Created in COMSOL Multiphysics 6.2

Newtonian Telescope Structural Analysis

Introduction

This tutorial demonstrates ray tracing through a deformed optical system. In this example, shows how a telescope is deformed under gravity and the effect this has on image quality.

The Newtonian Telescope model is used as the basis for this tutorial. First, a simple barrel and truss structure is added to the geometry, together with supports for the primary and secondary mirrors (Figure 1). The telescope can then be rotated about the azimuth axis. As a consequence, the optics will deform under the varying gravitational load (Figure 2).

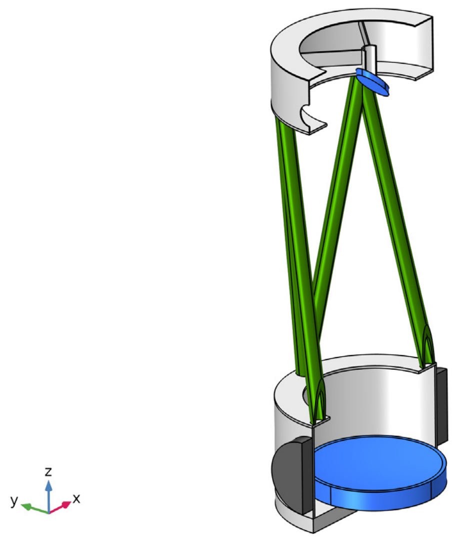


Figure 1: An overview of the telescope geometry used in the Newtonian Telescope Structural Analysis tutorial. The primary and secondary mirrors are blue. The cross-section of the truss is green and the barrels are light gray. The azimuth axis (dark gray) is located at the approximate center of mass.

This tutorial first demonstrates both a single-physics simulations using the **Geometrical Optics** interface, followed by with analysis of the structural deformation due to gravity using the **Solid Mechanics** interface. Other COMSOL multiphysics models demonstrate the impact of thermal deformation due to heat transfer and surface-to-surface radiation. See, for example, the Petzval Lens STOP Analysis and Petzval Lens STOP Analysis with Surface-to-Surface Radiation tutorials. The impact of ray-heating on the optical performance is demonstrated in the Thermally Induced Focal Shift in High-Power Laser Focusing Systems tutorial.

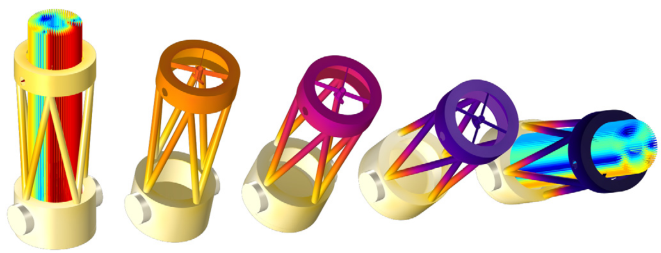


Figure 2: The telescope structure deforms due to gravity as the inclination is changed.

Model Definition

The geometry for this model can be inserted from a predefined geometry sequence. Full step-by-step instructions can be found in Appendix — Geometry Instructions. Further details of the telescope can be found in the Newtonian Telescope tutorial.

After insertion, the geometry will look like Figure 3. After adjusting the parameter (`theta`) defining the telescope inclination to 45.0°, the geometry will look like Figure 4.

Because the rays will be traced in a deformed geometry, in order to avoid discretization errors, the mesh needs to be refined on the primary mirror surface. See Figure 5. Additionally, the mesh on other elements (such as the truss) is refined so that the mesh remains well structured.

The model will include two studies. In **Study 1**, a ray trace will be performed on the undeformed (but inclined) geometry. In **Study 2** the ray trace will be performed following a computation of the structural deformation.

In each of these studies, a collimated and monochromatic bundle of rays with a hexapolar distribution is launched. The field angles correspond to the telescopes's angle of inclination and a field 2 arcmin removed from that angle.

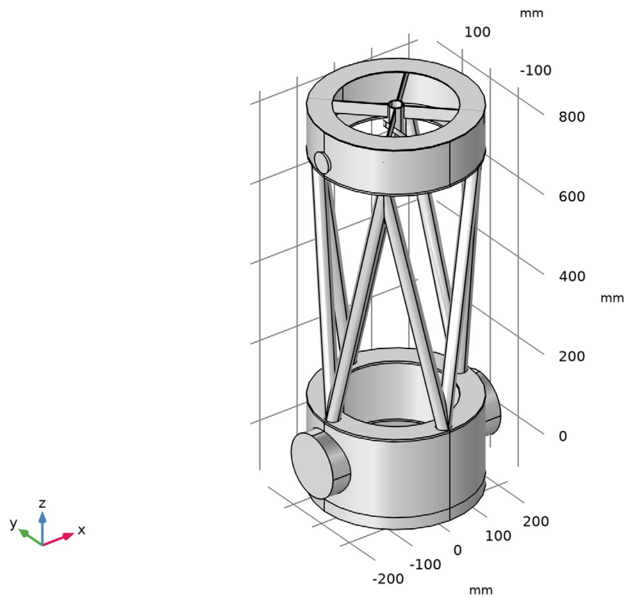


Figure 3: The Newtonian Telescope Structural Analysis geometry sequence.

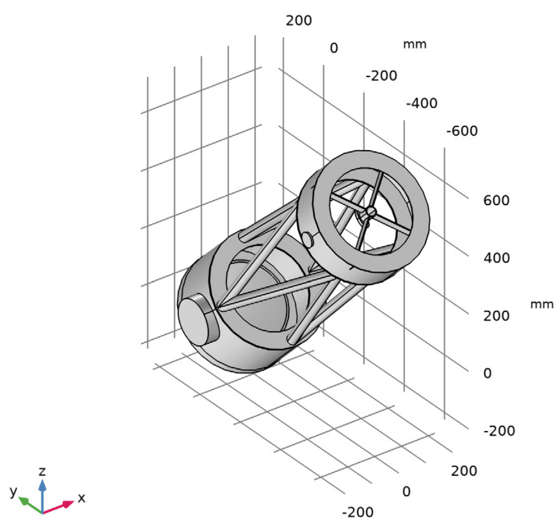


Figure 4: The geometry sequence at an inclination of 45.0°.

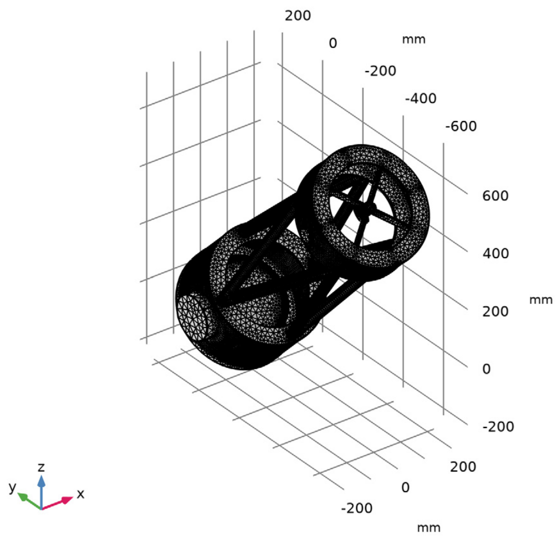


Figure 5: The Newtonian Telescope Structural Analysis mesh.

Results and Discussion

The results of a ray trace through the telescope without any deformation are shown in Figure 6. The corresponding spot diagrams can be seen in Figure 7. As expected, the image quality is perfect on-axis, and subject to coma at a field angle of 2 arcminutes. This is confirmed in the aberration diagram seen in Figure 8.

After including the structural deformation, the ray trace looks like Figure 9. This figure also shows the extent to which the telescope structure is deformed under gravity. That is just over 6 μm at this inclination.

The effect on the image quality can be seen in Figure 10. These spot diagrams lie on the “best focus” image planes. This is the plane where the on-axis RMS spot size is minimized. After deformation, the on-axis spot radius is now r_{rms} = 0.474 μm. This is also the contribution, in quadrature, to the degradation of the off-axis image quality.

As seen in the aberration diagram (Figure 11), the deformation contributes to a uncorrected defocus term.

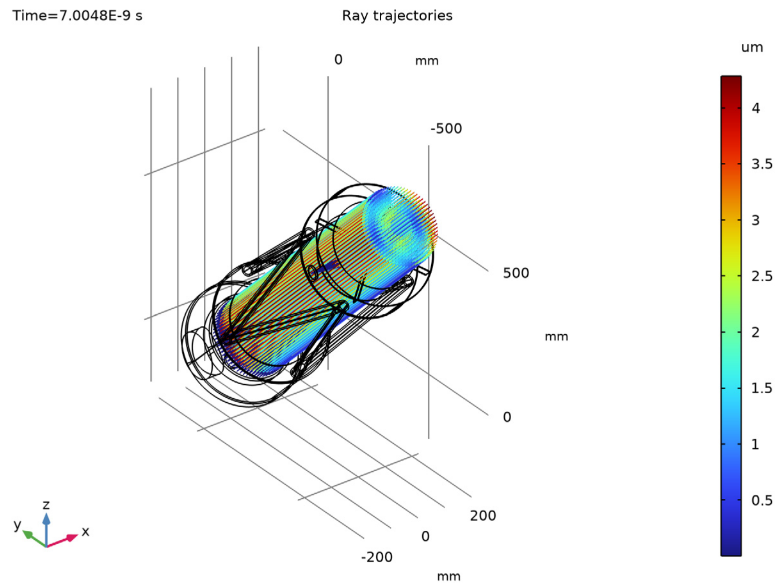


Figure 6: A ray trace through the undeformed geometry.

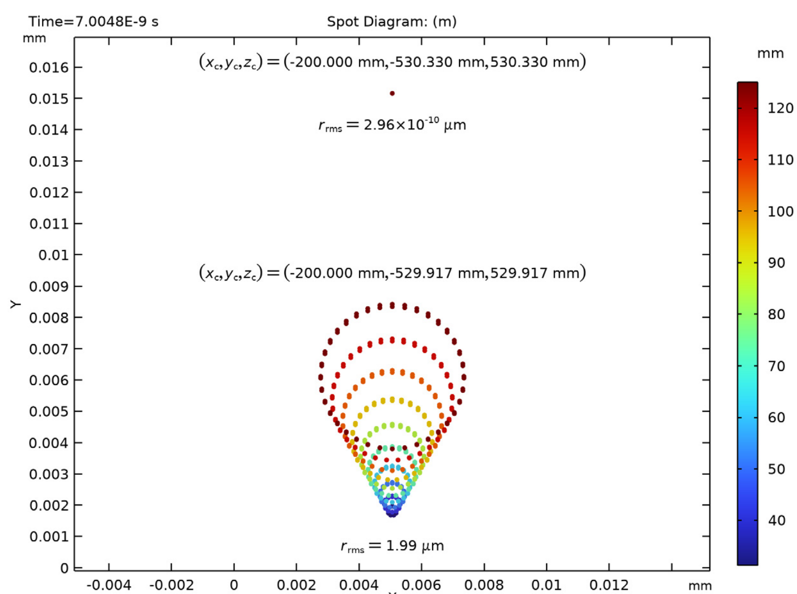


Figure 7: The undeformed spot diagram.

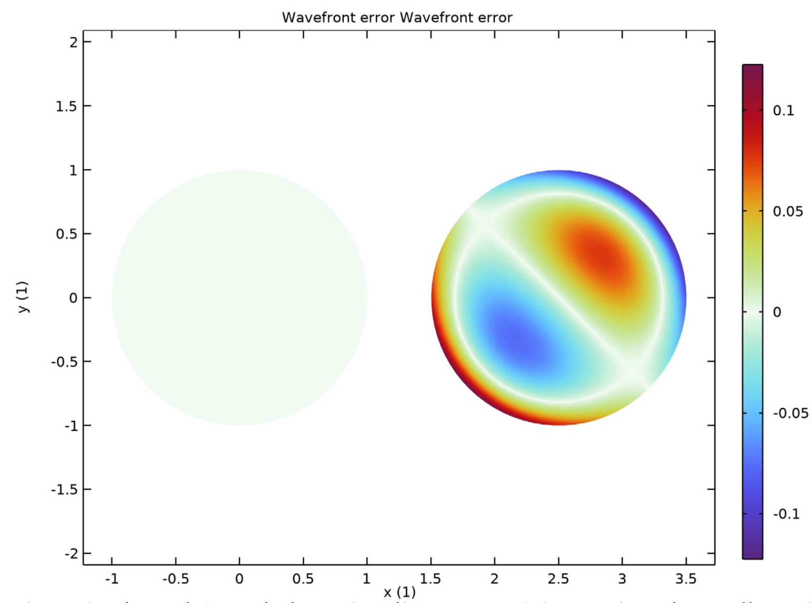


Figure 8: The undeformed aberration diagrams. Left is on-axis and uses all Zernike terms. Right is off-axis and shows only the dominant coma terms. The scale is in waves.

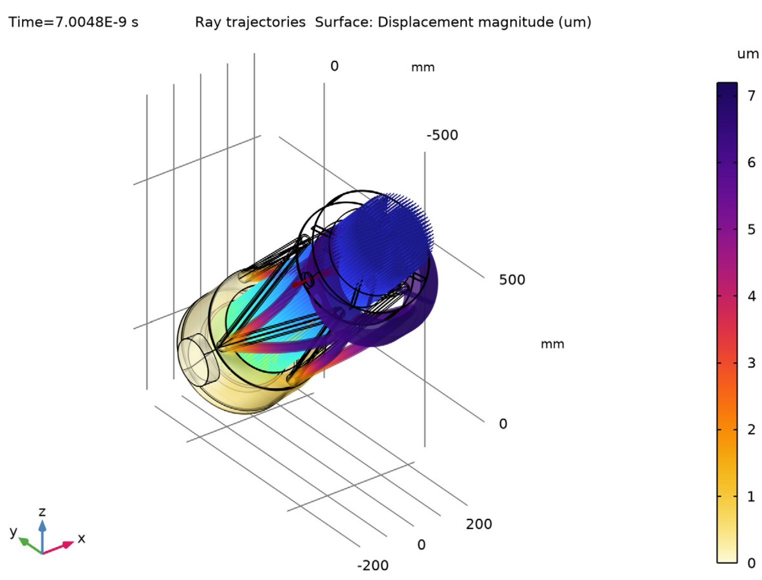


Figure 9: A ray trace using the deformed geometry. The scale is exaggerated in this view.

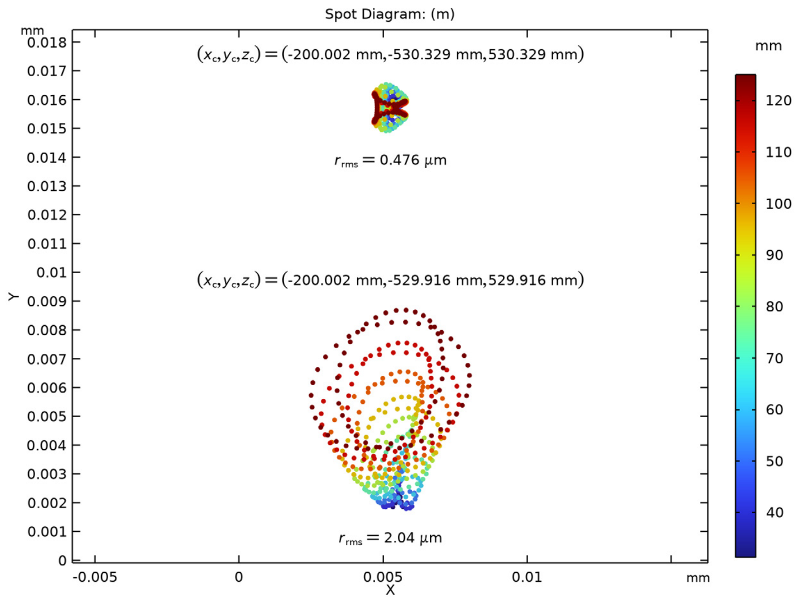


Figure 10: The spot diagram including structural deformation.

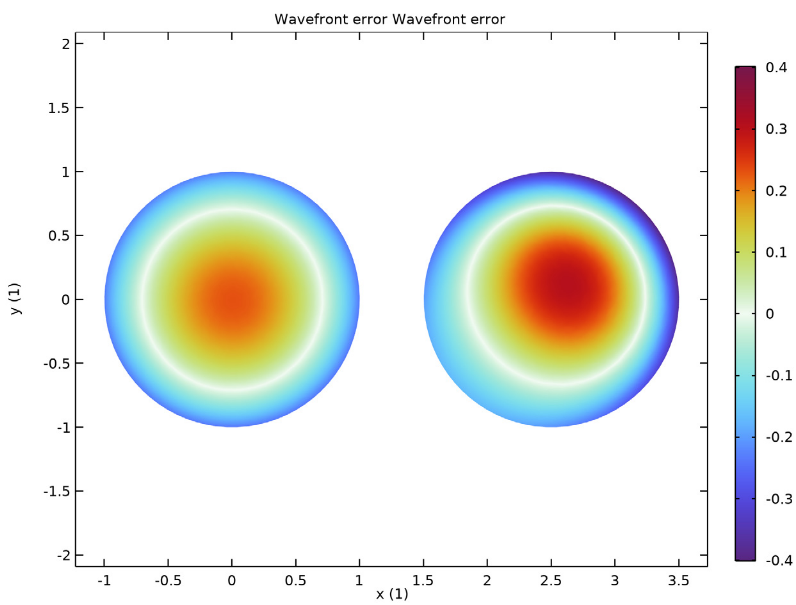


Figure 11: The deformed aberration diagram. Both on-axis (left) and off-axis (right) diagrams show only the defocus and coma Zernike terms.

Application Library path: `Ray_Optics_Module/Structural_Thermal_Optical_Performance_Analysis/newtonian_telescope_structural_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 Click **Study**.
5 In the **Select Study** tree, select **Preset Studies for Selected Physics Interfaces>Ray Tracing**.
6 Click **Done**.

First, a ray trace will be done on an undeformed telescope structure using only the **Geometrical Optics** interface. Later, the **Solid Mechanics** interface and associated studies will be added.

NEWTONIAN TELESCOPE STRUCTURAL ANALYSIS GEOMETRY SEQUENCE

Insert the prepared geometry sequence from file. You can read the instructions for creating the geometry in Appendix — Geometry Instructions.

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Geometry 1**.
2 In the **Settings** window for **Geometry**, type `Newtonian Telescope Structural Analysis Geometry Sequence` 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** and choose **Insert Sequence**.
5 Browse to the model's Application Libraries folder and double-click the file `newtonian_telescope_structural_analysis_geom_sequence.mph`.
6 In the **Insert Sequence** dialog box, click **OK**.

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

8 Click the **Orthographic Projection** button in the **Graphics** toolbar. Compare the resulting geometry to Figure 3. In the following steps, change the telescope inclination to 45 degrees.

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 were added when the geometry sequence was inserted.

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

Name	Expression	Value	Description
`theta`	`45[deg]`	0.7854 rad	`Telescope inclination`

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_structural_analysis_parameters.txt`.

NEWTONIAN TELESCOPE STRUCTURAL ANALYSIS GEOMETRY SEQUENCE

In the **Home** toolbar, click **Build All**. Compare the resulting geometry to Figure 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 tree, select **Built-in>Steel AISI 4340**.

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

7 In the tree, select **Built-in>Silica glass**.

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

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

MATERIALS

Steel AISI 4340 (mat2)

1 In the **Model Builder** window, under **Component 1 (comp1)>Materials** click **Steel AISI 4340 (mat2)**.

2 Select Domains 1, 7, 10–12, 14, and 16–19 only. This material is assigned to the primary mirror cell (and altitude axis), to the primary mirror supports, and to the secondary mirror supports.

Silica glass (mat3)

1 In the **Model Builder** window, click **Silica glass (mat3)**.

2 Select Domains 9 and 13 only. This material is assigned to each of the two mirror supports. The first material that was added (Aluminum 6063-T83) is assigned to the remaining domains.

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 Click **Clear Selection**. Because this is a fully reflecting telescope, the ray tracing does not require any domains to be selected.

4 Locate the **Ray Release and Propagation** section. In the **Maximum number of secondary rays** text field, type `0`.

5 Locate the **Additional Variables** section. Select the **Compute optical path length** check box. The optical path length will be used to create the aberration diagrams.

6 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.

Ray Properties 1

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

1 In the **Physics** toolbar, click **Global** and choose **Release from Grid**.

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

3 From the **Grid type** list, choose **Hexapolar**.

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

dx1	x
dy1	y
dz1	z

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

vx1	x
vy1	y
vz1	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 Specify the $\mathbf{r}_c$ vector as

vx2	x
vy2	y
vz2	z

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

vx2	x
vy2	y
vz2	z

Next, define the boundary conditions. These will be specular reflection on the mirror surfaces and absorption everywhere else. Note that in order to simplify this simulation, the telescope structure is not selected to be part of the Geometrical Optics physics. Therefore, rays will pass through obstructions such as the secondary supports.

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`. A ray striking the secondary mirror will reflect only if it has encountered a mirror surface (that is, the Primary Mirror) previously.

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

The default mesh will be improved on the primary mirror surface. The extra points added around the clear aperture circumference also increase the mesh resolution near the edges of the mirror.

Size 1

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

4 From the **Selection** list, choose **Mirror surface (Primary Mirror)**.

5 Locate the **Element Size** section. From the **Predefined** list, choose **Extremely fine**.

The mesh on the telescope truss (and some other surfaces) should be slightly refined.

Size 2

1 In the **Model Builder** window, right-click **Mesh 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 **Telescope Truss Union**.

5 Select Domains 3, 6, and 8 only.

6 Locate the **Element Size** section. From the **Predefined** list, choose **Fine**.

Size 3

1 Right-click **Mesh 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 **Boundary**.

4 Select Boundaries 20, 121, 122, 140, and 143 only.

5 Locate the **Element Size** section. From the **Predefined** list, choose **Fine**.

Free Tetrahedral 1

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

2 In the **Settings** window for **Free Tetrahedral**, click **Build All**. Compare the resulting mesh to Figure 5.

STUDY 1

Now, perform the ray trace on the undeformed geometry.

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 2.10*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 - Undeformed

In the following steps, we first modify the default ray trajectories plot and then create a spot diagram.

1 In the **Settings** window for **3D Plot Group**, type `Ray Diagram - Undeformed` 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 - Undeformed** node.

Color Expression 1

1 In the **Model Builder** window, expand the **Results>Ray Diagram - Undeformed> 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 colors the ray according to their radial distance of the centroid of each release feature on the image plane.

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

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

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

Spot Diagram - Undeformed

Now, create a 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 - Undeformed` in the **Label** text field.

3 Locate the **Plot Settings** section.

4 Select the **x-axis label** check box. In the associated text field, type `X`.

5 Select the **y-axis label** check box. In the associated text field, type `Y`.

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

Spot Diagram 1

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

2 In the **Settings** window for **Spot Diagram**, click to expand the **Focal Plane Orientation** section.

3 From the **Transverse direction** list, choose **User defined**. This allows the orientation of the spot diagram to be controlled.

4 In the **x** text field, type `0`.

5 In the **y** text field, type `cos(theta)`.

6 In the **z** text field, type `sin(theta)`.

7 Locate the **Layout** section. From the **Origin location** list, choose **Average over area**.

8 From the **Layout** list, choose **Rectangular grid**.

9 In the **Number of columns** text field, type `1`.

10 Click to expand the **Annotations** section. Select the **Show spot coordinates** check box.

11 From the **Coordinate system** list, choose **Global**. Using the **Global** coordinate system allows the z coordinate to be displayed.

12 In the **Display precision** text field, type `6`.

13 Select the **Fit annotations to spot** check box.

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)`.

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

5 Click the **Zoom Extents** button in the **Graphics** toolbar. Compare this figure to Figure 7.

Aberration Diagram - Undeformed

A wavefront aberration diagram will be created in the following steps.

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

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

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

Optical Aberration 1

1 In the **Aberration Diagram - Undeformed** toolbar, click **More Plots** and choose **Optical Aberration**.

2 In the **Settings** window for **Optical Aberration**, locate the **Filters** section.

3 Select the **Filter by release feature index** check box. By default, the first (on-axis) release is selected.

4 Locate the **Focal Plane Orientation** section. Click **Create Reference Hemisphere Dataset**. This will create an **Intersection Point 3D** dataset, with a reference hemisphere that is centered on the point that minimizes the on-axis RMS spot radius.

5 Locate the **Coloring and Style** section. Click **Change Color Table**.

6 In the **Color Table** dialog box, select **Rainbow>Dipole** in the tree.

7 Click **OK**.

8 In the **Settings** window for **Optical Aberration**, locate the **Coloring and Style** section.

9 From the **Scale** list, choose **Linear symmetric**.

Optical Aberration 2

1 Right-click **Optical Aberration 1** and choose **Duplicate**.

2 In the **Settings** window for **Optical Aberration**, locate the **Filters** section.

3 In the **Filter by release feature index** text field, type 2. This is the off-axis ray release.

4 Locate the **Position** section. In the **x** text field, type 2.5.

5 Locate the **Zernike Polynomials** section. From the **Terms to include** list, choose **Select individual terms**.

6 Select the **Z(3,-1), vertical coma** check box.

7 Select the **Z(3,1), horizontal coma** check box. As expected for a telescope with a parabolic primary mirror, the dominate off-axis aberration is coma.

8 Click to expand the **Inherit Style** section. From the **Plot** list, choose **Optical Aberration 1**.

9 In the **Aberration Diagram - Undeformed** toolbar, click **Plot**.

10 Click the **Zoom Extents** button in the **Graphics** toolbar. Compare this figure to Figure 8.

ADD PHYSICS

In the following steps, we add a structural mechanics interface so that the deformation of the telescope structure under gravity can be considered.

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

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

3 In the tree, select **Structural Mechanics>Solid Mechanics (solid)**. Next, ensure that the solid mechanics physics will not be considered in the existing study.

4 Find the **Physics interfaces in study** subsection. In the table, clear the **Solve** check box for **Study 1**.

5 Click **Add to Component 1** in the window toolbar.

6 In the **Home** toolbar, click **Add Physics** to close the **Add Physics** window.

SOLID MECHANICS (SOLID)

Gravity 1

Right-click **Component 1 (comp1)>Solid Mechanics (solid)** and choose **Gravity**.

Fixed Constraint 1

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

2 Select Boundaries 1 and 236 only. These are the end surfaces of the telescope's altitude axis. This axis passes through the telescope's nominal center of mass.

ADD STUDY

A new study will be used to do the combined structural and ray tracing simulation.

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

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

3 Find the **Studies** subsection. In the **Select Study** tree, select **Preset Studies for Some Physics Interfaces>Stationary**.

4 Find the **Physics interfaces in study** subsection. In the table, clear the **Solve** check box for **Geometrical Optics (gop)**.

That is, ensure that the stationary study does not include the **Geometrical Optics** interface.

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

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

STUDY 2

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 2.10*f`.

6 Select the **Include geometric nonlinearity** check box. Geometric nonlinearities must be included otherwise the ray trace will not be performed on the deformed telescope geometry.

7 Locate the **Physics and Variables Selection** section. In the table, clear the **Solve for** check box for **Solid Mechanics (solid)**.

The ray tracing study should not include the **Solid Mechanics** interface.

Next, modify the ray tracing study to disable the image plane. This allows the **Intersection Point 3D** datasets used by the spot and aberration diagrams to be computed automatically.

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

9 In the tree, select **Component 1 (comp1)>Geometrical Optics (gop)>Image Plane**.

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

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

RESULTS

Ray Diagram - Deformed

In the following steps ray and spot diagrams are created which show the results of a ray trace through the deformed telescope geometry. An aberration diagram is also created.

1 In the **Settings** window for **3D Plot Group**, type `Ray Diagram - Deformed` 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 - Deformed** node.

Color Expression 1

1 In the **Model Builder** window, expand the **Results>Ray Diagram - Deformed>Ray Trajectories 1** node, then click **Color Expression 1**.

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

3 Clear the **Color legend** check box.

Surface 1

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

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

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

4 Locate the **Coloring and Style** section. Click **Change Color Table**.

5 In the **Color Table** dialog box, select **Thermal>HeatCamera** in the tree.

6 Click **OK**.

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

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

9 Locate the **Expression** section. In the **Unit** field, type `um`.

Deformation 1

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

Transparency 1

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

2 In the **Ray Diagram - Deformed** toolbar, click **Plot**.

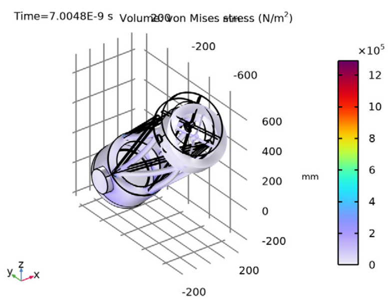
3 Click the **Zoom Extents** button in the **Graphics** toolbar. Compare the result to Figure 9.

Two additional plots are created by default. The plots below show the von Mises stress and the load within the telescope volume.

Stress (solid)

1 In the **Model Builder** window, under **Results** click **Stress (solid)**.

2 In the **Stress (solid)** toolbar, click **Plot**.



ADD PREDEFINED PLOT

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

2 Go to the **Add Predefined Plot** window.

3 In the tree, select **Study 2/Solution 2 (sol2)>Solid Mechanics>Applied Loads (solid)**.

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

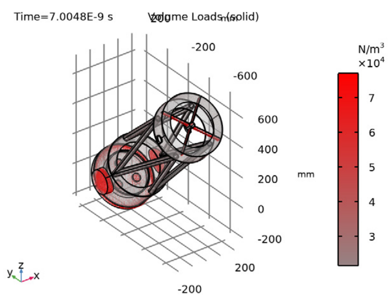
5 In the **Home** toolbar, click **Add Predefined Plot** to close the **Add Predefined Plot** window.

RESULTS

Volume Loads (solid)

1 In the **Model Builder** window, expand the **Applied Loads (solid)** node, then click **Volume Loads (solid)**.

2 In the **Volume Loads (solid)** toolbar, click **Plot**.



Spot Diagram - Undeformed

The existing undeformed spot diagram can be used to create a new spot diagram.

Spot Diagram - Deformed

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

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

3 Locate the **Data** section. From the **Dataset** list, choose **Ray 2**. This dataset was created when **Study 2** was run. It is necessary to use this dataset when using the **Automatic Focal Plane Calculation** below.

Spot Diagram 1

1 In the **Model Builder** window, expand the **Spot Diagram - Deformed** node, then click **Spot Diagram 1**.

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

3 Select the **Filter by release feature index** check box.

4 Locate the **Focal Plane Orientation** section. Click **Create Focal Plane Dataset**. This generates an **Intersection Point 3D** dataset that minimizes the RMS radius of the first ray release. The resulting point and normal values define the focal plane.

5 Locate the **Filters** section. Clear the **Filter by release feature index** check box. The intersection of all ray releases with the focal plane will now be shown.

6 In the **Spot Diagram - Deformed** toolbar, click **Plot**.

7 Click the **Zoom Extents** button in the **Graphics** toolbar. Compare this figure to Figure 10.

Aberration Diagram - Deformed

Finally, create a wavefront aberration diagram for the deformed ray trace.

1 In the **Home** toolbar, click **Add Plot Group** and choose **2D Plot Group**.
2 In the **Settings** window for **2D Plot Group**, type `Aberration Diagram - Deformed` in the **Label** text field.
3 Locate the **Color Legend** section. Select the **Show units** check box.
4 Locate the **Data** section. From the **Dataset** list, choose **Ray 2**.

Optical Aberration 1

1 In the **Aberration Diagram - Deformed** toolbar, click **More Plots** and choose **Optical Aberration**.
2 In the **Settings** window for **Optical Aberration**, locate the **Filters** section.
3 Select the **Filter by release feature index** check box.
4 Locate the **Focal Plane Orientation** section. Click **Create Reference Hemisphere Dataset**. Similar to the spot diagram, this generates an **Intersection Point 3D** dataset that is centered on the plane that minimizes the RMS radius of the first ray release. The reference hemisphere center and axis direction should be identical to the point and normal values in **Intersection Point 3D 1** which also define the focal plane.
5 Locate the **Zernike Polynomials** section. From the **Terms to include** list, choose **Select individual terms**.
6 Select the **Z(2,0), defocus** check box.
7 Select the **Z(3,-1), vertical coma** check box.
8 Select the **Z(3,1), horizontal coma** check box. In this diagram, the defocus term now dominates.
9 Locate the **Coloring and Style** section. Click **Change Color Table**.
10 In the **Color Table** dialog box, select **Rainbow>Dipole** in the tree.
11 Click **OK**.
12 In the **Settings** window for **Optical Aberration**, locate the **Coloring and Style** section.
13 From the **Scale** list, choose **Linear symmetric**.

Optical Aberration 2

1 Right-click **Optical Aberration 1** and choose **Duplicate**.
2 In the **Settings** window for **Optical Aberration**, locate the **Filters** section.
3 In the **Filter by release feature index** text field, type `2`. This is the off-axis ray release.
4 Locate the **Position** section. In the **x** text field, type `2.5`.

5 Locate the **Inherit Style** section. From the **Plot** list, choose **Optical Aberration 1**.

6 In the **Aberration Diagram - Deformed** toolbar, click **Plot**.

7 Click the **Zoom Extents** button in the **Graphics** toolbar. Compare this figure to Figure 11.

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**.

NEWTONIAN TELESCOPE STRUCTURAL ANALYSIS 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 Structural Analysis Geometry Sequence` in the **Label** text field.

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

GLOBAL DEFINITIONS

Load the model parameters 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_structural_analysis_geom_sequence_parameters.txt`.

NEWTONIAN TELESCOPE STRUCTURAL ANALYSIS GEOMETRY SEQUENCE

Center of Mass

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

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

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

4 Find the **Rotation** subsection. From the **Axis type** list, choose **xw-axis**.

5 In the **Rotation angle** text field, type `theta`.

Insert the Newtonian Telescope geometry sequence from file. For detailed instructions on creating this geometry see the appendix.

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

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

Primary Mirror (pi1)

1 In the **Model Builder** window, click **Primary Mirror (pi1)**.

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
n_extra_a	50	50	Number of extra azimuthal points

4 Locate the **Position and Orientation of Output** section. Find the **Coordinate system to match** subsection. From the **Work plane** list, choose **Center of Mass (wp1)**.

5 Find the **Displacement** subsection. In the **xw** text field, type `-cx`.

6 In the **yw** text field, type `-cy`.

7 In the **zw** text field, type `-cz`. These are the approximate coordinates of the center of mass defined in the **Parameters** node.

8 Find the **Rotation** subsection. In the **Rotation angle** text field, type `180`. Rotate the telescope by 180 degrees about the z-axis (optical axis).

9 Click to expand the **Point Selections** section. In the table, select the **Keep** check box for **Mirror vertex**.

10 Click **Build All Objects**.

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

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

GLOBAL DEFINITIONS

In the following steps a simple telescope tube part is created.

TELESCOPE TUBE

1 In the **Model Builder** window, right-click **Global Definitions** and choose **Geometry Parts>3D Part**.

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

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

Name	Default expression	Value	Description
`d0`	`350.0[mm]`	0.35 m	`Tube diameter`
`d1`	`300.0[mm]`	0.3 m	`Upper ring inner diameter`
`d2`	`300.0[mm]`	0.3 m	`Lower ring inner diameter`
`T1`	`10.0[mm]`	0.01 m	`Upper ring thickness`
`T2`	`10.0[mm]`	0.01 m	`Lower ring thickness`
`Tw`	`3.0[mm]`	0.003 m	`Wall thickness`
`L`	`200.0[mm]`	0.2 m	`Tube length`

Upper Ring Base

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

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

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

Name	Expression	Value	Description
d0	`d0`	0.35 m	Diameter, outer
d1	`d1`	0.3 m	Diameter, inner

Upper Ring

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

2 In the **Settings** window for **Extrude**, type `Upper Ring` 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)
`T1`

Lower Ring Base

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

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

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

Name	Expression	Value	Description
d0	d0	0.35 m	Diameter, outer
d1	d2	0.3 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 **Upper Ring Base (pi1)**.

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

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

Lower Ring

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

2 In the **Settings** window for **Extrude**, type `Lower 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)
T2

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

Wall Base

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

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

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

Name	Expression	Value	Description
d0	d0	0.35 m	Diameter, outer
d1	d0-2*Tw	0.344 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 **Upper Ring Base (pi1)**.

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

6 Find the **Displacement** subsection. In the **zw** text field, type `T1`.

Wall

1 In the **Geometry** toolbar, click **Extrude**.
2 In the **Settings** window for **Extrude**, type `Wall` in the **Label** text field.
3 On the object **pi3**, select Boundary 1 only.
4 Locate the **Distances** section. From the **Specify** list, choose **Vertices to extrude to**.
5 On the object **ext2**, select Point 1 only.
6 In the **Geometry** toolbar, click **Build All**.

NEWTONIAN TELESCOPE STRUCTURAL ANALYSIS GEOMETRY SEQUENCE

Now, use this part to create the telescope structure.

Lower Mount

1 In the **Geometry** toolbar, click **Part Instance** and choose **Telescope Tube**.
2 In the **Settings** window for **Part Instance**, type `Lower Mount` in the **Label** text field.
3 Locate the **Input Parameters** section. In the table, enter the following settings:

Name	Expression	Value	Description
d0	`d0_tube`	385 mm	Tube diameter
d1	`d1_tube`	275 mm	Upper ring inner diameter
d2	0	0 m	Lower ring inner diameter
T1	`5[mm]`	5 mm	Upper ring thickness
T2	`30[mm]`	30 mm	Lower ring thickness
Tw	`5[mm]`	5 mm	Wall thickness
L	`225[mm]`	225 mm	Tube length

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 rear (wp2)**.
6 Find the **Displacement** subsection. In the **zw** text field, type `-185.0[mm]`.

Primary Mirror Support 1

1 In the **Geometry** toolbar, click **Cylinder**. This cylinder will be used to construct a simple mirror support.
2 In the **Settings** window for **Cylinder**, type `Primary Mirror Support 1` in the **Label** text field.

3 Locate the **Coordinate System** section. From the **Take work plane from** list, choose **Primary Mirror (pi1)**.

4 From the **Work plane** list, choose **Mirror rear (wp2)**.

5 Locate the **Size and Shape** section. In the **Radius** text field, type `25`.

6 In the **Height** text field, type `10`.

7 Click **Build Selected**.

8 Locate the **Position** section. In the **yw** text field, type `75`.

Primary Mirror Support 1-3

1 In the **Geometry** toolbar, click **Transforms** and choose **Rotate**.

2 In the **Settings** window for **Rotate**, type `Primary Mirror Support 1-3` in the **Label** text field.

3 Select the object **cyl1** only.

4 Locate the **Rotation** section. In the **Angle** text field, type `0 120 240`.

5 Locate the **Coordinate System** section. From the **Take work plane from** list, choose **Primary Mirror (pi1)**.

Altitude Axis

1 In the **Geometry** toolbar, click **Cylinder**. This cylinder will be used to create the telescope altitude axis.

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

3 Locate the **Size and Shape** section. In the **Radius** text field, type `75`.

4 In the **Height** text field, type `450`.

5 Locate the **Position** section. In the **x** text field, type `-225`.

6 In the **z** text field, type `-cz`.

7 Locate the **Axis** section. From the **Axis type** list, choose **x-axis**.

8 Locate the **Coordinate System** section. From the **Take work plane from** list, choose **Primary Mirror (pi1)**.

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

Altitude Axis Partition Domains

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

2 In the **Settings** window for **Partition Domains**, type `Altitude Axis Partition Domains` in the **Label** text field.

3 On the object **cyl2**, select Domain 1 only.

4 Locate the **Partition Domains** section. From the **Partition with** list, choose **Faces**.

5 On the object **pi5(3)**, select Boundaries 1, 2, 7, and 10 only.

Altitude Axis Delete Entities

1 In the **Model Builder** window, right-click **Newtonian Telescope Structural Analysis Geometry Sequence** and choose **Delete Entities**.

2 In the **Settings** window for **Delete Entities**, type `Altitude Axis Delete Entities` in the **Label** text field.

3 Locate the **Entities or Objects to Delete** section. From the **Geometric entity level** list, choose **Domain**.

4 On the object **pard1**, select Domain 2 only.

Upper Mount

1 In the **Geometry** toolbar, click **Part Instance** and choose **Telescope Tube**.

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

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

Name	Expression	Value	Description
d0	`d0_tube`	385 mm	Tube diameter
d1	`d1_tube`	275 mm	Upper ring inner diameter
d2	`d1_tube`	275 mm	Lower ring inner diameter
T1	`5[mm]`	5 mm	Upper ring thickness
T2	`2[mm]`	2 mm	Lower ring thickness
Tw	`2[mm]`	2 mm	Wall thickness
L	`115.0[mm]`	115 mm	Tube length

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 **zw** text field, type `-40[mm]`.

Update the telescope secondary obstruction parameters so that the part can be used to create the secondary mirror mount.

Secondary Obstruction (pi3)

1 In the **Model Builder** window, click **Secondary Obstruction (pi3)**.

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	`35.0[mm]`	35 mm	Diameter, outer
d1	`30.0[mm]`	30 mm	Diameter, inner

4 Locate the **Position and Orientation of Output** section. Find the **Displacement** subsection. In the **xw** text field, type `0`.

5 In the **zw** text field, type `75.0[mm]`.

Secondary Mirror Mount

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

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

3 Locate the **General** section. From the **Extrude from** list, choose **Faces**.

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

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

6 On the object **pi2**, select Point 2 only.

Secondary Mirror Mount Partition Domains

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

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

3 On the object **ext1**, select Domain 1 only.

4 Locate the **Partition Domains** section. From the **Partition with** list, choose **Faces**.

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

Secondary Mirror Mount Delete Entities

1 In the **Model Builder** window, right-click **Newtonian Telescope Structural Analysis Geometry Sequence** and choose **Delete Entities**.

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

3 Locate the **Entities or Objects to Delete** section. From the **Geometric entity level** list, choose **Domain**.

4 On the object **pard2**, select Domain 1 only.

Secondary Support 1

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

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

3 Locate the **Size and Shape** section. In the **Width** text field, type `d0_tube`.

4 In the **Depth** text field, type `2.5[mm]`.

5 In the **Height** text field, type `30[mm]`.

6 Locate the **Position** section. From the **Base** list, choose **Center**.

7 In the **z** text field, type `58[mm]`.

8 Locate the **Rotation Angle** section. In the **Rotation** text field, type `45`.

9 Locate the **Coordinate System** section. From the **Take work plane from** list, choose **Secondary Mirror (pi2)**.

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

Secondary Support Partition Domains

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

2 In the **Settings** window for **Partition Domains**, type `Secondary Support Partition Domains` in the **Label** text field.

3 On the object **blk1**, select Domain 1 only.

4 Locate the **Partition Domains** section. From the **Partition with** list, choose **Faces**.

5 On the object **del2**, select Boundaries 1 and 10 only.

6 On the object **pi6(3)**, select Boundaries 5 and 9 only.

Secondary Support Delete Entities

1 Right-click **Newtonian Telescope Structural Analysis Geometry Sequence** and choose **Delete Entities**.

2 In the **Settings** window for **Delete Entities**, type `Secondary Support Delete Entities` in the **Label** text field.

3 Locate the **Entities or Objects to Delete** section. From the **Geometric entity level** list, choose **Domain**.

4 On the object **pard3**, select Domains 1, 3, and 5 only.

Secondary Support 1-2

1 In the **Geometry** toolbar, click **Transforms** and choose **Rotate**.

2 In the **Settings** window for **Rotate**, type `Secondary Support 1-2` in the **Label** text field.

3 Select the object **del3** only.

4 Locate the **Rotation** section. In the **Angle** text field, type `0 90`.

5 Locate the **Coordinate System** section. From the **Take work plane from** list, choose **Primary Mirror (pi1)**.

Image Plane Projection

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

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

3 Locate the **Size and Shape** section. In the **Radius** text field, type `22.5[mm]`.

4 In the **Height** text field, type `50[mm]`.

5 Locate the **Coordinate System** section. From the **Take work plane from** list, choose **Image Plane (pi4)**.

Image Plane Difference

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

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

3 Select the object **pi6(3)** only.

4 Locate the **Difference** section. Click to select the **Activate Selection** toggle button for **Objects to subtract**.

5 Select the object **cyl3** only.

Truss Base

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

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

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

Name	Expression	Value	Description
d0	35[mm]	35 mm	Diameter, outer
d1	25[mm]	25 mm	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 **Lower Mount (pi5)**.

5 Find the **Displacement** subsection. In the **xw** text field, type `R_truss`.

Truss 1

1 In the **Geometry** toolbar, click **Extrude**.
2 In the **Settings** window for **Extrude**, type `Truss 1` in the **Label** text field.
3 Locate the **General** section. From the **Extrude from** list, choose **Faces**.
4 On the object **pi7**, select Boundary 1 only.
5 Locate the **Distances** section. From the **Specify** list, choose **Vertices to extrude to**.
6 On the object **pi6(1)**, select Point 15 only.
7 Click to expand the **Displacements** section. In the table, enter the following settings:

Displacements xw (mm)	Displacements yw (mm)
dx_truss	dy_truss

Work Plane 2 (wp2)

1 In the **Geometry** toolbar, click **Work Plane**.
2 In the **Settings** window for **Work Plane**, locate the **Plane Definition** section.
3 From the **Plane type** list, choose **Transformed**.
4 From the **Take work plane from** list, choose **Primary Mirror (pi1)**.
5 Find the **Rotation** subsection. From the **Axis type** list, choose **xw-axis**.
6 In the **Rotation angle** text field, type `90`.

Work Plane 3 (wp3)

1 In the **Geometry** toolbar, click **Work Plane**.
2 In the **Settings** window for **Work Plane**, locate the **Plane Definition** section.
3 From the **Plane type** list, choose **Transformed**.
4 From the **Work plane to transform** list, choose **Work Plane 2 (wp2)**.
5 Find the **Rotation** subsection. From the **Axis type** list, choose **yw-axis**.
6 In the **Rotation angle** text field, type `-45`.

Truss Partition Domains 1

1 In the **Geometry** toolbar, click **Booleans and Partitions** and choose **Partition Domains**.
2 In the **Settings** window for **Partition Domains**, type `Truss Partition Domains 1` in the **Label** text field.
3 On the object **ext2**, select Domain 1 only.

4 Locate the **Partition Domains** section. From the **Work plane** list, choose **Work Plane 2 (wp2)**.

Truss Partition Domains 2

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

2 In the **Settings** window for **Partition Domains**, type `Truss Partition Domains 2` in the **Label** text field.

3 On the object **pard4**, select Domain 2 only.

Truss Delete Entities

1 Right-click **Newtonian Telescope Structural Analysis Geometry Sequence** and choose **Delete Entities**.

2 In the **Settings** window for **Delete Entities**, type `Truss Delete Entities` in the **Label** text field.

3 Locate the **Entities or Objects to Delete** section. From the **Geometric entity level** list, choose **Domain**.

4 On the object **pard5**, select Domains 1 and 3 only.

Truss 2

1 In the **Geometry** toolbar, click **Transforms** and choose **Mirror**.

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

3 Locate the **Input** section. Select the **Keep input objects** check box.

4 Select the object **del4** only.

5 Locate the **Normal Vector to Plane of Reflection** section. In the **y** text field, type `1`.

6 In the **z** text field, type `0`.

7 Locate the **Coordinate System** section. From the **Take work plane from** list, choose **Primary Mirror (pi1)**.

Telescope Truss 1-8

1 In the **Geometry** toolbar, click **Transforms** and choose **Rotate**.

2 In the **Settings** window for **Rotate**, type `Telescope Truss 1-8` in the **Label** text field.

3 Select the objects **del4** and **mir1** only.

4 Locate the **Rotation** section. In the **Angle** text field, type `0 90 180 270`.

5 Locate the **Coordinate System** section. From the **Take work plane from** list, choose **Primary Mirror (pi1)**.

Telescope Truss Union

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

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

3 Select the objects **rot3(1)**, **rot3(2)**, **rot3(3)**, **rot3(4)**, **rot3(5)**, **rot3(6)**, **rot3(7)**, and **rot3(8)** only.

4 Locate the **Union** section. Clear the **Keep interior boundaries** check box.

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

6 From the **Show in physics** list, choose **All levels**.

7 In the **Geometry** toolbar, click **Build All**. Compare the resulting geometry to Figure 3.