Created in COMSOL Multiphysics 6.2

Keck Telescope

Introduction

The Keck Telescope is a 10 meter diameter telescope with a Ritchey–Chrétien optical design. It is noted for being one of the first large optical telescopes to utilize a light weight segmented primary mirror. This tutorial demonstrates how to use parts from the Ray Optics Module Part Libraries to construct a model of the Keck Telescope segmented primary mirror. An overview of the Keck Telescope is shown in Figure 1.

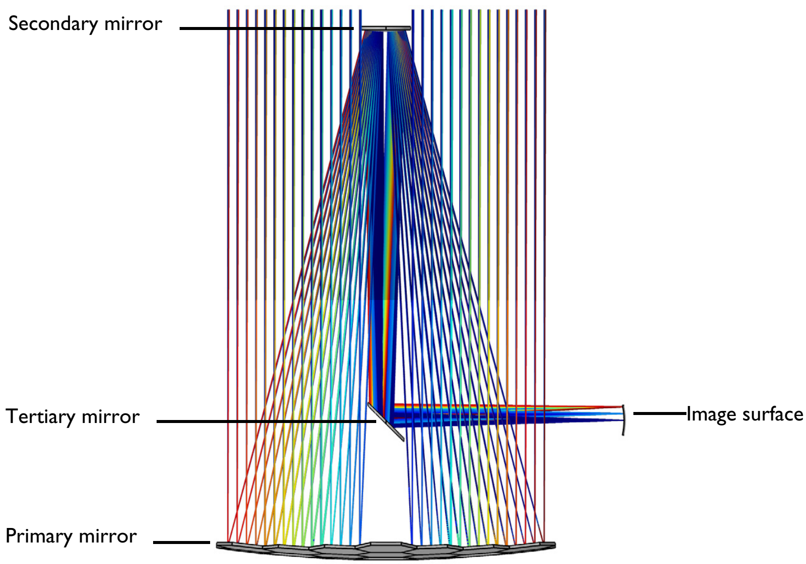

Figure 1: Overview of the Keck Telescope.

Model Definition

Details of the Keck Telescope can be found in Ref. 1 and Ref. 2. A summary of the parameters used in this tutorial is given in Table 1.

Details of the primary mirror geometry described below. Instances of the *Conic Mirror On Axis 3D* part and the *Elliptical Planar Mirror 3D* part are used to create the secondary and tertiary mirrors respectively. The curved image surface is created using a **Parametric Surface** primitive. The full Keck Telescope geometry sequence is shown in Figure 4.

TABLE 1: KECK TELESCOPE PARAMETERS.

Name	Value	Details
λ_{vac}	$550\ \text{nm}$	Vacuum wavelength
$\theta_{x,i}$	$0', 2.5', 5.0'$	Nominal x field angle, field i = 1,2,3
$\theta_{y,i}$	$0', 0', 0'$	Nominal y field angle, field i = 1,2,3
N_{ring}	20	Number of hexapolar rings
P_{nom}	$10.949\ \text{m}$	Entrance pupil diameter
Primary mirror:		
R_{prim}	$-35.00000\ \text{m}$	Primary mirror radius of curvature
k_{prim}	-1.0037963	Primary mirror conic constant
$d_{0,\text{prim}}$	$1.79\ \text{m}$	Primary mirror segment diameter
$T_{\text{c,prim}}$	$75.0\ \text{mm}$	Primary mirror segment center thickness
Z_{prim}	$0\ \text{m}$	Primary mirror position
Secondary mirror:		
R_{sec}	$4.849338\ \text{m}$	Secondary mirror radius of curvature
k_{sec}	-1.6430812	Secondary mirror conic constant
$d_{0,\text{sec}}$	$1.429\ \text{m}$	Secondary mirror diameter
$T_{\text{c,sec}}$	$150.0\ \text{mm}$	Secondary mirror center thickness (nominal)
Z_{sec}	$-15.35821\ \text{m}$	Secondary mirror position (relative to primary vertex)
Tertiary mirror:		
$d_{0,\text{ter}}$	$0.873\ \text{m}$	Tertiary mirror minor axis diameter
θ_{ter}	$45.0°$	Tertiary mirror fold angle
Z_{ter}	$-4.0\ \text{m}$	Tertiary mirror position (relative to primary vertex)
Image surface:		
d_{img}	$0.873\ \text{m}$	Image surface diameter (for $20'$ field of view)
C_{img}	$0.471\ \text{m}^{-1}$	Image surface curvature
Z_{img}	$-7.0\ \text{m}$	Image surface position (relative to tertiary exit plane)

PRIMARY MIRROR GEOMETRY

The telescope primary mirror geometry is constructed using instances of the *Conic Polygonal Mirror Off Axis 3D* part from the Ray Optics Part Library. It consists of 36 hexagonal segments with a common parent surface. These mirrors are arranged in a "four-ring" geometry (that is, with a missing central segment). There are 6 unique mirrors, each of which is replicated 6 times in a 6-fold rotational pattern. Details of the primary mirror segments are given in Table 2. The geometry of the first 6 mirrors can be seen in Figure 2 and in Figure 3 the complete primary mirror geometry can be seen.

TABLE 2: PRIMARY MIRROR SEGMENT PARAMETERS.

Segment	**Radial coordinate (r)**	**Polar Angle (σ)**	**Rotation angle (ϕ)**
1	1.55885 m	0°	30°
2	2.70000 m	30°	0°
3	3.11769 m	0°	30°
4	4.12432 m	$\mathrm{atan}(\sqrt{3}/5)$	$\mathrm{atan}(\sqrt{3}/5)$ - 30°
5	4.12432 m	$-\mathrm{atan}(\sqrt{3}/5)$	30° - $\mathrm{atan}(\sqrt{3}/5)$
6	4.67654 m	0°	30°

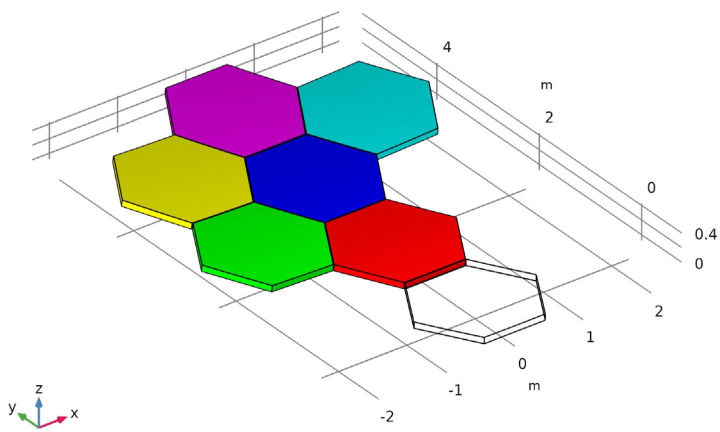

Figure 2: The 6 common off axis mirror segments. Each of the unique mirrors has been assigned a different color. The central (on axis) mirror is not used.

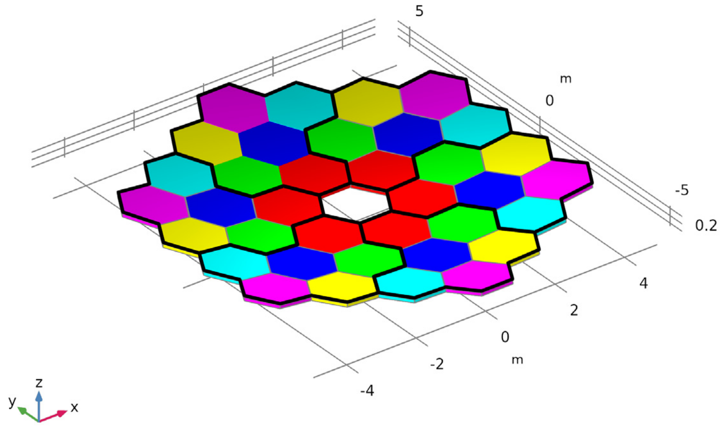

Figure 3: The primary mirror. The outline of the set of 6 common mirrors is shown in black.

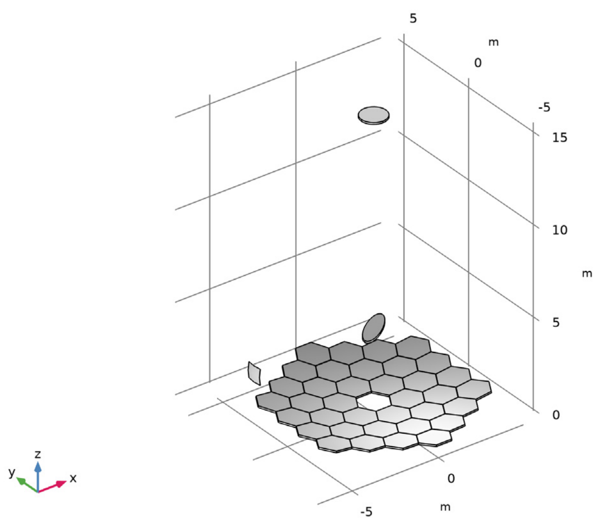

Figure 4: The complete Keck Telescope geometry sequence.

Results and Discussion

A ray trace has been performed at a single wavelength (550 nm) at three field angles (0, 2.5, and 5 arcminutes). Figure 5 shows the resulting ray trajectories; the **Color Expression** represents the ray positions on the image surface.

In Figure 6 the intersection of the rays with the image surface is shown. This spot diagram shows each of the three field angles, where the **Color Expression** is the initial radial location at the entrance pupil.

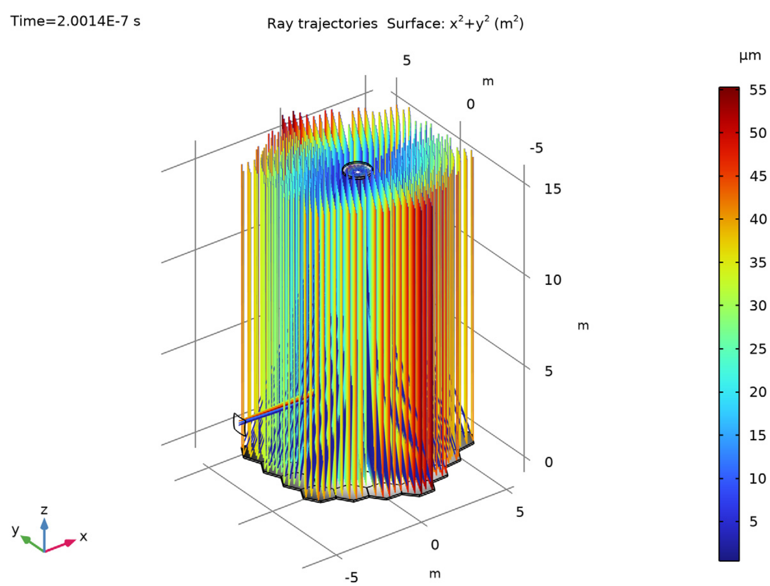

Figure 5: Ray diagram of the Keck Telescope colored by radial distance from the centroid.

References

1. J.E. Nelson and T.S. Mast, *Optical Design and Instrumentation of the Keck Observatory*, Proc. SPIE 0628, 1986.

2. J.E. Nelson, T.S. Mast, and S.M. Faber (editors), *The Design of the Keck Observatory and Telescope*, Keck Observatory Report No. 90, 1985.

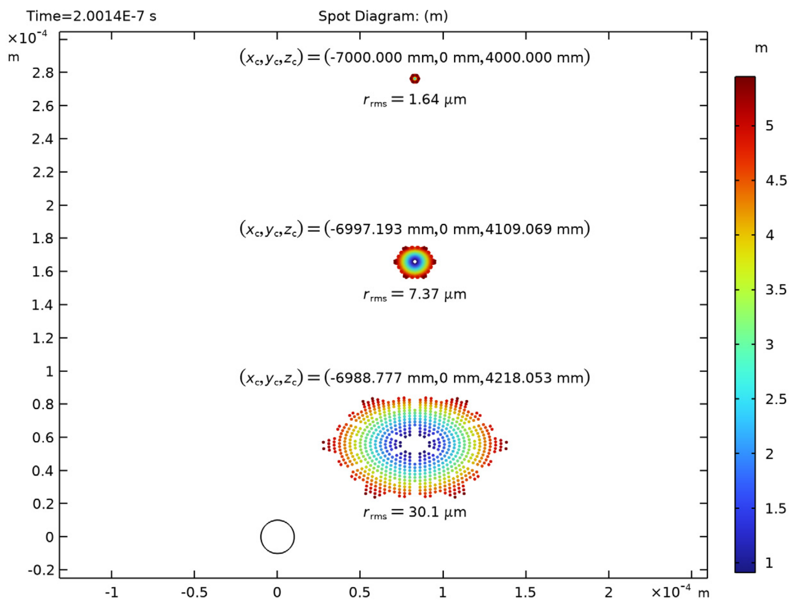

Figure 6: Spot diagram of the Keck Telescope colored by radial distance from the center of the entrance pupil.

Application Library path: `Ray_Optics_Module/Lenses_Cameras_and_Telescopes/keck_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

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 `keck_telescope_parameters.txt`. This text file contains the prescription for the telescope (including the segmented mirror geometry) as well as study parameters.

GEOMETRY 1

The Keck telescope can be constructing using several built-in parts from the Ray Optics Part Library. The Conic Polygonal Mirror Off Axis 3D part is used to create the hexagonal mirror segments, the Conic Mirror On Axis 3D part, is used for the secondary mirror, and the Elliptical Planar Mirror 3D part is used to define the tertiary mirror.

PART LIBRARIES

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

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

3 In the **Part Libraries** window, select **Ray Optics Module>3D>Mirrors> conic_polygonal_mirror_off_axis_3d** in the tree.

4 Click **Add to Geometry**.

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

6 Click **OK**.

GEOMETRY 1

Primary Mirror 1

To create the segmented primary mirror, begin by defining the 6 common off axis segments.

1 In the **Model Builder** window, under **Component 1 (comp1)>Geometry 1** click **Conic Polygonal Mirror Off Axis 3D 1 (pi1)**.

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

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

Name	Expression	Value	Description
R	`R_prim`	-35 m	Radius of curvature (+convex/-concave)
k	`k_prim`	-1.0038	Conic constant
Tc	`Tc_prim`	0.075 m	Center thickness
d0	`d0_prim`	1.79 m	Mirror full diameter
d_clear	`0`	0 m	Clear aperture diameter
dx	`r1`	1.5589 m	Mirror off axis distance
nix	`0.0`	0	Local optical axis, x-component
niy	`0.0`	0	Local optical axis, y-component
niz	`-1.0`	-1	Local optical axis, z-component
nxx	`0.0`	0	Mirror off axis direction, x-component
nxy	`1.0`	1	Mirror off axis direction, y-component
nxz	`0.0`	0	Mirror off axis direction, z-component
n_side	`nside`	6	Number of polygon sides
phi_rot	`phi1`	30 °	Polygon rotation angle
mtype	`mtype`	1	Mirror type (standard [0] or standalone [1])
show_vertex	`0`	0	Show mirror vertex (off [0] or on [1])
n_extra_r	`0`	0	Number of extra radial points
n_extra_a	`0`	0	Number of extra azimuthal points

4 Locate the **Position and Orientation of Output** section. Find the **Rotation** subsection. In the **Rotation angle** text field, type `rho1`.

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

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

7 Click **OK**. This selection, and those that follow will be used later in the model setup.

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

9 Click **New Cumulative Selection**.

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

11 Click **OK**.

Now, apply each of these selections.

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

13 In the table, enter the following settings:

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

In the steps that follow, duplicate the first mirror and change only those settings unique to the 5 remaining common segments.

Primary Mirror 2

1 Right-click **Primary Mirror 1** and choose **Duplicate**.

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

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

Name	Expression	Value	Description
dx	`r2`	2.7 m	Mirror off axis distance
phi_rot	`phi2`	0	Polygon rotation angle

4 Locate the **Position and Orientation of Output** section. Find the **Rotation** subsection. In the **Rotation angle** text field, type `rho2`.

Primary Mirror 3

1 Right-click **Primary Mirror 2** and choose **Duplicate**.

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

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

Name	Expression	Value	Description
dx	`r3`	3.1177 m	Mirror off axis distance
phi_rot	`phi3`	30 °	Polygon rotation angle

4 Locate the **Position and Orientation of Output** section. Find the **Rotation** subsection. In the **Rotation angle** text field, type `rho3`.

Primary Mirror 4

1 Right-click **Primary Mirror 3** and choose **Duplicate**.

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

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

Name	Expression	Value	Description
dx	r4	4.1243 m	Mirror off axis distance
phi_rot	phi4	-10.893 °	Polygon rotation angle

4 Locate the **Position and Orientation of Output** section. Find the **Rotation** subsection. In the **Rotation angle** text field, type `rho4`.

Primary Mirror 5

1 Right-click **Primary Mirror 4** and choose **Duplicate**.

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

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

Name	Expression	Value	Description
dx	r5	4.1243 m	Mirror off axis distance
phi_rot	phi5	10.893 °	Polygon rotation angle

4 Locate the **Position and Orientation of Output** section. Find the **Rotation** subsection. In the **Rotation angle** text field, type `rho5`.

Primary Mirror 6

1 Right-click **Primary Mirror 5** and choose **Duplicate**.

2 In the **Settings** window for **Part Instance**, type `Primary Mirror 6` in the **Label** text field.

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

Name	Expression	Value	Description
dx	r6	4.6765 m	Mirror off axis distance
phi_rot	phi6	30 °	Polygon rotation angle

4 Locate the **Position and Orientation of Output** section. Find the **Rotation** subsection. In the **Rotation angle** text field, type `rho6`.

Rotate 1 (rot1)

Now, create the segmented primary mirror by creating 6 copies of the 6 common segments. It would also be possible to create 36 unique mirror segments.

1 In the **Geometry** toolbar, click **Transforms** and choose **Rotate**.
2 Click in the **Graphics** window and then press Ctrl+A to select all objects.
3 In the **Settings** window for **Rotate**, locate the **Rotation** section.
4 In the **Angle** text field, type `range(0,60,300)`.

Next, add the secondary and tertiary mirrors, and define the image surface.

PART LIBRARIES

1 In the **Geometry** toolbar, click **Part Libraries**.
2 In the **Model Builder** window, click **Geometry 1**.
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**.

GEOMETRY 1

Secondary Mirror

1 In the **Model Builder** window, under **Component 1 (comp1)>Geometry 1** click **Conic Mirror On Axis 3D 1 (pi7)**.
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
R	`R_sec`	4.8493 m	Radius of curvature (+convex/-concave)
k	`k_sec`	-1.6431	Conic constant
Tc	`Tc_sec`	0.15 m	Center thickness
d0	`d0_sec`	1.429 m	Mirror full diameter
d1	0	0 m	Mirror surface diameter
d_clear	0	0 m	Clear aperture diameter
d_hole	0	0 m	Center hole diameter
nix	`0.0`	0	Local optical axis, x-component
niy	`0.0`	0	Local optical axis, y-component
niz	`-1.0`	-1	Local optical axis, z-component
n_extra_r	0	0	Number of extra radial points
n_extra_a	30	30	Number of extra azimuthal points

The extra azimuthal points are used to reduce the effects of discretization around the edge of the secondary mirror.

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 1 (pi1)**.

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

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

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

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

PART LIBRARIES

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

2 In the **Model Builder** window, click **Geometry 1**.

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**.

GEOMETRY 1

Tertiary Mirror

1 In the **Model Builder** window, under **Component 1 (comp1)>Geometry 1** click **Elliptical Planar Mirror 3D 1 (pi8)**.

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

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

Name	Expression	Value	Description
Tc	`75.0[mm]`	0.075 m	Mirror thickness
d0	`d0_ter`	1.04 m	Minor axis diameter
theta	`45.0[deg]`	45 °	Mirror angle
dx	`0`	0 mm	Offset from optical axis
nix	`0.0`	0	Local optical axis, x-component
niy	`0.0`	0	Local optical axis, y-component
niz	`1.0`	1	Local optical axis, z-component
nxx	`1.0`	1	Fold angle direction, x-component
nxy	`0.0`	0	Fold angle direction, y-component
nxz	`0.0`	0	Fold angle direction, z-component

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

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

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

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

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

Image Surface

Finally, a parametric surface is used to define the image surface.

1 In the **Geometry** toolbar, click **More Primitives** and choose **Parametric Surface**.

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

3 Locate the **Parameters** section. Find the **First parameter** subsection. In the **Minimum** text field, type `-d_img/2`.

4 In the **Maximum** text field, type `d_img/2`.

5 Find the **Second parameter** subsection. In the **Minimum** text field, type `-d_img/2`.

6 In the **Maximum** text field, type `d_img/2`.

7 Locate the **Expressions** section. In the **x** text field, type `s1`.

8 In the **y** text field, type `s2`.

9 In the **z** text field, type `C_img*(s1^2 + s2^2)/(1 + sqrt(1 - C_img^2*(s1^2 + s2^2)))*1[m]`. This is the equation of a sphere having a curvature `C_img`. This is the curvature defined in the **Parameters** node.

10 Locate the **Coordinate System** section. From the **Take work plane from** list, choose **Tertiary Mirror (pi8)**.

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

12 Locate the **Position** section. In the **zw** text field, type `Z_img`.

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

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

15 Click the **Go to Default View** button in the **Graphics** toolbar.

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

17 Click the **Zoom Extents** button in the **Graphics** toolbar. Compare the resulting geometry to Figure 4.

GEOMETRICAL OPTICS (GOP)

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

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

3 Click **Clear Selection**. Only mirrors are being used in this model. Clearing the domain selection allows the model to be run without adding materials.

4 Locate the **Ray Release and Propagation** section. In the **Maximum number of secondary rays** text field, type `0`. Stray light is not being traced, so reflected rays will not be produced at the lens surfaces.

5 Locate the **Additional Variables** section. Select the **Count reflections** check box. A count of the number of reflections is used as a filter for rendering rays in the ray diagram.

Mirrors

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

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

3 Locate the **Boundary Selection** section. From the **Selection** list, choose **Mirrors**. This is the cumulative selection defined above.

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**. Rays that hit any of these surfaces will be removed.

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 Surface**. The default wall condition `Freeze` will be applied to rays that reach the image surface.

Next, create release features for each of the field angles defined in the **Parameters** node.

Release from Grid 1

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

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

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

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

-dx1	x
-dy1	y
dz	z

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

0	x
0	y
1	z

6 In the R_c text field, type `R_nom`.

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

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

vx1	x
vy1	y
-vz	z

Release from Grid 2

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

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

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

-dx2	x
-dy2	y

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

vx2	x
vy2	y

Release from Grid 3

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

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

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

-dx3	x
-dy3	y

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

vx3	x
vy3	y

Ray Termination 1

1 In the **Physics** toolbar, click **Global** and choose **Ray Termination**.

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

3 From the **Spatial extents of ray propagation** list, choose **Bounding box, from geometry**. This will remove those rays that are not reflected by the segmented mirror.

MESH 1

Edit the default mesh to use finer boundary elements on the curved image surface.

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

2 In the **Settings** window for **Mesh**, locate the **Sequence Type** section.

3 From the list, choose **User-controlled mesh**.

Size 1

1 In the **Mesh** toolbar, click **Sizing** and choose **Size**.

2 Drag and drop below **Size**.

3 In the **Settings** window for **Size**, locate the **Geometric Entity Selection** section.

4 From the **Geometric entity level** list, choose **Boundary**.

5 Select Boundary 1 only.

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

7 Click **Build All**. The default Physics-controlled mesh is sufficient for this simulation.

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 In the **Lengths** text field, type `0 60`. This path length is sufficient to ensure that all rays reach the image plane.

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

Now, create a ray diagram.

RESULTS

Ray Diagram

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 is the radial coordinate relative to the centroid at the image plane for each release feature.

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

Surface 1

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

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

3 In the **Expression** text field, type `x^2+y^2`.

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

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

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

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 **Mirrors**.

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

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

Spot Diagram

Next, 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` 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**. Make some adjustments to the default **Spot Diagram** in order to show the spot size and coordinates on the curved image surface.

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**.

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

5 In the **y** text field, type `1`.

6 Locate the **Layout** section. From the **Layout** list, choose **Rectangular grid**.

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

8 In the **Vertical padding factor** text field, type `0`.

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

10 From the **Coordinate system** list, choose **Global**.

11 In the **Display precision** text field, type `7`.

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

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

14 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)`. 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 the resulting image to Figure 6.