RayLab
User Manual

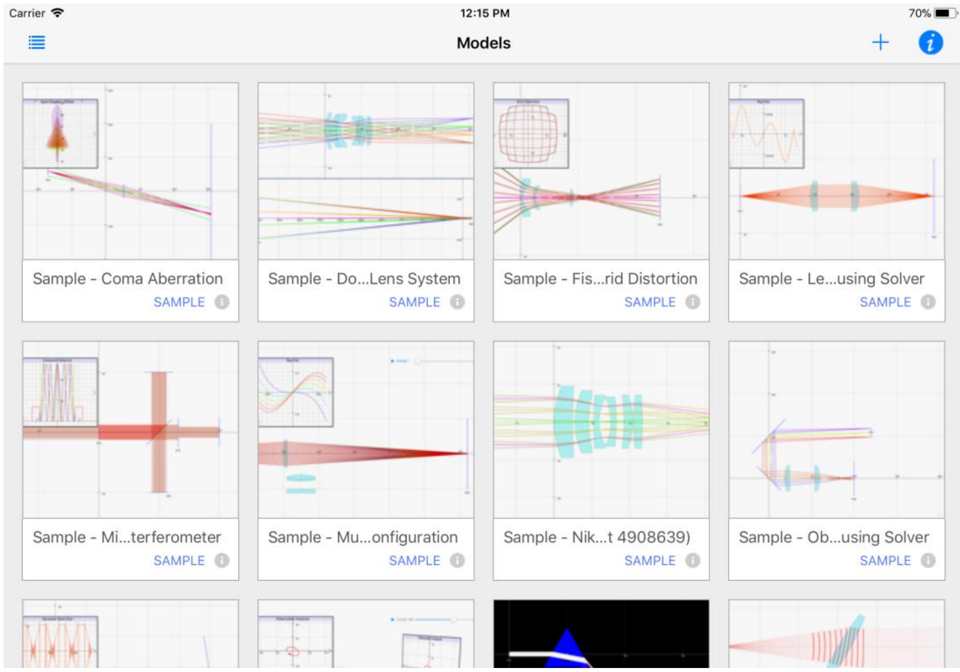
August 2018
www.raymak.com

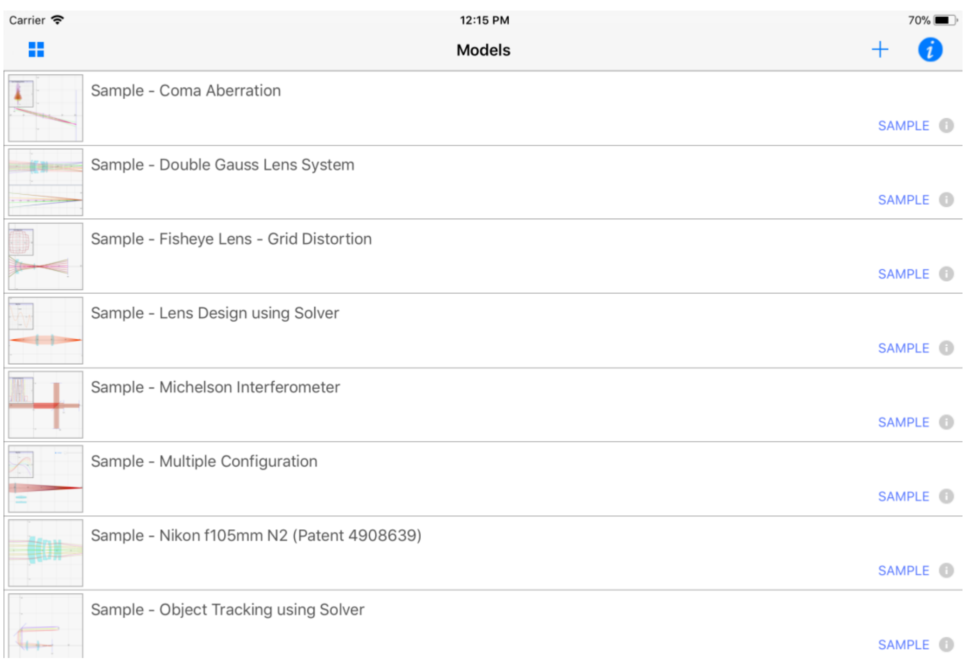
Contents

1. Introduction

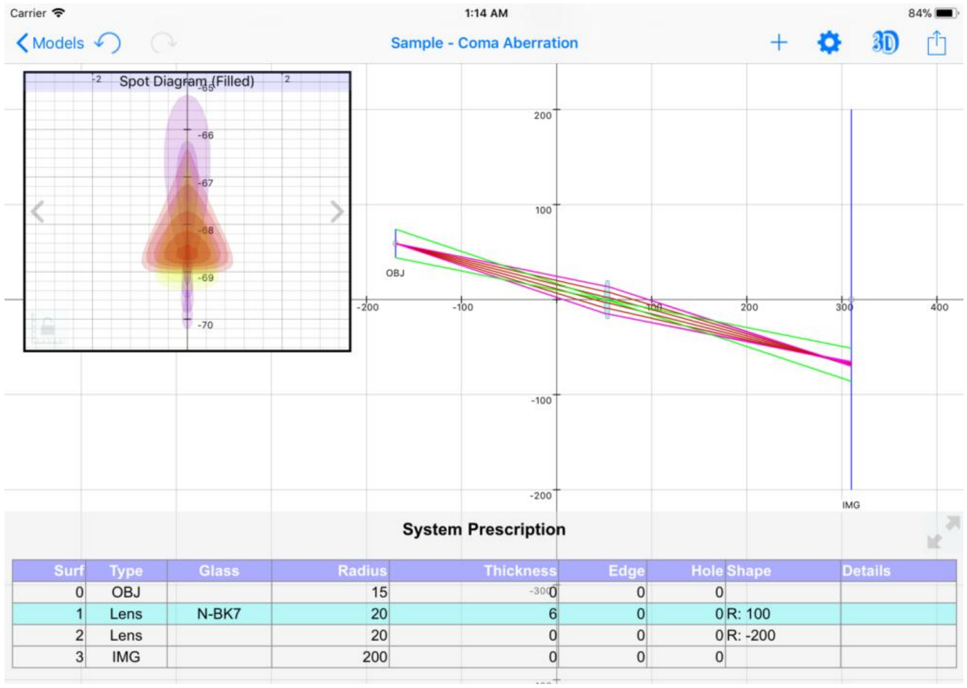
RayLab is an application for design and simulation of optics on iOS devices. It can be used as either as a learning tool, or to design real optical systems. It has been designed to balance an intuitive user interface with sophisticated optical modeling capabilities.

1.1. Model Browse Window





1.2. 2D Layout Window



The 2D Layout window is the default window which is displayed when creating a new model. It is useful for viewing axissymmetric systems, or systems which are planar. In this view optical components can only be moved in the y-z plane.

Overlaid on top of the layout window may be an Analysis window, as well as a Report pane (more on these later).

View Gestures

- Use a single finger away from any components to pan view.
- Use two fingers away from any components to zoom view.

Adding Components

- Tap the + symbol to add new optical components.

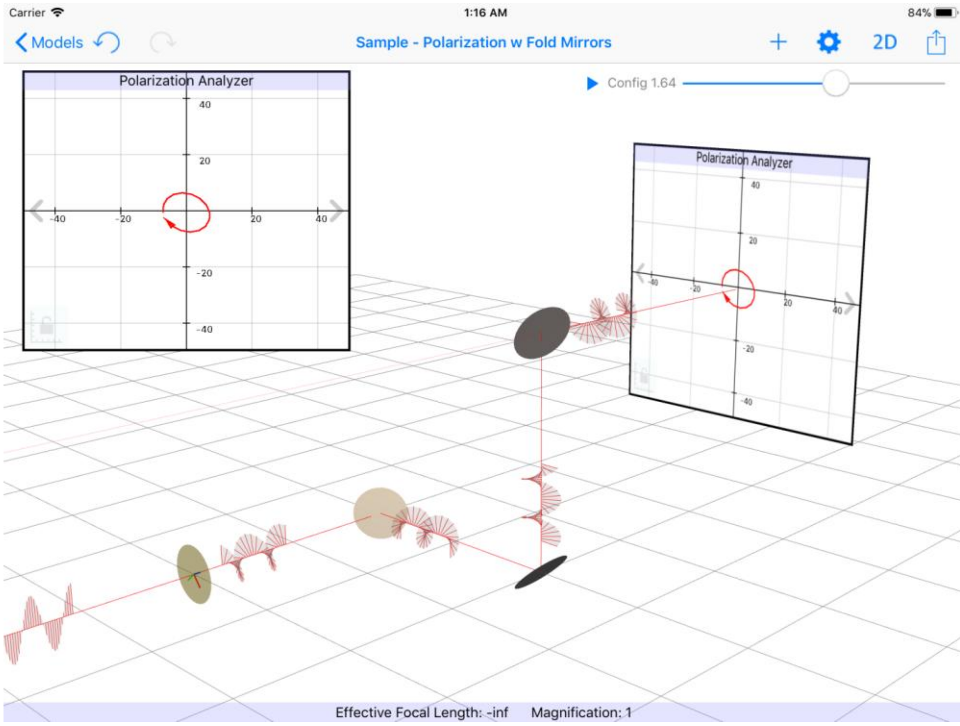
Moving Components

- Tap near the center of a component surface and drag to move the component.
- Tap on a component, and use a second finger to rotate the component.
- The ‘Lock On Axis’ option limits movement of components along the z axis. Turning this option off will allow full freedom of movement.

Modifying Components

- Tap + to add a new optical component to the model.
- Select a component surface by tapping near the center of the surface.
- With a surface selected, tap trashcan icon to delete the component.
- With a surface selected, tap lens icon to change surface properties.

1.3. 3D Layout Window



Tapping on the 3D toolbar icon will flip to a 3D Layout window. In this view optical components have full 6 degree of freedom. As with 2D Layout, an Analysis window, and a Report window may be overlaid on this view.

View Gestures

- Double tap to cycle thru standard 3D views.
- Use a single finger to tip/tilt the view.
- Use two fingers to zoom and rotate the view.

Adding Components

- Tap the + symbol to add new optical components.

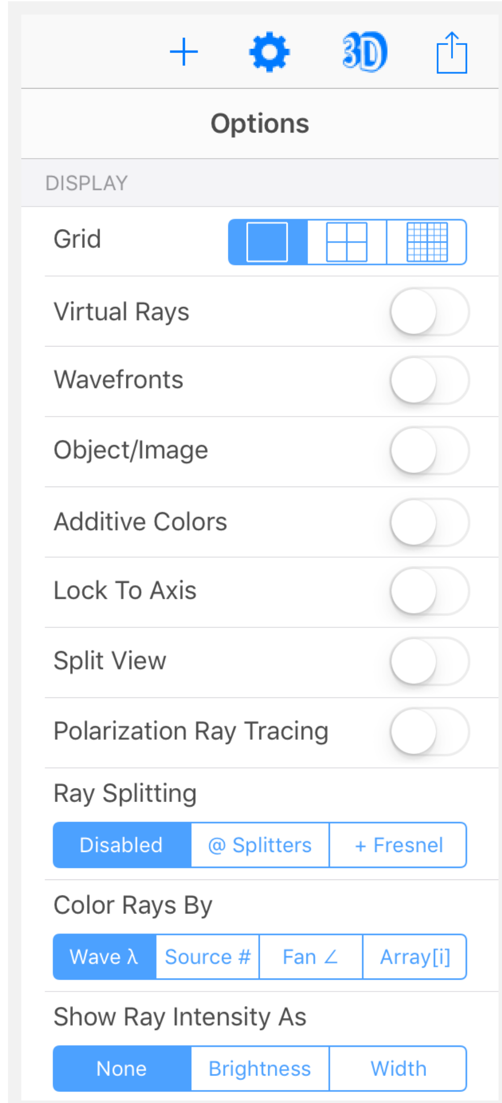
Moving Components

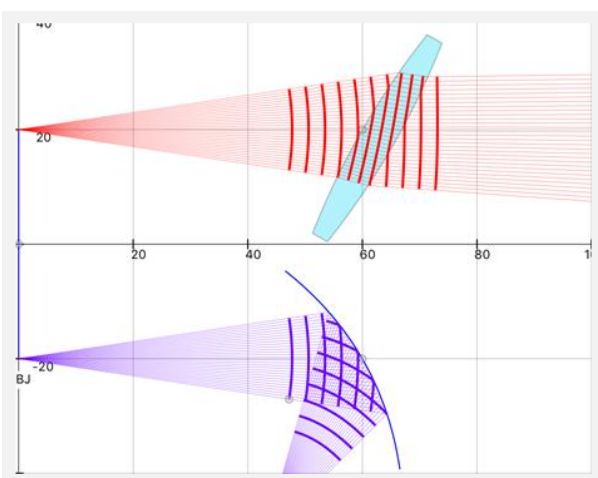
- Tap with one finger near the center of a component surface and drag to move the component in x-z plane.
- While moving tap somewhere with a second finger to move in x-y plane.
- The 'Lock On Axis' option changes the above behavior between global coordinates and local component coordinates.

1.4. System Options

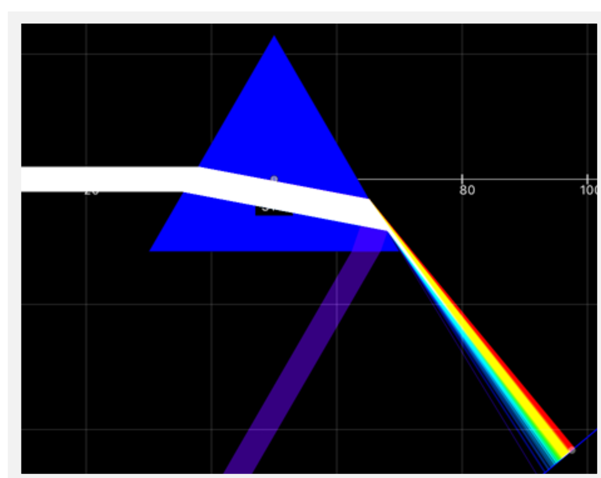
Tapping the gear icon in the toolbar will present the System Options window. From here various global options affecting the model can be modified.

The options window also allows selection of various Analysis Plots as well as various Reports.





Show Wavefronts

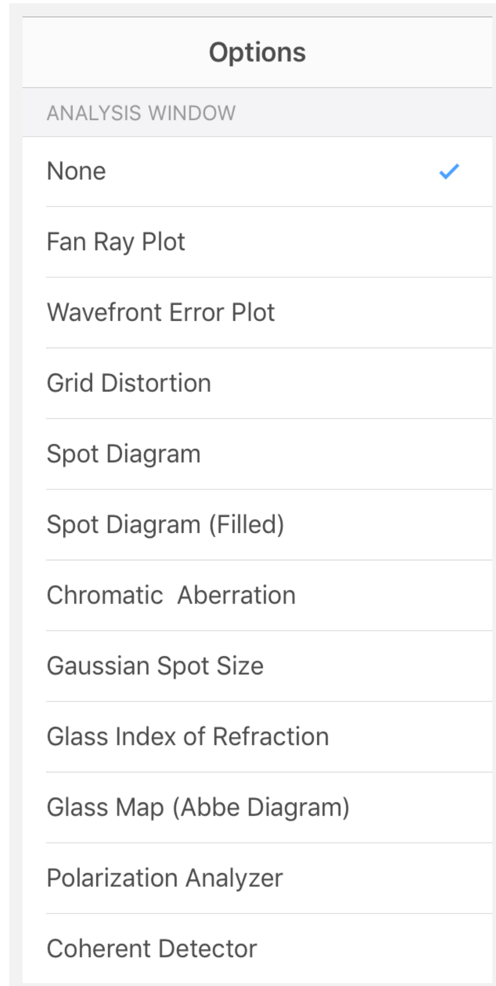


Additive Colors

1.5. Analysis Window

RayLab provides a range of analysis plots for examining the performance of the system. The analysis windows can be selected from the System Options menu.

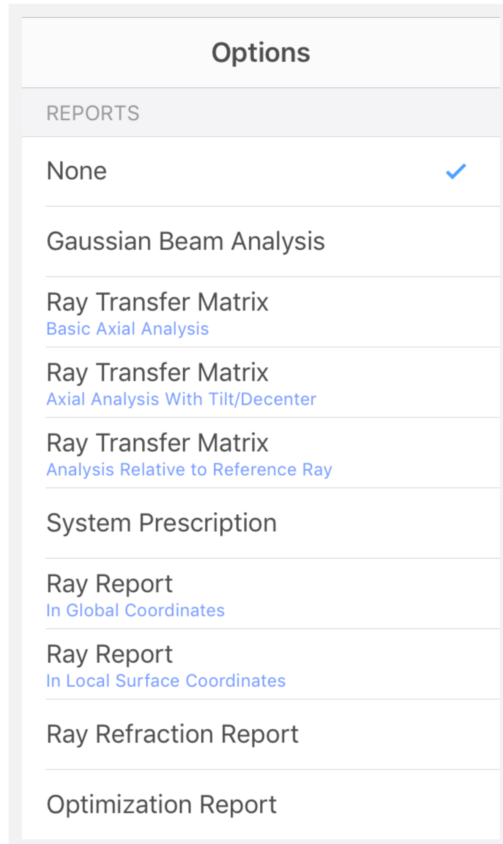
These are detailed in section 3. Analysis Window.



1.6. Report Window

RayLab provides a range of reports for displaying information about the system. The reports can be selected from the System Options menu.

These are detailed in section 4. Reports Window.

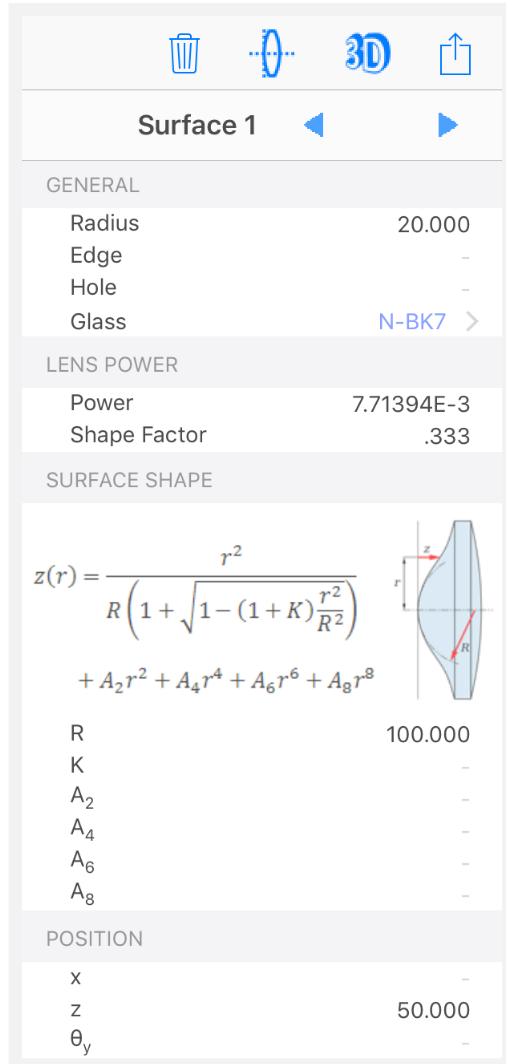


1.7. Surface Properties

When a surface is selected, tapping the lens icon in the toolbar displays the Surface Properties window.

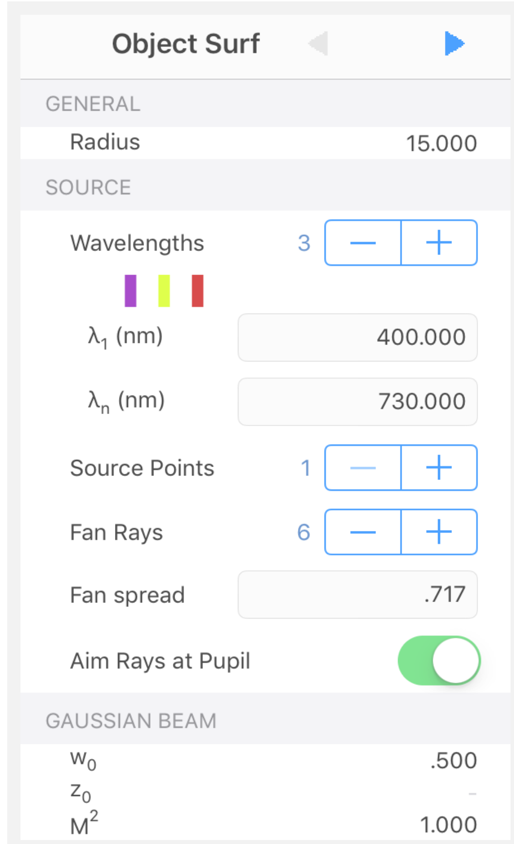
Here, various surface parameters as well as the surface position can be modified. Additional details are provided throughout the manual.

Tapping the left/right arrows will switch to the previous/next surface in the model.



1.8. Source/Object surface properties

All rays emanate from the first surface in the system (the Object surface) and travel until they reach the last surface (the Image surface). The radius of the Object surface determines how far apart the source point of the rays are.



You can specify:

- the number of wavelengths ($N_{wavelength}$)
- the number of source points (N_{srcPt})
- and the number of fan rays (N_{angle})

Total number of rays are the product of these 3 values ($N_{wavelength}$ * N_{srcPt} * N_{angle}). One would typically make two of these small, and the 3rd large. If you make all values large the app may become very slow.

The wavelengths are interpolated between λ_1 and λ_n.

The source points are interpolated between -radius and +radius of the source surface.

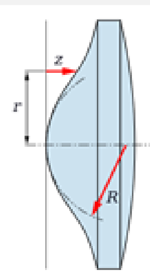
There are two modes for setting the angle of the rays:

- When the 'Aim at Pupil' is off the angle of the rays are interpolated between -θ and +θ where theta is controlled by the fan angle slider. In this mode rotating the source surface will change the direction which the rays are aimed.
- When the 'Aim at Pupil' is on, the rays are aimed at the system's Entrance Pupil. In this mode the fan angle slider actually controls how far apart the rays are on the entrance pupil. So at maximum value the rays reach the edge of the entrance pupil. Note that entrance pupil calculation are currently only valid for axial systems.

1.9. Asphere Surfaces

Most surface shapes are defined by using the asphere equation:

$$z(r) = \frac{r^2}{R\left(1+\sqrt{1-(1+K)\frac{r^2}{R^2}}\right)} + A_2 r^2 + A_4 r^4 + A_6 r^6 + A_8 r^8$$



R is the radius of curvature. Use negative values to flip orientation.

K is the conic constant.

K	Surface Shape
K < -1	Hyperbola
K = -1	Parabola
-1 < K < 0	Ellipse (prolate spheroid)
K = 0	Sphere
K > 0	Ellipse (oblate spheroid)

A2, A4, A6, A8 describe the deviation of the surface from the axially symmetric quadric surface specified by R and K. Note: If K=-1 then A2 is redundant.

To specify a **Flat Surface** leave all Shape parameters blank.

Specify the component size using the Radius parameter.

Stop parameter allows specifying a lip at the edge of a lens.

Three surface behaviors may be modeled by selecting different optical components:

- **Lens**: Rays hitting the surface will be refracted.
- **Mirror**: Rays hitting the surface will be reflected.
- **Grating**: Rays hitting the surface will be diffracted.

1.10. Fresnel Surfaces

A Fresnel lens uses less glass material than a normal lens by dividing the lens into a series of concentric rings. RayLab models an ideal Fresnel surface having infinitely many such rings by computing the intercept of the ray with a flat plane, but computing the surface normal according to the asphere equation.

Despite using the ideal model for ray tracing, the graphic representation of the Fresnel surfaces in RayLab use finite steps to indicate the multi-ring Fresnel construction

Two types of Fresnel components are available in RayLab. A Fresnel Lens and a Fresnel Mirror.

1.11. Periodic Surfaces

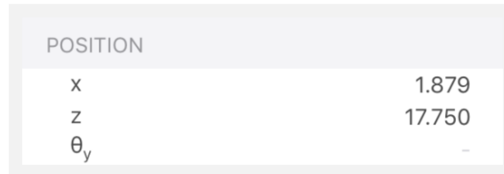
Periodic surfaces are used to represent micro lens arrays. The shape of the individual lenslets in the array is controlled using asphere parameters. And the spacing is governed by a Period parameter. The array pattern may be either Square or Hexagonal.

1.12. Spherical vs. Cylindrical Surfaces

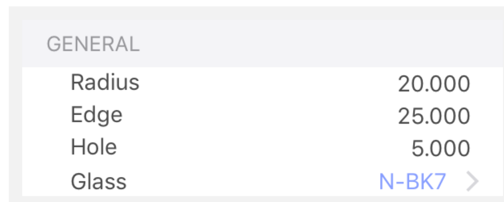
Cylindrical lenses use an asphere equation similar to the one in section 1.9. Asphere Surfaces. The only difference is that the equation is a function of the surface y coordinate instead of the radial r coordinate.

2. Optical Components

RayLab provides a variety of predefined optical elements. Each of these elements can be used as a starting point and then fully customized by modifying the shape/size parameters for each surface, as well as optical properties such as glass material. The parameters available vary with the type of optical element.



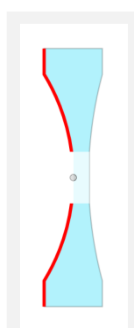
Optical elements are typically made up of multiple surfaces. The position of each surface can be controlled independently. In 2D layout, x, z, and Ty can be modified, while in 3D layout all 6 position parameters are adjustable. In most cases the position for the first surface of an optical element is defined in absolute coordinates. While, for subsequent surfaces they are defined relative to the position and orientation of the first surface.



In addition to position other parameters which are common to many surfaces are:

- Radius: radius of circular lenses/surfaces. In the case of cylindrical elements this corresponds to ½ of the surface height.
- Edge: used to produce a flat border around the lens. This is measured from the lens center, so only takes affect when it is larger than the radius.
- Hole: radius of hole at the center of the surface.
- Glass: The glass material for the lens which can be selected from the glass catalog or user defined (See section 14. Glass)

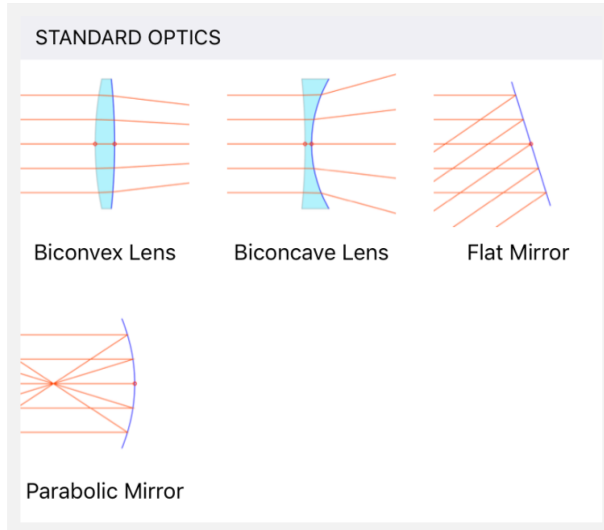
Below is an example of a concave lens with an edge and a hole.



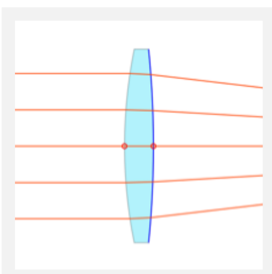
2.1. Standard Optics

The simplest and most commonly used optical elements are grouped in the Standard Optics category. These elements can be used in both 2D and 3D models.

They are detailed below.



2.1.1. Biconvex Lens



The Biconvex lens consists of a simple lens with two aspheric surfaces. Full range of aspheric shape parameters is supported. While initially biconvex, the shape of each surface is independently controlled, thus plano-convex, biconcave, plano-concave, or meniscus lenses can be modeled.

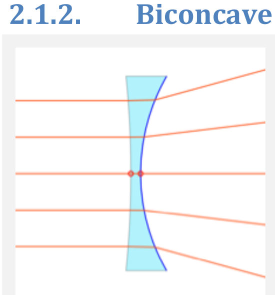
The shape of each surface is defined using the asphere equation as described in section 1.9 Asphere Surfaces.

Additionally, Power and Shape Factor can be used to simultaneously adjust the shape of both surfaces. When power or shape factor are modified, the radius of curvature of the two surfaces are recomputed, and the A2 parameter is reset to zero. Other asphere parameters are unchanged.

LENS POWER	
Power	-.020
Shape Factor	.333

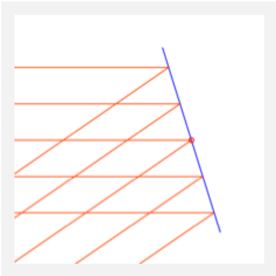
A Shape Factor of zero represents a symmetric lens, while Shape factor of -1 or 1 represent a flat first surface or second surface respectively.

2.1.2. Biconcave Lens



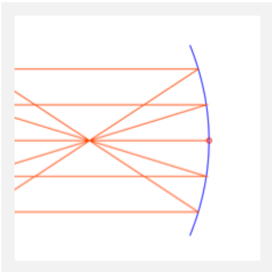
The Biconcave lens has all the same properties and parameter options as the Biconvex lens, but use different initial parameter values represent a concave lens.

2.1.3. Flat Mirror



Initially this element represents a flat circular mirror. However, it uses the full asphere shape equation, and can thus represent a variety of curved mirrors. It also allows for holes and flat edges.

2.1.4. Parabolic Mirror

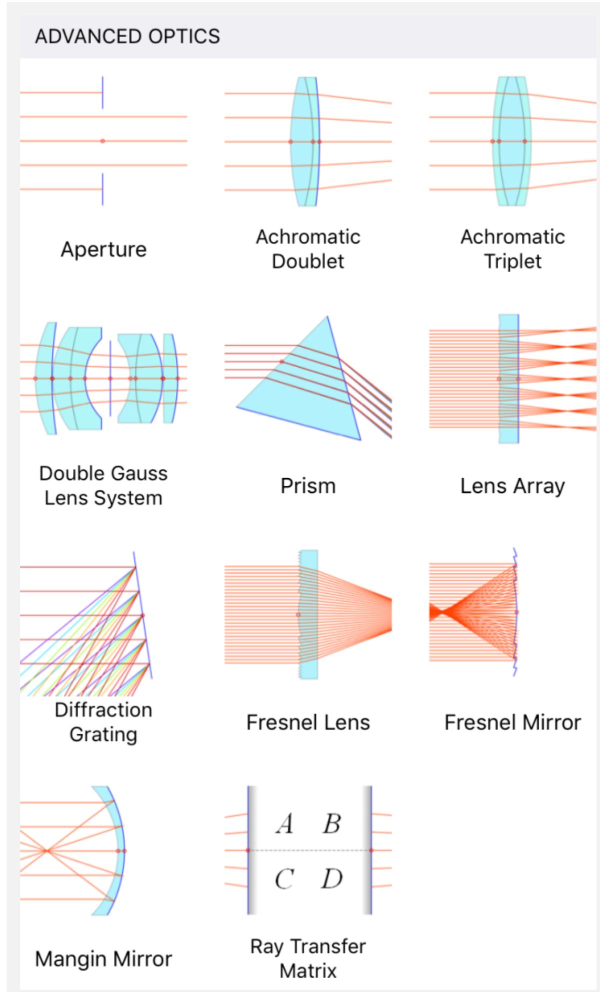


Initially this element represents a parabolic circular mirror. However, as with Flat Mirror element, it uses the full asphere shape equation, and can thus represent a variety of curved mirrors. It also allows for holes and flat edges.

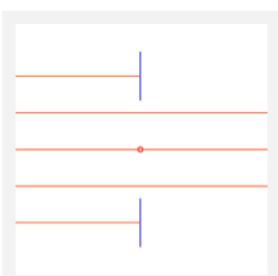
2.2. Advanced Optics

More complex optical elements are grouped in the Advanced Optics category. These elements can be used in both 2D and 3D models.

They are detailed below.

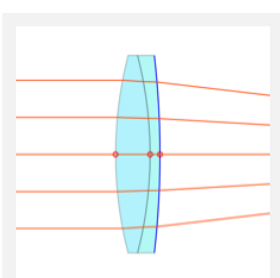


2.2.1. Aperture



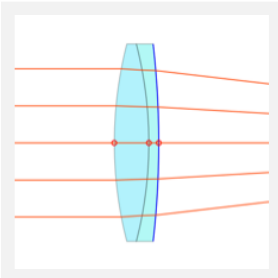
The aperture element is a circular disk with a hole. Rays pass thru the hole unimpeded, while rays which hit the sides are stopped. While initially flat, the shape of this element can be modified using asphere parameters.

2.2.2. Achromatic Doublet



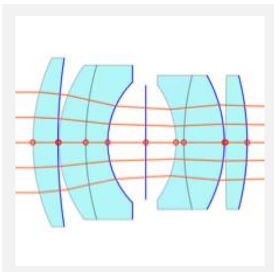
The Achromatic Doublet represents a pair of fused lens elements. Three surfaces are used, with the middle surface shared between the two elements. The shape of each surface can be independently controlled using asphere parameters, and two glass materials can be independently specified. The surfaces also support edge and hole parameters.

2.2.3. Achromatic Triplet

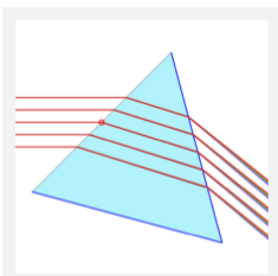


The Achromatic Triplet represents three fused lens elements. Four surfaces are used, with the 2nd and 3rd surfaces shared between their respective elements. The shape of each surface can be independently controlled using asphere parameters, and three glass materials can be independently specified. The surfaces also support edge and hole parameters.

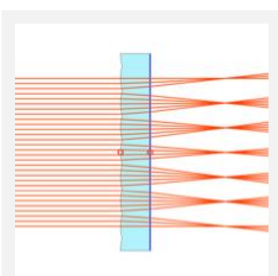
2.2.4. Double Gauss Lens System



2.2.5. Prism (2D)

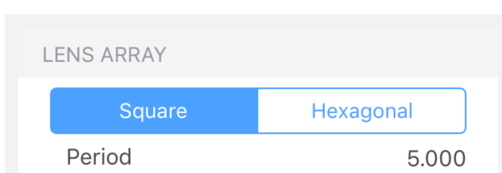


2.2.6. Lens Array

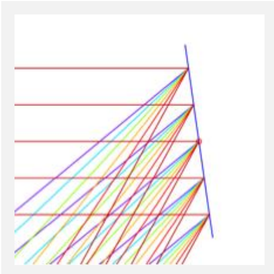


This element represents a micro lens array. The shape of the individual lenslets in the array is controlled using asphere parameters. And the spacing is governed by a Period parameter. Typically one surface of the element is flat while the other consists of a lens array. Alternatively, both surfaces of the element may specify independently controlled arrays.

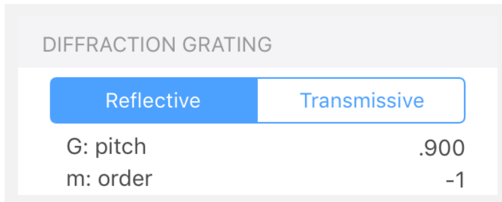
The array pattern may be either Square or Hexagonal.



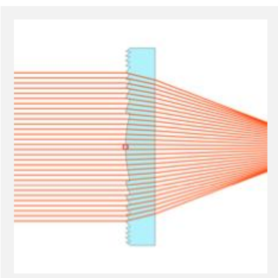
2.2.7. Diffraction Grating



This element represents a diffraction grating. Both Reflective and Transmissive gratings are supported. It is assumed the grating is a plane, and the grooves are assumed to be parallel to the y axis in the coordinate system of the surface. The pitch of the grating pattern may be specified using the G parameter which has units of 1/um.
The order of the grating is specified using the m parameter.

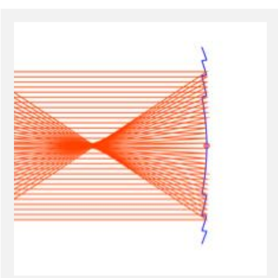


2.2.8. Fresnel Lens



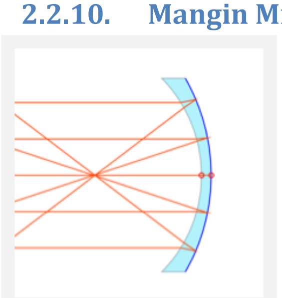
This element represents a Fresnel lens, using the modeling approach described in section 1.10 Fresnel Surfaces.

2.2.9. Fresnel Mirror



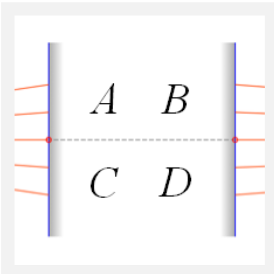
This element represents a Fresnel mirror, using the modeling approach described in section 1.10 Fresnel Surfaces.

2.2.10. Mangin Mirror



The Mangin mirror consists of a concave (negative meniscus) lens with spherical surfaces of different radii with the rear surface having a mirror coating. The shape of each surface is controlled using asphere shape parameters.

2.2.11. Ray Transfer Matrix

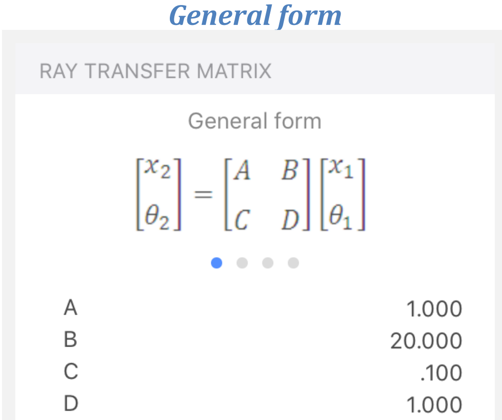


The Ray Transfer Matrix element can represent arbitrary group of optical elements using a 2x2 matrix. Two reference planes, considered the input and output planes, are used. The two planes can be independently positioned. Each ray hitting the first surface is represented by a 2 element vector, where the elements correspond to the ray offset relative to the surface origin and slope relative to surface normal. This vector is multiplied by the ABCD matrix to compute a two element vector representing the offset and slope of the output ray relative to the second surface.

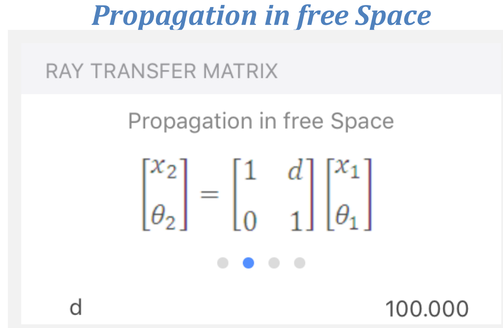
The calculation is repeated separately for both the x and y directions in the local surface coordinate systems.

While general/arbitrary ABCD matrices can be specified, RayLab also provides simplified input screens for common forms of the ABCD matrix.

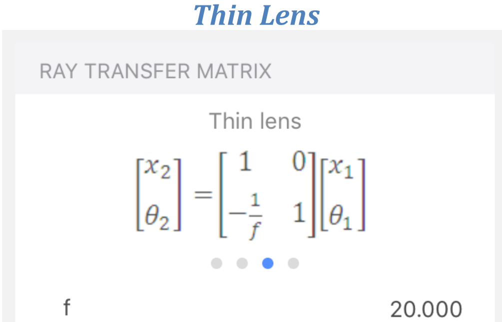
General form



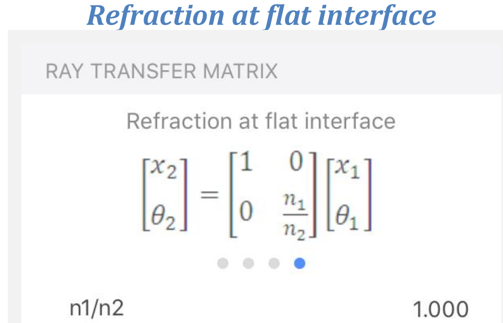
Propagation in free Space



Thin Lens



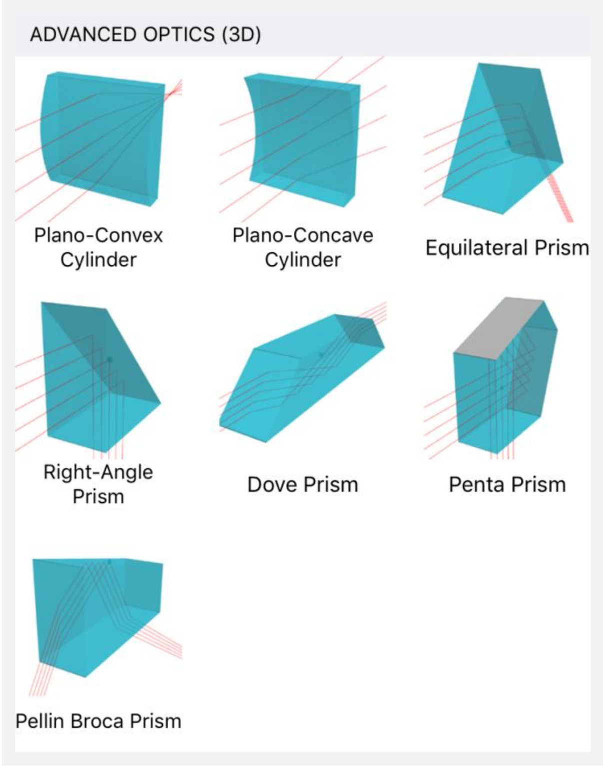
Refraction at flat interface



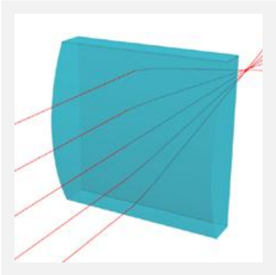
2.3. Advanced Optics (3D)

This category includes cylindrical elements and a variety of prisms.

Details are provided below.



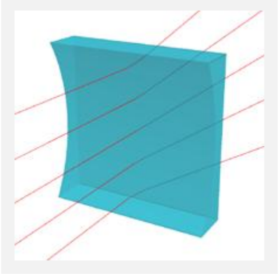
2.3.1. Plano-Convex Cylinder



This element represents an arbitrary cylindrical lens. Full range of aspheric shape parameters are supported (section 1.9 Asphere Surfaces). But unlike the spherical counterpart, the surface shape only depends on the y coordinate of the surface rather than the r (radial) coordinate. While initially plano-convex, the shape of each surface is independently controlled, thus plano-convex, biconcave, plano-concave, or meniscus style cylindrical lenses can be modeled.

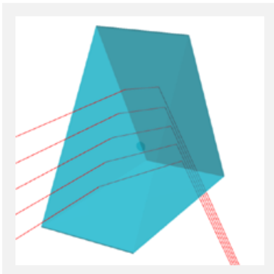
Additionally, Power and Shape Factor can be used to simultaneously adjust the shape of both surfaces. When power or shape factor are modified, the radius of curvature of the two surfaces are recomputed, and the A2 parameter is reset to zero. Other asphere parameters are unchanged.

2.3.2. Plano-Concave Cylinder



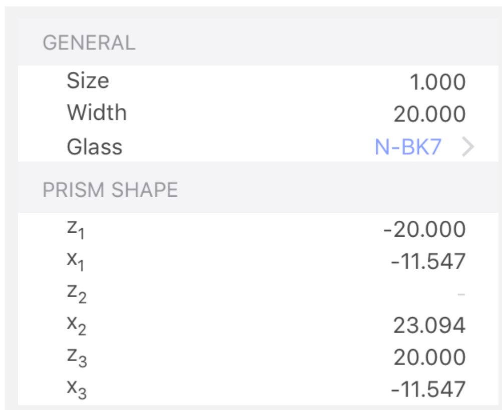
The Plano-concave Cylinder has all the same properties and parameter options as the Plano-convex Cylinder, but use different initial parameter values represent a concave cylinder.

2.3.3. Equilateral Prism



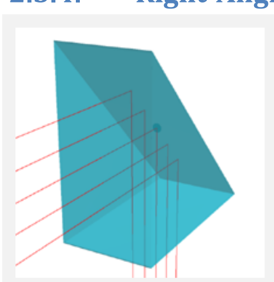
This element represents a prism. It utilizes a reference surface and 3 optical surfaces. The reference surface is not an optical surface but is used to specify all the properties of the prism. These include the width of the prism as well as the coordinates of all the prism vertices. A Size parameter is also available which scales the entire geometry. The other three surfaces are the actual optical surfaces of the prism. The properties of these surfaces are computed automatically from the values specified on the reference surface.

It should be noted that the lateral sides of the prism are not modeled by RayLab.



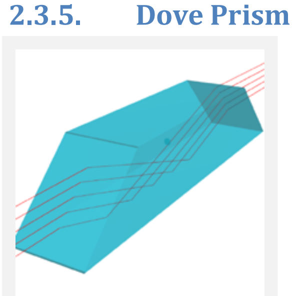
GENERAL	
Size	1.000
Width	20.000
Glass	N-BK7 >
PRISM SHAPE	
z_1	-20.000
x_1	-11.547
z_2	-
x_2	23.094
z_3	20.000
x_3	-11.547

2.3.4. Right-Angle Prism



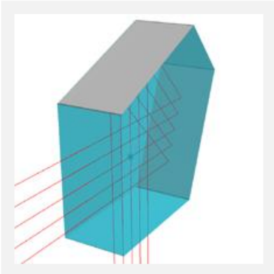
This element has the same properties and parameter options the Equilateral prism but has a different initial geometry.

2.3.5. Dove Prism



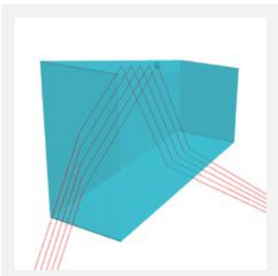
The Dove Prism has the same properties and parameter options the Equilateral prism but it uses 4 optical surfaces instead of 3.

2.3.6. Penta Prism



The Penta Prism has the same properties and parameter options the Equilateral prism but it uses 5 optical surfaces instead of 3. Additionally, one of the surfaces of a Penta Prism is a mirrored surface.

2.3.7. Pelin Broca Prism

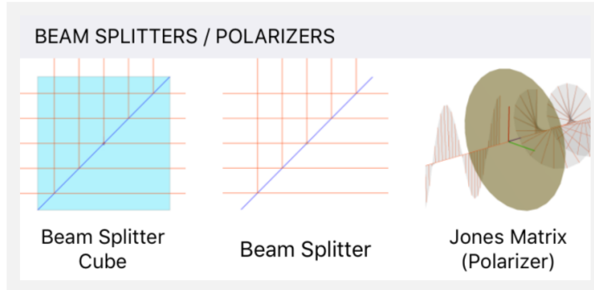


The Pellin–Broca prism is has the same properties and parameter options the Equilateral prism but it uses 4 optical surfaces instead of 3.

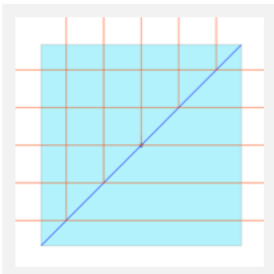
It is a constant-deviation dispersive prism consisting of a four-sided block of glass shaped as a right prism with 90°, 75°, 135°, and 60° angles on the end faces. Light enters the prism through face AB, undergoes total internal reflection from face BC, and exits through face AD. The refraction of the light as it enters and exits the prism is such that one particular wavelength of the light is deviated by exactly 90°.

The prism is commonly used to separate a single required wavelength from a light beam containing multiple wavelengths. [https://en.wikipedia.org/wiki/Pellin-Broca_prism]

2.4. Beam Splitters/Polarizers

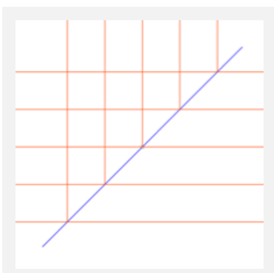


2.4.1. Beam Splitter Cube



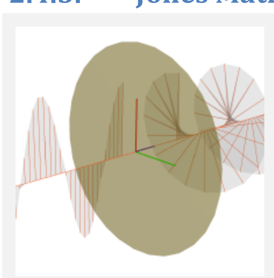
This element can represent either polarizing or non-polarizing beam splitter cubes. For additional information see section 11 Ray Splitting/Beam Splitters.

2.4.2. Beam Splitter (Pellicle)



This element can represent either polarizing or non-polarizing beam splitter with zero thickness. For additional information see section 11 Ray Splitting/Beam Splitters.

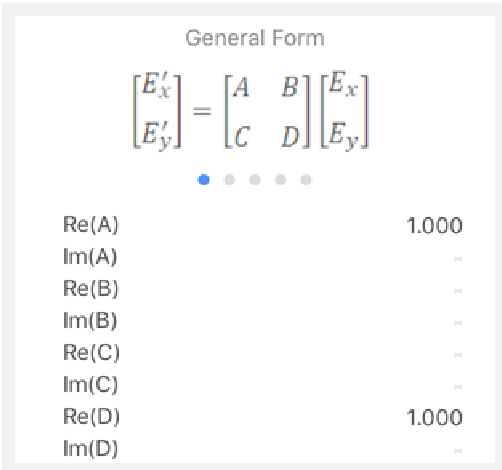
2.4.3. Jones Matrix (Polarizer)



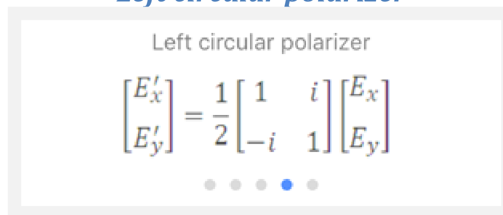
The Jones Matrix is a 2×2 complex matrix which describes the effect of the component on the polarization of the incident beam. This element assumes that the incident rays are normal to the surface.

The Jones Matrix element allows you to select matrices for a Linear polarizer, Right circular polarizer, or Left circular polarizer. You also have the option to model waveplates (retarders) such as a quarter-wave or half-wave plates. Finally, you have the option to define an arbitrary Jones Matrix by specifying the real and imaginary components of the 2×2 matrix.

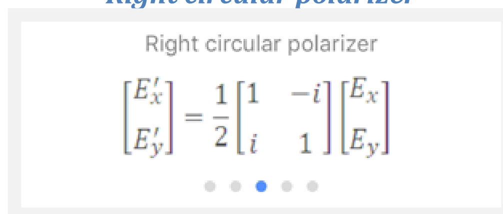
General Form



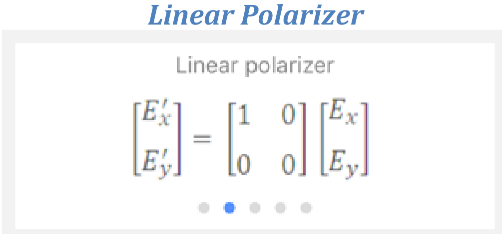
Left circular polarizer



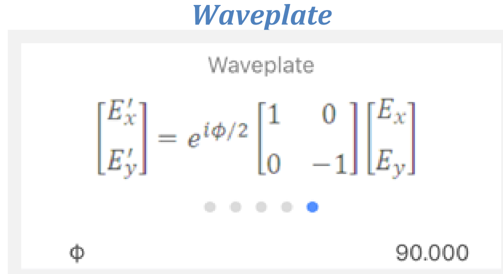
Right circular polarizer



Linear Polarizer



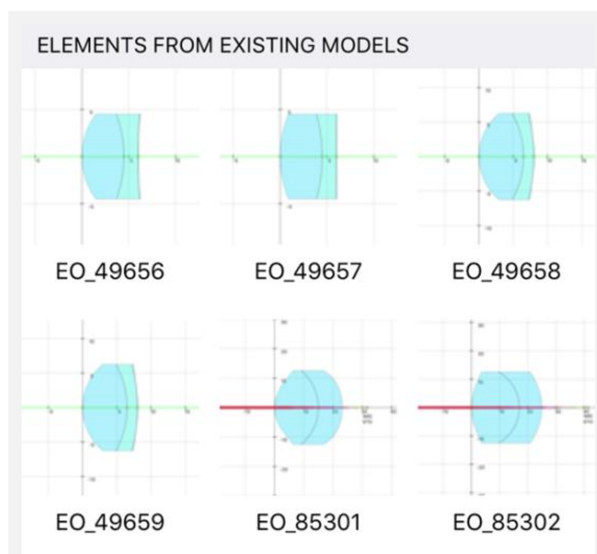
Waveplate



2.5. Elements from Existing Models

It is also possible to import components from existing models into a new model. The imported elements will be grouped together and move as a single unit.

This feature can be used in conjunction with Zemax Import to build up a local library of Commercial Off The Shelf (COTS) lenses. (Section 8. Zemax (.ZMX) File Import)

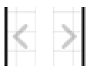


3. Analysis Window

RayLab provides a range of analysis windows for examining the performance of the system. The analysis windows can be selected from the System Options menu.

In most cases the Analysis Window displays information about the rays as they reach the IMG surface. Although in some instances this is not the case (e.g. Gaussian Spot Size, Glass Index, and Glass Map).

The axes on the analysis plots normally auto scale as the model changes. However the axes can be locked by tapping the lock icon in the bottom left of the window.



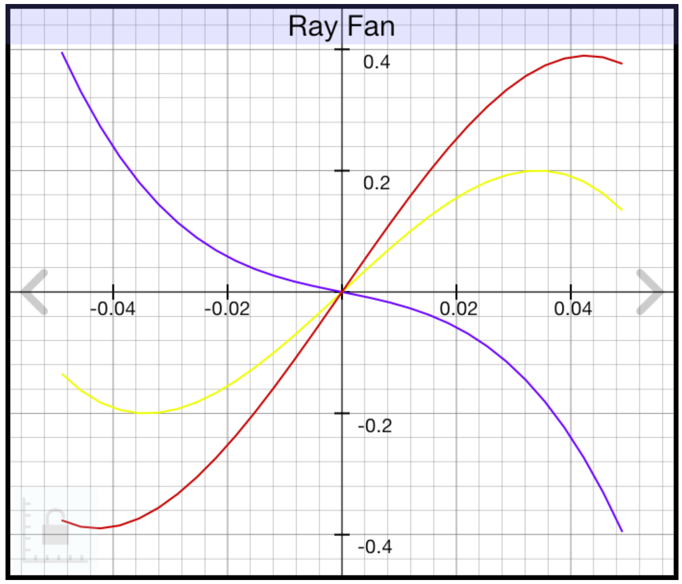
You can also quickly flip between different analysis plots by tapping the left/right arrows on either side of the analysis window instead of using the System Options menu.

The following analysis windows are provided:

- Fan Ray Plot
- Wavefront Error Plot
- Grid Distortion
- Spot Diagram
- Spot Diagram (Filled)
- Chromatic Aberration
- Gaussian Spot Size
- Glass Index of Refraction
- Glass Map (Abbe Diagram)
- Polarization Analyzer
- Coherent Detector

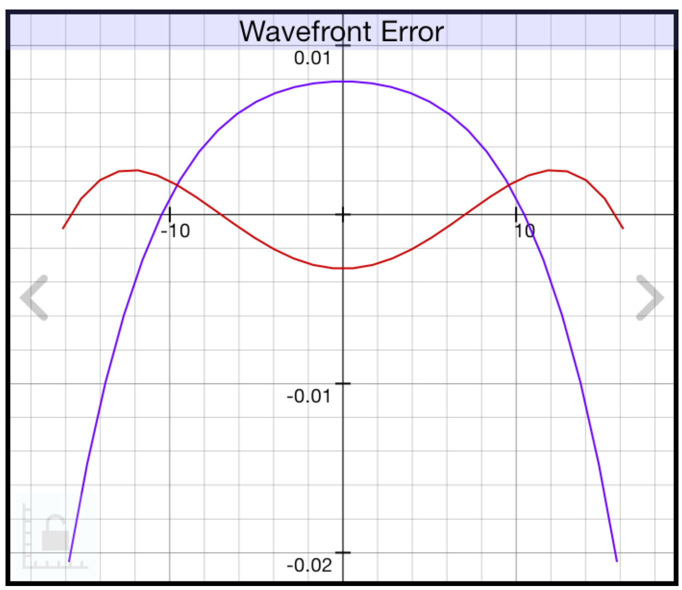
3.1. Fan Ray Plot

Fan Ray Plot displays the location at which rays hit the IMAGE surface as a function of the ray's fan angle. Use this plot to display ray aberration as a function of fan angle. In order to see a smooth plot, you should set the # of Fan Rays fairly high.



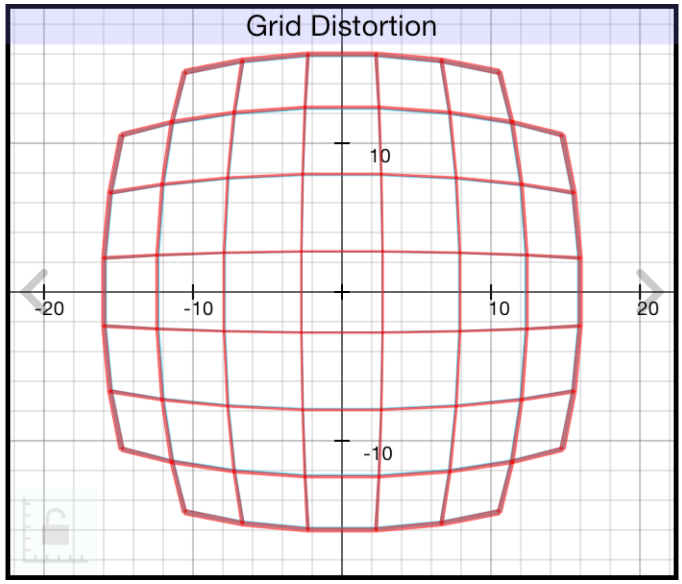
3.2. Wavefront Error Plot

Wavefront Error Plot displays the variation in optical path length between the OBJECT surface and the IMAGE surface as a function of source point location. Use this plot to see how flat the wavefront is on the IMAGE surface. In order to see a smooth plot, you should set the # of Source Points fairly high.



3.3. Grid Distortion

This plot show how regular square grid is distorted by the optical system. It can be used to study effects such as



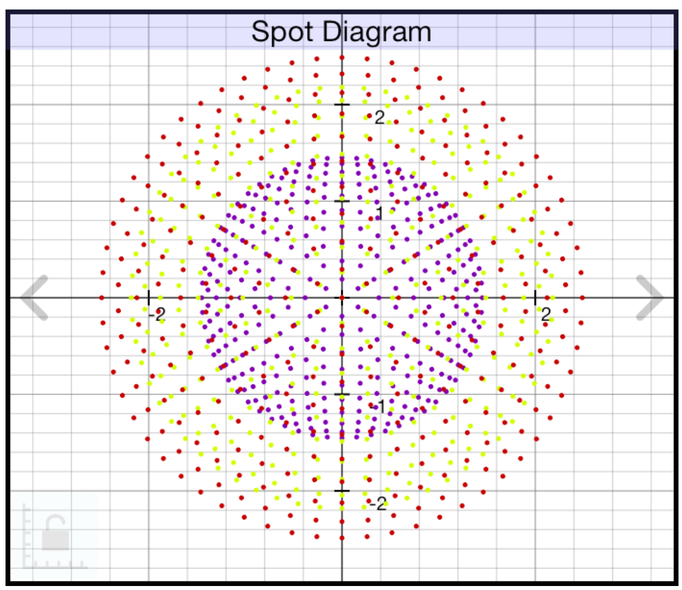
- **Barrel distortion**: In barrel distortion, image magnification decreases with distance from the optical axis. This is typically observed with a fisheye camera lens.
- **Pincushion distortion**: In pincushion distortion, image magnification increases with the distance from the optical axis.

See also:

- Distortion

3.4. Spot Diagram

A lens spot diagram shows how a circular "spot" of light which should appear as a "spot" on the IMAGE plane actually appears as a result of passing thru the optical system. It provides a visual indication of image quality produced by the lens system. It can be used to see effects such as spherical aberration, coma, astigmatism, and chromatic aberration.

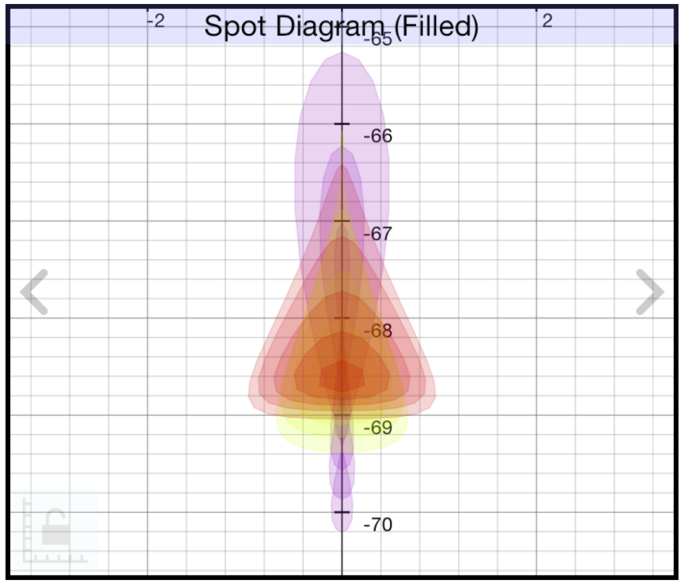


See also:

- Optical Aberration
- Spherical Aberration
- Coma
- Astigmatism

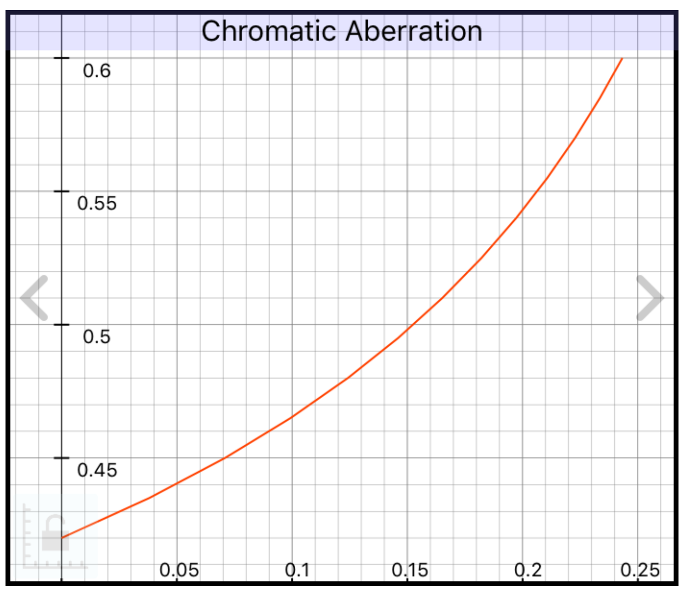
3.5. Spot Diagram (Filled)

This plot is similar to a Spot Diagram, but instead of drawing points for individual rays, displays shaded regions corresponding to cones of light from the source.



3.6. Chromatic Aberration

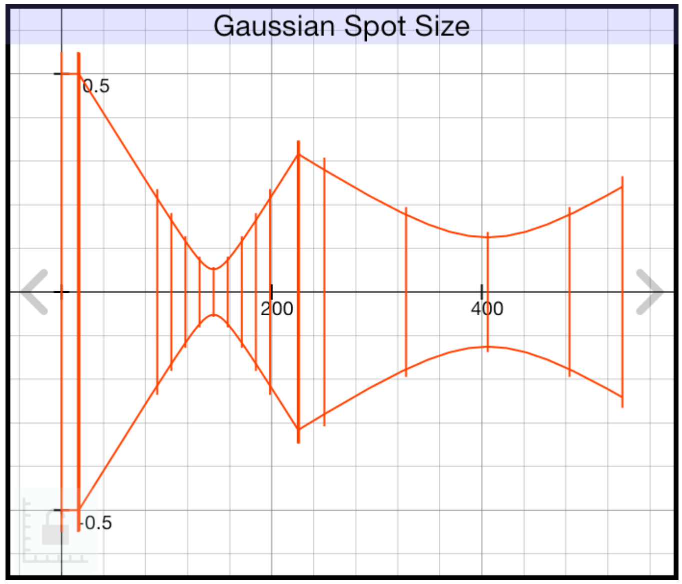
This plot shows Wavelength vs. the change in effective focal length.



3.7. Gaussian Spot Size

This plot shows beam radius as a function of distance for a laser beam as it travels thru the optical system. When focusing a laser beam, the spot size (radius) w(z) will be at a minimum value w0 at one place along the beam axis, known as the beam waist. As the beam passes thru various optical components, additional waists may be seen.

In addition to spot size, the plot shows location and curvature of beam wavefronts. Near the waist, wavefronts are displayed with a spacing of 1Rayleigh range (zR). Away from the waist, they are displayed as pairs with spacing of 10zR.

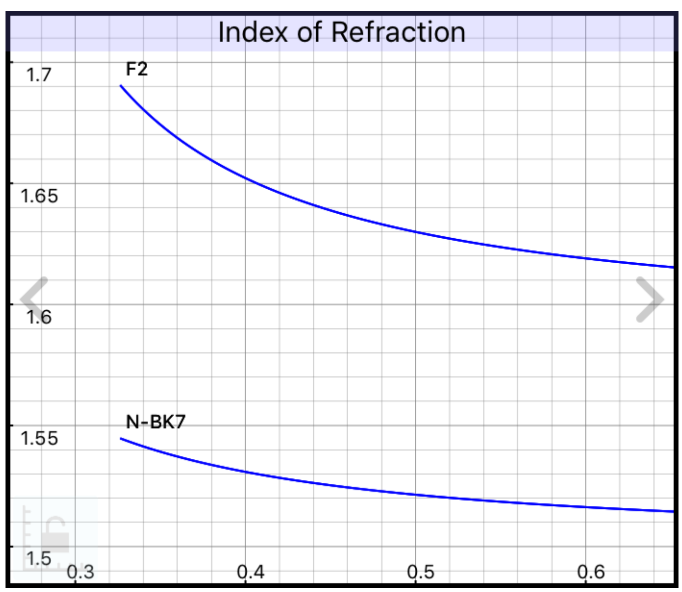


This plot is complimented by the Paraxial Gaussian Beam Analysis report.

For additional info refer to section 6 Gaussian Beams.

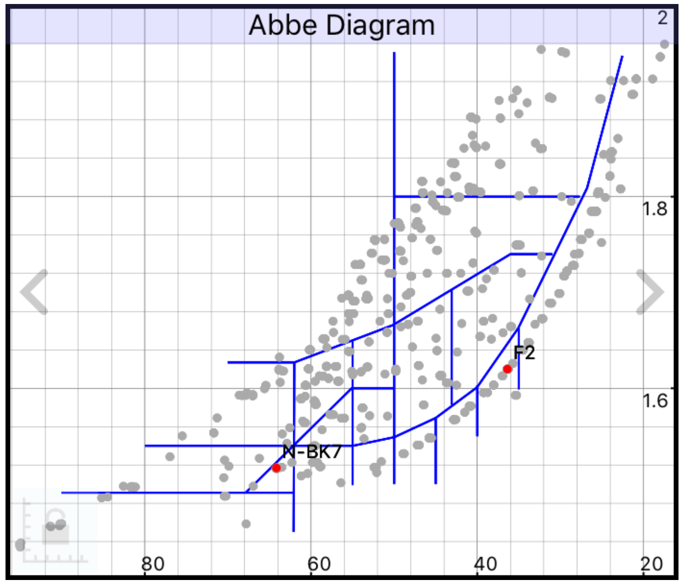
3.8. Glass Index of Refraction

The Glass Index of Refraction plot displays Index of refraction as a function of wavelength for the glass definitions used by the optical system. The range of wavelengths used corresponds to the wavelength range defined in the Source ray options.



3.9. Glass Map (Abbe Diagram)

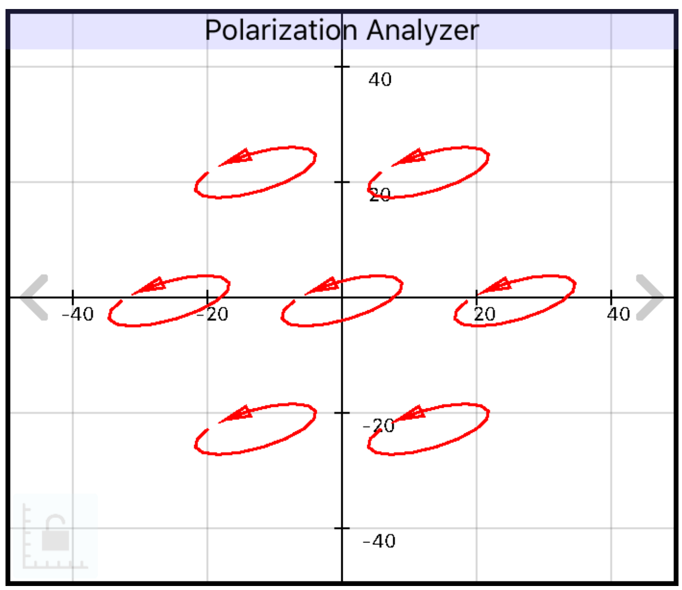
The Glass Map indicates the position of the glasses used by the optical system on an Abbe Diagram. Abbe number V_d of a material is plotted against its refractive index n_d. Optical glasses are categorized according to their positions on the diagram. Other glasses available in RayLab's glass catalogs are displayed as grey dots on the diagram.



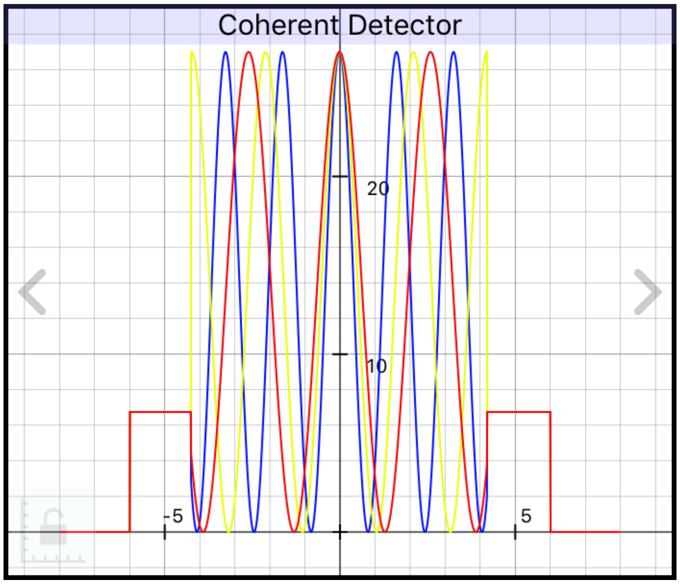
3.10. Polarization Analyzer

The Polarization Analyzer window displays the polarization state of every ray which is incident on the IMG surface.

For further information regarding polarization analysis see section 10. Polarization Ray Tracing.



3.11. Coherent Detector



The Coherent Detector window can be used along with Ray Splitting analysis to compute interference patterns. Interference patterns are produced when beams which have been split as by a beam splitter take different paths to reach the IMG surface. A separate interference pattern is produced at each wavelength. While RayLab does not model diffraction thru slits, interesting models such as the Michelson interferometer can be demonstrated using the Coherent Detector.

For addition information see section 11. Ray Splitting/Beam Splitters.

4. Reports Window

RayLab provides a range of reports for displaying information about the system. The reports can be selected from the System Options menu.

On the iPad the reports are displayed at the bottom of the model Layout screen. But they can be expanded to full screen view by tapping on the maximize icon.

On the iPhone reports can only be viewed in full screen mode.

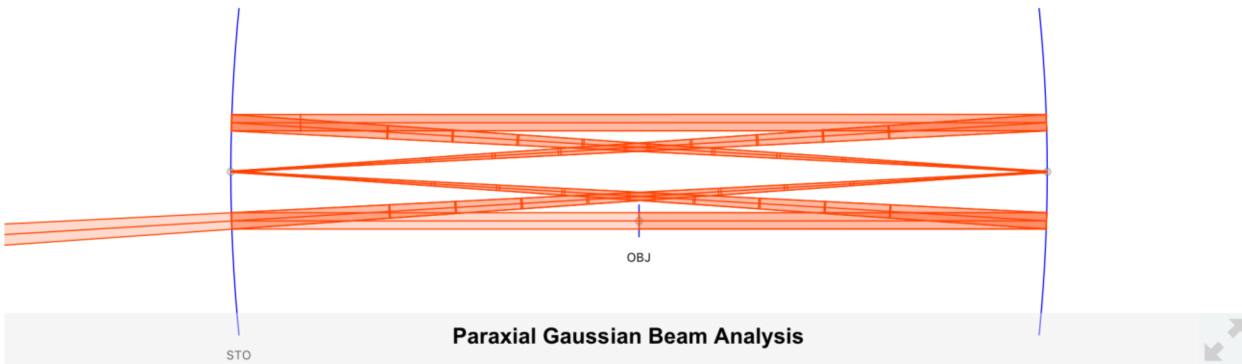
The following reports are available.

- Gaussian Beam Analysis
- Ray Transfer Matrix (Basic)
- Ray Transfer Matrix (with Tilt/Decenter)
- Ray Transfer Matrix (Relative to Reference Ray)
- System Prescription
- Ray Report (in Global Coordinates)
- Ray Report (in Local Surface Coordinates)
- Ray Refraction Report
- Optimization Report

4.1. Paraxial Gaussian Beam Analysis

The Paraxial Gaussian Beam Analysis report compliments the Gaussian Spot Size Analysis window. Complex Beam parameter is used along with the Ray Transfer Matrix analysis to compute the properties of a Gaussian beam at a particular point along the beam. These properties are listed at each surface for the beam segment following the surface. They include beam size, waist radius, waist location relative to the surface, radius of curvature, divergence, and Rayleigh length.

For additional info refer to section 6 Gaussian Beams.



Paraxial Gaussian Beam Analysis

Wavelength: 633.000 nm **M^2:** 2.00

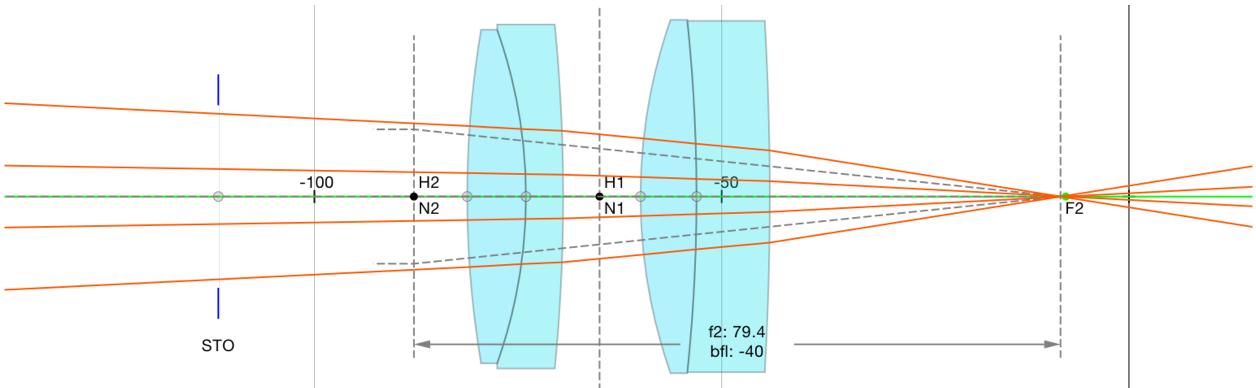
Surf	Size	Waist	Position	Radius	Divergence	Rayleigh
0	5.000000e-01	5.000000e-01	0.000000e+00	inf	8.059607e-04	6.203777e+02
1	5.004043e-01	4.024717e-02	4.981537e+01	-5.013971e+01	1.001264e-02	4.019637e+00
2	4.031283e-02	4.030156e-02	9.534272e-02	-1.704806e+02	9.999125e-03	4.030508e+00
1	5.010757e-01	4.997198e-01	4.568021e+01	-8.452089e+03	8.064125e-04	6.196826e+02
2	4.997315e-01	4.019305e-02	4.968148e+01	-5.000496e+01	1.002612e-02	4.008834e+00

4.2. Ray Transfer Matrix

The Ray Transfer Matrix report displays computed ABCD ray transfer matrices at each surface. The report includes 3 key entries for each surface.

- The distance from the previous surface.
- The ray transfer matrix of each surface (i.e. the matrix required to compute rays exiting the surface given the rays incident upon the surface.
- The cumulative ray transfer matrix from the OBJ surface to each surface.

Three variants of the Ray Transfer Matrix report are available.



Surface	Distance	Surface RTM	Total RTM
1	9843.09	$\begin{bmatrix} 1 & 0 \\ -0.0046723 & 0.659955 \end{bmatrix}$	$\begin{bmatrix} 1 & 9843.09 \\ -0.0046723 & -45.3299 \end{bmatrix}$
2	6.06464	$\begin{bmatrix} 1 & 0 \\ 0.000166853 & 0.937143 \end{bmatrix}$	$\begin{bmatrix} 0.971664 & 9568.18 \\ -0.00421649 & -40.8841 \end{bmatrix}$
3	2.36754	$\begin{bmatrix} 1 & 0 \\ 0.00292075 & 1.61689 \end{bmatrix}$	$\begin{bmatrix} 0.961682 & 9471.38 \\ -0.00400875 & -38.4415 \end{bmatrix}$

4.2.1. Basic Axial Analysis

This approach uses a 2x2 matrix (the standard ABCD matrix). It assumes all elements are on the z axis. Any tilt or decenter is ignored. Only the z coordinate of the surface vertices are used. This is the technique in most introductory descriptions of Ray Transfer Matrix analysis.

4.2.2. Axial Analysis with Tilt/Decenter

This approach uses a 3x3 matrix. In addition to the usual ABCD elements, two additional elements, E and F, are used to account for tilt and decenter of the optical surfaces. The technique is valid for nearly axial systems with small tilt or decenter relative to the z axis.

4.2.3. Analysis Relative to Reference Ray

This approach uses a 2x2 matrix as well. However, unlike the basic approach, ray offsets and angles are measured relative to the reference ray. This requires more sophisticated calculations for each surface to account for change in coordinate system. The technique is valid for analyzing a narrow pencil of rays which are close to the reference ray, even for non axial systems.

4.3. System Prescription

The System prescription report displays information about every optical surface in the system, including surface type, surface position, surface shape, surface glass, etc. It also reports the index of refraction for every glass material in the system at the wavelengths used during ray tracing.

System Prescription

Surf	Type	Glass	Radius	Thickness	Edge	Hole	Shape	Details
0	OBJ		5	0	0	0		
1	Mirr		28.2	0	0	0		
2	Mirr		20	0	0	0		
3	Lens	N-SF2	15	6.00001	0	0	R: 39.5427 K: 0.856248 A_2: 0.00402963	
4	Lens		15	0	0	0		
5	Lens	N-BK7	15	5.99998	0	0		
6	Lens		15	0	0	0	R: -39.5427	
7	IMG		20	0	0	0		

Surface Positions

Surf	x	y	z	tilt x	tilt y	tilt z
0	5.7088e+01	0.0000e+00	1.2331e+02	0.0000e+00	1.8195e+02	0.0000e+00
1	4.9620e+01	0.0000e+00	0.0000e+00	-0.0000e+00	-4.4027e+01	-0.0000e+00
2	0.0000e+00	0.0000e+00	0.0000e+00	-0.0000e+00	4.5000e+01	-0.0000e+00
3	0.0000e+00	0.0000e+00	1.8424e+01	-0.0000e+00	0.0000e+00	-0.0000e+00
4	8.9528e-13	0.0000e+00	2.4424e+01	-0.0000e+00	-1.2213e-12	-0.0000e+00
5	0.0000e+00	0.0000e+00	5.3814e+01	-0.0000e+00	0.0000e+00	-0.0000e+00
6	2.5466e-15	0.0000e+00	5.9814e+01	-0.0000e+00	0.0000e+00	-0.0000e+00
7	0.0000e+00	0.0000e+00	1.0000e+02	-0.0000e+00	0.0000e+00	-0.0000e+00

Glass Index of Refraction

	Wavelength	N-SF2	N-BK7
	600.000	1.647	1.516
	665.000	1.642	1.514
	730.000	1.638	1.512

4.4. Ray Report

The Ray report lists information about the position and direction of the rays in the model as they intersect each surface in the system. Two versions of the report are available, one providing information in the global coordinate system, and the other providing information in local surface coordinates.

4.4.1. In Global Coordinates

Ray Report

(In Global Coordinates)

Wavelength: 575.000 nm **Ray:** 1

Surf	Type	x	y	z	a_x	a_y	a_z
0	OBJ	0.000000e+00	0.000000e+00	0.000000e+00	-1.483405e-01	0.000000e+00	9.889364e-01
3	Lens	-5.111476e+00	0.000000e+00	3.407651e+01	-8.010420e-02	0.000000e+00	9.967865e-01
4	Lens	-5.576896e+00	0.000000e+00	3.986802e+01	-1.070896e-01	0.000000e+00	9.942494e-01
1	Lens	-7.322186e+00	0.000000e+00	5.607177e+01	-2.287270e-01	0.000000e+00	9.734906e-01
2	Lens	-8.654280e+00	0.000000e+00	6.174133e+01	-3.850551e-02	0.000000e+00	9.992584e-01
5	IMG	-1.852898e+01	0.000000e+00	3.180000e+02	-3.850551e-02	0.000000e+00	9.992584e-01

4.4.2. In Local Surface Coordinates

Ray Report

(In Local Surface Coordinates)

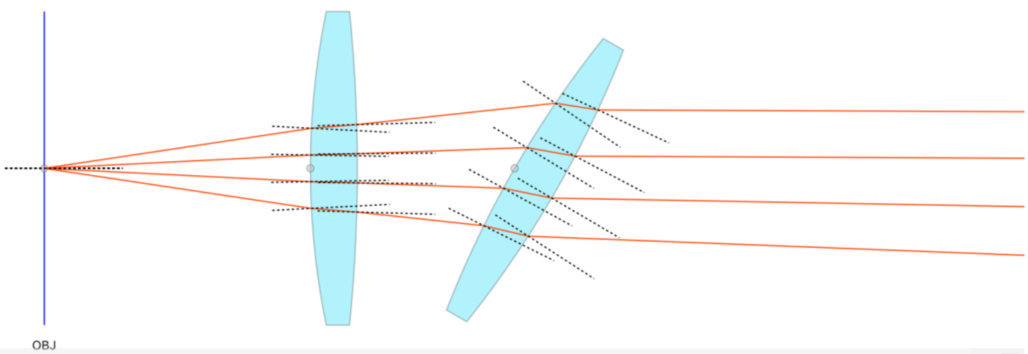
Wavelength: 575.000 nm **Ray:** 1

Surf	Type	x	y	z	a_x	a_y	a_z
0	OBJ	0.000000e+00	0.000000e+00	0.000000e+00	-1.483405e-01	0.000000e+00	9.889364e-01
3	Lens	-5.111476e+00	0.000000e+00	1.307223e-01	-8.010420e-02	0.000000e+00	9.967865e-01
4	Lens	-5.576896e+00	0.000000e+00	-7.776863e-02	-1.070896e-01	0.000000e+00	9.942494e-01
1	Lens	-8.305315e+00	0.000000e+00	2.591456e-01	2.886619e-01	0.000000e+00	9.574311e-01
2	Lens	-6.624148e+00	0.000000e+00	-1.647946e-01	4.662824e-01	0.000000e+00	8.846359e-01
5	IMG	-1.852898e+01	0.000000e+00	0.000000e+00	-3.850551e-02	0.000000e+00	9.992584e-01

4.5. Ray Refraction Report

The Ray Refraction report lists the input and output ray angles relative to the surface normals as well as the index of refraction on either side of the surface. When this report is active the surface normals are displayed in the lens view.

This report also identifies reflections and total internal reflections. It is of particular use in studying Snell's Law.



Ray Refraction Report

Wavelength: 575.000 nm **Ray:** 1

Surf	Type	n_{in}	n_{out}	θ_{in}	θ_{out}	
3	Lens	1.000	1.517	11.461	7.524	Refraction
4	Lens	1.517	1.000	2.997	4.550	Refraction
1	Lens	1.000	1.517	20.278	13.204	Refraction
2	Lens	1.517	1.000	19.628	30.643	Refraction
5	IMG	1.000	1.000	2.207	2.207	

4.6. Optimization Report

Optimization Report

Parameters

#	Surface	Param	Type	Value	Sensitivity	Ref Surface	Multiplier	Offset
0	0	ANGY	Variable	1.8195e+02	1.0000e+00			
1	1	ANGY	Variable	-4.4027e+01	1.0000e+00			
3	4	RADIUS	Calculate	1.5000e+01		3	1.0000e+00	0.0000e+00
4	5	RADIUS	Calculate	1.5000e+01		4	1.0000e+00	0.0000e+00
5	5	POSZ	Variable	5.3814e+01	1.0000e+00			
6	6	R	Calculate	-3.9543e+01		3	-1.0000e+00	0.0000e+00
7	6	RADIUS	Calculate	1.5000e+01		5	1.0000e+00	0.0000e+00

Operands

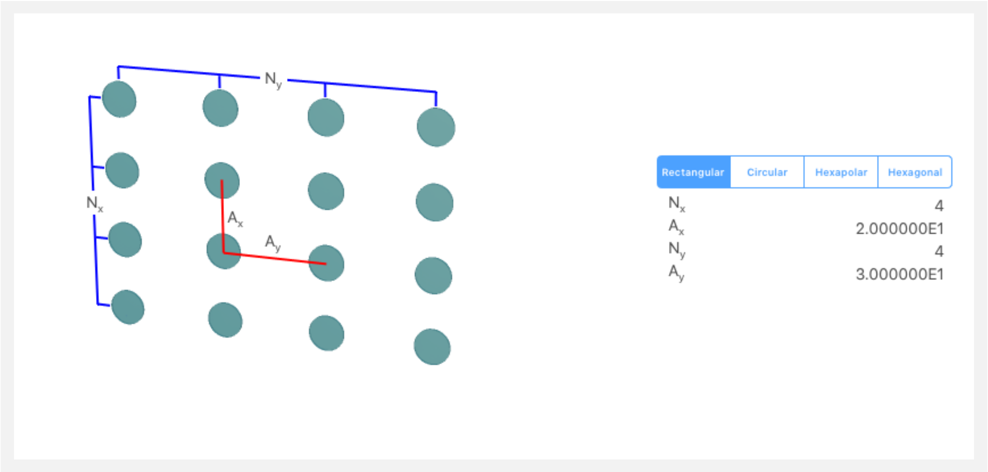
#	Type	Target	Weight	Cost	Contrib %
0	x @ Surf 1 (Ref Ray)	0.0000e+00	1.0000e+00	2.2231e+01	96.66
1	x @ IMG Surf (Ref Ray)	0.0000e+00	1.0000e+00	7.6850e-01	3.34
2	Focus	0.0000e+00	1.0000e+00	0.0000e+00	0.00

5. Source/Lens Arrays

Arrays of optical element or sources can be easily defined in RayLab and are much easier than defining multiple instances of each element. Arrays can be defined in a variety of patterns.

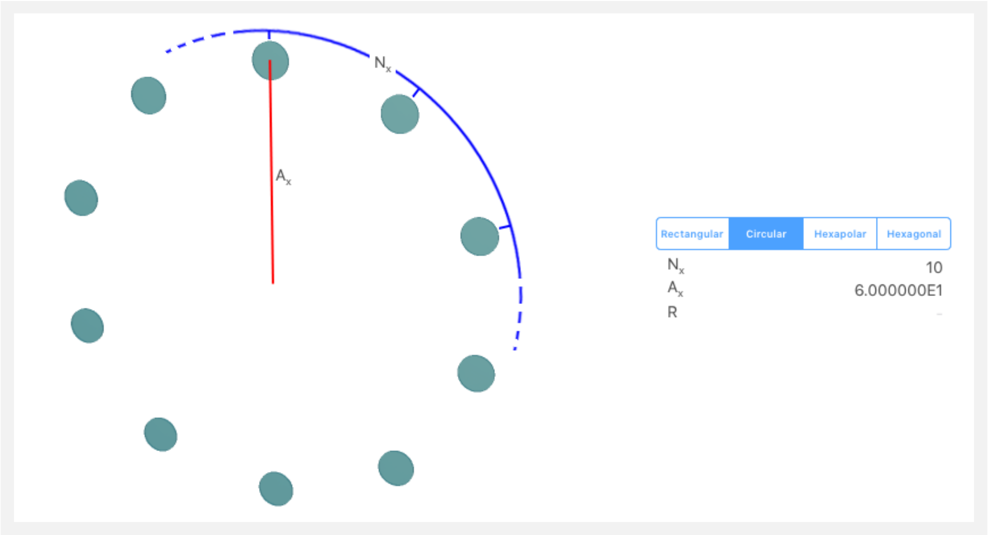
5.1.1. Rectangular Grid

The rectangular array allows you to define 1D or a 2D array with independently specified number of elements and spacing in both the X and Y direction.



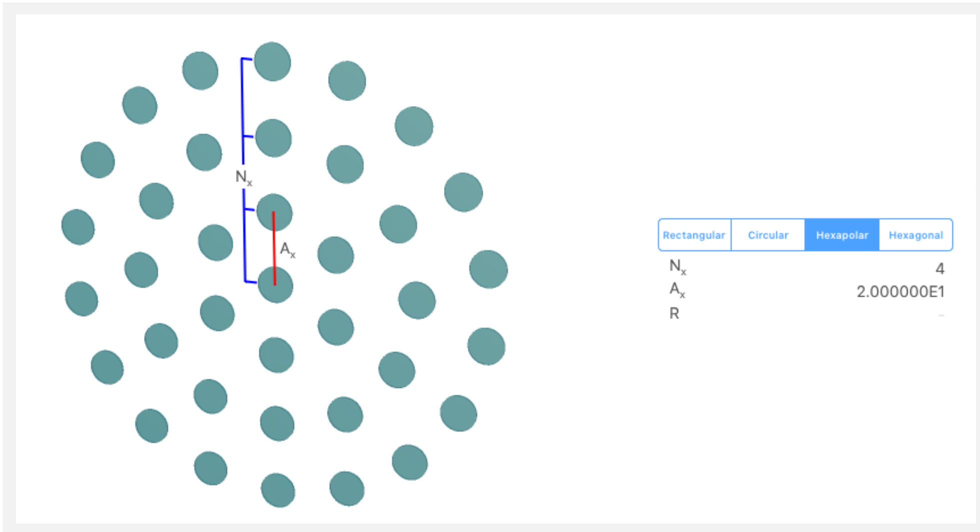
5.1.2. Circular Array

The circular array allows you to arrange any number of elements in a circle with desired radius.



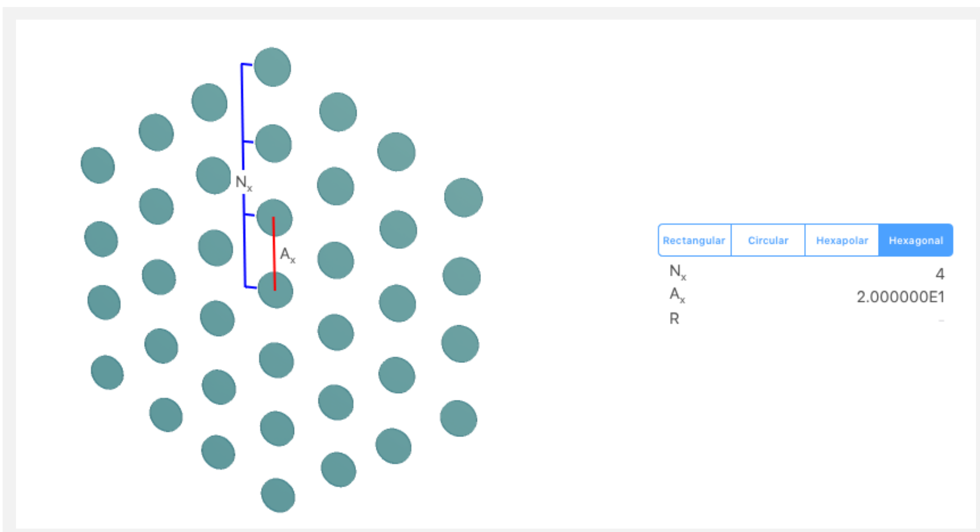
5.1.3. Hexapolar Grid

The hexapolar grid consists of a specified number of rings of elements. Each ring has six more elements than the previous ring. The spacing parameter is the radial spacing in the x direction.



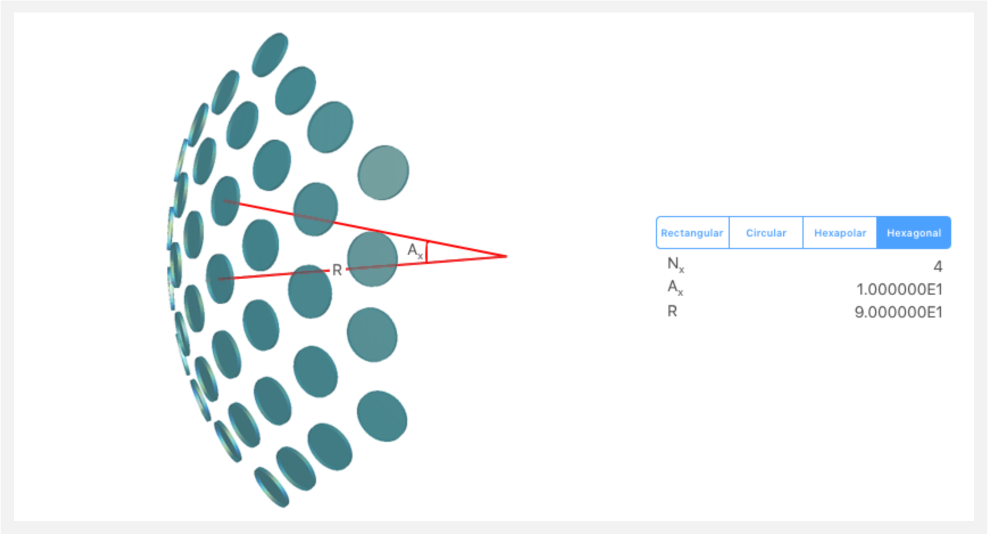
5.1.4. Hexagonal Grid

The hexagonal grid arranges the elements in a hexagonal pattern. As with the hexapolar grid the number of rings and spacing in the x direction are specified.



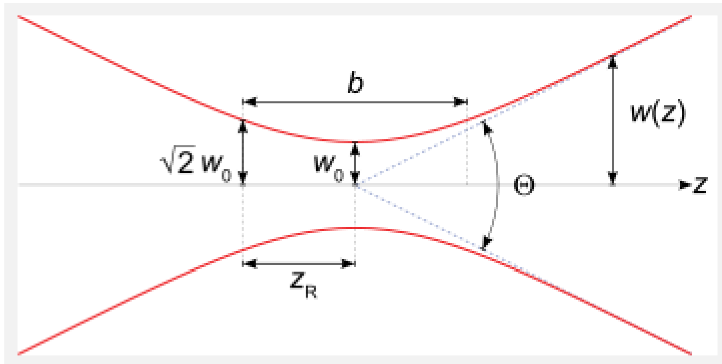
5.1.5. Planar/Spherical

The Circular, Hexapolar, and Hexagonal arrays can be arranged on a flat surface or a spherical surface. A spherical surface is used when R is not zero. In this case the spacing parameter is treated as an angle instead of a distance. The spherical option is not available for source arrays.


Rectangular
Circular
Hexapolar
Hexagonal
N_x
4
A_x
1.000000E1
R
9.000000E1
A_x
R

6. Gaussian Beams

RayLab provides the ability to model propagation of Gaussian beams using the Complex Beam Parameter and Ray Transfer Matrices (https://en.wikipedia.org/wiki/Complex_beam_parameter).



Gaussian beam width w(z) as a function of the axial distance z. w0: beam waist; b: depth of focus; zR: Rayleigh range; Θ: total angular spread. [Source: Wikipedia]

The complex beam parameter is denoted by q(z) and is a complex number defined as:

$$\frac{1}{q(z)} = \frac{1}{R(z)} - \frac{i\lambda_0}{\pi n w(z)^2}$$

Where R(z) is the beam radius of curvature at position z, and w(z) is the beam radius at z. This quantity is propagated thru the system using the ABCD Ray Transfer Matrix. RayLab uses the Ray Transfer Matrix computed relative to a Reference Ray for this purpose. The propagation using ABCD matrix takes the form:

$$\frac{1}{q_f} = \frac{C + D/q_i}{A + B/q_i}$$

The results of the analysis can be viewed in:

- Gaussian Spot Size Analysis window (Section 3.7)
- Paraxial Gaussian Beam Analysis report (Section 4.1)

7. Ray Transfer (ABCD) Matrix Analysis

Ray Transfer Matrices allow representing multiple optical elements with a single matrix. This technique uses the paraxial approximation, which means rays are assumed to be at a small angle and a small offset from the optical axis. See general introduction to Ray Transfer Matrices on Wikipedia.

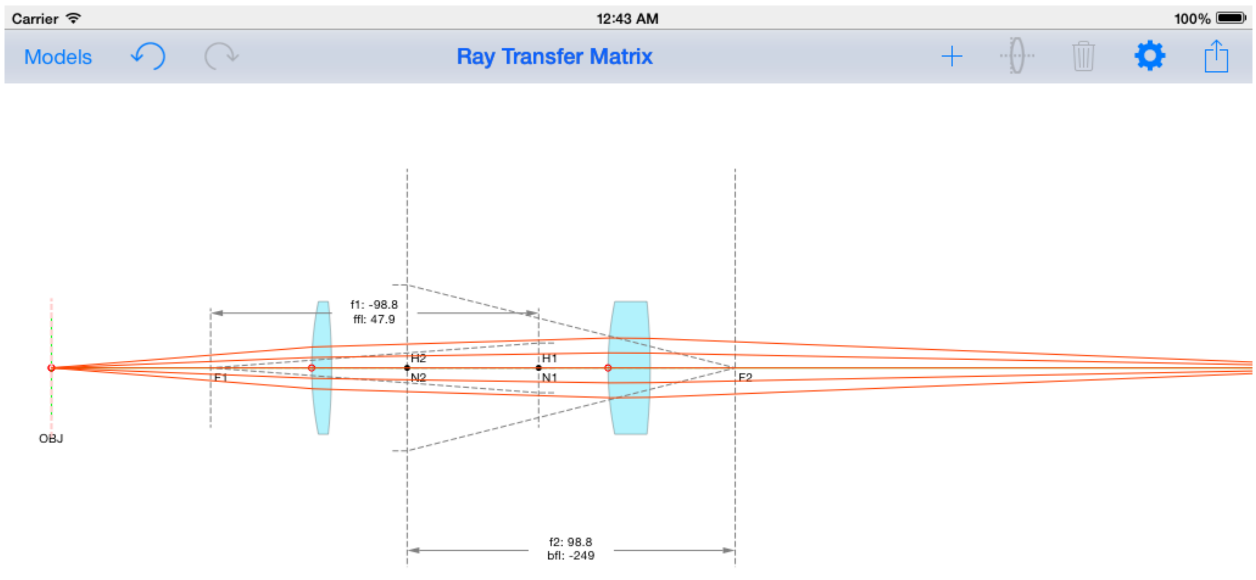
RayLab offers three analysis modes for computing Ray Transfer Matrices. These can be selected from the main model options menu.

All three modes use a reference ray leaving the object in order to determine the order in which optical surfaces are encountered. RayLab then computes the Ray Transfer Matrix by combining the RTMs for the encountered surfaces, as well as the RTMs representing their distances.

The 3 different analysis modes are as follows:

- Basic Axial Analysis: This approach uses a 2×2 matrix. It assumes all elements are on the z axis. Any tilt or decenter is ignored. Only the z coordinate of the surface vertices are used. This is the technique in most introductory descriptions of Ray Transfer Matrix analysis.
- Axial Analysis with Tilt/Decenter: This approach uses a 3×3 matrix. In addition to the usual ABCD elements, two additional elements, E and F, are used to account for tilt and decenter of the optical surfaces. The technique is valid for nearly axial systems with small tilt or decenter relative to the z axis.
- Analysis Relative to Reference Ray: This approach uses a 2×2 matrix as well. However, unlike the basic approach, ray offsets and angles are measured relative to the reference ray. This requires more sophisticated calculations for each surface to account for change in coordinate system. The technique is valid for analyzing a narrow pencil of rays which are close to the reference ray, even for non axial systems.

When performing Ray Transfer Matrix analysis, RayLab generates a report of all relevant matrices. It also uses the information to compute the cardinal points and surfaces for the system, and displays them in the main window.



Ray Transfer (ABCD) Matrices

Analysis Relative to Reference Ray

Wavelength: 575.000 nm

Surface	Distance	Surface RTM	Total RTM
0	0	$\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$	$\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$
3	78.3456	$\begin{bmatrix} 1 & 0 \\ -0.00340952 & 0.659048 \end{bmatrix}$	$\begin{bmatrix} 1 & 78.3456 \\ -0.00340952 & 0.391926 \end{bmatrix}$

Effective Focal Length: 111.934 Magnification: -2.061

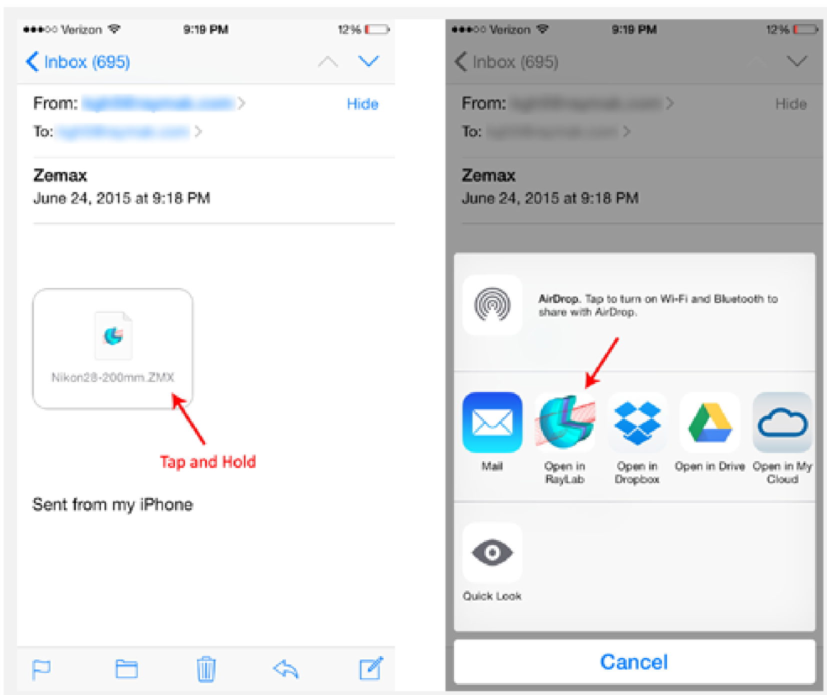
8. Zemax (.ZMX) File Import

Zemax (.ZMX) files can be imported into RayLab. Full 3D files can be imported if RayLab's 3D Modeling module has been enabled. In 2D, the Zemax importer works for axisymmetric systems or systems which are restricted to x-z plane.

- The STANDARD, COORDBRK, EVENASPH, FRESNELS, and DGRATING Zemax surface types are recognized in Sequential models.
- The Standard Lens and Elliptical Volume elements are recognized in Nonsequential models.
- Glasses are loaded by name and any unrecognized glass is replaced by Custom glass.

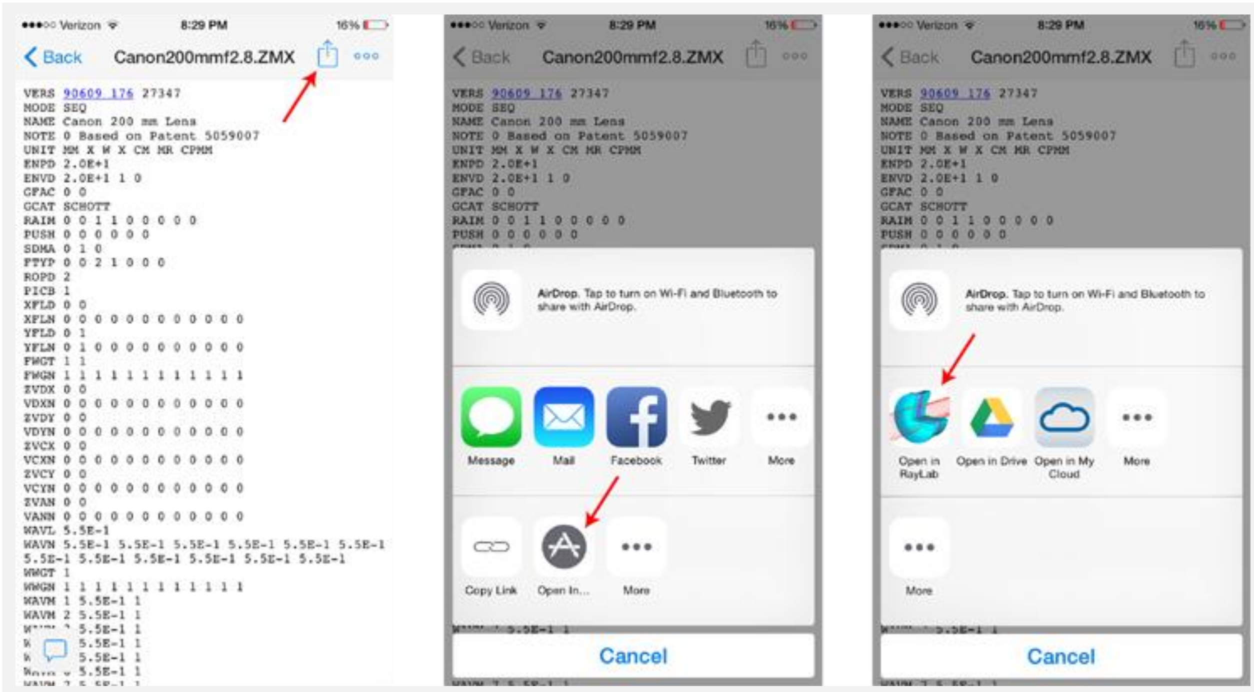
8.1. From Mail App

If the Zemax file is a Mail attachment, tap and hold the attachment until "Open in RayLab" option appears.



8.2. From Dropbox App

Alternatively use any file management App such as Dropbox, Google Drive, Documents, etc. to transfer the file to your device, and then select the "Open in RayLab" option within that App.



Many other file handling apps have a similar mechanism to Dropbox depicted above.

8.3. Import from Online Catalogs

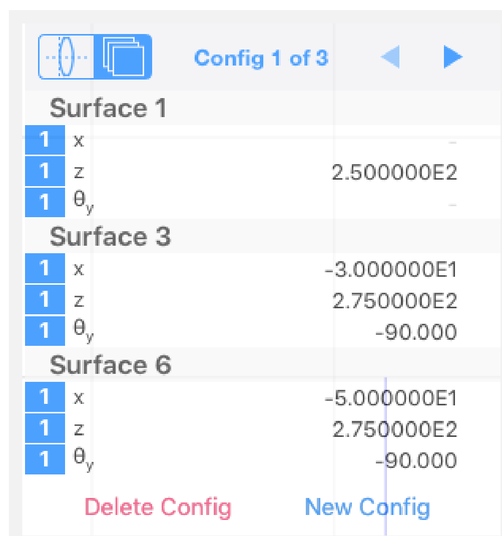
RayLab, also enables importing Zemax (.ZMX) definitions for Commercial Off The Shelf (COTS) lenses from a number of popular lens vendors. From the toolbar menu on RayLab's Model Browse window select 'Import from Optics Catalog'. Then follow the link provided for the desired vendor, and browse to find the .ZMX file for the component of your choice. When the ZMX file is opened you will be given the option to Import the model into RayLab.

9. Multi-Configuration Manager

The Multi-Configuration Manager allows definition of multiple configurations within the same model. Most surface properties can be placed under configuration control, and assigned different values for each configuration. Any parameter which is not under configuration control will have the same value in all configurations. You can easily switch between configurations or even view interpolated states. This functionality is ideal for modeling systems with moving elements such as zoom lenses, tracking systems, or for comparing different configurations of a system.

To use the multi-configuration feature proceed as follows:

1. Start with an initial model of the system, containing all the optical elements.
2. Select which surface parameters will be under configuration control by taping the ‘Multiple Configs’ button next to the parameter. For example you may choose [Surf 1 x coord], [Surf 1 radius], [Surf 5 z coord], etc.
3. Switch from the surface parameter view to the multi-config parameter view by using the multi-config-button.
4. Then tap ‘New Config’ to add as many configurations as needed.
5. You can then switch between different configurations, and adjust the parameter values in each case.

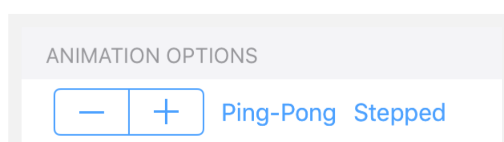


Each time you switch to another configuration the model is updated accordingly.

With multiple configurations a slider is displayed on the main window allowing you to switch between different configurations. The slider uniformly interpolates parameter values between successive configurations.

Multi-Configuration Animation

You also have the ability to animate between the different configurations. Among the animation options are:



- Ability to adjust speed of animation.
- Ability to switch between Loop, Ping-Pong, or Once modes.
- Ability to animate smoothly, or to pause at each configuration.

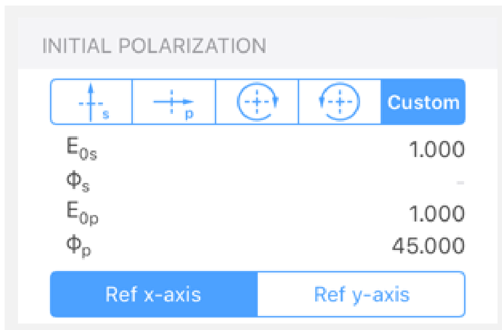
For an example, see the ‘**Sample – Zoom Lens (Multi Cfg)**’ model.

10. Polarization Ray Tracing

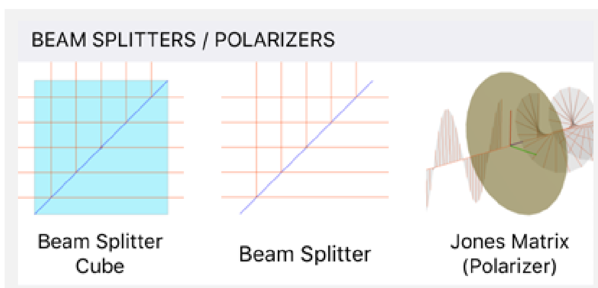
To simulate polarization in RayLab turn on Polarization Raytracing in the model Options window.

You can then specify the initial polarization of the rays in the properties window for the Object. The available options include:

- Horizontal or vertical linearly polarized light
- Left or Right Handed Circular polarized light
- Or arbitrary polarization state expressed using a Jones vector.



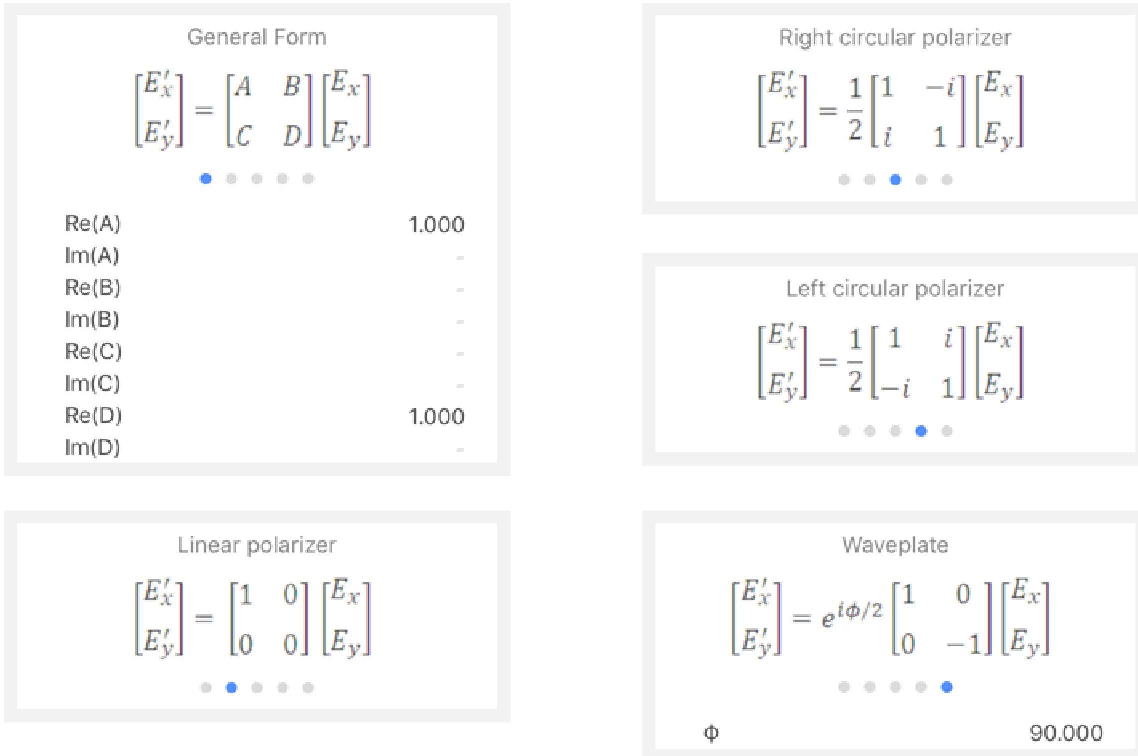
A variety of polarizing components can be modeled using the “Jones Matrix (Polarizer)” optical element.



The Jones Matrix is a 2×2 complex matrix which describes the effect of the component on the polarization of the incident beam. This element assumes that the incident rays are normal to the surface.

For more details on Jones Calculus see: https://en.wikipedia.org/wiki/Jones_calculus

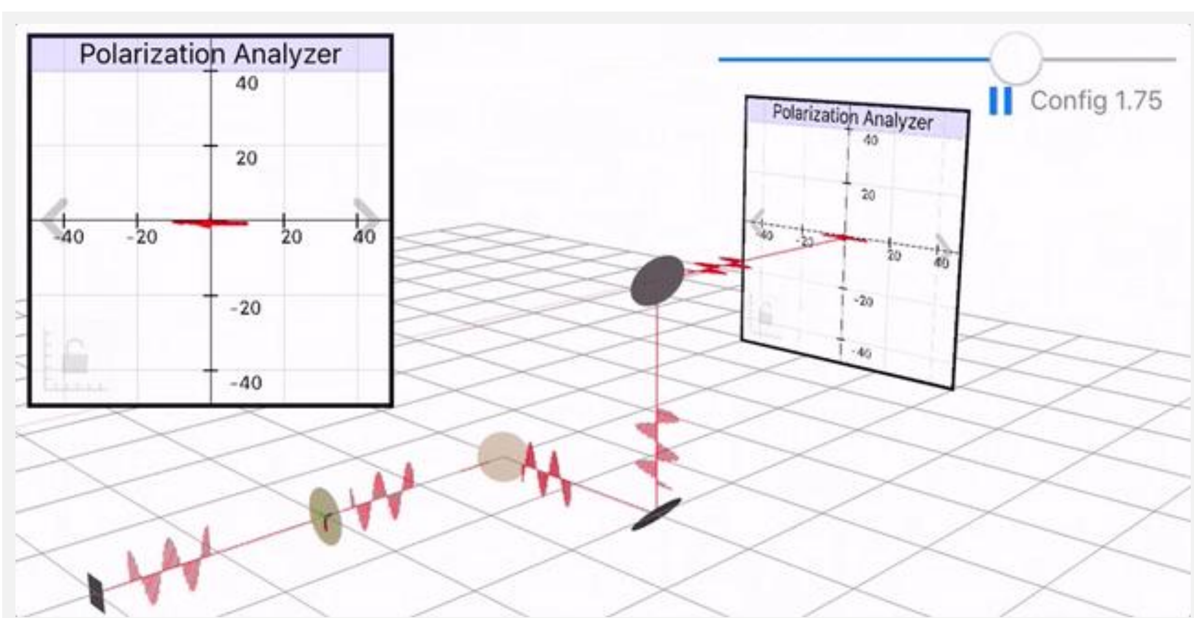
The Jones Matrix element allows you to select matrices for a Linear polarizer, Right circular polarizer, or Left circular polarizer. You also have the option to model waveplates (retarders) such as a quarter-wave or half-wave plates. Finally, you have the option to define an arbitrary Jones Matrix by specifying the real and imaginary components of the 2×2 matrix.



You can view the results of the polarization ray tracing in a number of ways:

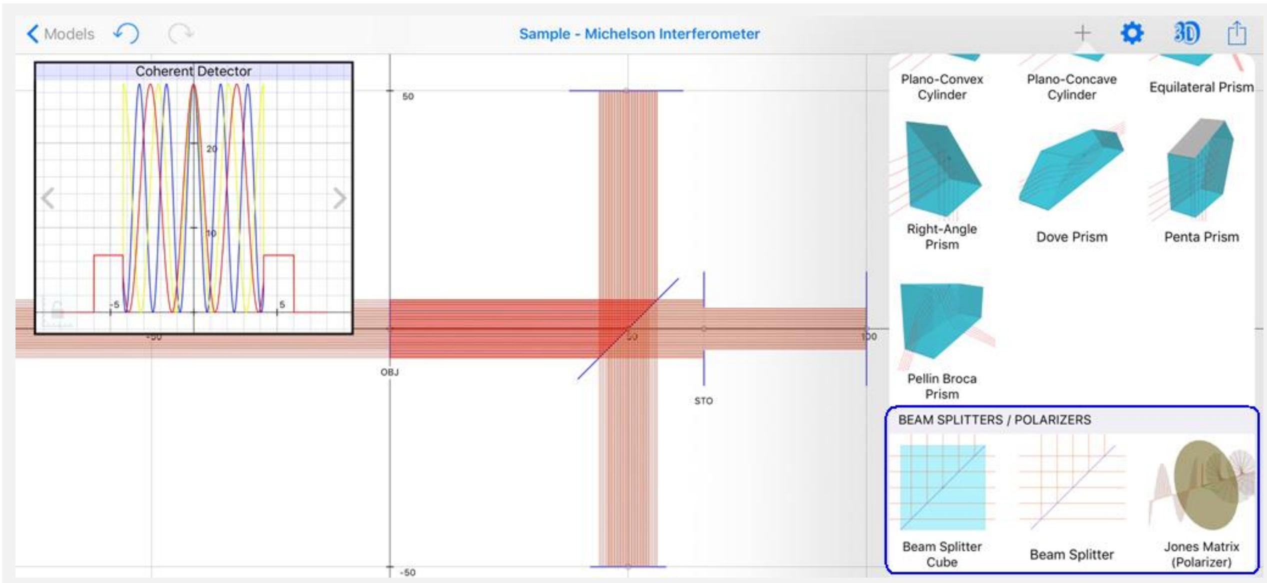
1. In the 3D layout view a representation of the electric field is displayed along each ray segment.
2. You can use the Polarization Analyzer window which displays the polarization state of each ray as it intersects the image surface.

Below is a sample model which displays results of polarization ray tracing for a rotating quarter-wave plate and three fold mirrors.



11. Ray Splitting/Beam Splitters

RayLab also has the capability to model Beam Splitters, and Interference Patterns



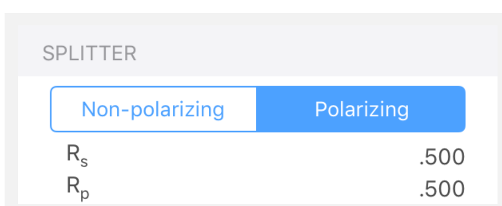
Two dedicated Splitters are available.

- Beam Splitter Cube
- Thin Beam Splitter (Pellicle)

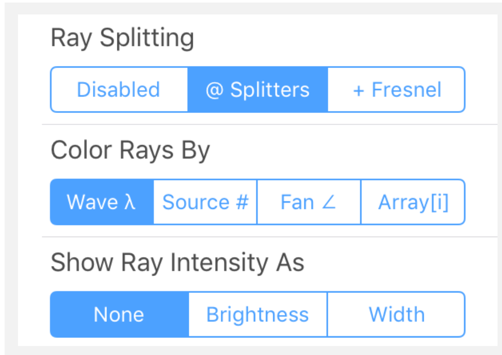
Both types of splitters support two modes of operation with respect to polarization.

- Polarizing
- Non-Polarizing

In Polarizing mode independent Reflectance can be specified for p and s polarization modes (Rp, Rs). In Non-polarizing mode, a single Reflectance R can be specified, and applies to both p and s polarizations.



Whether traced rays are split depends on the Ray Splitting mode selected in system options. Three modes of operation are available.



- Disabled: In this mode no ray splitting is performed. For every ray incident upon an optical surface, one ray leaves the surface. If the surface is a beam splitter surface, the ray is randomly reflected or transmitted in proportion to the reflectance squared.
- @Splitters: In this mode rays are split at a splitter surface. Both the transmitted and reflected rays are tracked thru the rest of the system along with information on the relative intensity of each ray. If Polarization tracing is on, s and p states are tracked separately. Otherwise average of Rs and Rp is used. Other surfaces behave normally with transmission ray being traced at glass interfaces.
- + Fresnel: In this mode, splitters behave as in the @Splitters mode. However the effect of Fresnel reflection is added to other glass interfaces. That is, non-splitter glass interfaces will produce both transmitted and reflected rays according to Fresnel equations.

When Ray Splitting mode is on, i.e. not Disabled, the intensity of each ray segment is computed by RayLab. This intensity is visible in some analysis window such as the Spot diagram. Additionally, in 2D Layout view the intensity can be represented by either the Brightness of the ray lines, or by the line widths. A non-linear scaling us used when displaying intensity as line width to make low intensity rays more visible.

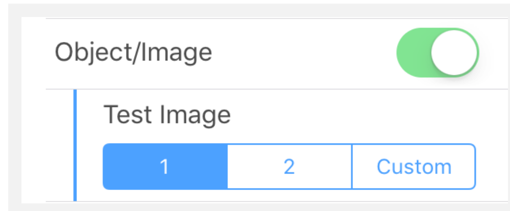
Coherent Detector

The coherent detector is a special analysis window particularly useful for use with optical systems containing beam splitters. It can be used to calculate interference patterns produced in systems such as a Michelson Interferometer. The coherent detector has limited spatial resolution. For best results use either a high number of Source Points or a high number of Fan Rays.

12. Image Formation

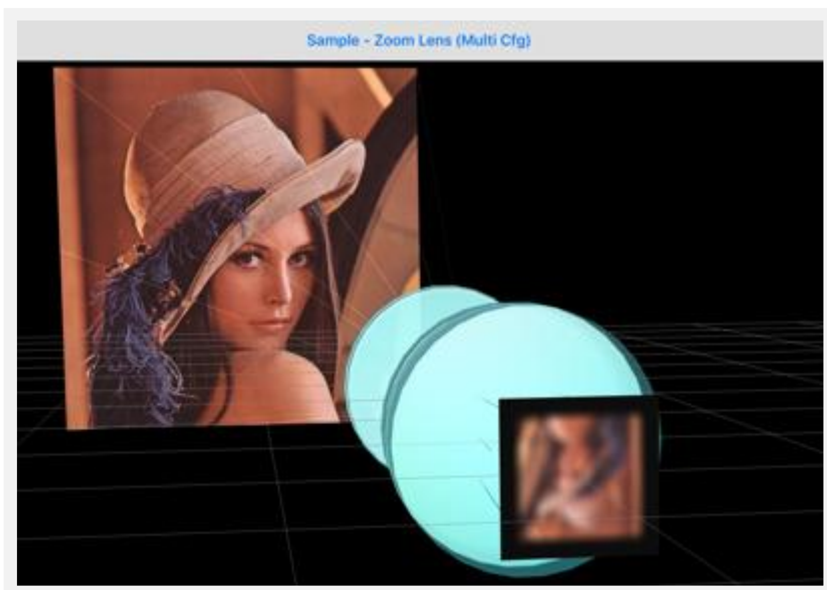
The Image Formation Simulation provides a means of evaluating image quality produced by an optical imaging system. It primarily accounts for effects of geometric and chromatic aberration and focusing. It is ideal for presenting performance of the system to non optical engineers.

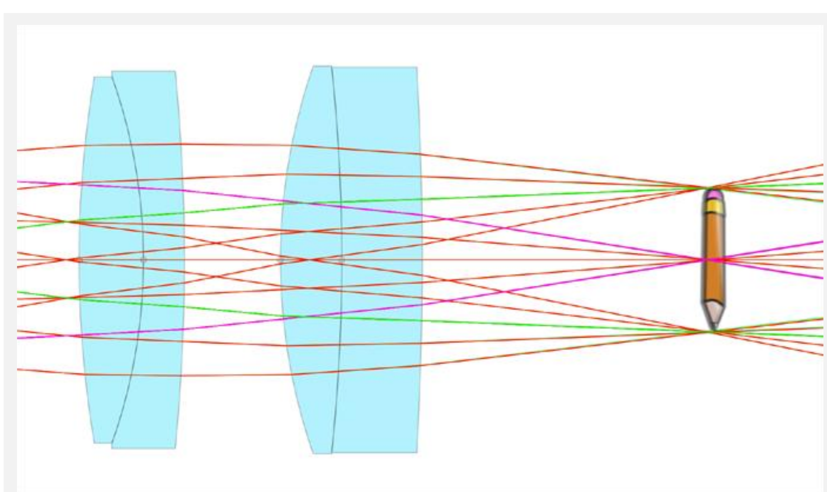
While in the 3D Layout view, turn on Object/Image. You can then choose from a number of test images/test patterns, or select a custom image from the iOS Photo Gallery.



The Test image will be placed at the OBJ surface, and the resulting image will be displayed on the IMG surface.

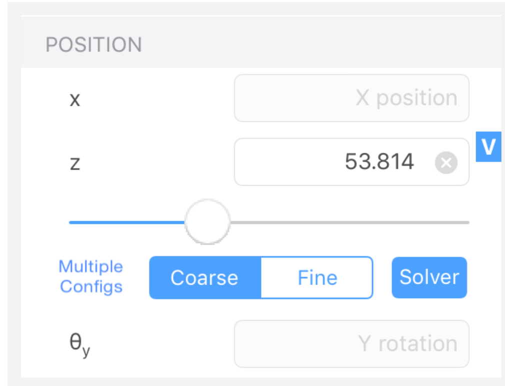
In 2D Layout view, an alternative simplified image formation graphic displays the location and size of the paraxial image for different wavelengths.





13. Solver/Optimizer

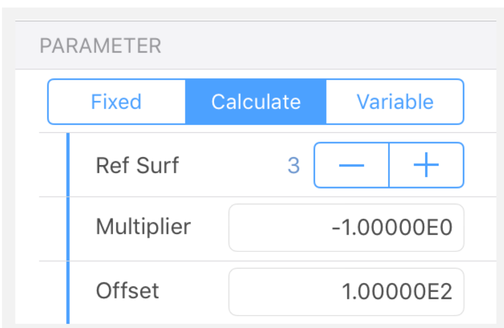
Most surface properties can be automatically computed by the solver. Each parameter may be calculated based on corresponding parameters of another surface, or may be designated as a variable in the general optimization routine.

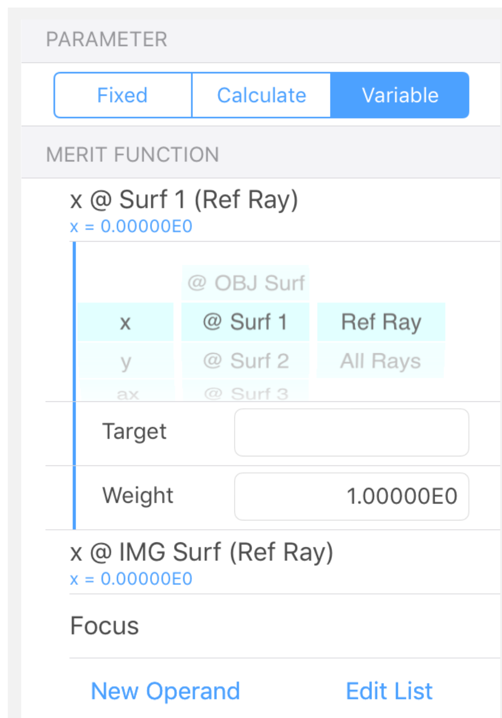


Start by selecting any parameter (for example z Position) from the Surface Property window, and tap on the **Solver** button.

Each Parameter may be designated as:

- Fixed: These parameters are set manually, and are ignored by the optimizer.
- Calculate: These parameters are calculated by applying a multiplier and an offset to the corresponding parameter from another surface.
- Variable: These parameters are solved for by optimizing a shared Merit function.





Arbitrary merit functions can be configured for the optimization routine by adding multiple operands. Example operands include auto focus, targeting desired focal length or magnification, or specifying desired position/angle of specific rays on arbitrary surfaces. The contribution from different operands are scaled by the specified weight and added to compute the total merit function.

For an example, see the following models:

- **'Sample - Lens Design using Solver'**
- **'Sample - Object Tracking using Solver'**

14. Glass Definitions

RayLab provides a number of glass catalogs from popular optical glass vendors for selecting the desired glass properties.

14.1. Custom Glass

In addition to selecting a glass material from one of the provided glass catalogs, custom glasses may be defined using one of four index of refraction formulas. Custom glass definitions are associated with a specific surface.

14.1.1. Cauchy Formula

$$n(\lambda) = A + B/\lambda^2$$

14.1.2. Sellmeier Formula

$$n^2(\lambda) = 1 + \frac{K_1\lambda^2}{\lambda^2 - L_1} + \frac{K_2\lambda^2}{\lambda^2 - L_2} + \frac{K_3\lambda^2}{\lambda^2 - L_3}$$

14.1.3. Schott Formula

$$\begin{aligned} n^2(\lambda) = {} & A_0 + A_1\lambda^2 \\ & + A_2/\lambda^2 + A_3/\lambda^4 + A_4/\lambda^6 + A_5/\lambda^8 \end{aligned}$$

14.1.4. Power Formula

$$\begin{aligned} n^2(\lambda) = {} & A_0 + A_1\lambda^2 + A_2\lambda^4 + A_3/\lambda^2 + A_4/\lambda^4 \\ & + A_5/\lambda^6 + A_6/\lambda^8 + A_7/\lambda^{10} + A_8/\lambda^{12} \end{aligned}$$

14.2. User Defined Glasses

User Defined Glasses are similar to Custom Glass definitions and provide the same choices for index of refraction formulas. However, unlike Custom Glasses which are associated with a specific surface, a User Defined Glass can be named and is then available to be referenced in multiple surfaces or in different Optical Systems.

14.3. Glass Catalogs

14.3.1. OHARA Glass Catalog

This catalog contains index of refraction formulas for the following 153 glasses:

OHARA Optical Glasses

S-FPL53	S-FSL 5	S-FPL51	S-BSL 7
S-NSL36	S-NSL 3	S-NSL 5	S-TIL 6
S-BAL12	S-TIL 2	S-TIL 1	S-BAL41
S-TIL26	S-BAL14	S-BAL 2	S-BAL 3
S-BAL11	S-TIL27	S-TIL25	S-BAM 3
S-BAL42	S-BAL35	S-FTM16	S-FPM2
S-TIM 8	S-TIM 5	S-BSM14	S-PHM53
S-BAM 4	S-BSM 2	S-TIM 3	S-NBM51
S-BSM 4	S-BSM 9	S-BSM28	S-PHM52
S-TIM 2	S-BSM16	S-BSM22	S-BSM10
S-BSM15	S-TIM 1	S-BAM12	S-BSM18
S-TIM27	S-BSM81	S-TIM22	S-BSM71
S-LAL54	S-LAL 7	S-NBH 5	S-BSM25
S-TIM39	S-BAH11	S-BAH32	S-BAH10
S-TIM25	S-NBH52	S-LAL56	S-LAL12
S-TIM28	S-LAL 9	S-LAL58	S-LAL13
S-LAM59	S-LAL14	S-TIM35	S-LAM51
S-BAH27	S-LAL 8	S-TIH 1	S-LAM 3
S-NBH 8	S-LAM58	S-LAM52	S-LAM61
S-LAL10	S-TIH18	S-BAH28	S-TIH10
S-LAL18	S-LAL59	S-NBH53	S-TIH 3
S-TIH13	S-LAL61	S-LAM60	S-LAM 2
S-LAM 7	S-NBH51	S-TIH 4	S-YGH51
S-LAM54	S-TIH14	S-LAM55	S-LAH66
S-TIH11	S-TIH23	S-LAH51	S-LAH64
S-NBH55	S-LAH52	S-LAM66	S-LAH63
S-LAH65V	S-TIH 6	S-LAH53	S-NPH 1
S-LAH59	S-LAH60	S-LAH55V	S-TIH53
S-NPH53	S-LAH71	S-LAH58	S-NPH 2
S-NPH 3	S-LAH79		

OHARA i-Line Glasses

S-FSL5Y	S-FPL51Y	BSL7Y	PBL6Y
PBL1Y	BAL15Y	PBL26Y	PBL25Y
PBL35Y	BAL35Y	PBM18Y	PBM8Y
BSM51Y	PBM2Y		

OHARA Low Tg Glasses

L-BSL 7	L-PHL 2	L-PHL 1	L-BAL42
L-BAL35	L-LAL12	L-TIM28	L-LAL13
L-LAM69	L-LAM72	L-LAM60	L-LAH87
L-LAH53	L-LAH81	L-LAH84	L-TIH53
L-LAH85	L-LAH83	L-NBH54	L-LAH86
L-BBH1			

14.3.2. SCHOTT Glass Catalog

This catalog contains index of refraction formulas for the following 120 glasses:

SCHOTT Optical Glasses

N-FK51A	N-FK5	N-PK52A	N-BK10
K10	N-ZK7	K7	P-BK7
N-BK7	N-BK7HT	N-K5	N-KF9
P-PK53	N-PK51	N-BAK2	N-BALF5
LLF1	N-PSK3	N-KZFS2	N-SK11
N-BAK4	N-BAK4HT	N-BAK1	N-BALF4
LF5	P-SK57Q1	P-SK57	N-SK5
P-SK58A	N-SK14	F5	N-BAF4
N-SK2	N-SK2HT	N-BAF52	P-SK60
N-SK4	N-KZFS4	N-KZFS4HT	N-SSK8
N-PSK53A	F2	F2HT	N-F2
N-SK16	N-SSK2	N-KZFS11	N-LAK21
N-SF2	SF2	N-LAK22	N-LAK7
N-BAF51	N-KZFS5	N-SSK5	N-BASF2
N-BAF10	SF5	N-SF5	N-LAK12
P-SF8	N-SF8	N-LAK9	P-LAK35
N-LAK14	N-SF15	N-BASF64	N-LAK8
N-SF1	SF1	N-LAK10	N-KZFS8

P-SF69	SF10	N-SF10	N-LAK34
N-LAF35	N-LAF2	LAFN7	N-LAF7
N-LAK33A	N-LAK33B	N-SF4	SF4
P-LAF37	N-SF14	N-LAF34	SF56A
N-SF11	SF11	N-LAF33	N-LAF21
N-LAF36	N-LASF45	N-LASF45HT	N-LASF44
N-SF6	N-SF6HT	N-SF6HTultra	SF6
SF6HT	N-LASF43	P-LASF47	P-LASF50
P-LASF51	N-LASF40	N-LASF41	N-SF57
N-SF57HT	N-SF57HTultra	SF57	SF57HTultra
N-LASF9	N-LASF9HT	N-LASF31A	N-LASF46A
N-LASF46B	P-SF67	N-SF66	P-SF68

14.3.3. SUMITA Glass Catalog

This catalog contains index of refraction formulas for the following 115 glasses:

SUMITA Optical Glasses

K-CaFK95	K-PFK90	K-PFK85	K-FK5
K-PFK80	K-PG325	K-SKF6	K-BK7
K-PBK40	K-PBK50	K-PMK30	K-PG375
K-BPG2	K-PSK11	K-GFK70	K-CSK120
K-SK5	K-PSK100	K-GFK68	K-PSK300
K-SK14	K-BaSF5	K-SK7	K-VC79
K-SK4	K-PSK200	K-SSK3	K-SSK1
K-SSK4	K-PSKn2	K-SSK9	K-SK16
K-SK16RH	K-SK15	K-BaF8	K-LaFK60
K-SK18	K-SK18RH	K-LaKn2	K-LaK6
K-BaF9	K-SFLD2	K-BaSF4	K-LaK7
K-PG395	K-LaK11	K-BaFn3	K-VC78
K-BaSF12	K-LaKn7	K-SFLD5	K-LaK12
K-BaFn1	K-LaFn1	K-SFLD8	K-LaK9
K-CD45	K-LaK13	K-VC80	K-LaFK55
K-LaK14	K-LaFn2	K-LaFn3	K-LaK8
K-ZnSF8	K-LaF3	K-SFLD1	K-LaK10
K-LaFn11	K-CD120	K-SFLD10	K-LaK18

K-LaKn12	K-LaKn14	K-LaFn5	K-LaF2
K-LaSKn1	K-SFLD4	K-VC82	K-SFLD14
K-LaFn9	K-LaFK50	K-LaSFn7	K-SFLD11
K-LaSFn4	K-LaSFn16	K-SFLD66	K-LaSFn3
K-VC100	K-LaSFn6	K-LaSFn2	K-SFLD6
K-LaSFn1	K-VC89	K-LaSFn10	K-LaSFn9
K-LaSFn14	K-LaSFn8	K-PSFn3	K-PSFn4
K-SFLDn3	K-LaSFn21	K-VC99	K-VC90
K-GIR79	K-LaSFn17	K-VC91	K-LaSFn22
K-PSFn1	K-LaSFn23	K-PSFn5	K-PSFn2
K-PSFn203	K-PSFn173	K-PSFn215	

14.3.4. HIKARI Glass Catalog

This catalog contains index of refraction formulas for the following 129 glasses:

HIKARI Optical Glasses

J-FK5	J-FK01	J-FKH1	J-FKH2
J-PKH1	J-PSK02	J-PSK03	J-PSKH1
J-BK7	J-BAK1	J-BAK2	J-BAK4
J-K3	J-K5	J-KZFH1	J-KF6
J-BALF4	J-BAF3	J-BAF4	J-BAF8
J-BAF10	J-BAF11	J-BAF12	J-BASF2
J-BASF6	J-BASF7	J-BASF8	J-SK2
J-SK4	J-SK5	J-SK10	J-SK11
J-SK12	J-SK14	J-SK15	J-SK16
J-SK18	J-SSK1	J-SSK5	J-SSK8
J-LLF1	J-LLF2	J-LLF6	J-LF5
J-LF6	J-LF7	J-F1	J-F2
J-F3	J-F5	J-F8	J-F16
J-SF1	J-SF2	J-SF4	J-SF5
J-SF6	J-SF7	J-SF8	J-SF10
J-SF11	J-SF13	J-SF14	J-SF15
J-SF03	J-SFS3	J-SFH1	J-SFH2
J-LAK7	J-LAK8	J-LAK9	J-LAK10
J-LAK12	J-LAK13	J-LAK14	J-LAK18

J-LAK01	J-LAK02	J-LAK04	J-LAK06
J-LAK09	J-LAK011	J-LASKH2	J-LAF2
J-LAF3	J-LAF7	J-LAF01	J-LAF02
J-LAF04	J-LAF05	J-LAF09	J-LAF010
J-LAF016	J-LAFH3	J-LASF01	J-LASF02
J-LASF03	J-LASF05	J-LASF08	J-LASF09
J-LASF010	J-LASF013	J-LASF014	J-LASF015
J-LASF016	J-LASF017	J-LASF021	J-LASFH2
J-LASFH6	J-LASFH9	J-LASFH13	J-LASFH15
J-LASFH17	J-LASFH24		

HIKARI Optical Glasses for Mold Lens

Q-FK01S	Q-FKH2S	Q-PSKH1S	Q-PSKH2S
Q-SK12S	Q-SK55S	Q-SF6S	Q-LAK13S
Q-LAK52S	Q-LAF010S	Q-LASF03S	Q-LASFH11S
Q-LASFH12S	Q-LASFH58S	Q-LASFH59S	

14.3.5. HOYA Glass Catalog

This catalog contains index of refraction formulas for the following 186 glasses:

HOYA Optical Glasses

FC5	FCD1	FCD1B	FCD10A
FCD100	FCD505	FCD515	FCD705
PCD4	PCD40	PCD51	BSC7
E-C3	BAC4	BACD5	BACD14
BACD16	BACD18	BACED5	LAC8
LAC14	TAC8	E-CF6	E-FEL1
E-FEL2	E-FL5	E-FL6	E-F2
E-F5	E-FD1	E-FD2	E-FD4
E-FD5	E-FD8	E-FD10	E-FD13
E-FD15	FD60	FD60-W	FD110
FD140	FD225	FDS24	FDS90
FDS90-SG	FDS90(P)	E-FDS1	E-FDS1-W
E-FDS2	E-FDS3	FDS18	FDS18-W
FF5	FF8	BAFD7	BAFD8

LAF2	NBF1	NBFD3	NBFD10
NBFD11	NBFD13	NBFD15	NBFD15-W
TAF1	TAF3	TAF3D	TAFD5F
TAFD5G	TAFD25	TAFD30	TAFD33
TAFD35	TAFD37	TAFD40	TAFD45
TAFD55	BACD2	BACD4	BACD11
BACD15	BAF10	BAF11	E-ADF10
E-ADF50	E-BACD10	E-BACED20	E-BAF8
E-F1	E-F3	E-F8	E-FD7
E-FEL6	E-LAF7	FCD10	LAC7
LAC9	LAC10	LAC12	LAC13
LACL60	LAF3	LBC3N	NBFD12
TAC2	TAC4	TAC6	TAF2
TAF4	TAF5	M-FCD1	MP-FCD1-M20
MC-FCD1-M20	M-FCD500	MP-FCD500-20	MC-FCD500-20
M-PCD4	MP-PCD4-40	MC-PCD4-40	M-PCD51
MP-PCD51-70	MC-PCD51-70	M-BACD5N	MP-BACD5N
MC-BACD5N	M-BACD12	MP-BACD12	MC-BACD12
M-BACD15	MP-BACD15	M-LAC8	MP-LAC8-30
M-LAC14	MP-LAC14-80	M-LAC130	MP-LAC130
MC-LAC130	M-TAC60	MP-TAC60-90	M-TAC80
MP-TAC80-60	M-FD80	MP-FD80	M-FDS1
MP-FDS1	M-FDS2	MP-FDS2	MC-FDS2
M-FDS910	MP-FDS910-50	MC-FDS910-50	M-LAF81
MP-LAF81	M-NBF1	MP-NBF1	MC-NBF1
M-NBFD10	MP-NBFD10-20	M-NBFD130	MP-NBFD130
MC-NBFD135	M-TAF1	MC-TAF1	M-TAF31
MP-TAF31-15	MC-TAF31-15	M-TAF101	MP-TAF101-100
MC-TAF101-100	M-TAF105	MP-TAF105	MC-TAF105
M-TAF401	MP-TAF401	MC-TAF401	M-TAFD51
MP-TAFD51-50	MC-TAFD51-50	M-TAFD305	MP-TAFD305
MC-TAFD305	M-TAFD307	MP-TAFD307	MC-TAFD307