reTORT Optical Design Software: Triplet to GRIN Use Case

1 Introduction

Here we will discuss a use case demonstrating the size, weight, and power (SWaP) reducing benefits of designing with gradient refractive index (GRIN) optics using our unique optimization methods. First, we designed the achromatic triplet featured in Figure 1 and described in Table 1. The triplet was designed to have a back focal length of **40 mm** and optimized using the wavlengths **468.133 nm**, **587.562 nm**, and **656.273 nm**. The focal shift present in the resultant triplet was approximately **120 µm** over the range from **450 nm** to **700 nm** light.

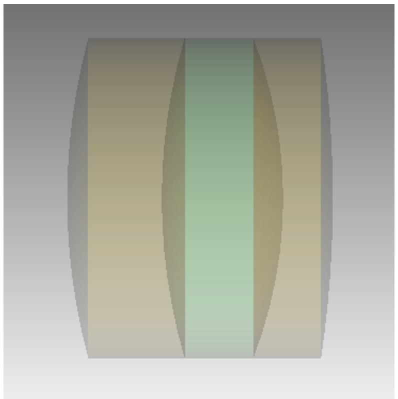


Figure 1: Achromatic Triplet

Type	Material	Thickness	Radius	Diameter
Stop	**N-SF10**	**4.4294 mm**	**28.787 mm**	**14 mm**
Surface	**N-BK7**	**5.6807 mm**	**26.763 mm**	**15 mm**
Surface	**N-SF10**	**2.3254 mm**	**−20.687 mm**	**15 mm**
Surface	air	**40 mm**	**−51.061 mm**	**15 mm**

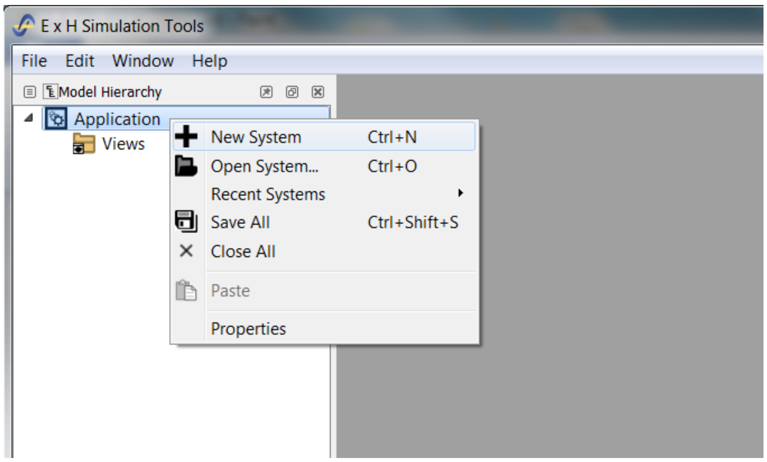
Table 1: Achromatic Triplet Specifications

This lens is somewhat reasonable and of a decently small form factor, however it can be replaced with a substantially smaller GRIN with similar performance. We will discuss the process of designing such a lens in Section 2. We will look into the resultant design in Section 3.

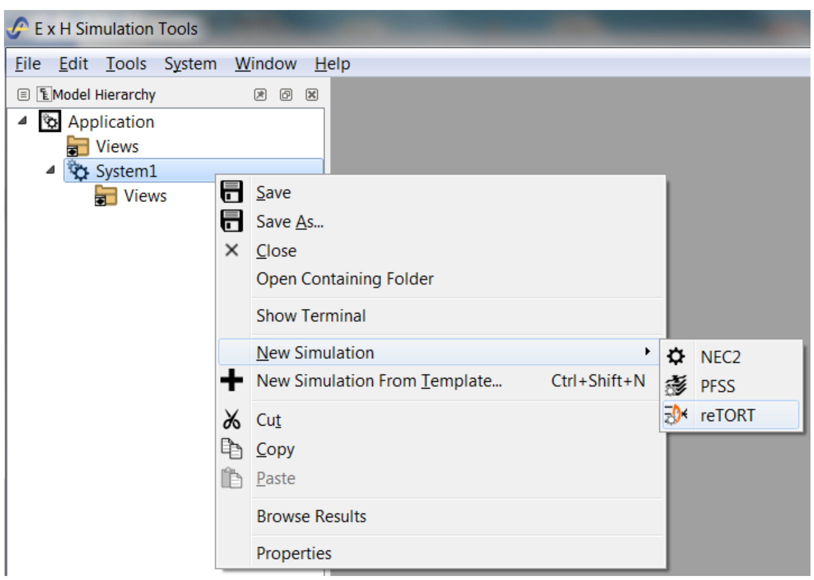
2 Creating the GRIN

Here we will describe the steps required to appropriately generate a GRIN design using **reTORT** to replace the triplet described in Section 1. For this application, we will give **reTORT** quite a number of variables to work with and allow it to design the lens for us. The following steps will guide you through the process of setting up this kind of design.

1. Create a new System in **GEMSIF** by right-clicking **Application** → **New System**.



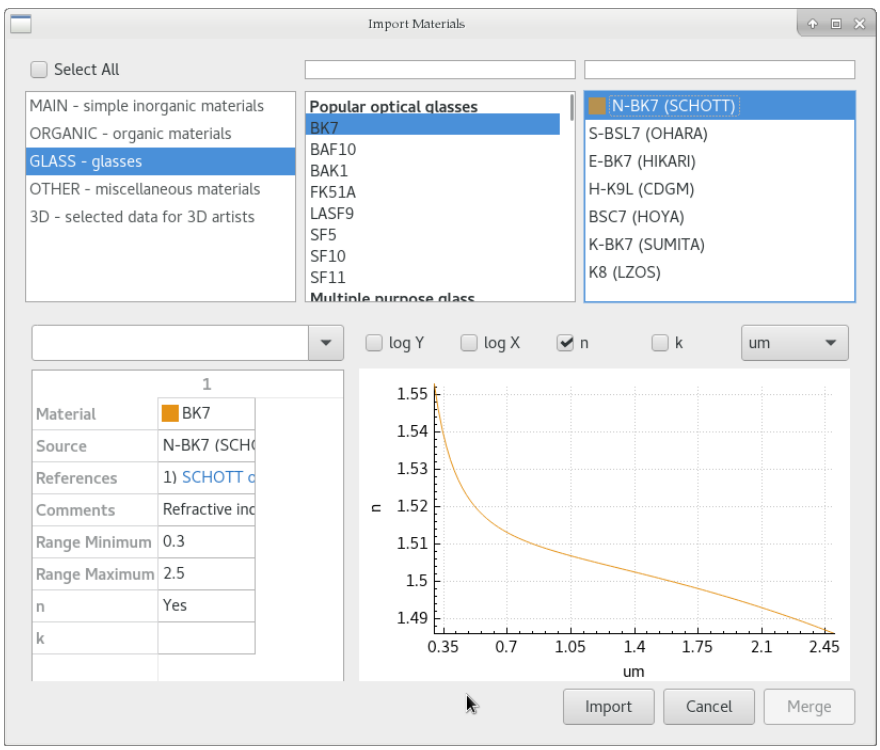
2. Create a new **reTORT** simulation by right-clicking **System1** → **New Simulation** → **reTORT**.



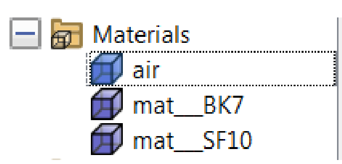
3. You will now see the default **reTORT** system that can be used as a starting point for your optical system. The default source (**BeamSource1**) uses the set of three wavelengths described in Section 1, however to appropriately design for this lens we will also need ray bundles from multiple incident angles. To change this, expand **reTORT** under the **Model Hierarchy** and also expand **reTORT** → **Sources** → **BeamSource1**. Click on the **BeamSource1** to open its **Property Editor**.

4. Modify the **Incident Elevation Angles** field to contain 2° in addition to the default 0° (separated by commas).

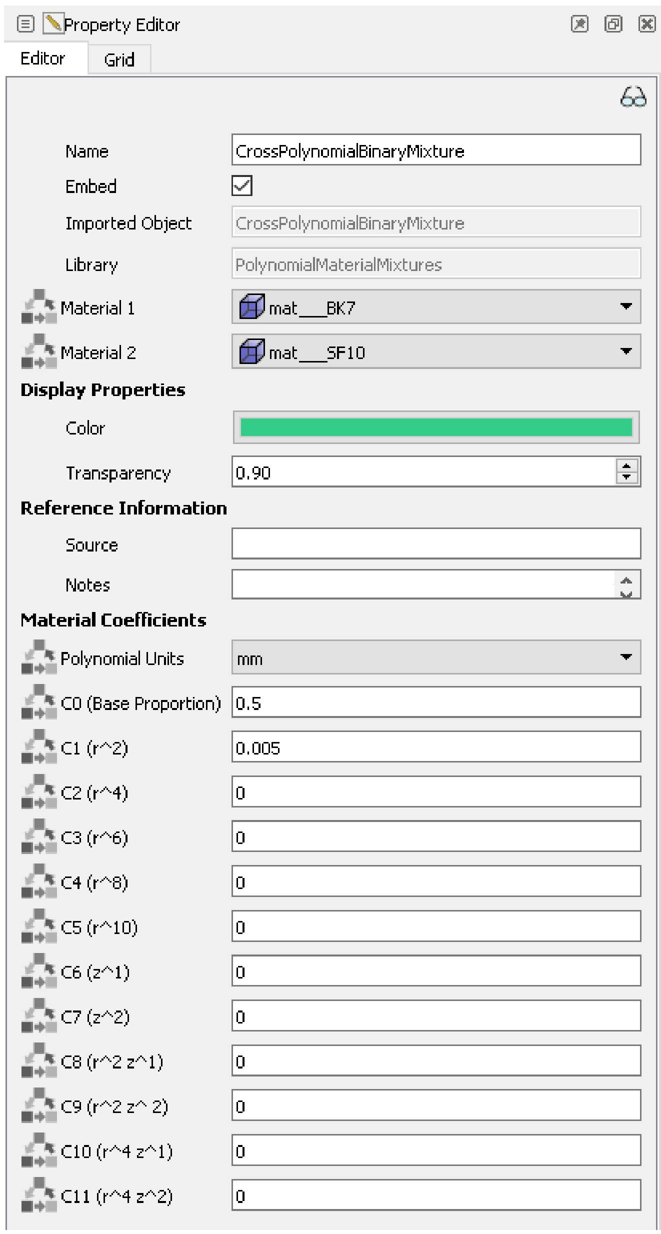
5. Next, we need to import materials to build a GRIN lens. We will use a **Binary Mixture** which allows us to take two dispersive materials and mix them using a polynomial mixing fraction ranging from **0** to **1** where **0** indicates **100**% of the first material and **1** indicates **100**% of the second material. First we will import the constituent materials. Open the **Material Import** window by right-clicking on **Materials** → **Import Material from Database**. For the first material, select **Glass** → **BK7** → **N-BK7 (SCHOTT)** and click **Import**.



6. For the second material, open the **Material Import** window again and select **Glass** → **SF10** → **N-SF10 (SCHOTT)** and click **Import**. You should now have two glass materials listed under **Materials** within the **Model Hierarchy**.



7. Now create a binary mixture by right-clicking on **Materials** → **PolynomialMaterialMixtures** → **New CrossPolynomialBinaryMixture**. Clicking on your newly created **CrossPolynomialBinaryMixture** under **Materials** should display its **Property Editor**. This editor will allow you to define the two materials that compose the binary mixture and also the material mixing fraction coefficients. Keep in mind that while these coefficients are defined according to the polynomial, they do not directly map to the refractive indices as they directly determine proportion of the two materials at any given point.



8. Change the **CrossPolynomialBinaryMixture**'s properties for **Material 1** to **BK7** and **Material 2** to **SF10**.

9. Change the following **Material Coefficients** to the following values **C0 (Base Proportion)** → **0.5**, **C1 (r^2)** → **0.005**, **C2 (r^4)** → **0.0**.

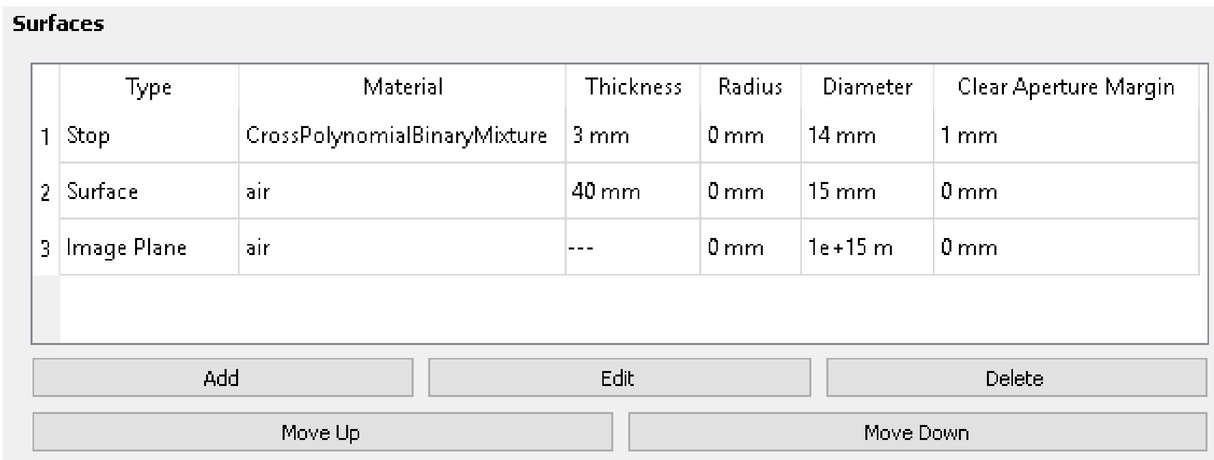
10. The next step will be to build our GRIN singlet lens element. Under **Elements** in the **Model Hierarchy**, select **LensStack1**.

11. In the **Property Editor**, add a new surface to the lens stack by clicking the **Add** button. There should now be three surfaces in the lens stack, including the default **Stop** and **Image Plane**.

12. Change the **Thickness** of the first surface to **3 mm** and its **Diameter** to **14 mm**. Then set its **Clear Aperture Margin** to **1 mm**. This will shrink the diameter of the source to match the aperture stop, while keeping the incident angles within the bounds of the lens.

13. Change the second surface's **Diameter** to **15 mm**. Then set its **Thickness** to **40 mm**, to specify the working distance from the image plane.

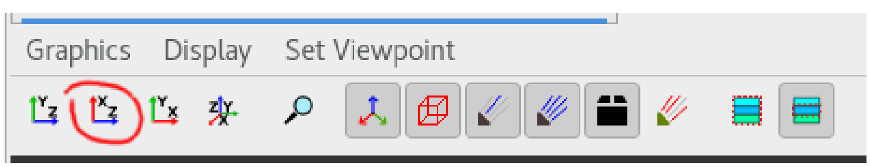
14. Change the material of the first surface by double-clicking the entry under the **Material** column and selecting **CrossPolynomialBinaryMixture** from the dropdown. Leave the default **Radius** of **0 mm** for all surfaces, which specifices a planar surface.



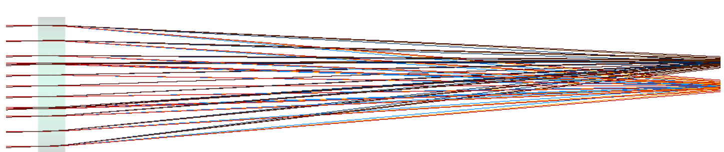
Surfaces

	Type	Material	Thickness	Radius	Diameter	Clear Aperture Margin
1	Stop	CrossPolynomialBinaryMixture	3 mm	0 mm	14 mm	1 mm
2	Surface	air	40 mm	0 mm	15 mm	0 mm
3	Image Plane	air	---	0 mm	1e+15 m	0 mm

15. Click on the X/Z plane orientation button on your **ModelView** window:



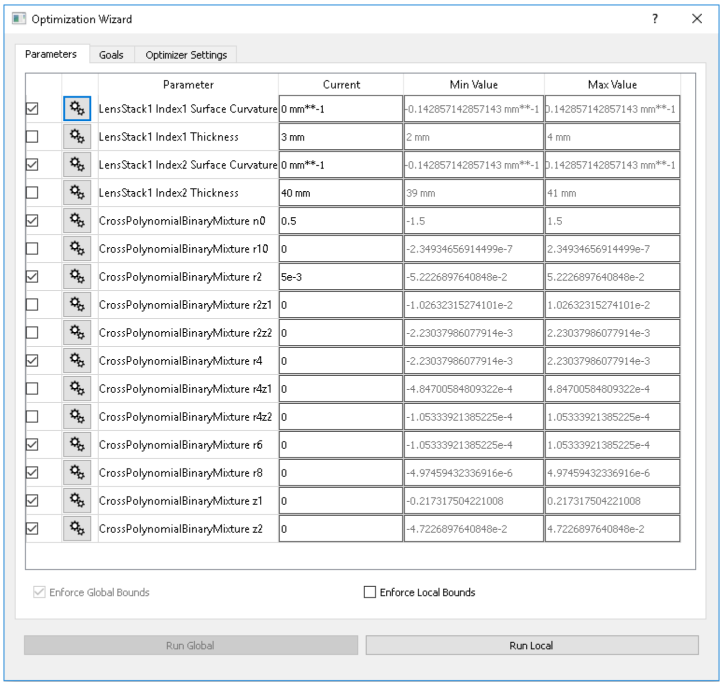
Right-click on the **reTORT** simulation and select **Run All**. Your **ModelView** should now show the lens and a ray-trace of both specified angles as in the below image.



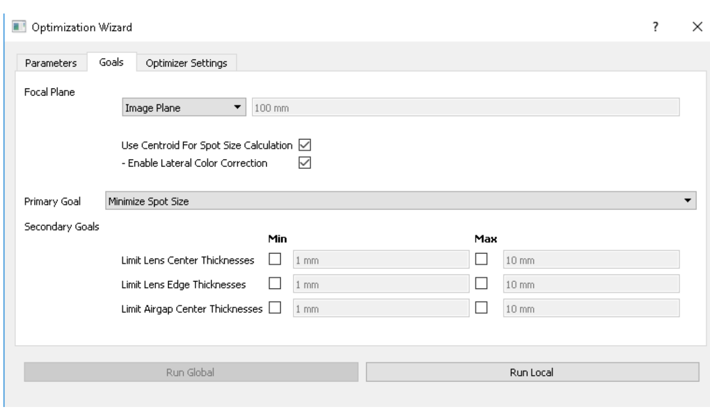
16. We must now optimize the GRIN to the appropriate behavior. Launch the optimization wizard by selecting **Tools** → **reTORT** → **Optimization Wizard**.

17. In the pop-up window, select **Local DLS Optimization** from the drop down menu.

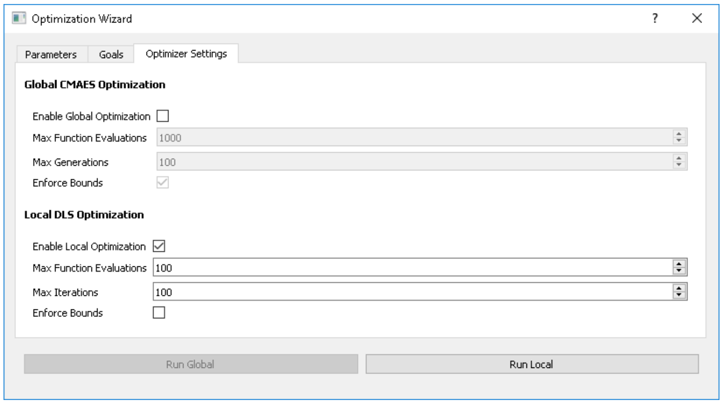
18. Select **Index1 Surface Curvature**, **Index2 Surface Curvature**, **n0**, **r2**, **r4**, **r6**, **r8**, **z1**, and **z2** by clicking the checkboxes next to each. These particular terms are selected from the plethora available as the most powerful terms necessary to create the desired behavior.



19. The **Goals** tab allows you to set the goals for the optimization. The wizard will automatically configure minimum and maximum index goals that correspond to the materials in the binary mixture, depending on the wavelengths in the system. Leave the **Focal Plane** option set to **Image Plane**, to use the working distance we specified earlier. It is also possible to optimize for an effective or back focal length independent of the Image Plane surface by changing that option. Leave the **Primary Goal** set to **Minimize Spot Size**, and leave the color correction options checked.

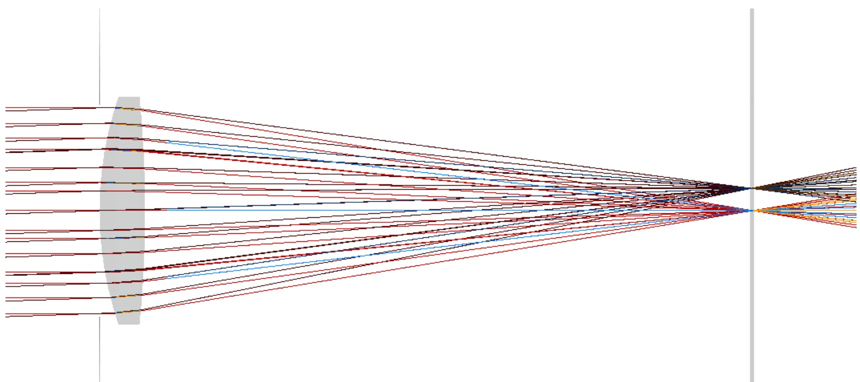


20. The final pane of the wizard allows configuration options to be changed for the global and local optimizations. The default values of **100** function evaluations and **100** maximum iterations should find a good solution for many systems. Now click **Run Local**.

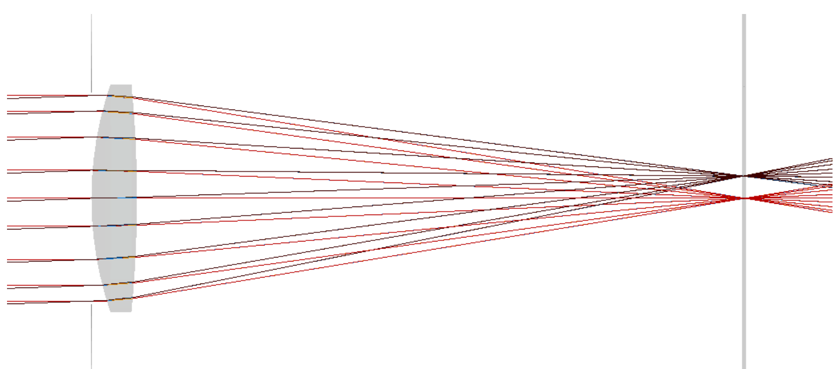


21. The optimization should now take a few moments and result with a well focusing GRIN.

Here is a ray-trace of the final system:



To show a cleaner ray-trace, click the **Choose Ray Bundles** button () at the top of the model view and select **Show Ray Planes** → **Meridonal** from the drop-down menu.



The final set of parameters might look something like in Table 2 below.

Name	Value
C0(n0)	**0.730395**
C1(r^2)	$\mathbf{-0.00597105}$
C2(r^4)	$\mathbf{-8.37334 \cdot 10^{-5}}$
C3(r^6)	$\mathbf{4.69635 \cdot 10^{-7}}$
C4(r^8)	$\mathbf{-2.66420 \cdot 10^{-8}}$
C6(z^1)	**0.0320444**
C7(z^2)	**0.00818006**
Surface 1 Radius	**23.1175 mm**
Surface 2 Radius	$\mathbf{-77.3678}$ **mm**

Table 2: Optimized Coefficients

Now you have generated the actual design of the GRIN. In Section 3 we will briefly analyze this design. Appendix A describes some additional metrics for analyzing the design and how to generate them.

3 Design Conclusion

We can see the size requirements, and subsequently weight requirements, are dramatically reduced with the resultant GRIN vs the original triplet from Section 1, but now we must analyze the performance to verify that the design is a reasonable one. For comparison we will look at focal drift plots for each design as shown in Figure 2. For instructions on the creation of these plots, please see Appendix B. As you can see, both designs demonstrate achromatic behavior, with the triplet having a focal drift of approximately **120 µm** over the range from **450 nm** to **650 nm**. The GRIN has an even better focal drift of roughly **70 µm** over the same range. The GRIN also has a much smaller volume than the triplet, offering a dramatic reduction in size and weight.

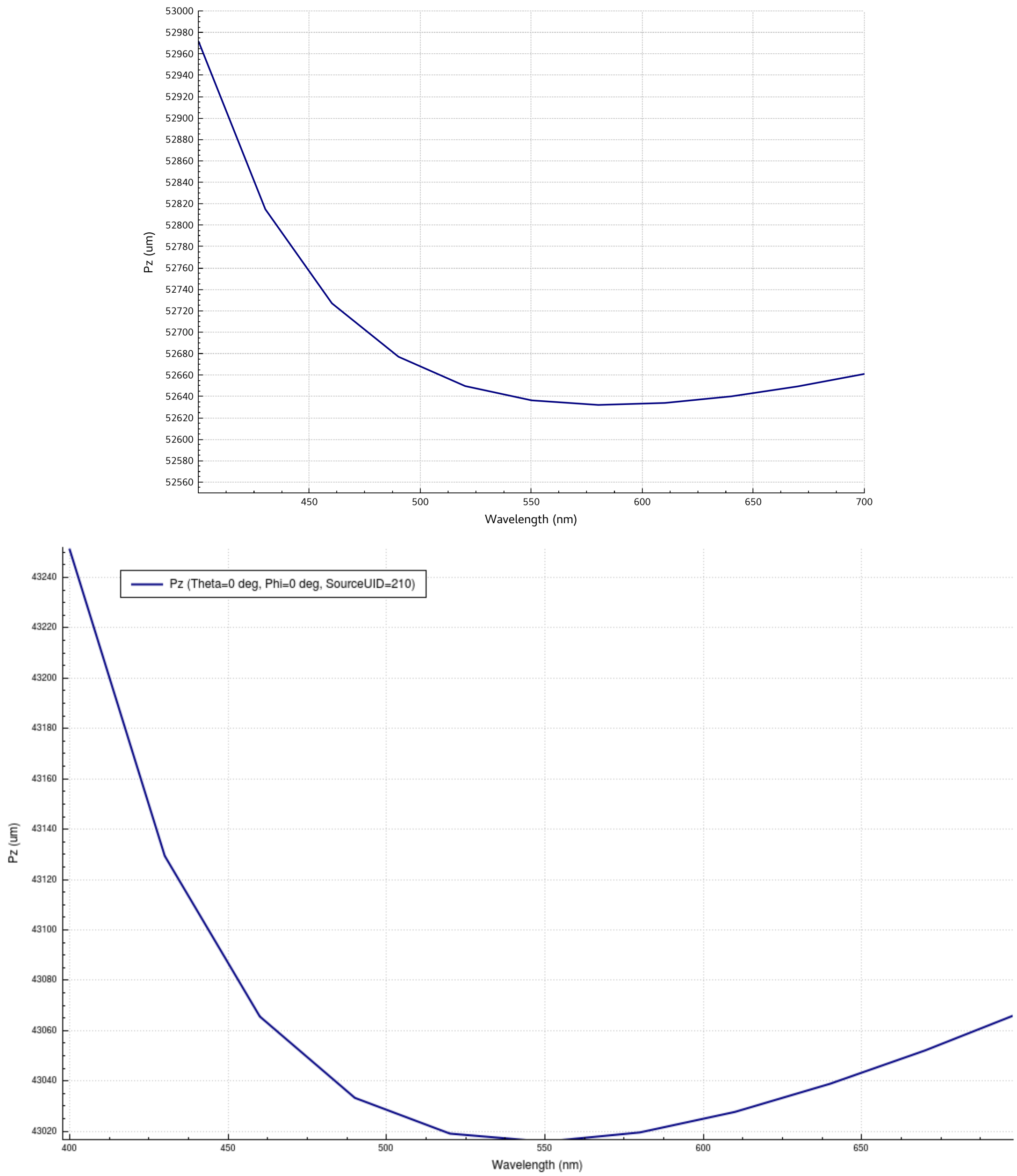


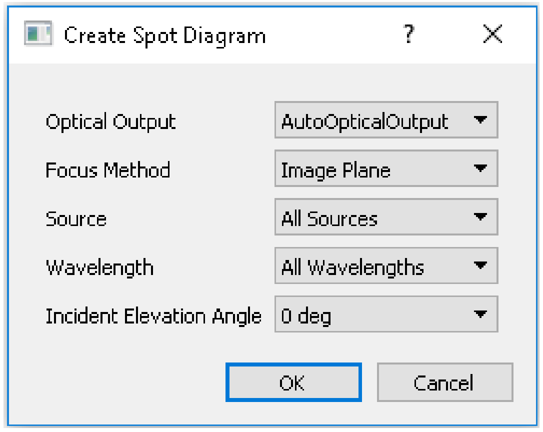
Figure 2: On-Axis Focal Drift Plots for the Triplet (top) and the GRIN Design (bottom)

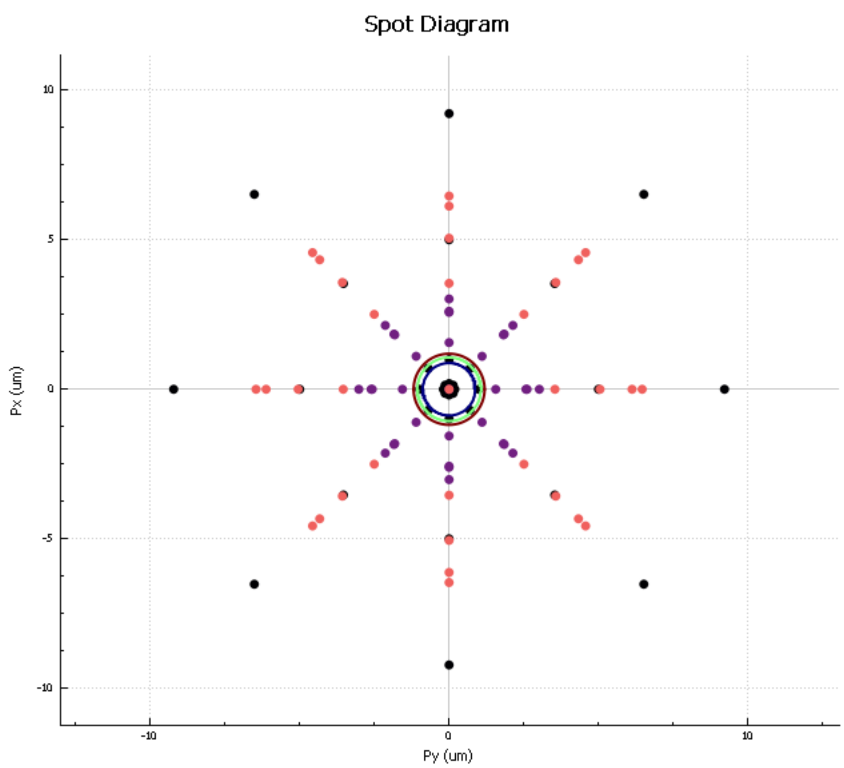
A Design Analysis Tools

The **reTORT** plugin offers a full suite of analysis tools and metrics for design and evaluation of your optical systems. In this section we will showcase a few such features for use in this and other designs.

A.1 Spot Diagrams

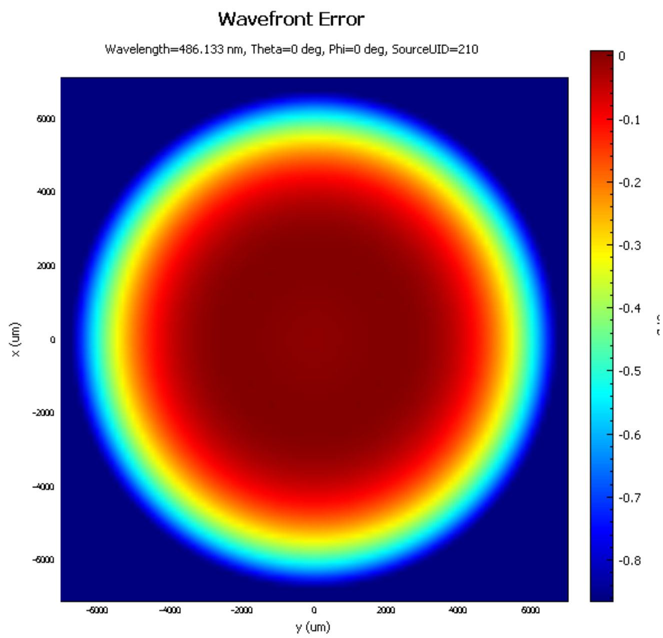
To see a spot diagram quickly and easily, click **Tools** → **reTORT** → **Create Spot Diagram** from the menu bar at the top of the window. This will result in a dialog box like below.





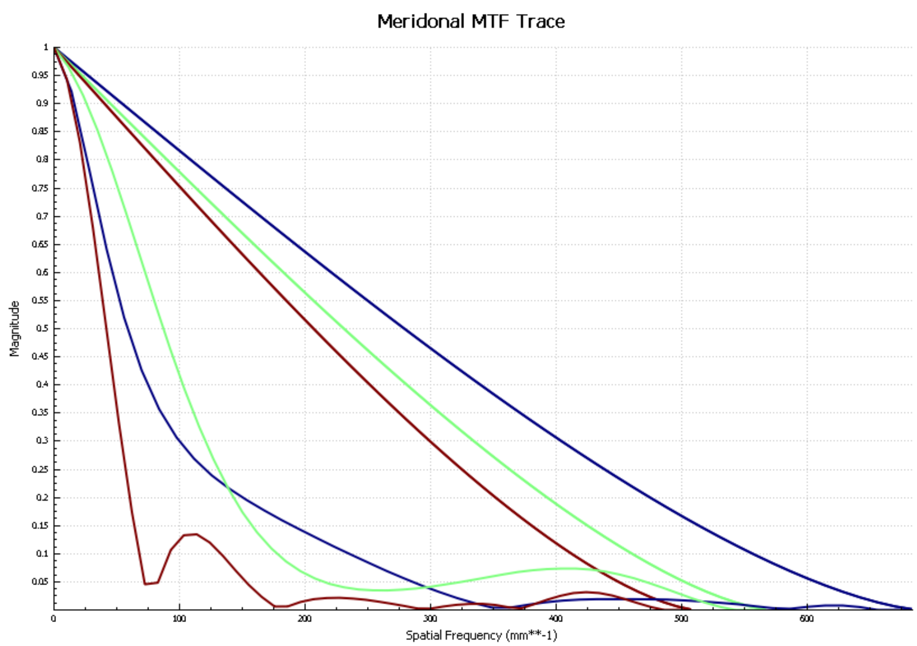
A.2 Wavefront Error Plots

To generate a wavefront error plot, click **Tools** → **reTORT** → **Create Wavefront Error Plot**. Through a similar dialog box you can select which wavelength and incident angle plots you wish to observe. Here is the 0° bundle at **486.133 nm** for example.



A.3 MTF Graphs

To generate a MTF graph, click **Tools** → **reTORT** → **Create MTF Graph**.



A.4 GRIN Profile View

To generate a heatmap view of the GRIN's refractive index profile, under the **Model Hierarchy** dock select **reTORT** → **Views** → **New Element Refractive Index**. Then select the newly generated **ElementView1** and open the property editor. Then select the only entry in the **Element** drop down menu. To view it in the mode shown in Figure 3, change the **Rendering Mode** to **Contour2Dy**, click the X-Z orientation button, and click the XYZ axes button to remove the rendered axes.

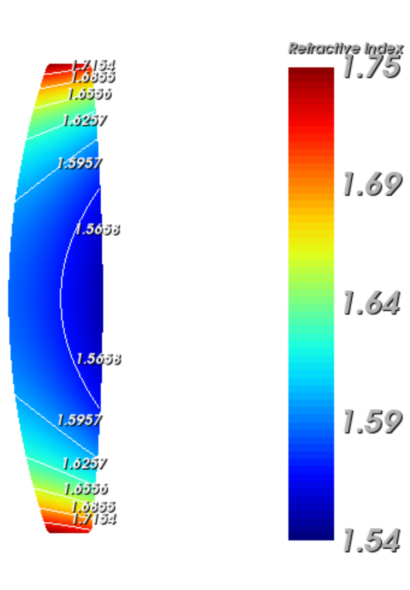


Figure 3: Element Refractive Index View

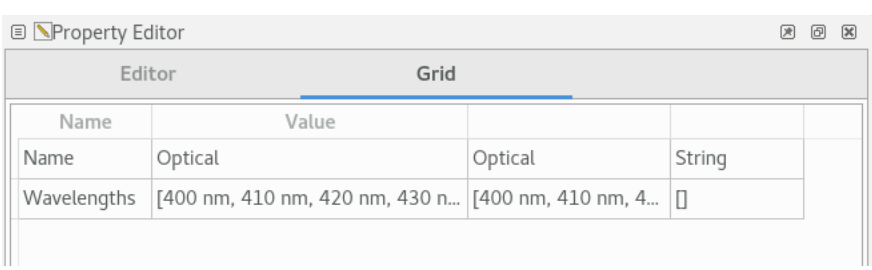
B Creation of the Focal Drift Plot and Manual Plot Creation

To follow are a set of steps to generate a focal drift plot like the ones seen in Figure 2.

Note: This is a detailed process and will teach a more "power-user" level of control of **reTORT** and its interface. This set of steps will also assume that you have have a system ready to analyze, such as that created in Section 2.

1. Beginning with the system that you have created, first we will want to lay the groundwork for the rendering of the plot itself. We will need to set the system to simulate the appropriate range of wavelengths with your system. Click on your system's wavelength spectrum, opening its **Property Editor**. In the example from Section 2 that is located at **reTORT** → **Sources** → **BeamSource1** → **Spectral Lines** → **Optical**.

2. This next step can be done in a manual fashion by clicking **Append** and assigning each a value along the range you would like, however an optional interface present in each **Property Editor** is the grid view. Click the **Grid** tab next to the **Editor** tab near the top of the **Property Editor** to open the grid view.



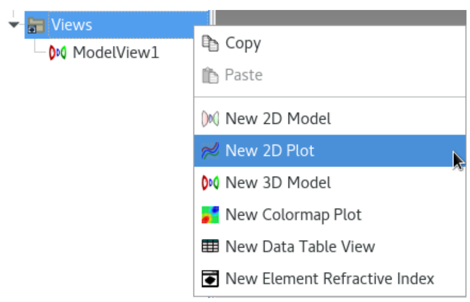
3. The grid view allows for more direct modification of values in your system. The first column of the grid view lists the names of each property of the associated object. The second column is the region of the grid view that you will edit to change the values of the various properties. The third and fourth columns are the evaluated version of the entry in the **Value** column and the type of information respectively. It is important to remember that when using this interface it is quite possible to invalidate your system by entering invalid information into these fields. The **Wavelengths** entry is an array of values with units attached. You may manually enter the set of wavelengths you wish to use here in the form of an array. The values used for Figure 2 were **30 nm** increments from **400 nm** to **700 nm** or as follows:

```
[400 nm, 430 nm, 460 nm, 490 nm, 520 nm, 550 nm, 580 nm, 610 nm, 640 nm, 670 nm, 700 nm]
```

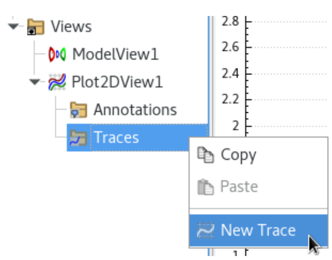
   Enter this array into the **Value** column in the **Wavelengths** row. Your system is now set to simulate these eleven wavelengths, which can take a while to simulate as there is a seperate set of rays for each wavelength/incident angle combination. It is advised that you change this set of wavelengths back to the original three after generating this plot as the system may not run quickly with so many rays to simulate.

4. An additional step is to generate a result that can be referenced to see the focal drift. Generate a new optical output through the **reTORT** → **Results** → **RayResult1** → **Outputs** → **New OpticalOutput** option. Set the **Focus Calculation Method** property of the new output to **Minimum RMS**. Also make sure the **Compute Spot Metrics** property is checked, to enable the **FocalPoint** result.

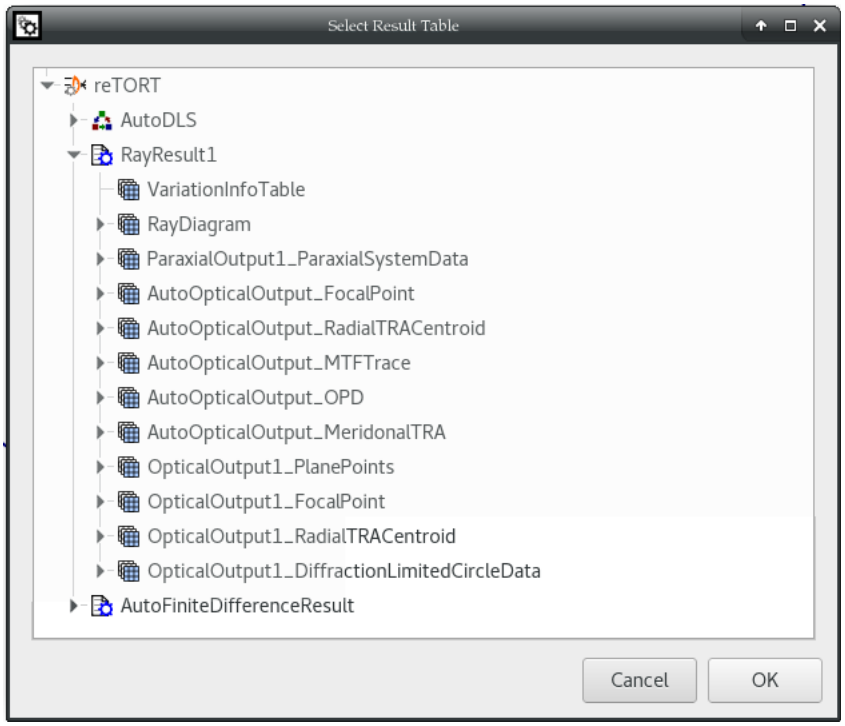
5. Now to create the plot itself. In the **Model Hierarchy**, right-click on **Views** and select **New 2D Plot**.



6. The plot now requires a **Trace**. **Traces** are the interface for selecting which data you wish to represent and in which ways you wish to represent it. Expand your newly created **Plot2DView1** and right-click on **Plot2DView1** → **Traces**. In this menu select **New Trace**.



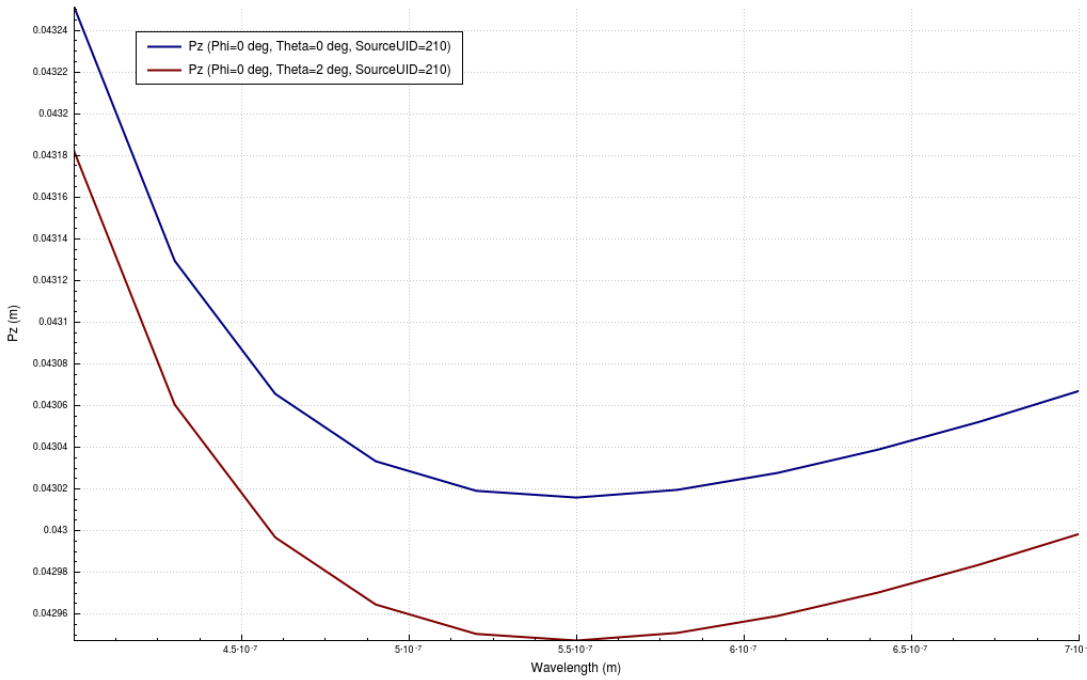
7. Click on the newly created **Trace1** to open its **Property Editor**. Next to the **Data Selection** field, click **Edit**. This will open a dialog box for selecting the data you wish to render. Select **reTORT** → **Results** → **RayResult1** → **OutputOutput1_FocalPoint**, and click **OK**. This table contains the focal point locations and spot sizes.



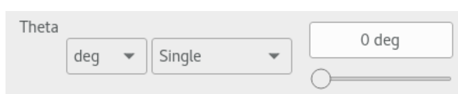
8. For the plots shown in Figure 2, we used the z location of the focal planes described in step 7 and the wavelengths added to the system in step 3. This information is present in the result table selected in step 7, and we apply it here by setting the **X-Data** field to **Wavelength** and the **Y-Data** field to **Pz**.

9. To render the plot, run your simulation by right-clicking **reTORT** in the **Model Hierarchy** and clicking **Run All**. You can alternatively press **F5** on the keyboard to do the equivalent. Furthermore, you can press **Shift+F5** to clear all current data and re-run the system at any time.

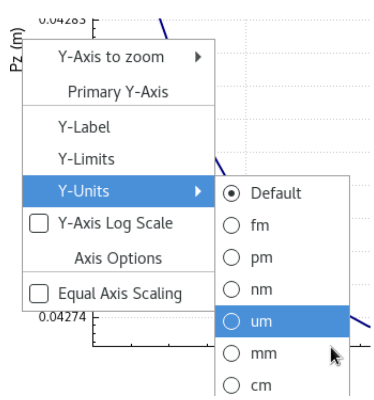
10. By default, the **Trace** will have two seperate data sets rendered, one per incident angle.



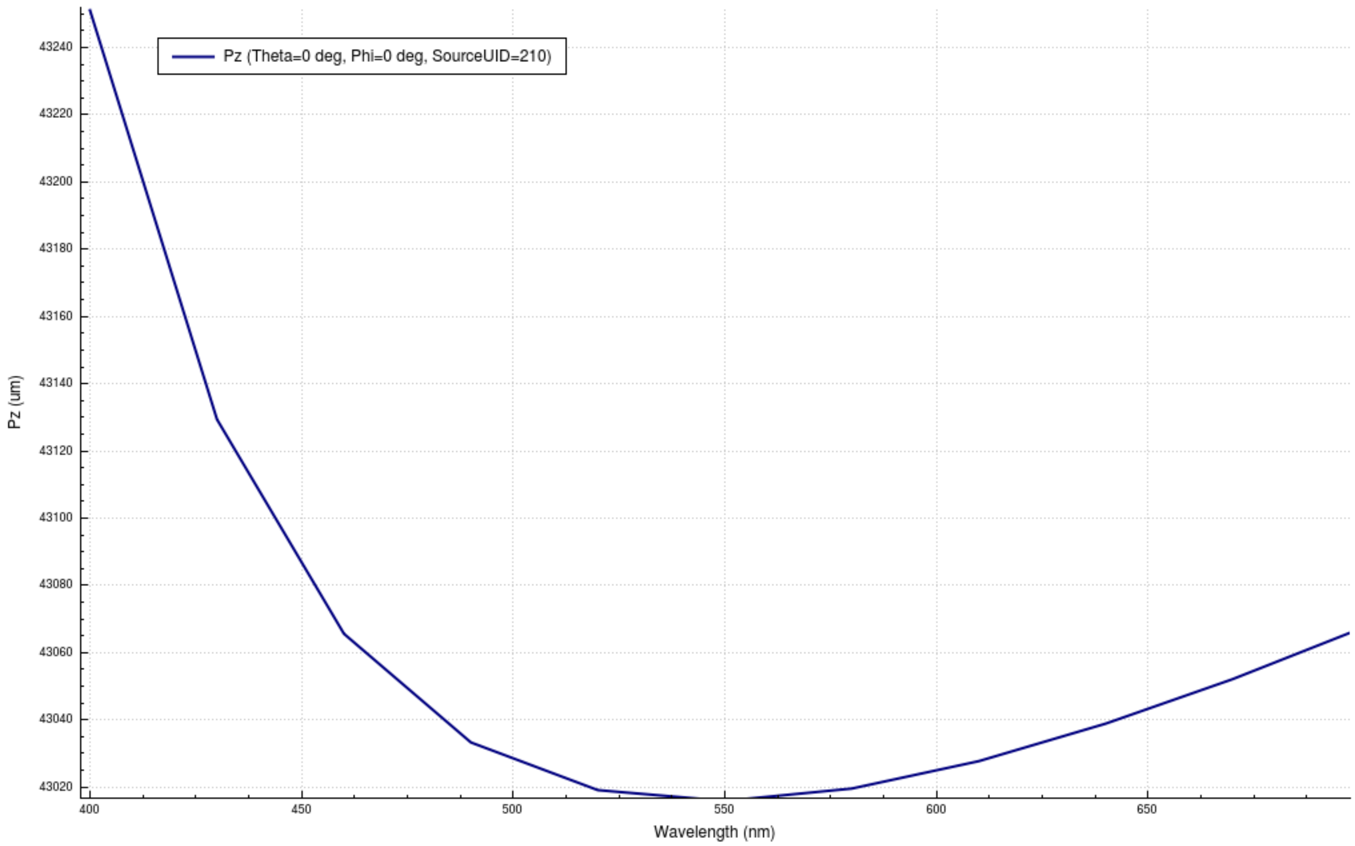
To change this to match the plots in Figure 2, change the **Theta** field in the **Property Editor** of **Trace1** from **Full** to **Single** and drag the small slider to select the incident angle you wish to render. For the plots in Figure 2, we used 0°.



11. You can also change the units displayed on each axis through the **Property Editor** for the plot itself, **Plot2DView1** in this case. Many of the options presented in the **Property Editor** can also be accessed through context menus on parts of the plot. Right-click on the title for the y-axis on the plot, in this case **Pz (m)** and change the units to **µm**. Then do the same for changing the scale of the x-axis, **Wavelength**, to **nm**.



Your plot should now look something like this:



This set of steps is a framework that can be used for rendering any of the data present in the results of your simulations.