Created in COMSOL Multiphysics 5.6

Newtonian Telescope

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Introduction

This tutorial model shows how to trace unpolarized light rays through a Newtonian telescope. The incoming light is reflected off a paraboloidal mirror onto a flat elliptically shaped secondary mirror which folds the optical path by 90 degrees toward a flat focal plane. The telescope geometry is parameterized in terms of the primary mirror focal length and diameter, and the distance of the focal plane from the optical axis. This type of telescope was invented by Newton in 1668 and it remains a popular choice for amateur astronomers (Ref. 1).

Model Definition

The model simulates the propagation of rays coming from sources located at infinity (celestial objects) into a Newtonian telescope.

The telescope geometry (see Figure 1) comprises two mirrors and two circular annuli. The primary mirror is a paraboloidal (conic constant k = -1) and has a radius of curvature of 2.0 m. The primary mirror has a clear aperture slightly larger than the nominal 250 mm entrance pupil diameter. This gives the telescope a 1.0 m focal length with an $f/4$ focal ratio. The secondary mirror is folded at 45.0°, and it is elliptically shaped so that the obstruction can be minimized. An offset is applied to the axis of the fold mirror so that the incident cone of rays is centered on the mirror. The fold is sized so as to permit a telescope field of view of ±30 arcminutes. The first circular annulus is placed ahead of the secondary mirror to emulate the obstruction by mount for this mirror. The second annulus is placed at the folded focal plane.

Because the primary mirror in this single-physics simulation is a paraboloid, a quadratic shape function can be used to determine boundary interactions. For the same reason, a relatively coarse mesh can be used on primary mirror surface (see Figure 2) while still giving high accuracy ray traces.

Results and Discussion

Figure 3 shows the result of a ray trace. In this rendering, only the tangential and sagittal rays are shown. The spot diagram shown in Figure 4 gives the location of the rays in the focal plane. The ***RMS*** spot size of an on-axis bundle of rays is extremely small (essentially zero), thereby demonstrating the high precision of this model.

Other field angles can be traced by adjusting the x and y field angles (`theta_x`, `theta_y`) parameters in the global definitions for this model.

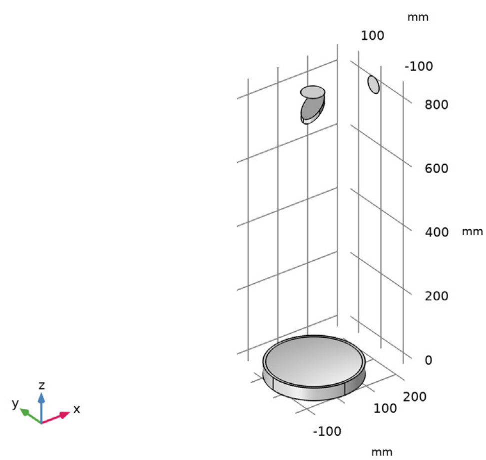

Figure 1: The Newtonian telescope geometry.

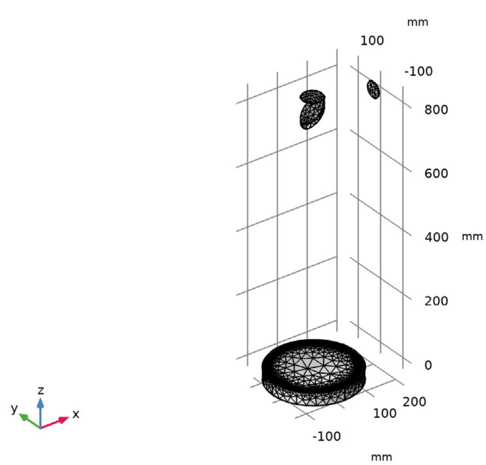

Figure 2: The Newtonian telescope mesh. Note that only the primary mirror surface is refined.

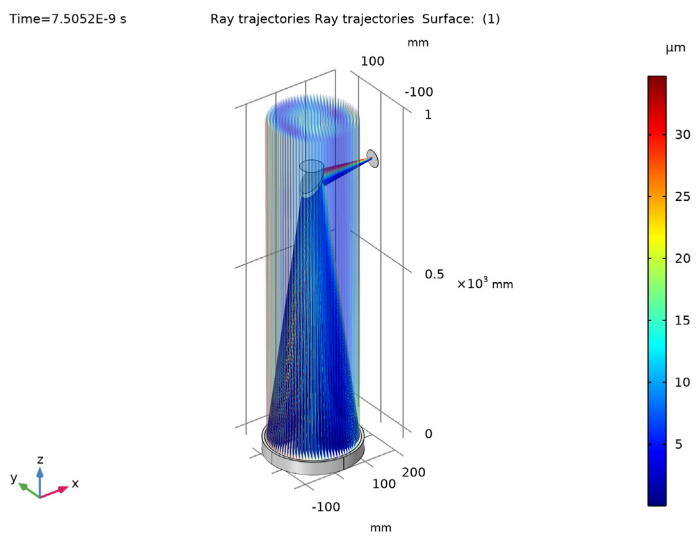

Figure 3: The Newtonian telescope ray diagram.

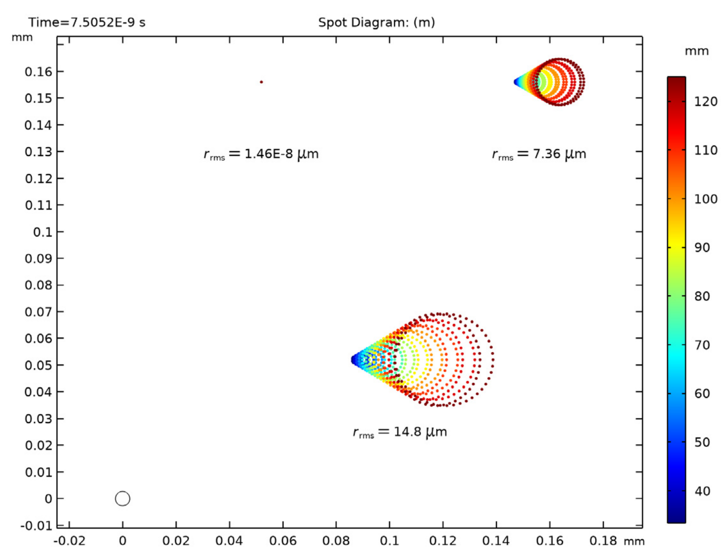

Figure 4: The Newtonian telescope spot diagram. The Airy ring is shown in the lower left-corner.

Reference

1. http://en.wikipedia.org/wiki/Newtonian_telescope.

Application Library path: `Ray_Optics_Module/Lenses_Cameras_and_Telescopes/newtonian_telescope`

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: Telescope Geometry

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

2 In the **Settings** window for **Parameters**, type `Parameters 1: Telescope Geometry` in the **Label** text field. The telescope geometry parameters will be added when the geometry sequence is inserted.

Parameters 2: Wavelengths and Fields

The wavelength and field parameters can be loaded from a text file.

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

2 In the **Settings** window for **Parameters**, type `Parameters 2: Wavelengths and Fields` 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 `newtonian_telescope_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 introduces less discretization error compared to the default, which uses linear and quadratic polynomials.

NEWTONIAN TELESCOPE

Insert the prepared geometry sequence from file. You can read the instructions for creating the geometry in the appendix.

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

2 In the **Settings** window for **Geometry**, type `Newtonian Telescope` in the **Label** text field.

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

4 In the **Geometry** toolbar, click **Insert Sequence**.

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

6 Right-click **Component 1 (comp1)>Newtonian Telescope** and choose **Build All Objects**.

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

8 Click the **Zoom Extents** button in the **Graphics** toolbar. Compare the resulting geometry to Figure 1.

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`.

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 for

specular reflection. This is appropriate for the highest accuracy ray traces in single-physics simulations, where the geometry is not deformed.

5 Locate the **Additional Variables** section. Select the **Count reflections** check box. The number of reflections (`gop.Nrefl`) can be used to control the behavior of physics features or during postprocessing.

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 n list, choose **User defined**. The rays only propagate in the empty space around the mirrors, not through the mirrors themselves, so the refractive index in the domains can be given an arbitrary value like n=1.

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`.

Release from Grid 1

In the following, hexapolar grid release features are added. The direction vectors and launch positions are set using the parameters defined above.

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
dz1	z

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

nix	x
niy	y
niz	z

6 In the R_c text field, type `d_pupil/2`.

7 In the N_c text field, type `N_hex`.

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

vx1	x
vy1	y
vz1	z

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
dz2	z

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

vx2	x
vy2	y
vz2	z

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
dz3	z

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

vx3	x
vy3	y
vz3	z

Next, define the boundary conditions, which will be specular reflection on the mirror surfaces and absorption everywhere else.

Primary Mirror

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

2 In the **Settings** window for **Mirror**, type `Primary Mirror` in the **Label** text field.

3 Locate the **Boundary Selection** section. From the **Selection** list, choose **Mirror surface (Primary Mirror)**.

Secondary Mirror

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

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

3 Locate the **Boundary Selection** section. From the **Selection** list, choose **Mirror surface (Secondary Mirror)**.

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

5 Locate the **Primary Ray Condition** section. From the **Primary ray condition** list, choose **Expression**.

6 In the *e* text field, type `gop.Nrefl>0`.

7 From the **Otherwise** list, choose **Pass through**.

Primary Obstructions

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

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

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

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

Secondary Obstructions

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

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

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

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

Image Plane

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

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

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

MESH 1

In the **Model Builder** window, under **Component 1 (comp1)** right-click **Mesh 1** and choose **Build All**. Compare this figure to Figure 2.

STUDY 1

Step 1: Ray Tracing

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

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

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

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

5 In the **Lengths** text field, type `0 2.25*f`. The maximum path length is slightly greater than twice the focal length of the telescope. This ensures that all rays reach the focal plane.

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

RESULTS

Ray Diagram

First, refine the default ray diagram plot. A spot diagram plot will be added below.

1 In the **Settings** window for **3D Plot Group**, type `Ray Diagram` in the **Label** text field.

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

3 In the **Model Builder** window, expand the **Ray Diagram** node.

Color Expression 1

1 In the **Model Builder** window, expand the **Results>Ray Diagram>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 `at('last',gop.rrel)`. This expression gives the radial distance from the centroid of the spot on the image plane generated by each release feature.

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

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 `gop.Nrefl>0`. This will render only the rays after reflection from the primary mirror.

Ray Trajectories 2

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

2 In the **Settings** window for **Ray Trajectories**, click to expand the **Inherit Style** section.

3 From the **Plot** list, choose **Ray Trajectories 1**.

Filter 1

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

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

3 In the **Logical expression for inclusion** text field, type `gop.Nrefl==0`.

Transparency 1

1 In the **Model Builder** window, right-click **Ray Trajectories 2** and choose **Transparency**.

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

3 In the **Transparency** text field, type `0.8`.

Surface 1

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

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

3 From the **Coloring** list, choose **Uniform**.

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

5 In the **Ray Diagram** toolbar, click **Plot**.

6 Click the **Zoom Extents** button in the **Graphics** toolbar. Compare this figure to Figure 3.

Now, create a spot diagram.

Spot Diagram

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

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

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

Spot Diagram 1

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

2 In the **Settings** window for **Spot Diagram**, click to expand the **Annotations** section.

3 Select the **Show circle** check box.

4 In the **Radius** text field, type `r_Airy`.

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 `at(0,gop.rrel)`. This is the radial coordinate relative to the centroid at the entrance pupil for each ray release.

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

5 Click the **Zoom Extents** button in the **Graphics** toolbar. Compare this figure to Figure 4.

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**.

NEWTONIAN TELESCOPE GEOMETRY SEQUENCE

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

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

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

GLOBAL DEFINITIONS

Load the parameters for the Newtonian Telescope geometry sequence from a text file.

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 `newtonian_telescope_geom_sequence_parameters.txt`.

NEWTONIAN TELESCOPE GEOMETRY SEQUENCE

The telescope geometry is created using predefined geometry Parts.

PART LIBRARIES

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

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

3 In the **Part Libraries** window, select **Ray Optics Module>3D>Mirrors>conic_mirror_on_axis_3d** in the tree.

4 Click **Add to Geometry**.

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

6 Click **OK**.

NEWTONIAN TELESCOPE GEOMETRY SEQUENCE

Primary Mirror

1 In the **Model Builder** window, under **Component 1 (comp1)> Newtonian Telescope Geometry Sequence** click **Conic Mirror On Axis 3D 1 (pi1)**.

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

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

Name	Expression	Value	Description
R	`-2*f`	-2000 mm	Radius of curvature (+convex/-concave)
k	`k`	-1	Conic constant
Tc	`Tc_prim`	35 mm	Center thickness
d0	`d0_prim`	275 mm	Mirror full diameter
d1	`d1_prim`	260 mm	Mirror surface diameter
d_clear	`d_clear`	0 m	Clear aperture diameter
d_hole	0	0 m	Center hole diameter
nix	`-nix`	-0	Local optical axis, x-component
niy	`-niy`	-0	Local optical axis, y-component
niz	`-niz`	-1	Local optical axis, z-component
n_extra_r	0	0	Number of extra radial points
n_extra_a	0	0	Number of extra azimuthal points

The input parameters are defined in the **Parameters 1** node.

4 Click to expand the **Boundary Selections** section. Click **New Cumulative Selection**.

5 In the **New Cumulative Selection** dialog box, type `Primary Obstructions` in the **Name** text field.

6 Click **OK**. This selection, and those that follow will be used to apply boundary conditions later in the model setup.

7 In the **Settings** window for **Part Instance**, locate the **Boundary Selections** section.

8 Click **New Cumulative Selection**.

9 In the **New Cumulative Selection** dialog box, type `Secondary Obstructions` in the **Name** text field.

10 Click **OK**.

11 In the **Settings** window for **Part Instance**, locate the **Boundary Selections** section.

12 Click **New Cumulative Selection**.

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

14 Click **OK**.

Now, apply each of these selections.

15 In the **Settings** window for **Part Instance**, locate the **Boundary Selections** section.

16 In the table, enter the following settings:

Name	Keep	Physics	Contribute to
Mirror surface	√	√	None
Mirror obstruction		√	Primary Obstructions
Mirror rear surface		√	Primary Obstructions
Mirror edges		√	Primary Obstructions

PART LIBRARIES

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

2 In the **Model Builder** window, click **Newtonian Telescope Geometry Sequence**.

3 In the **Part Libraries** window, select **Ray Optics Module>3D>Mirrors> elliptical_planar_mirror_3d** in the tree.

4 Click **Add to Geometry**.

5 In the **Select Part Variant** dialog box, select **Specify mirror angle and minor axis diameter** in the **Select part variant** list.

6 Click **OK**.

NEWTONIAN TELESCOPE GEOMETRY SEQUENCE

Secondary Mirror

1 In the **Model Builder** window, under **Component 1 (comp1)> Newtonian Telescope Geometry Sequence** click **Elliptical Planar Mirror 3D 1 (pi2)**.

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

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

Name	Expression	Value	Description
Tc	`Tc_sec`	10 mm	Mirror thickness
d0	`1.25*d_sec`	62.5 mm	Minor axis diameter
theta	`45.0[deg]`	45 °	Mirror angle
dx	`delta_sec`	4.4194 mm	Offset from optical axis
nix	0	0	Local optical axis, x-component
niy	0	0	Local optical axis, y-component
niz	`-1`	-1	Local optical axis, z-component
nxx	`-1`	-1	Fold angle direction, x component
nxy	0	0	Fold angle direction, y component
nxz	0	0	Fold angle direction, z component

As above, many of the input parameters are predefined. Note that the global optical axis is `nix=niy=0,niz=1`. Therefore, after each mirror reflection `niz` changes sign. The orientation of the fold angle is set so that the fold angle is -45 degrees with respect to the local optical axis, where the axis of rotation is the local y-axis.

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

5 From the **Work plane** list, choose **Mirror vertex intersection (wp1)**.

6 Find the **Displacement** subsection. In the **zw** text field, type `-(f-f_image)`. Note that the work plane that intersects the primary mirror vertex is defined prior to a reflection. Therefore, the relative position of the secondary mirror is negative.

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

Name	Keep	Physics	Contribute to
Mirror surface	√	√	None
Mirror edges		√	Secondary Obstructions
Mirror rear		√	Secondary Obstructions

PART LIBRARIES

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

2 In the **Model Builder** window, click **Newtonian Telescope Geometry Sequence**.

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

4 Click **Add to Geometry**.

NEWTONIAN TELESCOPE GEOMETRY SEQUENCE

Secondary Obstruction

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

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

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

Name	Expression	Value	Description
d0	`1.30*d_sec`	65 mm	Diameter, outer
d1	0	0 m	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 **Secondary Mirror (pi2)**.

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

6 Find the **Displacement** subsection. In the **xw** text field, type `-delta_sec`.

7 In the **zw** text field, type `d_sec`.

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

Name	Keep	Physics	Contribute to
All		√	Secondary Obstructions

Image Plane

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

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

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

Name	Expression	Value	Description
d0	d_image	50 mm	Diameter, outer
d1	0	0 m	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 **Secondary Mirror (pi2)**.

5 From the **Work plane** list, choose **Exit plane (wp4)**.

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

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

Name	Keep	Physics	Contribute to
All		√	Detector

8 Click **Build All Objects**.

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

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