Model created in COMSOL Multiphysics 6.4

Petzval Lens Geometric Modulation Transfer Function

Introduction

In this tutorial we demonstrate how to compute the geometric modulation transfer function (MTF) of a lens. The optical transfer function (OTF) is a measure of an optical systems ability to resolve an object at a given spatial frequency. The OTF is defined as

$$\mathrm{OTF} = \frac{\text{Image Contrast}}{\text{Object Contrast}} \ , \tag{1}$$

where the contrast is defined in terms of the intensity as

$$\text{Contrast} = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} \ . \tag{2}$$

The OTF is a vector quantity including a phase term. When referring to the modulation transfer function, only the amplitude is considered.

The modulation transfer function at a given spatial frequency ν can be computed from the line spread function (LSF). In the context of an image of a point source (or, a collimated source at infinity), the LSF is an integration in a single direction of the point spread function (PSF). The MTF is then given by (Ref. 1)

$$\mathrm{MTF}(\nu) = \sqrt{L_c^2(\nu) + L_s^2(\nu)} \ , \tag{3}$$

in which the expressions for L_c and L_s are

$$L_c = \frac{\int \mathrm{LSF}(\delta) \cos 2\pi\nu\delta \, d\delta}{\int \mathrm{LSF}(\delta) \, d\delta} \ , \tag{4}$$

and

$$L_s = \frac{\int \mathrm{LSF}(\delta) \sin 2\pi\nu\delta \, d\delta}{\int \mathrm{LSF}(\delta) \, d\delta} \ . \tag{5}$$

which is equivalent to the magnitude of the Fourier transform of the LSF. The LSF is given in terms of δ, the spatial location on the detector plane. The MTF, which is computed in the sagittal (x) or tangential (y) directions, is the response of the LSF to a signal that is spatially periodic at the frequency ν in either of these directions. Here, the fast Fourier transform (FFT) will be used to compute the MTF due to its computational efficiency.

Geometric Modulation Transfer Function

The MTF can be calculated using the results of a Geometrical Optics ray trace. The LSF is generated using the number density of ray intersections at the focal plane (that is, the spot diagram; see Figure 2). The LSF of the spot diagram shown in Figure 2 can be computed using the **Kernel Density Estimation (KDE)** dataset. Another approach is to use binning however the KDE approach ensures that the discretization error in estimating the LSF from a finite number of rays asymptotically approaches zero as the number of rays is increased. MTF is then computed using the **Spatial FFT** dataset.

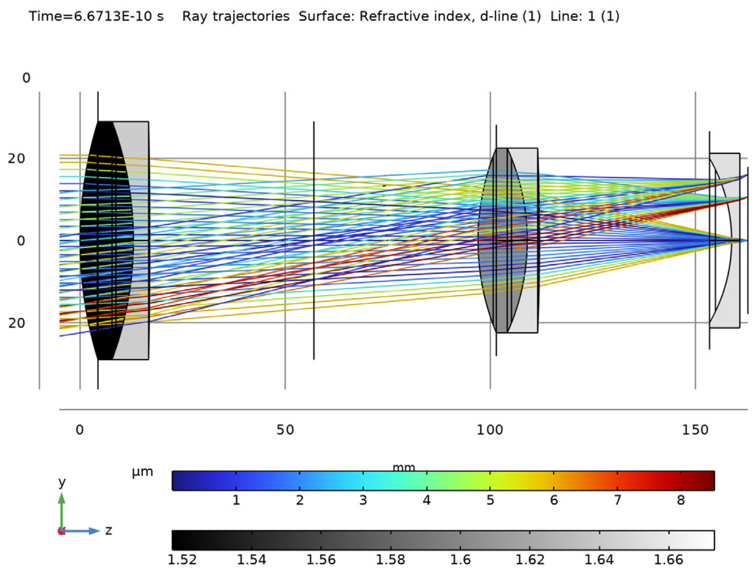


Figure 1: The Petzval lens with 3 fields.

Model Definition

The model used for this example is the Petzval Lens, which can be found in the Ray Optics Module Application Library. The lens has a 100 mm focal length and includes a field flattening lens to provide good image quality over a ±10° field of view (Ref. 2). An overview can be seen in Figure 1.

Detailed step-by-step instructions for creating and running the method can be found in the section Modeling Instructions.

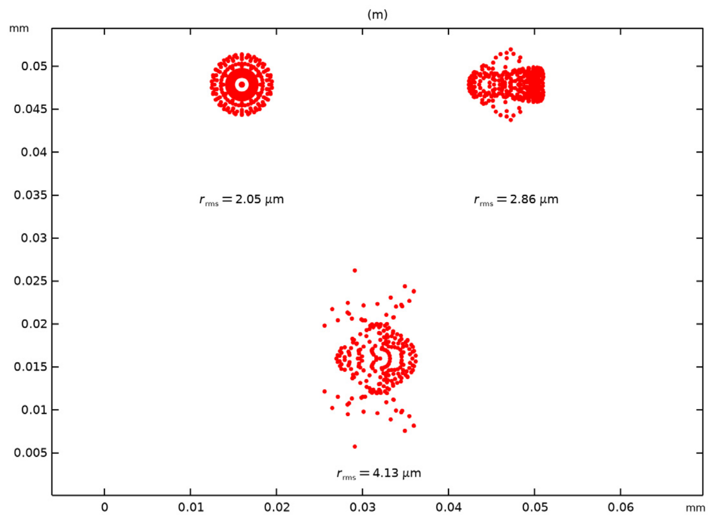


Figure 2: Spot diagram for 3 fields.

Results and Discussion

The accuracy of the MTF plots depend on the sufficient sampling of the exit pupil. Therefore, a small number of rays are released to confirm the initial settings such as **Intersection Point 3D** dataset parameters and the resulting MTF plot is shown in Figure 3. The number of rays are then increased until the MTF plots stop changing in the frequency range of interest as shown in Figure 4 to Figure 6.

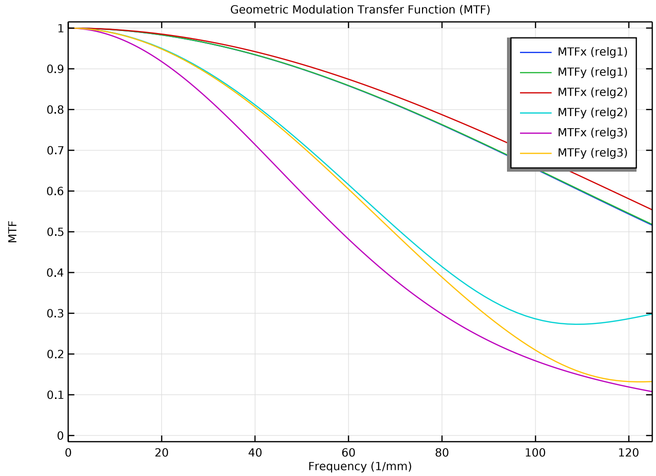


Figure 3: The modulation transfer function (MTF) of the Petzval lens with Nring = 12.

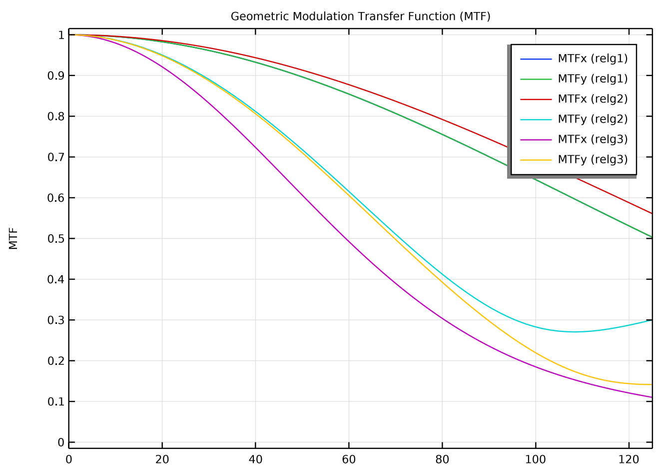


Figure 4: The modulation transfer function (MTF) of the Petzval lens with Nring = 50.

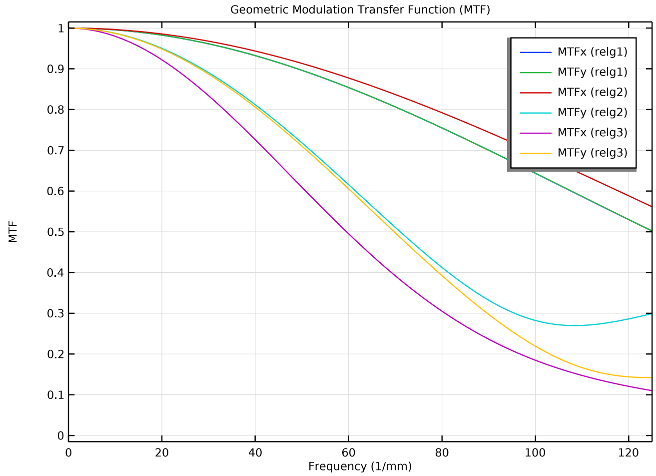


Figure 5: The modulation transfer function (MTF) of the Petzval lens with Nring = 70.

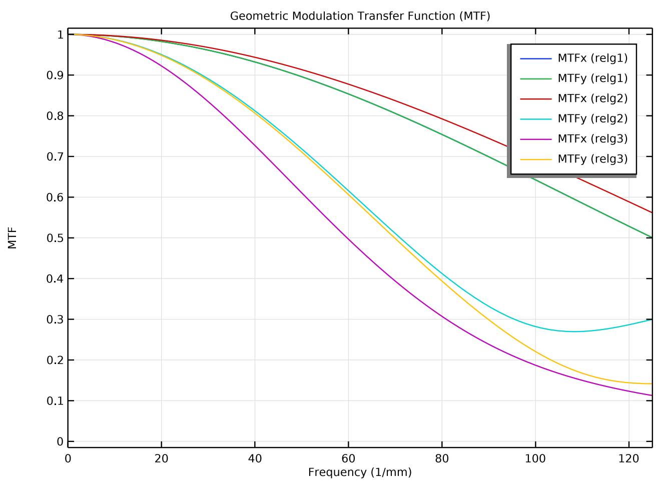


Figure 6: The modulation transfer function (MTF) of the Petzval lens with Nring = 100.

References

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

2. M.J. Kidger, *Fundamental Optical Design*, SPIE Press, 2001.

Application Library path: `Ray_Optics_Module/Lenses_Cameras_and_Telescopes/petzval_lens_geometric_modulation_transfer_function`

ROOT

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

APPLICATION LIBRARIES

1 In the **Model Builder** window, click the root node.

2 In the **Application Libraries** window, select **Ray Optics Module** > **Lenses, Cameras, and Telescopes** > **petzval_lens** in the tree.

3 Click **Open**.

GEOMETRICAL OPTICS (GOP)

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

2 In the **Settings** window for **Geometrical Optics**, locate the **Ray Release and Propagation** section.

3 From the **Wavelength distribution of released rays** list, choose **Monochromatic**.

4 Locate the **Results** section. From the **Results** list, choose **Plot spot diagram and geometric MTF**.

Ray Properties 1

1 In the **Model Builder** window, expand the **Geometrical Optics (gop)** node, then 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 `550[nm]`.

RESULTS

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

2 In the **Settings** window for **Results**, locate the **Update of Results** section.

3 Select the **Recompute all plot data after solving** checkbox.

4 Select the **Reevaluate all evaluation groups after solving** checkbox.

STUDY 1

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

2 Click **Reset Default Plots**.

RESULTS

Ray Diagram 1

1 In the **Model Builder** window, under **Results** click **Ray Diagram 1**.

2 In the **Ray Diagram 1** toolbar, click **Plot**.

3 Click the **Zoom Extents** button in the **Graphics** toolbar. Compare the resulting image to Figure 1.

Spot Diagram 1

Minimum RMS (root-mean-squared) width for the on-axis ray release can be computed using filter functionality of the Spot Diagram. Filtering will be activated to compute the intersection plane parameters and then subsequently deactivated to plot the Spot Diagram for all the releases.

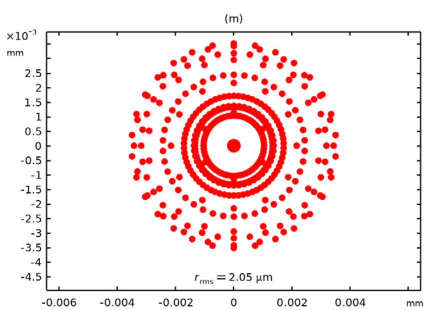
1 In the **Model Builder** window, expand the **Results** > **Spot Diagram** node, then click **Spot Diagram 1**.

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

3 Select the **Filter by release feature index** checkbox.

4 Click to expand the **Focal Plane Orientation** section. Click **Recompute Focal Plane Dataset**. Note that the new intersection plane position yields a much smaller RMS width.

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



6 Locate the **Filters** section. Clear the **Filter by release feature index** checkbox.

7 In the **Spot Diagram** toolbar, click **Plot**. Compare the resulting image to Figure 2.

Intersection Point 3D 1

The intersection Point 3D dataset parameters can be inspected and modified to values with a more reasonable precision.

1 In the **Model Builder** window, expand the **Results** > **Datasets** node, then click **Intersection Point 3D 1**.
2 In the **Settings** window for **Intersection Point 3D**, locate the **Surface** section.
3 Find the **Point** subsection. In the **x** text field, type `0`.
4 In the **y** text field, type `0`.
5 In the **z** text field, type `162.755[mm]`.
6 Find the **Normal vector** subsection. In the **x** text field, type `0`.
7 In the **y** text field, type `0`.

Evaluation groups must be evaluated again after changing the Intersection Point 3D dataset parameters to ensure the values are updated.

LSF Data (relg1)

1 In the **Model Builder** window, under **Results** click **LSF Data (relg1)**.
2 In the **LSF Data (relg1)** toolbar, click **Evaluate**.

LSF Data (relg2)

1 In the **Model Builder** window, click **LSF Data (relg2)**.
2 In the **LSF Data (relg2)** toolbar, click **Evaluate**.

LSF Data (relg3)

1 In the **Model Builder** window, click **LSF Data (relg3)**.
2 In the **LSF Data (relg3)** toolbar, click **Evaluate**.

Geometric MTF

1 In the **Model Builder** window, click **Geometric MTF**.
2 In the **Settings** window for **1D Plot Group**, locate the **Axis** section.
3 Select the **Manual axis limits** checkbox.
4 In the **x minimum** text field, type `0`.
5 In the **x maximum** text field, type `125`.
6 In the **Geometric MTF** toolbar, click **Plot**. Compare the resulting plot to Figure 3.

To ensure sufficient sampling of the exit pupil, the number of rays is increased and minimal changes to the Geometric MTF in the frequency range of interest is confirmed.

GLOBAL DEFINITIONS

Parameters 2: General

1 In the **Model Builder** window, under **Global Definitions** click **Parameters 2: General**.

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

3 In the table, enter the following settings:

Name	Expression	Value	Description
N_ring	50	50	Number of hexapolar rings

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

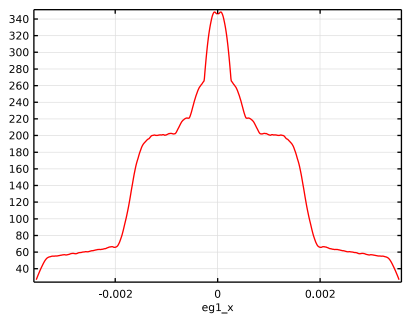
RESULTS

LSFx (eg1)

Line spread function (LSF) can be inspected by using the plot functionality of the KDE dataset.

1 In the **Model Builder** window, under **Results** > **Datasets** click **LSFx (eg1)**.

2 In the **Settings** window for **Kernel Density Estimation**, click **Plot**.



Geometric MTF

1 In the **Model Builder** window, under **Results** click **Geometric MTF**.

2 In the **Geometric MTF** toolbar, click **Plot**. Compare the resulting plot to Figure 4.

GLOBAL DEFINITIONS

Parameters 2: General

1 In the **Model Builder** window, under **Global Definitions** click **Parameters 2: General**.

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

3 In the table, enter the following settings:

Name	Expression	Value	Description
N_ring	70	70	Number of hexapolar rings

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

RESULTS

Geometric MTF

1 In the **Model Builder** window, under **Results** click **Geometric MTF**.

2 In the **Geometric MTF** toolbar, click **Plot**. Compare the resulting plot to Figure 5.

GLOBAL DEFINITIONS

Parameters 2: General

1 In the **Model Builder** window, under **Global Definitions** click **Parameters 2: General**.

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

3 In the table, enter the following settings:

Name	Expression	Value	Description
N_ring	100	100	Number of hexapolar rings

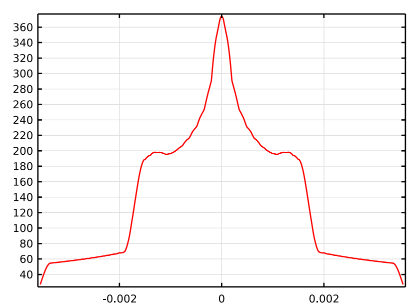
4 In the **Home** toolbar, click **Compute**.

RESULTS

LSFx (eg1)

1 In the **Model Builder** window, under **Results** > **Datasets** click **LSFx (eg1)**.

2 In the **Settings** window for **Kernel Density Estimation**, click **Plot**.



Geometric MTF

1 In the **Model Builder** window, under **Results** click **Geometric MTF**.

2 In the **Geometric MTF** toolbar, click **Plot**. Compare the resulting plot to Figure 6. It should be noted that the symmetries in the ray release will impact the spot diagram. Therefore, changes to the MTF due to different release types should be noted.