Created in COMSOL Multiphysics 6.0

Petzval Lens STOP Analysis

Introduction

Many optical systems are required to be operated in extreme environments, where temperature changes are significant. This will invariably induce deformations in the optical geometry. In order to simulate the effects of structural and thermal deformation on the optical performance of a lens a structural-thermal-optical performance (STOP) analysis should be performed. In this tutorial an integrated STOP analysis is demonstrated.

The Petzval Lens tutorial is used as the basis for this model, together with a simple barrel geometry (see Figure 1). The assembly is subjected to uniform temperature of –25°C and the effect on the displacement fields and image quality is shown..

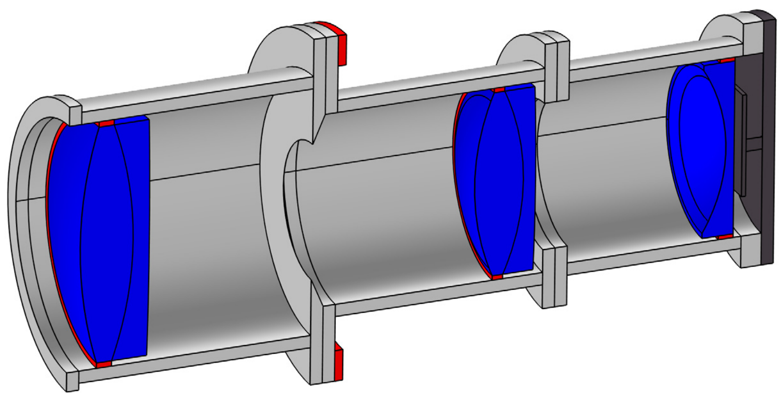


Figure 1: An overview of the Petzval Lens STOP analysis geometry. The lenses are shown in blue, the lens supports are colored red, and the detector assembly is dark gray. A simple barrel assembly connects these elements.

Model Definition

Details of the lens simulated in this tutorial can be found in the Petzval Lens tutorial (see Ref. 1, p. 191). For this model, a simple barrel geometry and detector assembly has been added. The instructions for creating the geometry can be found in Appendix — Geometry Instructions.

Following insertion into the model, the geometry sequence should look like Figure 2. The mesh also needs to be refined slightly in order to improve the discretization and to account for the overall change in size of the geometry. The resulting mesh is shown in Figure 3.

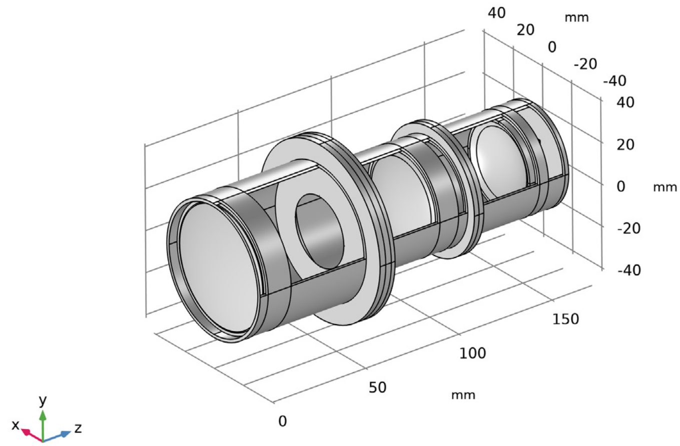


Figure 2: The Petzval Lens Stop Analysis geometry sequence.

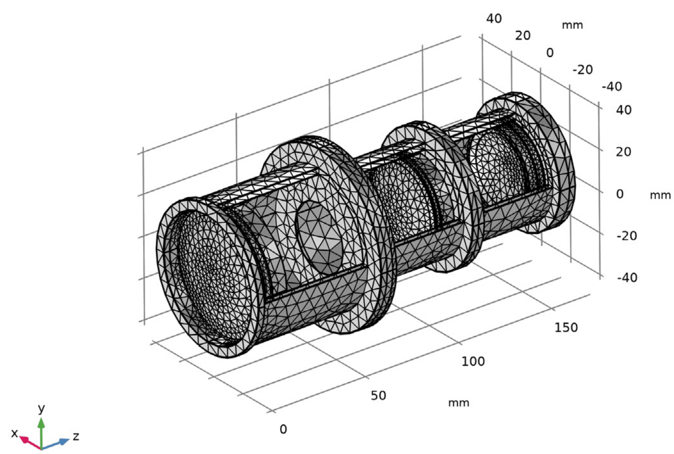


Figure 3: The Petzval Lens Stop Analysis mesh.

The refractive indices of the glasses are computed using the Sellmeier optical dispersion model which defines the refractive index as a function of the wavelength of light. The Sellmeier coefficients for each material are found in the Optical material library. For most of the optical glasses in the Optical material library, additional material properties including density, Young's modulus, Poisson's ratio, and coefficient of thermal expansion are also available.

The entire barrel detector assembly is assumed to made entirely from aluminum. This material is available in another built-in material library.

Each of the lenses is assumed to be held in place by a ring of room temperature vulcanized silicone (RTV). The properties of the RTV silicone are all nominal (that is, an average of various common RTV silicones). The temperature dependent properties of RTV silicone are also ignored (for example, Ref. 4 and Ref. 5). The thickness of the elastomer supports is computed using the nominal athermal equation given in Ref. 6, p. 203.

In this example the RTV is treated using a simple linear elastic material model. In an extremely high-fidelity simulation it might be preferable to use a hyperelastic material model for the RTV. For a model involving a nonlinear material model, see Petzval Lens STOP Analysis with Hyperelasticity.

The nominal temperature, wavelength, and field angles used in this simulation are given in Table 1.

TABLE 1: GLOBAL PARAMETER DEFINITIONS.

Parameter	Value	Description
T_0	-25°C	Nominal temperature
λ_{vac}	475 nm, 550 nm, 625 nm	Vacuum wavelengths
$\theta_{x,i}$	0°, 0°, 0°	Nominal x field angle, field i = 1,2,3
$\theta_{y,i}$	0°, 3.5°, 7.0°	Nominal y field angle, field i = 1,2,3
N_{ring}	15	Number of hexapolar rings.
P_{nom}	41.5 mm	Nominal entrance pupil diameter
P_{fac1}	-1.142	Pupil shift factor 1
P_{fac2}	-0.080	Pupil shift factor 2

Several of the parameters defined in Table 1 are used to derive additional parameters such as the ray direction vector components, the stop and image plane z-coordinates, and the entrance pupil location. Table 2 gives the expressions used to derive these parameters. Note that the pupil shift factor is an empirical approximation to ensure that the chief ray passes through the center of the stop at all field angles.

TABLE 2: GLOBAL PARAMETER DEFINITIONS (DERIVED).

Parameter	Value	Description
$v_{x,i}$	$\tan\theta_{x,i}$	Ray direction vector, x-component, field i.
$v_{y,i}$	$\tan\theta_{y,i}$	Ray direction vector, y-component, field i.
v_z	1	Ray direction vector, z-component
z_{stop}	$\sum_{n=1}^{2}(T_{\mathrm{c},n}+T_n)$	Stop z-coordinate, where $T_{c,n}$ is the central thickness of element n and T_n is the separation between elements n and n+1. Note that the stop is the 3rd element in the Petzval lens.
z_{image}	$\sum_{n=1}^{6}(T_{\mathrm{c},n}+T_n)$	Image plane z-coordinate, where $T_{c,n}$ is the central thickness of element n and T_n is the separation between elements n and n+1. Including the stop, the Petzval lens has 6 elements.
$P_{\mathrm{fac},i}$	$P_{\mathrm{fac1}}+P_{\mathrm{fac2}}\sin\theta_i$	Pupil shift factor, field i, where $\theta_i = \sqrt{\theta_{x,i}^2+\theta_{y,i}^2}$
Δx_i	$(\Delta z + P_{\mathrm{fac},i}\, z_{\mathrm{stop}})\tan\theta_{x,i}$	Pupil shift, x-coordinate, field i.
Δy_i	$(\Delta z + P_{\mathrm{fac},i}\, z_{\mathrm{stop}})\tan\theta_{y,i}$	Pupil shift, y-coordinate, field i.
$t_{s,i}$	$\frac{d}{2}\frac{(1-\nu_{\mathrm{e}})(\alpha_1-\alpha_2)}{\alpha_{\mathrm{e}}-\alpha_1-\nu_{\mathrm{e}}(\alpha_2-\alpha_1)}$	Athermal thickness of support i, where d is the lens diameter, α_e, α_1, and α_2, are the CTE's of the elastomer, the mount, and the lens respectively, and ν_e is Poissions ratio.

Results and Discussion

Following a Stationary study which computes the displacement field due to thermal expansion, a Ray Tracing study is made over three field angles and three wavelengths (see Table 1). The resulting temperature and displacement fields can be seen together with a ray trace in Figure 4 and Figure 5. Both figures also show the von Mises stress within the lenses (and barrel). The large stress within the second lens group is due to the significant difference between the coefficients of thermal expansion (CTE) of each element.

Figure 6 shows a spot diagram on the nominal image surface. That is, this is the detector surface after being subject to thermal and structural deformation at –25°C. The **Spot Diagram** plot can be used to determine the location of the best focus plane, defined as the plane for which the root mean square spot size is minimized. This is shown in Figure 7. Note that the plane of best focus is located 72 µm behind the nominal image surface.

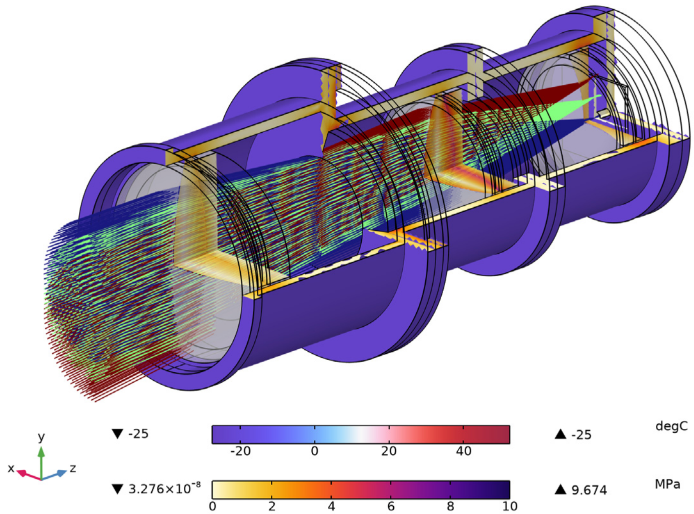


Figure 4: A ray trace shown together with a 3/4 section view of the Petzval lens assembly. The von Mises stress field is on the cross-sections.

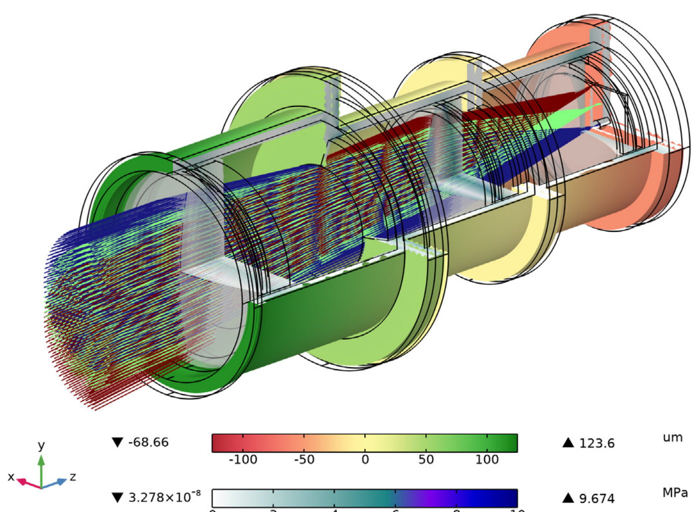


Figure 5: In this ray trace, the displacement field is shown together with the von Mises stress.

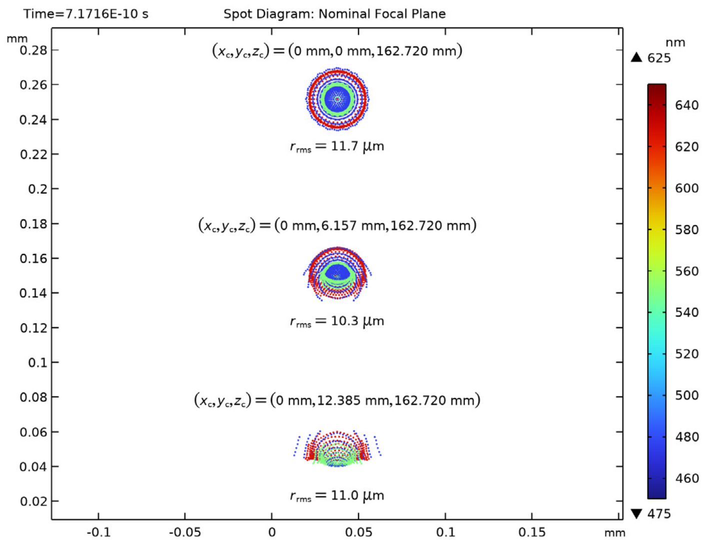


Figure 6: The image quality on the nominal image surface. This is the detector surface after being subject to thermal expansion.

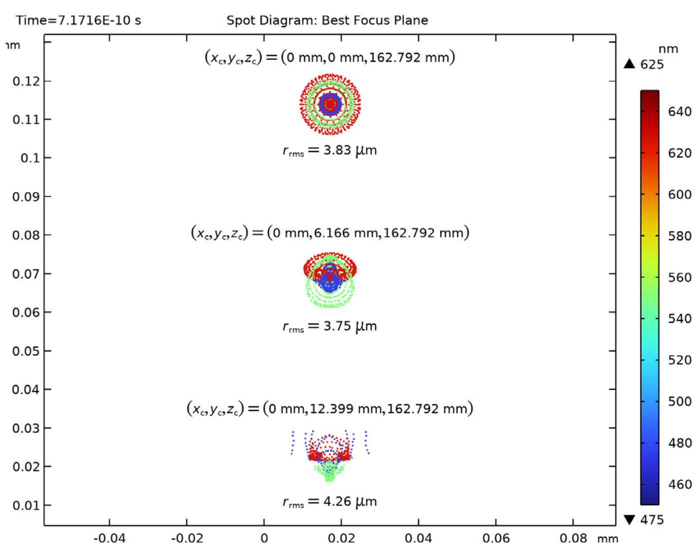


Figure 7: Image quality on the best focus plane. That is, this is the surface that gives the minimum RMS spot size on-axis. It is about 72 microns displaced from the nominal plane.

Related models

This tutorial model, in which STOP analysis is performed at a single uniform temperature, is extended in the following examples:

- Petzval Lens STOP Analysis Isothermal Sweep — A parametric sweep over a range of uniform temperatures is performed. The position of the best focus image plane is determined as a function of temperature.
- Petzval Lens STOP Analysis with Hyperelasticity — In this model the RTV lens supports are modeled as a hyperelastic material using the Nonlinear Structural Materials Module.
- Petzval Lens STOP Analysis with Surface-to-Surface Radiation — For this model, the lens assembly is placed inside a thermo-vacuum enclosure where the exterior temperature is significantly different from the interior. The lens assembly is exposed to this exterior through a pair of windows via surface-to-surface radiation. The resulting thermal gradient and displacement field within the optical system are shown together with the effect on image quality.

References

1. M.J. Kidger, *Fundamental Optical Design,* Bellingham WA, USA: SPIE Press, 2001.

2. https://www.us.schott.com/english/index.html.

3. http://www.oharacorp.com/catalog.html.

4. M.A. Salama, W.M. Rowe, and R.K. Yasui, "Thermoelatic Analysis of Solar Cell Arrays and their Material Properties." *Technical Memorandum 33-626*, NASA, 1973.

5. T.M. Mower, "Thermomechanical behavior of aerospace-grade RTV (silicone adhesive)." *International Journal of Adhesions and Adhesives* 87 (2018): 64-72.

6. P.R. Yoder, Jr., *Opto-Mechanical Systems Design*, Bellingham WA, USA: SPIE Press, 2006.

Application Library path: `Ray_Optics_Module/Structural_Thermal_Optical_Performance_Analysis/petzval_lens_stop_analysis`

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. In the **Select Physics** tree, select **Structural Mechanics>Solid Mechanics (solid)**.
5. Click **Add**.
6. Click **Study**.
7. In the **Select Study** tree, select **Empty Study**. The studies will be added below.
8. Click **Done**.

PETZVAL LENS STOP ANALYSIS GEOMETRY SEQUENCE

Insert the prepared geometry sequence from file. You can read the instructions for creating the geometry in Appendix — Geometry Instructions. Following insertion, the original Petzval Lens optical prescription will be available in the **Parameters** node.

1. In the **Model Builder** window, under **Component 1 (comp1)** click **Geometry 1**.
2. In the **Settings** window for **Geometry**, type `Petzval Lens Stop Analysis Geometry Sequence` in the **Label** text field.
3. In the **Geometry** toolbar, click **Insert Sequence** and choose **Insert Sequence**.
4. Browse to the model's Application Libraries folder and double-click the file `petzval_lens_stop_analysis_geom_sequence.mph`.
5. In the **Insert Sequence** dialog box, click **OK**.
6. In the **Geometry** toolbar, click **Build All**.
7. Click the **Orthographic Projection** button in the **Graphics** toolbar.
8. Click the **Click and Hide** button in the **Graphics** toolbar.
9. In the **Graphics** window toolbar, click ▾ next to **Select Objects**, then choose **Select Boundaries**.
10. On the object **fin**, select Boundary 19 only. Continue to select boundaries that allow the inside of the lens assembly to be seen. Orient the view to match Figure 2.

GLOBAL DEFINITIONS

Lens Prescription

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

2 In the **Settings** window for **Parameters**, type `Lens Prescription` in the **Label** text field. The lens prescription was added when the geometry sequence was inserted above. Next, create parameter nodes for material and general properties.

Material Properties

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

2 In the **Settings** window for **Parameters**, type `Material Properties` in the **Label** text field. These material properties contain other parameters than will be used in extensions of this study.

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_stop_analysis_material_parameters.txt`.

General Properties

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

2 In the **Settings** window for **Parameters**, type `General Properties` 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_stop_analysis_parameters.txt`.

Lens Prescription

1 In the **Model Builder** window, click **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
tS_1	tS_1_i	0.0013194 m	Lens group 1 support thickness
tS_2	tS_2_i	0.0010896 m	Lens group 1 support thickness
tS_3	tS_3_i	9.1902E-4 m	Lens group 1 support thickness

DEFINITIONS

Create a selection defining the lens barrels and detector assemblies. In this simulation it will be assumed they are made of the same material.

Lens Barrels and Detector

1 In the **Definitions** toolbar, click **Union**.
2 In the **Settings** window for **Union**, type `Lens Barrels and Detector` in the **Label** text field.
3 Locate the **Input Entities** section. Under **Selections to add**, click **Add**.
4 In the **Add** dialog box, in the **Selections to add** list, choose **All (Barrel 1)**, **All (Barrel 2)**, **All (Barrel 3)**, and **Detector Assembly**.
5 Click **OK**.

Lenses and Supports

Also, create a selection including only the lenses and supports.

1 In the **Definitions** toolbar, click **Union**.
2 In the **Settings** window for **Union**, type `Lenses and Supports` in the **Label** text field.
3 Locate the **Input Entities** section. Under **Selections to add**, click **Add**.
4 In the **Add** dialog box, in the **Selections to add** list, choose **Supports** and **All Lenses**.
5 Click **OK**.

Next, create operators to make the deformed image plane coordinates available to postprocessing features. Select three of the four image surface corners.

Average 1 (aveop1)

1 In the **Definitions** toolbar, click **Nonlocal Couplings** and choose **Average**.
2 In the **Settings** window for **Average**, locate the **Source Selection** section.
3 From the **Geometric entity level** list, choose **Point**.
4 Select Point 57 only.

Average 2 (aveop2)

1 Right-click **Average 1 (aveop1)** and choose **Duplicate**.
2 In the **Settings** window for **Average**, locate the **Source Selection** section.
3 Click **Clear Selection**.
4 Select Point 181 only.

Average 3 (aveop3)

1 Right-click **Average 2 (aveop2)** and choose **Duplicate**.
2 In the **Settings** window for **Average**, locate the **Source Selection** section.
3 Click **Clear Selection**.

4 Select Point 183 only.

MESH 1

Free Triangular 1

1. In the **Mesh** toolbar, click **Boundary** and choose **Free Triangular**.
2. In the **Settings** window for **Free Triangular**, locate the **Boundary Selection** section.
3. From the **Selection** list, choose **Clear Apertures**.

Size 1

1. Right-click **Free Triangular 1** and choose **Size**.
2. In the **Settings** window for **Size**, locate the **Element Size** section.
3. From the **Predefined** list, choose **Extremely fine**. Refine the mesh of the lens surfaces.

Free Tetrahedral 1

In the **Mesh** toolbar, click **Free Tetrahedral**.

Size 1

1. Right-click **Free Tetrahedral 1** and choose **Size**.
2. In the **Settings** window for **Size**, locate the **Geometric Entity Selection** section.
3. From the **Geometric entity level** list, choose **Domain**.
4. Select Domain 21 only.
5. Locate the **Element Size** section. From the **Predefined** list, choose **Finer**. This is part of the detector assembly.

Size 2

1. In the **Model Builder** window, right-click **Free Tetrahedral 1** and choose **Size**.
2. In the **Settings** window for **Size**, locate the **Geometric Entity Selection** section.
3. From the **Geometric entity level** list, choose **Domain**.
4. From the **Selection** list, choose **Supports**.
5. Locate the **Element Size** section. Click the **Custom** button.
6. Locate the **Element Size Parameters** section. Select the **Minimum element size** check box.
7. In the associated text field, type `2[mm]`.

Size

1. In the **Model Builder** window, under **Component 1 (comp1)>Mesh 1** click **Size**.
2. In the **Settings** window for **Size**, locate the **Element Size** section.

3 From the **Predefined** list, choose **Coarse**.

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

COMPONENT 1 (COMP1)

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

2 In the **Settings** window for **Component**, locate the **Curved Mesh Elements** section.

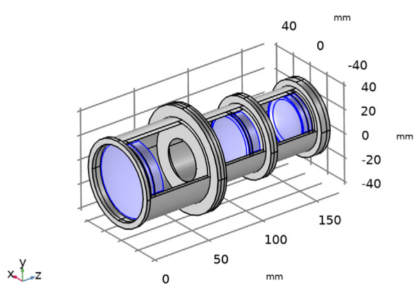
3 From the **Geometry shape function** list, choose **Cubic Lagrange**. The ray tracing algorithm used by the Geometrical Optics interface computes the refracted ray direction based on a discretized geometry via the underlying finite element mesh. A cubic geometry shape order usually introduces less discretization error compared to the default, which uses linear and quadratic polynomials.

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 **Domain Selection** section.

3 From the **Selection** list, choose **All Lenses**.



4 Locate the **Ray Release and Propagation** section. From the **Wavelength distribution of released rays** list, choose **Polychromatic, specify vacuum wavelength**. The list of polychromatic wavelengths will be entered below.

5 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. Note that because rays will be traced through a deformed geometry, it is not possible to use geometry normals for ray-boundary interactions. This check box should remained cleared.

6 Locate the **Material Properties of Exterior and Unmeshed Domains** section. From the **Optical dispersion model** list, choose **Air, Edlen (1953)**.

7 In the T_{ext} text field, type T0. The refractive index of the air surrounding the camera lens will be a function of 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**.

4 Click to expand the **Model Inputs** section. From the T list, choose **Common model input**.

GLOBAL DEFINITIONS

Default Model Inputs

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

2 In the **Settings** window for **Default Model Inputs**, locate the **Browse Model Inputs** section.

3 In the tree, select **General>Temperature (K) - minput.T**.

4 Find the **Expression for remaining selection** subsection. In the **Temperature** text field, type T0. This temperature is defined in the parameters node.

GEOMETRICAL OPTICS (GOP)

Material Discontinuity 1

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

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**. The default **Wall condition** is **Freeze**.

Release from Grid 1

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

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

nix	x
niy	y
niz	z

6 In the R_c text field, type `20.75[mm]`.
7 In the N_c text field, type `15`.
8 Locate the **Ray Direction Vector** section. Specify the $\mathbf{L}_0$ vector as

vx1	x
vy1	y
vz	z

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.

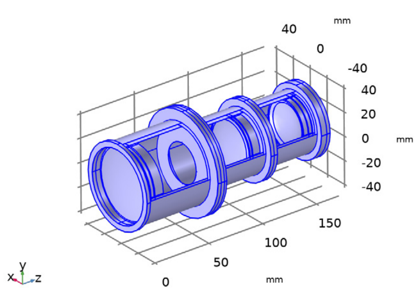
3 Specify the $\mathbf{q}_c$ vector as

dx3	x
dy3	y

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

vx3	x
vy3	y

SOLID MECHANICS (SOLID)



5 In the **Model Builder** window, under **Component 1 (comp1)** click **Solid Mechanics (solid)**.

6 In the **Settings** window for **Solid Mechanics**, click to expand the **Discretization** section.

7 From the **Displacement field** list, choose **Cubic serendipity**. As for the Geometrical Optics interface, a cubic shape order is chosen to reduce discretization error.

Linear Elastic Material 1

In the **Model Builder** window, under **Component 1 (comp1)>Solid Mechanics (solid)** click **Linear Elastic Material 1**.

Thermal Expansion 1

1 In the **Physics** toolbar, click **Attributes** and choose **Thermal Expansion**.

The temperature model input value of **Thermal Expansion** is by default the common model input. In this way, the uniform temperature T0 is applied to the Solid Mechanics.

Fixed Constraint 1

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

2 In the **Settings** window for **Fixed Constraint**, locate the **Boundary Selection** section.

3 From the **Selection** list, choose **All (Rigid Support)**. It is assumed that the lens assembly is attached to an external rigid structure via this annulus. The external structure does not otherwise participate in the physics.

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**.

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 **Built-in>Aluminum 6063-T83**.
4 Click **Add to Component** in the window toolbar.
5 In the **Home** toolbar, click **Add Material** to close the **Add Material** window.

MATERIALS

Aluminum 6063-T83 (mat5)

1 In the **Settings** window for **Material**, locate the **Geometric Entity Selection** section.
2 From the **Selection** list, choose **Lens Barrels and Detector**.

RTV

1 In the **Model Builder** window, right-click **Materials** and choose **Blank Material**.
2 In the **Settings** window for **Material**, locate the **Geometric Entity Selection** section.
3 From the **Selection** list, choose **Supports**.
4 In the **Label** text field, type RTV.

5 Locate the **Material Contents** section. In the table, enter the following settings:

Property	Variable	Value	Unit	Property group
Young's modulus	E	E_RTV	Pa	Young's modulus and Poisson's ratio
Poisson's ratio	nu	nu_RTV	1	Young's modulus and Poisson's ratio
Density	rho	rho_RTV	kg/m³	Basic
Coefficient of thermal expansion	alpha_iso ; alphaii = alpha_iso, alphaij = 0	alpha_RTV	1/K	Basic

STUDY 1

Add the studies necessary to perform a STOP analysis. First, add a stationary study to compute the geometry deformation at the nominal temperature. Next, add a Ray Tracing study to perform a ray trace through the deformed geometry.

Stationary

1 In the **Study** toolbar, click **Study Steps** and choose **Stationary>Stationary**.

2 In the **Settings** window for **Stationary**, locate the **Physics and Variables Selection** section.

3 In the table, enter the following settings:

Physics interface	Solve for	Equation form
Geometrical Optics (gop)		Automatic (Time dependent)
Solid Mechanics (solid)	√	Automatic (Stationary)

Ray Tracing

1 In the **Study** toolbar, click **Study Steps** and choose **Time Dependent>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 `0 215`. The maximum optical path length is sufficient to allow all rays to pass beyond the nominal location of the image plane.

6 Select the **Include geometric nonlinearity** check box. This ensures that the ray tracing is performed on the deformed geometry created in Step 1 of the Study.

7 Locate the **Physics and Variables Selection** section. In the table, enter the following settings:

Physics interface	Solve for	Equation form
Geometrical Optics (gop)	√	Automatic (Time dependent)
Solid Mechanics (solid)		Automatic (Stationary)

Disable the **Freeze** condition on the image plane so that spot diagrams on both the nominal (deformed) image plane and the best focus image plane can be generated.

8 Select the **Modify model configuration for study step** check box.

9 In the tree, select **Component 1 (Comp1)>Geometrical Optics (Gop)>Image**.

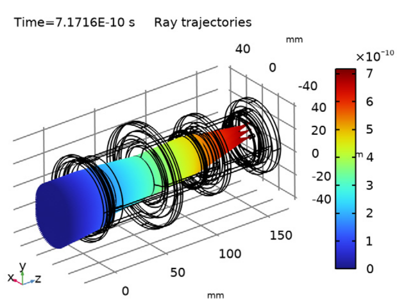
10 Right-click and choose **Disable**.

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

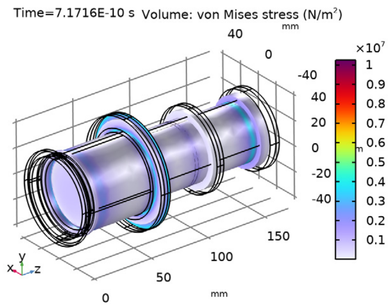
RESULTS

Ray Trajectories (gop)

The Ray Trajectories plot and the Stress plots (see below) are created by default with this combination of physics and study steps.



Stress (solid)



Study 1/Solution 1 (sol1)

In the **Model Builder** window, expand the **Results>Datasets** node, then click **Study 1/ Solution 1 (sol1)**.

Selection

1 In the **Results** toolbar, click **Attributes** and choose **Selection**.
2 In the **Settings** window for **Selection**, locate the **Geometric Entity Selection** section.
3 From the **Geometric entity level** list, choose **Domain**.
4 From the **Selection** list, choose **All Lenses**. This selection is used to limit the domains in which some datasets will be processed.

Create an **Intersection Point 3D** dataset to show the image quality on the defomed image surface. Later, use the Spot Diagram postprocessing feature to generate a second **Intersection Point 3D** dataset that lies on plane which minimizes the RMS image quality on-axis.

Intersection Point 3D 1

1 In the **Results** toolbar, click **More Datasets** and choose **Intersection Point 3D**.
2 In the **Settings** window for **Intersection Point 3D**, locate the **Surface** section.
3 From the **Plane entry method** list, choose **Three points**.
4 In row **Point 1**, set **x** to `aveop1(x)`.
5 In row **Point 1**, set **y** to `aveop1(y)`.
6 In row **Point 1**, set **z** to `aveop1(z)`.
7 In row **Point 2**, set **x** to `aveop2(x)`.
8 In row **Point 2**, set **y** to `aveop2(y)`.
9 In row **Point 2**, set **z** to `aveop2(z)`.

10 In row **Point 3**, set **x** to `aveop3(x)`.

11 In row **Point 3**, set **y** to `aveop3(y)`.

12 In row **Point 3**, set **z** to `aveop3(z)`. These points are three of the four image surface corners.

Temperature

In the following steps, the Ray Trajectories plot is duplicated and extended to show the temperature field within the lens assembly together with the von Mises stress within the lenses.

Temperature

1 In the **Model Builder** window, right-click **Ray Trajectories (gop)** and choose **Duplicate**.

2 In the **Settings** window for **3D Plot Group**, type `Temperature` in the **Label** text field.

3 Click to expand the **Title** section. From the **Title type** list, choose **None**.

4 Locate the **Plot Settings** section. From the **View** list, choose **New view**.

5 Locate the **Color Legend** section. Select the **Show maximum and minimum values** check box.

6 Select the **Show units** check box.

7 From the **Position** list, choose **Bottom**.

8 Click to expand the **Number Format** section. Select the **Manual color legend settings** check box.

9 In the **Precision** text field, type `4`.

Ray Trajectories 1

1 In the **Model Builder** window, expand the **Temperature** node, then click **Ray Trajectories 1**.

2 In the **Settings** window for **Ray Trajectories**, locate the **Extra Time Steps** section.

3 From the **Maximum number of extra time steps rendered** list, choose **All**.

Color Expression 1

1 In the **Model Builder** window, expand the **Ray Trajectories 1** node, then click **Color Expression 1**.

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

3 In the **Expression** text field, type `gop.prf`. This is the Ray release feature index; that is, the field number.

4 In the **Unit** field, type `um`.

5 Locate the **Coloring and Style** section. Clear the **Color legend** check box.

Filter 1

1 In the **Model Builder** window, click **Filter 1**.

2 In the **Settings** window for **Filter**, locate the **Ray Selection** section.

3 From the **Rays to include** list, choose **Logical expression**.

4 In the **Logical expression for inclusion** text field, type `at(0,qx>0.1[mm])`. Restrict the rays visible to one half of the view. Also, rays are not rendered just beyond the nominal, undeformed image plane z-coordinate.

Surface 1

1 In the **Model Builder** window, right-click **Temperature** and choose **Surface**.

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

3 In the **Expression** text field, type `solid.T`.

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

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

6 In the **Minimum** text field, type `-27.5`.

7 In the **Maximum** text field, type `52.5`.

8 Locate the **Coloring and Style** section. From the **Color table** list, choose **WaveLight**.

Selection 1

1 Right-click **Surface 1** and choose **Selection**.

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

3 From the **Selection** list, choose **Assembly Surfaces**.

Filter 1

1 In the **Model Builder** window, right-click **Surface 1** and choose **Filter**.

2 In the **Settings** window for **Filter**, locate the **Element Selection** section.

3 In the **Logical expression for inclusion** text field, type `x>0.5[mm] || y<-0.5[mm]`.

Surface 2

1 Right-click **Surface 1** and choose **Duplicate**.

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

3 In the **Expression** text field, type `1`.

4 Locate the **Coloring and Style** section. From the **Coloring** list, choose **Uniform**.

5 From the **Color** list, choose **Gray**.

Transparency 1

Right-click **Surface 2** and choose **Transparency**.

Selection 1

1 In the **Settings** window for **Selection**, locate the **Selection** section.

2 From the **Selection** list, choose **Lens Exteriors**.

Slice 1

1 In the **Model Builder** window, right-click **Temperature** and choose **Slice**.

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

3 In the **Expression** text field, type `solid.mises`.

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

5 Locate the **Plane Data** section. In the **Planes** text field, type `1`.

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

7 In the **Maximum** text field, type `10`.

8 Locate the **Coloring and Style** section. From the **Color table** list, choose **HeatCamera**.

9 From the **Color table transformation** list, choose **Reverse**.

Selection 1

1 Right-click **Slice 1** and choose **Selection**.

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

3 From the **Selection** list, choose **Lens Barrels and Detector**.

Filter 1

1 In the **Model Builder** window, right-click **Slice 1** and choose **Filter**.

2 In the **Settings** window for **Filter**, locate the **Element Selection** section.

3 In the **Logical expression for inclusion** text field, type `y>0`.

Slice 2

1 Right-click **Slice 1** and choose **Duplicate**.

2 In the **Settings** window for **Slice**, locate the **Plane Data** section.

3 From the **Plane** list, choose **zx-planes**.

4 In the **Planes** text field, type `1`.

5 Click to expand the **Inherit Style** section. From the **Plot** list, choose **Slice 1**.

Filter 1

1 In the **Model Builder** window, expand the **Slice 2** node, then click **Filter 1**.

2 In the **Settings** window for **Filter**, locate the **Element Selection** section.

3 In the **Logical expression for inclusion** text field, type `x<0`.

Slice 3

In the **Model Builder** window, under **Results>Temperature** right-click **Slice 1** and choose **Duplicate**.

Selection 1

1 In the **Model Builder** window, expand the **Slice 3** node, then click **Selection 1**.

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

3 From the **Selection** list, choose **Lenses and Supports**.

Slice 3

1 In the **Model Builder** window, click **Slice 3**.

2 In the **Settings** window for **Slice**, locate the **Inherit Style** section.

3 From the **Plot** list, choose **Slice 2**.

Transparency 1

1 Right-click **Slice 3** and choose **Transparency**.

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

3 In the **Transparency** text field, type `0.25`.

Slice 4

In the **Model Builder** window, under **Results>Temperature** right-click **Slice 2** and choose **Duplicate**.

Selection 1

1 In the **Model Builder** window, expand the **Slice 4** node, then click **Selection 1**.

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

3 From the **Selection** list, choose **Lenses and Supports**.

Transparency 1

1 In the **Model Builder** window, right-click **Slice 4** and choose **Transparency**.

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

3 In the **Transparency** text field, type `0.25`.

4 In the **Temperature** toolbar, click **Plot**.

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

6 Click the **Show Grid** button in the **Graphics** toolbar. Orient the resulting figure to match Figure 4.

Displacement

Copy and modify the temperature plot to illustrate the displacement field within the lens assembly.

Displacement

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

2 In the **Settings** window for **3D Plot Group**, type `Displacement` in the **Label** text field.

Surface 1

1 In the **Model Builder** window, expand the **Displacement** node, then click **Surface 1**.

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

3 In the **Expression** text field, type `w`.

4 In the **Unit** field, type `um`.

5 Locate the **Range** section. In the **Minimum** text field, type `-125`.

6 In the **Maximum** text field, type `125`.

7 Locate the **Coloring and Style** section. From the **Color table** list, choose **TrafficLight**.

8 From the **Color table transformation** list, choose **Reverse**.

Deformation 1

1 Right-click **Surface 1** and choose **Deformation**. This is used to exaggerate the lens thermal deformation.

2 In the **Settings** window for **Deformation**, locate the **Scale** section.

3 Select the **Scale factor** check box.

4 In the associated text field, type `25`.

Deformation 1

1 In the **Model Builder** window, right-click **Surface 2** and choose **Deformation**.

2 In the **Settings** window for **Deformation**, locate the **Scale** section.

3 Select the **Scale factor** check box.

4 In the associated text field, type `25`.

Slice 1

1 In the **Model Builder** window, under **Results>Displacement** click **Slice 1**.

2 In the **Settings** window for **Slice**, locate the **Coloring and Style** section.

3 From the **Color table** list, choose **AuroraAustralis**.

4 From the **Color table transformation** list, choose **None**.

Deformation 1

1 Right-click **Slice 1** and choose **Deformation**.

2 In the **Settings** window for **Deformation**, locate the **Scale** section.

3 Select the **Scale factor** check box.

4 In the associated text field, type `25`.

Deformation 1

In the **Model Builder** window, right-click **Slice 2** and choose **Deformation**.

Deformation 1

In the **Model Builder** window, right-click **Slice 3** and choose **Deformation**.

Deformation 1

1 In the **Model Builder** window, right-click **Slice 4** and choose **Deformation**.

2 In the **Displacement** toolbar, click **Plot**. Orient the result to match Figure 5.

Spot Diagrams

Finally, create two spot diagrams. The first will show the image quality on the nominal image plane. That is, the deformed image surface from the geometry. The second spot diagram will show the spots on the plane of best focus, using the on-axis rays.

Spot Diagram, Nominal

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, Nominal` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **None**.

4 Click to expand the **Title** section. From the **Title type** list, choose **Manual**.

5 In the **Title** text area, type `Spot Diagram: Nominal Focal Plane`.

6 Locate the **Color Legend** section. Select the **Show maximum and minimum values** check box.

7 Select the **Show units** check box.

Spot Diagram 1

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

2 In the **Settings** window for **Spot Diagram**, locate the **Data** section.

3. From the **Image surface** list, choose **Intersection Point 3D 1**. This is the **Intersection Point 3D** dataset defined above using three corners of the deformed image surface.
4. Locate the **Layout** section. From the **Layout** list, choose **Rectangular grid**.
5. In the **Number of columns** text field, type `1`.
6. From the **Origin location** list, choose **Average over area**.
7. In the **Vertical padding factor** text field, type `1`.
8. Click to expand the **Annotations** section. Select the **Show spot coordinates** check box.
9. From the **Coordinate system** list, choose **Global**.
10. In the **Display precision** text field, type `6`.

Color Expression 1

1. Right-click **Spot Diagram 1** and choose **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, Nominal** toolbar, click **Plot**. The first spot diagram should look like Figure 6.

Spot Diagram, Best Focus

1. In the **Model Builder** window, right-click **Spot Diagram, Nominal** and choose **Duplicate**.
2. In the **Settings** window for **2D Plot Group**, type `Spot Diagram, Best Focus` in the **Label** text field.
3. Locate the **Title** section. In the **Title** text area, type `Spot Diagram: Best Focus Plane`.
4. Locate the **Plot Settings** section. From the **View** list, choose **New view**.

Spot Diagram 1

1. In the **Model Builder** window, expand the **Spot Diagram, Best Focus** node, then click **Spot Diagram 1**.
2. In the **Settings** window for **Spot Diagram**, locate the **Data** section.
3. From the **Image surface** list, choose **Ray 1**.
4. Locate the **Filters** section. Select the **Filter by release feature index** check box. The rays from the on-axis release will be used.

5 Click to expand the **Focal Plane Orientation** section. From the **Normal to focal plane** list, choose **User defined**. The default is that the image plane normal direction is the z-axis.

6 From the **Transverse direction** list, choose **User defined**.

7 Click **Create Focal Plane Dataset**.

8 Locate the **Filters** section. Clear the **Filter by release feature index** check box.

9 In the **Spot Diagram, Best Focus** toolbar, click **Plot**.

10 Click the **Zoom Extents** button in the **Graphics** toolbar. The second spot diagram should look like Figure 7.

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**.

PETZVAL LENS STOP ANALYSIS GEOMETRY SEQUENCE

Insert the prepared Petzval Lens geometry sequence from file. The instructions for creating the lens geometry can be found in the appendix of the Petzval Lens tutorial.

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 STOP Analysis Geometry Sequence`.

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_stop_analysis_petzval_lens_geom_sequence.mph`. Following insertion, the full lens prescription will be available in the **Parameters** node.

Add parameters to define the dimensions of the lens supports.

GLOBAL DEFINITIONS

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_stop_analysis_geom_sequence_parameters.txt`Now, modify the clear aperture on the first surface of lens 1, the size of the aperture stop and the dimensions of the image plane.

5 In the table, enter the following settings:

Name	Expression	Value	Description
d1_clear_1	0	0	L1, surface 1 clear aperture diameter
d0_S	dS_1	0.06 m	Stop maximum diameter
d0_D	25.0[mm]	0.025 m	Detector diameter

PETZVAL LENS STOP ANALYSIS GEOMETRY SEQUENCE

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

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

3 In the **Model Builder** window, under **Component 1 (comp1)** click **Petzval Lens STOP Analysis Geometry Sequence**.

4 In the **Settings** window for **Geometry**, in the **Graphics** window toolbar, click ▾ next to **Go to Default View**, then choose **Go to ZY View**.

5 Click the **Zoom Extents** button in the **Graphics** toolbar. Orient the view to place the optical axis (z-axis) horizontal and the y-axis vertical.

GLOBAL DEFINITIONS

In the following steps a geometry part will be created. This part will be used to create barrels which will hold each of the three Petzval lens groups.

BARREL

1 In the **Model Builder** window, expand the **Global Definitions>Geometry Parts** node.

2 Right-click **Global Definitions>Geometry Parts** and choose **3D Part**.

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

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

Name	Default expression	Value	Description
L	50.0[mm]	0.05 m	Length
D_in	50.0[mm]	0.05 m	Inner diameter
T_wall	3.0[mm]	0.003 m	Wall thickness
D1_out	65.0[mm]	0.065 m	Front ring outer diameter
D1_in	45.0[mm]	0.045 m	Front ring inner diameter
D2_out	75.0[mm]	0.075 m	Rear ring outer diameter
D2_in	45.0[mm]	0.045 m	Rear ring inner diameter
L1	3.0[mm]	0.003 m	Front ring thickness
L2	3.0[mm]	0.003 m	Rear ring thickness

Central Barrel Annulus

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

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

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

Name	Expression	Value	Description
d0	D_in+2*T_wall	0.056 m	Diameter, outer
d1	D_in	0.05 m	Diameter, inner

4 Locate the **Position and Orientation of Output** section. Find the **Displacement** subsection. In the **zw** text field, type `L1`.

Central Barrel

1 In the **Geometry** toolbar, click **Extrude**.

2 In the **Settings** window for **Extrude**, type `Central Barrel` in the **Label** text field.

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

4 Locate the **Distances** section. In the table, enter the following settings:

Distances (m)
L-(L1+L2)

Front Ring Annulus

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

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

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

Name	Expression	Value	Description
d0	`D1_out`	0.065 m	Diameter, outer
d1	`D1_in`	0.045 m	Diameter, inner

Front Ring

1 In the **Geometry** toolbar, click **Extrude**.

2 In the **Settings** window for **Extrude**, type `Front Ring` in the **Label** text field.

3 On the object **pi2**, select Boundary 1 only.

4 Locate the **Distances** section. In the table, enter the following settings:

Distances (m)
`L1`

Rear Ring Annulus

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

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

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

Name	Expression	Value	Description
d0	`D2_out`	0.075 m	Diameter, outer
d1	`D2_in`	0.045 m	Diameter, inner

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

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

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

Rear Ring

1 In the **Geometry** toolbar, click **Extrude**.

2 In the **Settings** window for **Extrude**, type `Rear Ring` in the **Label** text field.

3 On the object **pi3**, select Boundary 1 only.

4 Locate the **Distances** section. In the table, enter the following settings:

Distances (m)
L2

5 Select the **Reverse direction** check box.

All

1 In the **Geometry** toolbar, click **Booleans and Partitions** and choose **Union**.

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

3 Click in the **Graphics** window and then press Ctrl+A to select all objects.

4 Locate the **Selections of Resulting Entities** section. Select the **Resulting objects selection** check box.

Front Plane

1 In the **Geometry** toolbar, click **Work Plane**.

2 In the **Settings** window for **Work Plane**, type `Front Plane` in the **Label** text field.

3 Locate the **Plane Definition** section. From the **Plane type** list, choose **Transformed**.

4 From the **Take work plane from** list, choose **Front Ring Annulus (pi2)**.

5 From the **Work plane to transform** list, choose **Surface (wp1)**.

Rear Plane

1 In the **Geometry** toolbar, click **Work Plane**.

2 In the **Settings** window for **Work Plane**, type `Rear Plane` in the **Label** text field.

3 Locate the **Plane Definition** section. From the **Plane type** list, choose **Transformed**.

4 From the **Take work plane from** list, choose **Rear Ring Annulus (pi3)**.

5 From the **Work plane to transform** list, choose **Surface (wp1)**.

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

Next, modify the dimensions of the lens group apertures. These will be extruded to create the lens supports.

PETZVAL LENS STOP ANALYSIS GEOMETRY SEQUENCE

Group 1 Aperture (pi8)

1 In the **Model Builder** window, under **Component 1 (comp1)>** **Petzval Lens STOP Analysis Geometry Sequence** click **Group 1 Aperture (pi8)**.

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

3 In the table, enter the following settings:

Name	Expression	Value	Description
d0	dS_1	60 mm	Diameter, outer

Group 2 Aperture (pi9)

1 In the **Model Builder** window, click **Group 2 Aperture (pi9)**.

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

3 In the table, enter the following settings:

Name	Expression	Value	Description
d0	dS_2	47 mm	Diameter, outer

Group 3 Aperture (pi10)

1 In the **Model Builder** window, click **Group 3 Aperture (pi10)**.

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

3 In the table, enter the following settings:

Name	Expression	Value	Description
d0	dS_3	44.5 mm	Diameter, outer

4 Locate the **Position and Orientation of Output** section. Find the **Displacement** subsection. In the **zw** text field, type `4`.

Group 1 Support

1 In the **Geometry** toolbar, click **Extrude**.

2 In the **Settings** window for **Extrude**, type `Group 1 Support` in the **Label** text field.

3 On the object **pi8**, select Boundary 1 only.

4 Locate the **Distances** section. From the **Specify** list, choose **Vertices to extrude to**.

5 On the object **pi2**, select Point 11 only.

6 Locate the **Selections of Resulting Entities** section. Find the **Cumulative selection** subsection. Click **New**.

7 In the **New Cumulative Selection** dialog box, type `Supports` in the **Name** text field.

8 Click **OK**.

Group 2 Support

1 In the **Geometry** toolbar, click **Extrude**.

2 In the **Settings** window for **Extrude**, type `Group 2 Support` in the **Label** text field.

3 On the object **pi9**, select Boundary 1 only.

4 Locate the **Distances** section. From the **Specify** list, choose **Vertices to extrude to**.

5 On the object **pi5**, select Point 11 only.

6 Locate the **Selections of Resulting Entities** section. Find the **Cumulative selection** subsection. From the **Contribute to** list, choose **Supports**.

Group 3 Support

1 In the **Geometry** toolbar, click **Extrude**.

2 In the **Settings** window for **Extrude**, type `Group 3 Support` in the **Label** text field.

3 On the object **pi10**, select Boundary 1 only.

4 Locate the **Distances** section. From the **Specify** list, choose **Vertices to extrude to**.

5 On the object **pi6**, select Point 12 only.

6 Locate the **Selections of Resulting Entities** section. Find the **Cumulative selection** subsection. From the **Contribute to** list, choose **Supports**.

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

Barrel 1 (pi11)

1 In the **Geometry** toolbar, click **Parts** and choose **Barrel**.

2 In the **Settings** window for **Part Instance**, locate the **Position and Orientation of Output** section.

3 Find the **Coordinate system in part** subsection. From the **Work plane in part** list, choose **Front Plane (wp1)**.

4 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 vertex intersection (wp1)**.

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

Name	**Expression**	**Value**	**Description**
L	T_1+Tc_1+Tc_2+T_2+6[mm]	63 mm	Length
D_in	dS_1	60 mm	Inner diameter
T_wall	3.0[mm]	3 mm	Wall thickness
D1_out	70.0[mm]	70 mm	Front ring outer diameter
D1_in	dS_1	60 mm	Front ring inner diameter

Name	Expression	Value	Description
D2_out	85.0[mm]	85 mm	Rear ring outer diameter
D2_in	d1_S	33.262 mm	Rear ring inner diameter
L1	3.0[mm]	3 mm	Front ring thickness
L2	3.0[mm]	3 mm	Rear ring thickness

7 Locate the **Position and Orientation of Output** section. Find the **Displacement** subsection. In the **zw** text field, type -3.0[mm].

8 Click to expand the **Domain Selections** section. In the table, select the **Keep** check box for **All**.

Cone 1 (cone1)

1 In the **Geometry** toolbar, click **Cone**.

2 In the **Settings** window for **Cone**, locate the **Coordinate System** section.

3 From the **Take work plane from** list, choose **Barrel 1 (pi11)**.

4 From the **Work plane** list, choose **Rear Plane (wp2)**.

5 Locate the **Size and Shape** section. In the **Height** text field, type 3[mm].

6 In the **Bottom radius** text field, type d1_S/2.

7 In the **Top radius** text field, type dS_2/2.

8 Locate the **Position** section. In the **zw** text field, type -3[mm].

Difference 1 (dif1)

1 In the **Geometry** toolbar, click **Booleans and Partitions** and choose **Difference**.

2 Select the object **pi11** only.

3 In the **Settings** window for **Difference**, locate the **Difference** section.

4 Find the **Objects to subtract** subsection. Click to select the **Activate Selection** toggle button.

5 Select the object **cone1** only.

Barrel 2 (pi12)

1 In the **Geometry** toolbar, click **Parts** and choose **Barrel**.

2 In the **Settings** window for **Part Instance**, locate the **Position and Orientation of Output** section.

3 Find the **Coordinate system in part** subsection. From the **Work plane in part** list, choose **Front Plane (wp1)**.

4 Find the **Coordinate system to match** subsection. From the **Take work plane from** list, choose **Barrel 1 (pi11)**.

5 From the **Work plane** list, choose **Rear Plane (wp2)**.

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

Name	Expression	Value	Description
L	T_3+Tc_4+Tc_5+2[mm]	57 mm	Length
D_in	dS_2	47 mm	Inner diameter
T_wall	3.0[mm]	3 mm	Wall thickness
D1_out	85.0[mm]	85 mm	Front ring outer diameter
D1_in	dS_2	47 mm	Front ring inner diameter
D2_out	65.0[mm]	65 mm	Rear ring outer diameter
D2_in	d2_clear_5+3[mm]	35.984 mm	Rear ring inner diameter
L1	3.0[mm]	3 mm	Front ring thickness
L2	3.0[mm]	3 mm	Rear ring thickness

7 Locate the **Domain Selections** section. In the table, select the **Keep** check box for **All**.

Barrel 3 (pi13)

1 In the **Geometry** toolbar, click **Parts** and choose **Barrel**.

2 In the **Settings** window for **Part Instance**, locate the **Position and Orientation of Output** section.

3 Find the **Coordinate system in part** subsection. From the **Work plane in part** list, choose **Front Plane (wp1)**.

4 Find the **Coordinate system to match** subsection. From the **Take work plane from** list, choose **Barrel 2 (pi12)**.

5 From the **Work plane** list, choose **Rear Plane (wp2)**.

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

Name	Expression	Value	Description
L	T_5+Tc_6+T_6	50.777 mm	Length
D_in	dS_3	44.5 mm	Inner diameter
T_wall	3.0[mm]	3 mm	Wall thickness
D1_out	65.0[mm]	65 mm	Front ring outer diameter
D1_in	d2_clear_5+3[mm]	35.984 mm	Front ring inner diameter
D2_out	60.0[mm]	60 mm	Rear ring outer diameter

Name	Expression	Value	Description
D2_in	dS_3	44.5 mm	Rear ring inner diameter
L1	3.0[mm]	3 mm	Front ring thickness
L2	5.0[mm]	5 mm	Rear ring thickness

7 Locate the **Domain Selections** section. In the table, select the **Keep** check box for **All**.

Finally, create a simplified detector mount.

Detector

1 In the **Geometry** toolbar, click **Extrude**.

2 In the **Settings** window for **Extrude**, type `Detector` in the **Label** text field.

3 Locate the **General** section. From the **Input faces** list, choose **Image Plane**.

Detector Mount

1 In the **Geometry** toolbar, click **Cylinder**.

2 In the **Settings** window for **Cylinder**, type `Detector Mount` in the **Label** text field.

3 Locate the **Size and Shape** section. In the **Radius** text field, type `1.5[mm]`.

4 In the **Height** text field, type `4.0[mm]`.

5 Locate the **Coordinate System** section. From the **Take work plane from** list, choose **Barrel 3 (pi13)**.

6 From the **Work plane** list, choose **Rear Plane (wp2)**.

7 Locate the **Position** section. In the **zw** text field, type `-4.0[mm]`.

Detector Mount Rear

1 In the **Geometry** toolbar, click **Cylinder**.

2 In the **Settings** window for **Cylinder**, type `Detector Mount Rear` in the **Label** text field.

3 Locate the **Size and Shape** section. In the **Radius** text field, type `30.0[mm]`.

4 In the **Height** text field, type `3.0[mm]`.

5 Locate the **Coordinate System** section. From the **Take work plane from** list, choose **Barrel 3 (pi13)**.

6 From the **Work plane** list, choose **Rear Plane (wp2)**.

Detector Assembly

1 In the **Geometry** toolbar, click **Booleans and Partitions** and choose **Union**.

2 In the **Settings** window for **Union**, type `Detector Assembly` in the **Label** text field.

3 Select the objects **cyl1**, **cyl2**, and **ext4** only.

4 Locate the **Selections of Resulting Entities** section. Select the **Resulting objects selection** check box.

Rigid Support

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

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

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

Name	**Expression**	**Value**	**Description**
d0	`85.0[mm]`	85 mm	Diameter, outer
d1	`70.0[mm]`	70 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 **Barrel 2 (pi12)**.

5 From the **Work plane** list, choose **Front Plane (wp1)**.

6 Find the **Displacement** subsection. In the **zw** text field, type `5.0[mm]`.

7 Click to expand the **Boundary Selections** section. In the table, select the **Keep** check box for **All**.

Rigid Support Ring

1 In the **Geometry** toolbar, click **Extrude**.

2 In the **Settings** window for **Extrude**, type `Rigid Support Ring` in the **Label** text field.

3 On the object **pi14**, select Boundary 1 only.

4 Locate the **Distances** section. In the table, enter the following settings:

Distances (mm)
`2.0[mm]`

5 Select the **Reverse direction** check box.

6 Locate the **Selections of Resulting Entities** section. Find the **Cumulative selection** subsection. From the **Contribute to** list, choose **Supports**.

Assembly Surfaces

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

2 In the **Settings** window for **Complement Selection**, type `Assembly Surfaces` in the **Label** text field.

3 Locate the **Geometric Entity Level** section. From the **Level** list, choose **Boundary**.

4 Locate the **Input Entities** section. Click **Add**.

5 In the **Add** dialog box, select **Lens Exteriors** in the **Selections to invert** list.

6 Click **OK**.

7 In the **Settings** window for **Complement Selection**, click **Build All Objects**.

8 Click the **Zoom Extents** button in the **Graphics** toolbar. Compare the resulting geometry to Figure 2.