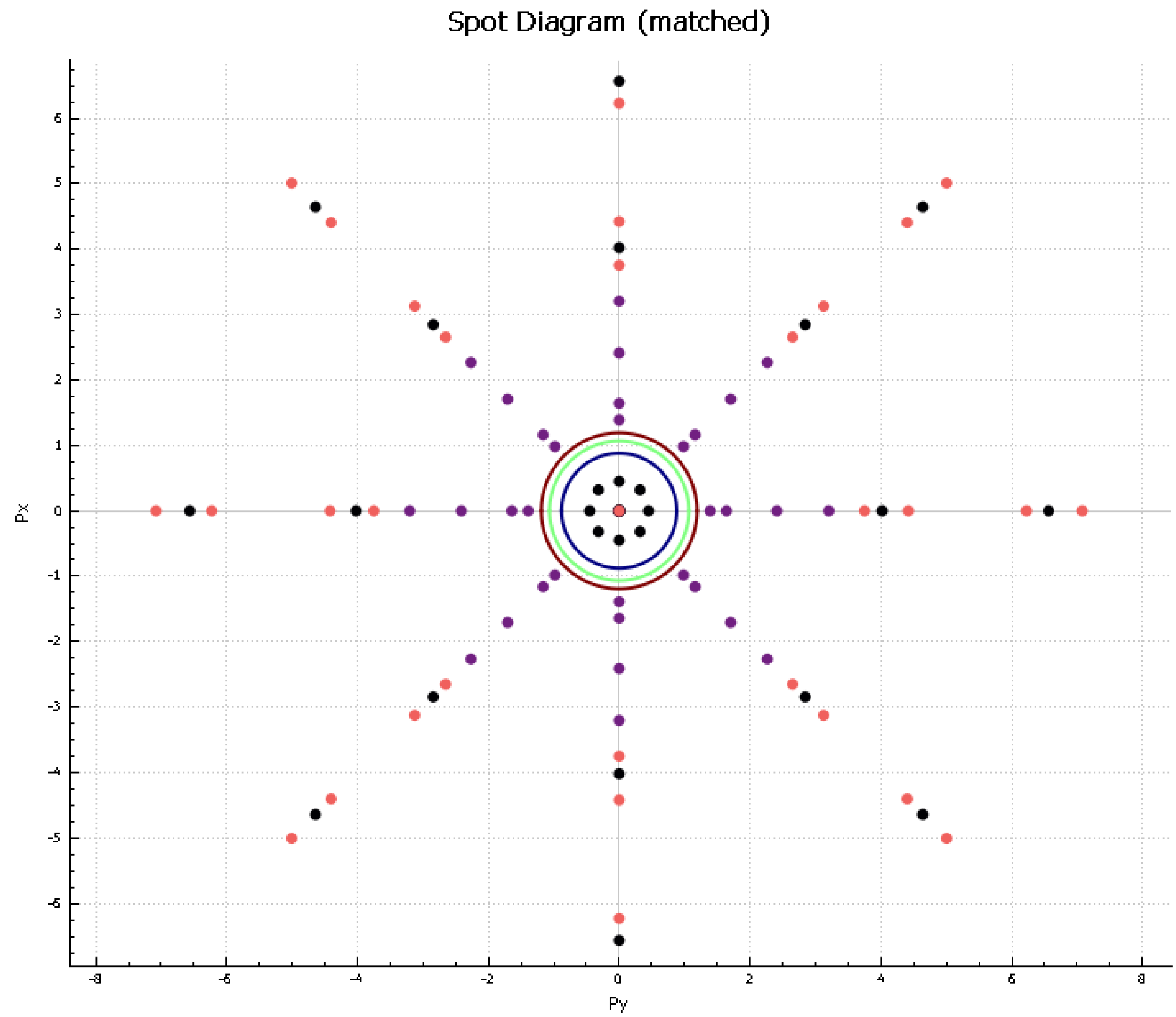




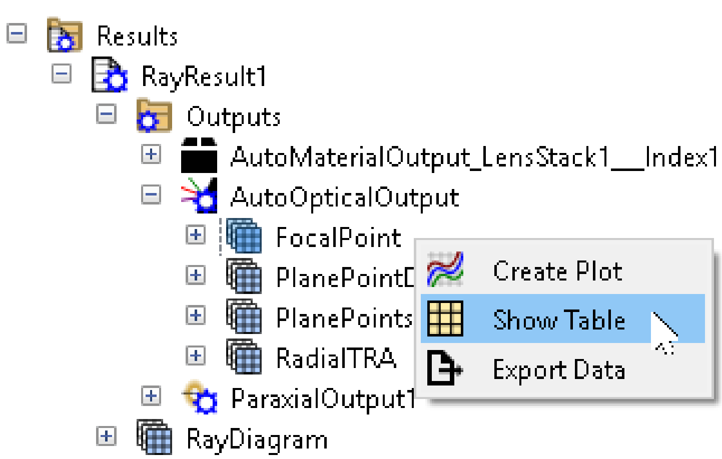


The following images compare the original spot diagram to the current spot diagram after running the wavefront-matching optimization.





Spot size information can be found by right-clicking the FocalPoint table under AutoOpticalOutput in the Model Hierarchy, and selecting Show Table. This table should be available by default, but can be enabled by checking the optical output's "Compute Spot Metrics" property.



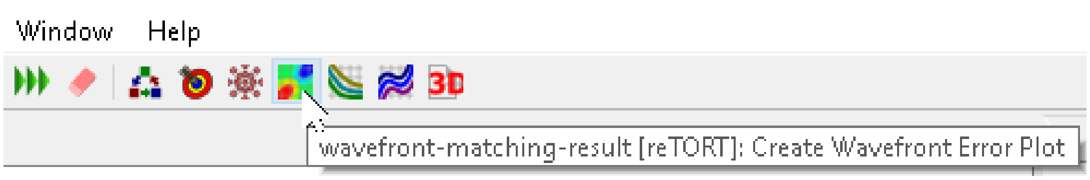
Original Spot Sizes:

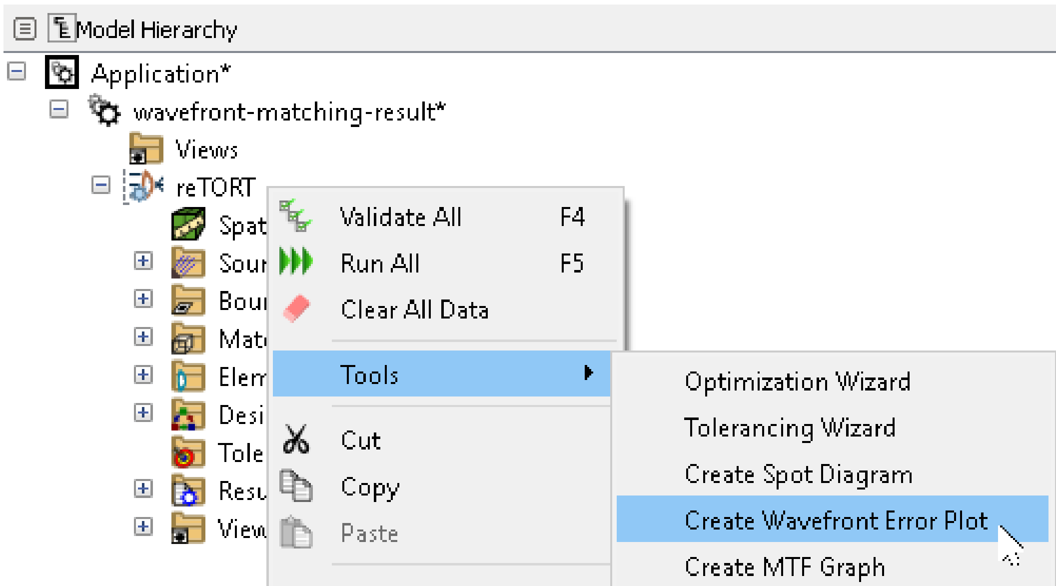
	SourceUID	Wavelength (m)	Theta (deg)	Phi (deg)	RMS Diameter (um)	Peak Diameter (um)	RMS Radius (um)
1	219	4.8613E-07	0.0000000000...	0.00000000...	7.872603	15.770546	3.9363014
2	219	4.8613E-07	2.0000000000...	0.00000000...	13.461383	28.615653	6.7306914
3	219	5.8756E-07	0.0000000000...	0.00000000...	5.856467	6.663753	2.9282336
4	219	5.8756E-07	2.0000000000...	0.00000000...	13.372085	30.764094	6.6860425
5	219	6.5627E-07	0.0000000000...	0.00000000...	13.030251	14.704744	6.5151254
6	219	6.5627E-07	2.0000000000...	0.00000000...	9.060076	23.977446	4.5300382

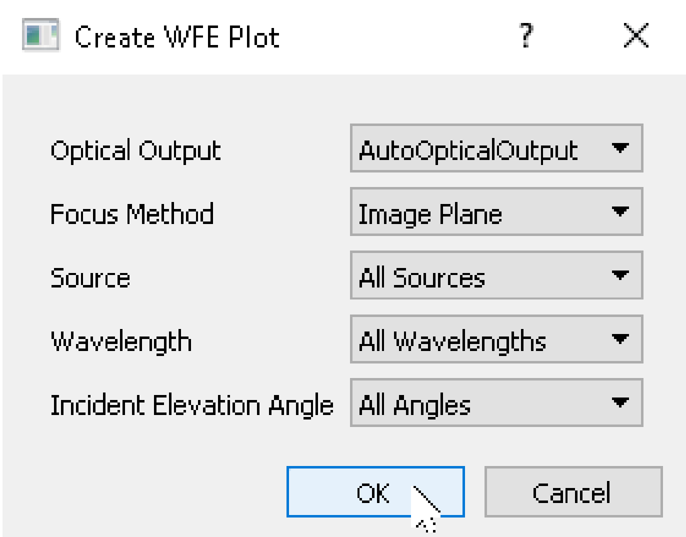
Matched Spot Sizes:

	SourceUID	Wavelength (m)	Theta (deg)	Phi (deg)	RMS Diameter (um)	Peak Diameter (um)	RMS Radius (um)
1	219	4.8613E-07	0.0000000...	0.0000000...	7.155468	13.128791	3.5777342
2	219	4.8613E-07	2.0000000...	0.0000000...	13.181147	26.985426	6.5905734
3	219	5.8756E-07	0.0000000...	0.0000000...	4.917887	6.406843	2.4589437
4	219	5.8756E-07	2.0000000...	0.0000000...	14.159021	37.287597	7.0795107
5	219	6.5627E-07	0.0000000...	0.0000000...	11.803629	14.158332	5.9018145
6	219	6.5627E-07	2.0000000...	0.0000000...	9.884660	31.103301	4.9423301

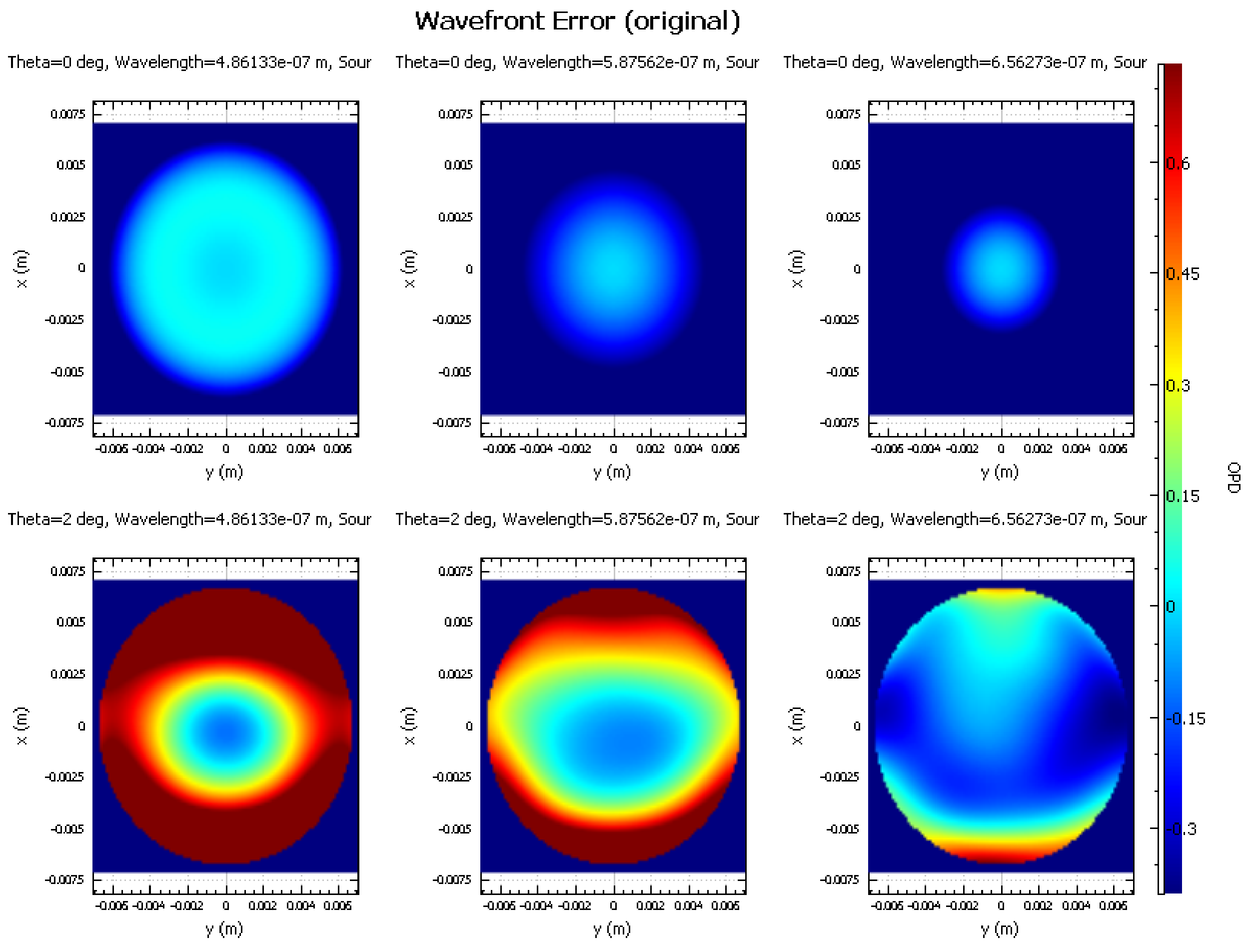
We can also compare the wavefront profiles, by clicking the wavefront icon in the toolbar, or right-clicking on reTORT in the Model Hierarchy and selecting Tools > Create Wavefront Error Plot. Again, select the desired wavelengths and incident angles to show, and click OK.

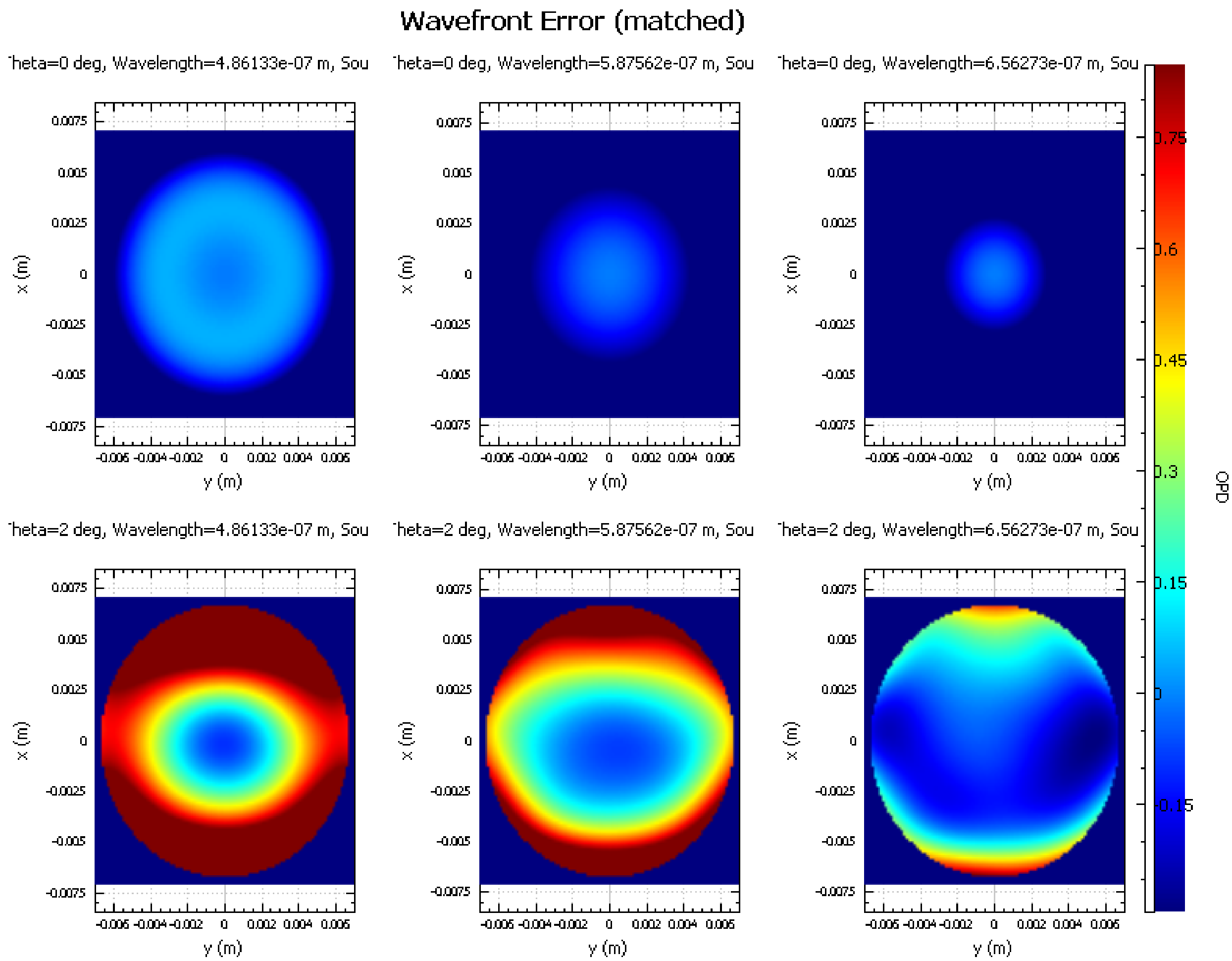




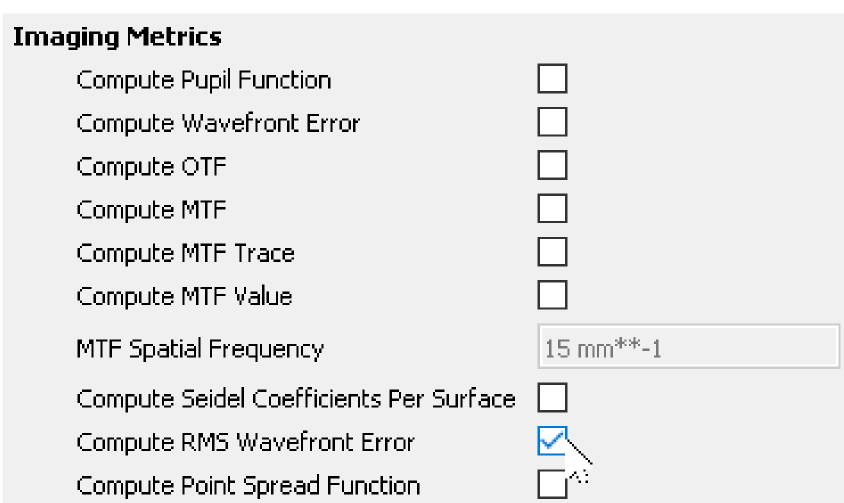


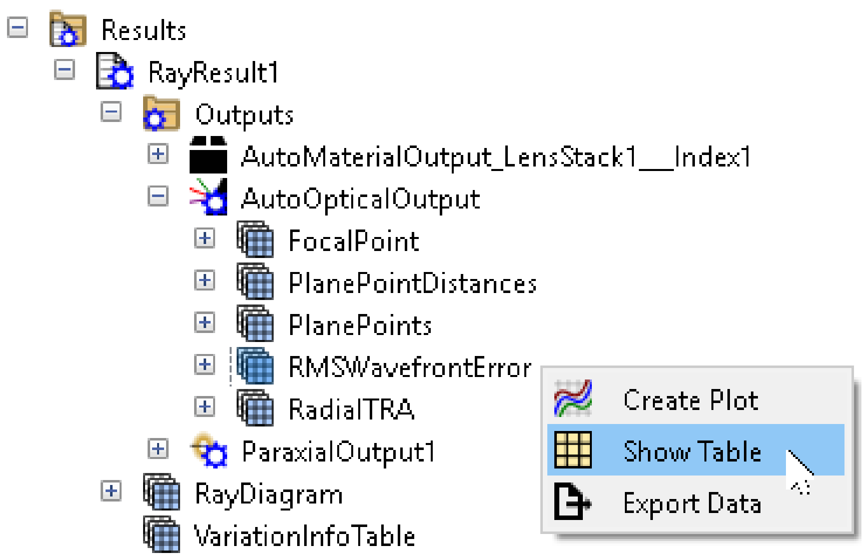
The following images compare the original wavefront error to the post-optimization wavefront.


Wavefront Error (original)
Theta=0 deg, Wavelength=4.86133e-07 m, Sour
Theta=0 deg, Wavelength=5.87562e-07 m, Sour
Theta=0 deg, Wavelength=6.56273e-07 m, Sour
Theta=2 deg, Wavelength=4.86133e-07 m, Sour
Theta=2 deg, Wavelength=5.87562e-07 m, Sour
Theta=2 deg, Wavelength=6.56273e-07 m, Sour
x (m)
y (m)
OPD



The RMS wavefront error can be found by selecting AutoOpticalOutput in the Model Hierarchy, and checking the “Compute RMS Wavefront Error” checkbox in the Property Editor dock. Then right-click the RMSWavefrontError table in the Model Hierarchy, and select Show Table. Run the simulation if necessary to see the wavefront error for each wavelength and incident angle.





The following images compare the original RMS wavefront error to the post-optimization WFE.

Original RMS WFE:

	SourceUID	Wavelength (m)	Theta (deg)	Phi (deg)	RMS Wavefront Error
1	219	4.8613E-07	0.0000000000...	0.00000000...	0.23083570
2	219	4.8613E-07	2.0000000000...	0.00000000...	0.89959327
3	219	5.8756E-07	0.0000000000...	0.00000000...	0.40134026
4	219	5.8756E-07	2.0000000000...	0.00000000...	0.52020938
5	219	6.5627E-07	0.0000000000...	0.00000000...	0.81815664
6	219	6.5627E-07	2.0000000000...	0.00000000...	0.20451195

Matched RMS WFE:

	SourceUID	Wavelength (m)	Theta (deg)	Phi (deg)	RMS Wavefront Error
1	219	4.8613E-07	0.000000000...	0.0000000...	0.21482948
2	219	4.8613E-07	2.000000000...	0.0000000...	0.92072060
3	219	5.8756E-07	0.000000000...	0.0000000...	0.34986183
4	219	5.8756E-07	2.000000000...	0.0000000...	0.58169928
5	219	6.5627E-07	0.000000000...	0.0000000...	0.75699824
6	219	6.5627E-07	2.000000000...	0.0000000...	0.20766168

Appendix: Additional Tips for Using the Optimization Wizard with Custom Goals

Because this guide modified the optimizations that were configured by the optimization wizard, there could be interference if the optimization wizard is run a second time. If custom changes are made to the auto-generated optimizations, it's important to keep the potential consequences in mind before running the wizard again.

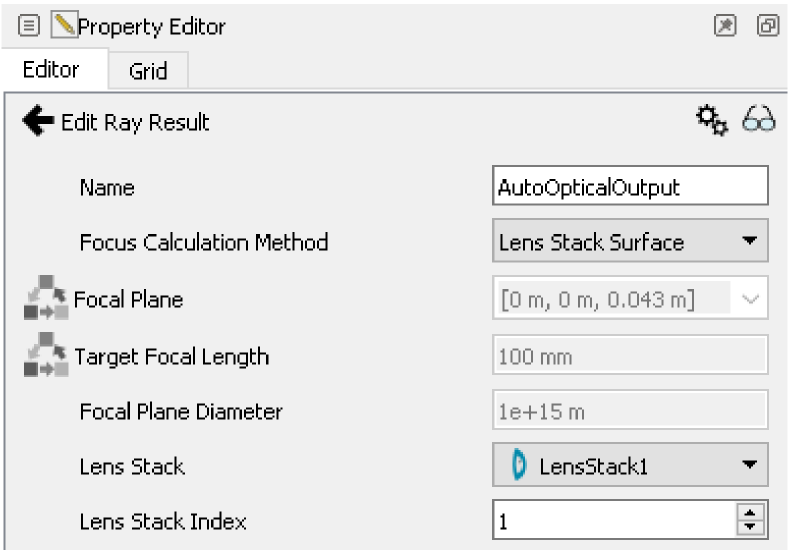
For instance, if we had not renamed the "MinSpotSize" goal, running the optimization wizard would reset the changes we made and turn it into a spot size goal again. To turn the goal back into a spot-diagram-matching goal, we would need to click the goal's Edit button to change the result again, and change the Data column it refers to.

However, because we renamed the "MinSpotSize" goal to "MatchSpotDiagram", running the wizard again will create a new MinSpotSize goal instead, in addition to our modified goal. To correct this, simply delete the new MinSpotSize goal once the optimization wizard has been closed.

The optimization wizard will only make changes to optimizations with the names "AutoCMAES" and "AutoDLS". If we want to prevent any interference with the optimization wizard at all, we can copy and rename the optimizations before making our changes. If the optimization is run after that, the custom versions of the optimizations will be unaffected. However, this also means that any changes to the custom optimizations must be made manually, since the optimization wizard will not modify them.

In addition to the auto-generated optimizations, custom changes to the AutoOpticalOutput can also be overwritten by the optimization wizard. For instance, the optimization and tolerancing wizards only support the Image Plane, Back Focal Length/BFL, and Effective Focal Length/EFL focus methods. Because we left the AutoOpticalOutput's Focus Method property set to Image Plane, this won't cause any issues in this case.

However, we could have set the focus method to something like "Lens Stack Surface" instead. The Lens Stack Surface focus method would let us match the wavefront at a specific surface in the middle of a lens stack, which is controlled by the "Lens Stack" and "Lens Stack Index" properties in AutoOpticalOutput's Property Editor. Because the Lens Stack Surface focus method is not supported by the wizard, running the optimization wizard a second time would have reverted the focus method to one of the supported options, and we would need to correct it before matching the wavefront profile.



Some of the AutoOpticalOutput's results may also change when running the optimization wizard a second time. For instance, running the optimization wizard might disable the RMS wavefront error result that we used when analyzing the optimization results. To prevent interference from the optimization wizard, we can copy and rename the optical output to something other than "AutoOpticalOutput". If the spot-matching goal was already configured, be sure to click its Edit button and point it to the new optical output.