Created in COMSOL Multiphysics 6.2

Petzval Lens Optimization

Introduction

This example shows how to use an **Optimization** study to update the optical prescription for a multi-element objective lens when one of the glasses is replaced. Because of slight differences in the refractive index and Abbe number of the replacement glass compared to the original glass, some small adjustments to the geometry sequence are required to ensure that the lens still produces a high-quality image.

For an introduction to ray optics simulation of a Petzval Lens (without the **Optimization** study), see the tutorial model *Ray_Optics_Module/Lenses_Cameras_and_Telescopes/ petzval_lens*.

Model Definition

The Petzval lens setup used in this example includes two cemented doublets and a field flattener. Each of the two cemented doublets typically consists of a crown glass (low refractive index, less dispersion) on the side the object, and a flint glass (higher index, greater dispersion) on the side facing the image plane.

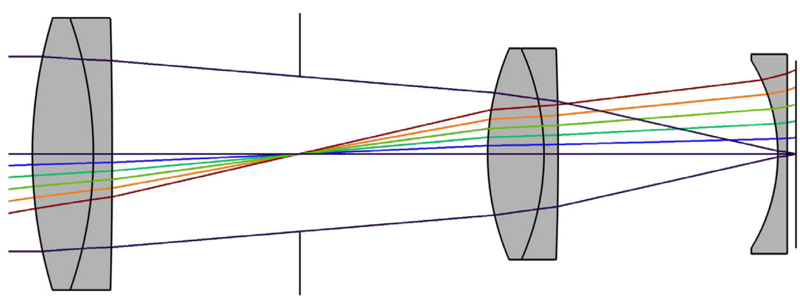

Figure 1: Overview of the Petzval lens. The lens includes a field-flattening element. In this view the marginal rays of an on-axis trace are shown, together with the chief ray of 5 additional fields.

DISPERSION IN OPTICAL GLASS

The refractive index of an optical glass always depends on the wavelength of the light passing through it. A common way to compare the optical properties of different glasses is by comparing their values of the d-line refractive index n_d and Abbe number V_d,

$$V_\mathrm{d} = \frac{n_\mathrm{d} - 1}{n_\mathrm{F} - n_\mathrm{C}}$$

where

- The d-line is a yellow helium spectral line at about 587.56 nm,
- The F-line is a blue hydrogen spectral line at about 486.13 nm, and
- The C-line is a red hydrogen spectral line at about 656.28 nm.

Keeping the d-line refractive index constant, a lower Abbe number means that the refractive index of the glass is more sensitive to changes in the refractive index (greater dispersion), while a higher Abbe number means lower sensitivity (less dispersion).

Historically, optical glasses have been roughly categorized as crown glasses and flint glasses. On average, the crown glasses have lower index and higher Abbe number, while flint glasses have higher index and lower Abbe number. A scatter plot of refractive index versus Abbe number for comparing different glasses is called an Abbe diagram.

A common way to report the Abbe number and d-line refractive index of a glass is through a six-digit glass code. In the glass code, the first three digits are the digits of the refractive index (after the decimal point) and the last three digits are the Abbe number (multiplied by 10). For example, a glass with code 654321 has a d-line refractive index of 1.654 and an Abbe number of 32.1.

CHOOSING A REPLACEMENT GLASS

There are many legitimate reasons why an optical designer might want to replace the glass in a lens system:

- The new glass might be less expensive, more readily available, or be easier to work with.
- The new glass might have other desirable material properties, such as a lower coefficient of thermal expansion, lower density, or superior scratch resistance.
- The new glass might be produced in a more environmentally friendly way.
- The old glass might contain additives such as lead, cadmium, or arsenic that can be hazardous to human health.

Regardless of the reason for the change, the integration of optimization tools into optical ray tracing software can be used to modify an existing optical prescription to use a replacement glass with similar (but not exactly the same) optical properties.

In this example, the geometry sequence is based on the optical prescription shown in Table 1, which in turn was inspired by a prescription from Ref. 1, p. 191. The focal length is 100.0 mm and the focal ratio is approximately $f/2.4$. The instructions for creating the lens geometry can be found in the Appendix — Geometry Instructions.

TABLE 1: PETZVAL LENS PARAMETERS.

Index	**Name**	**Radius (mm)**	**Thickness (mm)**	**Material**	**Clear radius (mm)**
—	Object	∞	∞	—	—
1	Lens 1	99.56266	13.00000	N-BK7	28.478
2	Lens 2	-86.84002	4.00000	S-BAH32	26.276
—	—	-1187.63858	40.00000	—	22.020
3	Stop	∞	40.00000	—	16.631
4	Lens 3	57.47191	12.00000	N-SK2	20.543
5	Lens 4	-54.61865	3.00000	N-SF5	20.074
—	—	-614.68633	46.82210	—	16.492
6	Lens 5	-38.17110	2.00000	N-SF5	17.297
—	—	∞	1.9548	—	18.940
—	Image	∞	—	—	17.904

In 2018 the glass in the second element, S-BAH32 glass from the Ohara corporation, was changed to a “special order” glass (Ref. 2), with a notice that “Special order types may be still available for some time, but we do not guarantee, on your order we can melt these types”. Thereafter, potential replacement glasses for S-BAH32 were considered. The six-digit glass code of the S-BAH32 glass is 670393, meaning it has a d-line refractive index of 1.670 and an Abbe number of 39.3. Two potential replacement glasses were identified:

- Schott N-BASF64, glass code 704394 (n_d = 1.704, V_d = 39.4)
- Schott N-KZFS5, glass code 654397 (n_d = 1.654, V_d = 39.7)

Ultimately the Schott N-KZFS5 glass was chosen. This glass has nearly the same Abbe number as the Ohara S-BAH32 glass but a slightly lower d-line refractive index. Therefore, if the glass is simply replaced without any updates to the geometry sequence, the resolution of the lens system will be significantly diminished. Figure 4 and Figure 5 show the ray and spot diagrams when using the unmodified prescription from Table 1.

SETTING UP THE OPTIMIZATION STUDY

To improve the image quality when using the replacement glass, an **Optimization** study was performed. The control parameters for this study were perturbations in the lens radii of curvature. Since the model geometry includes two cemented double lenses and a field flattener with one curved surface, a total of seven control parameters were used. The objective function is the sum of the squares of the root mean square (rms) spot sizes for three different field angles (on-axis, 6°, and 9°). In addition, rays of three different vacuum wavelengths were released (475 nm, 550 nm, and 625 nm).

Although the **Optimization** study supports both gradient-based and gradient-free optimization methods, only the gradient-free methods are appropriate to use with ray optics simulation, because the degrees of freedom solved for are discrete ray coordinates and directions rather than the values of a continuous field variable. The **BOBYQA** optimization method was used because it is well-suited to optimization problems with a fairly large number of control parameters but no constraints.

The original model geometry was constructed by repeated insertion of part instances from the COMSOL Part Libraries, mainly the “Spherical Lens 3D” part. Since these parts are parameterized representations of the lens surfaces, it was convenient to add perturbations the radii of curvature of each curved refracting surface.

Results and Discussion

The Petzval lens geometry sequence is shown in Figure 2 and the mesh can be seen in Figure 3.

A ray tracing analysis of the original geometry yields the ray diagram shown in Figure 4 and the spot diagram (in the nominal image plane) shown in Figure 5. The rms spot size is on the order of several hundred micrometers for all three field angles.

After the **Optimization** study is run, the ray and spot diagrams of the resulting geometry are shown in Figure 6 and Figure 7. Compared to the previous solution, the rms spot sizes have been reduced by a factor of almost 100.

It is important to note that optimization methods generally seek a local minimum in the objective function by varying the control parameters, not a global minimum in the prescribed range of control parameter values. Therefore, different values of the radii of curvature in the optimized geometry may be found, especially if a different set of initial values is given. This may cause the spot diagram to look slightly different from Figure 7, although the spot sizes should be comparable in magnitude. Lens optimization is a rich design space, and the solution presented here is only one of many possible local minima.

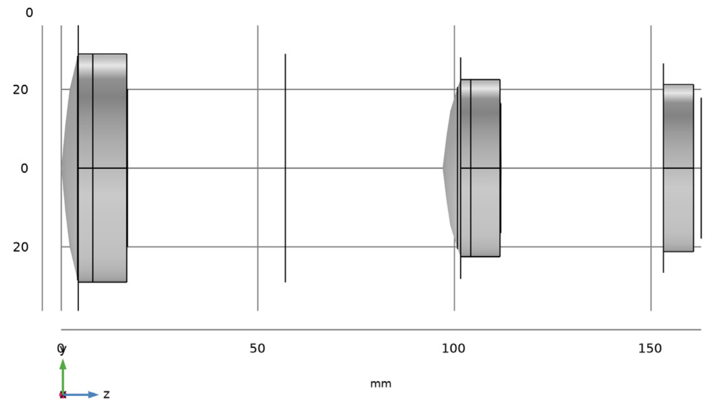

Figure 2: The Petzval lens geometry sequence.

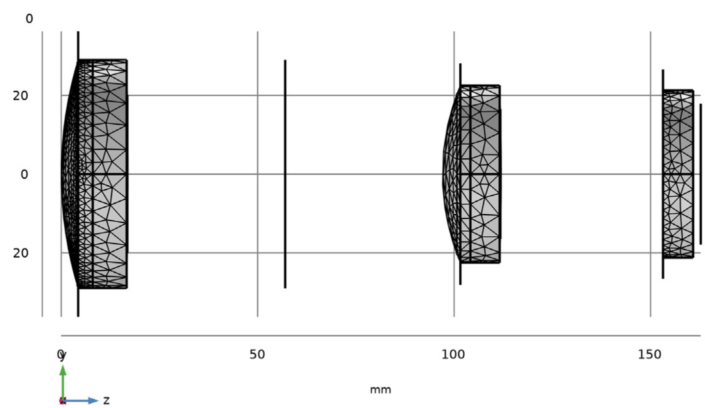

Figure 3: The Petzval lens mesh.

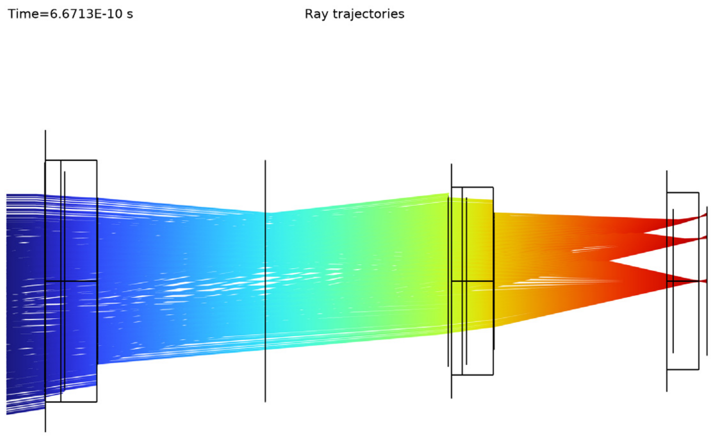

Figure 4: Ray diagram of the Petzval lens before optimization. A close-up look shows that the rays are not well focused at the nominal image plane.

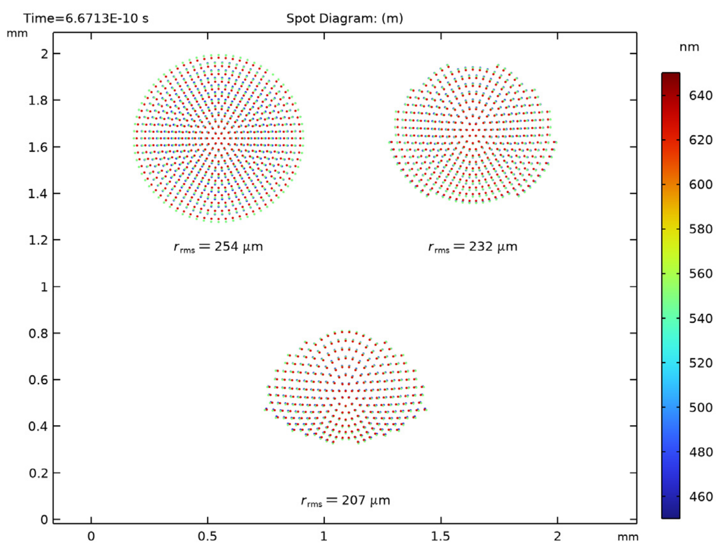

Figure 5: Spot diagram of the Petzval lens in the nominal image plane before optimization.

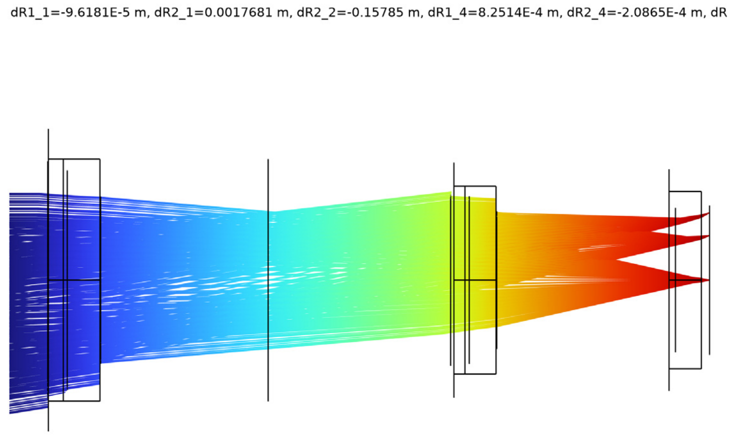

Figure 6: Ray diagram for the optimized Petzval lens. with replacement glass.

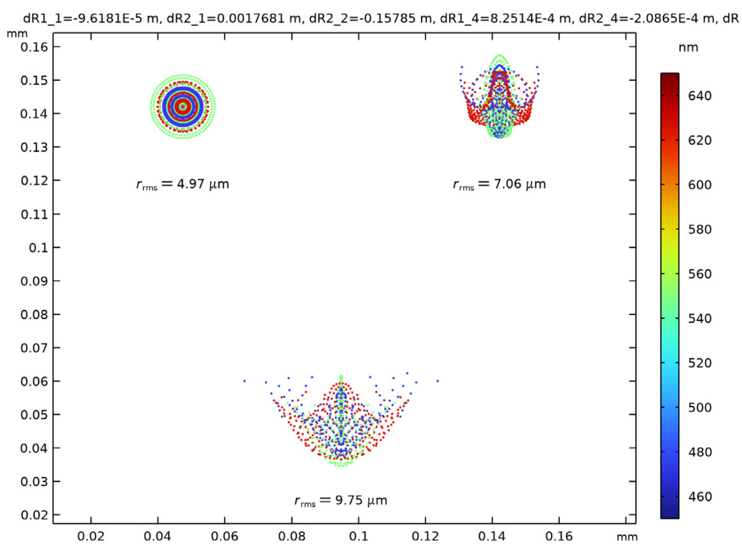

Figure 7: Spot diagram array for the optimized Petzval lens with replacement glass.

References

1. M.J. Kidger, *Fundamental Optical Design*, SPIE Press, 2001.

2. Ohara team, "Review of Glass Portfolio", published 24 Jan 2018, last accessed 12 Jul 2021, https://www.ohara-gmbh.com/en/dialog/news/details/news/review-of-glass-portfolio-1.html.

Application Library path: `Ray_Optics_Module/Lenses_Cameras_and_Telescopes/petzval_lens_optimization`

Modeling Instructions

From the **File** menu, choose **New**.

NEW

In the **New** window, click **Model Wizard**.

MODEL WIZARD

1 In the **Model Wizard** window, click **3D**.

2 In the **Select Physics** tree, select **Optics>Ray Optics>Geometrical Optics (gop)**.

3 Click **Add**.

4 Click **Study**.

5 In the **Select Study** tree, select **Preset Studies for Selected Physics Interfaces>Ray Tracing**.

6 Click **Done**.

GLOBAL DEFINITIONS

Parameters 1: Lens Prescription

1 In the **Model Builder** window, under **Global Definitions** click **Parameters 1**.

2 In the **Settings** window for **Parameters**, type `Parameters 1: Lens Prescription` in the **Label** text field. The lens prescription will be added when the geometry sequence is inserted in the following section.

Parameters 2: General

The Petzval Lens simulation parameters can be loaded from a text file.

1 In the **Home** toolbar, click **Parameters** and choose **Add>Parameters**.

2 In the **Settings** window for **Parameters**, type `Parameters 2: General` in the **Label** text field.

3 Locate the **Parameters** section. Click **Load from File**.

4 Browse to the model's Application Libraries folder and double-click the file `petzval_lens_optimization_parameters.txt`.

PETZVAL LENS

Insert the prepared geometry sequence from file. You can read the instructions for creating the geometry in the appendix. Following insertion, the lens definitions will be available in the **Parameters 1: Lens Prescription** node.

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Geometry 1**.

2 In the **Settings** window for **Geometry**, locate the **Units** section.

3 From the **Length unit** list, choose **mm**.

4 In the **Label** text field, type `Petzval Lens`.

5 In the **Geometry** toolbar, click **Insert Sequence** and choose **Insert Sequence**.

6 Browse to the model's Application Libraries folder and double-click the file `petzval_lens_optimization_geom_sequence.mph`.

7 In the **Geometry** toolbar, click **Build All**.

8 Click the **Orthographic Projection** button in the **Graphics** toolbar.

9 In the **Graphics** window toolbar, click ▾ next to **Go to Default View**, then choose **Go to ZY View**. This will orient the view to place the optical axis (z-axis) horizontal and the y-axis vertical. Compare the resulting geometry to Figure 2.

ADD MATERIAL

1 In the **Home** toolbar, click **Add Material** to open the **Add Material** window.

2 Go to the **Add Material** window.

3 In the tree, select **Optical>Schott Glass>Schott N-BK7 Glass**.

4 Click **Add to Component** in the window toolbar.

5 In the tree, select **Optical>Schott Glass>Schott N-KZFS5 Glass**.

6 Click **Add to Component** in the window toolbar.

7 In the tree, select **Optical>Schott Glass>Schott N-SK2 Glass**.

8 Click **Add to Component** in the window toolbar.

9 In the tree, select **Optical>Schott Glass>Schott N-SF5 Glass**.

10 Click **Add to Component** in the window toolbar.

11 In the **Home** toolbar, click **Add Material** to close the **Add Material** window.

MATERIALS

Schott N-BK7 Glass (mat1)

1 In the **Model Builder** window, under **Component 1 (comp1)>Materials** click **Schott N-BK7 Glass (mat1)**.

2 In the **Settings** window for **Material**, locate the **Geometric Entity Selection** section.

3 From the **Selection** list, choose **Lens Material 1**.

Schott N-KZFS5 Glass (mat2)

1 In the **Model Builder** window, click **Schott N-KZFS5 Glass (mat2)**.

2 In the **Settings** window for **Material**, locate the **Geometric Entity Selection** section.

3 From the **Selection** list, choose **Lens Material 2**.

Schott N-SK2 Glass (mat3)

1 In the **Model Builder** window, click **Schott N-SK2 Glass (mat3)**.

2 In the **Settings** window for **Material**, locate the **Geometric Entity Selection** section.

3 From the **Selection** list, choose **Lens Material 3**.

Schott N-SF5 Glass (mat4)

1 In the **Model Builder** window, click **Schott N-SF5 Glass (mat4)**.

2 In the **Settings** window for **Material**, locate the **Geometric Entity Selection** section.

3 From the **Selection** list, choose **Lens Material 4**.

GEOMETRICAL OPTICS (GOP)

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Geometrical Optics (gop)**.

2 In the **Settings** window for **Geometrical Optics**, locate the **Ray Release and Propagation** section.

3 From the **Wavelength distribution of released rays** list, choose **Polychromatic, specify vacuum wavelength**. The list of polychromatic wavelengths will be entered below.

4 In the **Maximum number of secondary rays** text field, type `0`. In this simulation stray light is not being traced, so reflected rays will not be produced at the lens surfaces.

5 Locate the **Material Properties of Exterior and Unmeshed Domains** section. From the **Optical dispersion model** list, choose **Air, Edlen (1953)**. The lenses are assumed to be surrounded by air at room temperature.

Medium Properties 1

1. In the **Model Builder** window, under **Component 1 (comp1)>Geometrical Optics (gop)** click **Medium Properties 1**.
2. In the **Settings** window for **Medium Properties**, locate the **Medium Properties** section.
3. From the **Refractive index of domains** list, choose **Get dispersion model from material**. Each of the materials added above contain the optical dispersion coefficients which can be used to compute the refractive index as a function of wavelength.

Material Discontinuity 1

1. In the **Model Builder** window, click **Material Discontinuity 1**.
2. In the **Settings** window for **Material Discontinuity**, locate the **Rays to Release** section.
3. From the **Release reflected rays** list, choose **Never**.

Release from Grid 1

Release the rays from a hexapolar grid, using quantities defined in the **Parameters** node.

1. In the **Physics** toolbar, click **Global** and choose **Release from Grid**.
2. In the **Settings** window for **Release from Grid**, locate the **Initial Coordinates** section.
3. From the **Grid type** list, choose **Hexapolar**.
4. Specify the $\mathbf{q}_c$ vector as

`dx1`	x
`dy1`	y
`dz`	z

The **Center location** of the hexapolar grid will change according to the field angle.

5. Specify the $\mathbf{r}_c$ vector as

`nix`	x
`niy`	y
`niz`	z

The **Cylinder axis direction** is the same as the global optical axis.

6. In the R_c text field, type `P_nom/2`.
7. In the N_c text field, type `N_ring`.

8 Locate the **Ray Direction Vector** section. Specify the $\mathbf{L}_0$ vector as

vx1	x
vy1	y
vz	z

The **Ray direction vector** is calculated using the field angles defined in the **Parameters** node.

9 Locate the **Vacuum Wavelength** section. From the **Distribution function** list, choose **List of values**.

10 In the **Values** text field, type `475[nm] 550[nm] 625[nm]`.

Release from Grid 2

1 Right-click **Release from Grid 1** and choose **Duplicate**.

2 In the **Settings** window for **Release from Grid**, locate the **Initial Coordinates** section.

3 Specify the $\mathbf{q}_c$ vector as

dx2	x
dy2	y

4 Locate the **Ray Direction Vector** section. Specify the $\mathbf{L}_0$ vector as

vx2	x
vy2	y

Release from Grid 3

1 Right-click **Release from Grid 2** and choose **Duplicate**.

2 In the **Settings** window for **Release from Grid**, locate the **Initial Coordinates** section.

3 Specify the $\mathbf{q}_c$ vector as

dx3	x
dy3	y

4 Locate the **Ray Direction Vector** section. Specify the $\mathbf{L}_0$ vector as

vx3	x
vy3	y

Obstructions

1 In the **Physics** toolbar, click **Boundaries** and choose **Wall**.

2 In the **Settings** window for **Wall**, type `Obstructions` in the **Label** text field.

3 Locate the **Boundary Selection** section. From the **Selection** list, choose **Obstructions**.

4 Locate the **Wall Condition** section. From the **Wall condition** list, choose **Disappear**.

Stop

1 In the **Physics** toolbar, click **Boundaries** and choose **Wall**.

2 In the **Settings** window for **Wall**, type `Stop` in the **Label** text field.

3 Locate the **Boundary Selection** section. From the **Selection** list, choose **Aperture Stop**.

4 Locate the **Wall Condition** section. From the **Wall condition** list, choose **Disappear**.

Image

1 In the **Physics** toolbar, click **Boundaries** and choose **Wall**.

2 In the **Settings** window for **Wall**, type `Image` in the **Label** text field.

3 Locate the **Boundary Selection** section. From the **Selection** list, choose **Image Plane**.

MESH 1

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Mesh 1**.

2 In the **Settings** window for **Mesh**, locate the **Physics-Controlled Mesh** section.

3 From the **Element size** list, choose **Fine**. Slightly refine the mesh for this study to ensure that rays passing close the edge of apertures are traced.

4 Click **Build All**. The mesh should looks like Figure 3.

STUDY 1

Step 1: Ray Tracing

1 In the **Model Builder** window, under **Study 1** click **Step 1: Ray Tracing**.

2 In the **Settings** window for **Ray Tracing**, locate the **Study Settings** section.

3 From the **Time-step specification** list, choose **Specify maximum path length**.

4 From the **Length unit** list, choose **mm**.

5 In the **Lengths** text field, type `0 200`. The maximum optical path length is sufficient for rays released at large field angles to reach the image plane.

6 In the **Home** toolbar, click **Compute**.

RESULTS

Ray Trajectories (gop)

The default plot is a ray diagram with a color expression based on time, which is proportional to optical path length.

1 In the **Settings** window for **3D Plot Group**, locate the **Color Legend** section.

2 Clear the **Show legends** check box.

3 Click the **Show Grid** button in the **Graphics** toolbar.

4 Click the **Show Axis Orientation** button in the **Graphics** toolbar.

Compare this image to Figure 4. The rays appear to converge some distance away from the nominal image plane.

Spot Diagram

In the following steps, a spot diagram is created, and a custom color expression is added.

1 In the **Home** toolbar, click **Add Plot Group** and choose **2D Plot Group**.

2 In the **Settings** window for **2D Plot Group**, type `Spot Diagram` in the **Label** text field.

3 Locate the **Color Legend** section. Select the **Show units** check box.

Spot Diagram 1

In the **Spot Diagram** toolbar, click **More Plots** and choose **Spot Diagram**.

Color Expression 1

1 In the **Spot Diagram** toolbar, click **Color Expression**.

2 In the **Settings** window for **Color Expression**, locate the **Expression** section.

3 In the **Expression** text field, type `gop.lambda0`.

4 From the **Unit** list, choose **nm**.

5 Click to expand the **Range** section. Select the **Manual color range** check box.

6 In the **Minimum** text field, type `450`.

7 In the **Maximum** text field, type `650`.

8 In the **Spot Diagram** toolbar, click **Plot**.

9 Click the **Zoom Extents** button in the **Graphics** toolbar. Compare the resulting image to Figure 5.

GLOBAL DEFINITIONS

Parameters 3: Optimization

1 In the **Home** toolbar, click Pi **Parameters** and choose **Add>Parameters**.

2 In the **Settings** window for **Parameters**, type `Parameters 3: Optimization` in the **Label** text field.

3 Locate the **Parameters** section. Click **Load from File**.

4 Browse to the model's Application Libraries folder and double-click the file `petzval_lens_optimization_opt_parameters.txt`.

Parameters 1: Lens Prescription

1 In the **Model Builder** window, click **Parameters 1: Lens Prescription**.

2 In the **Settings** window for **Parameters**, locate the **Parameters** section.

3 In the table, enter the following settings:

Name	Expression	Value	Description
R1_1	99.56266[mm]+dR1_1	0.099563 m	L1, surface 1 radius of curvature
R2_1	-86.84002[mm]+dR2_1	-0.08684 m	L1, surface 2 radius of curvature
R2_2	-1187.63858[mm]+dR2_2	-1.1876 m	L2, surface 2 radius of curvature
R1_4	57.47191[mm]+dR1_4	0.057472 m	L3, surface 1 radius of curvature
R2_4	-54.61865[mm]+dR2_4	-0.054619 m	L3, surface 2 radius of curvature
R2_5	-614.68633[mm]+dR2_5	-0.61469 m	L4, surface 2 radius of curvature
R1_6	-38.17110[mm]+dR1_6	-0.038171 m	L5, surface 1 radius of curvature

ADD STUDY

1 In the **Home** toolbar, click **Add Study** to open the **Add Study** window.

2 Go to the **Add Study** window.

3 Find the **Studies** subsection. In the **Select Study** tree, select **Preset Studies for Selected Physics Interfaces>Ray Tracing**.

4 Click **Add Study** in the window toolbar.

5 In the **Home** toolbar, click **Add Study** to close the **Add Study** window.

STUDY 2

Step 1: Ray Tracing

1 In the **Settings** window for **Ray Tracing**, locate the **Study Settings** section.

2 From the **Time-step specification** list, choose **Specify maximum path length**.

3 In the **Lengths** text field, type `0 200`.

4 From the **Length unit** list, choose **mm**.

Optimization

1 In the **Study** toolbar, click **Optimization** and choose **Optimization**.

2 In the **Settings** window for **Optimization**, locate the **Optimization Solver** section.

3 From the **Method** list, choose **BOBYQA**.

4 In the **Optimality tolerance** text field, type `0.001`.

5 Locate the **Objective Function** section. In the table, enter the following settings:

Expression	Description	Evaluate for
`comp1.gop.relg1.rrms^2`		Ray Tracing
`comp1.gop.relg2.rrms^2`		Ray Tracing
`comp1.gop.relg3.rrms^2`		Ray Tracing

6 Locate the **Control Variables and Parameters** section. Click **Load from File**.

7 Browse to the model's Application Libraries folder and double-click the file `petzval_lens_optimization_study_settings.txt`.

Solution 2 (sol2)

1 In the **Study** toolbar, click **Show Default Solver**.

2 In the **Model Builder** window, expand the **Solution 2 (sol2)** node, then click **Time-Dependent Solver 1**.

3 In the **Settings** window for **Time-Dependent Solver**, click to expand the **Time Stepping** section.

4 From the **Steps taken by solver** list, choose **Manual**.

5 In the **Time step** text field, type `200[mm]/c_const`.

6 In the **Study** toolbar, click **Compute**.

RESULTS

Ray Trajectories (gop) 1

1 In the **Settings** window for **3D Plot Group**, locate the **Data** section.

2 From the **Time (s)** list, choose **6.6713E-10**.

3 Locate the **Color Legend** section. Clear the **Show legends** check box.

4 In the **Ray Trajectories (gop) 1** toolbar, click **Plot**.

Compare this image to Figure 6. The rays appear to converge some distance away from the nominal image plane.

Spot Diagram 1

1 In the **Model Builder** window, right-click **Spot Diagram** and choose **Duplicate**.

2 In the **Settings** window for **2D Plot Group**, locate the **Data** section.

3 From the **Dataset** list, choose **Ray 2**.

4 In the **Spot Diagram 1** toolbar, click **Plot**.

Compare this image to Figure 7.

5 Click the **Zoom Extents** button in the **Graphics** toolbar.

Appendix — Geometry Instructions

From the **File** menu, choose **New**.

NEW

In the **New** window, click **Model Wizard**.

MODEL WIZARD

1 In the **Model Wizard** window, click **3D**.

2 Click **Done**.

GLOBAL DEFINITIONS

The detailed parameters of the lens can be imported from a text file. The prescription for the Petzval lens with a field flattener can be found in Ref. 1, pg 192.

Parameters 1

1 In the **Model Builder** window, under **Global Definitions** click **Parameters 1**.

2 In the **Settings** window for **Parameters**, locate the **Parameters** section.

3 Click **Load from File**.

4 Browse to the model's Application Libraries folder and double-click the file `petzval_lens_optimization_geom_sequence_parameters.txt`.

Petzval Lens Parameters

The parameters that define the Petzval lens geometric sequence are found in `petzval_lens_optimization_geom_sequence_parameters.txt`. These will be described in the tables below.

1 First, define the global optical axis. This is used to orient the first lens only. The orientation of each subsequent lens will be relative to the preceding one.

Parameter	Description
`nix`	Global optical axis, x-component
`niy`	Global optical axis, y-component
`niz`	Global optical axis, z-component

2 Next, define the parameters for each of the lens elements. Each lens requires 8 parameters in addition to the ray incident directions (which are set using the global values).

Parameter	Description
`R1_[n]`	Radius of curvature, surface 1, lens [n]
`R2_[n]`	Radius of curvature, surface 2, lens [n]
`Tc_[n]`	Center thickness, lens [n]
`d0_[n]`	Outer diameter, lens [n]
`d1_[n]`	Diameter, surface 1, lens [n]
`d2_[n]`	Diameter, surface 2, lens [n]
`d1_clear_[n]`	Clear aperture diameter, surface 1, lens [n]
`d2_clear_[n]`	Clear aperture diameter, surface 2, lens [n]

3 Finally, define the remaining lens parameters.

Parameter	Description
`T_[n]`	Distance between lenses [n] and [n+1].
`d0_S`	Stop maximum (outer) diameter
`d1_S`	Stop minimum (clear) diameter
`d0_D`	Diameter of image plane

PETZVAL LENS GEOMETRY SEQUENCE

Start constructing the lens geometry.

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Geometry 1**.

2 In the **Settings** window for **Geometry**, type `Petzval Lens Geometry Sequence` in the **Label** text field.

3 Locate the **Units** section. From the **Length unit** list, choose **mm**.

Insert the first of the Petzval Lens elements.

PART LIBRARIES

1 In the **Home** toolbar, click **Windows** and choose **Part Libraries**.

2 In the **Part Libraries** window, select **Ray Optics Module>3D>Spherical Lenses> spherical_lens_3d** in the tree.

3 Click **Add to Geometry**.

4 In the **Select Part Variant** dialog box, select **Specify clear aperture diameter** in the **Select part variant** list.

5 Click **OK**. This part is used for each of the 5 Petzval Lens elements.

PETZVAL LENS GEOMETRY SEQUENCE

Lens 1

1 In the **Model Builder** window, under **Component 1 (comp1)> Petzval Lens Geometry Sequence** click **Spherical Lens 3D 1 (pi1)**.

2 In the **Settings** window for **Part Instance**, type `Lens 1` in the **Label** text field.

3 Locate the **Input Parameters** section. Click **Load from File**.

4 Browse to the model's Application Libraries folder and double-click the file `petzval_lens_optimization_geom_sequence_lens1.txt`. The files `petzval_lens_optimization_geom_sequence_lens`*m*`.txt`, where *m*=`1,...,5`, contain references to each of the individual lens parameters. This avoids having to enter the values manually. Note that the *z*-axis is the optical axis throughout this geometry; that is, `nix=niy=0`, `niz=1`.

5 Click **Build Selected**.

6 Click the **Orthographic Projection** button in the **Graphics** toolbar.

7 In the **Graphics** window toolbar, click ▾ next to **Go to Default View**, then choose **Go to ZY View**. This will orient the view to place the optical axis (that is, the *z*-axis) horizontally and the *y*-axis vertically.

Create cumulative selections defining the materials, clear apertures, obstructions and image plane that can be used within the final ray trace.

Cumulative Selections

In the **Geometry** toolbar, click **Selections** and choose **Cumulative Selections**.

Lens Material 1

1 Right-click **Cumulative Selections** and choose **Cumulative Selection**.

2 In the **Settings** window for **Selection**, type `Lens Material 1` in the **Label** text field.

Lens Material 2

1 In the **Model Builder** window, right-click **Cumulative Selections** and choose **Cumulative Selection**.

2 In the **Settings** window for **Selection**, type `Lens Material 2` in the **Label** text field. In the same manner, add selections for `Lens Material 3`, `Lens Material 4`, `Lens Exteriors`, `Clear Apertures`, `Obstructions`, `Aperture Stop`, and `Image Plane`.

Lens 1 (pi1)

Now, apply these selections.

1 In the **Model Builder** window, under **Component 1 (comp1)> Petzval Lens Geometry Sequence** click **Lens 1 (pi1)**.

2 In the **Settings** window for **Part Instance**, click to expand the **Domain Selections** section.

3 In the table, enter the following settings:

Name	Keep	Physics	Contribute to
All		√	Lens Material 1

4 Click to expand the **Boundary Selections** section. In the table, enter the following settings:

Name	Keep	Physics	Contribute to
Exterior		√	Lens Exteriors
Surface 1		√	Clear Apertures
Surface 2		√	Clear Apertures
Surface 1 obstruction		√	Obstructions
Surface 2 obstruction		√	Obstructions
Edges		√	Obstructions

Lens 2

Continue constructing the lens. Add the second lens element.

1 In the **Geometry** toolbar, click **Part Instance** and choose **Spherical Lens 3D**.

2 In the **Settings** window for **Part Instance**, type `Lens 2` in the **Label** text field.

3 Locate the **Input Parameters** section. Click **Load from File**.

4 Browse to the model's Application Libraries folder and double-click the file `petzval_lens_optimization_geom_sequence_lens2.txt`.

Each lens element can be positioned in the geometry by referencing it to an existing work plane. For this example, use a work plane that is defined by the vertex on the exit surface of the prior lens element.

5 Locate the **Position and Orientation of Output** section. Find the **Coordinate system to match** subsection. From the **Take work plane from** list, choose **Lens 1 (pi1)**.

6 From the **Work plane** list, choose **Surface 2 vertex intersection (wp2)**.

7 Find the **Displacement** subsection. In the **zw** text field, type `T_1`. This is the distance along the optical axis between the exit surface of lens 1 and the entrance surface of lens 2.

8 Locate the **Domain Selections** section. In the table, enter the following settings:

Name	Keep	Physics	Contribute to
All		√	Lens Material 2

9 Locate the **Boundary Selections** section. In the table, enter the following settings:

Name	Keep	Physics	Contribute to
Exterior		√	Lens Exteriors
Surface 1		√	Clear Apertures
Surface 2		√	Clear Apertures
Surface 1 obstruction		√	Obstructions
Surface 2 obstruction		√	Obstructions
Edges		√	Obstructions

PART LIBRARIES

Next, insert the stop.

1 In the **Geometry** toolbar, click **Part Libraries**.

2 In the **Part Libraries** window, select **Ray Optics Module>3D>Apertures and Obstructions>circular_planar_annulus** in the tree.

3 Click **Add to Geometry**. This part is also used to define the image plane and additional obstructions.

Stop

1 In the **Model Builder** window, under **Component 1 (comp1)>** **Petzval Lens Geometry Sequence** click **Circular Planar Annulus 1 (pi3)**.

2 In the **Settings** window for **Part Instance**, type `Stop` in the **Label** text field.

3 Locate the **Input Parameters** section. In the table, enter the following settings:

Name	Expression	Value	Description
d0	`d0_S`	58 mm	Diameter, outer
d1	`d1_S`	33.262 mm	Diameter, inner
nix	`0`	0	Local optical axis, x-component
niy	`0`	0	Local optical axis, y-component
niz	`1`	1	Local optical axis, z-component

4 Locate the **Position and Orientation of Output** section. Find the **Coordinate system to match** subsection. From the **Take work plane from** list, choose **Lens 2 (pi2)**.

5 From the **Work plane** list, choose **Surface 2 vertex intersection (wp2)**.

6 Find the **Displacement** subsection. In the **zw** text field, type `T_2+Tc_3`.

7 Locate the **Boundary Selections** section. In the table, enter the following settings:

Name	Keep	Physics	Contribute to
All		√	Aperture Stop

Lens 3

The remaining lenses are similarly defined. Next, add the third lens element.

1 In the **Geometry** toolbar, click **Part Instance** and choose **Spherical Lens 3D**.

2 In the **Settings** window for **Part Instance**, type `Lens 3` in the **Label** text field.

3 Locate the **Input Parameters** section. Click **Load from File**.

4 Browse to the model's Application Libraries folder and double-click the file `petzval_lens_optimization_geom_sequence_lens3.txt`.

5 Locate the **Position and Orientation of Output** section. Find the **Coordinate system to match** subsection. From the **Take work plane from** list, choose **Stop (pi3)**.

6 From the **Work plane** list, choose **Surface (wp1)**.

7 Find the **Displacement** subsection. In the **zw** text field, type T_3.

8 Locate the **Domain Selections** section. In the table, enter the following settings:

Name	Keep	Physics	Contribute to
All		√	Lens Material 3

9 Locate the **Boundary Selections** section. In the table, enter the following settings:

Name	Keep	Physics	Contribute to
Exterior		√	Lens Exteriors
Surface 1		√	Clear Apertures
Surface 2		√	Clear Apertures
Surface 1 obstruction		√	Obstructions
Surface 2 obstruction		√	Obstructions
Edges		√	Obstructions

Lens 4

Next, add the fourth lens element.

1 In the **Geometry** toolbar, click **Part Instance** and choose **Spherical Lens 3D**.

2 In the **Settings** window for **Part Instance**, type Lens 4 in the **Label** text field.

3 Locate the **Input Parameters** section. Click **Load from File**.

4 Browse to the model's Application Libraries folder and double-click the file `petzval_lens_optimization_geom_sequence_lens4.txt`.

5 Locate the **Position and Orientation of Output** section. Find the **Coordinate system to match** subsection. From the **Take work plane from** list, choose **Lens 3 (pi4)**.

6 From the **Work plane** list, choose **Surface 2 vertex intersection (wp2)**.

7 Find the **Displacement** subsection. In the **zw** text field, type T_4.

8 Locate the **Domain Selections** section. In the table, enter the following settings:

Name	Keep	Physics	Contribute to
All		√	Lens Material 4

9 Locate the **Boundary Selections** section. In the table, enter the following settings:

Name	Keep	Physics	Contribute to
Exterior		√	Lens Exteriors
Surface 1		√	Clear Apertures
Surface 2		√	Clear Apertures
Surface 1 obstruction		√	Obstructions
Surface 2 obstruction		√	Obstructions
Edges		√	Obstructions

Lens 5

Now, add the fifth and last lens element. This element gives the Petzval a flat image plane.

1 In the **Geometry** toolbar, click **Part Instance** and choose **Spherical Lens 3D**.

2 In the **Settings** window for **Part Instance**, type `Lens 5` in the **Label** text field.

3 Locate the **Input Parameters** section. Click **Load from File**.

4 Browse to the model's Application Libraries folder and double-click the file `petzval_lens_optimization_geom_sequence_lens5.txt`.

5 Locate the **Position and Orientation of Output** section. Find the **Coordinate system to match** subsection. From the **Take work plane from** list, choose **Lens 4 (pi5)**.

6 From the **Work plane** list, choose **Surface 2 vertex intersection (wp2)**.

7 Find the **Displacement** subsection. In the **zw** text field, type `T_5`.

8 Locate the **Domain Selections** section. In the table, enter the following settings:

Name	Keep	Physics	Contribute to
All		√	Lens Material 4

9 Locate the **Boundary Selections** section. In the table, enter the following settings:

Name	Keep	Physics	Contribute to
Exterior		√	Lens Exteriors
Surface 1		√	Clear Apertures
Surface 2		√	Clear Apertures
Surface 1 obstruction		√	Obstructions
Surface 2 obstruction		√	Obstructions
Edges		√	Obstructions

PART LIBRARIES

Define the square image plane.

1 In the **Geometry** toolbar, click **Part Libraries**.

2 In the **Part Libraries** window, select **Ray Optics Module>3D>Apertures and Obstructions> rectangular_planar_annulus** in the tree.

3 Click **Add to Geometry**.

PETZVAL LENS GEOMETRY SEQUENCE

Image

1 In the **Model Builder** window, under **Component 1 (comp1)> Petzval Lens Geometry Sequence** click **Rectangular Planar Annulus 1 (pi7)**.

2 In the **Settings** window for **Part Instance**, type `Image` in the **Label** text field.

3 Locate the **Input Parameters** section. In the table, enter the following settings:

Name	Expression	Value	Description
w0	d0_D	35.808 mm	Width, outer
h0	d0_D	35.808 mm	Height, outer
w1	0	0 m	Width, inner
h1	0	0 m	Height, inner
nix	0	0	Local optical axis, x-component
niy	0	0	Local optical axis, y-component
niz	1	1	Local optical axis, z-component
nwx	1	1	Rectangle width direction, x-component
nwy	0	0	Rectangle width direction, y-component
nwz	0	0	Rectangle width direction, z-component

4 Locate the **Position and Orientation of Output** section. Find the **Coordinate system to match** subsection. From the **Take work plane from** list, choose **Lens 5 (pi6)**.

5 From the **Work plane** list, choose **Surface 2 vertex intersection (wp2)**.

6 Find the **Displacement** subsection. In the **zw** text field, type `T_6`.

7 Locate the **Boundary Selections** section. In the table, enter the following settings:

Name	Keep	Physics	Contribute to
All		√	Image Plane

8 Click **Build All Objects**.

9 Click the **Zoom Extents** button in the **Graphics** toolbar.

Create a selection that includes all lenses. This can be used to define physics features.

All Lenses

1 In the **Geometry** toolbar, click **Selections** and choose **Explicit Selection**.

2 In the **Settings** window for **Explicit Selection**, type `All Lenses` in the **Label** text field.

3 On the object **pi1**, select Domain 1 only.

4 On the object **pi2**, select Domain 1 only.

5 On the object **pi4**, select Domain 1 only.

6 On the object **pi5**, select Domain 1 only.

7 On the object **pi6**, select Domain 1 only.

Petzval Lens Apertures

The following commands are used to insert each of the lens apertures. The annulus clear aperture diameters are determined by the outer diameter of the current lens element. Each lens aperture is positioned at either the entrance or exit lens surface edges.

Group 1 Aperture

1 In the **Geometry** toolbar, click **Part Instance** and choose **Circular Planar Annulus**.

2 In the **Settings** window for **Part Instance**, type `Group 1 Aperture` in the **Label** text field.

3 Locate the **Input Parameters** section. In the table, enter the following settings:

Name	Expression	Value	Description
d0	`1.25*d0_1`	72.5 mm	Diameter, outer
d1	`d0_1`	58 mm	Diameter, inner
nix	0	0	Local optical axis, x-component
niy	0	0	Local optical axis, y-component
niz	1	1	Local optical axis, z-component

4 Locate the **Position and Orientation of Output** section. Find the **Coordinate system to match** subsection. From the **Take work plane from** list, choose **Lens 1 (pi1)**.

5 From the **Work plane** list, choose **Surface 1 edge (wp3)**.

6 Locate the **Boundary Selections** section. In the table, enter the following settings:

Name	Keep	Physics	Contribute to
All		√	Obstructions

Group 2 Aperture

1 In the **Geometry** toolbar, click **Part Instance** and choose **Circular Planar Annulus**.

2 In the **Settings** window for **Part Instance**, type `Group 2 Aperture` in the **Label** text field.

3 Locate the **Input Parameters** section. In the table, enter the following settings:

Name	Expression	Value	Description
d0	`1.25*d0_4`	56.25 mm	Diameter, outer
d1	`d0_4`	45 mm	Diameter, inner
nix	`0`	0	Local optical axis, x-component
niy	`0`	0	Local optical axis, y-component
niz	`1`	1	Local optical axis, z-component

4 Locate the **Position and Orientation of Output** section. Find the **Coordinate system to match** subsection. From the **Take work plane from** list, choose **Lens 3 (pi4)**.

5 From the **Work plane** list, choose **Surface 1 edge (wp3)**.

6 Locate the **Boundary Selections** section. In the table, enter the following settings:

Name	Keep	Physics	Contribute to
All		√	Obstructions

Group 3 Aperture

1 In the **Geometry** toolbar, click **Part Instance** and choose **Circular Planar Annulus**.

2 In the **Settings** window for **Part Instance**, type `Group 3 Aperture` in the **Label** text field.

3 Locate the **Input Parameters** section. In the table, enter the following settings:

Name	Expression	Value	Description
d0	`1.25*d0_6`	53.125 mm	Diameter, outer
d1	`d0_6`	42.5 mm	Diameter, inner
nix	`0`	0	Local optical axis, x-component
niy	`0`	0	Local optical axis, y-component
niz	`1`	1	Local optical axis, z-component

4 Locate the **Position and Orientation of Output** section. Find the **Coordinate system to match** subsection. From the **Take work plane from** list, choose **Lens 5 (pi6)**.

5 From the **Work plane** list, choose **Surface 1 edge (wp3)**.

6 Locate the **Boundary Selections** section. In the table, enter the following settings:

Name	Keep	Physics	Contribute to
All		√	Obstructions

7 In the **Geometry** toolbar, click **Build All**. Compare the resulting image to Figure 2.