Created in COMSOL Multiphysics 5.6

Double Gauss Lens — Parametric Sweep

Introduction

This tutorial is an extension of the Double Gauss Lens tutorial. The double Gauss lens is a multiple element objective lens commonly used in imaging systems. It is capable of high quality imagery over moderately large field angles, at modest to high speed.

The model is constructed using multiple instances of standard parts from the built-in Part Library for the Ray Optics Module. Next, a parametric sweep over multiple wavelengths and field angles is made. Finally, the resulting ray and spot diagrams are displayed.

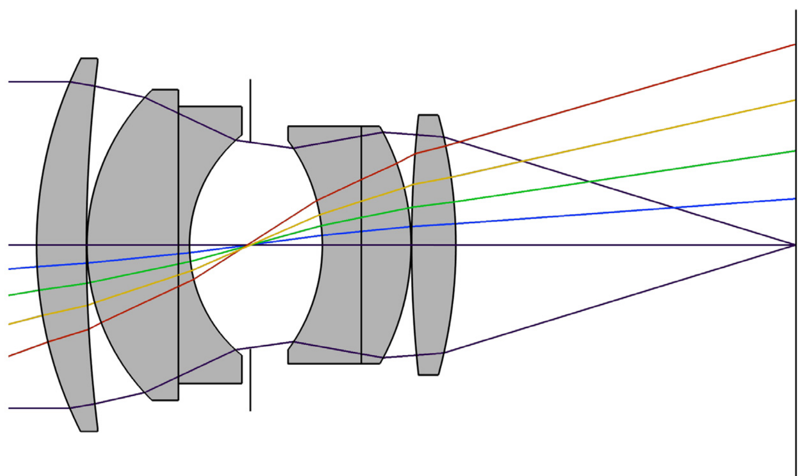

Figure 1: Overview of a double Gauss lens. In this view the marginal rays of an on-axis trace are shown, together with the chief ray of 4 additional fields.

Model Definition

The double Gauss lens simulated in this study is an $f/1.7$, 100.2 mm focal length, $19°$ field of view lens by Lautebacher & Brendel (Agfa Camera Werk Ag, U.S. Patent 2784643), from Ref. 1, p. 323. The parameters of this lens are shown in Table 1 and an overview of the lens can be seen in Figure 1. The instructions for creating the lens geometry can be found in the Appendix — Geometry Instructions of the Double Gauss Lens tutorial.

TABLE 1: DOUBLE GAUSS LENS PARAMETERS.

Index	Name	Radius (mm)	Thickness (mm)	Material	Clear radius (mm)
—	Object	∞	∞	—	—
1	Lens 1	75.050	9.000	LaF3	33.0
—	—	270.700	0.100	—	33.0
2	Lens 2	39.270	16.510	BaF11	27.5
3	Lens 3	∞	2.000	SF5	27.5
—	—	25.650	10.990	—	19.5
4	Stop	∞	13.000	—	18.6
5	Lens 4	-31.870	7.030	SF5	18.5
6	Lens 5	∞	8.980	LaF3	21.0
—	—	-43.510	0.100	—	21.0
7	Lens 6	221.140	7.980	BaF11	23.0
—	—	-88.790	61.418	—	23.0
—	Image	∞	—	—	42.5

In addition to the lens parameters used to define the lens geometry, a set of parameters are required to define the ray trace. These are detailed in Table 2. The parameters defining the scope of the parametric sweep can be found in Table 3.

TABLE 2: GLOBAL PARAMETER DEFINITIONS.

Parameter	Value	Description
λ_{vac}	550 nm	Nominal (vacuum) wavelength
θ_x	0°	Nominal x field angle
θ_y	0°	Nominal y field angle
N_{ring}	18	Number of hexapolar rings (N_{ring} = 18 will give a total of 1027 rays)
P_{nom}	58.941 mm	Nominal entrance pupil diameter
P_{fac1}	-1.15	Pupil shift factor 1
P_{fac2}	-0.60	Pupil shift factor 2

TABLE 3: PARAMETRIC SWEEP PARAMETER DEFINITIONS.

Parameter	Value	Description
λ_{num}	3	Number of wavelengths
λ_{mid}	550 nm	Central wavelength
λ_{step}	100 nm	Wavelength step
$\lambda_{\mathrm{min/max}}$	$\lambda_{\mathrm{mid}} \mp (\lambda_{\mathrm{num}} - 1)\frac{\lambda_{\mathrm{step}}}{2}$	Minimum/Maximum wavelength
$\theta_{x,\mathrm{num}}$	1	Number of x fields
$\theta_{y,\mathrm{num}}$	2	Number of y fields
$\theta_{x,\mathrm{step}}$	$0°$	x field step
$\theta_{y,\mathrm{step}}$	$10°$	y field step
$\theta_{x,\mathrm{min}}$	$0°$	Minimum x field
$\theta_{x,\mathrm{max}}$	$\theta_{x,\,\mathrm{min}} + (\theta_{x,\,\mathrm{num}} - 1)\theta_{x,\,\mathrm{step}}$	Maximum x field
$\theta_{y,\mathrm{min}}$	$0°$	Minimum y field
$\theta_{y,\mathrm{max}}$	$\theta_{y,\,\mathrm{min}} + (\theta_{y,\,\mathrm{num}} - 1)\theta_{y,\,\mathrm{step}}$	Maximum y field

Several of the parameters defined in Table 2 are used to derive additional parameters such as the ray direction vector components, the stop and image plane z-coordinates, as well as the entrance pupil location. Table 4 gives the expressions used to derived these parameters. Note that the pupil shift factor is used in a empirical approximation to ensure that the chief ray passes through the center of the stop at all field angles.

TABLE 4: GLOBAL PARAMETER DEFINITIONS (DERIVED).

Parameter	Value	Description
v_x	$\tan\theta_x$	Ray direction vector, x-component
v_y	$\tan\theta_y$	Ray direction vector, y-component
v_z	1	Ray direction vector, z-component
z_{stop}	$\sum_{n=1}^{3}(T_{c,n} + T_n)$	Stop z-coordinate, where $T_{\mathrm{c,n}}$ 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 4th element in the Double Gauss lens

TABLE 4: GLOBAL PARAMETER DEFINITIONS (DERIVED).

Parameter	Value	Description
z_{image}	$\sum_{n=1}^{7}(T_{c,n}+T_n)$	Image plane z-coordinate, where $T_{\text{c,n}}$ is the central thickness of element n and T_{n} is the separation between elements n and $n+1$. Including the stop, the Double Gauss lens has 7 elements.
P_{fac}	$P_{\text{fac1}} + P_{\text{fac2}}\sin\theta$	Pupil shift factor, where $\theta = \sqrt{\theta_x^2+\theta_y^2}$
Δx_{pupil}	$(\Delta z_{\text{pupil}} + P_{\text{fac}}\, z_{\text{stop}})\tan\theta_x$	Pupil shift, x-coordinate
Δy_{pupil}	$(\Delta z_{\text{pupil}} + P_{\text{fac}}\, z_{\text{stop}})\tan\theta_y$	Pupil shift, y-coordinate

Results and Discussion

The double Gauss lens geometry is created by inserting each lens element (including the stop) sequentially. That is, each sequent element is placed relative to the prior one. This process is simplified by making use of the predefined work planes within the part instances.

It is important to appreciate that the ray tracing method used by the Geometrical Optics interface is inherently nonsequential, so the same result could be obtained by placing part instances within the geometry in any order. In order to limit the rays to those which reach the focal plane, additional aperture stops and obstructions are added to the geometry. These items can also be placed by using the predefined work planes from each of the lens part instances. The double Gauss lens geometry sequence is shown in Figure 2.

The results of a ray trace made with 3 different wavelengths and two field points can be seen in Figure 3. In this view the ray trajectories are colored by the normalized radial distance from the centroid of each monochromatic spot. This makes it possible to visualize the relative contribution of the rays to the final image quality to be easily visualized.

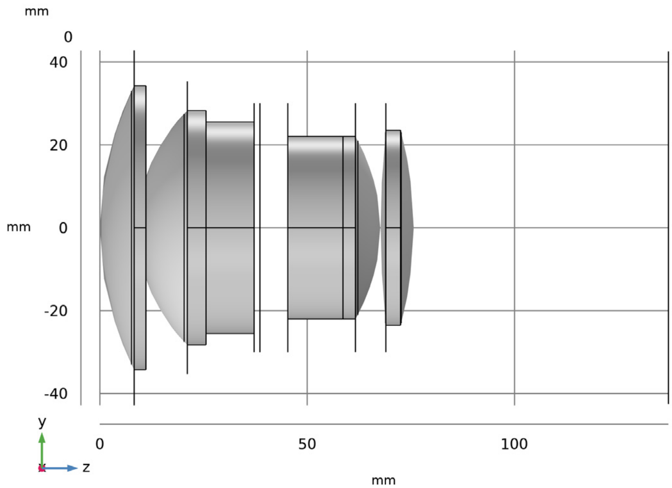

Figure 2: The double Gauss lens geometry sequence.

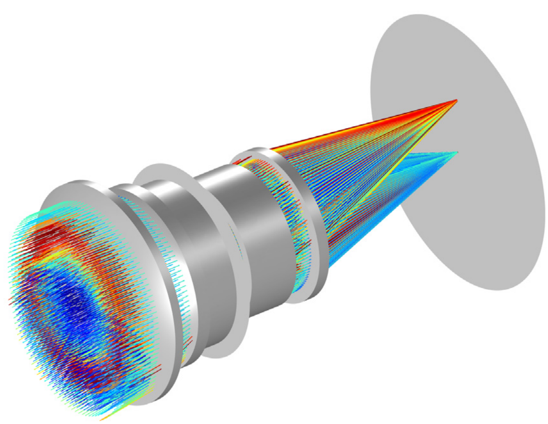

Figure 3: Ray diagram of the double Gauss lens colored by their radial distance from the centroid on the image plane.

Figure 4 and Figure 5 show spot diagrams from the on axis and off axis fields respectively. The spots are colored according to wavelength, and the root mean square (RMS*)* spot radius for each wavelength is also shown.

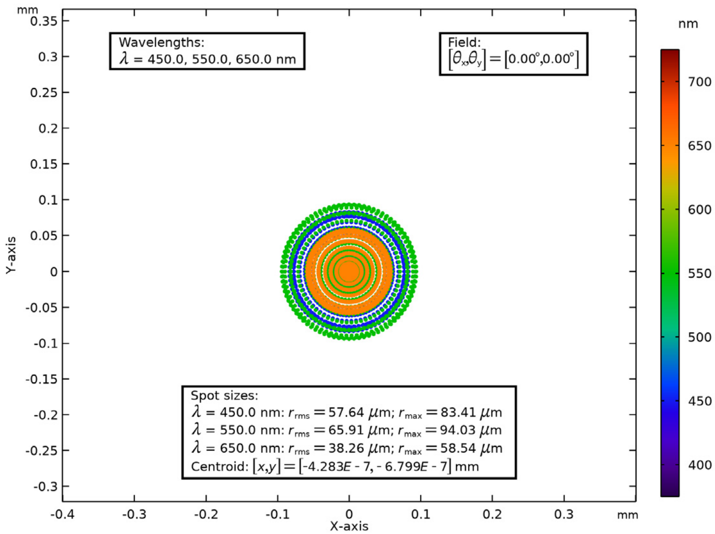

Figure 4: Spot diagram for the on axis field (field 1).

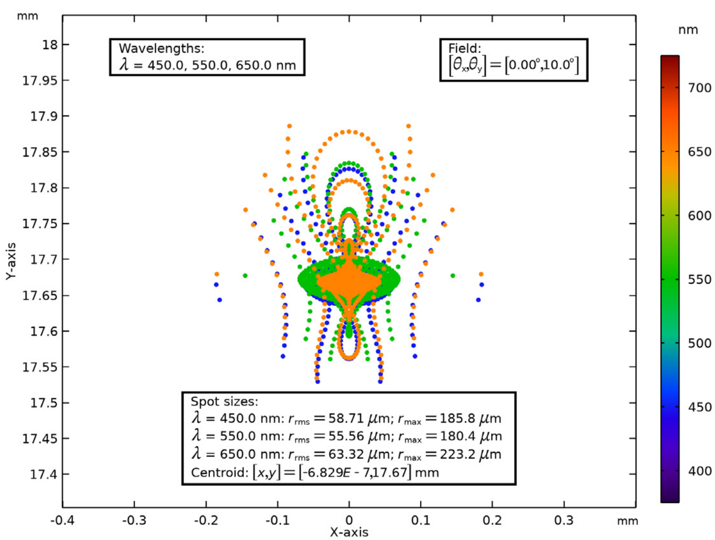

Figure 5: Spot diagram for the off axis field (field 2).

Reference

1. W.J. Smith, *Modern lens design*, vol. 2. New York, NY, USA: McGraw-Hill, 2005.

Application Library path: `Ray_Optics_Module/Lenses_Cameras_and_Telescopes/double_gauss_lens_parametric`

Note: This tutorial extends the Double Gauss Lens tutorial. The Application Library path for that simulation is: *Ray_Optics_Module/Lenses_Cameras_and_Telescopes/double_gauss_lens*.

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 Double Gauss Lens Parametric simulation parameters can be loaded from a text file.

1 In the **Home** toolbar, click Pi **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 `double_gauss_lens_parametric_parameters.txt`.

COMPONENT 1 (COMP1)

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

2 In the **Settings** window for **Component**, locate the **General** section.

3 Find the **Mesh frame coordinates** subsection. 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.

DEFINITIONS

Load the variable definitions from a text file. These variables are used during postprocessing of the results. Note that the `withsol` variables have been defined to reflect the range of the parametric sweep.

Variables 1

1 In the **Model Builder** window, expand the **Component 1 (comp1)>Definitions** node.

2 Right-click **Definitions** and choose **Variables**.

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

4 Click **Load from File**.

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

DOUBLE GAUSS 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** node.

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Geometry 1**.
2 In the **Settings** window for **Geometry**, type `Double Gauss Lens` in the **Label** text field.
3 In the **Geometry** toolbar, click **Insert Sequence**.
4 Browse to the model's Application Libraries folder and double-click the file `double_gauss_lens_geom_sequence.mph`.
5 In the **Geometry** toolbar, click **Build All**.
6 Click the **Orthographic Projection** button in the **Graphics** toolbar. Orient the view to place the *z*-axis (optical axis) horizontal and the *y*-axis vertical.
7 Click the **Zoom Extents** button in the **Graphics** toolbar. 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>Glasses>Optical Glass: Hoya>Hoya LAF3**.
4 Click **Add to Component** in the window toolbar.
5 In the tree, select **Optical>Glasses>Optical Glass: Hoya>Hoya BAF11**.
6 Click **Add to Component** in the window toolbar.
7 In the tree, select **Optical>Glasses>Optical Glass: Schott>Schott N-SF5**.
8 Click **Add to Component** in the window toolbar.
9 In the **Home** toolbar, click **Add Material** to close the **Add Material** window.

MATERIALS

Hoya LAF3 (mat1)

1 In the **Model Builder** window, under **Component 1 (comp1)>Materials** click **Hoya LAF3 (mat1)**.
2 In the **Settings** window for **Material**, locate the **Geometric Entity Selection** section.
3 From the **Selection** list, choose **Lens Material 1**. Each of the 6 lenses has been assigned to one of three lens material selections.

Hoya BAF11 (mat2)

1 In the **Model Builder** window, click **Hoya BAF11 (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-SF5 (mat3)

1 In the **Model Builder** window, click **Schott N-SF5 (mat3)**.

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

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

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 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.

4 Select the **Use geometry normals for ray-boundary interactions** check box. In this simulation, the geometry normals are used to apply the boundary conditions on all refracting surfaces. This is appropriate for the highest accuracy ray traces in single-physics simulations, where the geometry is not deformed.

   The following variables are not needed to trace the rays but may be useful during postprocessing.

5 Locate the **Additional Variables** section. Select the **Compute optical path length** check box.

6 Select the **Count reflections** check box.

7 Select the **Store ray status data** check box.

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 **Optical dispersion model** 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**.

Ray Properties 1

1 In the **Model Builder** window, click **Ray Properties 1**.

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

3 In the λ_0 text field, type `lam_vac`. This wavelength was defined in the **Parameters** node. It will be updated during the **Parametric Sweep**.

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

dx	x
dy	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

vx	x
vy	y
vz	z

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

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** (**Freeze**) will be used.

MESH 1

In the **Model Builder** window, under **Component 1 (comp1)** right-click **Mesh 1** and choose **Build All**. The default physics-controlled mesh settings can be used in this simulation.

STUDY 1

In the following steps a parametric sweep study is constructed allowing the Double Gauss lens to be traced over multiple wavelengths and field angles.

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

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

3 Clear the **Generate default plots** check box. In this study, the plots will be created manually.

4 Clear the **Generate convergence plots** check box.

Parametric Sweep

1 In the **Study** toolbar, click **Parametric Sweep**.

2 In the **Settings** window for **Parametric Sweep**, locate the **Study Settings** section.

3 From the **Sweep type** list, choose **All combinations**.

4 Click **Add**.

5 Click **Add**.

6 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
lam_vac (Nominal vacuum wavelength)	range(lam_min,lam_step, lam_max)	nm
theta_y (Nominal Y field angle)	range(theta_y_min, theta_y_step, theta_y_max)	deg

Step 1: Ray Tracing

1 In the **Model Builder** window, 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 **Study** toolbar, click **Compute**.

RESULTS

Create a plot showing the ray trajectories with color expressions, as well as a spot diagram in the image plane.

In the **Model Builder** window, expand the **Results** node.

Ray 1

Create a **Ray** dataset to use with the Ray Diagrams.

1 In the **Model Builder** window, expand the **Results>Datasets** node.

2 Right-click **Results>Datasets** and choose **More Datasets>Ray**.

3 In the **Settings** window for **Ray**, locate the **Ray Solution** section.

4 From the **Solution** list, choose **Parametric Solutions 1 (sol2)**.

Create a **Cut Plane** dataset to make image plane spot diagrams.

Image Plane

1 In the **Results** toolbar, click **Cut Plane**.

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

3 Locate the **Data** section. From the **Dataset** list, choose **Ray 1**.

4 Locate the **Plane Data** section. From the **Plane** list, choose **xy-planes**.

5 In the **z-coordinate** text field, type `z_image`.

Ray Diagram

In the following steps, a ray diagram is created showing all field angles and wavelengths and a custom color expression is added.

Ray Diagram

1 In the **Results** toolbar, click **3D Plot Group**.

2 In the **Settings** window for **3D Plot Group**, type `Ray Diagram` 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. Clear the **Plot dataset edges** check box. The lenses will be rendered using a **Mesh** plot.

Mesh 1

Create a **Mesh** plot to render the lens elements as solids.

1 Right-click **Ray Diagram** and choose **Mesh**.

2 In the **Settings** window for **Mesh**, click to expand the **Title** section.

3 Locate the **Level** section. From the **Level** list, choose **Volume**.

4 Locate the **Coloring and Style** section. From the **Element color** list, choose **Gray**.

5 From the **Wireframe color** list, choose **None**.

Ray Diagram

Add **Surface** plots to show the stop and image plane.

Surface 1

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

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

3 From the **Dataset** list, choose **Study 1/Solution 1 (sol1)**.

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

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

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 **Aperture Stop**.

Surface 2

In the **Model Builder** window, under **Results>Ray Diagram** right-click **Surface 1** and choose **Duplicate**.

Selection 1

1. In the **Model Builder** window, expand the **Surface 2** node, then click **Selection 1**.
2. In the **Settings** window for **Selection**, locate the **Selection** section.
3. From the **Selection** list, choose **Image Plane**.

Ray Diagram

In the **Model Builder** window, click **Ray Diagram**.

Ray Trajectories 1

1. In the **Ray Diagram** toolbar, click **More Plots** and choose **Ray Trajectories**.
2. In the **Settings** window for **Ray Trajectories**, locate the **Data** section.
3. From the **Dataset** list, choose **Ray 1**.
4. From the **Parameter value (lam_vac (nm))** list, choose **450**.
5. From the **Parameter value (theta_y (deg))** list, choose **0**.
6. Click to expand the **Title** section. From the **Title type** list, choose **None**.

Color Expression 1

1. Right-click **Ray Trajectories 1** and choose **Color Expression**.

   Color the rays according to the normalized radial distance from the centroid.
2. In the **Settings** window for **Color Expression**, locate the **Expression** section.
3. In the **Expression** text field, type `at('last',gop.rall/gop.rmaxall)`.

Filter 1

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

   Select only rays that reach the image plane; i.e., the final ray status (`fs`) is 2 (frozen).
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 `gop.fs==2`.

Ray Trajectories 1

For all other wavelength and field angles, the details used for the first wavelength and field angle can be duplicated.

Ray Trajectories 2

1 Right-click **Ray Trajectories 1** and choose **Duplicate**.

2 In the **Settings** window for **Ray Trajectories**, locate the **Data** section.

3 From the **Parameter value (lam_vac (nm))** list, choose **550**.

4 Click to expand the **Inherit Style** section. From the **Plot** list, choose **Ray Trajectories 1**. This step only needs to be taken on the first duplication.

Ray Trajectories 3

1 Right-click **Ray Trajectories 2** and choose **Duplicate**.

2 In the **Settings** window for **Ray Trajectories**, locate the **Data** section.

3 From the **Parameter value (lam_vac (nm))** list, choose **650**.

Ray Trajectories 4

1 Right-click **Ray Trajectories 3** and choose **Duplicate**.

2 In the **Settings** window for **Ray Trajectories**, locate the **Data** section.

3 From the **Parameter value (lam_vac (nm))** list, choose **450**.

4 From the **Parameter value (theta_y (deg))** list, choose **10**.

Ray Trajectories 5

1 Right-click **Ray Trajectories 4** and choose **Duplicate**.

2 In the **Settings** window for **Ray Trajectories**, locate the **Data** section.

3 From the **Parameter value (lam_vac (nm))** list, choose **550**.

Ray Trajectories 6

1 Right-click **Ray Trajectories 5** and choose **Duplicate**.

2 In the **Settings** window for **Ray Trajectories**, locate the **Data** section.

3 From the **Parameter value (lam_vac (nm))** list, choose **650**.

Spot Diagrams

In the following steps, image plane spot diagrams for each field angle are created, and custom color expressions are added.

First, create a spot diagram for the on-axis field.

Spot Diagram 1

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 1` 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. Select the **x-axis label** check box.
5. In the associated text field, type `X-axis`.
6. Select the **y-axis label** check box.
7. In the associated text field, type `Y-axis`.
8. Locate the **Color Legend** section. Select the **Show units** check box.

Poincaré Map 1

1. In the **Spot Diagram 1** toolbar, click **More Plots** and choose **Poincaré Map**.
2. In the **Settings** window for **Poincaré Map**, locate the **Data** section.
3. From the **Cut plane** list, choose **Image Plane**.
4. From the **Parameter value (lam_vac (nm))** list, choose **450**.
5. From the **Parameter value (theta_y (deg))** list, choose **0**.

Color Expression 1

1. Right-click **Poincaré Map 1** and choose **Color Expression**.
2. In the **Settings** window for **Color Expression**, locate the **Expression** section.
3. In the **Expression** text field, type `lam_vac`.
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 `375`.
7. In the **Maximum** text field, type `725`.
8. Locate the **Coloring and Style** section. From the **Color table** list, choose **Spectrum**.

Poincaré Map 2

1. In the **Model Builder** window, under **Results>Spot Diagram 1** right-click **Poincaré Map 1** and choose **Duplicate**.
2. In the **Settings** window for **Poincaré Map**, locate the **Data** section.
3. From the **Parameter value (lam_vac (nm))** list, choose **550**.
4. Click to expand the **Inherit Style** section. From the **Plot** list, choose **Poincaré Map 1**.

Poincaré Map 3

1. Right-click **Poincaré Map 2** and choose **Duplicate**.
2. In the **Settings** window for **Poincaré Map**, locate the **Data** section.
3. From the **Parameter value (lam_vac (nm))** list, choose **650**.

Annotation 1

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

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

3 From the **Dataset** list, choose **Study 1/Solution 1 (sol1)**.

4 Locate the **Annotation** section. In the **Text** text field, type `Wavelengths: \\ $\lambda$ = eval(lam1/1[nm]), eval(lam2/1[nm]), eval(lam3/1[nm]) nm`.

5 Select the **Allow evaluation of expressions** check box.

6 From the **Geometry level** list, choose **Global**.

7 Locate the **Position** section. In the **X** text field, type `qx_ave0-1.5*r_max`.

8 In the **Y** text field, type `qy_ave0+1.5*r_max`.

9 Click to expand the **Advanced** section. In the **Expression precision** text field, type `4`.

10 Locate the **Coloring and Style** section. Select the **LaTeX markup** check box.

11 Clear the **Show point** check box.

12 Select the **Show frame** check box.

Annotation 2

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

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

3 In the **Text** text field, type `Field: \\ $\left[\theta_\textrm{x}, \theta_\textrm{y}\right] = \left[eval(theta_x0/1[deg])^\circ, eval(theta_y0/1[deg])^\circ\right]$`.

4 Locate the **Position** section. In the **X** text field, type `qx_ave0+1.5*r_max`.

5 Locate the **Advanced** section. In the **Expression precision** text field, type `3`.

6 Locate the **Coloring and Style** section. From the **Anchor point** list, choose **Upper right**.

Annotation 3

1 Right-click **Annotation 2** and choose **Duplicate**.

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

3 In the **Text** text field, type `Spot sizes: \\ λ = eval(lam1/1[nm]) nm: $r_\textrm{rms} = eval(1e3*r_rms0_1)~\mu$m; $r_\textrm{max} = eval(r_max0_1/1[um])~\mu$m \\ λ = eval(lam2/1[nm]) nm: $r_\textrm{rms} = eval(1e3*r_rms0_2)~\mu$m; $r_\textrm{max} = eval(r_max0_2/1[um])~\mu$m \\ λ = eval(lam3/1[nm]) nm: $r_\textrm{rms} = eval(1e3*r_rms0_3)~\mu$m; $r_\textrm{max} =`

`eval(r_max0_3/1[um])~\mu$m \\ Centroid: $[x,y] = [eval(qx_ave0), eval(qy_ave0)]$ mm.`

4 Locate the **Position** section. In the **X** text field, type `qx_ave0`.

5 In the **Y** text field, type `qy_ave0-1.30*r_max`.

6 Locate the **Advanced** section. In the **Expression precision** text field, type `4`.

7 Locate the **Coloring and Style** section. From the **Anchor point** list, choose **Lower middle**.

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

9 Click the **Zoom Extents** button in the **Graphics** toolbar. Compare the plot to Figure 4.

Now, create a spot diagram for the off-axis field.

Spot Diagram 2

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

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

Poincaré Map 1

1 In the **Model Builder** window, expand the **Spot Diagram 2** node, then click **Poincaré Map 1**.

2 In the **Settings** window for **Poincaré Map**, locate the **Data** section.

3 From the **Parameter value (theta_y (deg))** list, choose **10**.

Poincaré Map 2

1 In the **Model Builder** window, click **Poincaré Map 2**.

2 In the **Settings** window for **Poincaré Map**, locate the **Data** section.

3 From the **Parameter value (theta_y (deg))** list, choose **10**.

Poincaré Map 3

1 In the **Model Builder** window, click **Poincaré Map 3**.

2 In the **Settings** window for **Poincaré Map**, locate the **Data** section.

3 From the **Parameter value (theta_y (deg))** list, choose **10**.

Annotation 1

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

2 In the **Settings** window for **Annotation**, locate the **Position** section.

3 In the **X** text field, type `qx_ave1-1.5*r_max`.

4 In the **Y** text field, type `qy_ave1+1.5*r_max`.

Annotation 2

1. In the **Model Builder** window, click **Annotation 2**.
2. In the **Settings** window for **Annotation**, locate the **Annotation** section.
3. In the **Text** text field, type `Field: \\ $\left[\theta_\textrm{x}, \theta_\textrm{y}\right] = \left[eval(theta_x1/1[deg])^\circ, eval(theta_y1/1[deg])^\circ\right]$`.
4. Locate the **Position** section. In the **X** text field, type `qx_ave1+1.5*r_max`.
5. In the **Y** text field, type `qy_ave1+1.5*r_max`.

Annotation 3

1. In the **Model Builder** window, click **Annotation 3**.
2. In the **Settings** window for **Annotation**, locate the **Annotation** section.
3. In the **Text** text field, type `Spot sizes: \\ λ = eval(lam1/1[nm]) nm: $r_\textrm{rms} = eval(1e3*r_rms1_1)~\mu$m; $r_\textrm{max} = eval(r_max1_1/1[um])~\mu$m \\ λ = eval(lam2/1[nm]) nm: $r_\textrm{rms} = eval(1e3*r_rms1_2)~\mu$m; $r_\textrm{max} = eval(r_max1_2/1[um])~\mu$m \\ λ = eval(lam3/1[nm]) nm: $r_\textrm{rms} = eval(1e3*r_rms1_3)~\mu$m; $r_\textrm{max} = eval(r_max1_3/1[um])~\mu$m \\ Centroid: $[x,y] = [eval(qx_ave1), eval(qy_ave1)]$ mm`.
4. Locate the **Position** section. In the **X** text field, type `qx_ave1`.
5. In the **Y** text field, type `qy_ave1-1.30*r_max`.
6. In the **Spot Diagram 2** toolbar, click **Plot**.
7. Click the **Zoom Extents** button in the **Graphics** toolbar. Compare the resulting image to Figure 5.

Appendix — Geometry Instructions

The lens geometry is identical to that used in the Double Gauss Lens tutorial: *Ray_Optics_Module/Lenses_Cameras_and_Telescopes/double_gauss_lens*. For details instructions see Appendix — Geometry Instructions.