Zemax, LLC

Getting Started With OpticStudio 15

May 2015

www.zemax.com

sales@zemax.com
support@zemax.com

Contents

Contents 3

Getting Started With OpticStudio™ 7

Congratulations on your purchase of Zemax OpticStudio! 7
Important notice 8
Installation 9
License Codes 10
Network Keys and Clients 11
Troubleshooting 11
Customizing Your Installation 12

Navigating the OpticStudio Interface 13

System Explorer 16
File Tab 17
Setup Tab 18
Analyze Tab 18
Analyze Tab (Non-Sequential UI Mode) 20
Optimize Tab 21
Tolerance Tab 22
Libraries Tab 22
Part Designer Tab 23
Programming Tab 24
Help Tab 25
Using Spreadsheet Editors 25
Using Analysis Windows 27
Using the Shaded Model 29
Arranging Windows 29
Printing Windows 30

Tutorials 32

Tutorial 1: A Walk-Through an OpticStudio Design 32
Tutorial 1.1: The Lens Data Editor 39
Tutorial 1.2: Analysis Windows 41
Tutorial 1.3: The System Explorer 43
Tutorial 1.4: The Normalized Coordinate System 47
Tutorial 2: Defining, Positioning and Moving Surfaces 52

Tutorial 2.1: Working in Three Dimensions 56
Tutorial 3: A Multi-Configuration Design 60
Tutorial 4: Exporting To Mechanical CAD Packages 75
Tutorial 5: Optimization 78
Tutorial 5.1: The Lens Specification 78
Tutorial 5.2: Entering the Basic System in the System Explorer 79
Tutorial 5.3: Entering the Basic System in the Lens Data Editor 83
Tutorial 5.4: Tips and Tricks for Successful Optimization 104
Tutorial 6: Non-Sequential Ray Tracing (Professional and Premium only) 108
Tutorial 6.1: A Simple Example 108
Tutorial 6.2: Object Positioning & Definition 118
Tutorial 6.3: Combining Sequential and Non-Sequential Ray-Tracing 124
Tutorial 6.4: Tracing Rays and Getting Data 126
Tutorial 6.5: Complex Object Creation 136
Tutorial 7: Optimizing Non-Sequential Systems 141
Tutorial 8: Colorimetry 146
Tutorial 9: Polarization, Coatings & Scattering 149
Tutorial 9.1: Polarization 150
Tutorial 9.2: Thin-Film Coatings 154
Tutorial 9.3: Ray Splitting 163
Tutorial 9.4: Ray Scattering 166
Tutorial 9.5: Importance Sampling 169
Tutorial 9.6: Bulk and Fluorescent Scattering 170
What's Next? 172
Getting Technical Support 174
References on Lens Design 175

Converting from Zemax13 and Older 176

Zemax 13 File Menu 178
Zemax 13 Editors menu 179
Zemax 13 System Tab 181
Zemax 13 Analysis Menu 185
Zemax 13 Tools Menu 190
Zemax 13 Reports Menu 198
Zemax 13 Macros Menu 199
Zemax 13 Extensions Menu 200
Zemax 13 Help Menu 201
2D Analysis Windows 202
3D Analysis Windows 203
Shaded Model 203
Editors 203

Conventions and Definitions 203

Index 221

Getting Started With OpticStudio™

Congratulations on your purchase of Zemax OpticStudio!

OpticStudio is the industry standard optical system design software, combining sequential lens design, analysis, optimization, tolerancing, physical optics, non-sequential optical system design, polarization, thin-film modeling and mechanical CAD Import/Export in a single, easy-to-use package.

Although OpticStudio is easy to use, optical system design is a very broad area of engineering. This guide is intended to get you started using OpticStudio quickly. It is the first place to start if you are new to OpticStudio, or if you are upgrading from previous versions of Zemax.

We strongly recommend you take the time to work all the way through this infromation on getting started with OpticStudio. It covers:

- Installing OpticStudio, and customizing its appearance and file locations to your preference
- Entering a simple sequential design
- Understanding the normalized definitions OpticStudio uses
- An overview of the multiple configurations capability
- How to export components and rays to mechanical CAD packages
- Optimizing a simple lens
- Using some of the powerful tools OpticStudio makes available
- Tilting and decentering optical components
- Entering a simple non-sequential system, tracing rays, and using detectors
- Colorimetry
- Thin-Film Coatings
- Surface, bulk and fluorescent scattering

Also, our web-based Knowledge Base at www.zemax.com/kb is an indispensible resource for all OpticStudio users. It contains tutorials, worked examples and answers to many frequently-asked questions.

Important notice

All other product names or trademarks are property of their respective owners.

Information in the help file documentation is subject to change without notice and does not represent a commitment on the part of the vendor. The software described in this documentation is furnished under a license agreement and may be used or copied only in accordance with the terms of the agreement.

Zemax LLC provides this publication “as is” without warranty of any kind, either express or implied, including but not limited to the implied warranties or conditions of merchantability or fitness for a particular purpose. In no event shall Zemax LLC be liable for any loss of profits, loss of business, loss of use or data, interruption of business, or for indirect, special, incidental, or consequential damages of any kind, even if Zemax LLC has been advised of the possibility of such damages arising from any defect or error in this publication or in the Software.

Installation

There are two simple steps to installing OpticStudio, which must be followed in order. All files are downloaded from www.zemax.com/downloads.

Step 1: Install the Key Driver and Plug in the Key

The key driver installation is straightforward. Double-click the key driver installer once you have downloaded it, and choose the ‘Complete’ installation of all program features.

A dialog box will also ask for your permission to modify the firewall settings of your computer to allow remote users of your computer to run ZEMAX using Remote Desktop. If you want to authorize this, click "Yes", otherwise click "No". To change this setting, just re-run the key driver installer.

Plug the key in once the key driver installation is complete, and Windows will detect the hardware key. The green LED at the end of the key will illuminate.

Step 2: Install Zemax OpticStudio

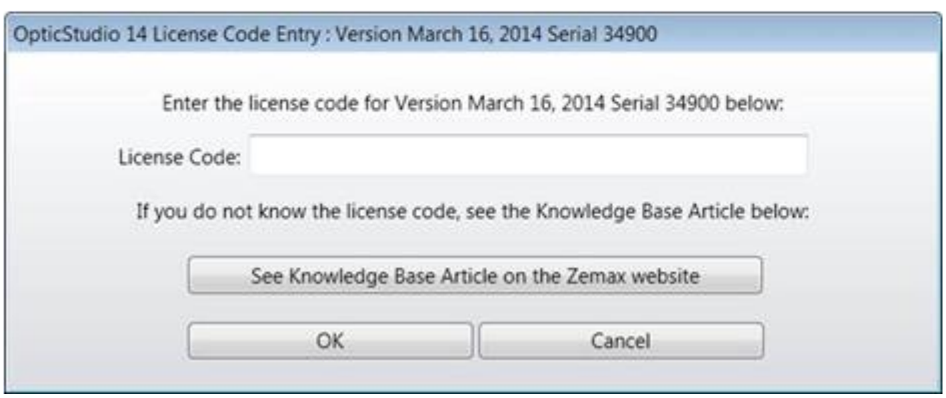
The OpticStudio installer is similarly straightforward. Download and run the installer and step through the on-screen instructions. You may choose where within the \program files\ hierarchy OpticStudio is installer (by default this is C:\Program Files\Zemax OpticStudio\). If you choose a different folder, any future updates you install will remember this location and treat it as the default, until you define a different location.

Note that the installer will automatically scan your computer to verify the presence of Microsoft prerequisites that are required to run OpticStudio. If any of the prerequisite components are missing, the necessary files will be downloaded and installed. These will subsequently be kept up to date by Windows Update.

For more detailed instructions on installing OpticStudio for the first time, please our knowledge base article:
http://www.zemax.com/support/knowledgebase/installing-opticstudio-for-the-first-time

License Codes

OpticStudio contains built-in license codes for all keys that were eligible to run this version at the time this version was compiled. If you have purchased a new key, this license code will not be built in, and OpticStudio will download the latest version of the license code file from the zemax.com website automatically. If for any reason it still cannot get a valid license code, the following dialog will appear:



Use Alt-Print_Screen to copy the dialog to the clipboard and paste it into an email to support@zemax.com. We will promptly send you the license code or further instructions.

Note: Please do not phone for a license code! License codes are complex multi-character strings and cannot be reliably given over the phone. Emailing the screenshot of the dialog box to us is the quickest and most error-free way of getting your license code.

Network Keys and Clients

Zemax OpticStudio can also be supplied with 5, 10, 25 and 50-user network keys. Installation is almost identical, except that the key driver and hardware key are installed on one computer (called the 'keyserver' machine) and Zemax OpticStudioand the Prerequisites installed on as many other machines as you wish (the 'client' computers). When a client machine starts OpticStudio, it looks to the keyserver machine to see if a license is available, and if so, OpticStudio starts.

Installation of the key driver on the keyserver machine is identical to the normal installation, except that you obviously MUST allow the firewall settings to be adjusted to allow network access to the key.

Installation of OpticStudio on the client machines is also identical to the normal installation, except that you must tell OpticStudio where to look for the keyserver machine after installation. Navigate to whatever folder you installed OpticStudio in (by default this is C:\Program Files\Zemax OpticStudio\) and locate a file called sntlconfig.xml.bak. Rename this file to sntlconfig.xml, and open it in Notepad. Edit the following line:

```
<ContactServer>
10.0.0.1
</ContactServer>
```

Replace the default entry 10.0.0.1 with the IP address of your keyserver machine and save the file.

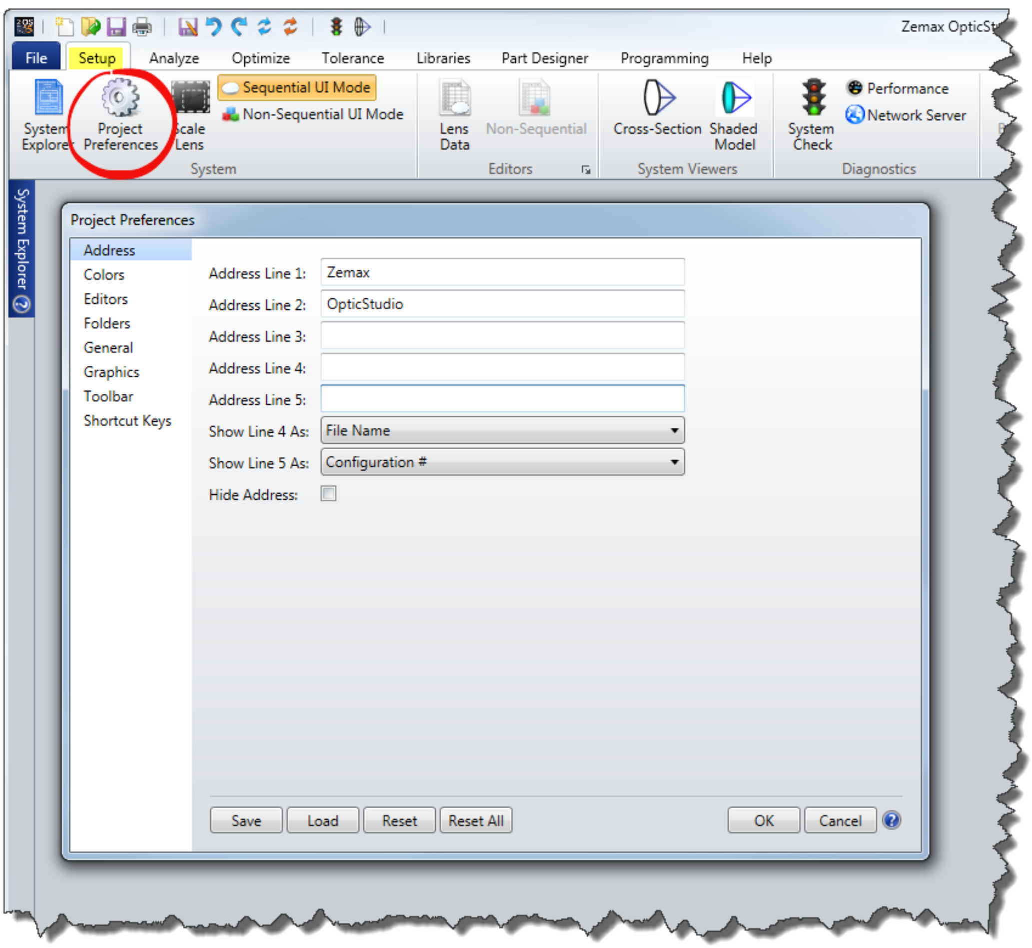
Troubleshooting

OpticStudio will run without problem in the vast majority of cases. If you do experience problems, then visit our Knowledge Base at www.zemax.com/kb. Look at the Category 'Installation and Troubleshooting' for help.

Make sure your key is plugged in!

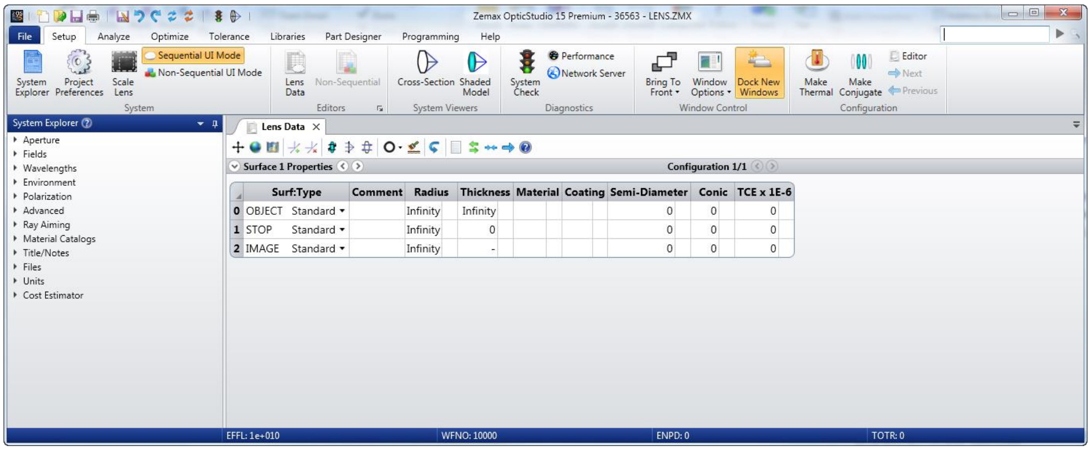
Customizing Your Installation

OpticStudio installs using several default settings which you may prefer to change. You can also set these defaults up on a project basis, so that all designs for a specific project use the same settings. Start OpticStudio, and navigate to Setup…Project Preferences:



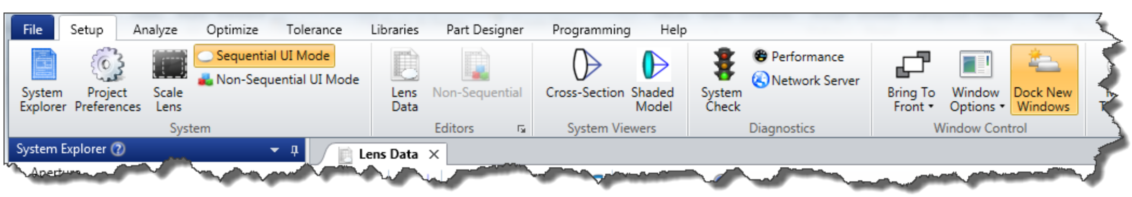
Navigating the OpticStudio Interface

The OpticStudio user interface provides a fast, flexible platform for the design and evaluation of almost any optical system.



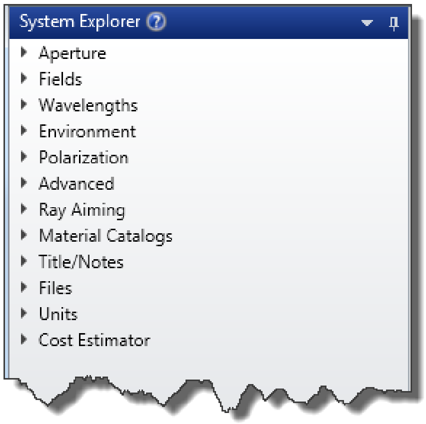
It consists of several key areas:

1. A **ribbon bar** which provides easy access to all the program's features, clustered in task-oriented tabs. Each tab contains groups of icons. In this example:

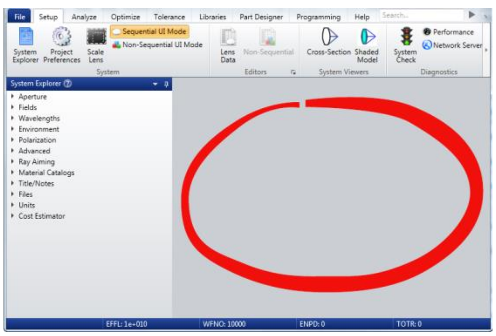


Setup is the name of the ribbon bar, and *System*, *Editors*, and *System Viewers* are examples of groups.

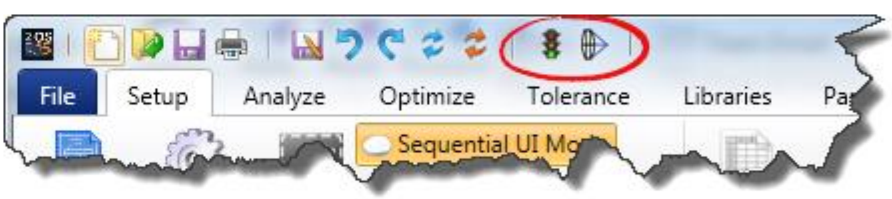
2. The System Explorer, which can be displayed or hidden at any time. This contains system-specific information about the optical system under design.



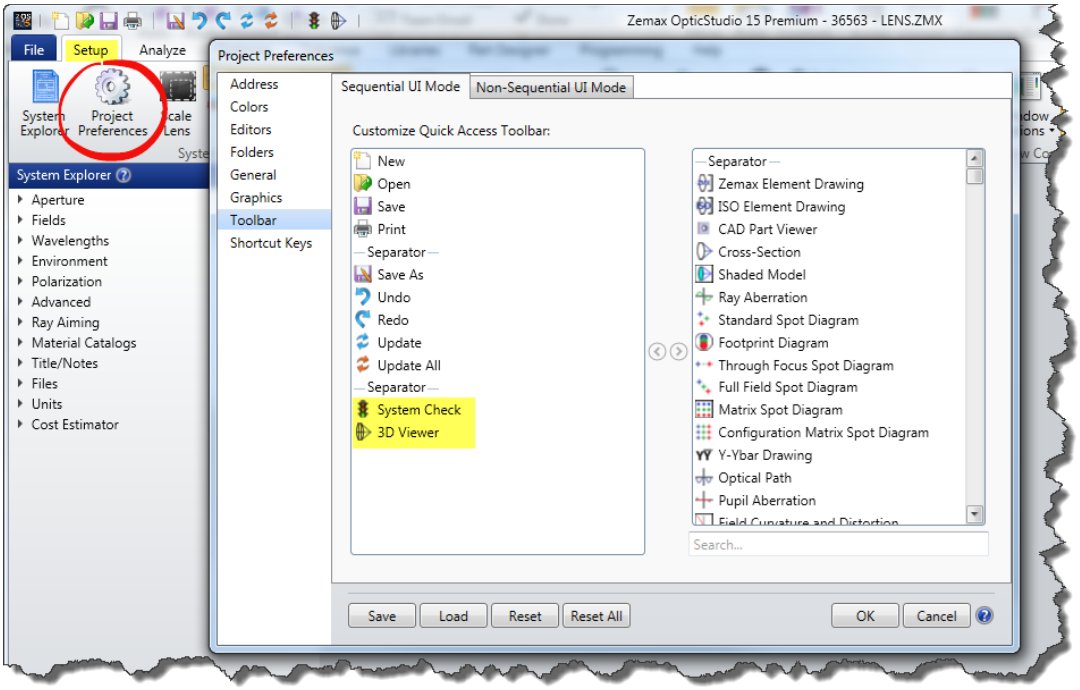
3. A **workspace**, which is the main area in which you will do your work.



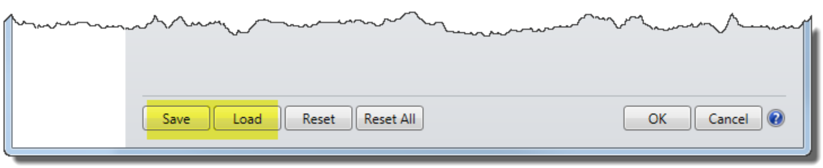
4. A user definable **Quick Access Toolbar** which allows you to place your most commonly used features on the desktop for single-click access.



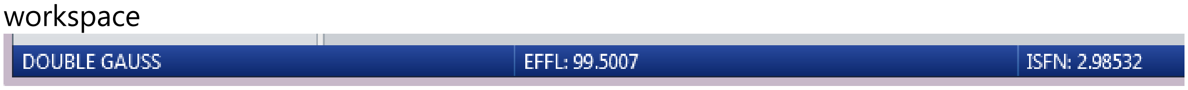
The toolbar is configured under Setup…Project Preferences…Toolbars.



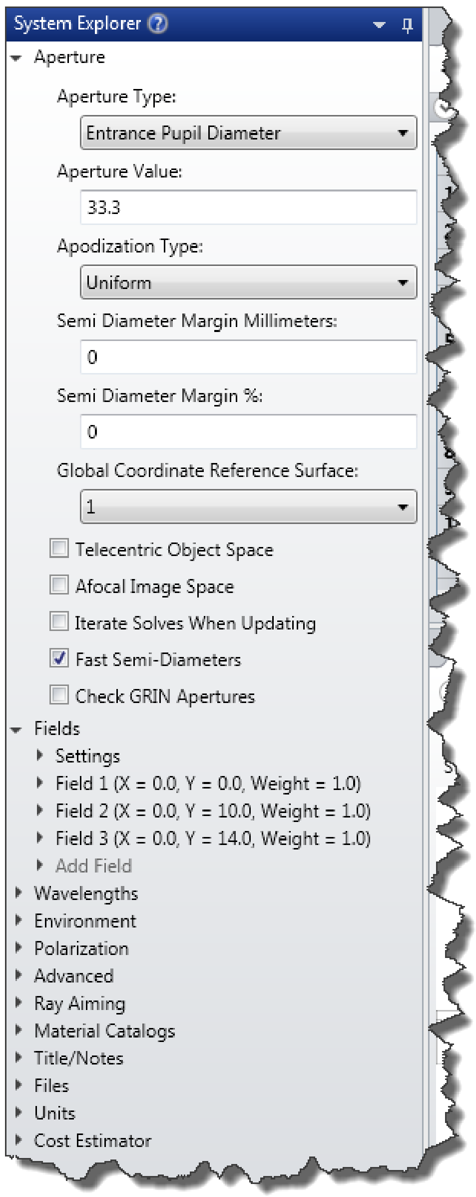
Multiple Project Preferences may be created and recalled to customize the user interface to the work in hand.



5. A **status bar**, which displays useful information about the design at the bottom of the workspace

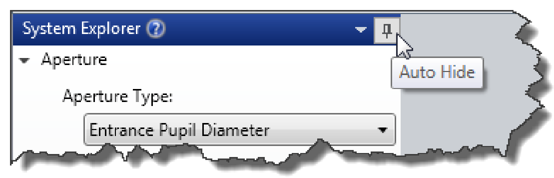


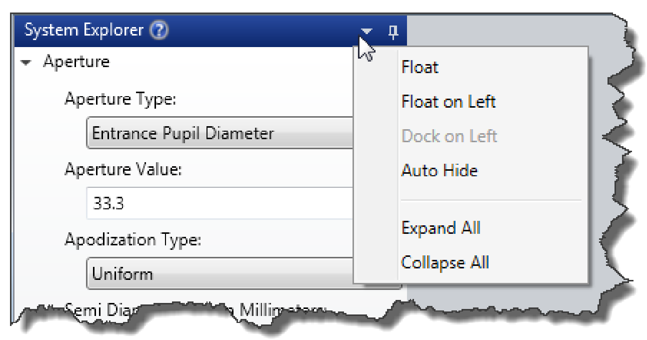
System Explorer



The System Explorer shows the basic system settings that are usually input at the very start of a design project. Typically, these settings are not optimized, but it can be done if needed.

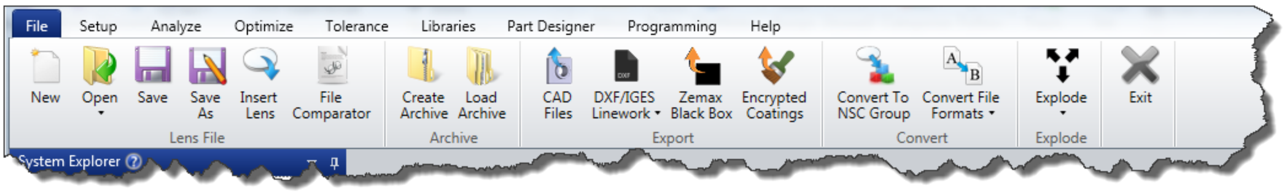
The groups within the System Explorer can be expanded, closed, and reorganized as desired, and the whole System Explorer can be hidden or expanded at any time using the controls in the upper right corner:





Full details are given in the System Explorer section of the Help Files Setup Tab chapter.

File Tab



The File tab contains all the file input/output functions, split into these groups:

The **Lens File** group contains all the normal Windows file management tasks like file opening, saving etc. OpticStudio files are stored in .ZMX format files, along with associated .CFG files that contain configuration settings and .SES files that contain settings data for all windows that were open at the time the file was saved.

The **Archive** group lets you create and open OpticStudio Archive files. These are stored in .ZAR format, and contain all the files needed to open the file on another computer with OpticStudio installed on it. All OpticStudio data, glass catalogs, coatings, CAD files, SolidWorks™ etc files used by the lens design are compressed into this single file so that you can easily make backups of the design as it progresses through the design process, or transfer the design to another machine.

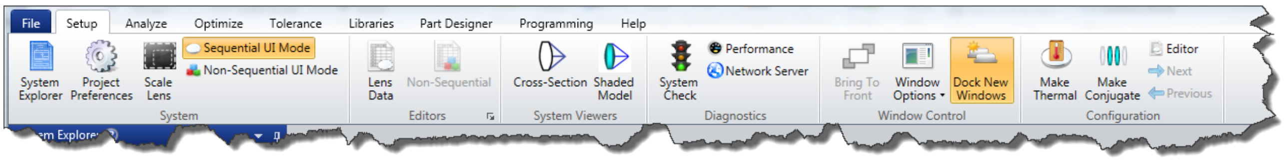
The **Export** group provides access to all the export capabilities in OpticStudio, including exporting to STEP, IGES, SAT and STL format CAD files, and exporting to DXF and IGES linework diagrams. The OpticStudio Black Box feature allows you to encrypt a range of surfaces in the lens data spreadsheet, which can be given to other OpticStudio users without revealing the details of the design itself. This lets you give fully ray-traceable files to customers, or to other colleagues on a need-to-know basis, that give exact results on ray tyrace but do not reveal the design prescription.

The **Encrypted Coatings** feature is a similar capability for thin-film coatings, and allows the full prescription of a thin-film coating to be exported in an encrypted format that allows exact ray tracing without making the design itself available.

The **Convert** group lets you convert between OpticStudio' sequential (lens design) and non-sequential (system design) modes, and also converts various file formats (like .MAT Matlab® , .INT interferometer data and .f3d OptiWave data) between original and OpticStudio formats.

See the Help Files File Tab chapter for full details of all options.

Setup Tab



This tab is used when you start each design project, and is visited infrequently or not at all after initial setup.

The **System** group puts everything to do with basic system setup in one place. Project Preferences lets you customize the OpticStudio installation, folder locations, quick access toolbar etc and save these settings to a project configuration file.

The **Editors** group gives access to the spreadsheets that are used to define the optical system on a surface by surface or object by object basis.

The **System Viewers** group gives access to the layout plots that are used to view the optical system itself.

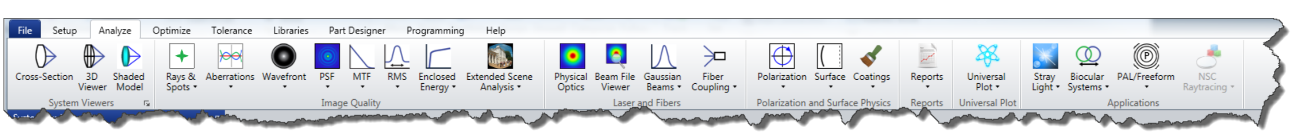
Diagnostics lets you check the OpticStudio file. The System Check utility traps many common setup errors.

Windows Control defines how windows in the OpticStudio workspace behave. Windows can be docked, float freely, be tiled and cascaded etc.

Configuration is used is the design has multiple versions, which is typically the case for zoom lenses, thermal analysis of lenses over a range of temperatures, scanning lenses and lenses with moving parts. The Configuration group appears on all ribbons if more than one configuration is defined.

See the Help Files Setup Tab chapter for full details of all options.

Analyze Tab



This tab provides access to all of OpticStudio' analysis features in sequential UI mode. Almost all imaging system design is done in this UI mode. Analysis features provide detailed performance data over a wide range of requirements. Analysis features never change the underlying design, but provide diagnostic information on the design that is used to guide any required changes.

The **System Viewers** tab gives access to the layout plots that are used to view the optical system itself.

The **Image Quality** tab provides access to all the analyses used in the design of imaging and afocal systems, including ray-trace data, aberration data, wavefront, Point Spread Functions and more.

Lasers and Fibers gives access to laser-system-specific features such as simple Gaussian Beam Analysis, Physical Optics and fiber coupling calculations.

Polarization and Surface Physics computes the performance of thin-film coatings on individual surfaces, overall system performance as a function of polarization and plots of surface sag, phase and curvature.

Reports provides text based analyses for presentation purposes.

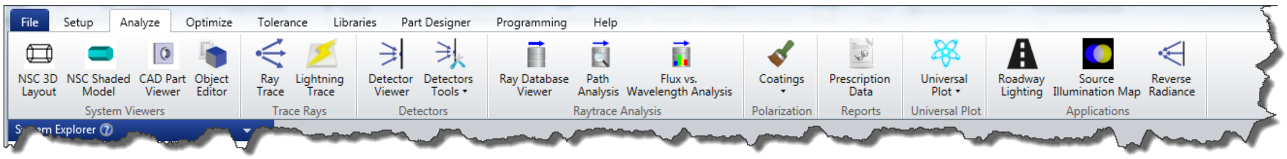
Universal Plots allow you to create your own analysis features if required.

Applications show application-specific analysis features such as Biocular system analysis, freeform and Progressive Addition Lens analysis, and also access to the full non-sequential features of OpticStudio.

If the lens uses multiple configurations, the Configuration group (see Setup tab) is also shown.

See the Help Files Analyze Tab chapter for full details.

Analyze Tab (Non-Sequential UI Mode)



This tab provides access to all of OpticStudio' analysis features in non-sequential UI mode, which is used for most illumination, stray light, lighting, etc. designs. Analysis features provide detailed performance data over a wide range of requirements. Analysis features never change the underlying design, but provide diagnostic information on the design that is used to guide any required changes.

The **System Viewers** group gives access to the layout plots that are used to view the optical system itself.

Trace Rays initiates ray tracing using either the comprehensive non-sequential ray-trace engine, or a faster, approximate method called LightningTrace™ that is very useful if the source can be approximated as a point source.

Detectors and **Raytrace Analysis** groups provide a wide range of analyses on a previously performed raytrace.

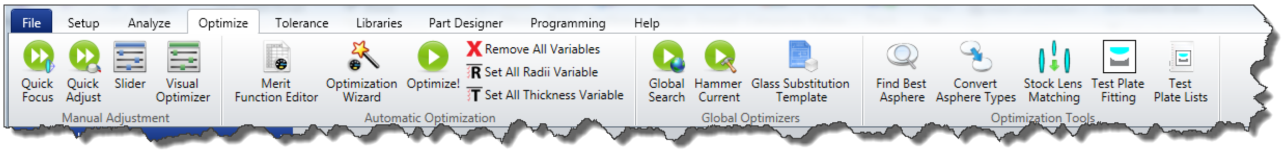
Polarization computes the performance of thin-film coatings on individual faces of objects.

Universal Plots allow you to create your own analysis features if required.

Applications show application-specific analysis features such as Roadway Lighting Analysis

See the Help Files Analyze Tab chapter for full details.

Optimize Tab



This tab is where you control the Zemax optimization capabilities.

Manual Adjustment contains a series of features that let you manually adjust the design for desired performance. This group is only available in Sequential UI mode.

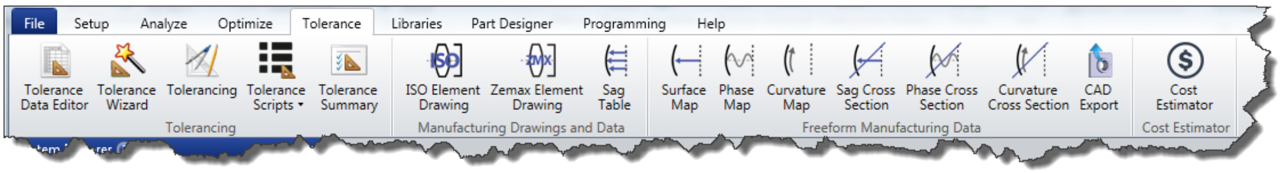
Automatic Optimization provides access to the Merit Function Editor, which is how a system's performance specification is defined in Zemax. The Optimization Wizard lets you quickly generate a merit function based on the most common requirements (smallest spot, best wavefront error, least angular deviation) which can then be edited to your exact requirements.

Global Optimization is used in two main scenarios: at the start of a design process (Global) in order to generate design forms for further analysis, and after initial optimization (Hammer) to exhaustively improve the current design.

Optimization Tools performs a range of post-optimization functions such as finding the best surface to asphherize or swapping lenses in the current design for catalog optics. This group is only available in Sequential UI mode

See the Help Files Optimize Tab chapter for full details.

Tolerance Tab



Tolerancing allows you to see the effect of finite manufacturing and assembly tolerances on the design.

In the **Tolerancing** group, the Tolerance Data Editor is where you will enter the tolerances you wish to place on each parameter. The Tolerance Wizard will quickly set up a set of tolerances which you can then edit.

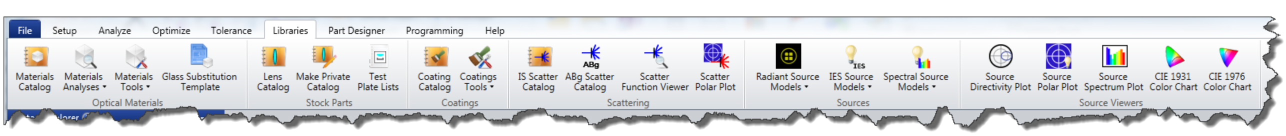
The **Manufacturing Drawings and Data** group (Sequential UI mode only) creates manufacturing drawings in ISO 10110 format and a Zemax-specific format, as well as exporting data about the surface to cross-check manufacturing setup.

The **Freeform Manufacturing Data** group provides surface information that can be used in manufacturing a tolerancing.

The **Cost Estimator** is a tool that estimates the cost to manufacture a lens.

See the Help Files Tolerance Tab chapter for full details.

Libraries Tab



OpticStudio ships with a lot of data on optical materials, stock lenses, thin-film coatings and light sources built in, in the form of catalog data, plus you can add your own data as well. This tab provides access to all the catalog data that ships with OpticStudio and also lets you enter your own data.

The **Optical Materials** group gives access to catalogs of glasses, plastics, birefringent media and more.

The **Stock Parts** group holds all the vendor lens catalogs in Zemax, which can be quickly searched to find the correct lenses for your application.

The **Coatings** group contains data and tools for designing thin-film coatings and applying them to optical surfaces.

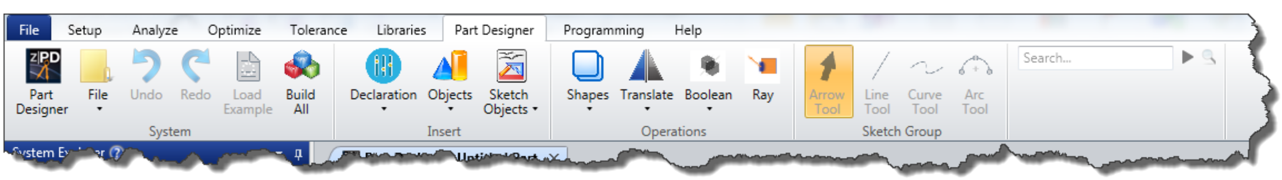
The **Scattering** group gives access to Zemax's surface scattering libraries and scatter viewers. The IS Scatter Catalog contains measured data for a range of optical finishes including various matt blacks, ground glass and anisotropic scattering surfaces.

The **Sources** group gives access to the libraries of Radiant Source (spatial, angular and optionally wavelength) data and IES (angular only) data. Spectral (color) information can be added to data files that do not have it, and there are several source viewer options.

The **Source Viewers** group includes tools for modeling source directivity plots and spectra.

See Help Files The Libraries Tab chapter for full details.

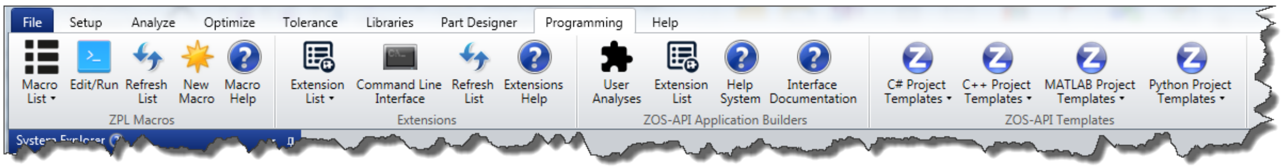
Part Designer Tab



The Part Designer is a sophisticated geometry creation tool capable of making parametric objects which are optimizable within OpticStudio Premium. Part Designer is only available in the Non-Sequential UI mode.

See the Help Files Part Designer Tab chapter for full details.

Programming Tab



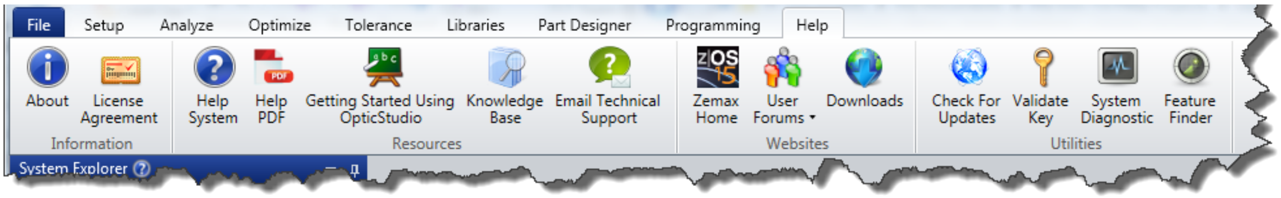
Although OpticStudio has a huge range of features and analysis options, there is always some special feature or requirement. That's why OpticStudio has programming interfaces built right in. The first **is Zemax Programming Language (ZPL)**, which is a very easy to learn scripting language similar to Basic. With ZPL, it is easy to perform special calculations, display data in different ways and automate repetitive keyboard tasks, amongst many others.

'**Extensions'** are external programs that can take control of Zemax, instruct it to perform analyses and extract data from it. MatLab® and Python are two of the most common programs to work with OpticStudio, plus you can write your own program which can use zclient, our Software Development Kit (SDK) for applications programmers.

Zemax OpticStudio also has a **ZOS-API** programming interface which can be used in a .NET environment, using C#, or any other .NET-capable language. In addition, ZOSAPI can also be used in a .COM environment, using C++, or any other .COM-capable language.

See the Help Files Programming Tab chapter for full details.

Help Tab

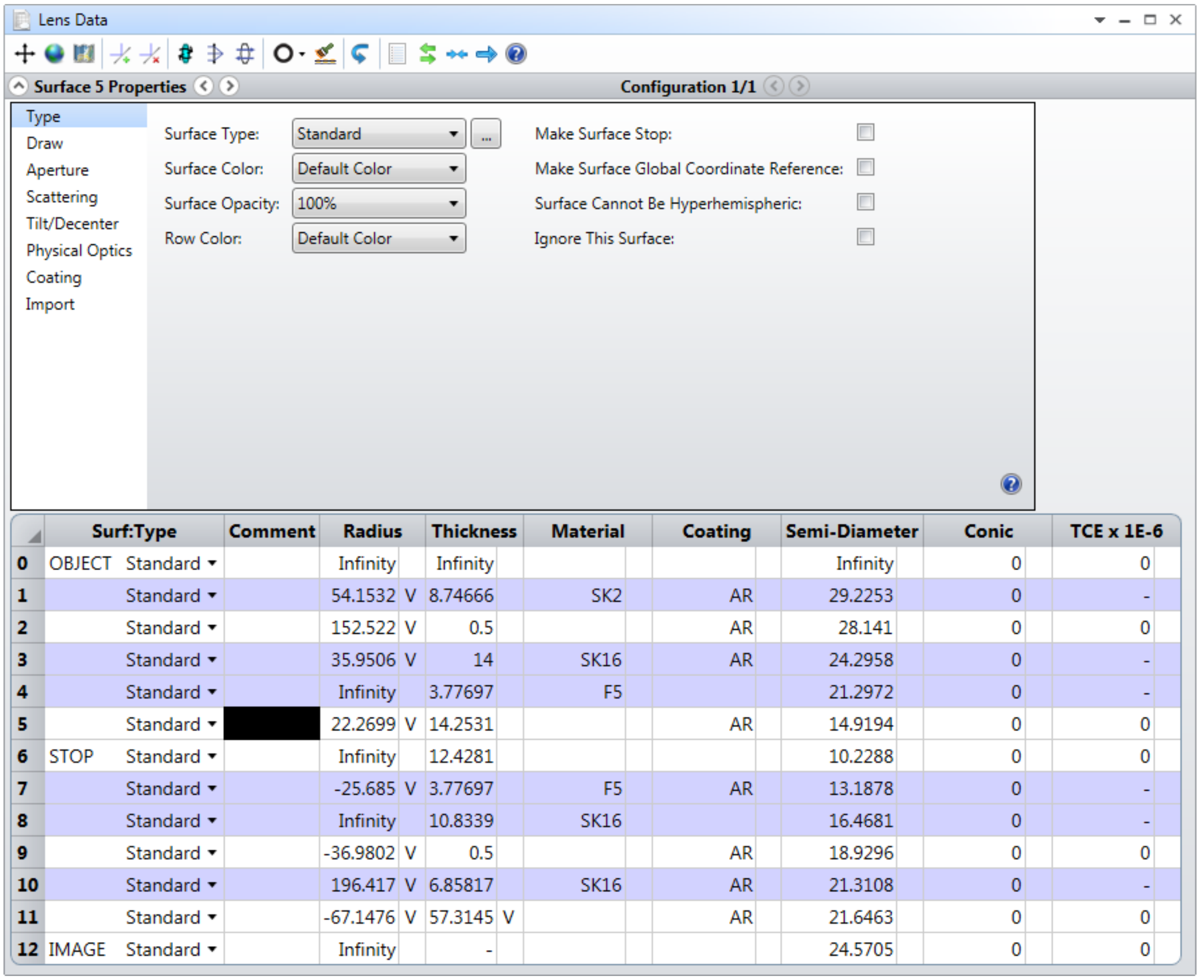


The Help tab provides links to this Help file, plus links to our web-based Knowledge Base, website, and user forums.

See the Help Files Help Tab chapter for full details.

Using Spreadsheet Editors

Most data about your optical system is contained in one or more spreadsheets. OpticStudio's spreadsheets are designed to behave like Microsoft Excel® sheets as much as possible, to make them familiar. There are some specific optical system design touches to make you very productive when using OpticStudio. Here is a typical Editor:



	Surf:Type		Comment	Radius		Thickness		Material	Coating	Semi-Diameter	Conic	TCE x 1E-6
0	OBJECT	Standard		Infinity		Infinity				Infinity	0	0
1		Standard		54.1532	V	8.74666		SK2	AR	29.2253	0	-
2		Standard		152.522	V	0.5			AR	28.141	0	0
3		Standard		35.9506	V	14		SK16	AR	24.2958	0	-
4		Standard		Infinity		3.77697		F5		21.2972	0	-
5		Standard		22.2699	V	14.2531			AR	14.9194	0	0
6	STOP	Standard		Infinity		12.4281				10.2288	0	0
7		Standard		-25.685	V	3.77697		F5	AR	13.1878	0	-
8		Standard		Infinity		10.8339		SK16		16.4681	0	-
9		Standard		-36.9802	V	0.5			AR	18.9296	0	0
10		Standard		196.417	V	6.85817		SK16	AR	21.3108	0	-
11		Standard		-67.1476	V	57.3145	V		AR	21.6463	0	0
12	IMAGE	Standard		Infinity		-				24.5705	0	0

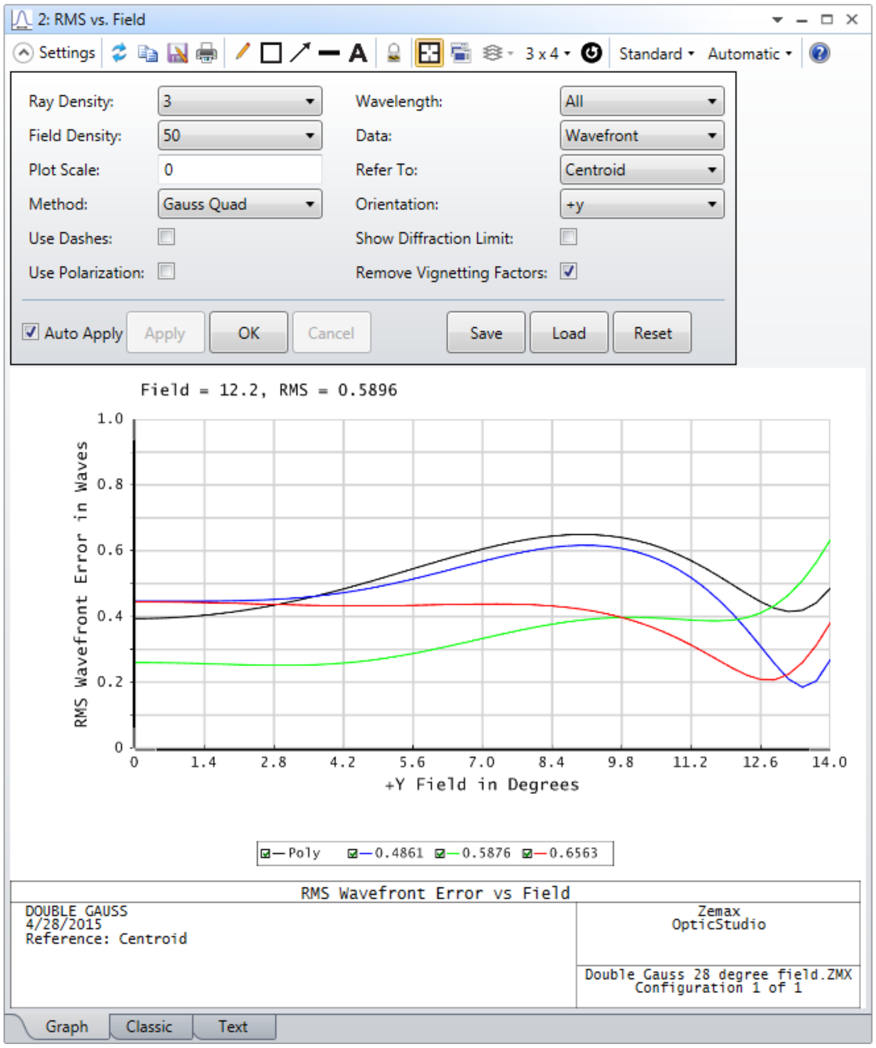
All Editors contain three areas:

1. A Toolbar area at the top which provides tools for manipulating the data in the editor and performing tasks specific to that data. For example, the first icon in the Lens Data Editor above is a Tilt/Decenter elements tool which allows any group of elements to be tilted and decentered.
2. A collapsible Properties dialog that lets you see and set detailed data about each row or item in the editor. This is typically reserved for data that is set once and then not changed frequently. The Properties can be hidden (collapsed) when not needed.
3. The Spreadsheet region which is where the data you need to work with is kept. Spreadsheet cell data can be entered directly, or can be calculated by Solves, which act similarly to spreadsheet functions in Excel®

Each Editor, its toolbar and Properties is discussed in detail in its own chapter.

For more information see the “Using the Editors” section in the Help Files under The Setup Tab > Editors Group.

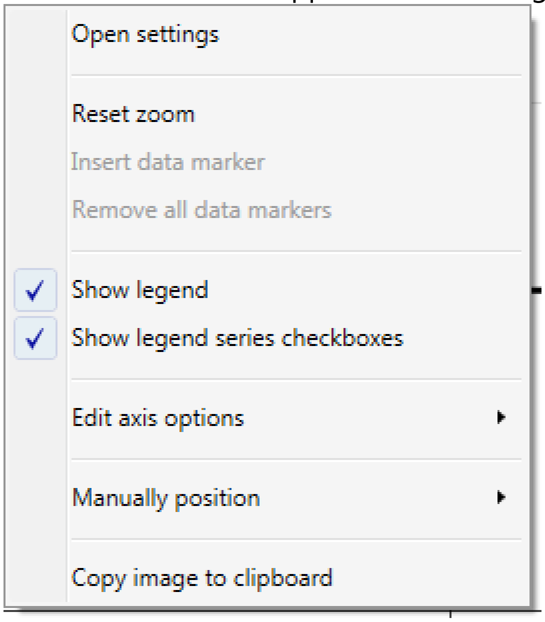
Using Analysis Windows



All Analysis windows contain four main areas:

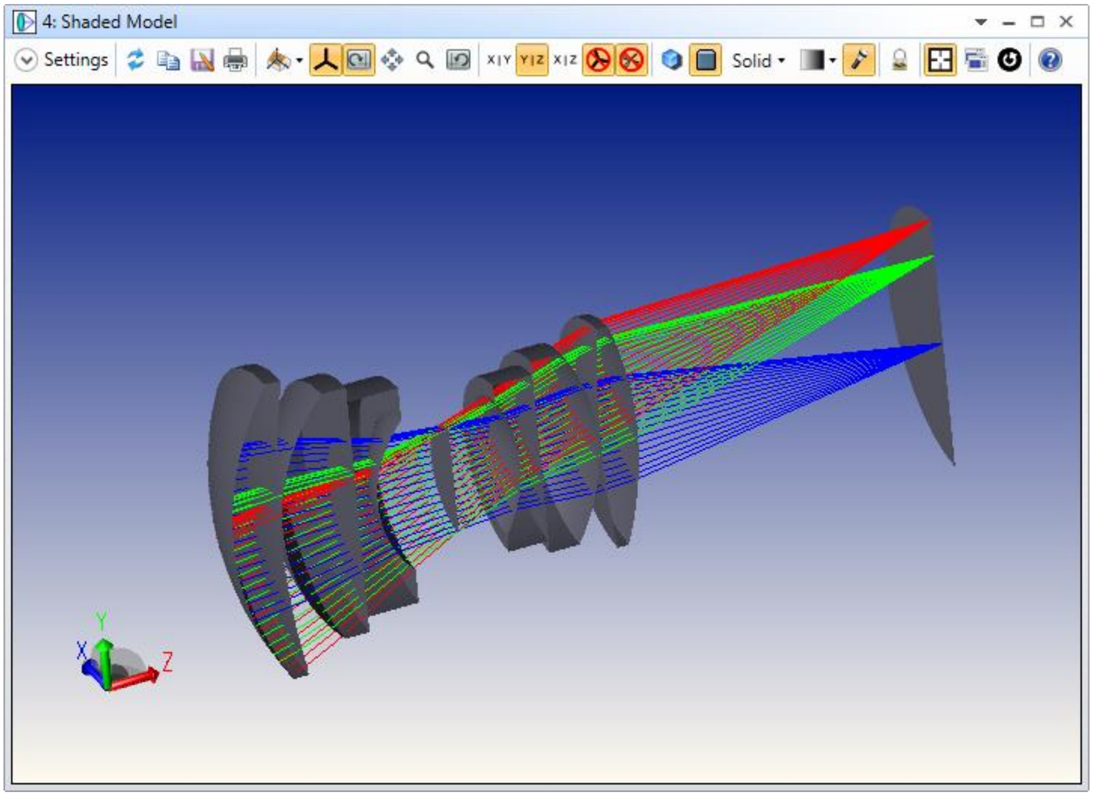
1. A toolbar, which is common across all Analysis windows. This gives access to the Analysis Settings, which control the calculation, and various controls like print, copy, save as etc
2. The Settings dialog, which can be shown or hidden by using the Setting control on the toolbar.
3. The data analysis itself, which can be shown in three ways: as a graphic, as a text listing and (some windows only) in 'Classic' mode which uses the graphics libraries from older versions of Zemax.

4. A context menu that appears when the right-mouse button is clicked:



For more information see the Help Files Analyze Tab chapter.

Using the Shaded Model



The Shaded Model lets you view your system through an advanced graphics view familiar to anyone who has used modern CAD programs. Mouse control of the view is intuitive, and the toolbar gives access to default views (Isometric, X-Y, Y-Z and Z-Y) and cutting planes which can be used interactively to show the level of detail you need. There are options for wireframe, hidden line or solid modeling views.

See the Shaded Model section of the Help Files Analyze Tab chapter for full details.

Arranging Windows

Windows can be free-floating or docked, and docked windows can be tiled in any way you wish. This is best described in a video:

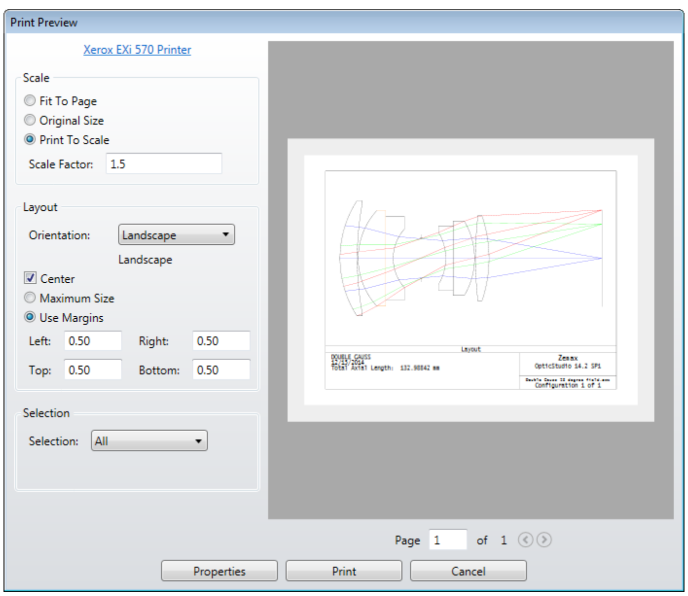
Watch the video: Arranging Windows :

http://zemax.com/products/opticstudio/feature-explorer/user-interface/window-management

Printing Windows

The Graphics section of the Help Files > Setup Tab > Project Preferences includes settings for printing layout plots to scale and the default printing orientation.

In addition, the printer icon in the toolbar of any analysis window will bring up a Print Preview dialog window. This dialog allows you to configure options such as the desired printer, scaling, and page ranges. The print shortcut key will also open the Print Preview window, and by default this shortcut is "Ctrl + P".



Advanced Settings

Use the link with the selected printer name at the top-left corner, or the Properties button to choose the desired printer as well as advanced printer driver settings. Note that the 'Print' button on the advanced settings dialog does not actually print, but merely accepts the new settings and closes the dialog.

Orientation

The orientation controls whether the output is printed in Portrait or Landscape mode. There are four options:

1. Default – use the current value from the printer advanced settings.
2. Automatic – determine the best fit based on the paper dimensions and selected scaling mode.
3. Portrait
4. Landscape

Immediately below the orientation selection box, the computed orientation will be displayed (useful when selecting Default or Automatic).

Scaling

Scaling determines how the graphic is scaled to fit the output pages. Note that all scaling options are applied equally to both axes (i.e. aspect ratio is maintained). There are currently three options:

1. Fit To Page – take up the most space possible on a single page.
2. Original Size – attempt to print at exactly the size the input text or graphic is currently displayed on the screen (not the size in the preview window).
3. Print To Scale (only for layout plots) - the layout plot will be printed at a 1:1 scale based on the lens units.

The Center option is used to pad the graphic so that it is centered on the print page(s), rather than on the upper-left hand corner.

Selection

There are several options to select which of the available pages are printed. Use the preview page controls at the bottom right to decide which pages you want printed, and then choose from the following options:

1. All
2. Range – used to select a contiguous range of pages to print, from x to y.
3. Current – only print the current preview page.
4. Selected (only for text) – only print the currently selected analysis text. Note that this option is only available when printing text, and only when a block was selected before opening the print dialog.

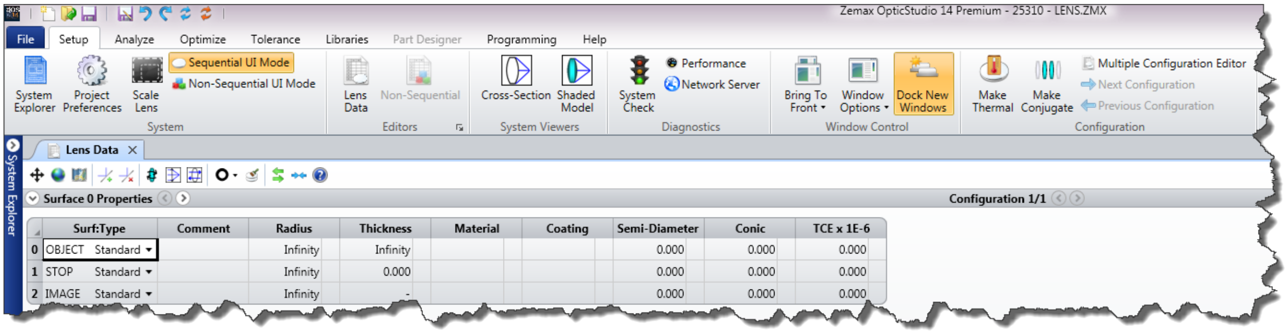
Tutorials

In this section we give several examples of how to use OpticStudio. We strongly recommend that you take the time to work through this section.

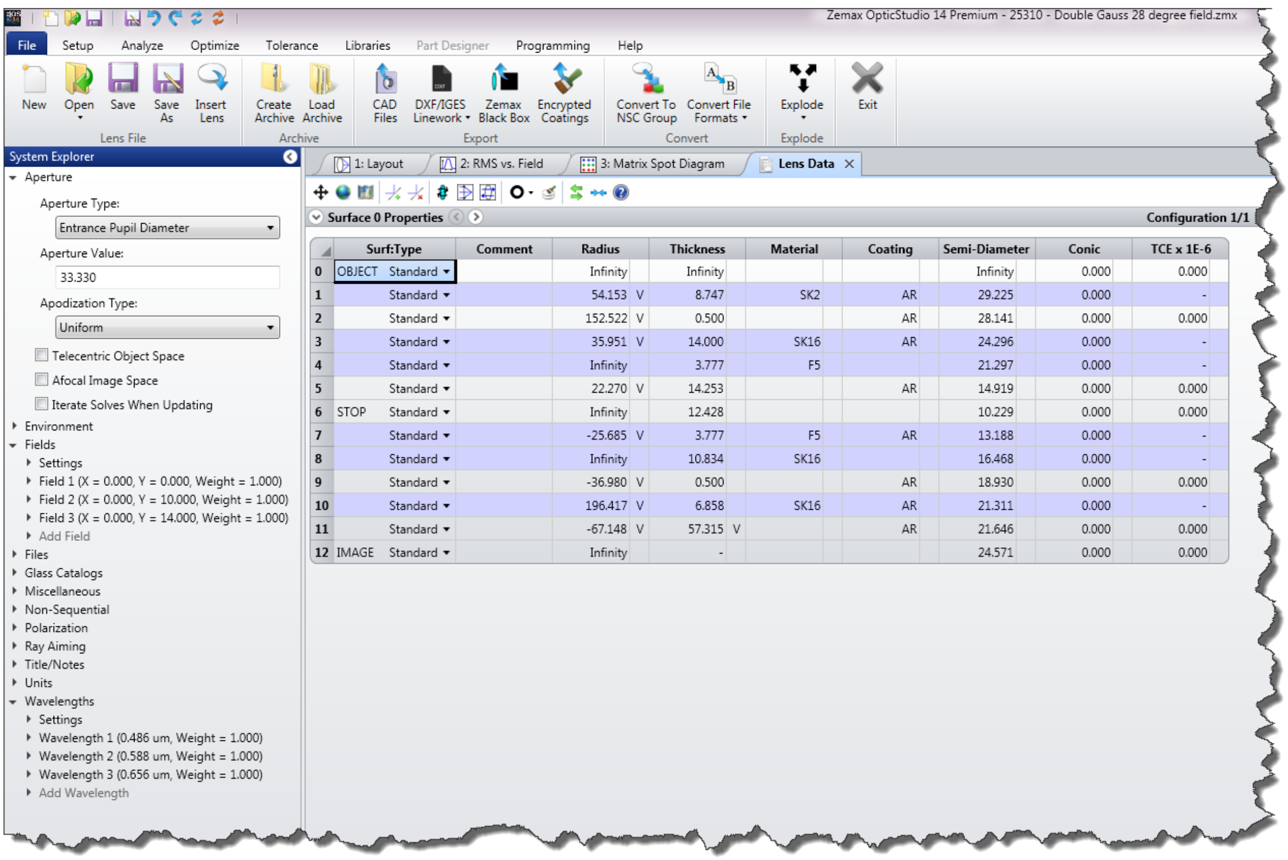
If you are viewing this in an HTML dialog, expand the "Tutorials" topic in the Contents tab to view the subsections.

Tutorial 1: A Walk-Through an OpticStudio Design

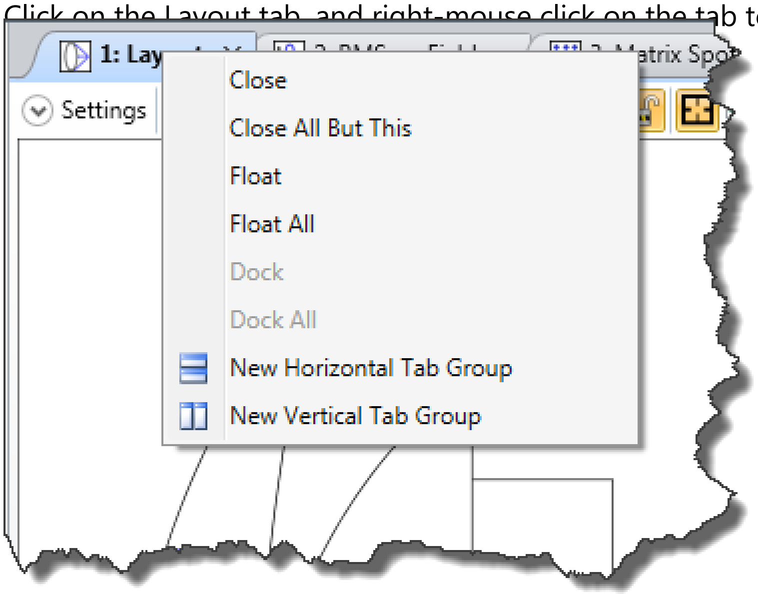
In this example we open one of the sample files provided with OpticStudio and get familiar with the use of the various controls. Open OpticStudio (click File…New if it is already open) and in the Setup tab choose 'Dock New Windows'



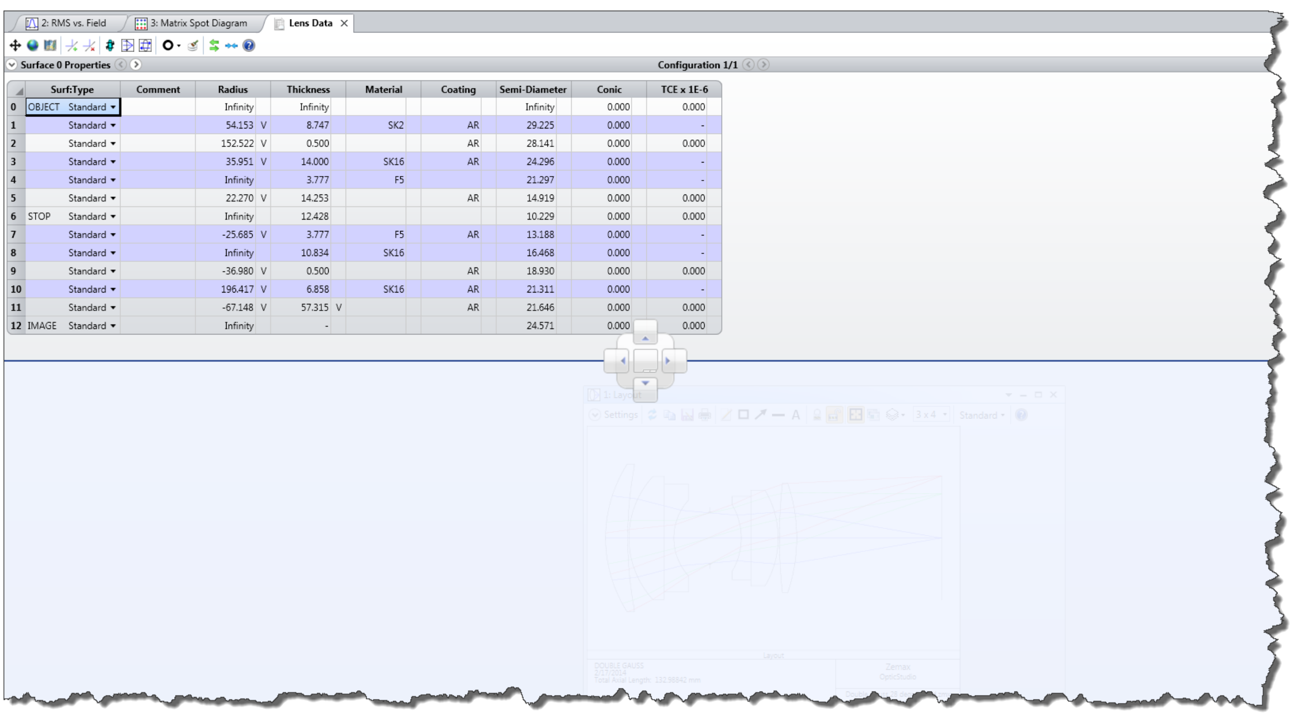
Then click on File...Open and select the file {Current User}\Documents\Zemax\Samples\Sequential\Objectives\Double Gauss 28 degree field.zmx. This is a classic lens design, and even if you intend to use only the non-sequential mode of OpticStudio you should still follow this example. The user interface is common to both sequential and non-sequential ray-tracing, and users of all versions of OpticStudio will be able to work through this example. The OpticStudio window will look like so:



Click on the Layout tab, and right-mouse click on the tab to show the window placement menu:

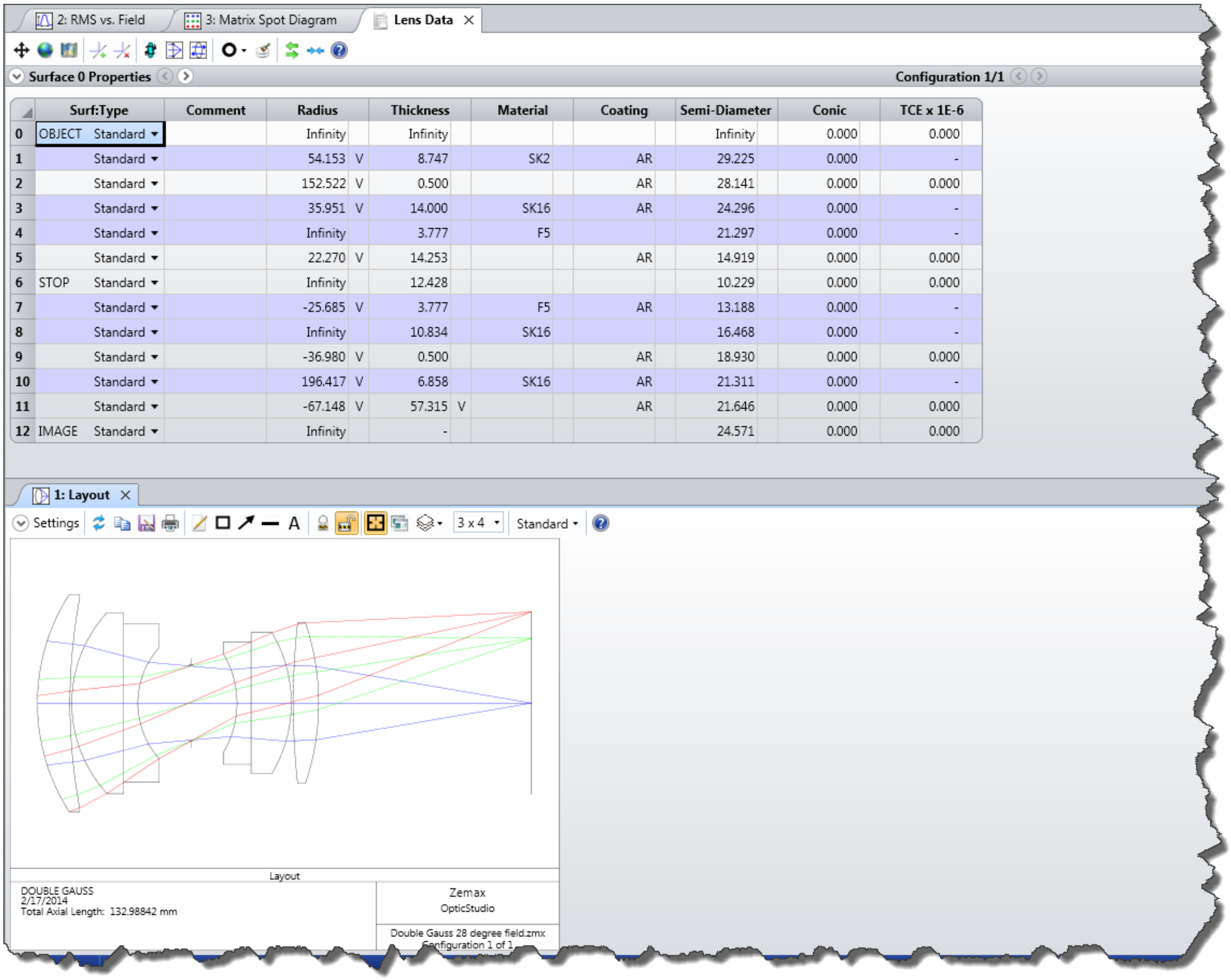


Experiment with floating and docking windows. Then click on the Layout tab with the left-mouse-button and drag the window away from the dock until the Window Manager icon appears. Use this to place the layout below the other three windows:

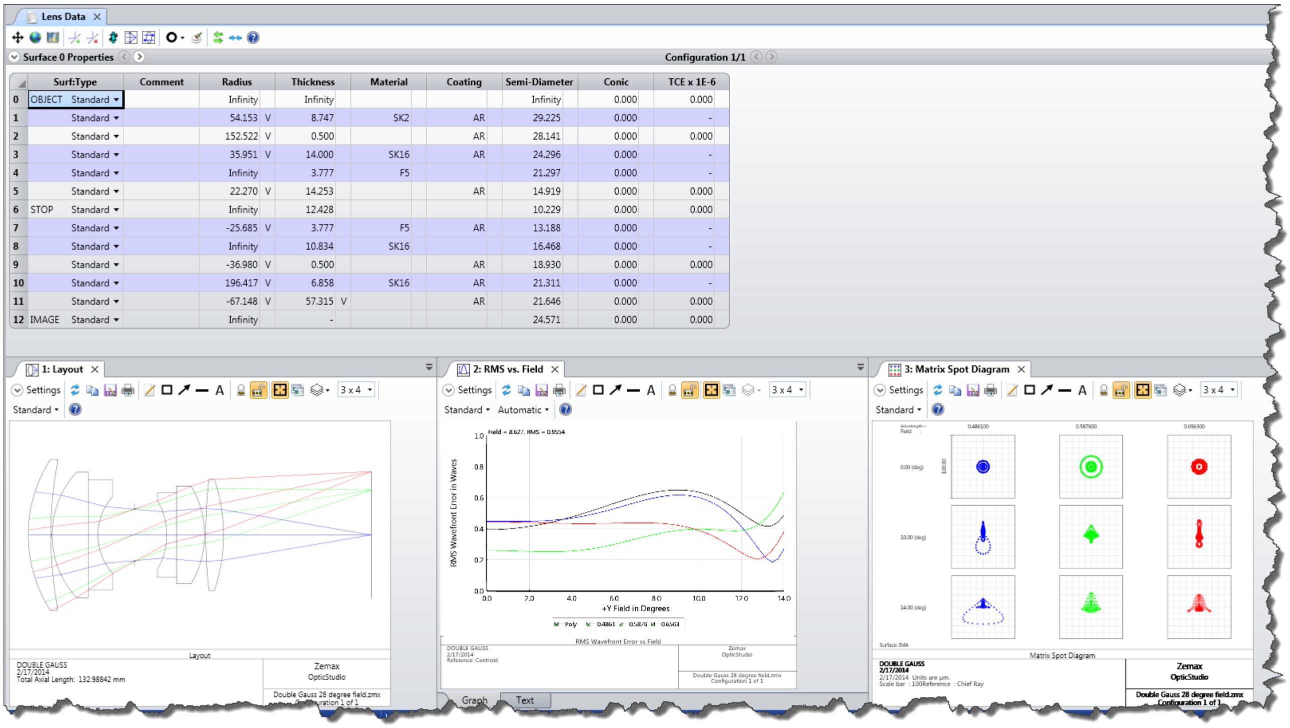


	Surf:Type	Comment	Radius	Thickness	Material	Coating	Semi-Diameter	Conic	TCE x 1E-6
0	OBJECT Standard		Infinity	Infinity			Infinity	0.000	0.000
1	Standard		54.153 V	8.747	SK2	AR	29.225	0.000	-
2	Standard		152.522 V	0.500		AR	28.141	0.000	0.000
3	Standard		35.951 V	14.000	SK16	AR	24.296	0.000	-
4	Standard		Infinity	3.777	F5		21.297	0.000	-
5	Standard		22.270 V	14.253		AR	14.919	0.000	0.000
6	STOP Standard		Infinity	12.428			10.229	0.000	0.000
7	Standard		-25.685 V	3.777	F5	AR	13.188	0.000	-
8	Standard		Infinity	10.834	SK16		16.468	0.000	-
9	Standard		-36.980 V	0.500		AR	18.930	0.000	0.000
10	Standard		196.417 V	6.858	SK16	AR	21.311	0.000	-
11	Standard		-67.148 V	57.315 V		AR	21.646	0.000	0.000
12	IMAGE Standard		Infinity	-			24.571	0.000	0.000

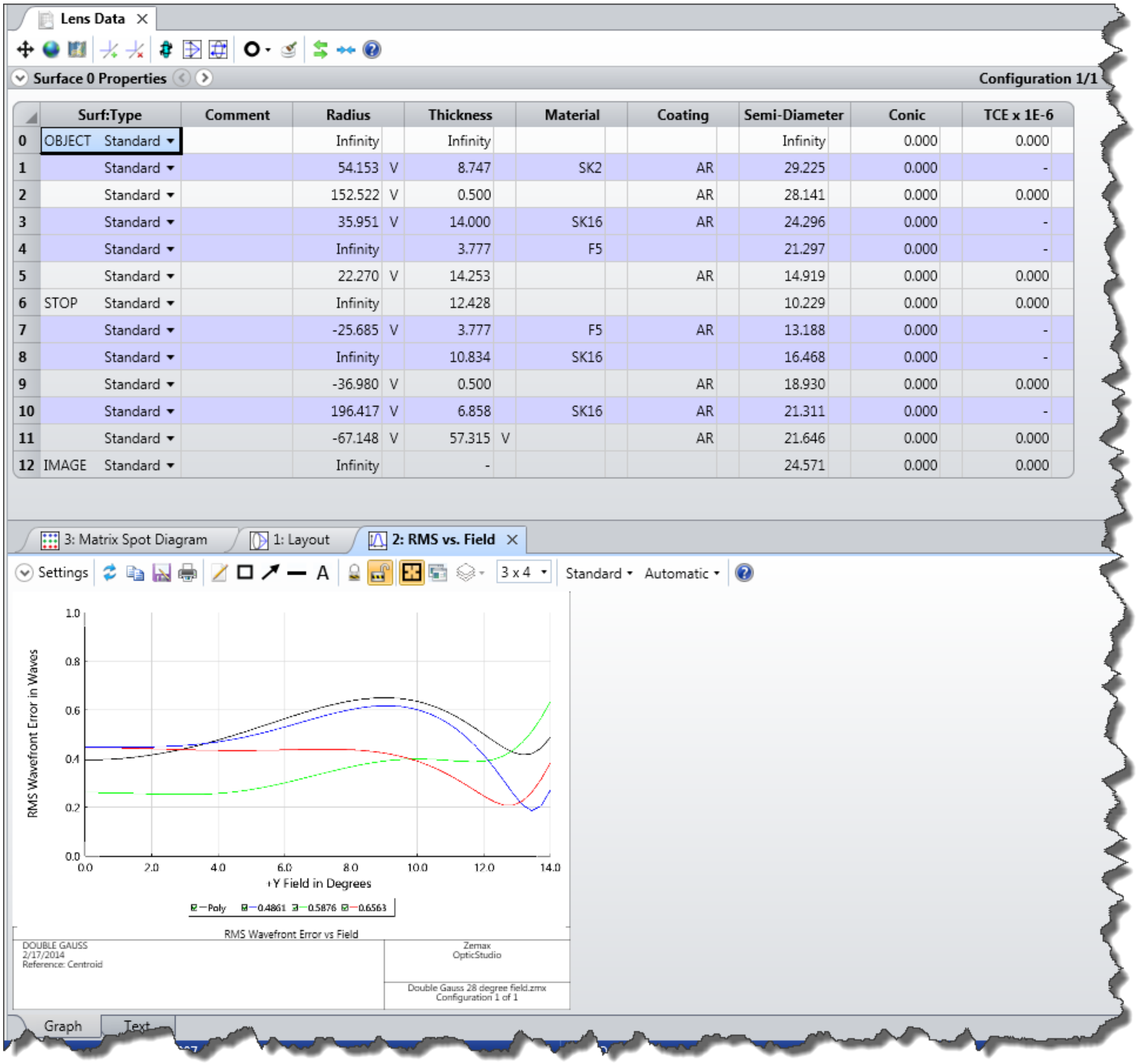
And release the mouse button:



Repeat this process to get the following workspace layout:

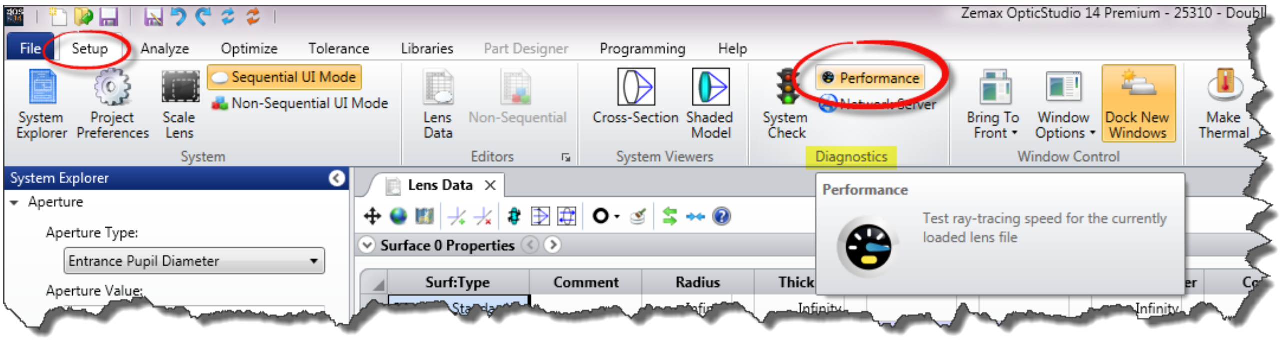


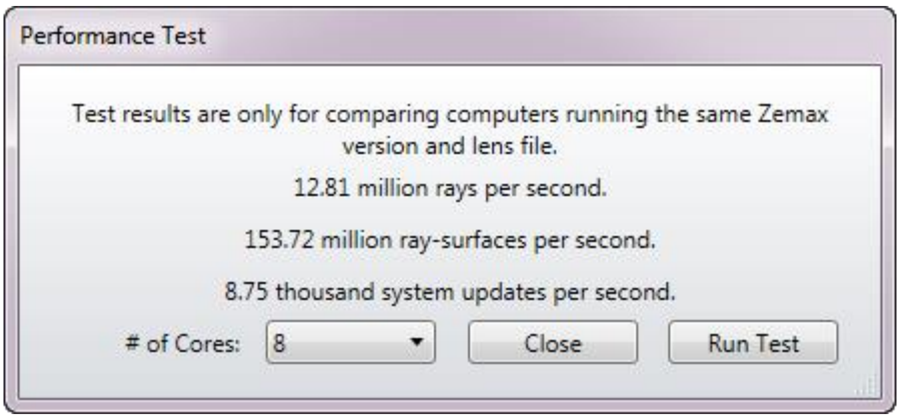
Then make this arrangement:



This shows one of the key features of the OpticStudio interface. Any open window many be floating (placed where you put it, and independent of any other window), or arranged in the workspace, or placed in a tab group with any other window etc.

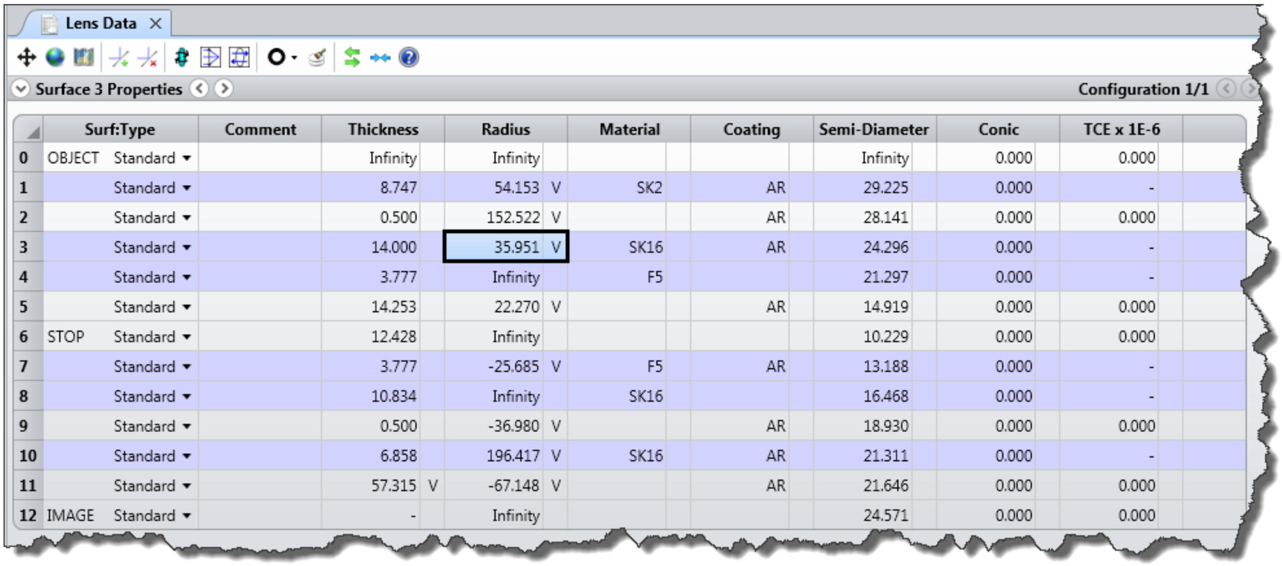
Next, within the Setup tab, click on Performance in the Diagnostics group:





This will give you a simple metric of how fast OpticStudio is on your computer. It also shows one of the best features of OpticStudio: its ability to use multiple CPUs in your computer, if available, to trace millions of rays per second. Calculations are split up and spread over all available CPUs, and the results stitched back together again, without any user interaction.

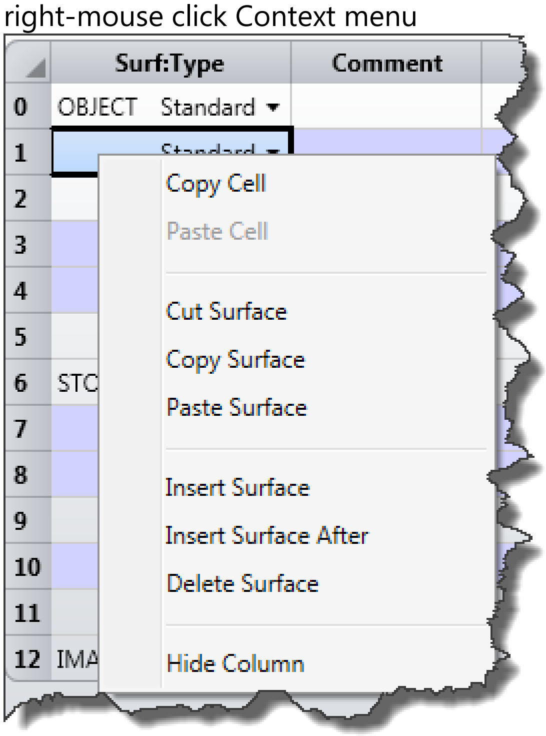
Tutorial 1.1: The Lens Data Editor



	Surf:Type	Comment	Thickness	Radius	Material	Coating	Semi-Diameter	Conic	TCE x 1E-6
0	OBJECT Standard		Infinity	Infinity			Infinity	0.000	0.000
1	Standard		8.747	54.153 V	SK2	AR	29.225	0.000	-
2	Standard		0.500	152.522 V		AR	28.141	0.000	0.000
3	Standard		14.000	35.951 V	SK16	AR	24.296	0.000	-
4	Standard		3.777	Infinity	F5		21.297	0.000	-
5	Standard		14.253	22.270 V		AR	14.919	0.000	0.000
6	STOP Standard		12.428	Infinity			10.229	0.000	0.000
7	Standard		3.777	-25.685 V	F5	AR	13.188	0.000	-
8	Standard		10.834	Infinity	SK16		16.468	0.000	-
9	Standard		0.500	-36.980 V		AR	18.930	0.000	0.000
10	Standard		6.858	196.417 V	SK16	AR	21.311	0.000	-
11	Standard		57.315 V	-67.148 V		AR	21.646	0.000	0.000
12	IMAGE Standard		-	Infinity			24.571	0.000	0.000

In sequential ray-tracing, light is traced from its source, called the 'Object' surface, to surface 1, then to surface 2, 3, etc. until it lands on the final 'Image' surface. For historical reasons this surface is always called the Image surface, even though the optical system may not form an image of the source. A laser beam expander or eyepiece for example may be afocal: this is covered later.

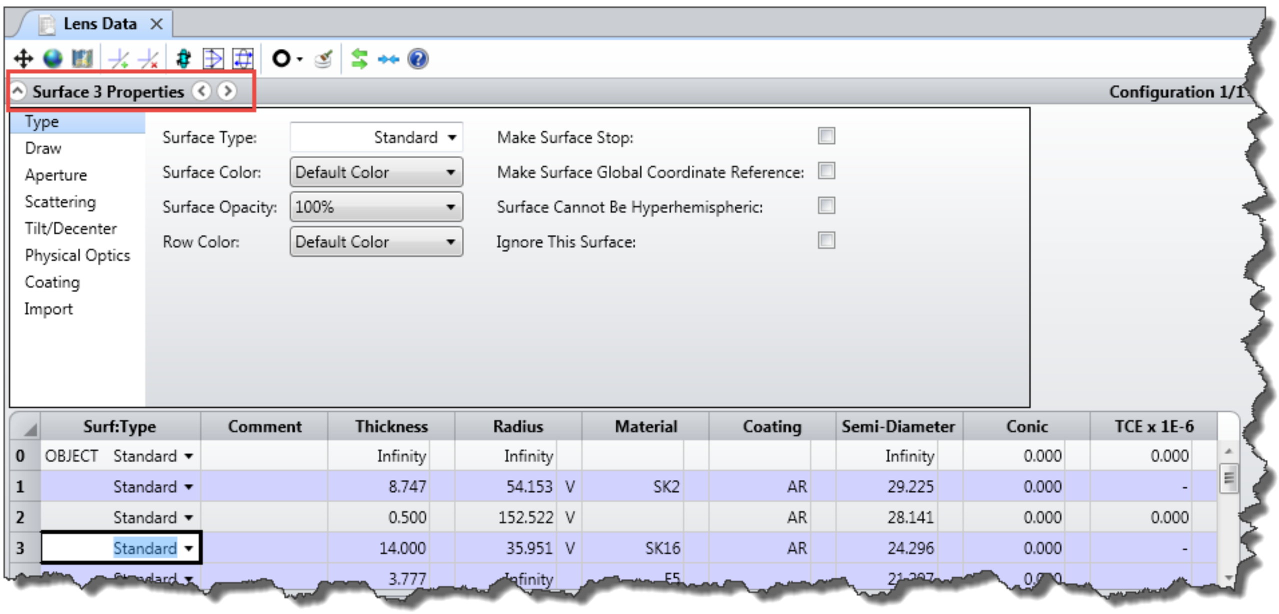
Surfaces are inserted or deleted in the editor using the Insert or Delete keyboard keys, or via the right-mouse click Context menu



which also allows individual cells or the entire spreadsheet to be copied to the clipboard. Column widths can be varied by placing the cursor in the top row, over the column separator. When the cursor turns to a ↔ symbol, click and hold the left mouse button to resize the column. Columns can be moved by clicking on the column header, holding the mouse down and dragging.

The 'V' next to some parameters means that this parameter is 'variable'. OpticStudio is allowed to change the values in such cells in order to improve the performance. This will be discussed in more detail later.

Surfaces also have a set of properties that are not directly visible in the editor until the Property Inspector is opened. These are generally those properties that are set and then not changed. To see these properties, move the mouse over the Type cell of the chosen surface, and double click.

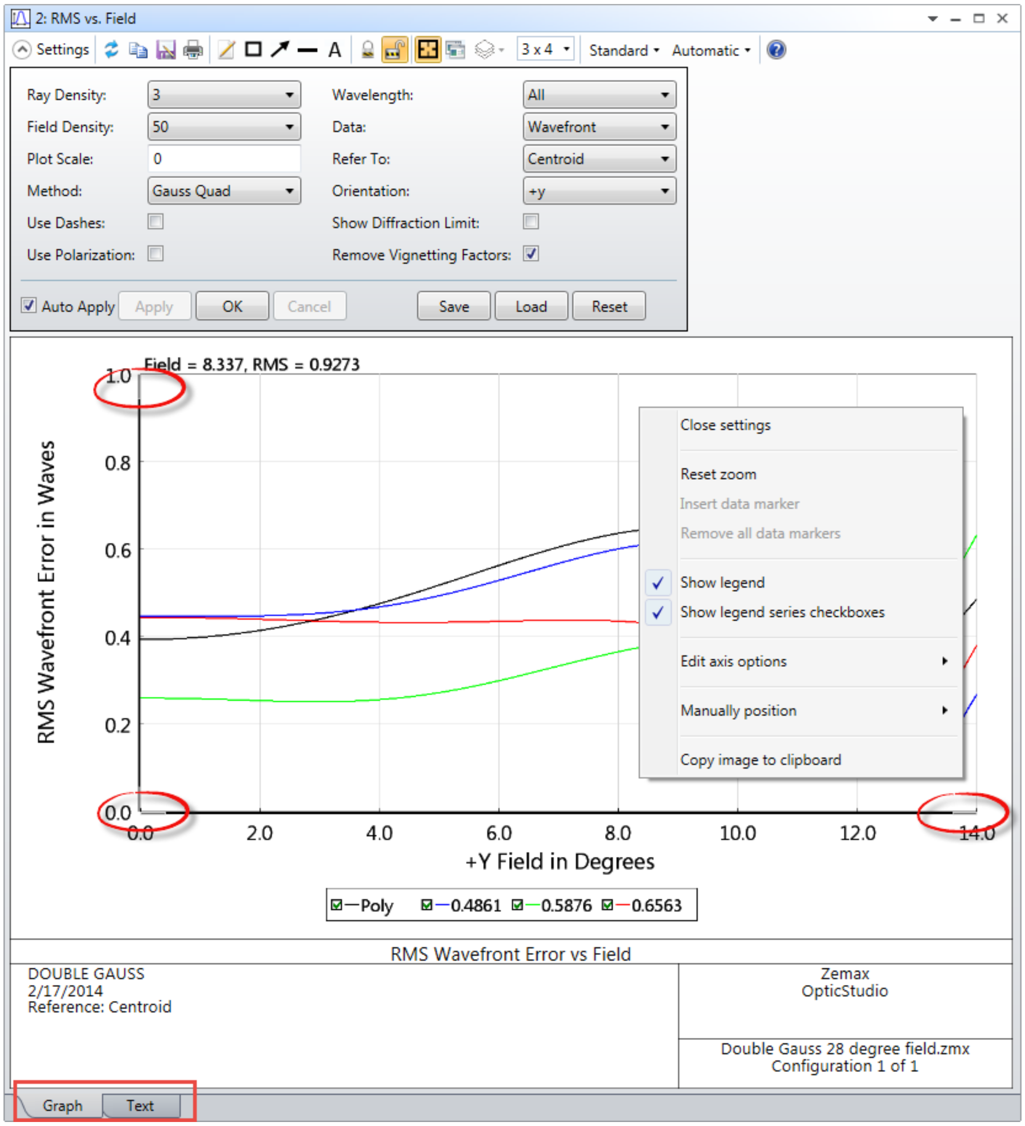


Alternatively, click on the Property Inspector as shown above. A multi-tab dialog appears. From the Surface Type drop-down list you can select the type of the surface, which can be aspheric, diffraction grating, toroidal, etc.

Spend some time exploring each tab. The most commonly used tabs are the Type, Draw, Aperture and the Tilt/Decenter tabs. Press the Help button on each tab to read the on-line Help.

Tutorial 1.2: Analysis Windows

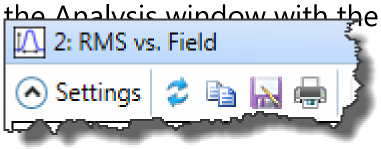
Analysis windows provide either graphical or text-based data computed from the lens as entered in the Editor. Analysis windows never change the lens data: they provide diagnostic information of the various aspects of the lens system's performance.



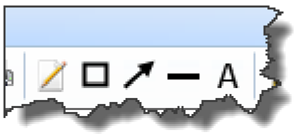
Analysis windows all operate with the same user interface and have the same menu bar:

- Pressing the Settings icon will toggle a dialog box that controls the input parameters passed to the calculation. The Save, Load and Reset buttons allow default settings to be saved, recalled or reset to 'factory' defaults. If you save the settings of any window, those become the defaults for every file that does not have its own settings, so your preferences automatically flow through all your work.

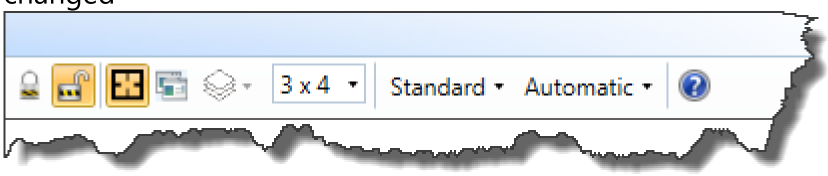
- Pressing the Update menu item (next to the Settings icon), or double-clicking anywhere in the Analysis window with the left mouse button, will make the Analysis window recompute



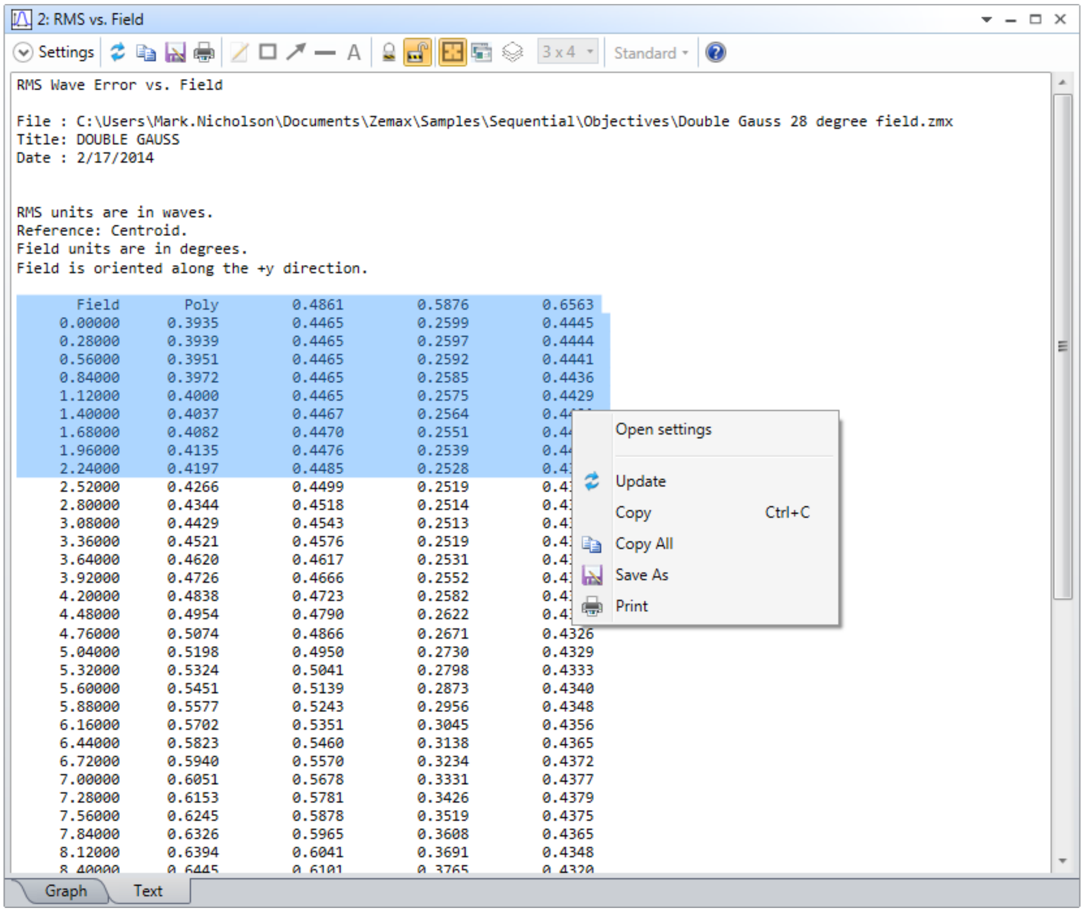
- There are standard Copy, Save As and Print icons
- Right-mouse-clicking will make a context menu show. Analysis windows showing three dimensional data have more options than 2D data plots
- A set of annotation tools let you mark up the analysis feature with text, boxes, arrows, lines etc.:



- Windows can be locked, unlocked, cloned, overlaid and have their drawing resolution changed

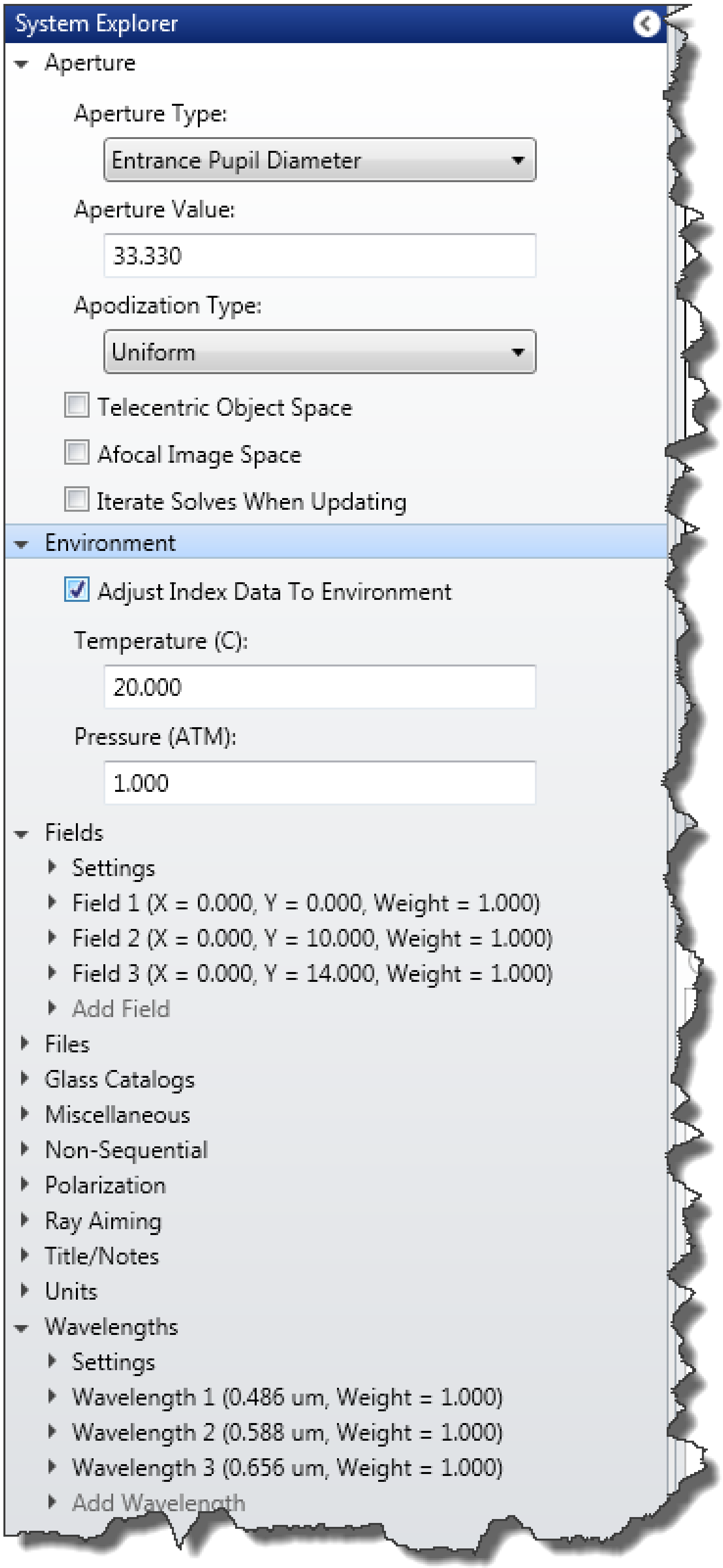


- You can zoom in on a section of interest by clicking the left mouse button, holding it down and dragging it over the region you wish to zoom in on, or by clicking and dragging the grey bars at the ends of the x and y axis, or by choosing 'Edit Axis Options' from the right-mouse menu. A text tab shows the data on which the calculation is based. This can be copied to the clipboard in whole or in part (by highlighting the section desired and right mouse clicking) or saved to a text file.



Spend some time playing with the features of the Analysis windows. Remember Analysis windows never change the data in the design, so you cannot do any damage!

Tutorial 1.3: The System Explorer



The System Explorer defines the light entering the system as well as many other basic system parameters. Data entered in the System Explorer is usually set once and not altered, or altered only occasionally as the design matures, although full optimization of System Explorer data is supported if needed. For example, the Aperture of this lens is set to be 'Entrance Pupil Diameter', so the EPD is specified directly, and is set to be 33.33 'Lens Units'. All items having units of length are given in Lens Units except where specifically noted. Click on the Units tab to see what the Lens Units of this lens are (they can be mm, cm, meters or inches).

Entrance Pupil Diameter (EPD) defines the size of the on-axis bundle of light entering the lens system. In the double-Gauss sample file we are using, which is a traditional SLR-type camera lens, OpticStudio traces rays at this height through the lens and computes the size of the aperture stop surface (marked as STOP in the Lens Data Editor), drawn in red opposite. The aperture stop surface is usually a ring diaphragm, so in reality the radial size of this surface defines the EPD, not the other way around.

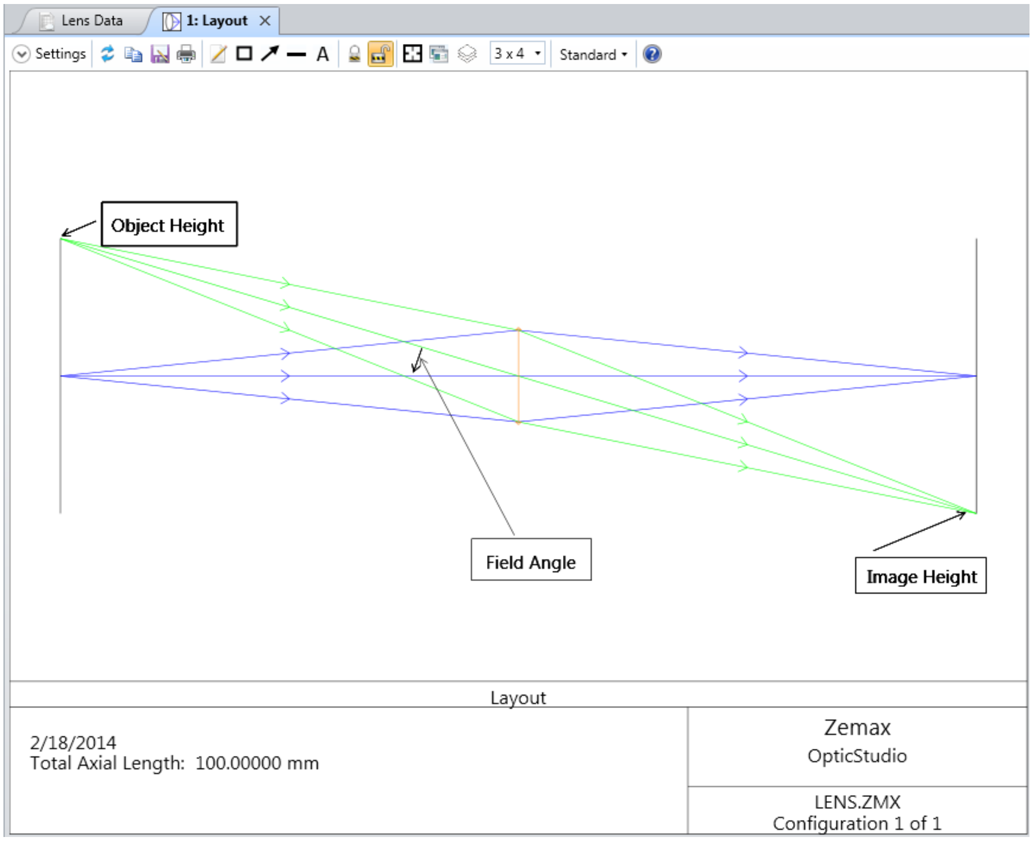
If you prefer this alternative definition, then choose the Aperture Type in the General dialog box to be 'Float by Stop', and then change the semi-diameter of the STOP surface to say 8 mm. Double-click all the open Analysis windows to make them update to reflect this change, and notice the change in the lens apertures and performance. OpticStudio automatically computes the appropriate size of each surface so that all light passes through each surface.

Another commonly used Aperture Type is 'Object Space NA' which is appropriate when the source is something like an optical fiber that radiates out in a defined numerical aperture. Use 'Object Cone Angle' if the source is defined by a source angle in degrees instead of NA.

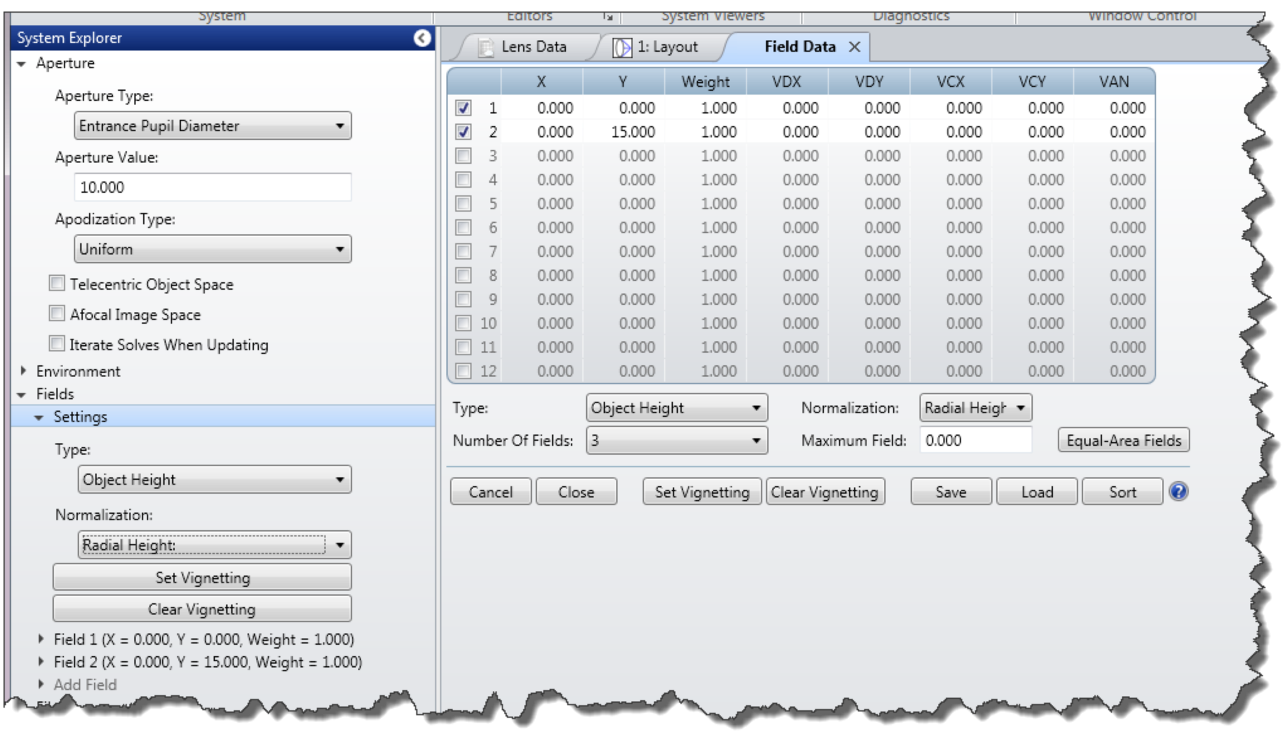
The Fields Section

The term "Field" is short for field-of-view and it can be defined in three ways, one of which supports two options:

- The height of the object scene being imaged
- The height of the image being formed, which may be chosen to be either a real or paraxial image height
- The angle subtended by the object scene at the lens

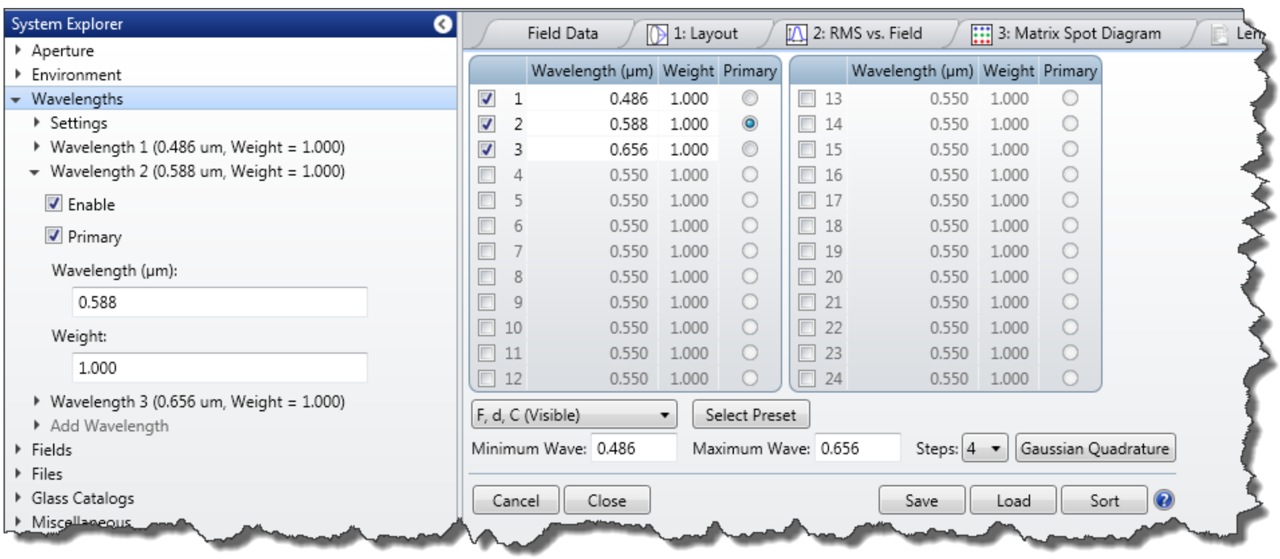


Field data can be entered by expanding the Fields section of the System Explorer, or by double-clicking the Fields data section to show a dialog box:



In the double Gauss sample file, we cannot use Object Height as a definition because the object surface is at infinity. Instead, the field angle subtended at the pupil is used, and this is commonly done in camera design. Alternatively, we might use image height when the detector is a fixed size like a CCD chip, and in this case the field of view is defined by what the detector can 'see' when looking out through the lens.

The Wavelengths Section



Wavelengths are always entered in microns. Wavelength weights can be used to define relative spectral intensity, or simply to define which wavelengths are most important in a design. The 'primary' wavelength is used as a default wavelength: for example, if asked to compute effective focal length, OpticStudio will compute it at the primary wavelength if no wavelength is specified.

Wavelength data is entered in the System Explorer by expending the Wavelengths data section, or by double-clicking it to give a dialog box.

Tutorial 1.4: The Normalized Coordinate System

Because there are six ways to define system aperture, and four ways to define field of view, it is convenient to work in normalized coordinates. When performing the initial setup of your system you should choose the most appropriate aperture definition, and the most appropriate field definition, and enter the data for both of these. Subsequently, all calculations use normalized units, and you do not have to refer to the specific values entered or definitions used.

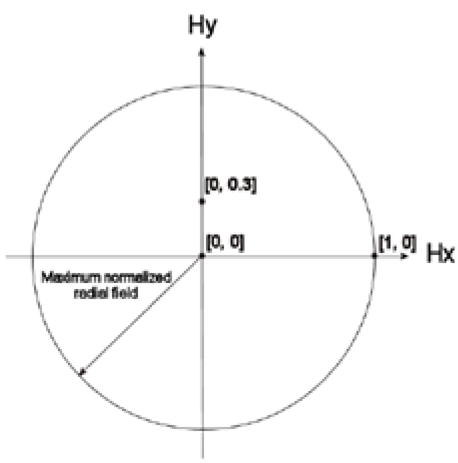
Normalized Field Coordinates

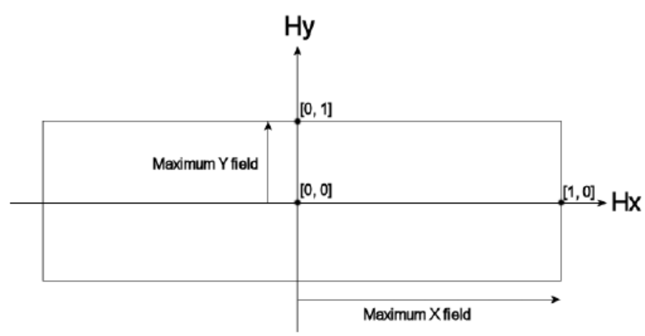
Normalized field coordinates Hx and Hy are used throughout OpticStudio, its documentation, and in the wider optical design literature. The normalized field coordinate (0, 1) for example, is always at the top of the field of view in y, whether the field points are defined as angles or heights, and regardless of the magnitude of the field coordinates. Similarly the field coordinate (0,0) is always at the center of the field of view.

For example, suppose 3 field points are defined in the (x, y) directions using object height in lens units of millimeters at (0, 0), (10, 0), and (0, 3). The field point with the maximum radial coordinate is the second field point, and the maximum radial field is therefore 10 mm. The normalized coordinate (H_x =0, H_y = 1) refers to the location on the object surface (as the field of view is defined in object height) of x= 0, y =10 mm. The normalized coordinate (H_x = 1, H_y = 0) refers to the object surface location (10, 0).

You can then define any point within the field of view of the lens by its (H_x, H_y) coordinates, as long as $H_x^2 + H_y^2 \leq 1$.

This is referred to as radial field normalization, as the normalized field coordinates represent points on a unit circle. OpticStudio also supports rectangular field normalization, in which the normalized field coordinates represent points on a unit rectangle.





Normalized Pupil Coordinates

Similarly, normalized pupil coordinates are also used throughout OpticStudio, its documentation, and in the wider optical design literature. You define the system aperture using whatever definition is most useful, and thereafter we use the normalized pupil coordinates Px and Py to define any point within a unit circle. Therefore, the point (0,1) represents a point at the top of the bundle of rays entering the system, and (0, 0) is a point at the center of the ray bundle, no matter what the definition of system aperture is or what value it has.

Using the Normalized Coordinates

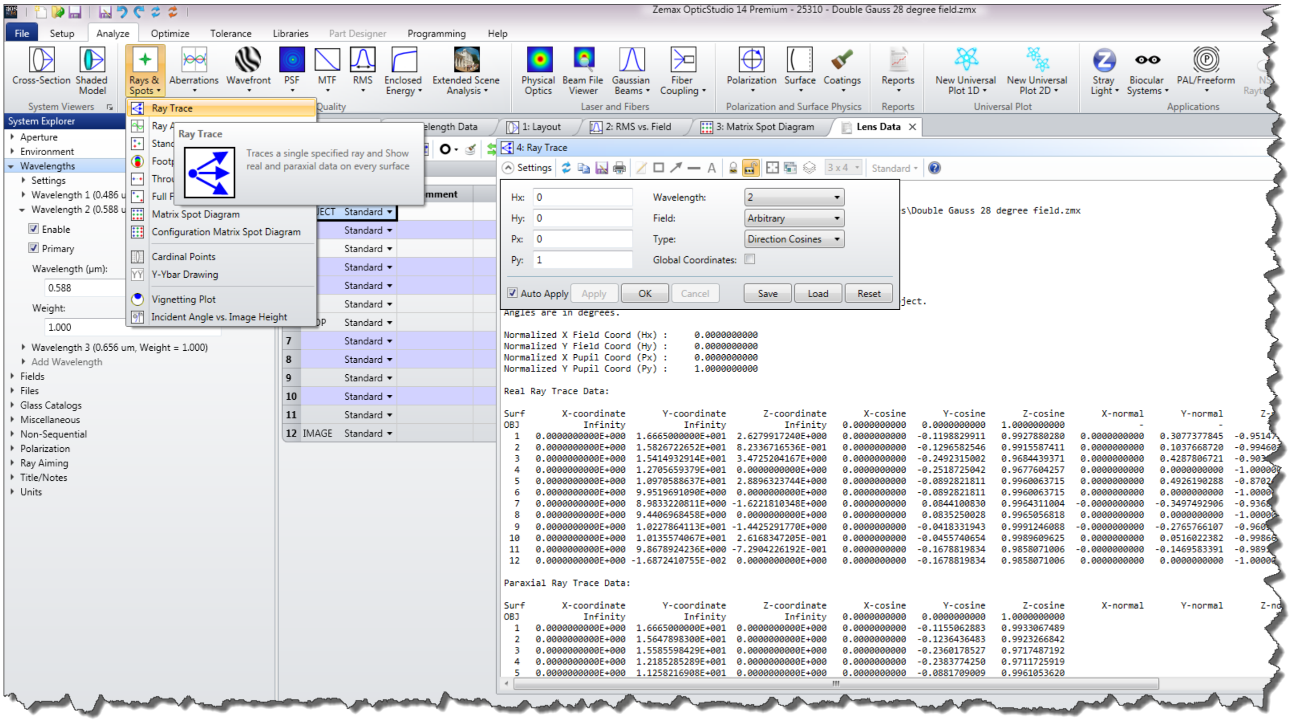
Re-open the double Gauss 28 degree field sample file in order to undo any changes you may have made in the earlier sections. Open the Field section of the System Explorer and note that the field is defined as angle in degrees, and the maximum field point has a value of 14°. This is a half-angle, and so the full field of view is 28°.

Note: OpticStudio is always clear on the definitions it uses, but these definitions are not universal in the optics industry. Always clarify with your customers what definitions they use for important system specifications to avoid costly errors!

Then expand the Aperture section of the System Explorer and note that the system aperture is defined as Entrance Pupil Diameter, value 33.33. Go to the Units tab to see that the lens units are millimeters, so the EPD is 33.33 mm.

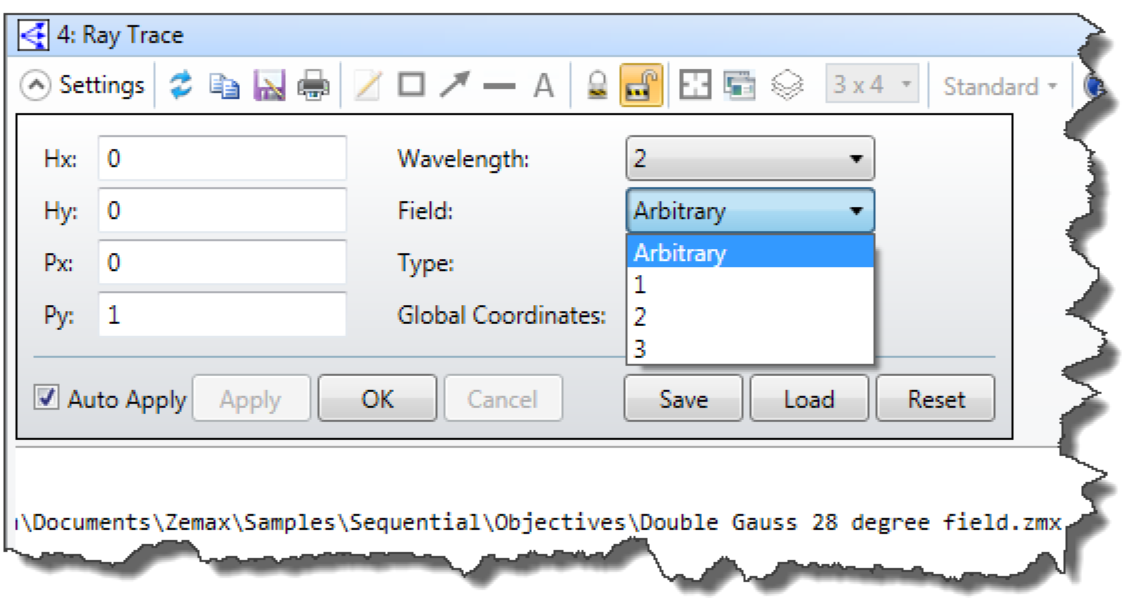
Lastly, expand the Wavelength section and note that the design uses three wavelengths, at 0.4861, 0.5876 and 0.6563 microns respectively. The primary wavelength is set as wavelength number 2, which is 0.5876 microns.

Now click on the Analysis tab, and select Rays and Spots…Ray Trace. This is the most fundamental calculation in OpticStudio: the tracing of a single ray. Right-mouse click on this window to bring up its Settings dialog box:



Note how you can define any ray by where it starts on the object surface in normalized (H_x, H_y) coordinates, and where it goes to in the pupil in normalized (P_x, P_y) coordinates. Try tracing some rays, and look at the data provided by this feature. You are given the (x,y,z) position of the ray, the direction cosines of the ray, and the path length of the ray at each surface of the system. This is the fundamental data on which all the calculations in sequential ray tracing are based.

Note also that instead of defining 'arbitrary' field coordinates (H_x, H_y) you can also define the starting coordinates of the ray by the field point number:



Since field point 3 defines the maximum radial field, it is at (0, 1) in normalized field coordinates. Field point 2 is likewise at (0, .714) and field point 1 is at (0, 0). Depending on the Analysis feature selected, field points can be defined by either their field point number (as entered in the Field dialog box) or by their (H_x, H_y) values.

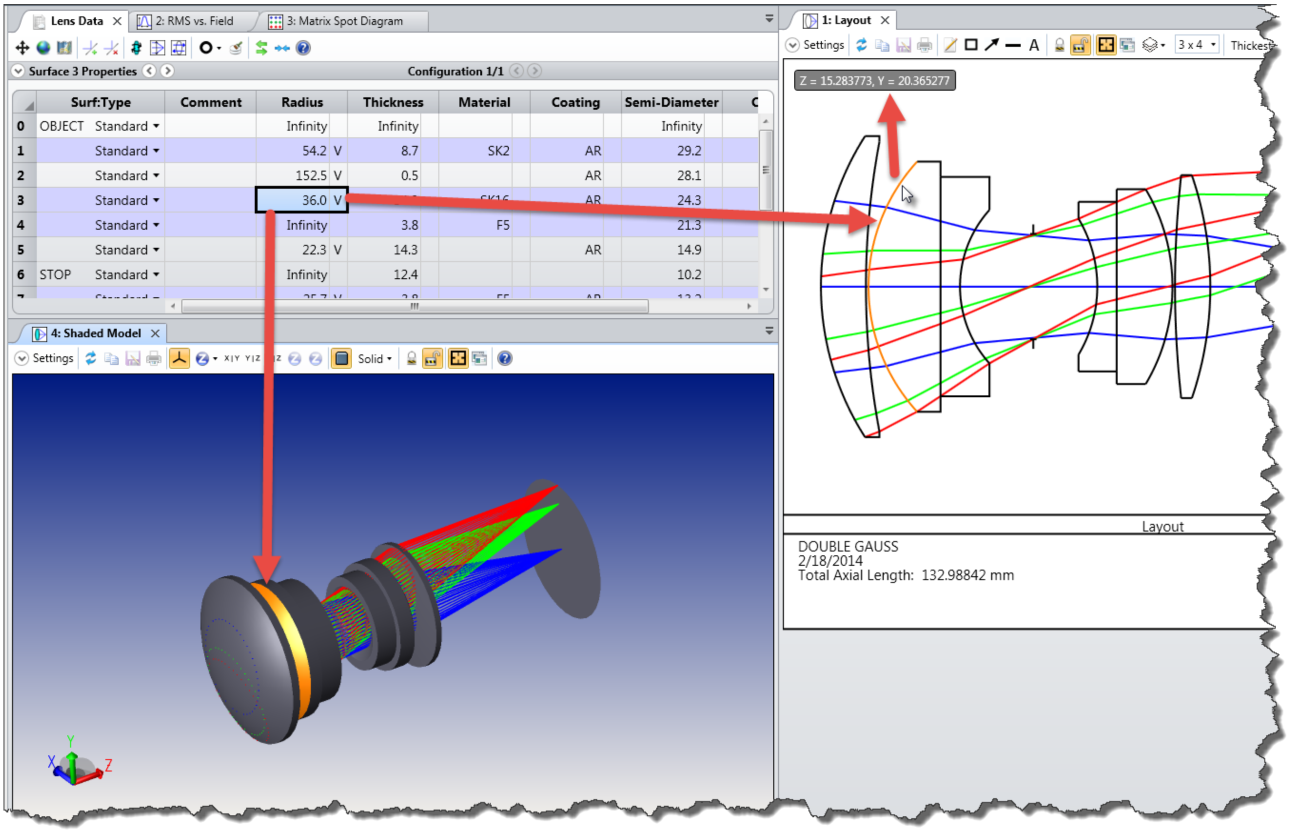
Tutorial 2: Defining, Positioning and Moving Surfaces

Click on File…Open and select the file {Current User}\Documents\Zemax\Samples\Sequential\Objectives\Double Gauss 28 degree field.zmx. If you already have this file open from Tutorial 1, re-open it to lose any changes you may have made during that tutorial.

In 'sequential' lens design, light always starts at surface 0, the 'object' surface, and is traced to surface 1, then surface 2, then 3 etc. It therefore makes sense to position surfaces relative to each other. Returning to the double Gauss sample file, look at the Lens Data Editor, and click on surface 3. Note that this surface is drawn in red in the Layout plots when you click on it in the editor.

Rays propagate from left to right in the layout, and this direction is the +Z axis. The +Y axis goes from the bottom to the top of the window, and the +X axis goes 'into' the screen. If you position your right hand, such that your middle finger is touching surface 1 in the layout window and points into the screen, your index finger is pointing towards the right hand of the screen, and your thumb is pointing upwards, you have the classic 'right hand coordinate system' used throughout OpticStudio and in most of the optical design literature. The Coordinate Axes are always drawn in the Shaded Model plot, below

Also, observe that as you move your mouse over the layout window, the coordinates of the mouse pointer are shown in the title bar of the window:



If you move the mouse across the Layout window, you will see the Z coordinate change, and as you move the mouse up or down the window, the Y value will change.

The Lens Data Editor shows the following data for surface 1 (if you are using the Demonstration version of OpticStudio, fewer decimal places are shown:

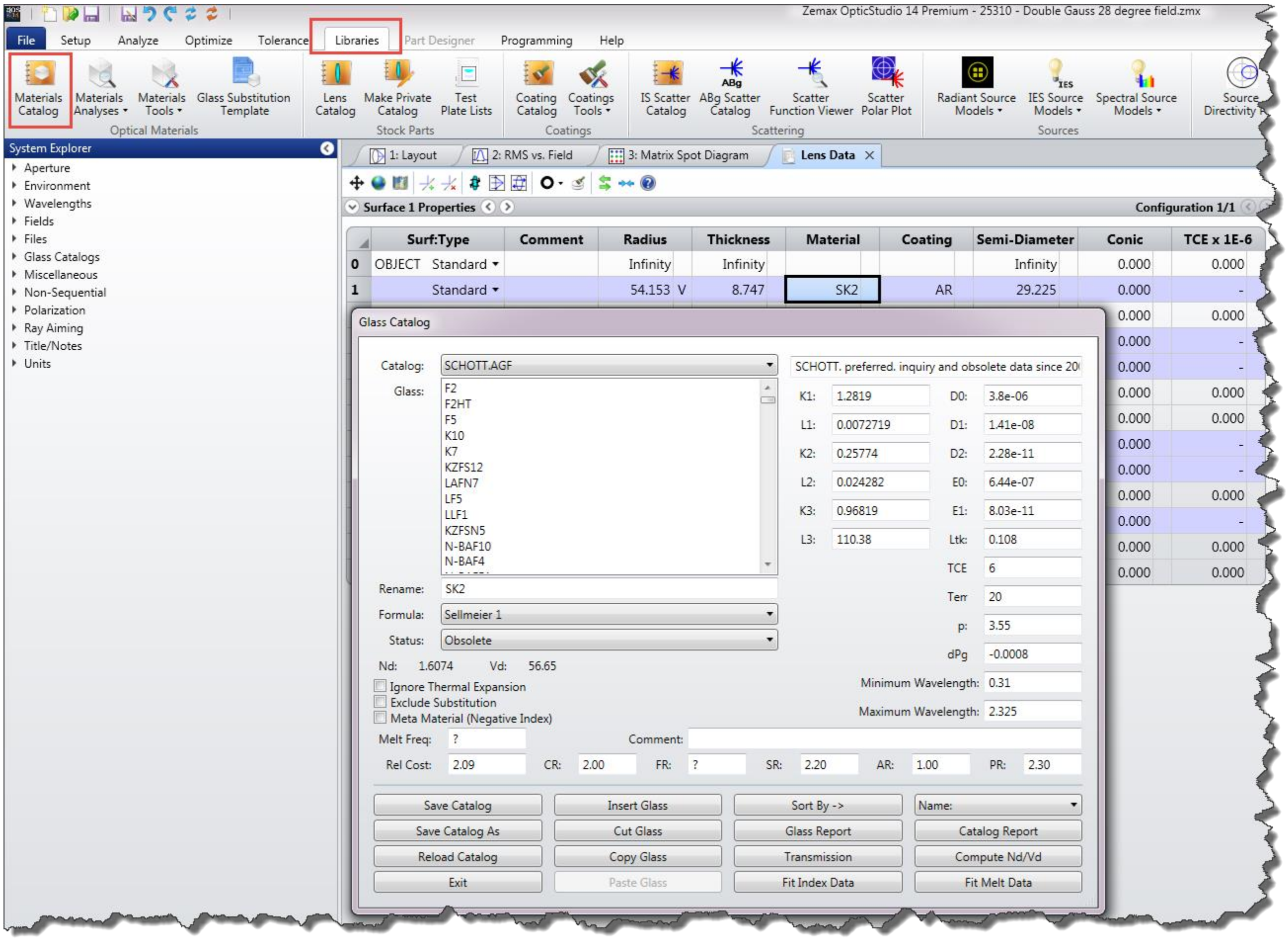
```
Radius of curvature:  54.153
Thickness:            8.747
Material:             SK2
Semi-diameter:        29.225
Conic:                0
```

Remember that any lengths where the units are not explicitly given are in “Lens Units”, which are in mm for this file (see System Explorer ‘Units’ section).

The radius of curvature of surface 1 is 54.153 mm. This is a positive number because the center of curvature lies in positive Z. By contrast, surface 7 has a radius of curvature of -25.685 mm because its center of curvature lies in –Z.

Surface 1’s thickness of 8.747 mm means that surface 2 is located 8.747 in positive Z relative to surface 1. “Thickness” is therefore the distance along Z of two surfaces. We refer to this as ‘thickness’ in the editor rather than ‘z-distance’ because if you were to hold the lens formed by surfaces 1 and 2 in your hand, you would naturally describe the lens as having a center thickness.

Surface 1's Material type is set to SK2, which means that the space between surface 1 and surface 2 is filled by a particular glass called SK2. Click on the SK2 glass in the editor, and then click on the Libraries tab and then the Materials Catalog icon:



This shows that SK2 is a material in the Schott catalog, and it gives all the data OpticStudio knows about the glass.

Note: A full discussion of this dialog is outside of the scope of this Tutorial. See the "Using Glass Catalogs" section of the Technical Reference for full details.

Next, see that surface 2 has no entry for its Glass column, and is instead blank. That means that surface 2 is made of 'Air' at Standard Temperature and Pressure. Both temperature and pressure can be changed, both at a system level and on a surface-by-surface basis. This has important, but subtle, effects. First, the index of refraction of glass depends upon both temperature and wavelength; relative indices which are measured with respect to air also change with pressure. Second, glass expands and contracts with temperature, which can change the radius, thickness, or other dimensions of a lens. Third, the distances between lenses change due to the expansion and contraction of the mounting material.

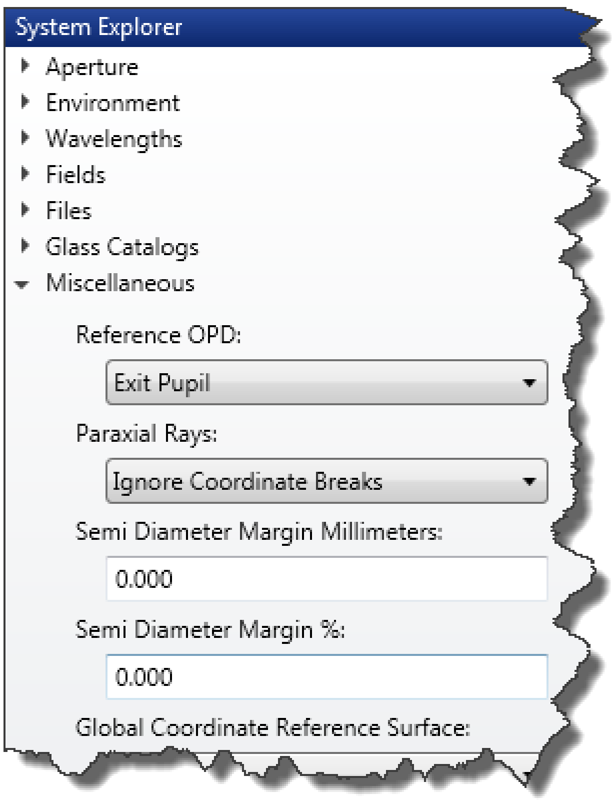
The thermal analysis features of OpticStudio can account for all these effects. OpticStudio can be used to analyze and optimize a design for any specific temperature or for a range of temperatures.

This is outside of the scope of this Guide, however, and we will assume that the whole lens is at 20° C, 1 Atm pressure.

Note: See the "Thermal Analysis" section of the Technical Reference for full details of the comprehensive temperature and pressure modelling capabilities of OpticStudio.

The "Semi-Diameter" column shows the radial height of the surface (it is called Semi-Diameter to avoid confusion with radius of curvature). This can be computed in two ways: automatically by OpticStudio (the default), or directly entered by the user.

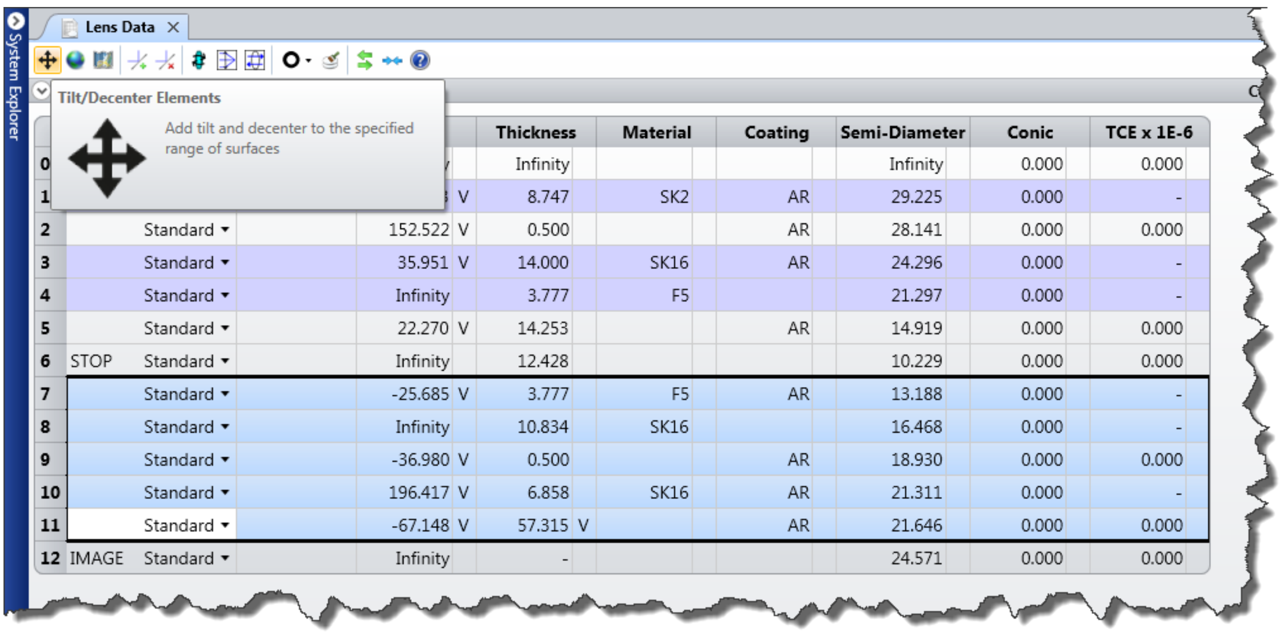
The automatic calculation sets the semi-diameter to ensure that the edge rays always pass through the lens. This means that the lenses are 'just big enough' to pass the full aperture of rays from across the field of view. Usually, lenses are made a little larger than this, so there is some unused glass that can be used to hold the lens in its mount without blocking the beam. You can specify the additional amount easily by adding a semi-diameter margin in System Explorer's Miscellaneous group.



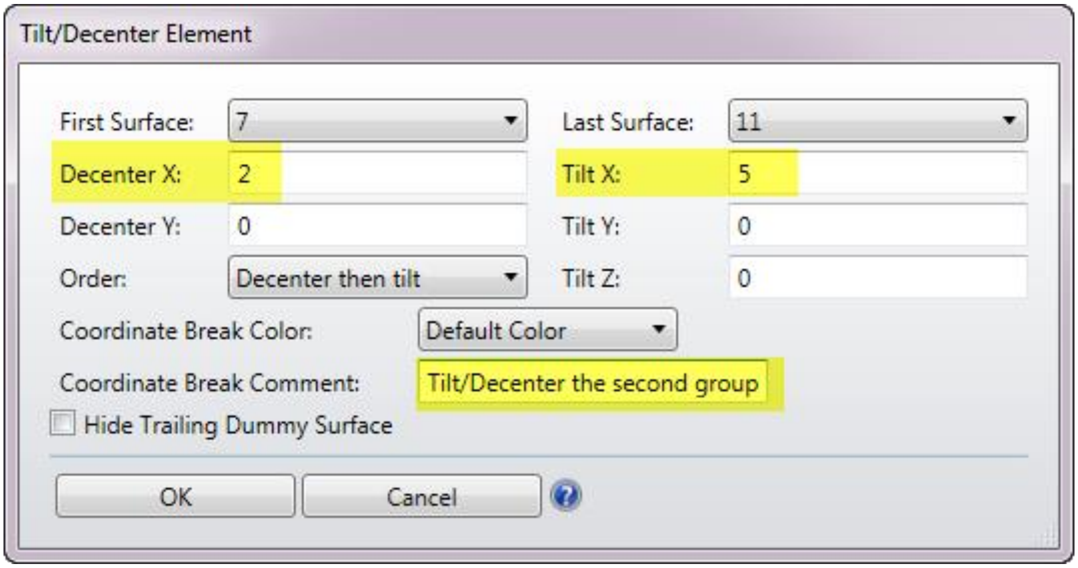
Tutorial 2.1: Working in Three Dimensions

The double Gauss example lens is an axially symmetric lens, and so each surface is simply positioned a distance in Z away from the previous surface. But what about systems in which optical components are tilted or decentered with respect to each other?

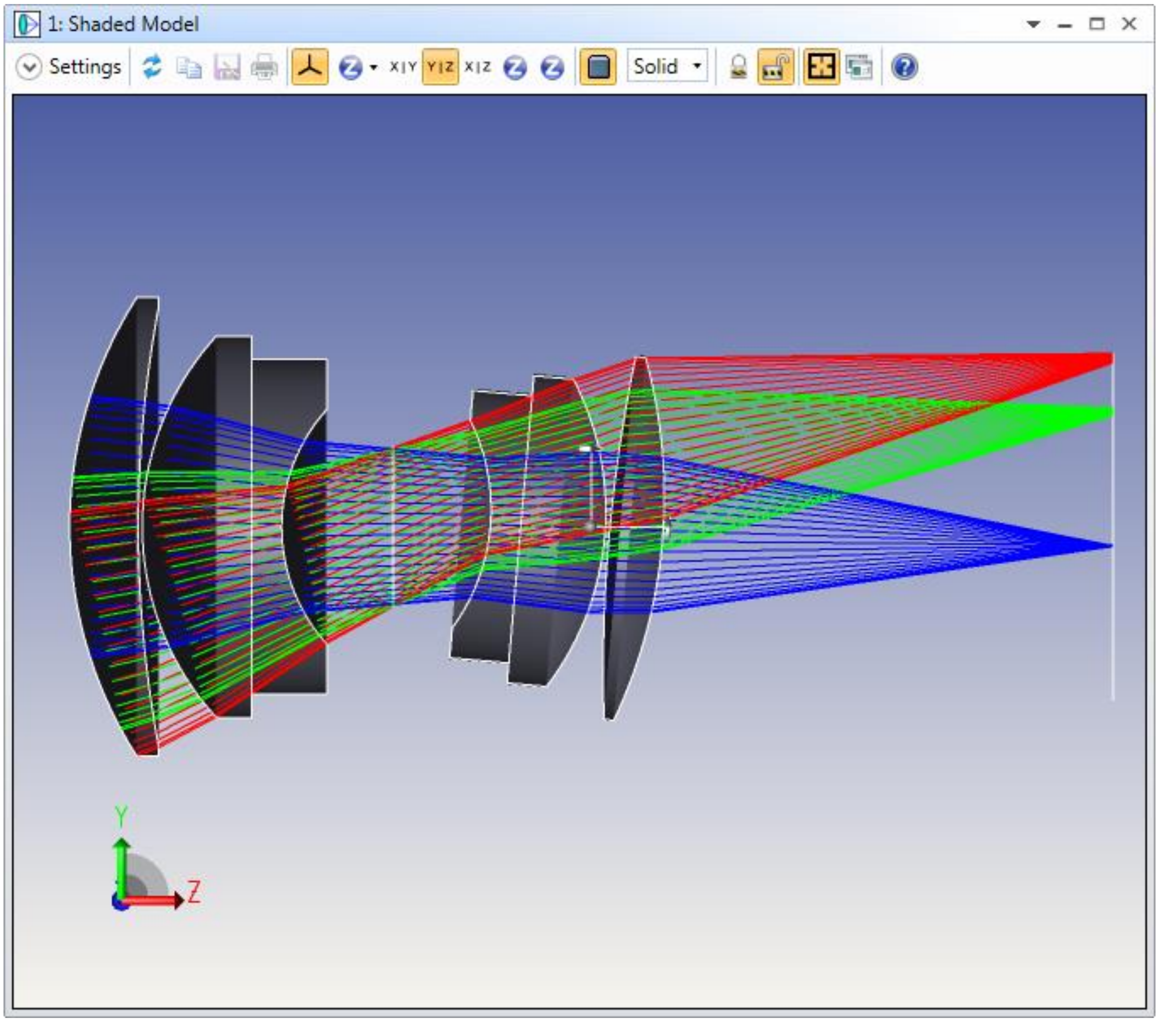
Let's imagine that the second group of elements (the doublet and singlet after the stop) is tilted and decentered with respect to the first. Click on surface 7 in the Lens Data Editor, then hold the left-mouse button down while dragging with the mouse to highlight surfaces 7 to 11. Alternatively, click on surface 7, and press the Shift key while also pressing the down cursor key to highlight surfaces 7-11.



In the Lens Data Editor's Toolbar, click the Tilt/Decenter Elements icon and configure it as shown:

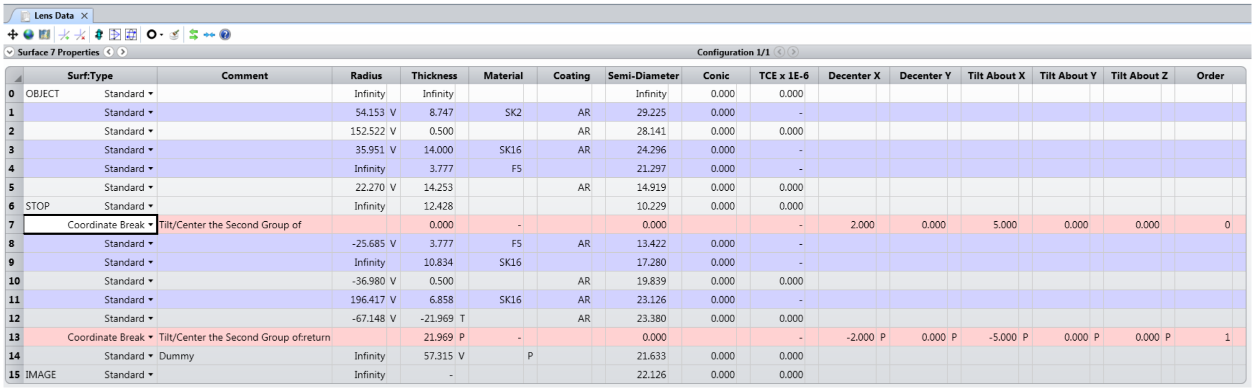


After you press OK, click on System…Update All to update all the open windows. Note that the Layout plot displays a warning 'Cannot perform 2D layout on non-axial system'. Close this window, and click on the Analyze Tab, System Viewers group and choose the Shaded Model. Configure it like so:



You can see that the second group of elements has been shifted in the y-direction (upwards in the Shaded Model) and rotated around x (the x-axis points into the screen). Click anywhere inside the 3D Layout window so that this window is active (the title bar will appear brighter than the other OpticStudio Analysis windows). The layout can be rotated by using the mouse or by the Rotation X/Y/Z controls in the Settings dialog box for this window.

Return to the Lens Data Editor, and see that OpticStudio has now entered two new surfaces into the design and that the editor now has additional columns.



Lens Data

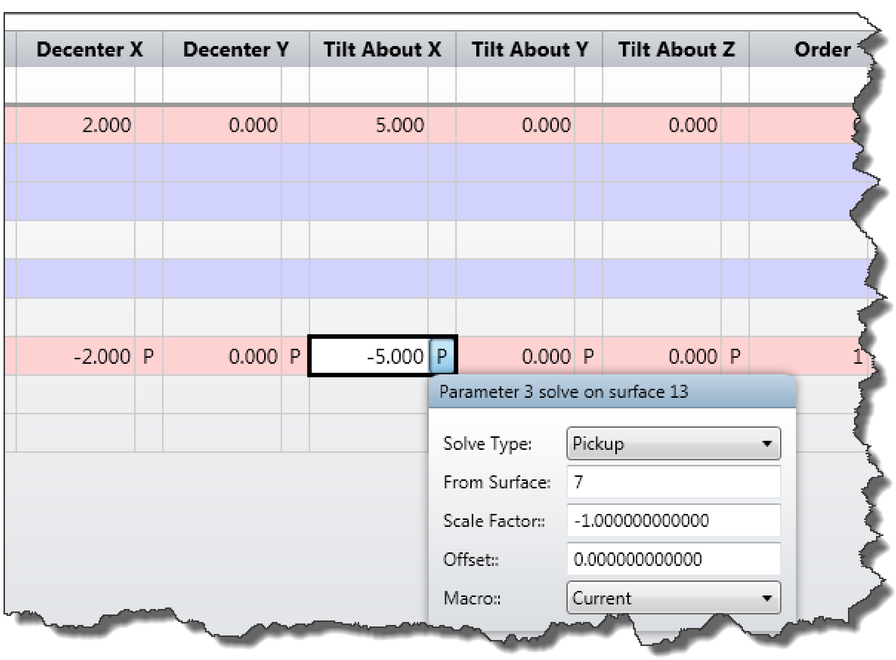
Surface 7 Properties — Configuration 1/1

#	Surf:Type		Comment	Radius	Thickness	Material	Coating	Semi-Diameter	Conic	TCE x 1E-6	Decenter X	Decenter Y	Tilt About X	Tilt About Y	Tilt About Z	Order
0	OBJECT	Standard		Infinity	Infinity			Infinity	0.000	0.000						
1		Standard		54.153 V	8.747	SK2	AR	29.225	0.000	-						
2		Standard		152.522 V	0.500		AR	28.141	0.000	0.000						
3		Standard		35.951 V	14.000	SK16	AR	24.296	0.000	-						
4		Standard		Infinity	3.777	F5		21.297	0.000	-						
5		Standard		22.270 V	14.253		AR	14.919	0.000	0.000						
6	STOP	Standard		Infinity	12.428			10.229	0.000	0.000						
7		Coordinate Break	Tilt/Center the Second Group of		0.000	-		0.000		-	2.000	0.000	5.000	0.000	0.000	0
8		Standard		-25.685 V	3.777	F5	AR	13.422	0.000	-						
9		Standard		Infinity	10.834	SK16		17.280	0.000	-						
10		Standard		-36.980 V	0.500		AR	19.839	0.000	0.000						
11		Standard		196.417 V	6.858	SK16	AR	23.126	0.000	-						
12		Standard		-67.148 V	-21.969 T		AR	23.380	0.000	0.000						
13		Coordinate Break	Tilt/Center the Second Group of:return		21.969 P	-		0.000		-	-2.000 P	0.000 P	-5.000 P	0.000 P	0.000 P	1
14		Standard	Dummy	Infinity	57.315 V	P		21.633	0.000	0.000						
15	IMAGE	Standard		Infinity	-			22.126	0.000	0.000						

These are called Coordinate Break (CB) surfaces. Coordinate Break surfaces have no optical effect; they just define a new coordinate system relative to the previous surface's coordinate system. Click on the first CB surface, and scroll to the right in the Editor. See that the surface has a decentration in x, then y, and a tilt in x, y, and z. If you filled in the dialog as shown above, you should see a decentration in y of 2 mm, a tilt about x of 5 degrees, and have an order flag of 0. This means that the CB will execute 'left to right', meaning that the decentration in x is done first, then the decentration in y, then the tilt in x, etc.

Now look at the second CB. It has a decentration in y of -2 mm and a tilt in x of -5 degrees. This 'undoes' the tilt/decentration of the first CB. Also its order flag is not zero, so it executes 'right to left'. This means that the second CB undoes the first CB, and restores the coordinate system to its original frame of reference.

Note also the letter P next to the decenters and tilts of the second CB. This indicates that a 'Pick-Up Solve' has been placed on this parameter. Click on the P symbol of the Tilt-X parameter of the second CB, and the pickup dialog will open:



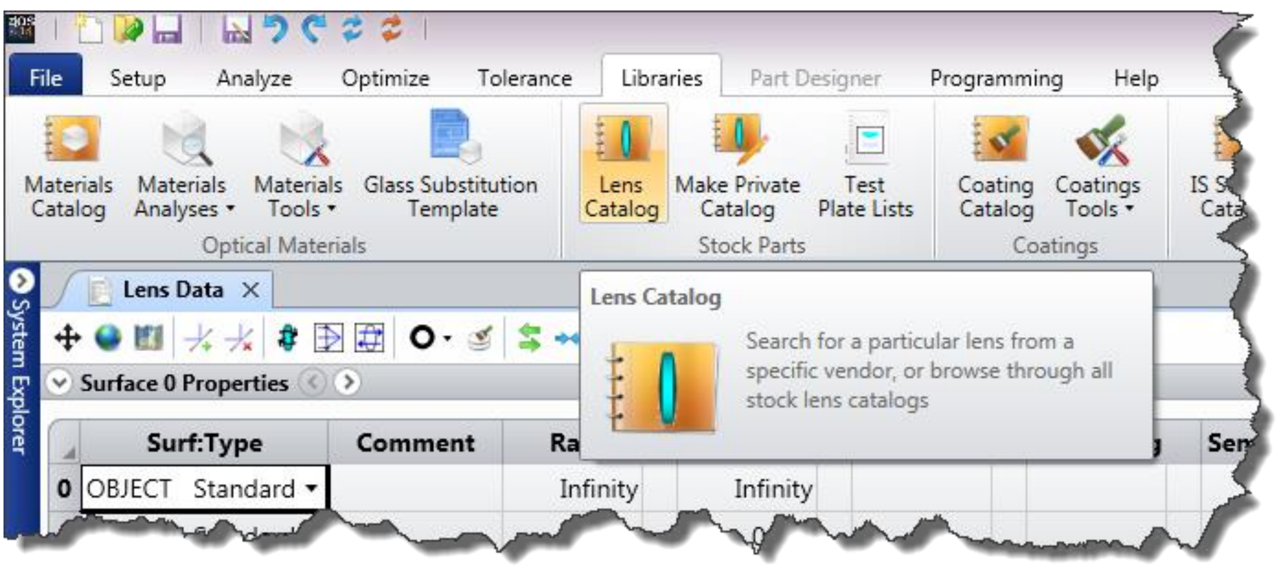
This locks the value of parameter 3 on surface 13 to be whatever the value of parameter 2, surface 7 is, except the sign is the opposite. The pick-up solve is one of the Editor's most useful features, as it allows one part of an optical system to be locked to another.

Note: If you visit the OpticStudio User's Knowledge Base at www.zemax.com/kb, look at the category Sequential Ray Tracing/3D Geometries for many helpful articles about the use of Coordinate Break surfaces.

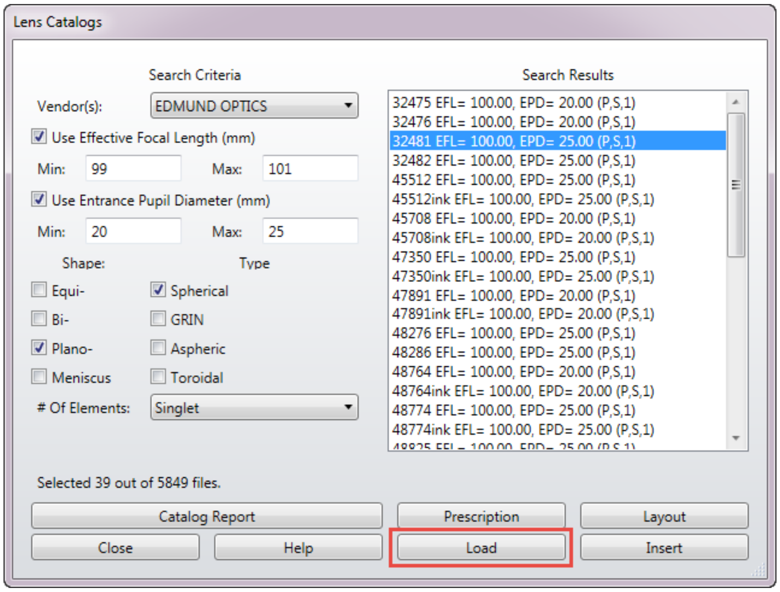
Tutorial 3: A Multi-Configuration Design

OpticStudio can also work with multiple configurations, or versions, of a design. This is typically used to model zoom lenses (where the spacings between lenses changes), systems where the temperature changes, and systems where the angle of a scanning mirror changes, amongst many others. We will use this now to model a system in which the spot produced by a catalog lens is scanned by a mirror over the image surface.

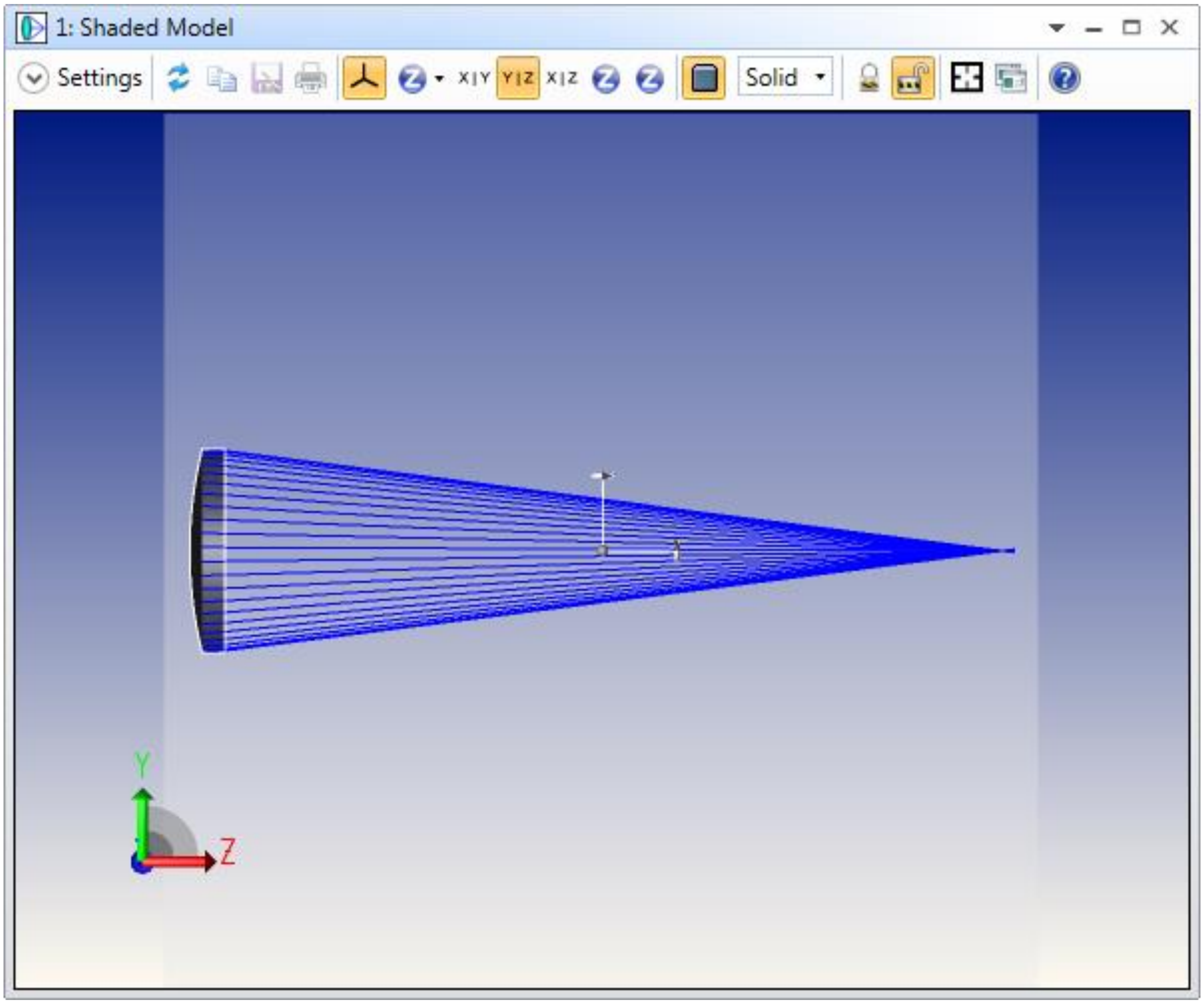
OpticStudio includes the lens catalogs of all the major vendors so you can easily find catalog lenses. Click File…New to clear OpticStudio, and click on Libraries…Lens Catalog:



and configure the dialog box like so:



This searches for plano-convex singlet lenses with focal lengths between 99 and 101 mm, and Entrance Pupil Diameters between 20 and 25 mm. Note that there are 27 lenses that meet these criteria out of the 4060 files included in the Edmund Optics catalog. Select the lens 32481, and press the Load button. OpticStudio then loads this stock lens:

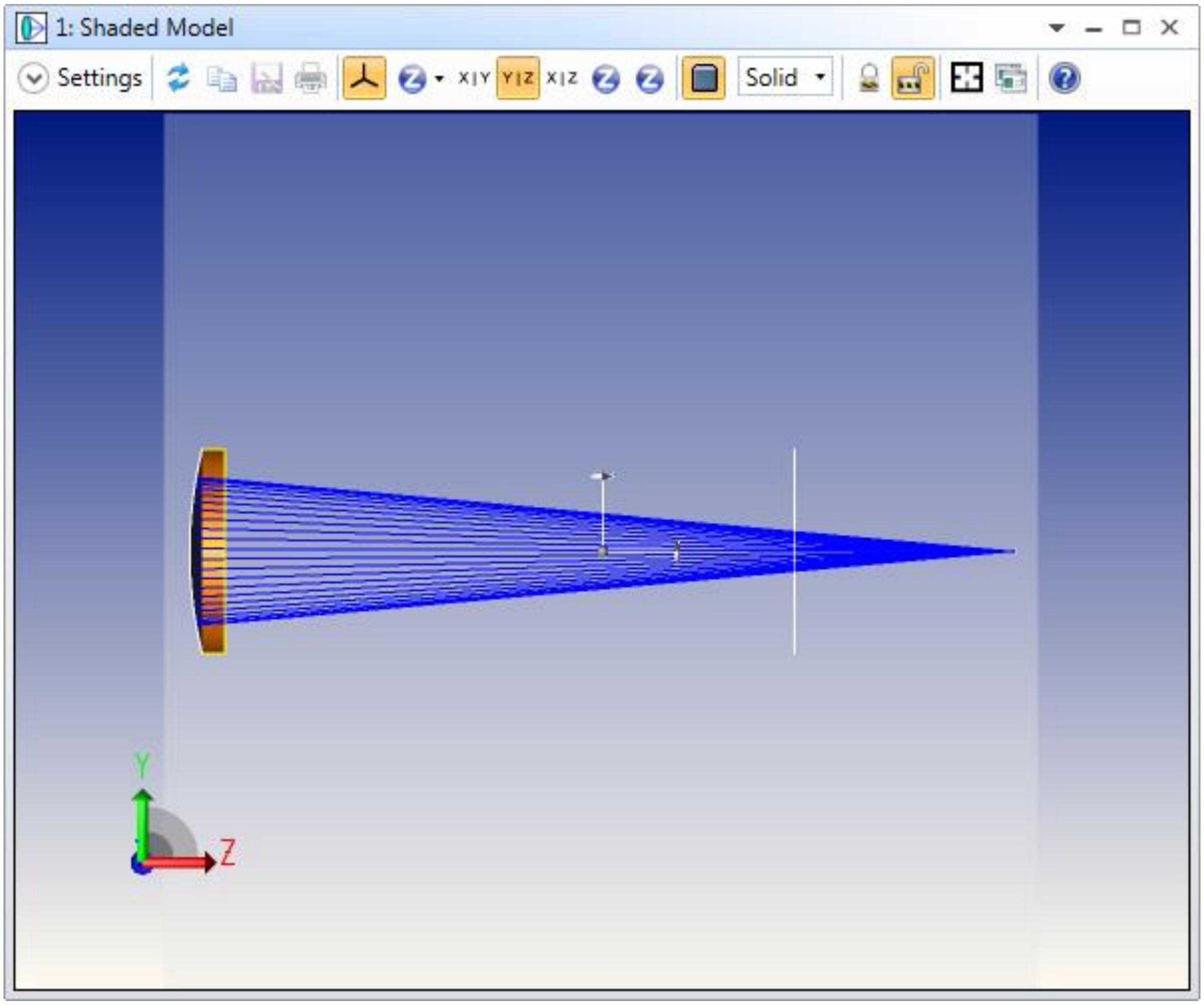


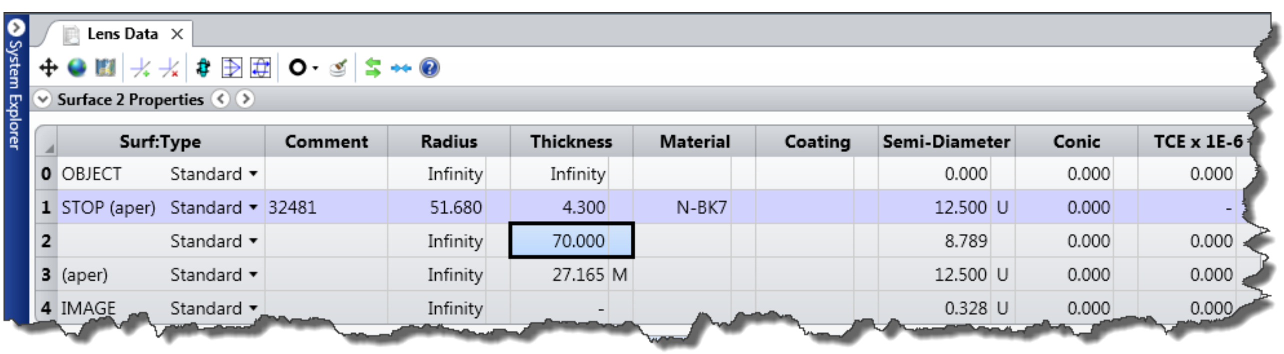
This uses the Shaded model in the YZ orientation, with a Y|Z slicing plane used to give a cross-section view as well as the solid model view.

Our goal is to design a scanning mirror that scans the focal spot through ±10° around a nominal 90° reflection angle.

First, note that the lens has been entered so that it is illuminated right up to the edge of its mechanical aperture. Since the lens will be held in a mount of some sort, we need to reduce the Entrance Pupil Diameter a little (since this is a catalog lens, the mechanical diameter is fixed). Open the System Explorer, and set the Aperture to be 18. Check the Units tab to see what the Lens Units are.

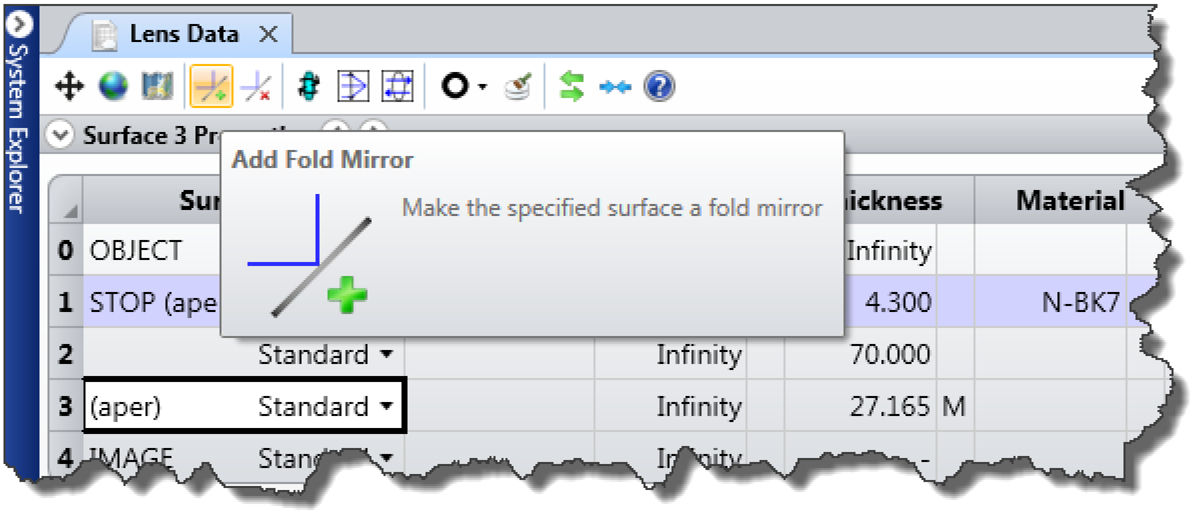
Next, click anywhere on surface 2 in the Lens Data Editor, to highlight surface2. Note that the thickness of this surface is controlled by a marginal ray height solve, and can be seen by the M following the thickness. This keeps the lens at paraxial focus. We will discuss solves more later. For now, simply press Insert after clicking on surface 2, to insert a new surface. Give this surface a thickness of 70 mm, and note that the thickness of the last surface automatically changes to keep this lens in focus:



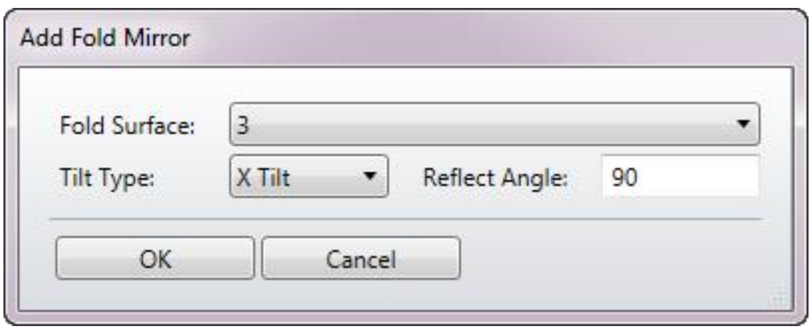


	Surf:Type		Comment	Radius	Thickness		Material	Coating	Semi-Diameter		Conic	TCE x 1E-6
0	OBJECT	Standard		Infinity	Infinity				0.000		0.000	0.000
1	STOP (aper)	Standard	32481	51.680	4.300		N-BK7		12.500	U	0.000	-
2		Standard		Infinity	70.000				8.789		0.000	0.000
3	(aper)	Standard		Infinity	27.165	M			12.500	U	0.000	0.000
4	IMAGE	Standard		Infinity	-				0.328	U	0.000	0.000

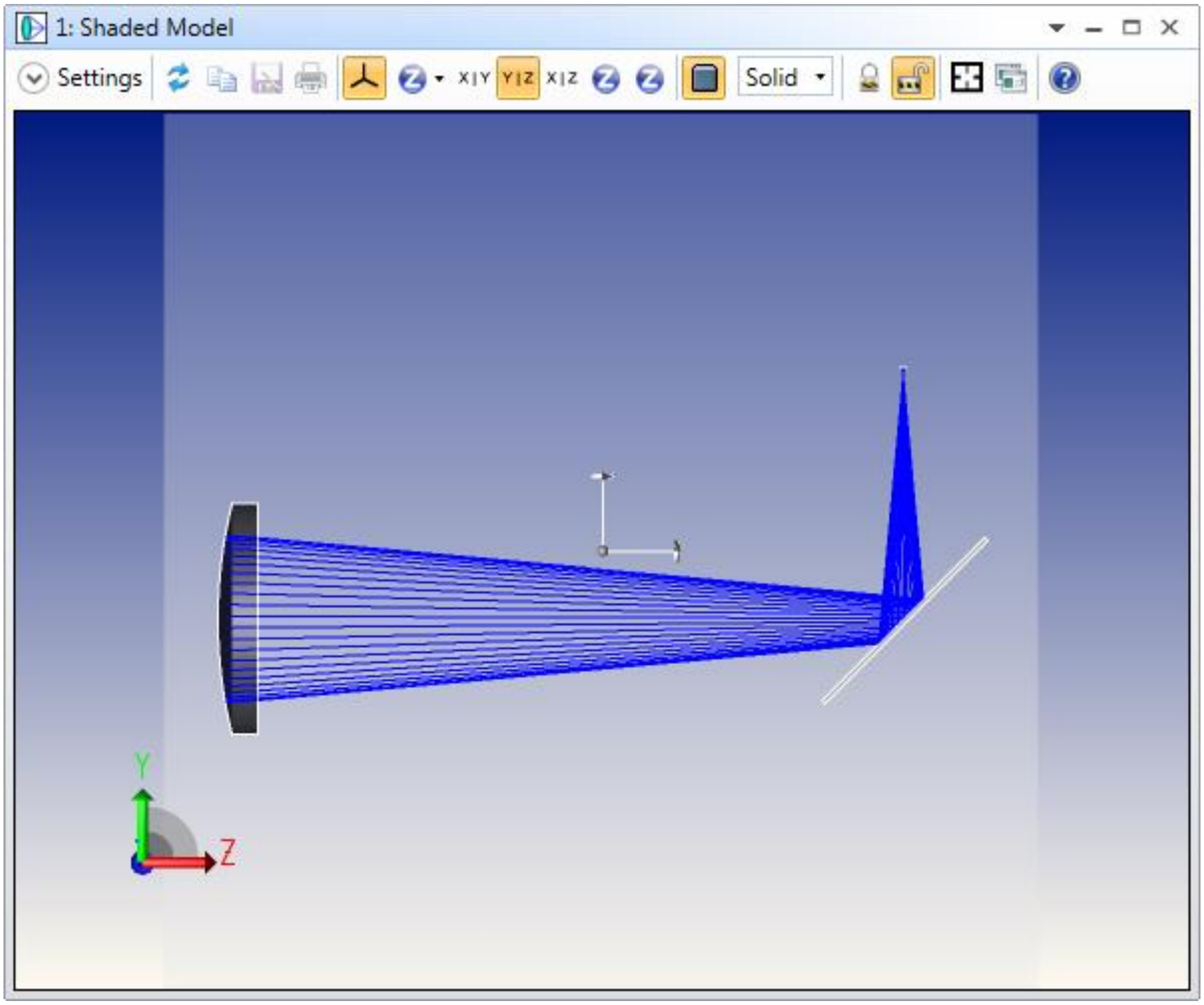
We will now make surface 3 a 'Fold Mirror' which just reflects the light through some angle. Click on surface 3, and then click on the Add Fold Mirror icon in the Lens Data Editor toolbar:



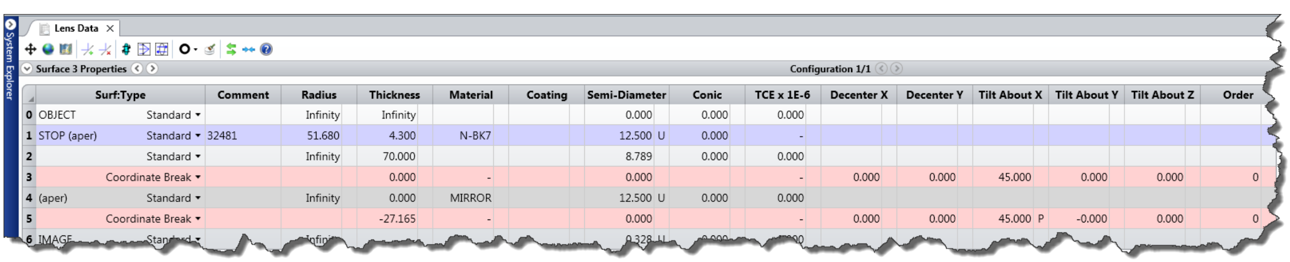
and configure it like so:



The Shaded Model will now show:



The Add Fold Mirror tool inserts two dummy surfaces, one before and one after the selected fold surface. The fold surface then has its material type set to MIRROR, which is a special status that tells OpticStudio that light should now reflect from this surface rather than refract into it. The two newly inserted adjacent surfaces are set to be Coordinate Breaks with the appropriate tilt angles. The second tilt angle is set as a pickup from the first tilt angle. Finally, all subsequent surface thicknesses and curvatures change sign to account for the new mirror.



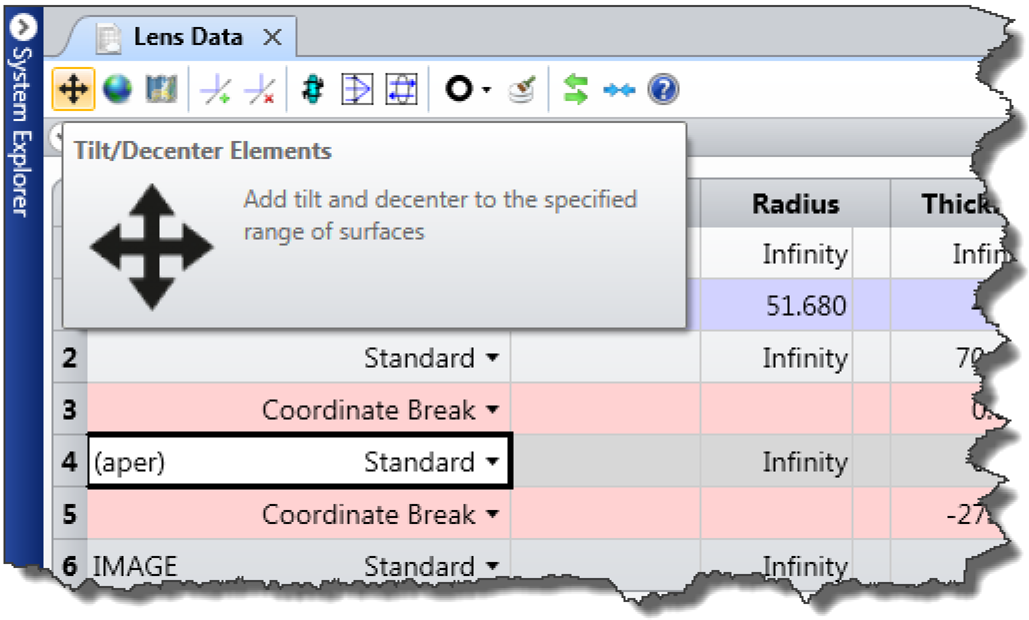
Lens Data

Surface 3 Properties — Configuration 1/1

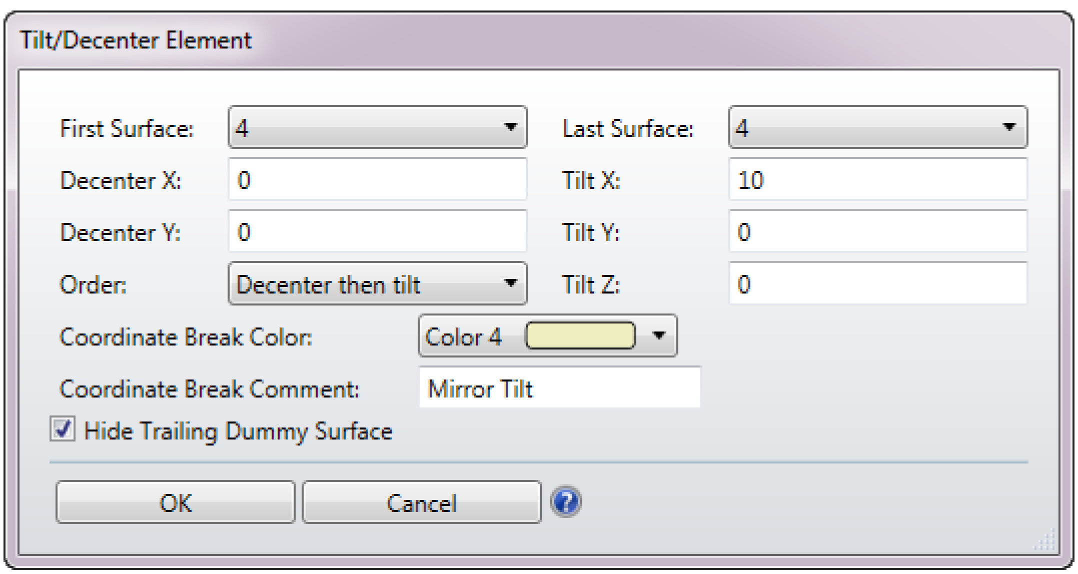
	Surf:Type	Comment	Radius	Thickness	Material	Coating	Semi-Diameter	Conic	TCE x 1E-6	Decenter X	Decenter Y	Tilt About X	Tilt About Y	Tilt About Z	Order
0	OBJECT Standard		Infinity	Infinity			0.000	0.000	0.000						
1	STOP (aper) Standard	32481	51.680	4.300	N-BK7		12.500 U	0.000	-						
2	Standard		Infinity	70.000			8.789	0.000	0.000						
3	Coordinate Break			0.000	-		0.000		-	0.000	0.000	45.000	0.000	0.000	0
4	(aper) Standard		Infinity	0.000	MIRROR		12.500 U	0.000	0.000						
5	Coordinate Break			-27.165	-		0.000		-	0.000	0.000	45.000 P	-0.000	0.000	0
6	IMAGE [illegible]		[illegible]				0.328 U	[illegible]	[illegible]						

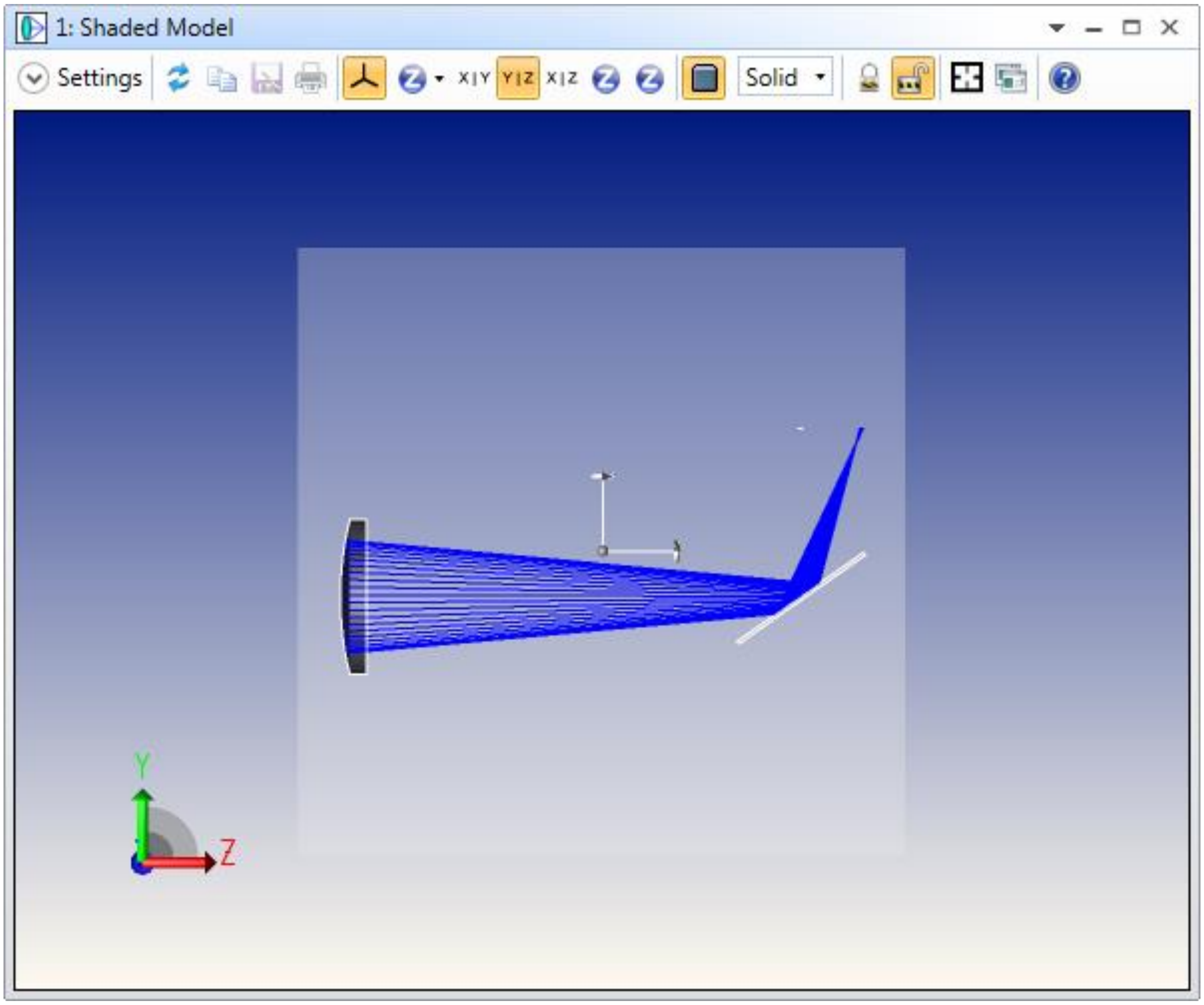
Remember that light normally propagates in +Z (left to right) but after a mirror it obviously goes in the other direction. Using the Add Fold Mirror/Delete Fold Mirror tools automates all the tedious sign conversions.

We now want to scan this mirror through ±10°. We will initially tilt it through +10°, and then use multiple configurations to define multiple tilt angles. Click on surface 4 (which is the mirror surface now) and press the Tilt/Decenter icon in the Toolbar:



And configure as follows:



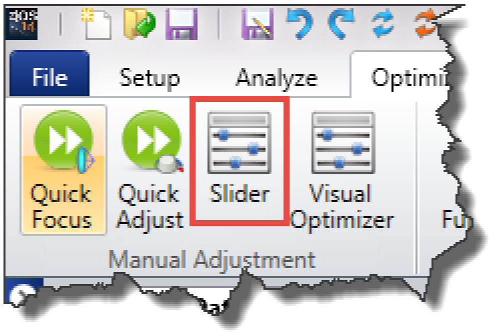


The Tilt/Decenter Element tool has operated just as it did in the earlier double-Gauss example, and it has added two more Coordinate Break surfaces, with pickups, that tilt the mirror surface. The two sets of Coordinate Breaks are ‘nested’, such that the set added by the Tilt/Decenter tool are inside the pair added by the Fold Mirror tool:

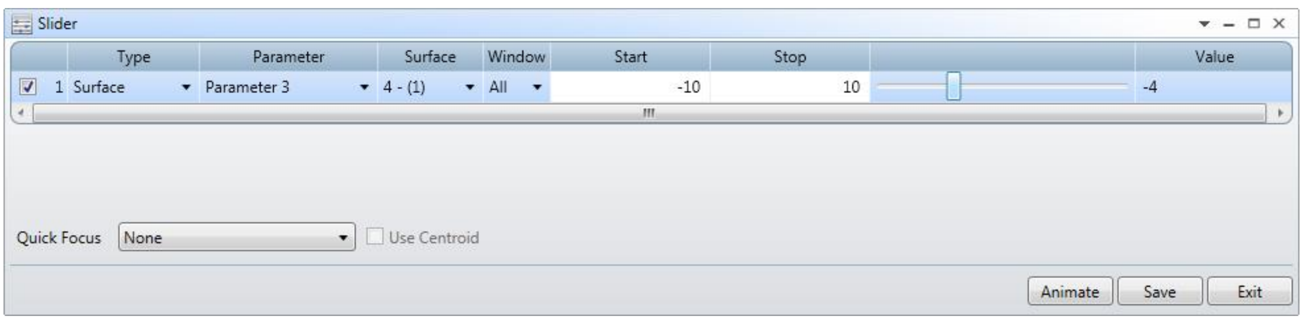
Lens Data — Surface 4 Properties — Configuration 1/1

	Surf:Type		Comment	Radius	Thickness	Material	Coating	Semi-Diameter	Conic	TCE x 1E-6	Decenter X	Decenter Y	Tilt About X	Tilt Ab
0	OBJECT	Standard		Infinity	Infinity			0.000	0.000	0.000				
1	STOP (aper)	Standard	32481	51.680	4.300	N-BK7		12.500 U	0.000	-				
2		Standard		Infinity	70.000			8.789	0.000	0.000				
3		Coordinate Break			0.000	-		0.000		-	0.000	0.000	45.000	
4		Coordinate Break	Mirror Tilt		0.000	-		0.000		-	0.000	0.000	10.000	0
5	(aper)	Standard		Infinity	0.000	MIRROR		12.500 U	0.000	0.000				
6		Coordinate Break	Mirror Tilt:return		0.000	-		0.000		-	0.000 P	0.000 P	-10.000 P	0.
7		Coordinate Break			-27.165	-		0.000		-	0.000	0.000	45.000 P	-0
8	IMAGE	Standard		Infinity				[illegible] U	0.000	0.000				

You can vary the +10° value by hand, and watch the Shaded Model, or click on the Optimize tab and select the Slider icon

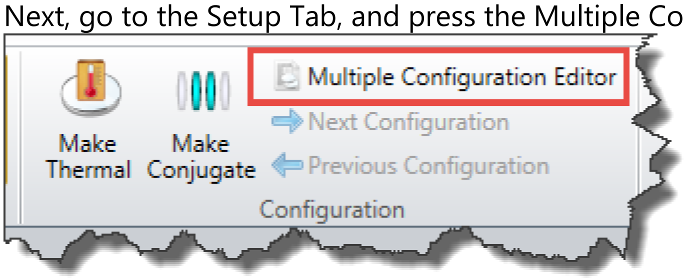


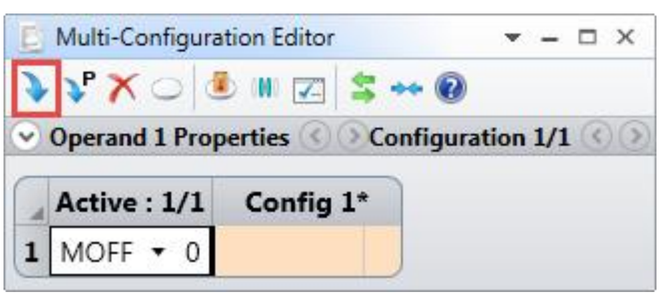
and configure it like so:



Press the 'Animate' button and all open windows will update as the Tilt About X (parameter 3) of surface 4 is scanned. You can also just drag the slider with the mouse. Now exit the slider, and reset the tilt in surface 4 to +10 degrees if needed.

Next, go to the Setup Tab, and press the Multiple Configuration icon in the Configurations group:

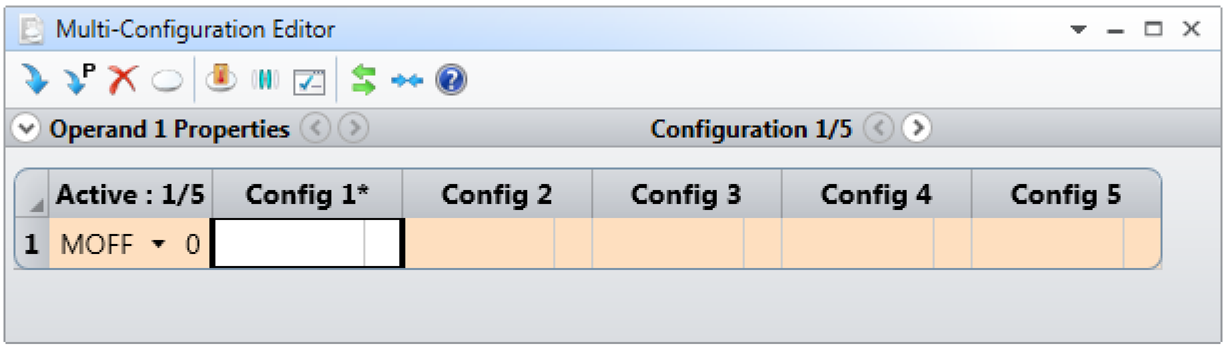




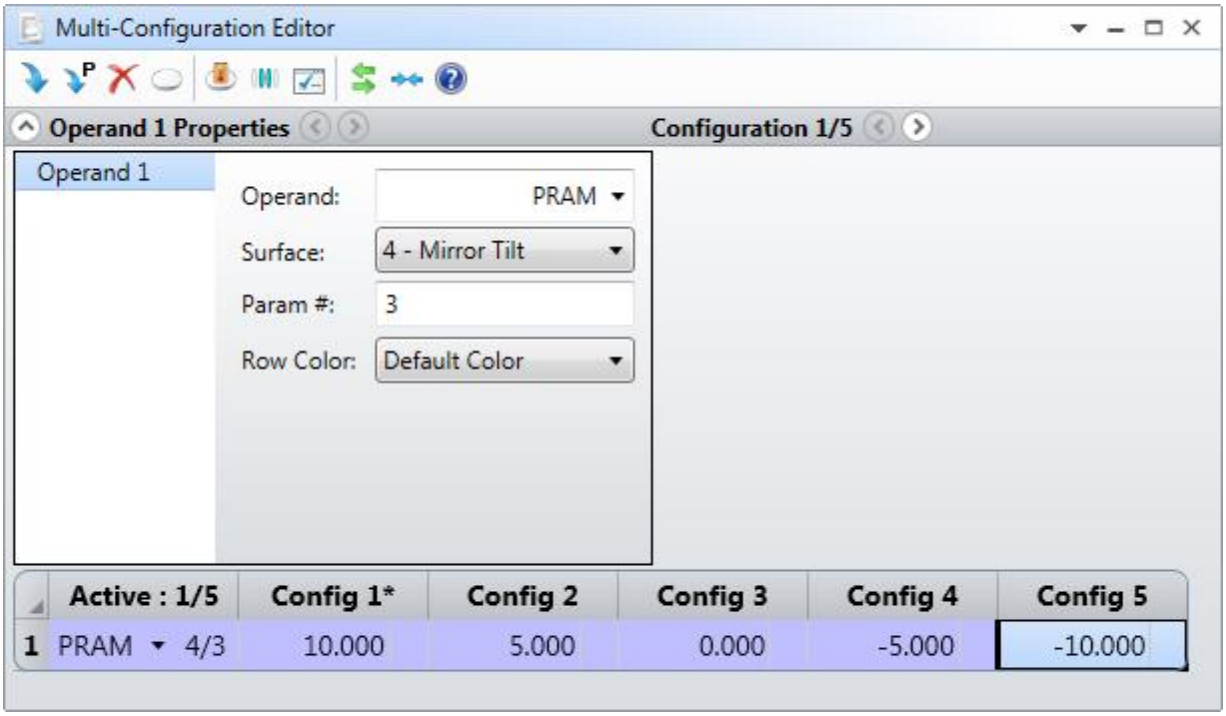
The lens currently has only one configuration, and the multiple-configuration operand MOFF ("Multiconfiguration OFF") is a placeholder that affects nothing, and allows you to enter comments in the editor if desired.

Note: The Multi-Configuration Editor is used to define everything that is different between configurations.

We will define 5 configurations, representing scan angles of +10°, +5°, 0°, -5° and -10° respectively. Click on the Multi-Configuration Editor, and press the Insert Configuration icon (highlighted above) four times. Alternatively, you can either right-mouse-click…Insert Configuration four times, or press the <Shift><Ctrl><Insert> keys simultaneously four times, that a total of five configurations results:

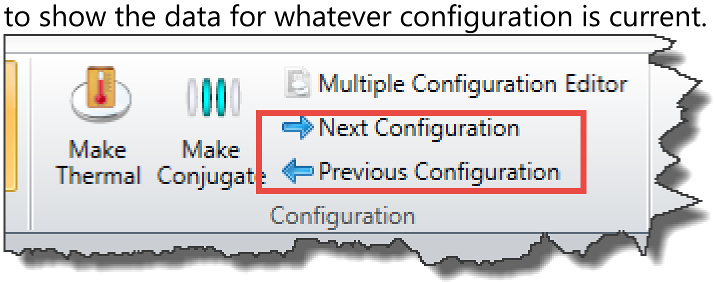


Each line in the Multi-Configuration Editor is an operand that acts on a parameter in the Lens Data Editor or some other System parameter and allows its value to be changed. Move the mouse over the 'MOFF' operand and double-left-click to edit the operand. All the multiple configuration operands OpticStudio supports can be selected from the drop-down list in the resulting dialog. Set it up like so:



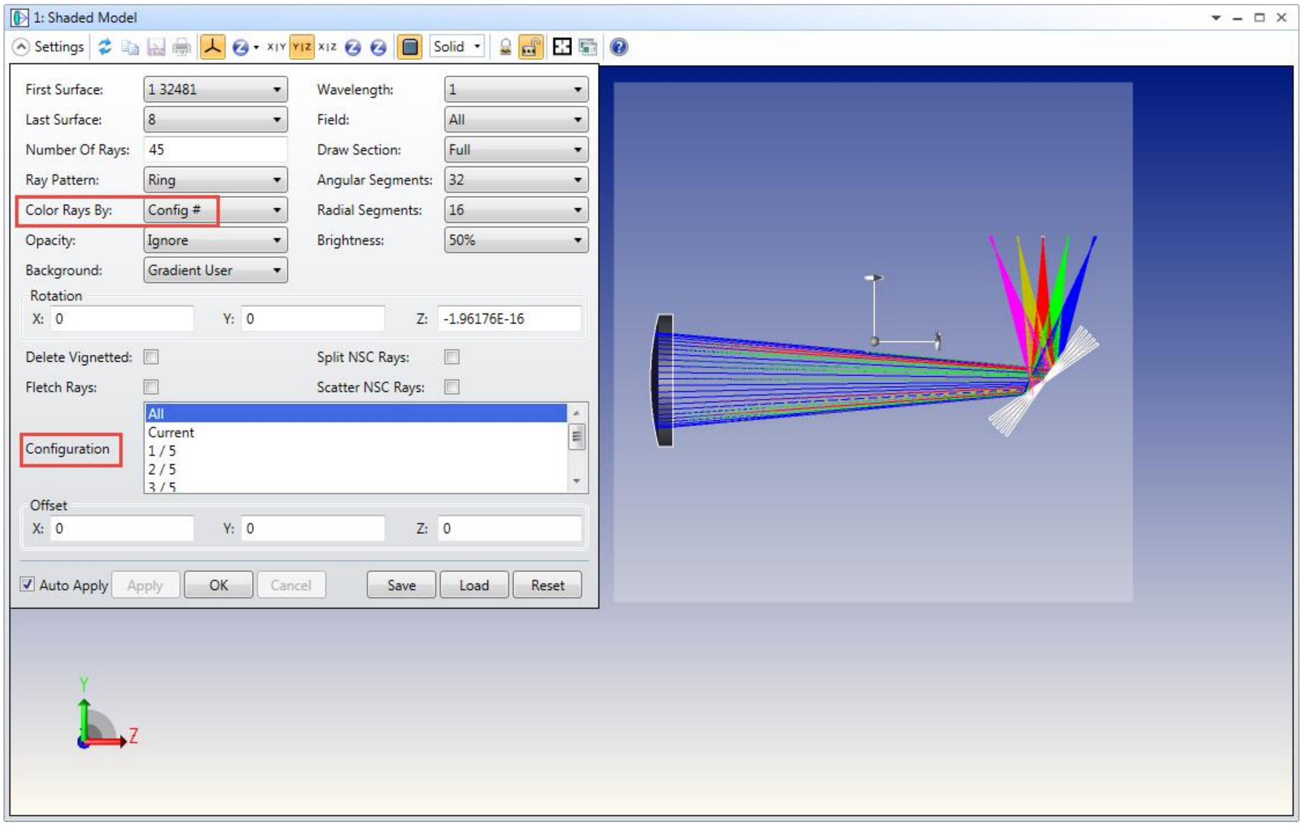
So that the PRAM operand picks up parameter data, in this case parameter 3 of surface 4, and changes it between 10, 5, 0, -5 and 10 degrees.

Use the <cntl>A keys to change the current configuration, and note that all open windows update to show the data for whatever configuration is current. Alternatively, use these controls:



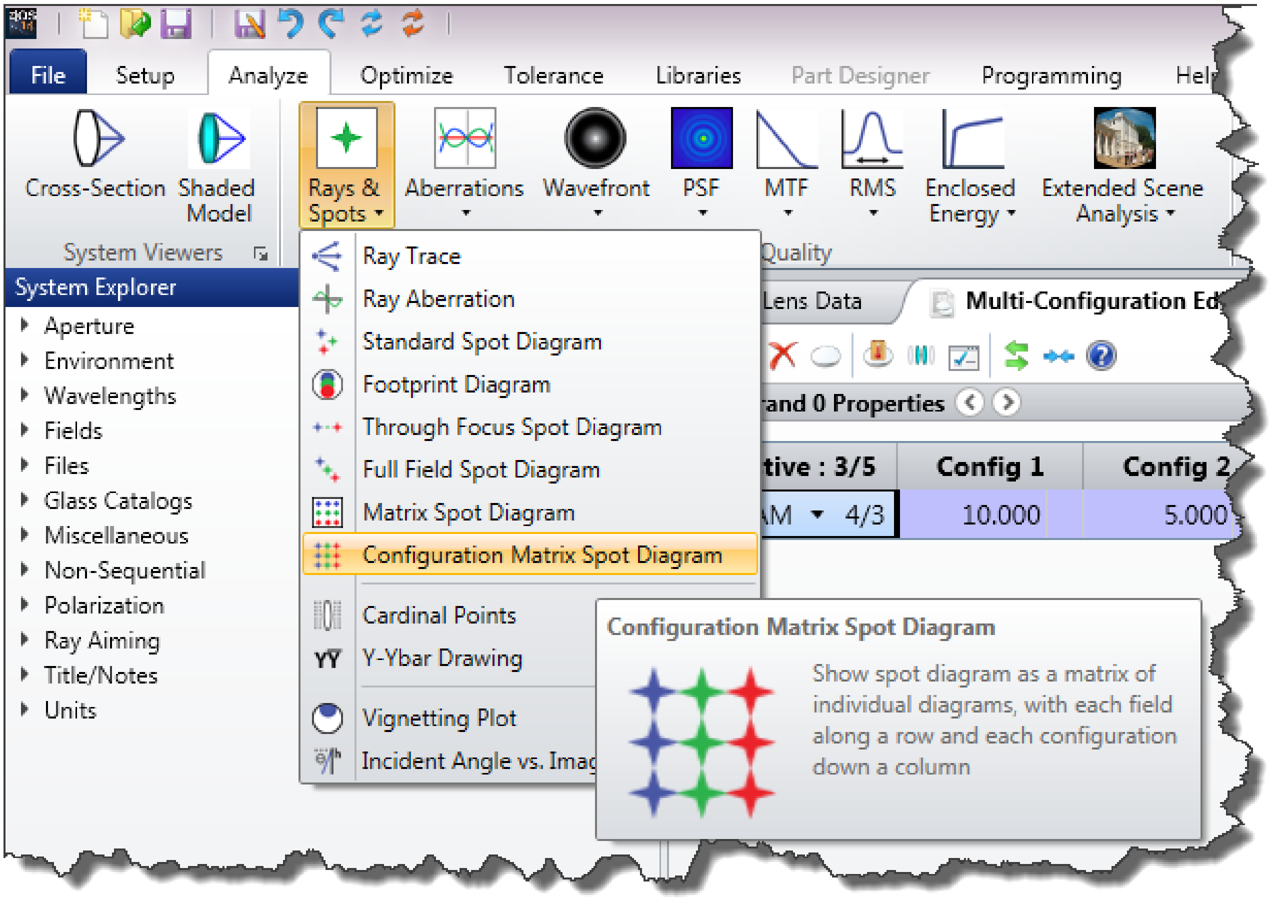
(Note that the Configuration group now appears on all tabs except the File tab as soon as the Multi-configuration Editor contains more than one configuration). You can also double-click on the header of each configuration's column to make it the active configuration.

Configure the Shaded Model like so:

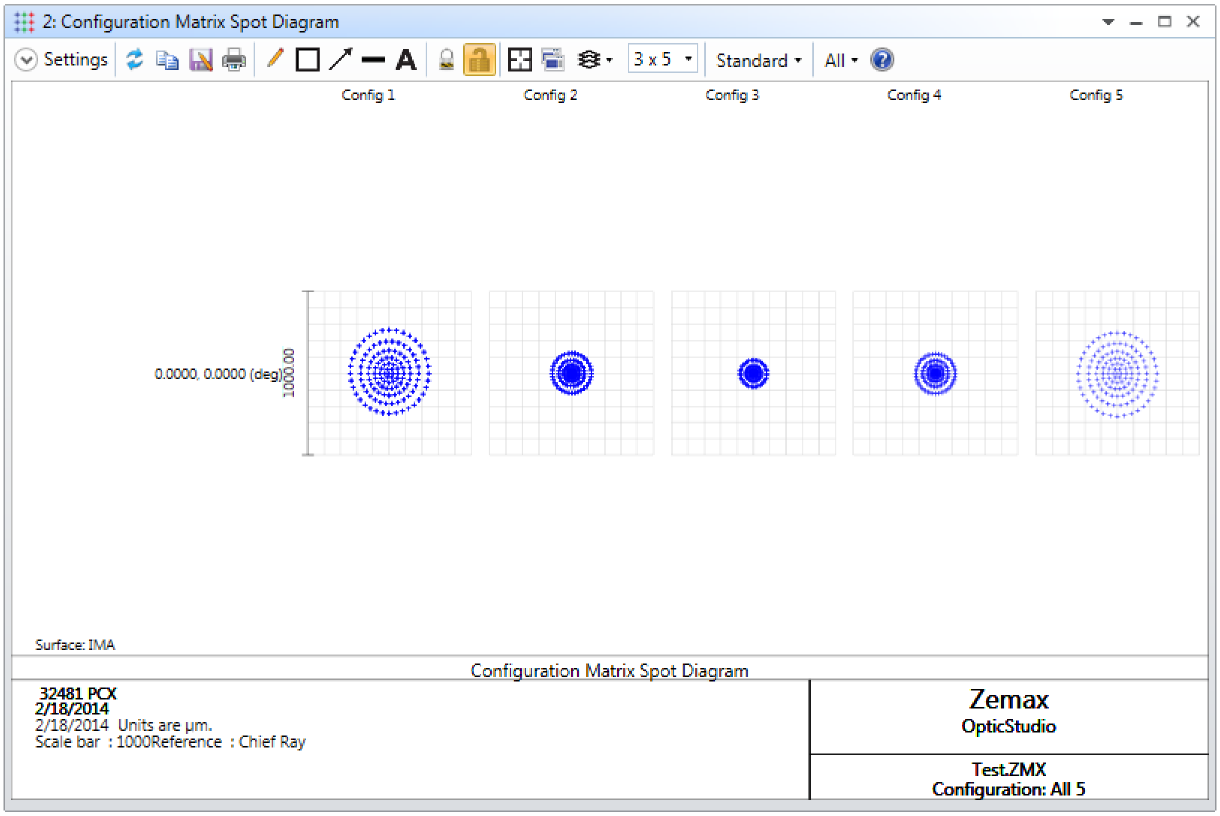


Note you can select any number of individual configurations to draw, like 1/5 and 4/5 by just selecting the desired configurations in the drop-down list.

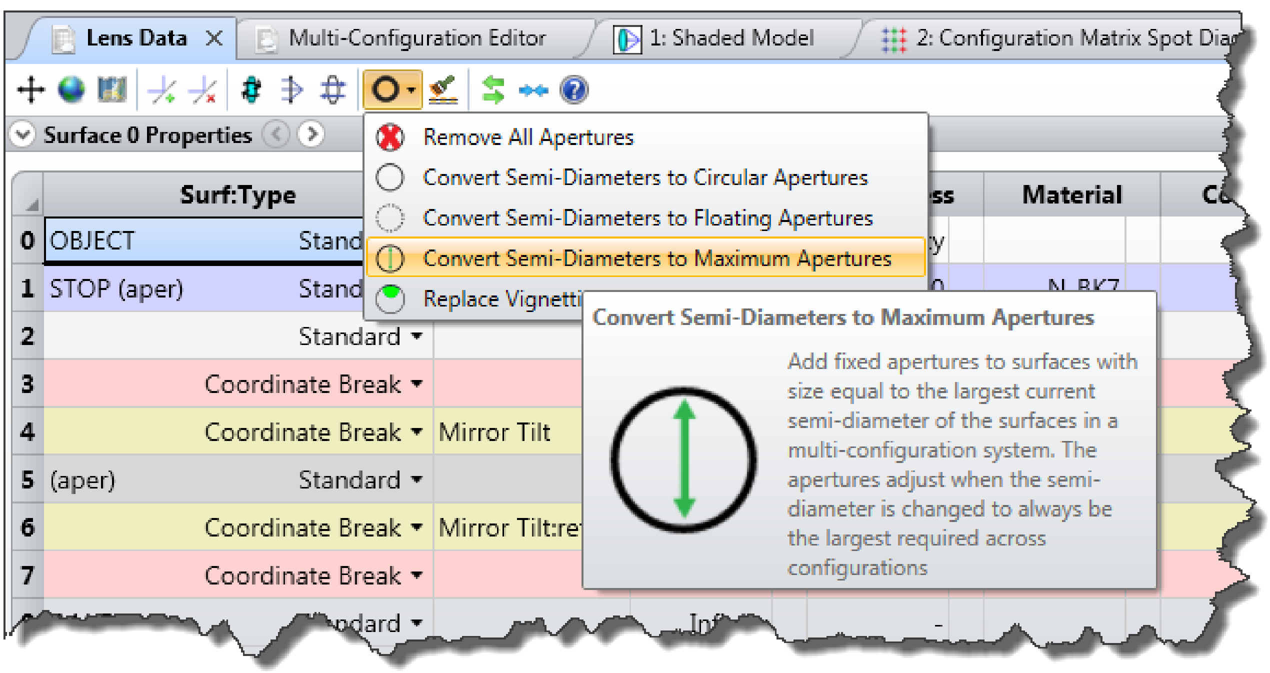
Finally, click on the Analyze Tab…Spot Diagrams…Configuration Matrix



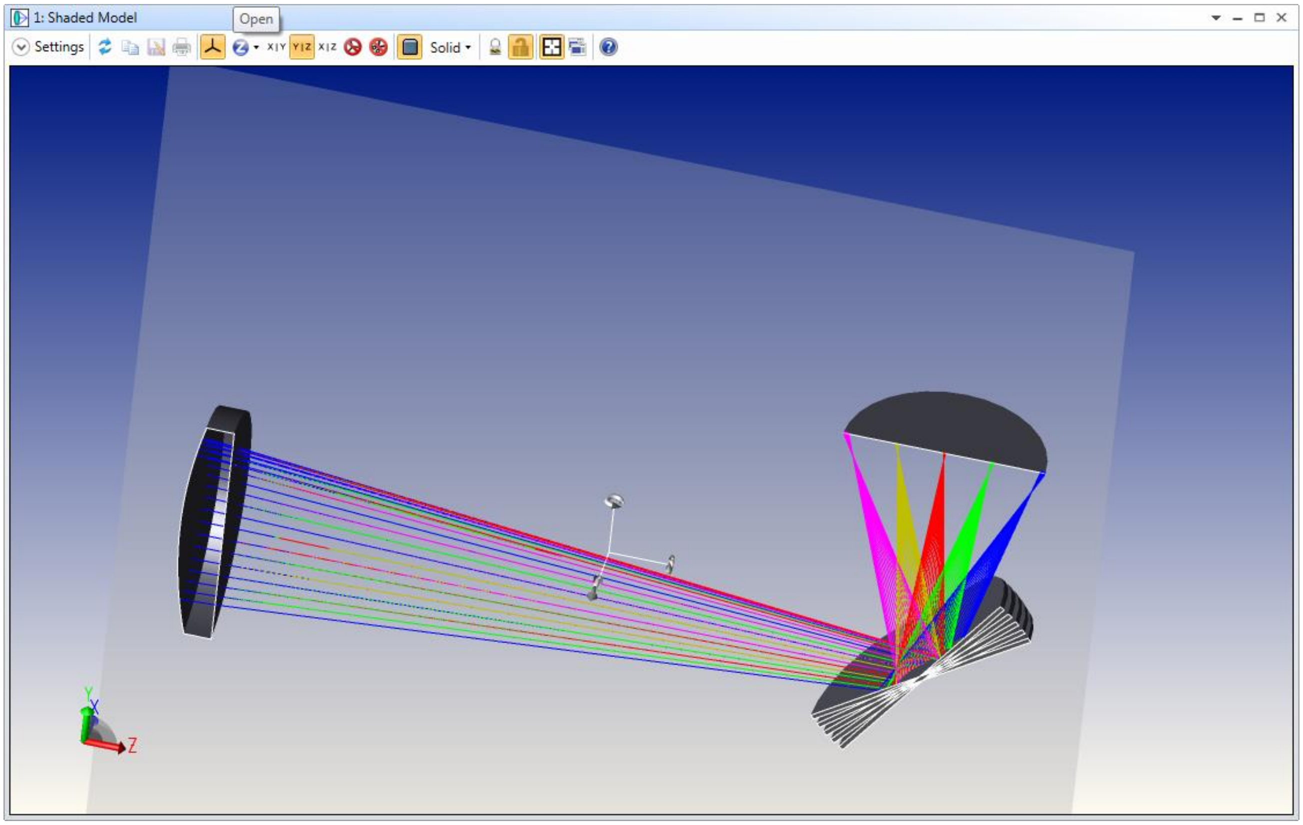
to see how the spot varies with scan angle:



Finally, on the Lens Data Editor Toolbar, choose Apertures…Convert Semi-Diameters to Maximum Apertures

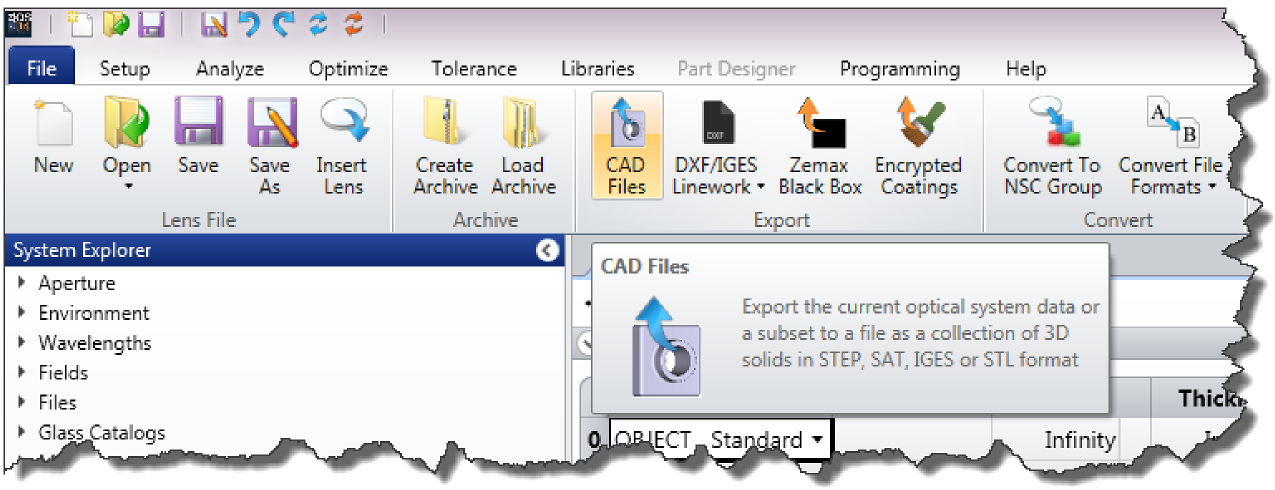


This will set the semi-diameters of all surfaces to the largest of whichever configuration needs it:

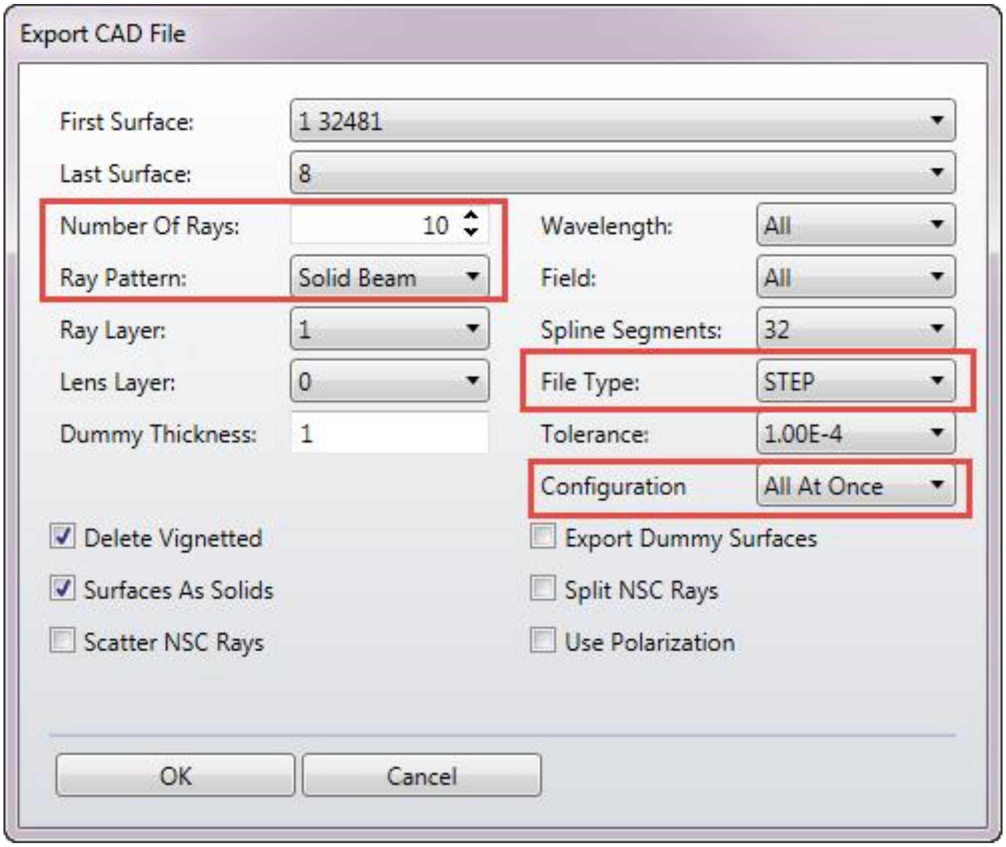

1: Shaded Model
Open
Settings
Solid
Y
X
Z

Tutorial 4: Exporting To Mechanical CAD Packages

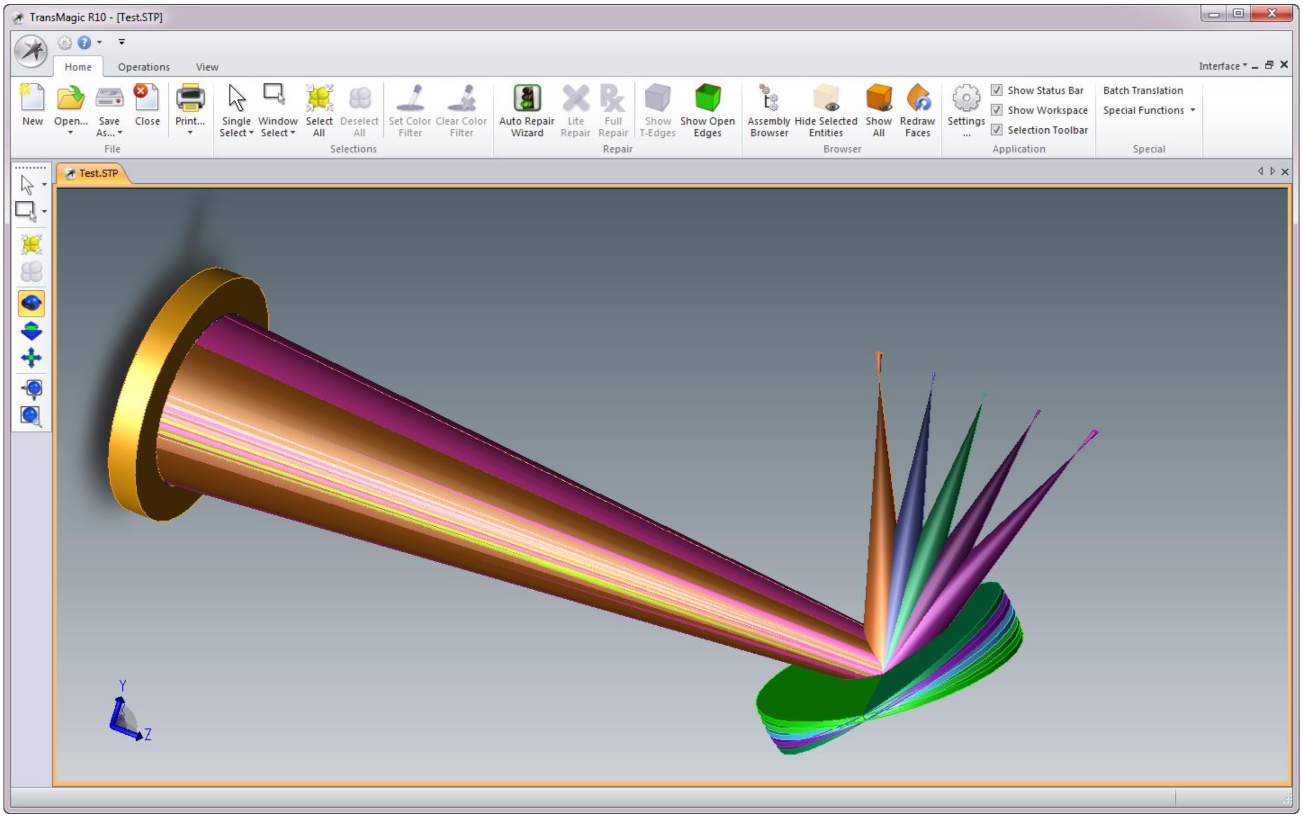
At some point in your lens design, you may want to export the lens design into a mechanical design package so that you or your mechanical engineering colleagues can design lens mounts and other opto-mechanical components alongside the lenses and rays. This is easily achieved using the Export group in the File tab:



Using the file designed in Turorial 3, export it like so:



And load the file produced into your 3D CAD package of choice:



Note: If you are using SolidWorks™, and do not see the exported rays, visit the OpticStudio User's Knowledge Base at www.zemax.com/kb and search for "SolidWorks" to get advice on how to set SolidWorks' importer options.

This lets you see easily the range of motion of the mirror, the envelope of the rays, and the optical components. Multiple configurations can be exported as separate files, as separate layers of the same file, or 'all at once' as done here.
Importing CAD objects is discussed in the non-sequential ray-tracing section of this Guide.

Tutorial 5: Optimization

So far, we have loaded a lens file, and used Analysis features to look at the performance of the system. Optimization takes this to the next level: OpticStudio will actively work with you to obtain the best possible system performance, and not simply report what the system performance is.

Note: Even if you intend to use only the non-sequential mode of OpticStudio you should work through this example, as the concepts of optimization are the same in non-sequential ray-tracing as in sequential.

Optimization is a three step process:

- First, a basic lens design is entered which has the correct field of view, wavelength, system aperture, number of surfaces, etc. This system should be traceable without error.
- Next, some parameters in the Editor are defined as variables. This means that OpticStudio can change the value of these variable parameters in order to better meet the design specification.
- Last, the design specification is expressed as a series of design goals called a merit function. The merit function ultimately is expressed as a single number, and the closer to zero this number is, the closer the design is to your desired performance.

Optimization then changes the values of the defined variable parameters so that the merit function is reduced to its minimum value. OpticStudio contains several different optimization algorithms, two local optimizers and two global optimizers. In this example we will use the Damped Least Squares local optimizer, and the Hammer global optimizer.

Also, this three-step optimization process may be repeated several times during the design process. After optimization, the system performance may still not be as required, and more lenses may be needed, or you may choose to make some surfaces aspheric and repeat the optimization with the aspheric parameters set as variables.

Tutorial 5.1: The Lens Specification

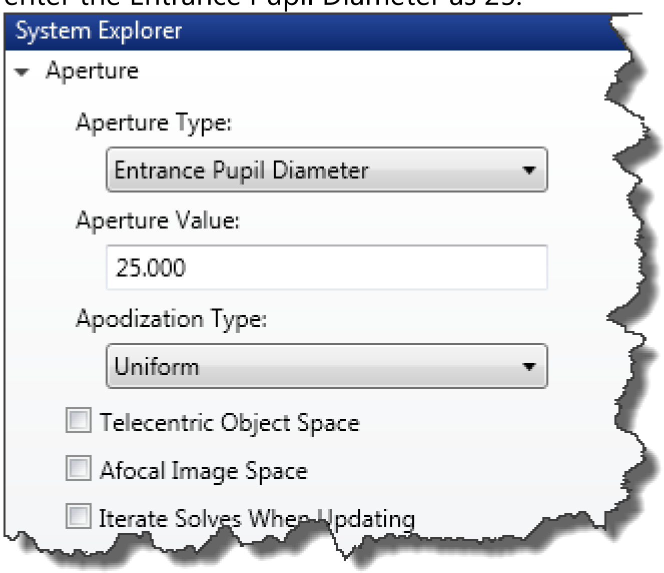
Here is the specification of the lens we are to design:

```
Design a cemented doublet that works at f/5 over the visible region of
the spectrum. The field of view is 10° full field of view, and the object
is a very long distance away from the lens. The lens aperture is 25 mm
entrance pupil diameter, and the lens must be at least 2 mm wider in
diameter than the optical beam to allow for mounting clearance.
```

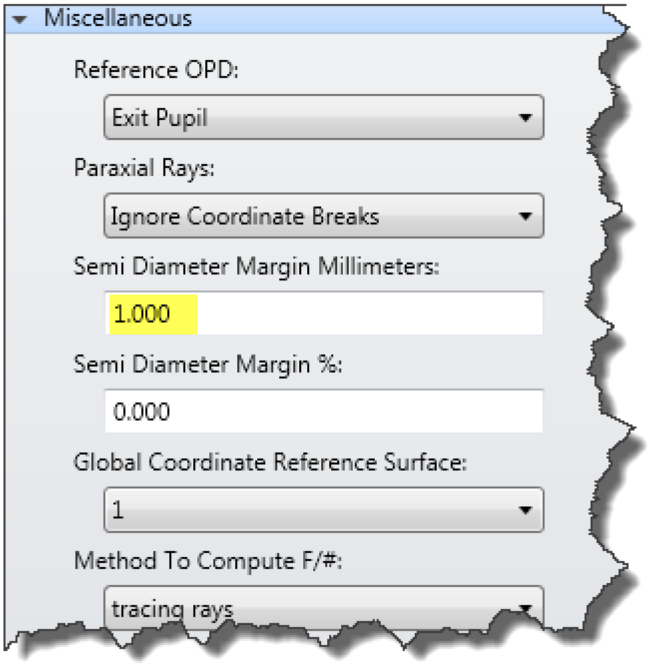
Tutorial 5.2: Entering the Basic System in the System Explorer

Press File...New to clear OpticStudio and start a new design. We will start by defining the incoming light, by its aperture, wavelength, and field of view. All of this is defined in the System Explorer sidebar.

The system aperture has been defined as 25 mm entrance pupil diameter, with at least a 27 mm mechanical diameter to allow for mounting of the lens. In the System Explorer Aperture Group, enter the Entrance Pupil Diameter as 25:

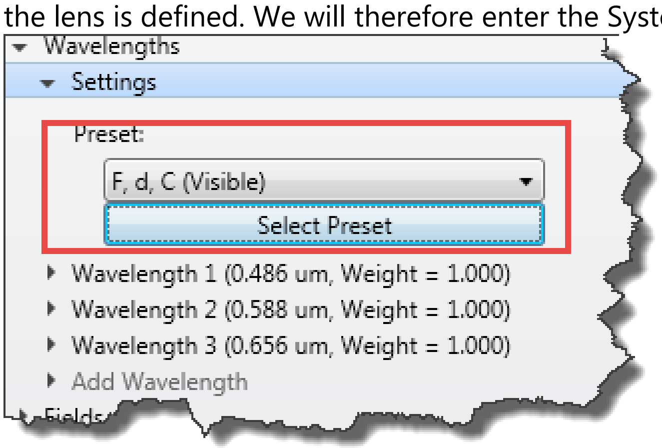


Lens units are millimeters by default, which you can confirm by clicking on the Units tab of the dialog box. We also have a requirement for the lens to be mechanically 2 mm larger in diameter than its working aperture, so click on the Miscellaneous tab and enter a 1 mm semi-diameter margin like so:



Note that OpticStudio works with semi-diameters, not diameters, so a 1 mm semi-diameter margin gives a 2 mm diameter margin.

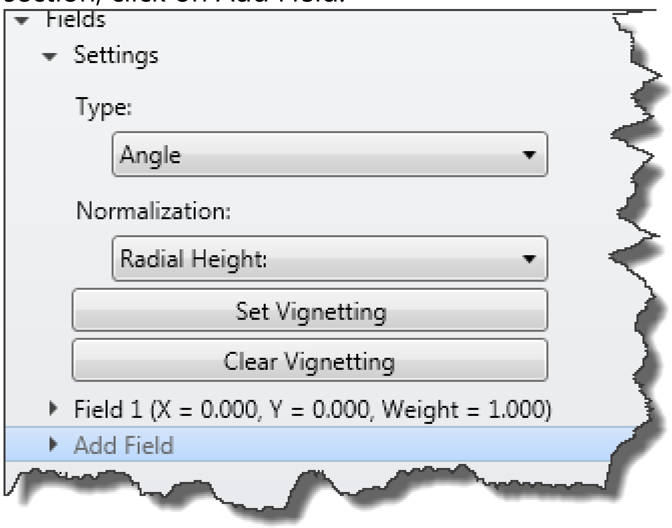
We will now define the wavelength of the light. This specification is a little vague on this important system parameter. For example, what is the 'visible spectrum', and at exactly what wavelength should the system be f/5? We will assume that the 'visible' region is that covered by the F, d and C spectroscopic lines. This is a very common assumption in visible system design. We will further assume that the d-line, being the central wavelength, should be the wavelength at which the f/# of the lens is defined. We will therefore enter the System wavelengths as follows



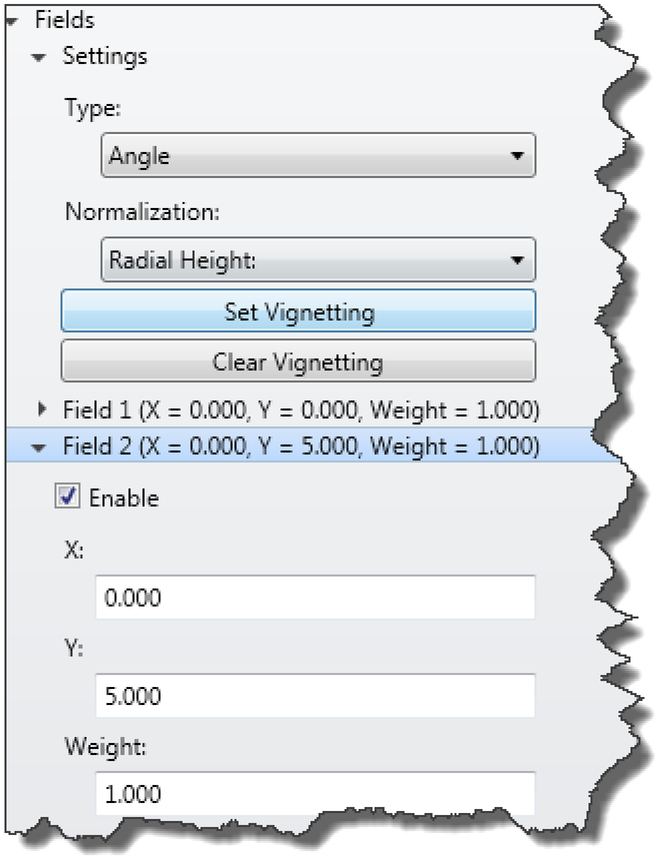
In the drop-down list next to the 'Select' button, choose the spectrum "F, d, C (visible)" and press the Select button to copy this spectrum into the Wavelength Data dialog. This sets three wavelengths, in ascending order, and sets wavelength #2 as the primary wavelength.

Note: In real life, any time you find yourself making assumptions about what specifications mean, always refer back to the customer! Part of your QA process should be to do a point-by-point comparison of each specified parameter, how it has been entered into OpticStudio and how it will be tested in the built system.

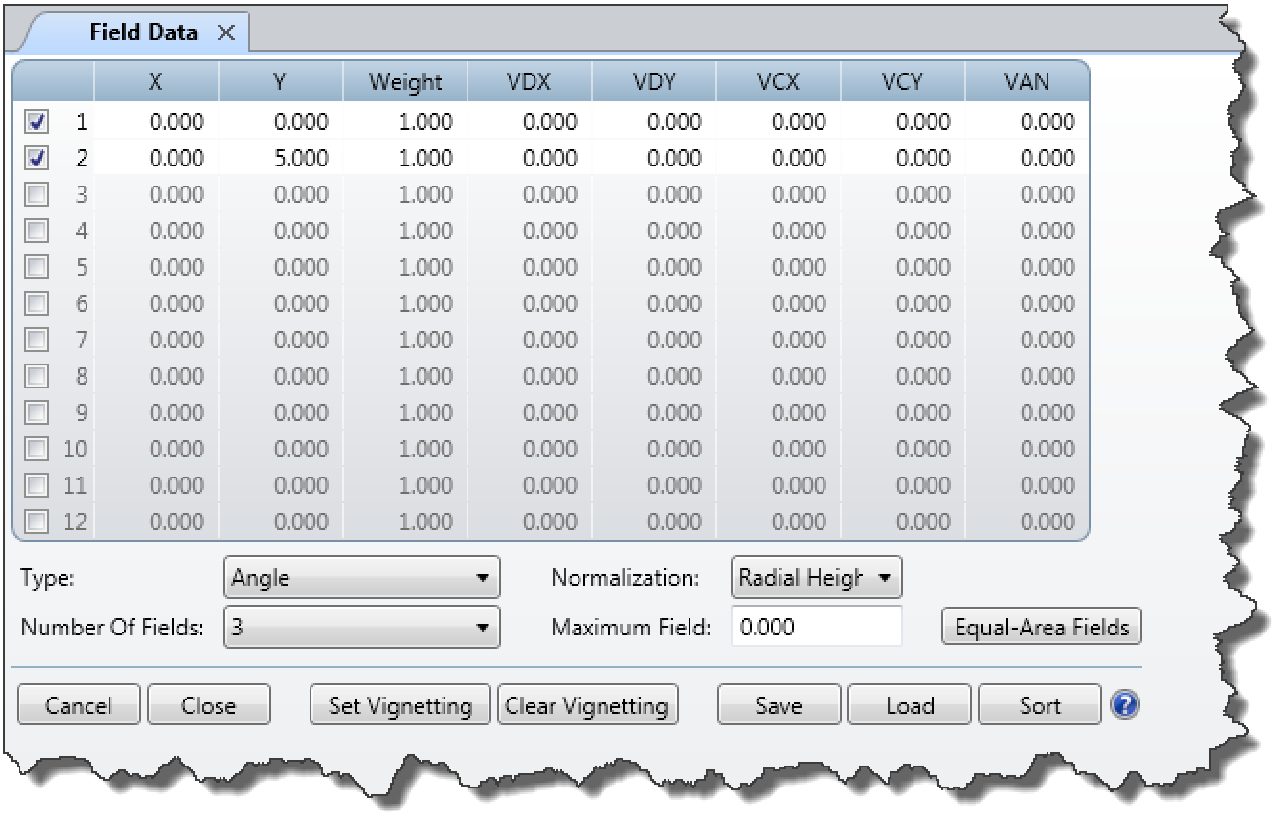
Last, we will define the field of view, which is 10° full field of view, hence 5° half-field. In the Field section, click on Add Field:



And enter the new field point like so:



Alternatively, just double-click on the 'Fields' line at the top of this section, and enter the data though a standard dialog box:



		X	Y	Weight	VDX	VDY	VCX	VCY	VAN
☑	1	0.000	0.000	1.000	0.000	0.000	0.000	0.000	0.000
☑	2	0.000	5.000	1.000	0.000	0.000	0.000	0.000	0.000
☐	3	0.000	0.000	1.000	0.000	0.000	0.000	0.000	0.000
☐	4	0.000	0.000	1.000	0.000	0.000	0.000	0.000	0.000
☐	5	0.000	0.000	1.000	0.000	0.000	0.000	0.000	0.000
☐	6	0.000	0.000	1.000	0.000	0.000	0.000	0.000	0.000
☐	7	0.000	0.000	1.000	0.000	0.000	0.000	0.000	0.000
☐	8	0.000	0.000	1.000	0.000	0.000	0.000	0.000	0.000
☐	9	0.000	0.000	1.000	0.000	0.000	0.000	0.000	0.000
☐	10	0.000	0.000	1.000	0.000	0.000	0.000	0.000	0.000
☐	11	0.000	0.000	1.000	0.000	0.000	0.000	0.000	0.000
☐	12	0.000	0.000	1.000	0.000	0.000	0.000	0.000	0.000

Note: As the lens is rotationally symmetric we do not need to specify a field point at y = -5°, or at x = 5° or -5°. Always define your field points in +y only unless you specifically require a non-rotationally-symmetric lens system. We have now entered everything we need about the light coming into the lens: its diameter, wavelength and field of view.

Tutorial 5.3: Entering the Basic System in the Lens Data Editor

We now need to enter the first-guess data for the optical surfaces in this lens system. As we know we will be designing a cemented doublet, we know we will need a total of six surfaces: the OBJECT surface, STOP surface, the front, middle and rear doublet lens surfaces and the IMAGE surface. Go to the Setup Tab, and click the Lens Data icon in the Editor group. Click on the IMAGE surface in the Lens Data Editor, and press the Insert key 3 times to insert the correct number of surfaces, and enter the following data:

Lens Data

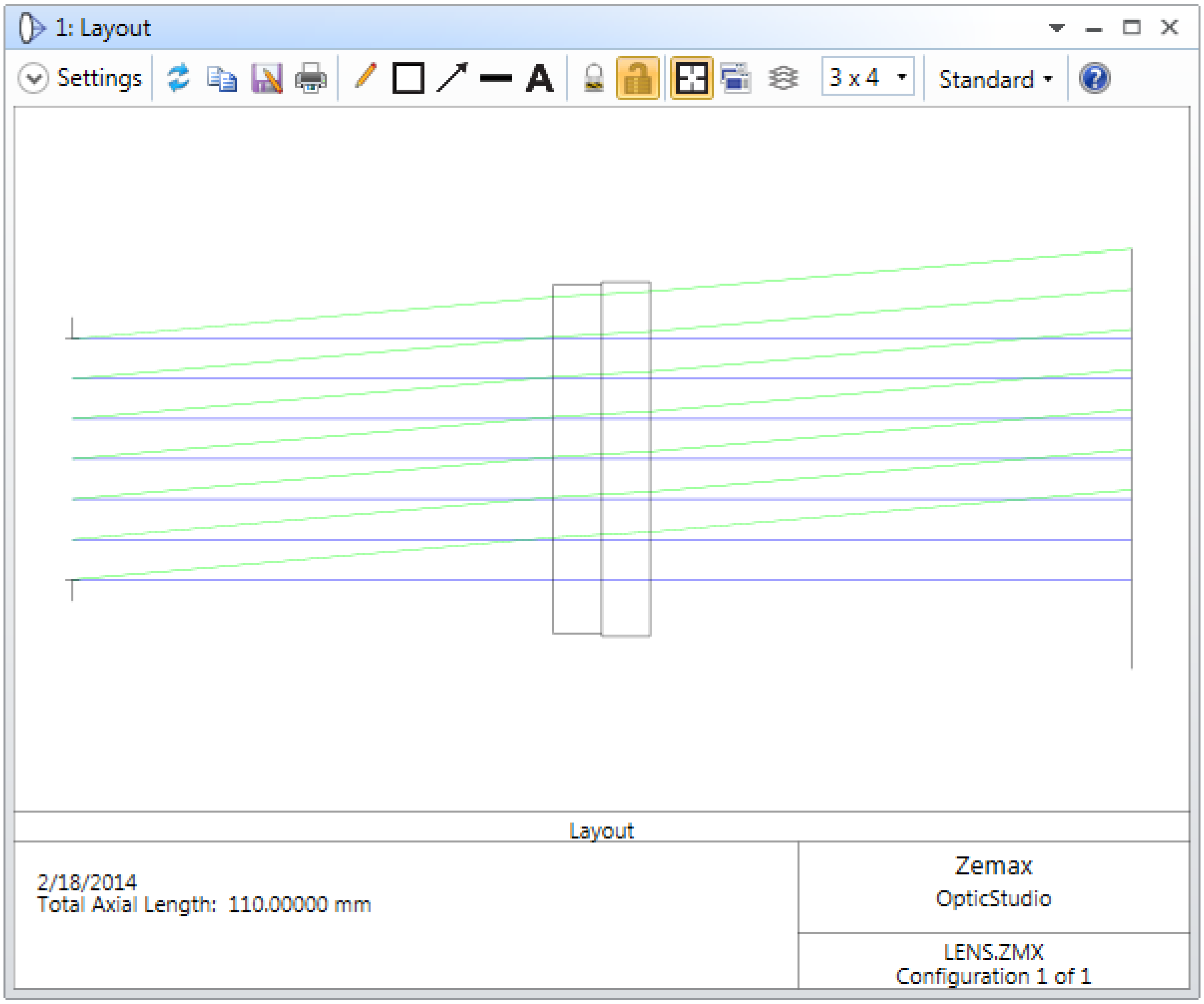
Surface 5 Properties — Configuration 1/1

	Surf:Type		Comment	Radius	Thickness	Material	Coating	Semi-Diameter	Conic	TCE x 1E-6
0	OBJECT	Standard		Infinity	Infinity			Infinity	0.000	0.000
1	STOP	Standard		Infinity	50.000			12.500	0.000	0.000
2		Standard	front	Infinity	5.000	N-BK7		17.874	0.000	-
3		Standard	middle	Infinity	5.000	F2		18.163	0.000	-
4		Standard	rear	Infinity	50.000			18.433	0.000	0.000
5	IMAGE	Standard		Infinity	-			21.807	0.000	0.000

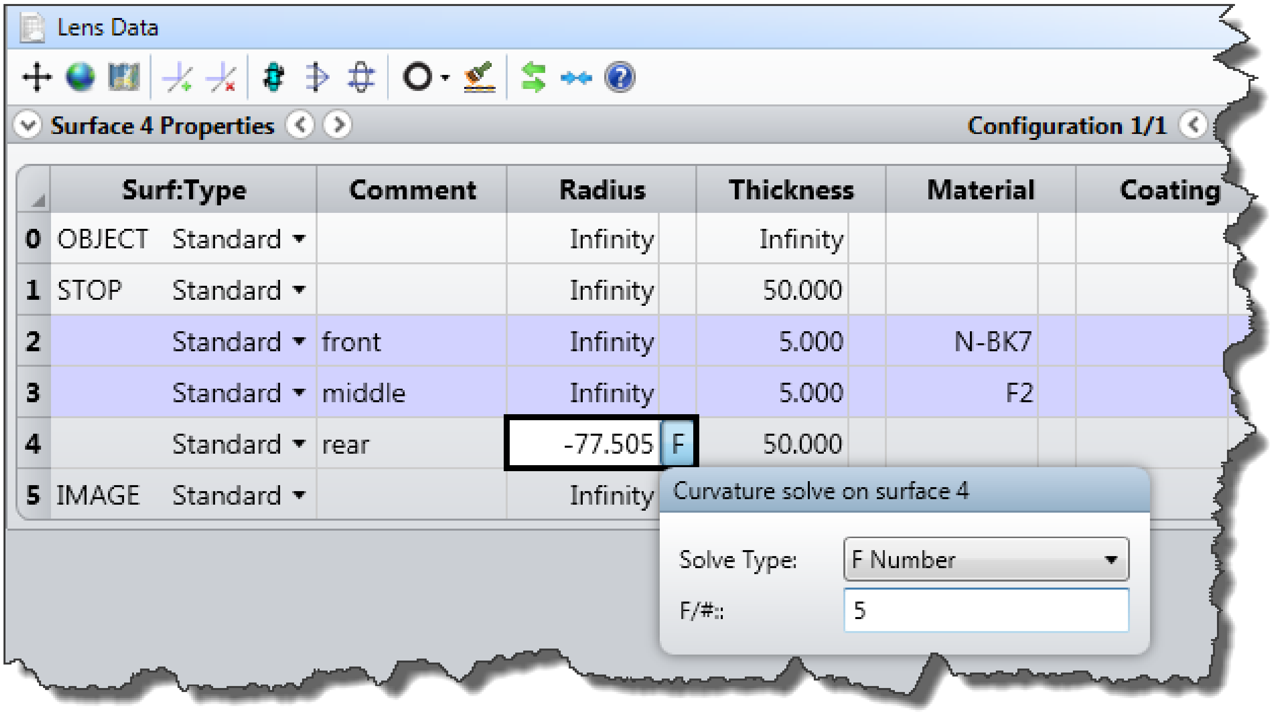
Note: If you are using the demonstration version, OpticStudio will display fewer decimal places. This does not affect the accuracy of the calculations or results.

Because the specification says that the OBJECT scene is 'a very long distance' away from the lens we have set the OBJECT surface thickness to 'Infinity'. You do this by typing the word "Infinity" or just the letter "i" (without the quotation marks) in the editor cell.

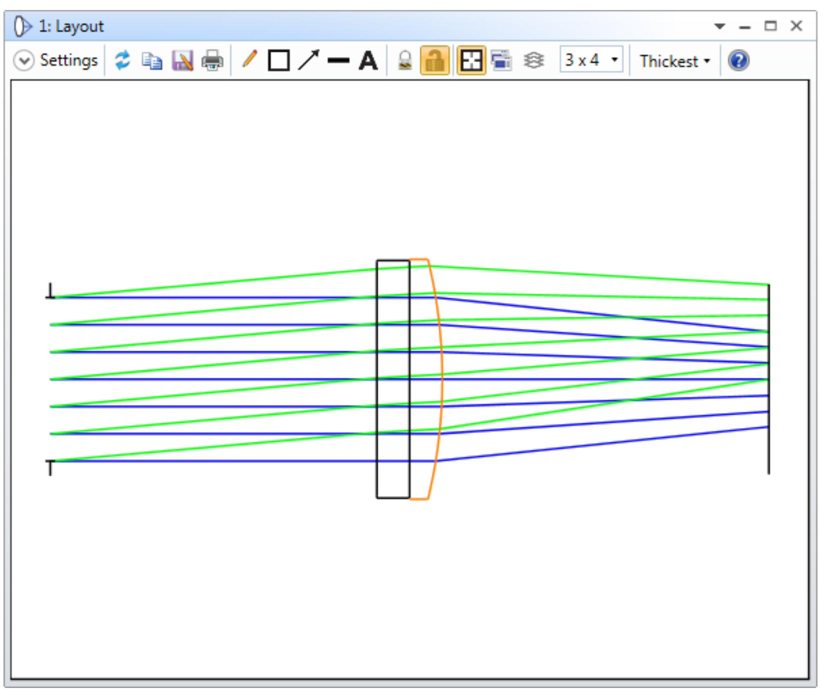
Do not enter anything in the semi-diameter data column. OpticStudio will work this out for you, and include the requested margin so that the lens is larger than the incoming beam. Use the Cross-section layout (in the Setup and Analyze tabs) to show the design so far:



Now our system has a requirement that it must be f/5. There is a simple way to achieve this, click the cell to the right of the radius of curvature cell of the last lens surface, and choose an f-number solve like so:



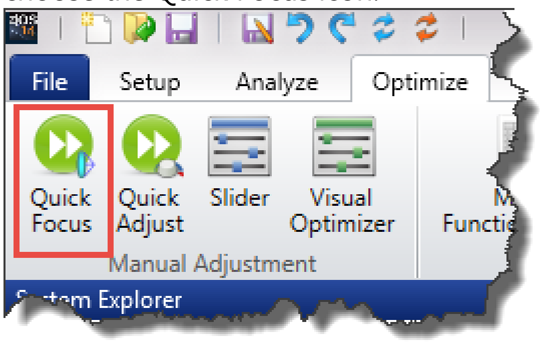
OpticStudio will immediately compute the radius of curvature that yields an f/5 cone of light:



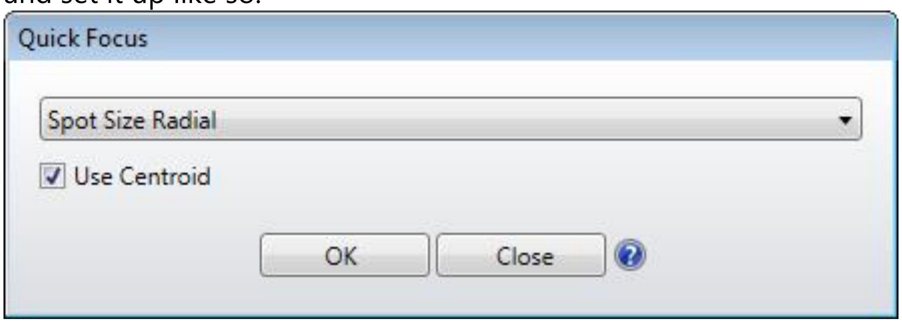
Try altering the radii of curvature of the other two surfaces, and you will see that the f/# solve automatically updates to enforce the condition that the lens be f/5. A solve is the most efficient way to enforce a system constraint.

Note: Read the "Solves" section of the Technical Reference in its entirety. A solid understanding, and use, of solves is one of the hallmarks of the professional lens designer!

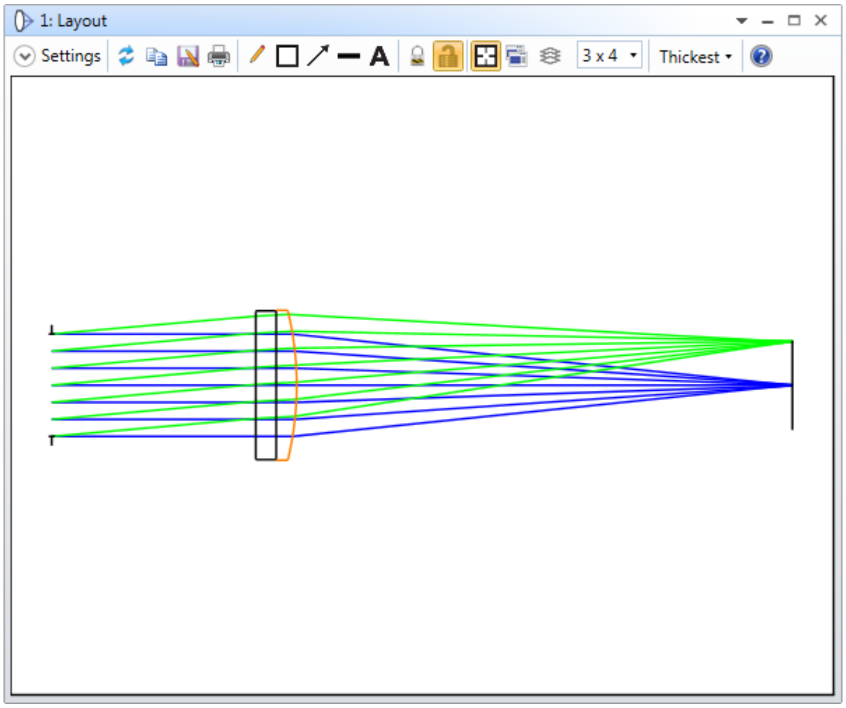
Now we will bring the lens into focus. Go to the Optimize tab, and in the Manual Optimization tab choose the Quick Focus icon:



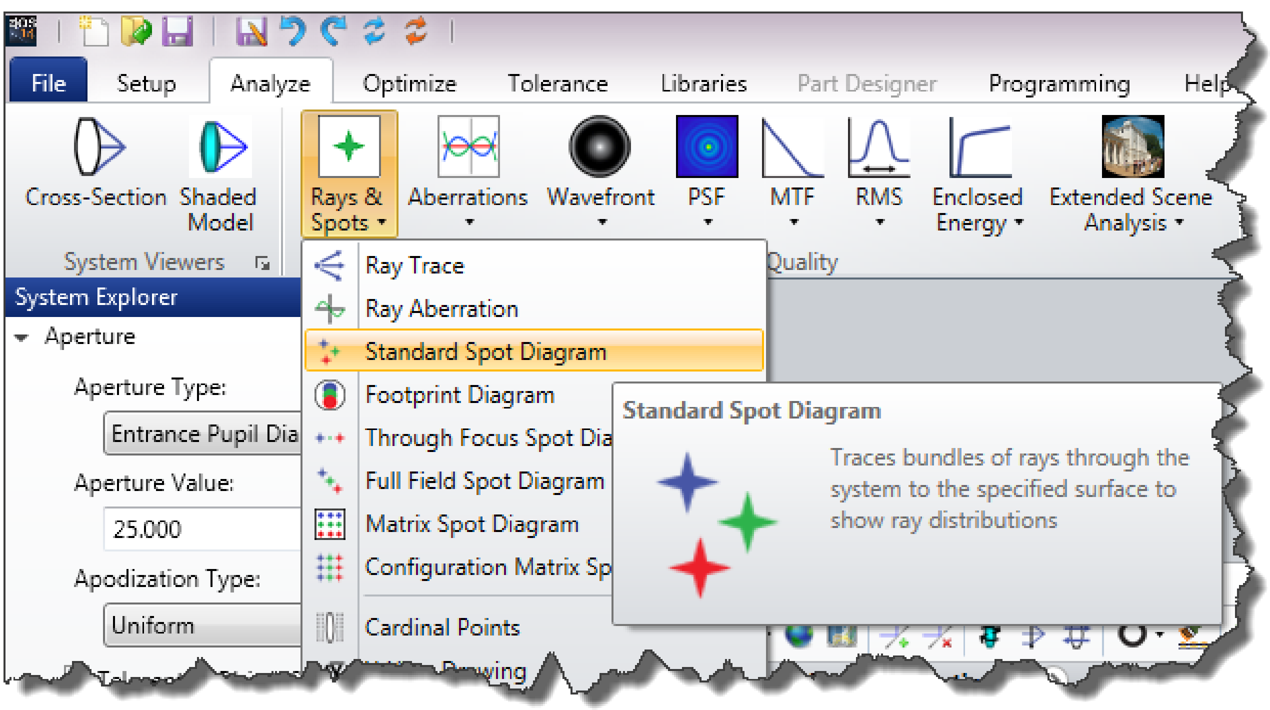
and set it up like so:

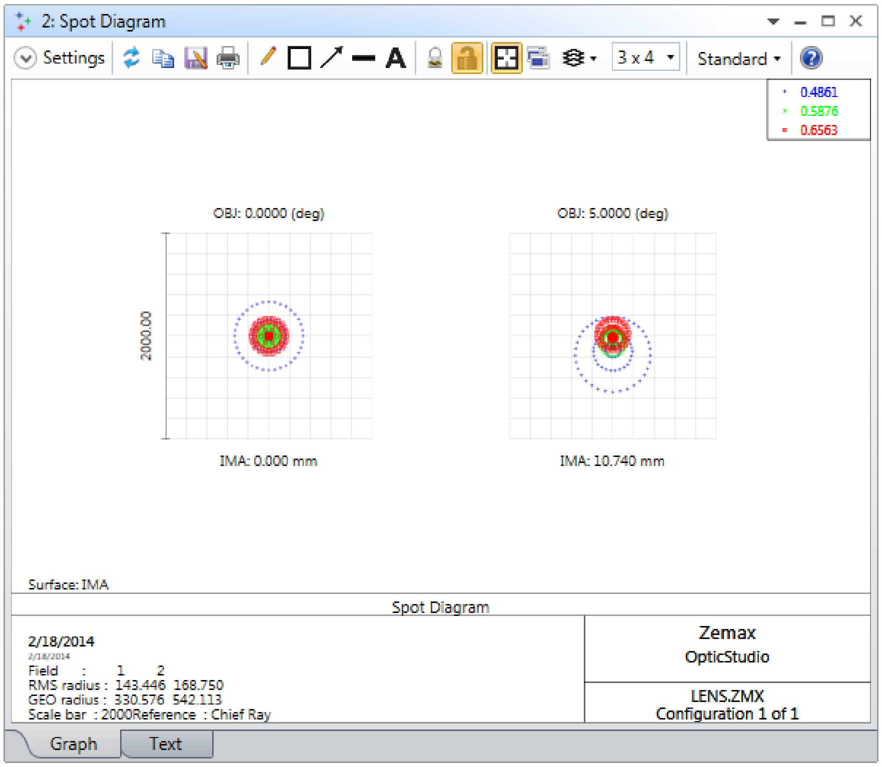


Update the cross-section window to see the final 'basic setup':



So now we have an f/5 lens, operating over the visible with a 5 degree field of view. Open a spot diagram by clicking on the Standard Spot Diagram in the Rays and Spots menu of the Analyze tab:





The RMS spot radius is 143µ on axis, and about 169µ at the 5° field point. Check that you get the same data as shown here, and if not go back through the exercise step by step to make sure your system is correctly set up.

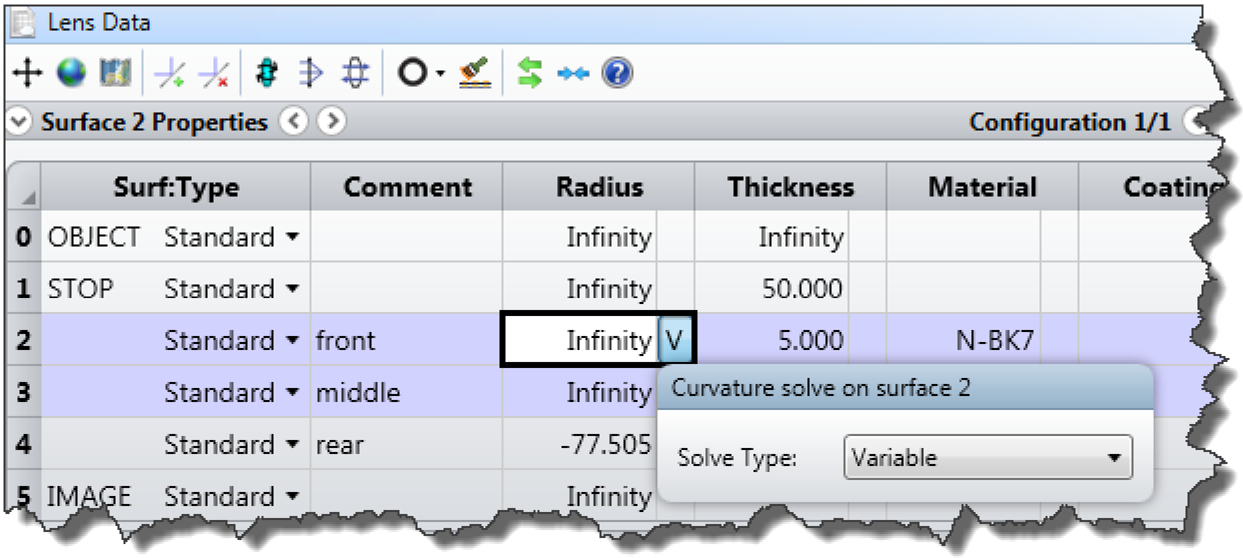
Note: Finally, click on Setup Tab…System Check in the 'Diagnostics' group. This invaluable utility checks your file for the most common setup faults. Although not every possible fault can be caught by such a utility, anything it does report should be checked, and anything classed as an 'Error' must be rectified before proceeding.

Then click on File…Save As, to save the file as 'basic setup.zmx'.

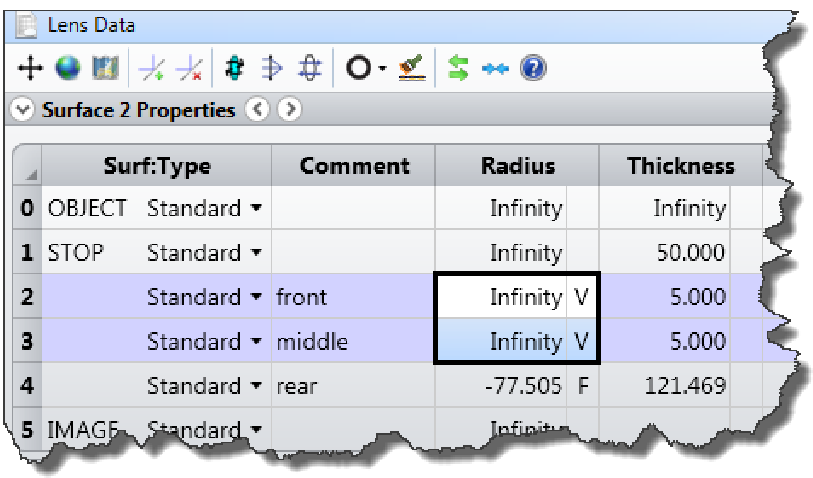
Setting Variables

Our basic system setup is certainly an f/5 lens that meets the specification of aperture, wavelength and field of view, but it is not necessarily the best possible lens for the job. In fact, with only one curved surface, it is highly unlikely to be the best possible lens for the job! We are now going to optimize the lens to get the best possible performance.

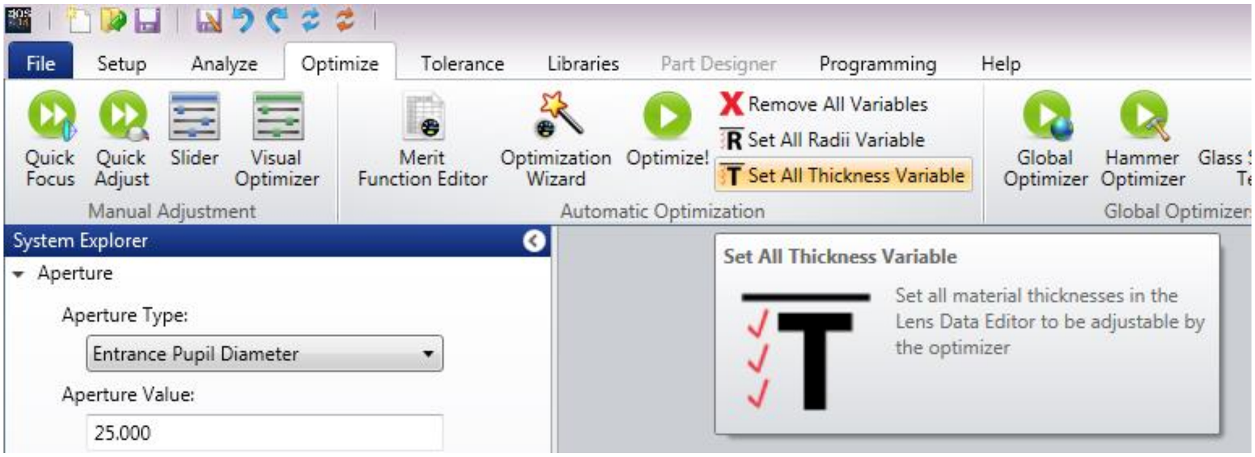
First we will tell OpticStudio what it may change. We do this by clicking on the cell to the right of the parameter we want, and selecting the 'variable' solve:



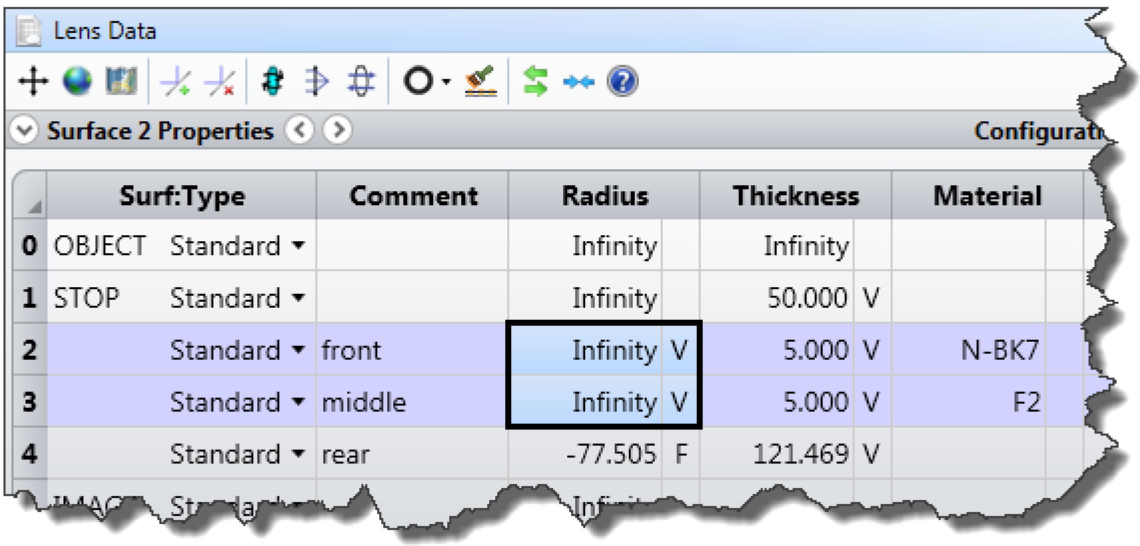
Or we can highlight the cells we want OpticStudio to change the values of, and use the keyboard shortcut <Cntl>Z (press and hold the Cntl button, and then press the z button on the keyboard):



Or, in the Automatic Optimization group of the Optimize tab, we can use set all radii variable/set all thicknesses variable:



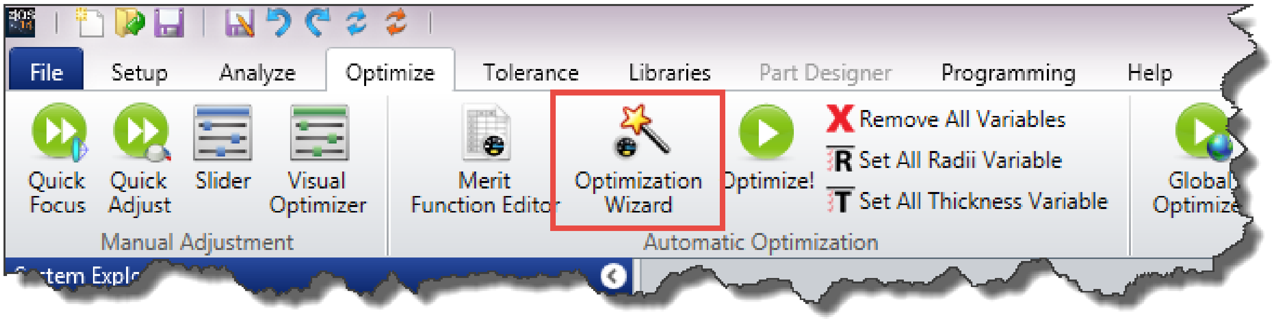
To set a total of six variables:



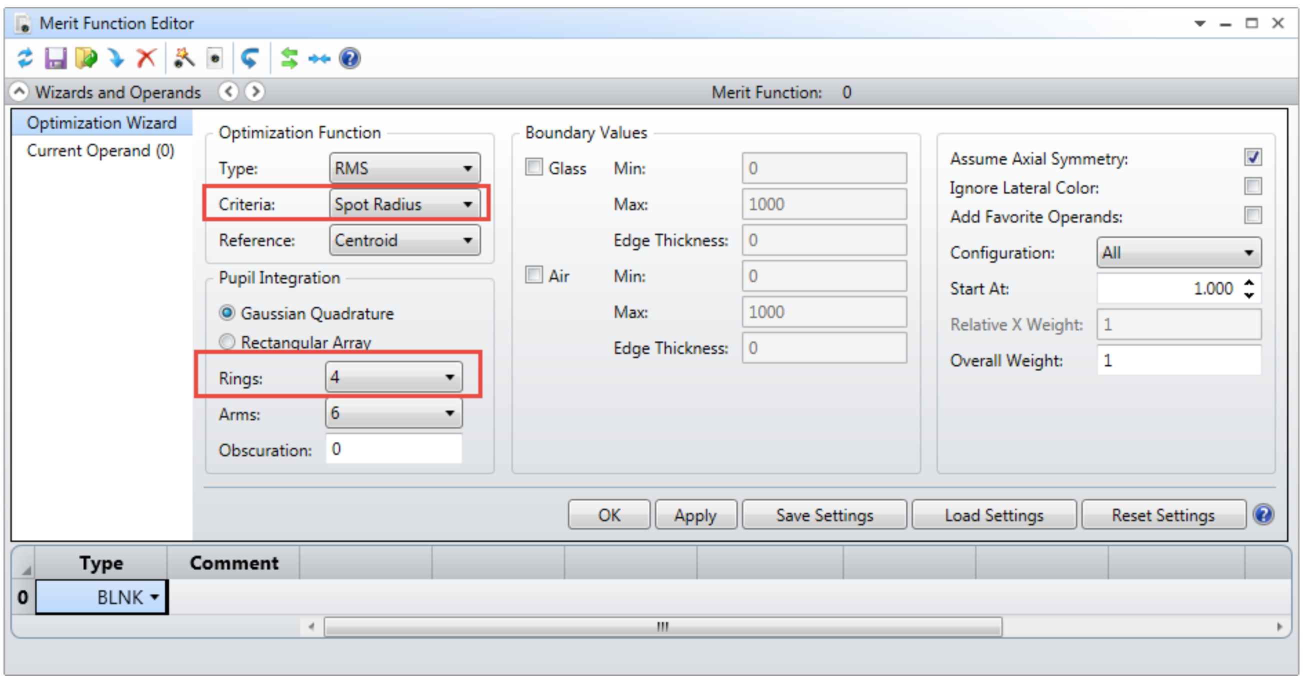
The status flag V indicates variables that OpticStudio may change the values of, just as the F flag means that the rear surface's radius of curvature is set by an f/# solve. As OpticStudio modifies the values of the variables, the f/# solve will automatically update to maintain the lens at f/5.

Defining the Merit Function

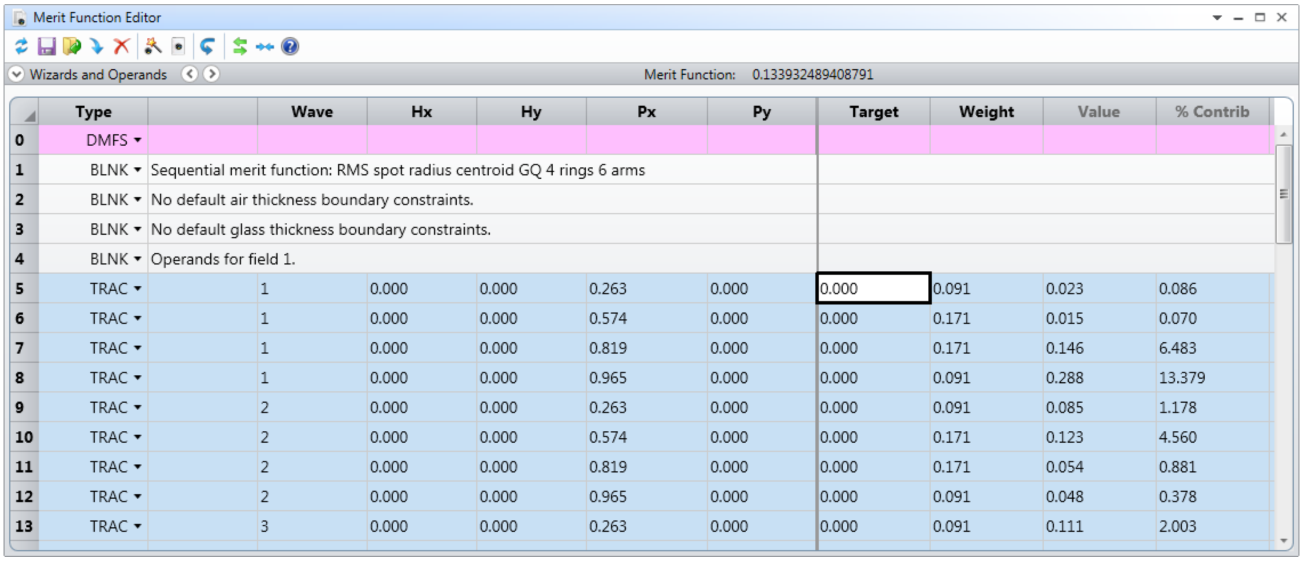
Next we will build the merit function for this design. In the Optimize tab, click on Optimization Wizard in the Automatic Optimization group:



This will open the Merit Function Editor, and also activate the Optimization Wizard in the Property Inspector area of the Editor. Because this is a focal system, we want the smallest RMS spot radius, choose RMS Spot Radius, relative to the centroid, and set the number of rings to 4 (we will discuss this in more detail later, for now just make these changes) and press the OK button to close the Optimization Wizard:



OpticStudio will then write out a merit function like so:



Merit Function Editor

Wizards and Operands — Merit Function: 0.133932489408791

	Type		Wave	Hx	Hy	Px	Py	Target	Weight	Value	% Contrib
0	DMFS										
1	BLNK	Sequential merit function: RMS spot radius centroid GQ 4 rings 6 arms									
2	BLNK	No default air thickness boundary constraints.									
3	BLNK	No default glass thickness boundary constraints.									
4	BLNK	Operands for field 1.									
5	TRAC		1	0.000	0.000	0.263	0.000	0.000	0.091	0.023	0.086
6	TRAC		1	0.000	0.000	0.574	0.000	0.000	0.171	0.015	0.070
7	TRAC		1	0.000	0.000	0.819	0.000	0.000	0.171	0.146	6.483
8	TRAC		1	0.000	0.000	0.965	0.000	0.000	0.091	0.288	13.379
9	TRAC		2	0.000	0.000	0.263	0.000	0.000	0.091	0.085	1.178
10	TRAC		2	0.000	0.000	0.574	0.000	0.000	0.171	0.123	4.560
11	TRAC		2	0.000	0.000	0.819	0.000	0.000	0.171	0.054	0.881
12	TRAC		2	0.000	0.000	0.965	0.000	0.000	0.091	0.048	0.378
13	TRAC		3	0.000	0.000	0.263	0.000	0.000	0.091	0.111	2.003

Each row in the Merit Function Editor contains an operand, which computes some value. The TRAC operand, for example, computes the radial point at which a specified ray lands on the image plane, relative to the average of all rays from that field point. Note that each TRAC operand traces a ray defined by its wavelength number, and its (Hx, Hy, Px, Py) normalized coordinates. Different operands will take different arguments, and the names of the arguments are given in the header row of the Editor.

Each operand that computes a value returns that value in the 'Value' column of the editor. The operand is also given a target value to achieve, and a weight. The merit function value is then computed as:

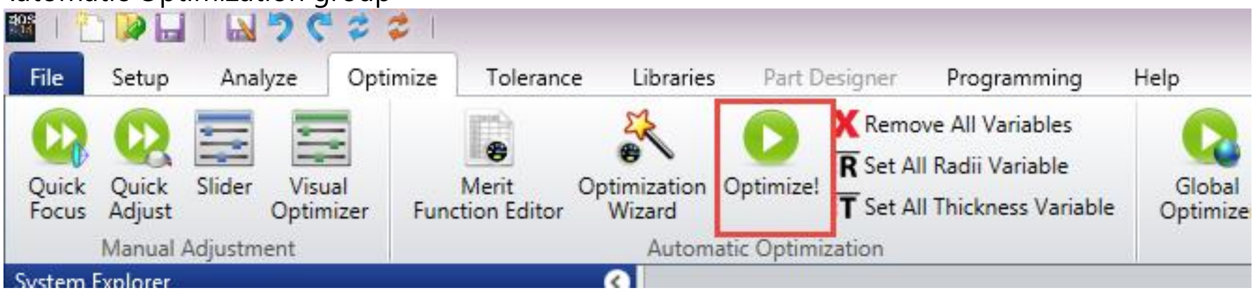
$$MF^2 = \frac{\sum W_i (V_i - T_i)^2}{\sum W_i}$$

where W_i is the weight of the ith operand, V_i is its computed value and T_i is its target value, and the summation is over all the operands in the merit function. As the computed values of the operands move towards their target values, the merit function value approaches zero. Because the difference between the target and actual values of each operand is squared, any deviation from the target value yields an increasingly positive value of the merit function.

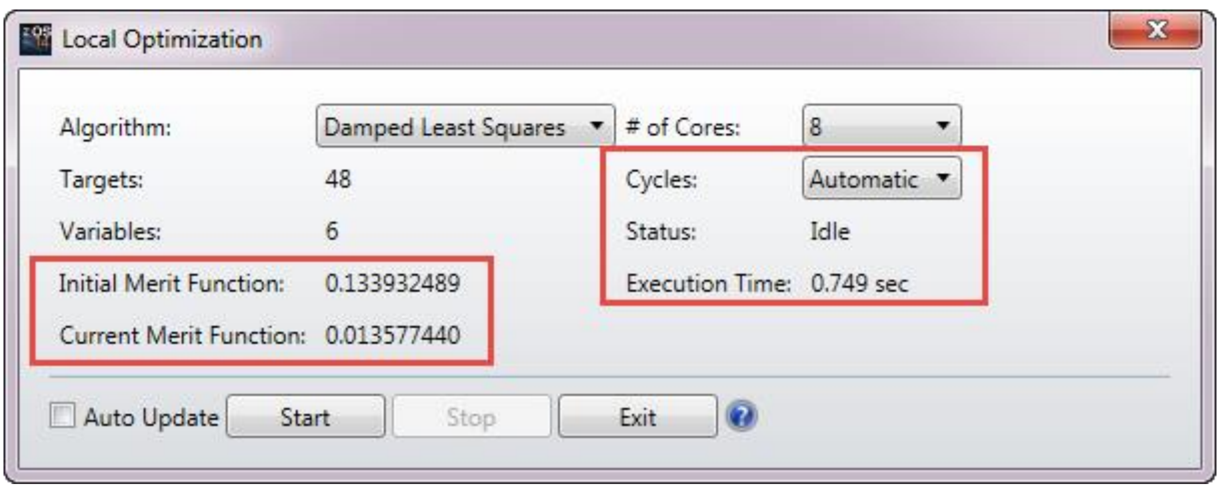
Note: The goal of the optimizer is to reduce the merit function to zero, or as close as possible, by adjusting the values of the variable parameters in the Lens Data Editor.

Optimizing the Lens

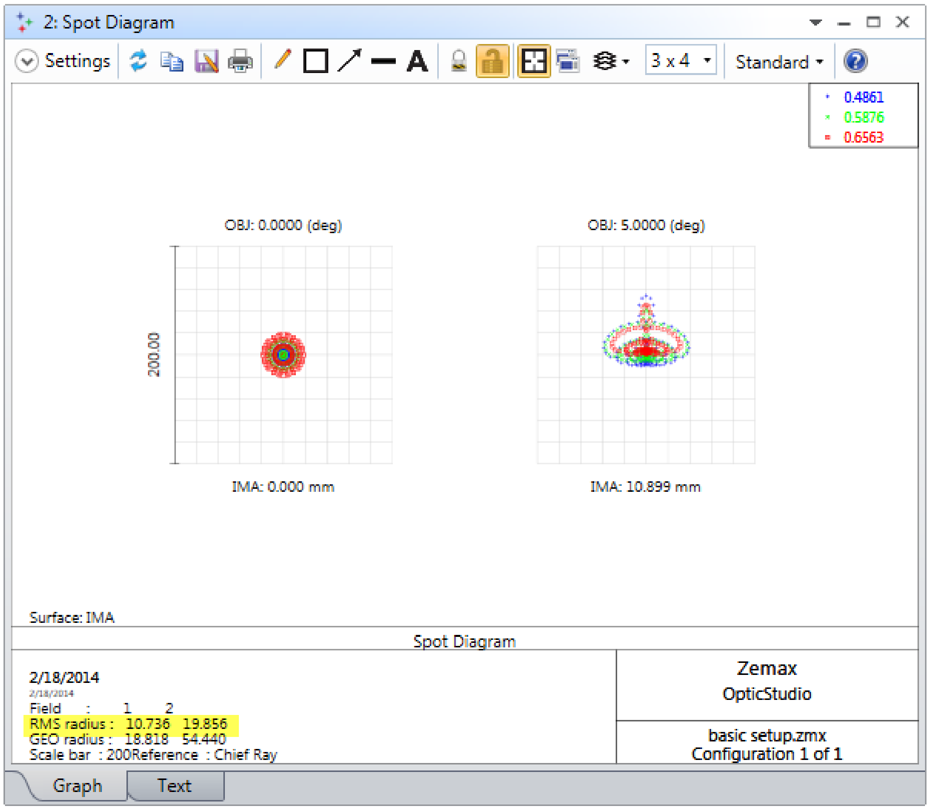
Now that we have defined the variables and the merit function, click the Optimize! icon in the Automatic Optimization group



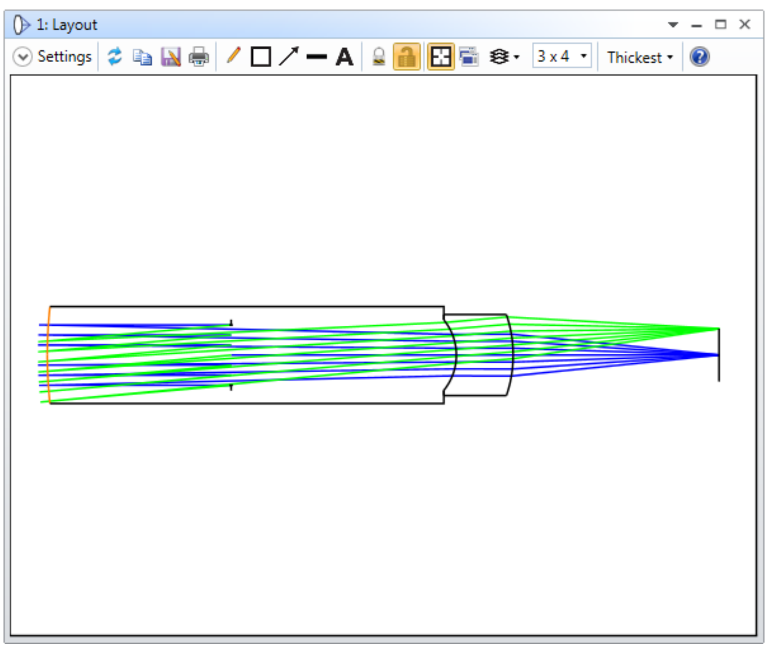
And then press the Automatic button. Note that the optimizer is multi-threaded and will split the calculation over all the CPUs in your machine if that will speed the calculation up.



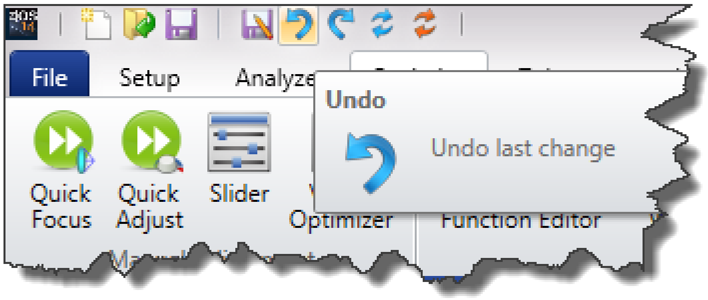
The merit function value quickly falls, and the Spot Diagram plot shows the improved performance (double-click it to make it update). The RMS spot radius is now 11μ on axis, and about 20μ at the 5° field point, compared to 143μ and 168μ prior to the optimization. That's a big improvement!



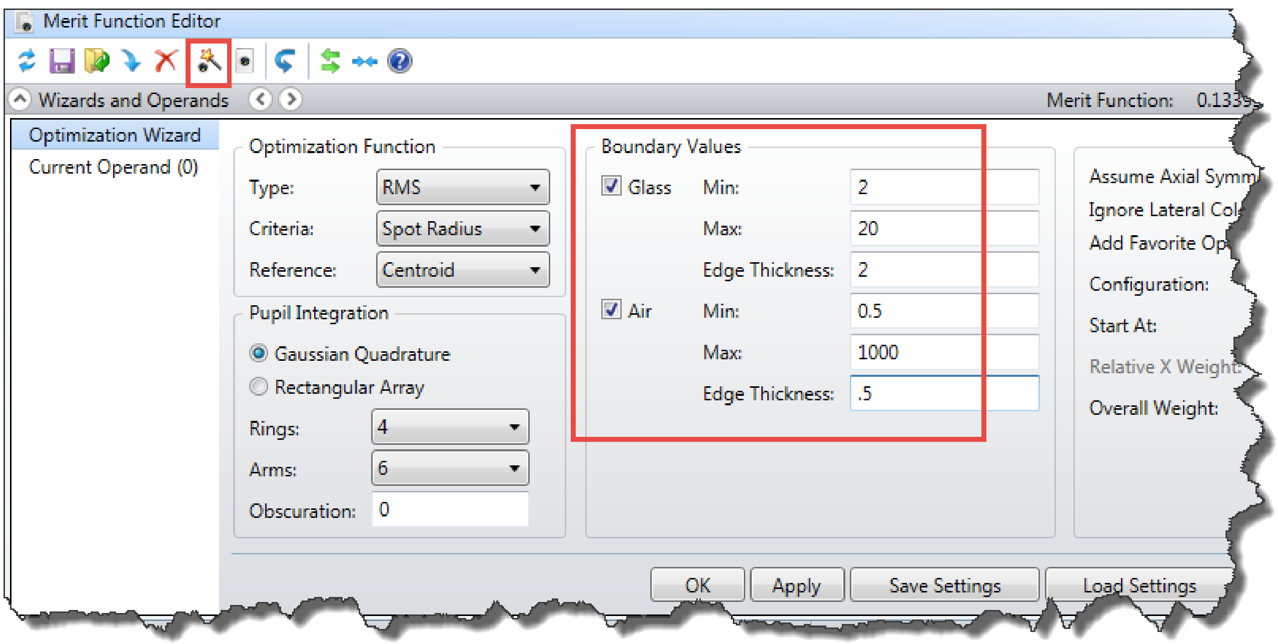
However, there is a clear problem, which can be seen in the Layout plot:



The lens is unfeasibly thick! We have told OpticStudio to minimize the RMS spot radius, but have given it no guidance about any constraints it must operate within. Press the F3 button, or click on the Undo icon:

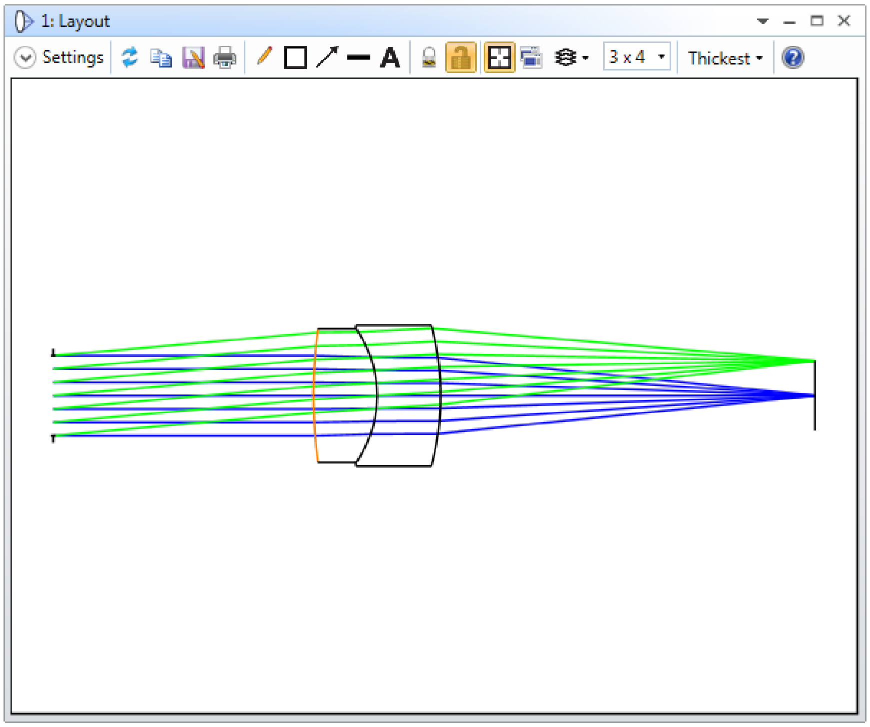


This will undo the optimization and restore the previous, un-optimized system. Click on the Optimization Wizard again (it is in the Merit Function Editor toolbar as well as the Optimize tab) and set up the following changes

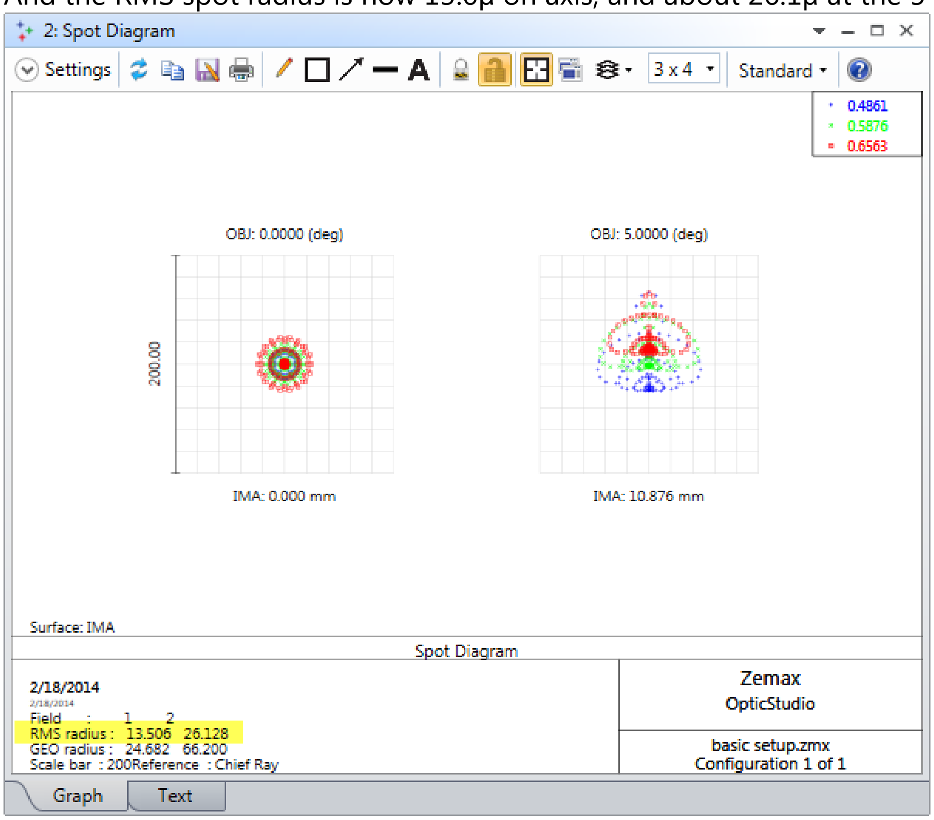


These settings require that the lens elements have a center thickness somewhere in the range between 2 and 20 mm, and that the lens edge-thickness be greater than 2 mm (this is a useful constraint to aid manufacturability). Any surfaces made of air must have thicknesses between 0.5 and 1000 mm, which is not necessary in this design, but in a multi-element design will prevent lens elements from hitting each other or being unreasonably far away from each other, and is therefore added here for completeness.

Click OK to enforce the changes. Press the Optimize! icon again, and we get a much better design:



And the RMS spot radius is now 13.6µ on axis, and about 26.1µ at the 5° field point:

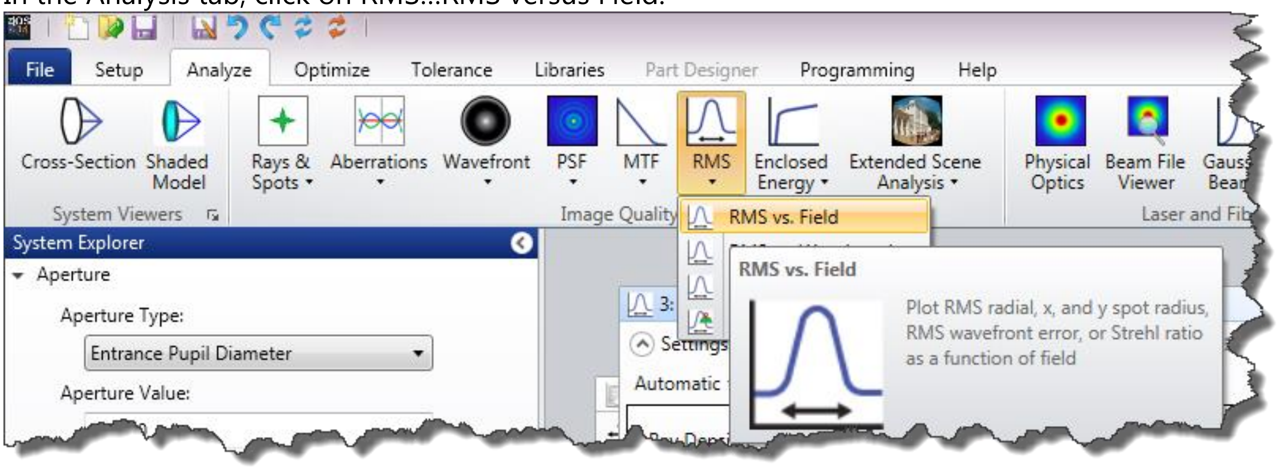


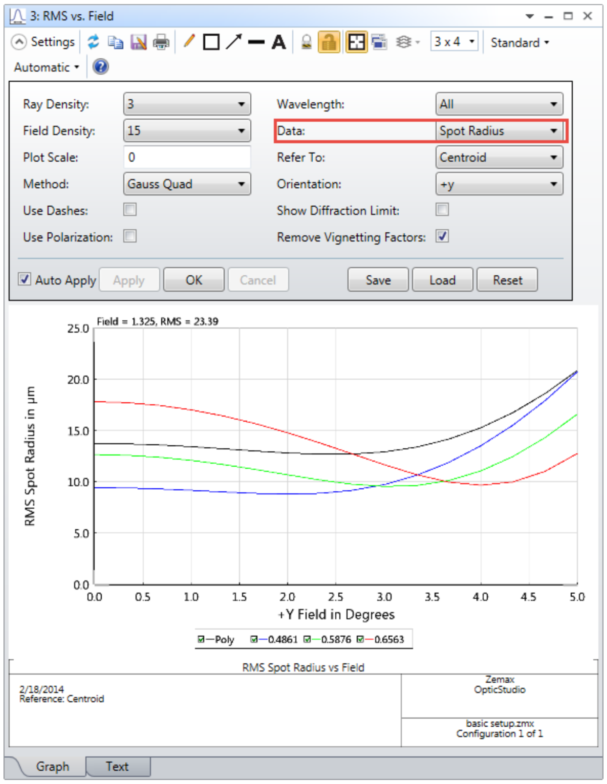
Note: The key point is that for successful optimization, the merit function should contain both the optical targets you want to achieve, plus constraints that will prevent OpticStudio from producing *unwanted design shapes. Typical constraints include the thickness of elements, weight, maximum acceptable distortion, etc.*

Are There Enough Field Points?

We optimized this lens using just two field points, at 0° and 5°. Although the RMS spot radius looks well controlled at these two points, how do we know that at some intermediate field point the performance of the lens does not degrade?

In the Analysis tab, click on RMS…RMS versus Field:



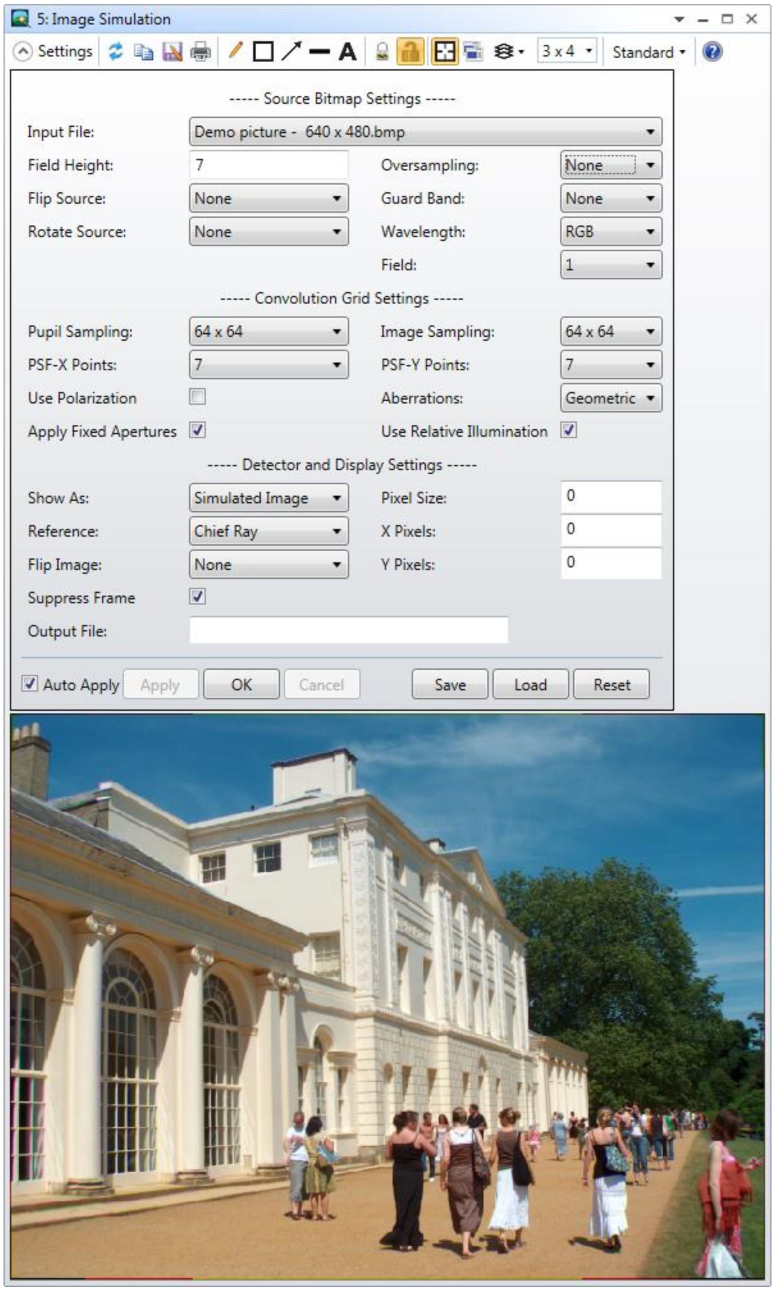


This plot shows how the RMS spot radius varies as a function of field, with field as a continuous variable. We are using 15 points across the 5° field, and plotting the RMS spot radius for each wavelength individually and as a polychromatic average. Note that the RMS spot never exceeds its value at the extreme fields of 0° and 5°. Therefore, two field points provide adequate control in this design. If the curve shows exceeds the value at the maximum or minimum field points, add more field points as required.

Note: If you change the number of field points, or the number of wavelengths, you must rebuild the merit function to include your changes into it.

A similar RMS vs. Wavelength plot allows you to check that you have adequate control with the defined number of wavelengths, as does Analyze… Aberrations…Chromatic Focal Shift and Analyzed…Aberrations…Lateral Color.

Another excellent way to look at the optical behavior over field and wavelength is to use Analyze…Extended Scene Analysis…Image Simulation. Configure it like so:

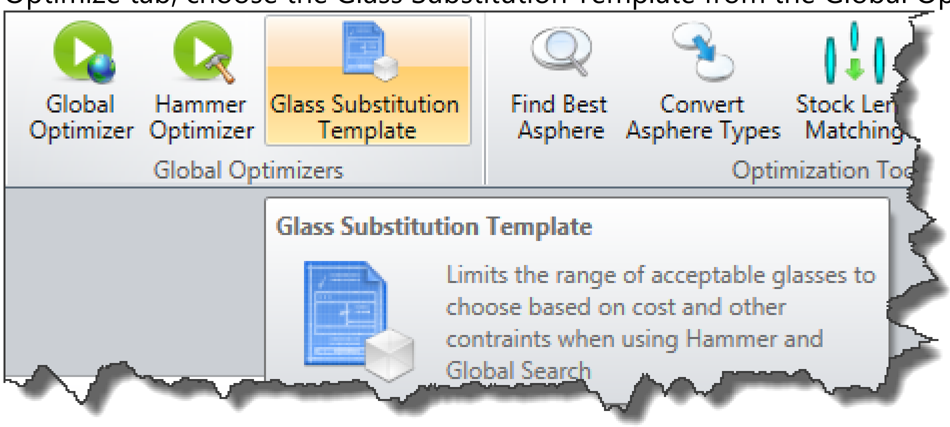


This will produce a simulation of what a real source scene, described by an input bitmap, will look like when imaged by the lens. This analysis is amazingly fast, taking literally only a few seconds to produce the image below. This feature is ideal for communicating real-world optical performance to non-optical specialists.

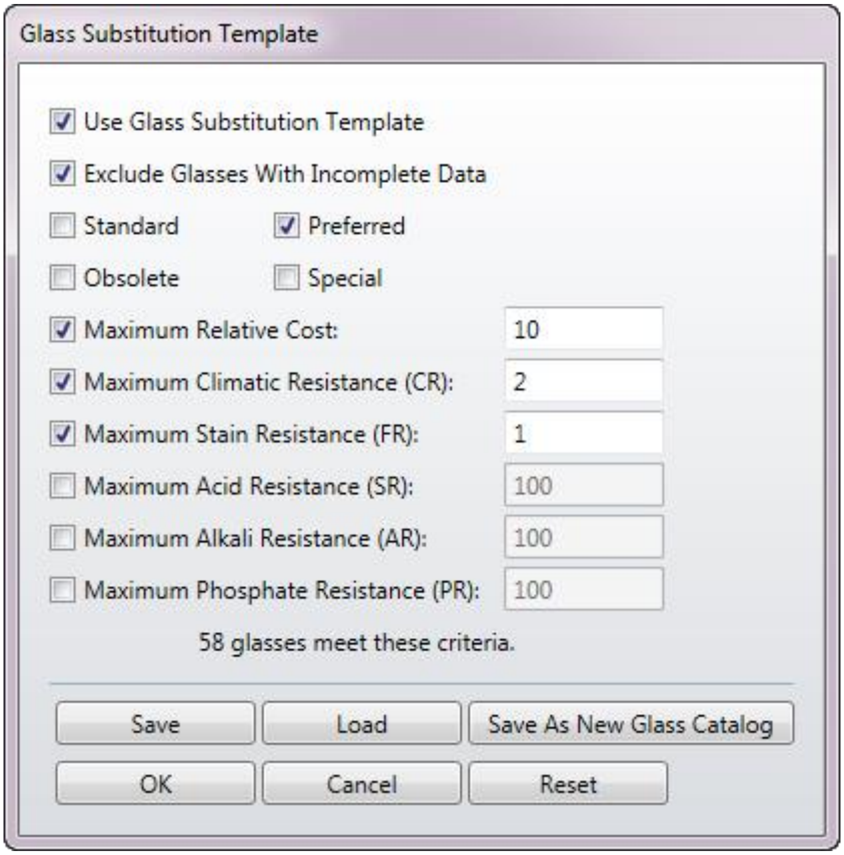
Glass Optimization

There is an important difference between optimizing glasses and other system parameters. Parameters like radii of curvature, thicknesses, etc. can be smoothly varied: a thickness of 10.0 mm can become 10.00001mm for example. However, glasses are only available with discrete properties: you cannot simply perturb a glass to get a slightly different refractive index! Instead, we use a method called Glass Substitution to swap out the glasses that the design currently uses for other glasses.

The first step is to define a template for the glasses OpticStudio is allowed to choose. Within the Optimize tab, choose the Glass Substitution Template from the Global Optimizers group:

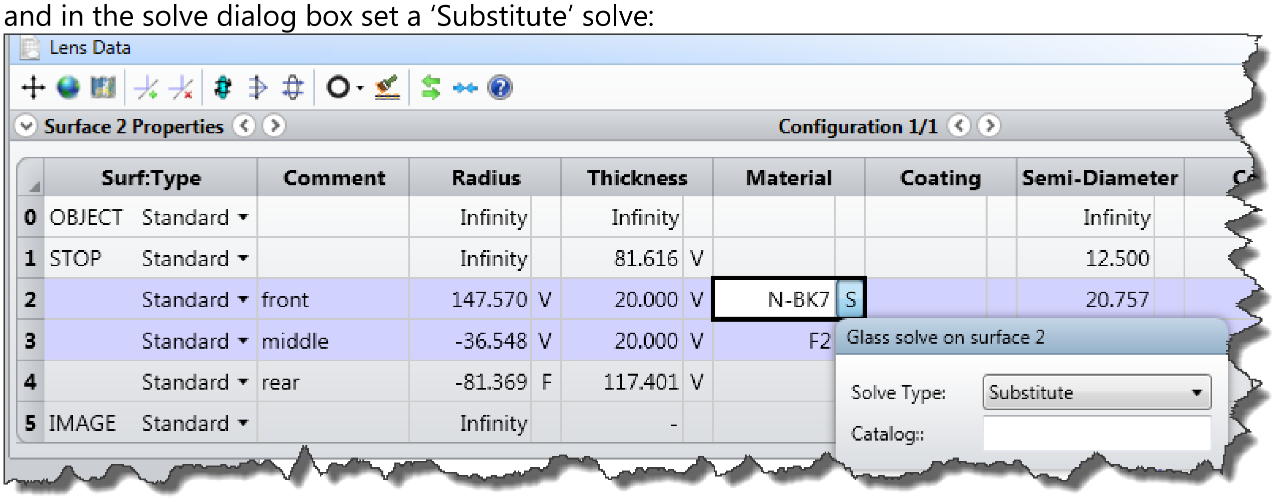


And configure it like so:

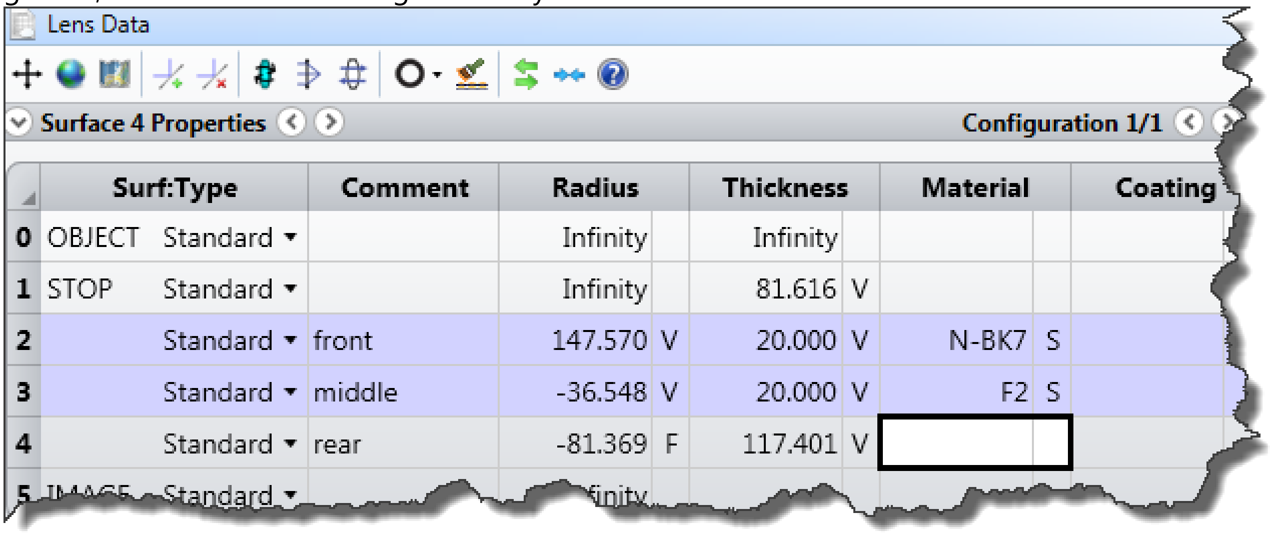


We are telling OpticStudio to use only Preferred optical glasses (a status flag that indicates the glass is easily available and does not have any unusual properties). In addition, each glass must cost no more than 10 times the price of N-BK7 (the relative cost), and must have a Climate Resistance factor of 2 or better and a Stain Resistance factor of 1 or better. There are a total of 58 glasses in the currently loaded catalog (by default the Schott glass catalog is loaded) that meet these criteria, and these are the only ones that will be selected for substitution.

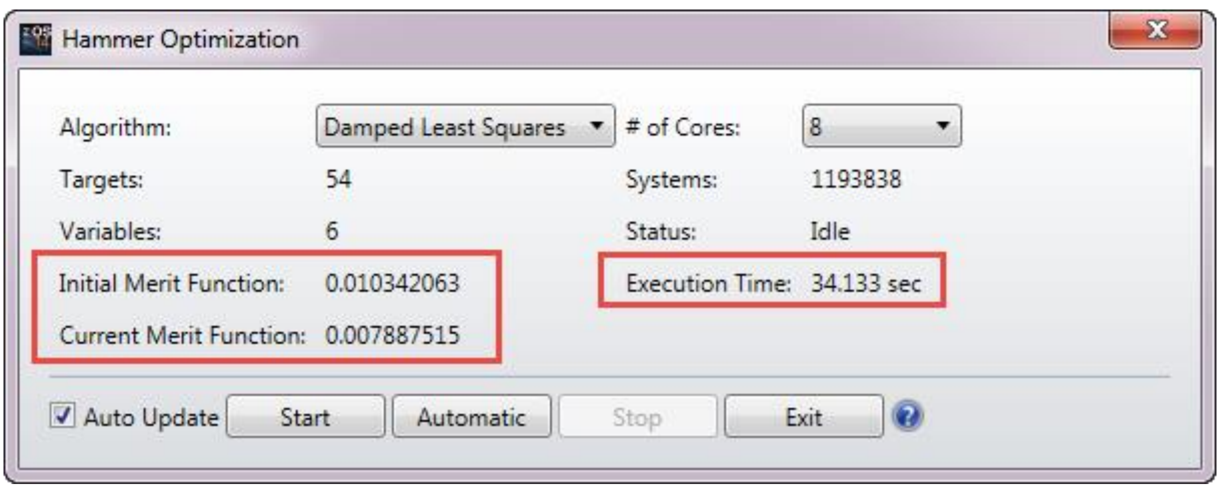
Then click on the cell top the right of the material of surface number 2, which is currently N-BK7, and in the solve dialog box set a 'Substitute' solve:



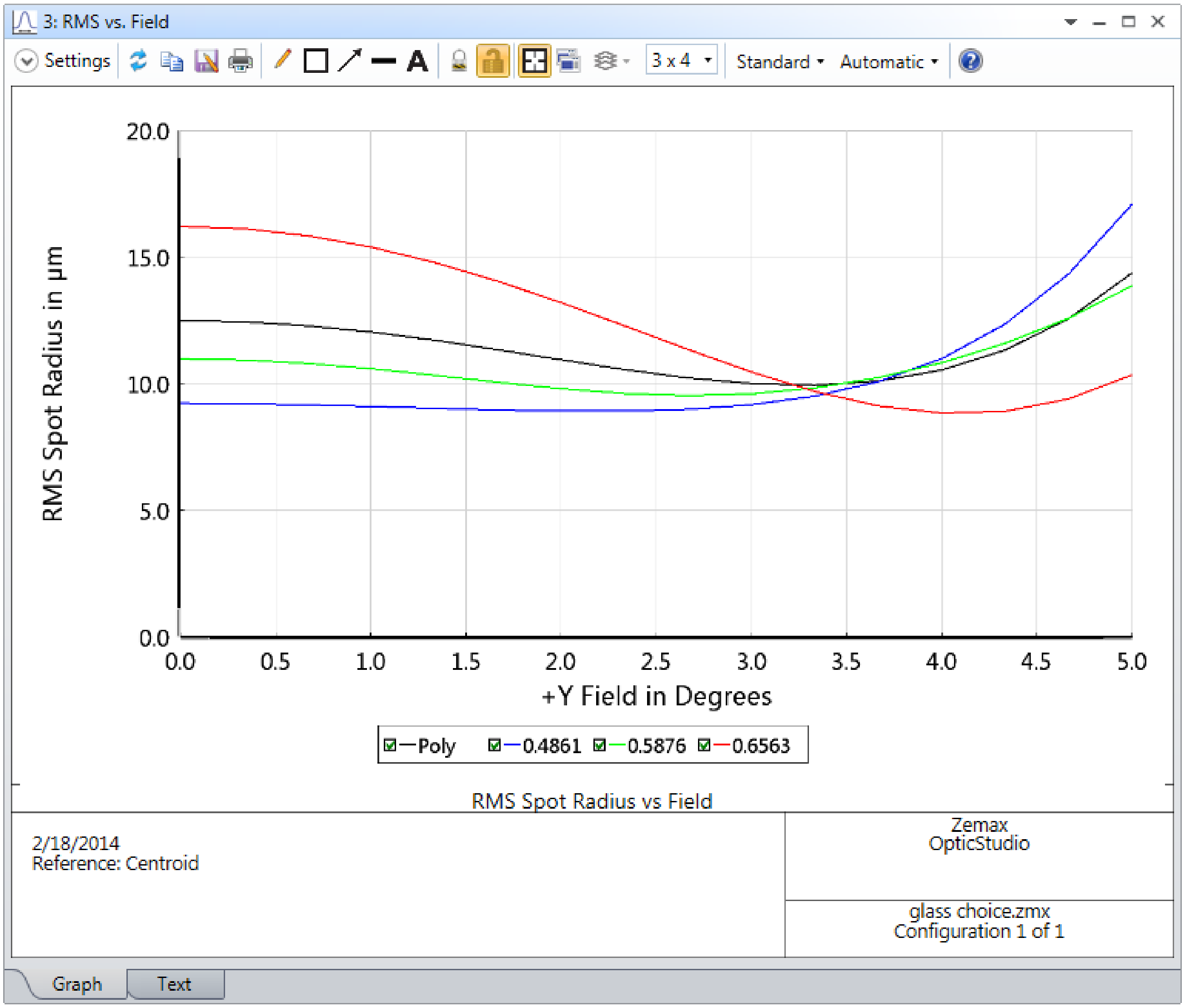
Repeat this for the F2 on surface 3. The Lens Data Editor should show an S status next to the glasses, to indicate that these glasses may be substituted:



The glass substitution method is too complex for the local optimizer. Instead, use the Hammer optimizer in the Global Optimizers group and OpticStudio will quickly find the best glasses for this design:



Check the glasses in the Glass Catalog to ensure they meet the specification (click on the glass, and go to Libraries...Materials Catalogs). The design now has an RMS spot radius below 19μ everywhere across the field of view:



Tutorial 5.4: Tips and Tricks for Successful Optimization

The following tips and tricks are useful guidelines for how to make the best use of OpticStudio's wide and powerful optimization features.

Use Physically Significant Merit Functions

Before you start to design your lens, think about how it will be tested and used. Test methods fall into a number of broad categories:

- Imaging onto CCD arrays or (less common) photographic films. RMS Spot Radius is usually a good performance indicator in this case. If the final system is expected to have less than about 2 waves of aberration, use RMS Wavefront Error instead.
- If you will test your lens on an interferometer, optimize for RMS Wavefront error.
- If you will test your lens on an MTF measurement rig, use RMS wavefront error. MTF improves as RMS wavefront error approaches zero. If you need further improvement, use the various MTF* operands described in the Optimization chapter of the Technical Reference to target MTF performance at specific spatial frequencies.
- If you are designing an afocal system like a beam expander, switch the lens to Afocal Mode via the switch on the System Explorer's Aperture section. Use RMS Angular Radius if you expect more than about 2 waves of aberration in the final system, and RMS wavefront error if you expect less than 2 waves of aberration.

Don't Optimize Aberration Coefficients Directly

It is tempting to attempt to 'control' the lens under optimization by targeting Seidel aberrations like SPHA, COMA, etc. directly in the merit function, and then using fifth-order aberrations for better control (see the macro fifthord.zpl, or the optimization macro ZPL03.zpl for example). While this is perfectly possible to do in OpticStudio, we do not recommend it, for the following reasons:

- Aberrations are difficult to compute in tilted and decentered systems, or systems with components like aspheric surfaces, diffractive components or GRINs.
- The Gaussian Quadrature (GQ) method OpticStudio uses for RMS Spot Radius and RMS Default Merit Functions are exact to a specified order of wavefront aberration. If you use n rings in the default merit function, you then have control of all wavefront aberrations up to order $r^{(2n-1)}$. In the doublet lens we designed, we used 4 rings and therefore could control all aberrations up to r^7, which is a higher order than fifth order aberrations can achieve. See G. W. Forbes, "Optical system assessment for design: numerical ray tracing in the Gaussian pupil", J. Opt. Soc. Am. A, Vol. 5, No. 11, p1943 (1988) for a very readable and full account of this useful technique.
- We are usually interested in optimizing for real-world performance metrics like spot size, wavefront error, MTF, etc. Fifty years ago aberration theory was a useful computational shortcut, but 21st century computers and multi-threaded software like OpticStudio are massively faster than the tools available then. Optimizing directly for the desired

performance is more practical than optimizing for some intermediate function that we hope will then go on to give us the desired performance. Optimize for what you want to test the built system for!

- Note for example that in the optimization of the doublet we did not need to target chromatic effects like axial or lateral color directly: the default RMS spot radius merit function provided this automatically.
- The exception to this is distortion, because distortion affects only the location of the image, not its quality. Operands like DIMX, DISG, etc. can be used to control distortion.

Use the Optimization Wizard

We recommend that you use the Optimization Wizard as the foundation of your merit function construction. This generates a 'Default Merit Function' which is the bedrock of your optimization function. Ultimately imaging systems are characterized by RMS spot radius or wavefront error, and afocal systems by RMS angular radius or wavefront error. The Optimization Wizard also automates the construction of the most common opto-mechanical constraints designers require, such as lens edge and center thickness constraints.

Additional goals and constraints can be easily added by inserting your own operands above the Wizard's operands in the editor. OpticStudio writes out the dummy operand DMFS (Default Merit Function Start) to indicate where the default merit function starts, and you should not hand-edit the operands below this line. Just click on the DMFS operand and press the insert key to insert new lines above the default merit function.

Use Hammer Often

The Hammer optimizer is used to improve a lens that has already been optimized by the local optimizer. Get in the habit of leaving the Hammer to run on an optimization problem when you are working on something else. The Hammer can be left to run overnight, or over weekends or even weeks if necessary.

Use Adequate Boundary Conditions

You should always add boundary constraints to your merit function, as well as optical targets. This yields two important benefits:

- OpticStudio will produce designs you can build, and that meet your non-optical goals! For example you should always constrain edge and center thicknesses of lenses to be reasonable, and you can add constraints on length, weight, etc. as required by your application.
- Good boundary constraints speed up the global optimizers because OpticStudio does not look in regions of parameter space where the boundaries are violated. This can speed up Global Search in particular by orders of magnitude.

Use the System Check Utility

The System Check utility, on the Setup tab, is an invaluable aid to ensuring there are no accidental errors in the system setup. Although not every possible fault can be found by such a utility, anything it does report should be checked, and anything classed as an 'Error' must be rectified.

Tutorial 6: Non-Sequential Ray Tracing (Professional and Premium only)

Note: Even if you intend to use only the non-sequential mode of OpticStudio, you should work through the previous tutorials before starting this one. ***Sequential and non-sequential modes share many common user interface concepts and methods which are described in those chapters and are not repeated here.***

Non-sequential ray-tracing is a powerful and general technology for tracing rays in systems where there are multiple optical paths. Typical uses include:

- Illumination systems, especially those with multiple or complex optical sources
- Systems such as interferometers, in which light that has travelled through several different optical systems must be coherently recombined
- Opto-mechanical stray light analysis in otherwise sequential optical systems
- LCD backlighting
- Bio-optical systems, particularly those based on scattering from tissue or fluorescent scattering

Non-sequential ray tracing assumes that there is no pre-defined path for any ray. A ray is launched and hits whatever object is in its path, and it may then reflect, refract, diffract, scatter, split into child rays, etc. It is a far more general technology than sequential ray-tracing, and is therefore somewhat slower in terms of ray-tracing speed but more general in its scope.

Sequential designs can be converted easily to non-sequential mode by using Convert to NSC Group on the File tab.

Tutorial 6.1: A Simple Example

Click on File…New to start a new OpticStudio design. Then click on Setup…Non-Sequential UI Mode. A new editor, the Non-Sequential Component Editor, (NSCE) will appear. The Analyze and Tolerancing tabs are not the same as in sequential mode.

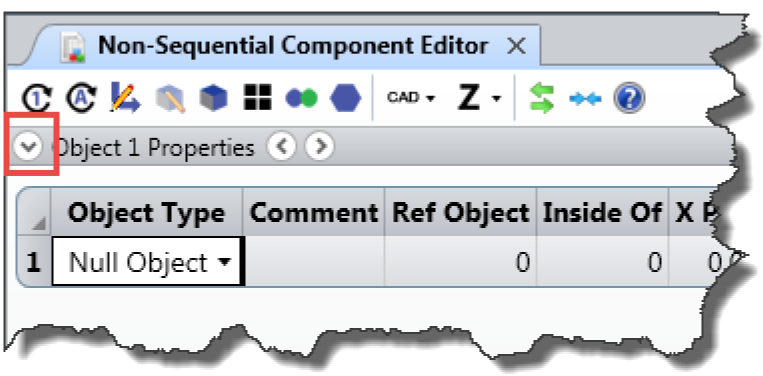
The NSCE is very similar to the Lens Data editor or the merit function editor in look and feel, and if you know how to use these editors the NSCE holds no surprises. The NSCE consists of a toolbar, Property Inspector and spreadsheet region, just like the other Editors

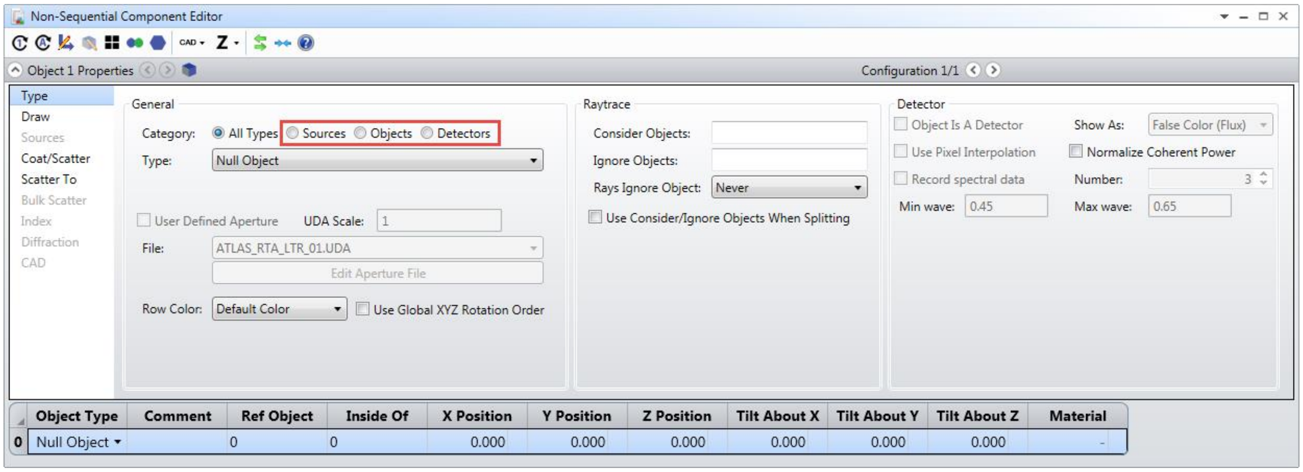
However, in non-sequential mode we deal with 'components' or 'objects' rather than 'surfaces'. Objects are full 3D volumes, not a collection of individual surfaces.

There are three basic types of object:

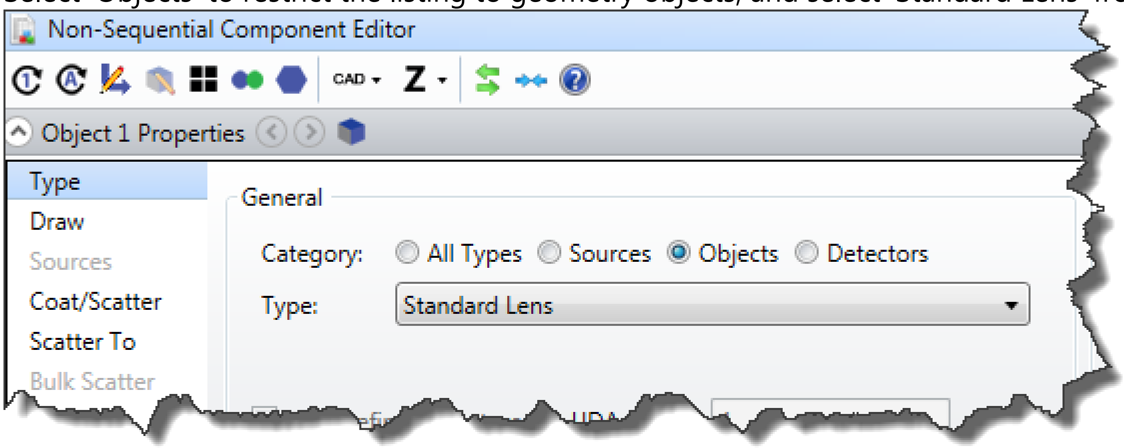
- Source objects, from which rays are launched into the non-sequential system
- Geometry objects, which define the optical components (lenses, prisms, mirrors, CAD objects, etc.) that the rays reflect, refract, scatter or diffract from
- Detector objects, which detect rays and give quantitative data of optical performance like irradiance, radiant intensity etc.

Open the Properties Inspector for Object 1 in the NSCE:

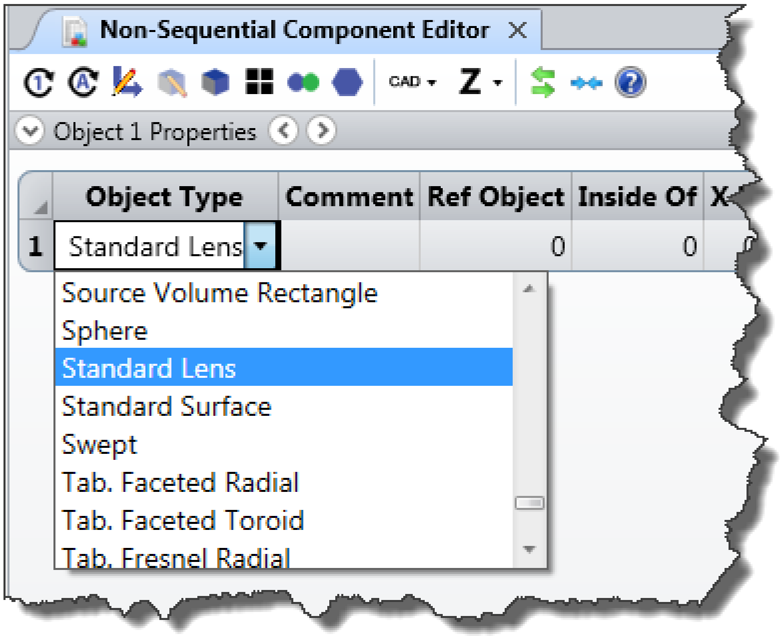




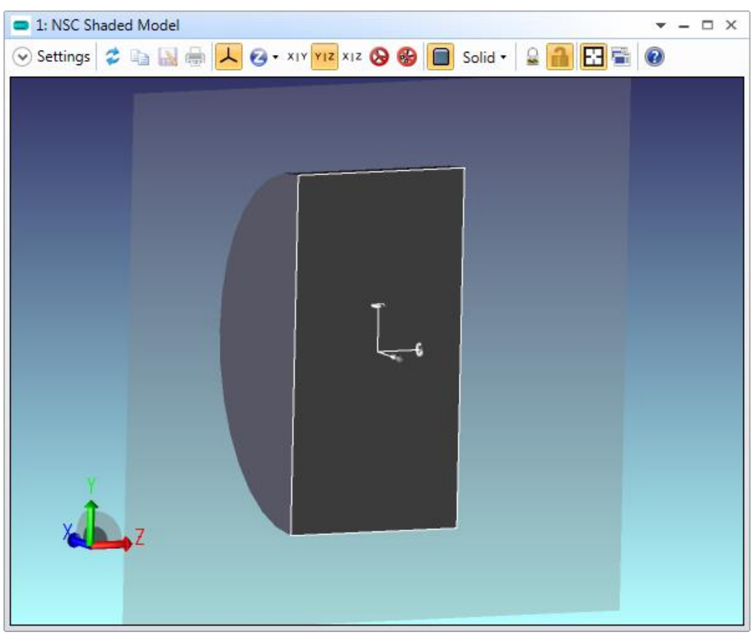
Select 'Objects' to restrict the listing to geometry objects, and select 'Standard Lens' from the list:



And close the Property Inspector. Note you can also just type directly into the Object Type cell in the editor, or use the drop-down list:



Open a Shaded Model plot to see the object and use a Y|Z cutting plane to make the layout more meaningful.

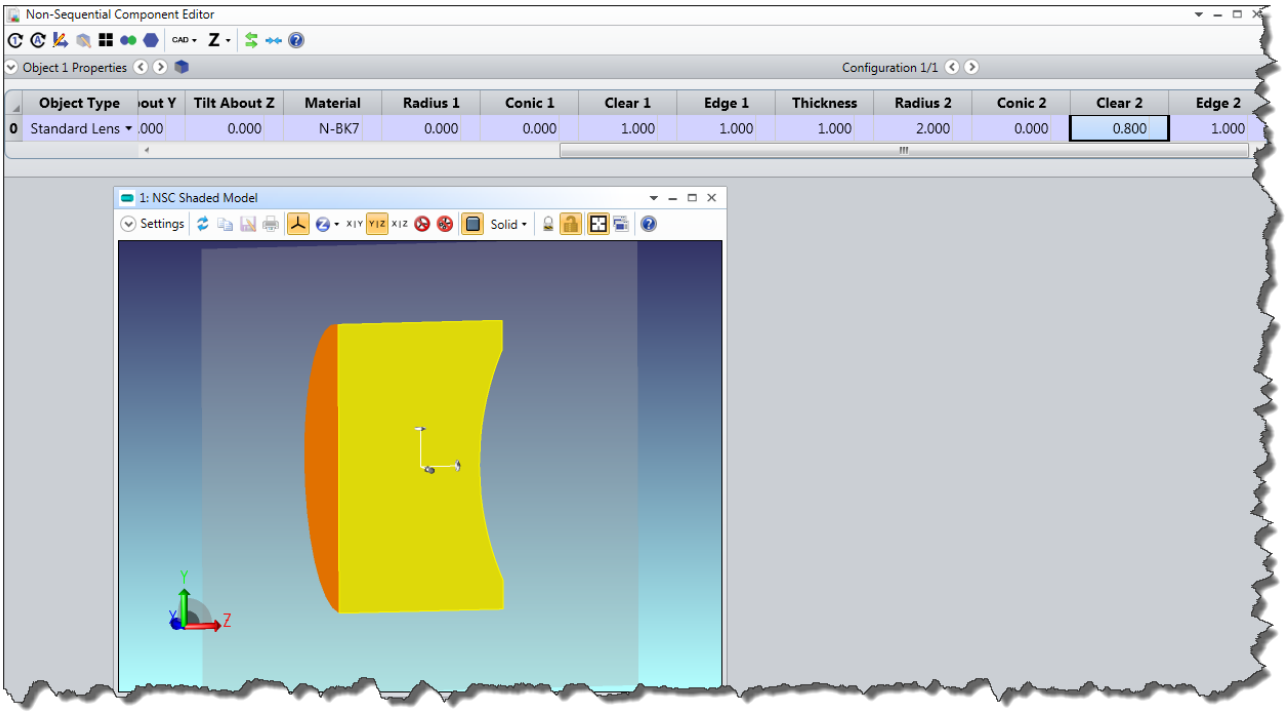


Note that you have a single 'Standard Lens' object that defines the entire object, rather than two surfaces and a thickness. Looking at the editor, you can position this object at any (x, y, z) location, and tilt it about x, y, z. You can then enter the glass type the object is made from, and its defining parameter data. Enter the following data:

```
All positions and tilts: 0.0
```

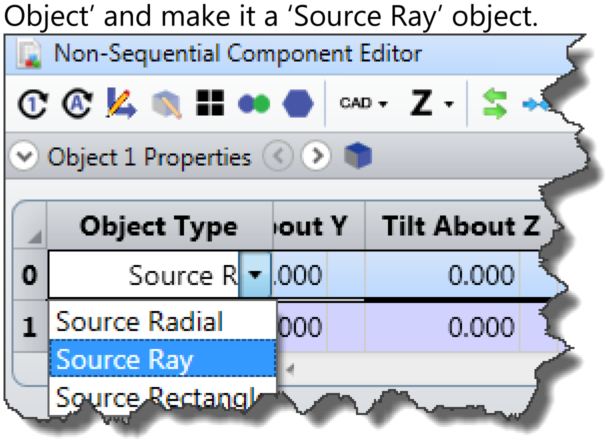
```
Material:                 N-BK7
Radius 1:                 5.0
Conic 1:                  0
Clear 1, Edge 1:               both 1.0
Thickness:                1.0
Radius 2:                 2.0
Conic 2:                  0
Clear 2:                  0.8
Edge 2:                   1.0
```

You should see this:



This is a fully parametric lens, modeled as a solid object and not a collection of surfaces.

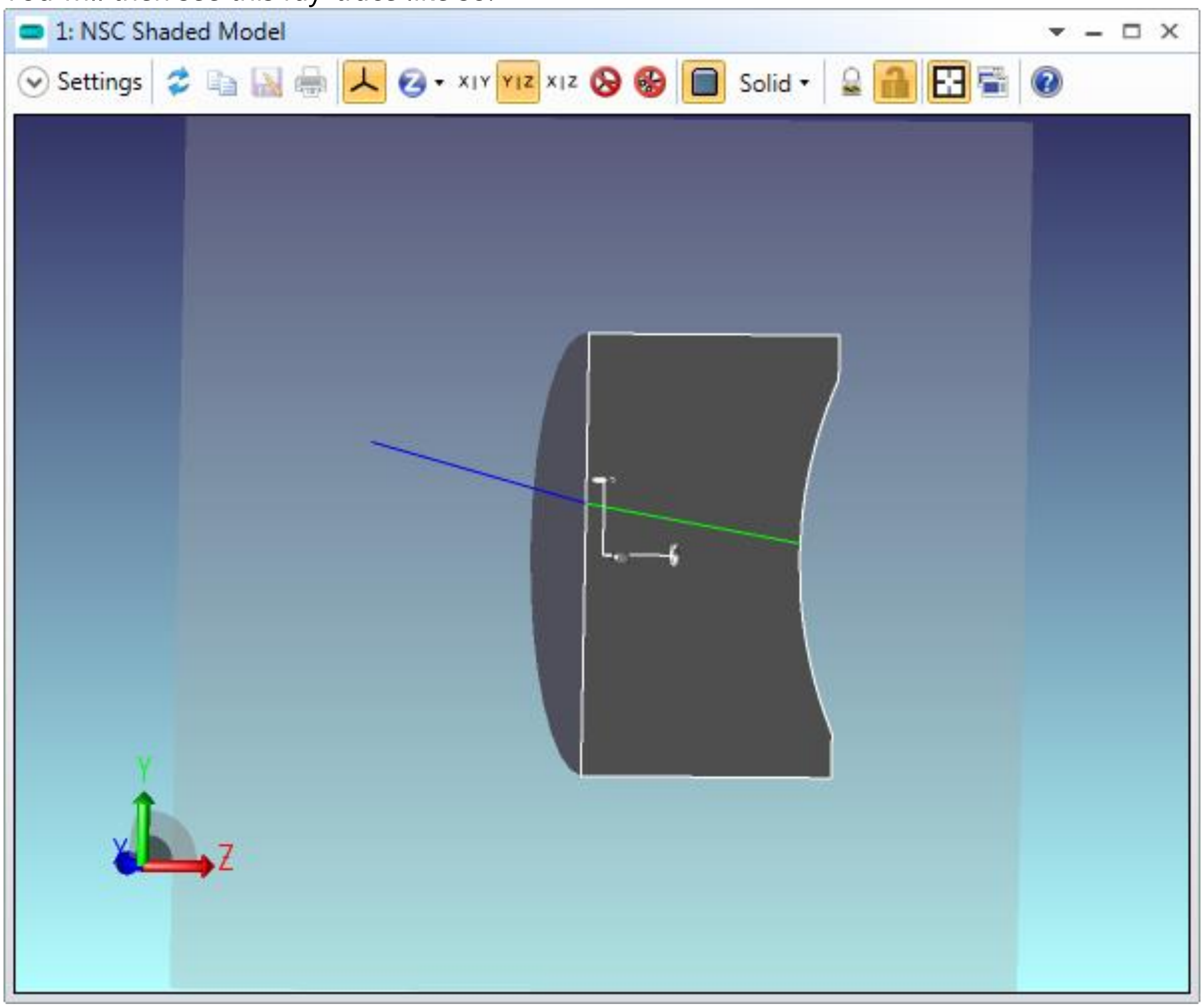
Next, click on the lens object in the editor again and press the Insert button to create a new ‘Null Object’ and make it a ‘Source Ray’ object.



Enter the following data:

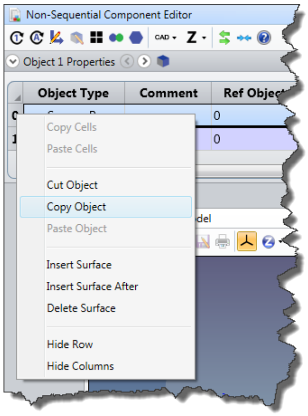
```
All parameters are 0.0 except:
Y position:          0.5
Z position:          -1.0
Tilt About X:        15.0
Layout Rays:         1
```

You will then see this ray-trace like so:



You may have to adjust the slicing plane manipulator slightly to see the whole ray trace. The ray is traced from the source to the front face of the lens, and then onto the second face of the lens. As there is no further object for the ray to hit, OpticStudio draws it for a short distance and then stops tracing it.

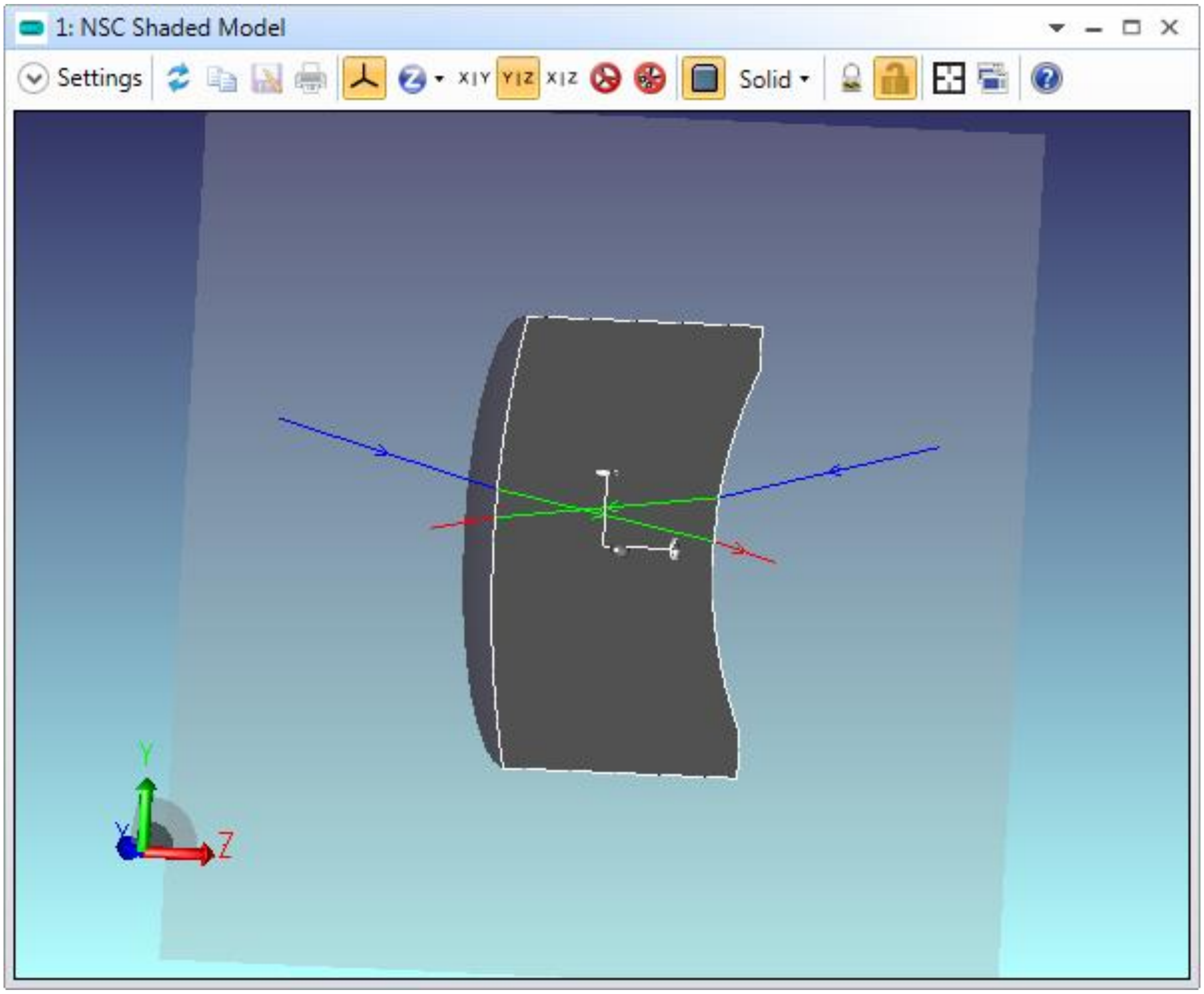
Now click on the row number of the Source Ray object to select the whole row, right mouse click and select 'Copy Object'.



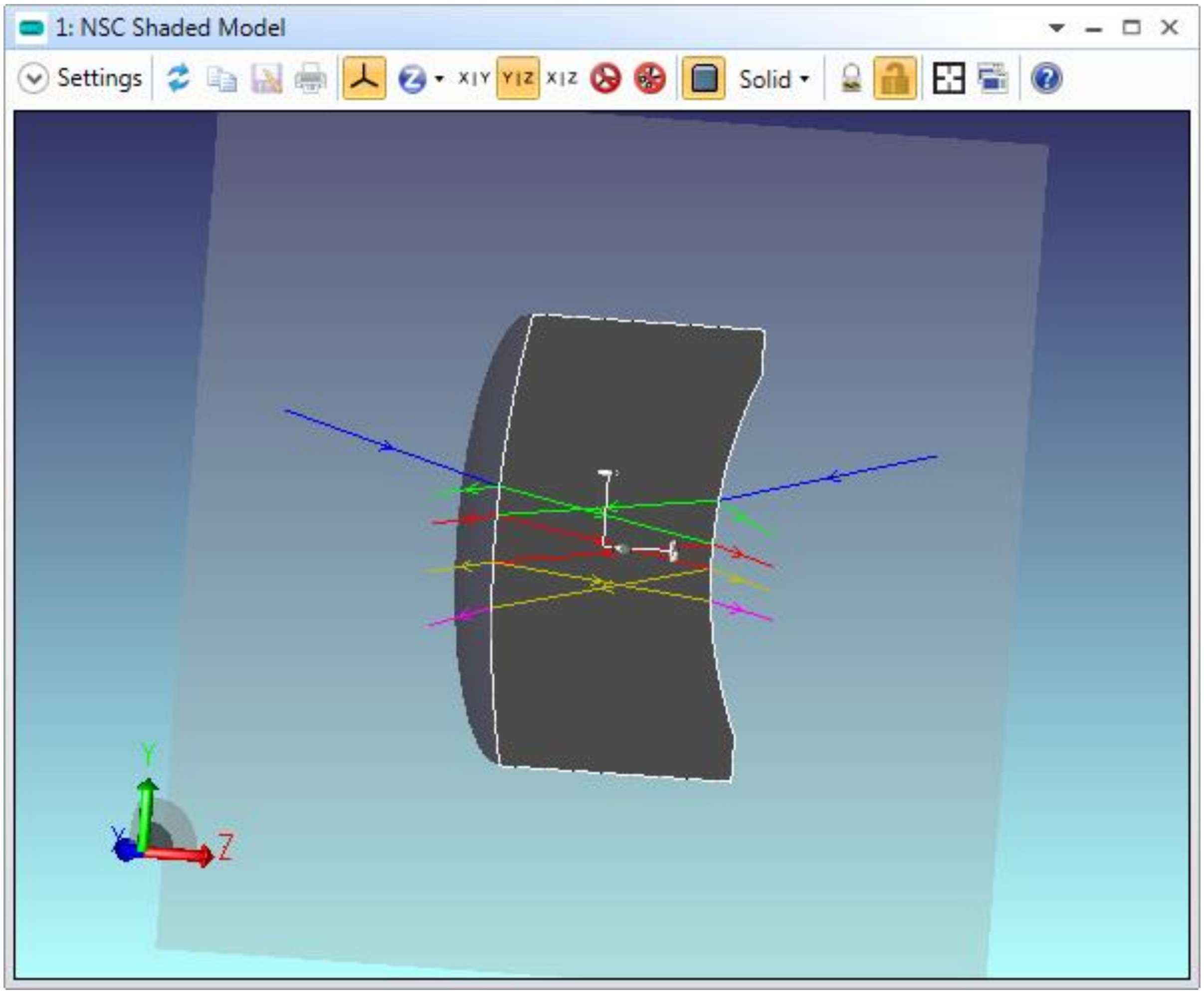
Click on the row again so it is no longer highlighted and press <Cntl>V or right-mouse click again and select Paste Object to paste the object back into the editor as a new object. You should now have two identical source objects. Modify the parameters of one of them as follows:

```
Z position:      2.0
Tilt About X:    -15.0
Tilt About Y:    180.0
```

Do not change any other parameters. Update the layout as you make each change so you can see what is happening. You should see two sources, one on either side of the lens.



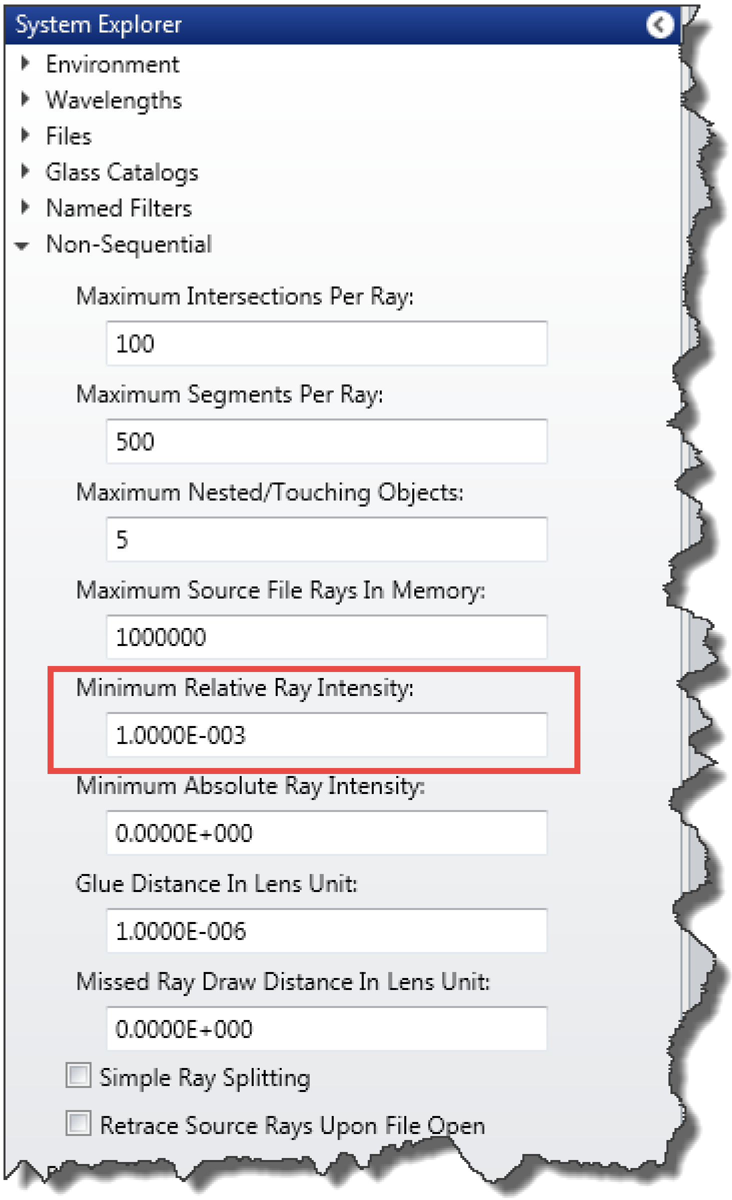
Now, on the Settings of the Layout plot, select the options to 'Split Rays' and 'Fletch rays':



This simple example shows the key benefits of non-sequential ray tracing:

- You do not have to tell rays where to go. Rays are launched and then interact with whatever objects are in their path.
- When a ray hits a refractive object, part of its energy is reflected and part is transmit-ted. OpticStudio can produce 'child' rays that take the reflected energy, and these child rays then interact with whatever is in their path, and in turn produce children of their own, which can have children of their own, etc.
- As well as being partially reflected and refracted, rays can also scatter at the surface of an object or inside its volume (called bulk scattering to distinguish it from surface scattering).
- Sources, objects and detectors are placed in a global coordinate system, and can be positioned and tilted independently of each other. In addition, if it is required, objects can be positioned relative to other objects, which we will discuss later.

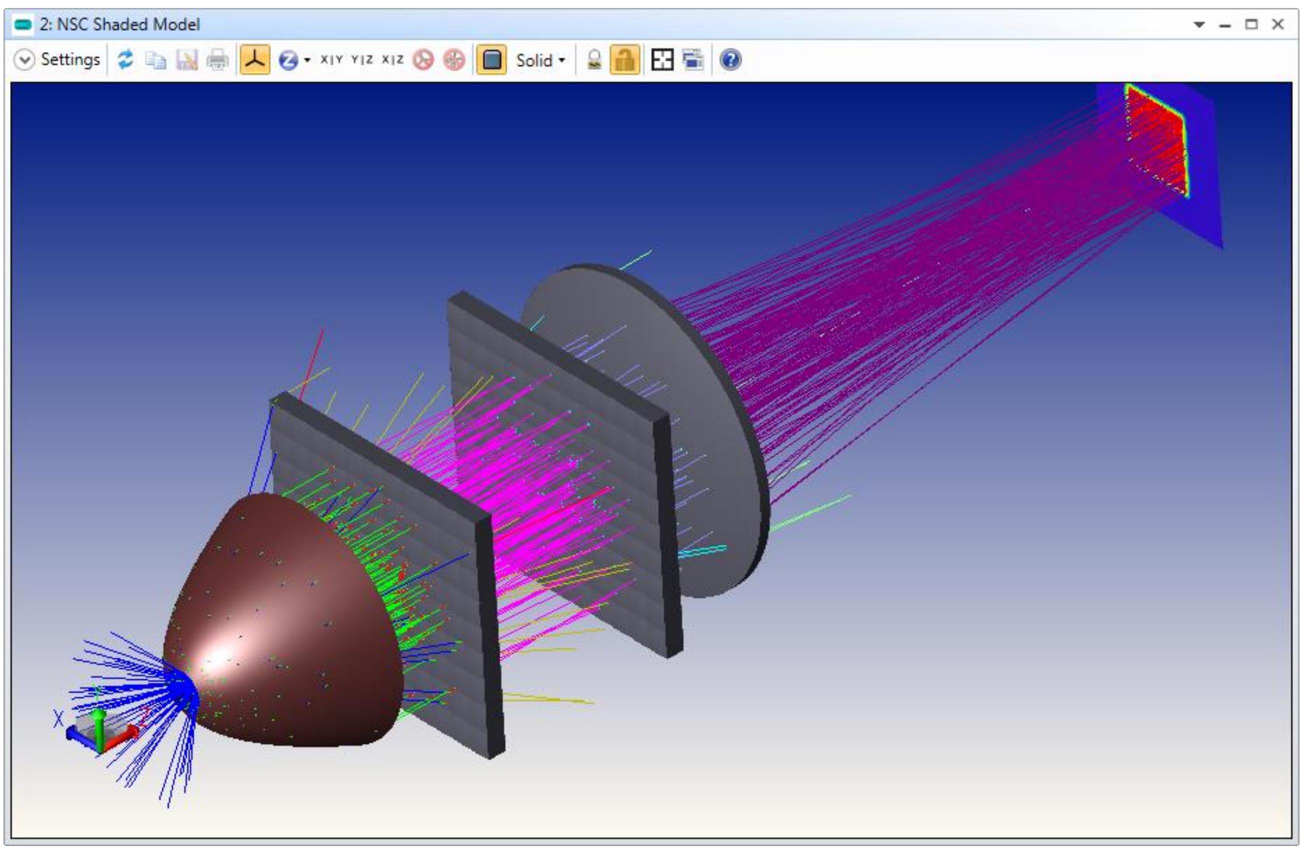
Because rays can be split into transmitted, reflected and scattered components, as each ray splits it contains less and less energy. We need to put some limits on the ray-tracing to prevent OpticStudio from tracing rays with insignificant amounts of energy. This is defined in the System Explorer, in the Non-Sequential grouping:



Try varying this parameter and observe how it affects the number of child rays produced. Set it to 10^{-2} and note you get fewer rays; at 10^{-12} you will get many more.

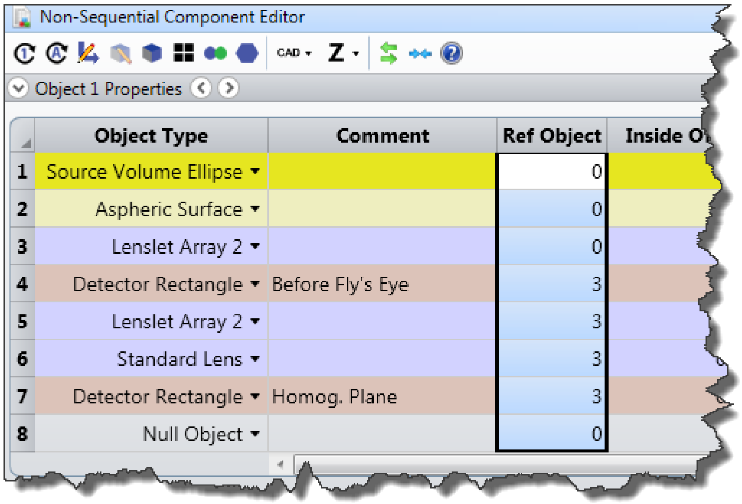
Tutorial 6.2: Object Positioning & Definition

The Non-Sequential Component Editor provides an easy way to define the non-sequential optical system, and the inter-relationships between components. Open the sample file in the Samples\Non-sequential\Miscellaneous folder called “Digital Projector Flys Eye Homogenizer.zmx”. The system contains an elliptical source volume that approximates the shape of the fireball in an arc lamp inside a parabolic mirror. The output light enters a homogenizing optical system that consists of two fly’s eye lenslet arrays and a field lens. The homogenizer is manufactured as a complete sub-system which is then placed into the optical beam produced by the source and parabolic mirror.



Object Positioning

Note how the objects are referenced:


Non-Sequential Component Editor

Object 1 Properties

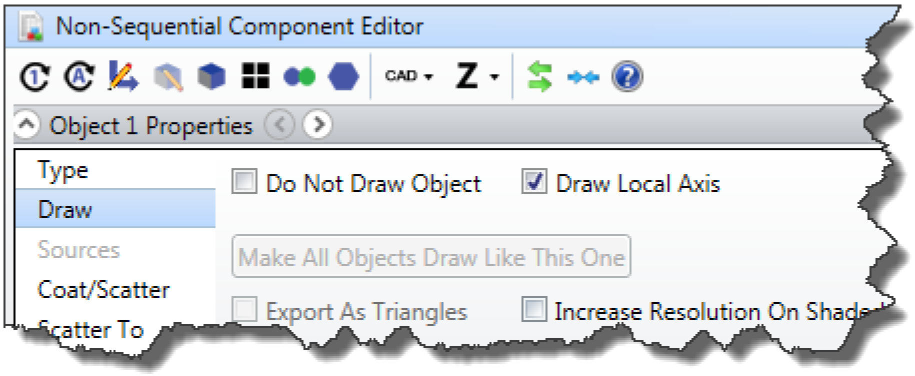
	Object Type	Comment	Ref Object	Inside O
1	Source Volume Ellipse		0	
2	Aspheric Surface		0	
3	Lenslet Array 2		0	
4	Detector Rectangle	Before Fly's Eye	3	
5	Lenslet Array 2		3	
6	Standard Lens		3	
7	Detector Rectangle	Homog. Plane	3	
8	Null Object		0	

Every object has a number, shown in the left-most column of the editor, and a 'Reference Object'. Ref Object 0 is the global coordinate reference point of the whole 3D space, and objects 1, 2 and 3 are positioned relative to this coordinate system. Objects 4, 5, 6, and 7 are positioned relative to object 3, and they therefore are positioned like a sub-assembly: try moving object 3, and notice that objects 4-7 automatically move as well. So the position of object 3 defines the position of the homogenizer assembly.

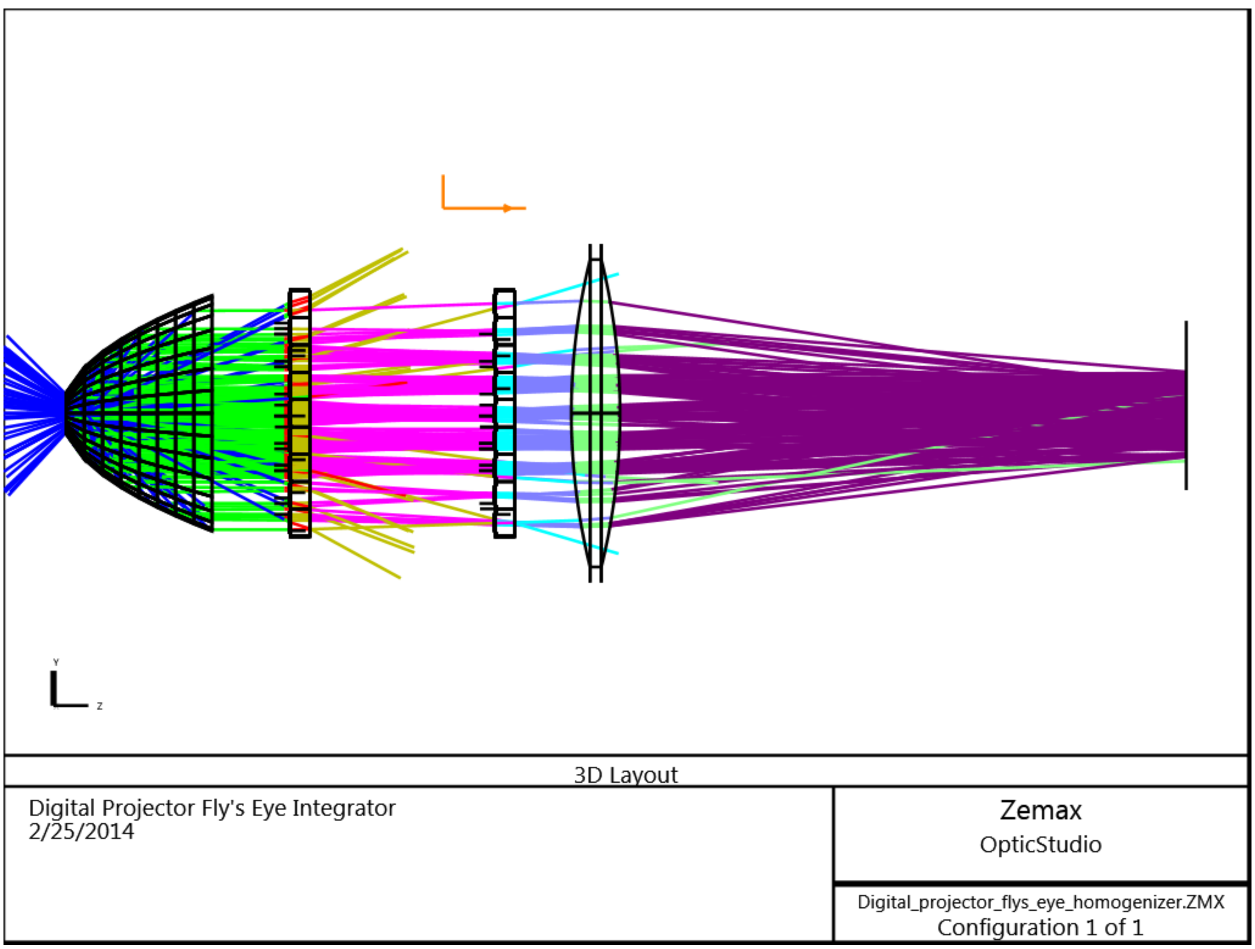
Note: Any object can be positioned relative to any prior-defined object, which can be positioned relative to any other object defined prior to it, etc.

Imagine we now want to move the homogenizer about some arbitrary point. Click anywhere on object 1, and press the Insert key, so that you now have a 'Null Object' as object 1, and all other object numbers have automatically incremented. The Lenslet Array object that serves as the reference for the homogenizer assembly is therefore now object 4.

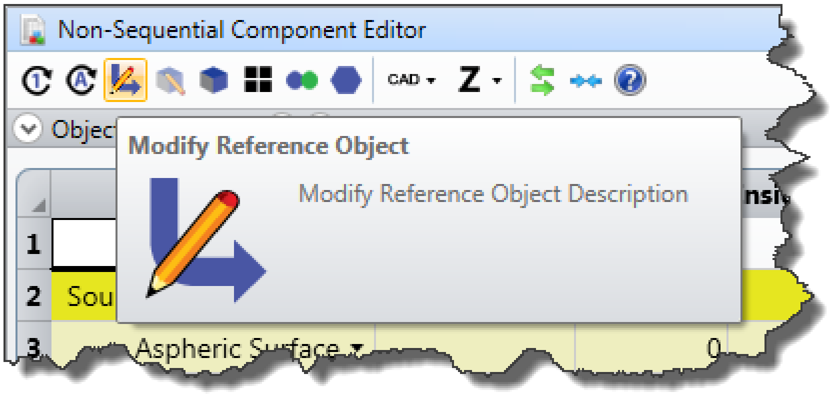
Null objects have no optical properties, and so they are useful for defining reference and pivot points, for example. Position the null object at y = 40, z = 70, and then double-click on the object type to show the object properties tab:



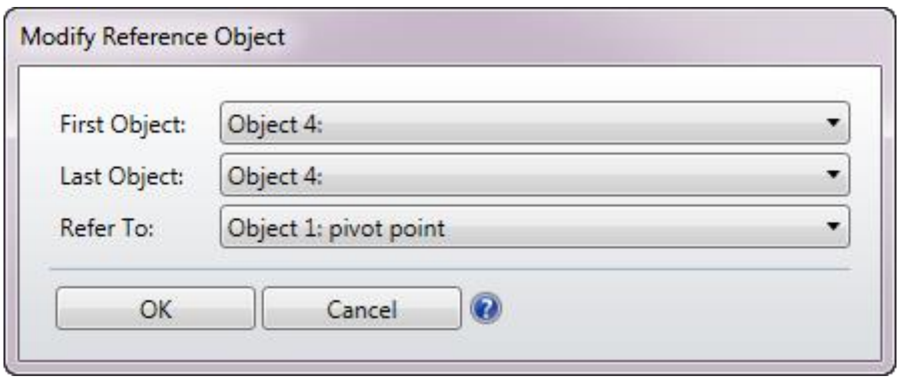
On the Draw tab, check the 'Draw Local Axis' control. On the NSC 3D Layout, the Null object's local axes are now drawn (note that local axes are never drawn in the Shaded Model).



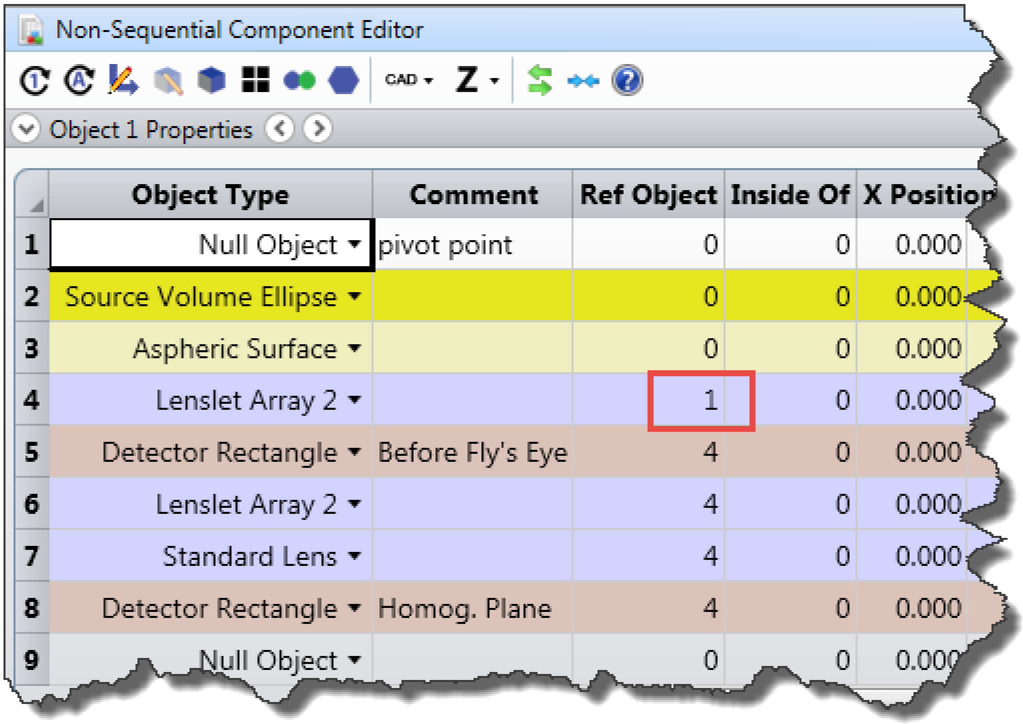
On the Non-Sequential Component Editor's toolbar, choose the Modify Reference Object tool:



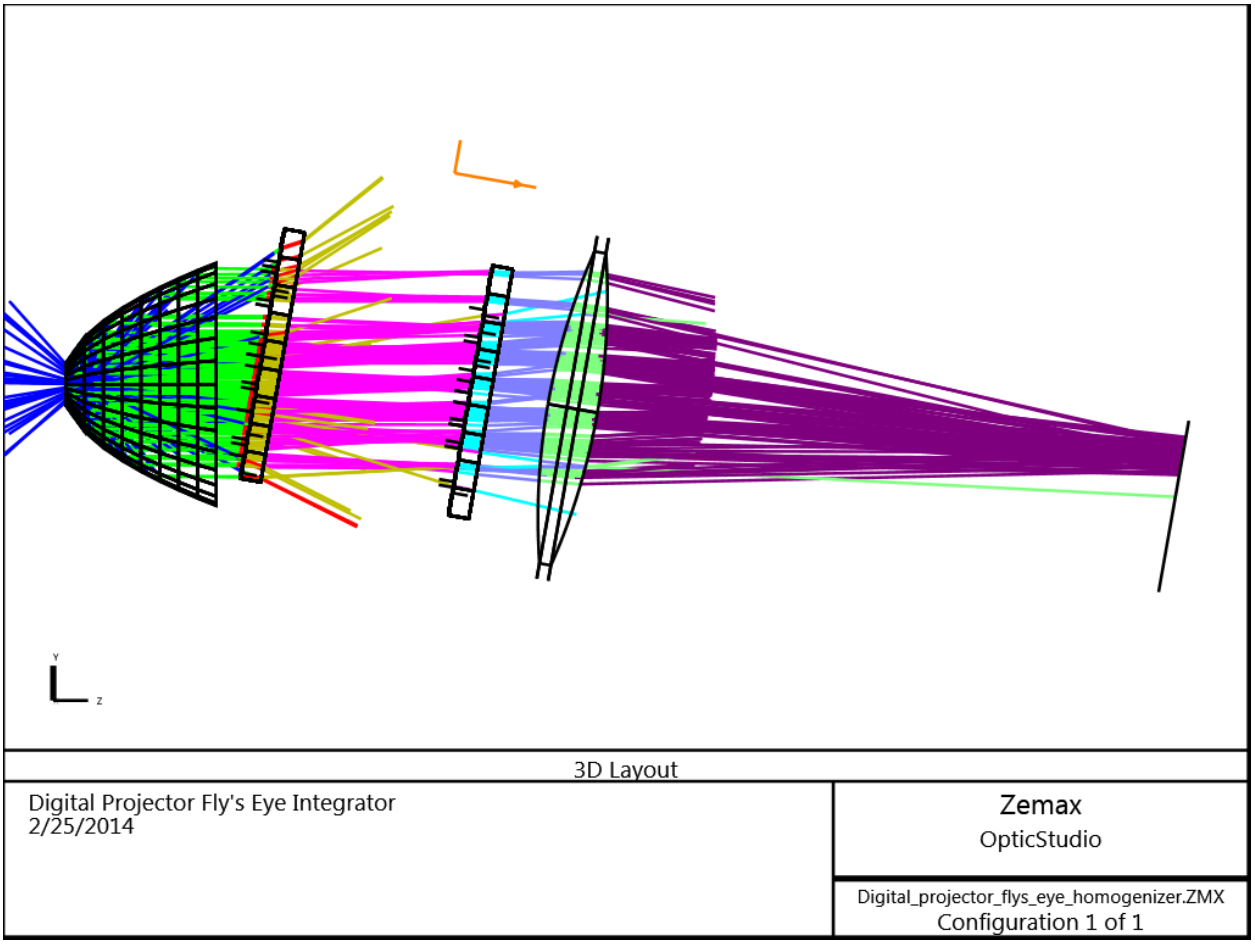
And set it like so:



OpticStudio will now modify object 4's properties so that it is positioned relative to object 1, while retaining its absolute position and orientation in global coordinates. In other words, object 4 has not moved, but its position is now defined relative to a different object. The subsequent objects are still positioned relative to object 4:

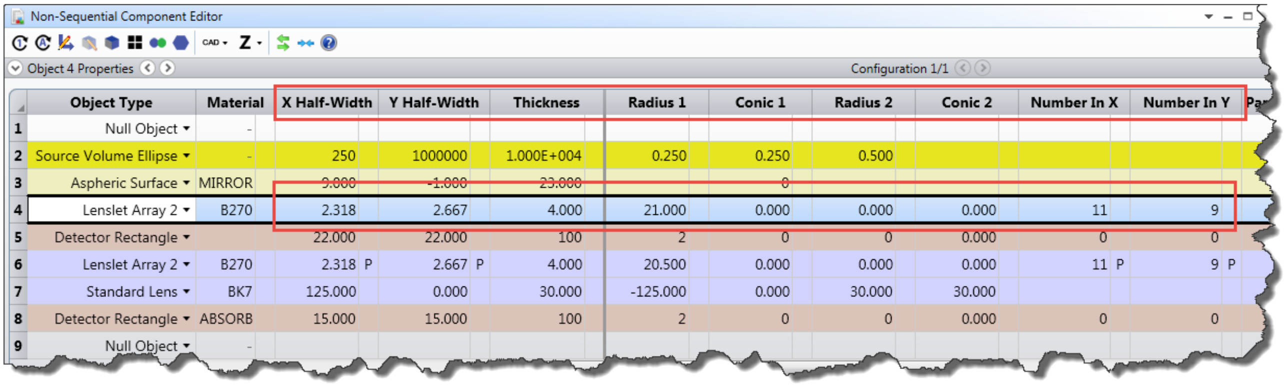


If you now apply a Tilt About X of 10 degrees to object 1, you will see that the whole homogenizer assembly pivots about object 1, but the lamp assembly remains in place:



Object Parameters

As well as being positioned, objects are given their defining parameters in the NSC Editor. For example, the Lenslet 2 object is defined by parameters like x and y halfwidths, thickness, radii of curvature and conic constant, and numbers of lenslets in x and y.



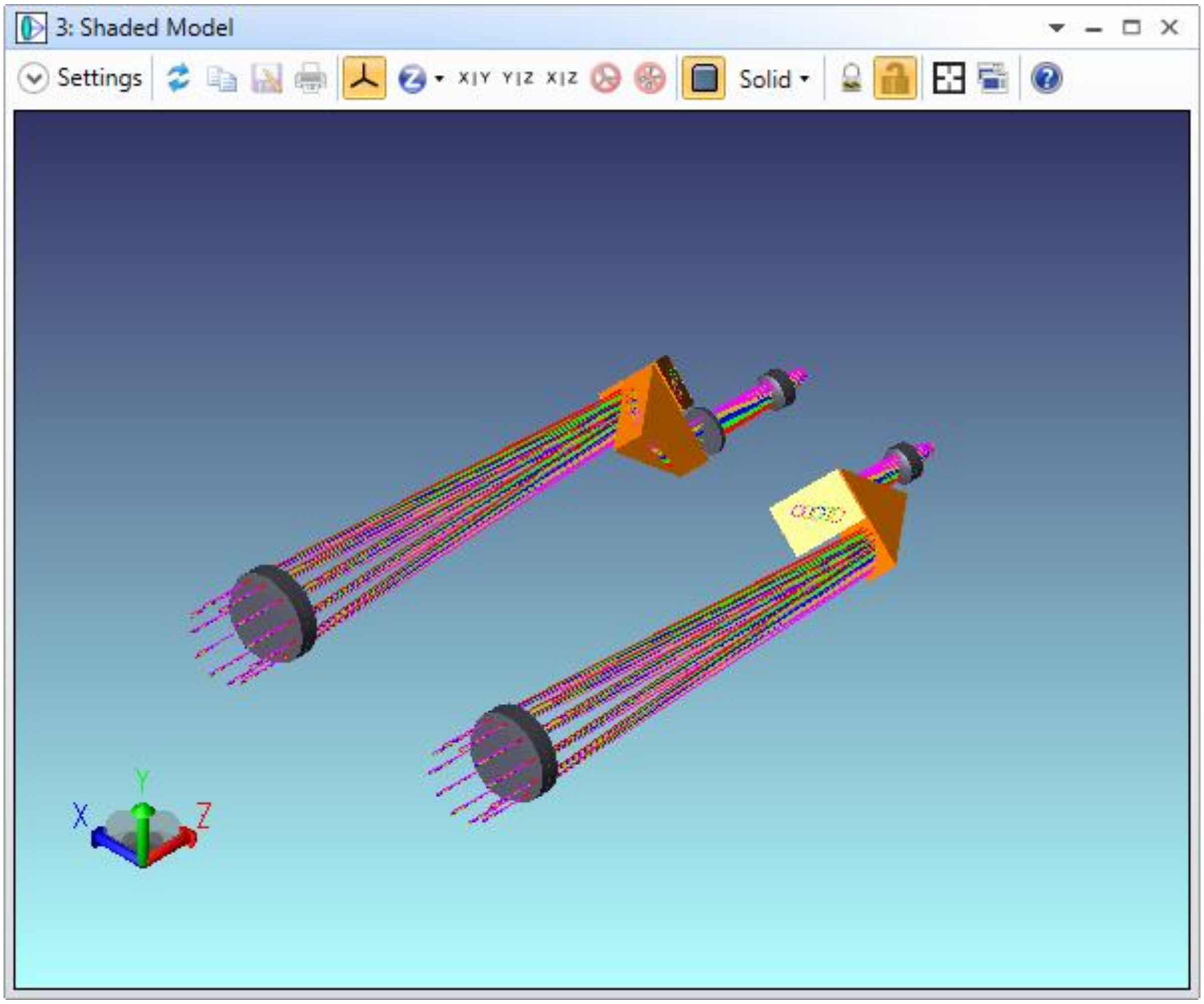
	Object Type	Material	X Half-Width	Y Half-Width	Thickness	Radius 1	Conic 1	Radius 2	Conic 2	Number In X	Number In Y
1	Null Object	-									
2	Source Volume Ellipse	-	250	1000000	1.000E+004	0.250	0.250	0.500			
3	Aspheric Surface	MIRROR	9.000	-1.000	23.000		0				
4	Lenslet Array 2	B270	2.318	2.667	4.000	21.000	0.000	0.000	0.000	11	9
5	Detector Rectangle		22.000	22.000	100	2	0	0	0.000	0	0
6	Lenslet Array 2	B270	2.318 P	2.667 P	4.000	20.500	0.000	0.000	0.000	11 P	9 P
7	Standard Lens	BK7	125.000	0.000	30.000	-125.000	0.000	30.000	30.000		
8	Detector Rectangle	ABSORB	15.000	15.000	100	2	0	0	0.000	0	0
9	Null Object	-									

There is a great advantage to this parametric approach. Parametric objects require relatively little memory, are fast to ray-trace, and can be changed easily. They are also optimizable, just like sequential surfaces.
Further, interrelationships between objects can be easily defined via pickup solves. Note that the second lenslet object uses pickups on several parameters to lock itself to the first lenslet object (Note the letter P on some of the defining properties of this lens, which denotes a pickup solve). This is a great advantage during optimization, as changes to one parameter can automatically flow through the whole system.

Tutorial 6.3: Combining Sequential and Non-Sequential Ray-Tracing

Most imaging systems are well described by the orderly sequential approach used in the Lens Data Editor. However, there are cases where an otherwise sequential system has some region in which there is a need for non-sequential ray-tracing. Prism assemblies are a classic example, in which different parts of the beam interact with different faces of the prism(s) in a different order to other parts of the beam.

For example in Samples\Sequential\Afocal\Binocular_System.ZMX:

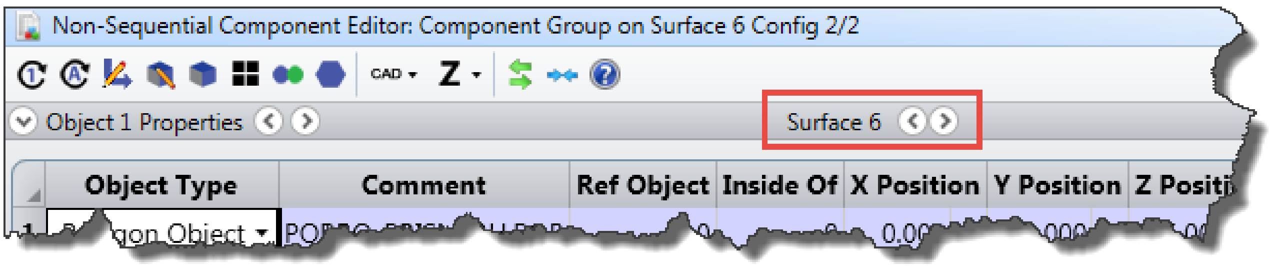


We have a classic sequential doublet objective and a Kellner eyepiece, just like any other sequential system. Note that a special sequential surface type called a **Non-Sequential Component** is used between the lens and eyepiece. This acts like the 'entry port' into the non-sequential world defined in the non-sequential component editor.
The parameters on the Non-Sequential Component surface in the Lens Data Editor define the location of the 'exit port', which is how rays come back to the sequential ray tracer. This is referred to as 'hybrid' or 'mixed' Sequential\Non-sequential ray tracing.

When a sequential ray hits the Non-Sequential Component surface in the Lens Data Editor, it is passed to the non-sequential ray-tracer and it interacts with whatever objects are defined in the NSC Editor and are in the ray's path. When the ray hits the region defined by the exit port in the Lens Data Editor, it is transferred back to the sequential ray-tracer and interacts with the subsequent sequential surfaces.

Note: Sequential rays cannot split inside the non-sequential group.

A sequential system can contain any number of Non-Sequential Component surfaces. The objects 'inside' each Non-Sequential Component group are independent of each other. You can easily switch between non-sequential component groups by clicking the Surface in the NSCE menu bar. This surface corresponds to the surface number of the NSC group in the Lens Data Editor, and is only shown if there is more than one NSC group inside the Lens data Editor.



If a ray does not hit the exit port, it is terminated and it does not return to the sequential ray-trace.

Note: If the marginal and chief rays are not traceable through NS groups, OpticStudio cannot compute important sequential parameters like pupil positions and f/#.

Tutorial 6.4: Tracing Rays and Getting Data

Ray tracing in hybrid non-sequential mode works exactly as it does in sequential mode, except that there is no paraxial ray-tracing inside an NS group. In pure non-sequential we use source objects to launch rays and detector objects to get quantitative information.

Source Objects

Source objects are objects that launch rays into the optical system with the appropriate spatial and angular distributions to represent the radiance of the real sources in your system.

Source objects fall into two categories:

- Parametric sources, like the Source Diode or Source Filament, in which the source radiance is computed from some equation, and you enter the parameters for this equation via the editor.
- Measured sources, like the Source IESNA, Source EULUMDAT, and Source File. Note that IESNA and EULUMDAT data files contain only far-field (angular) data and model the source as a spatial point. The .DAT and .SDF formats, used by the Source file object, contain both spatial and angular ray data, and so define the full radiance of the source. Data in these formats are provided free by many LED and lamp manufacturers, and can also be exported by third party programs like Radiant Zemax' ProSource and Opsira's Luca Raymaker. The .DAT and .SDF formats are documented in the Users' manual in both ASCII and binary formats. The difference between the two formats is that the .SDF format contains spectral (wavelength) data, whereas the .DAT format does not.

Source wavelengths are defined in the System Explorer Wavelength group, just like sequential systems, although other definitions are also available, and will be discussed later in the section on Colorimetry. Source Units (Watts or Lumens) are chosen under the System Explorer Units group.

Sources are positioned in global coordinates in exactly the same way as any other object. All sources use parameters 1-5 of the Non-Sequential Component Editor to define some basic information about the source. These are:

- # Layout Rays: Defines how many random rays to launch from the source when creating layout plots. This is typically a small number, say less than 100, and is used only for drawing purposes.
- # Analysis Rays: Defines how many random rays to launch from the source when performing analysis. This is typically a much larger number and may be millions or even billions of rays.
- Power (units): Power is the total power over the defined range of the source. The power units are specified by the system source units in the System Explorer.
- Wavenumber: The wavenumber to use when tracing random rays. Zero means polychromatic, which chooses ray wavelengths randomly with the weighting defined on the wavelength data editor.
- Color #: The pen color to use when drawing rays from this source. If zero, the default color will be chosen. The RGB values of each pen are defined under Project Preferences.

Parametric sources will then use further parameters to define their radiance.

Source objects are not made of any material. Rays, once launched, have no further interaction with source objects. Rays are normally launched into air, but can be launched inside some other refractive index if desired. Define a geometry object with the correct shape and refractive index first and then locate the source object inside it, and then use the "Inside Of" parameter to tell OpticStudio to launch the rays inside that object's refractive index.

Note: Source objects must use the Inside of parameter when the source is placed inside a geometry object, otherwise incorrect ray-tracing will result.

Detector Objects

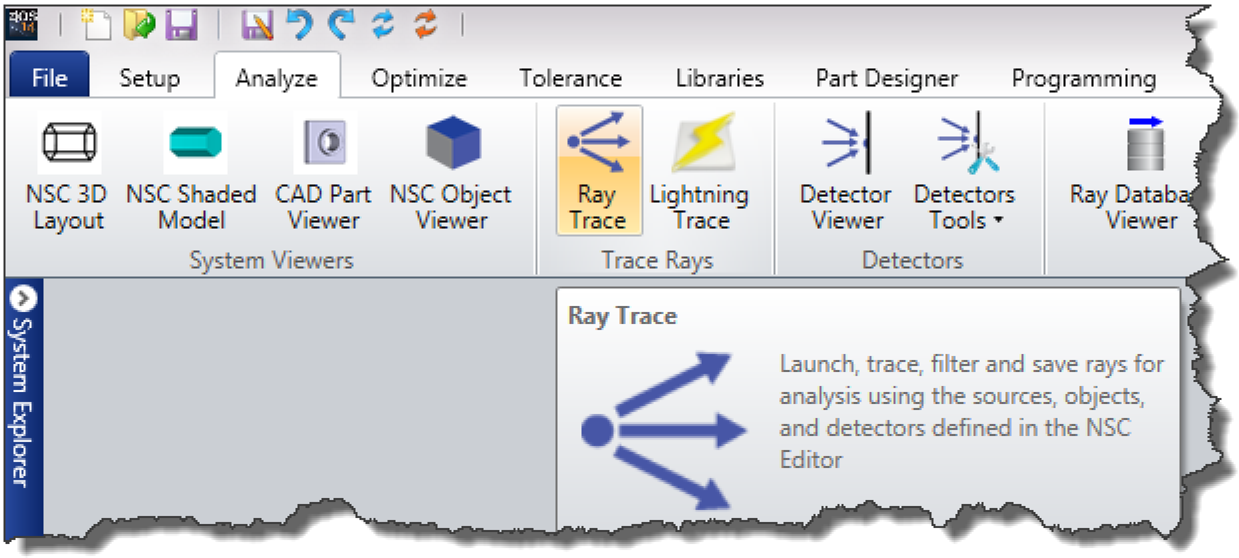
Rays are detected by Detector objects. Almost any kind of geometry object can be used as a detector also, but the dedicated Detector objects are designed for the task of displaying spatial and angular data and provide the controls users need to represent data the way it is measured experimentally.

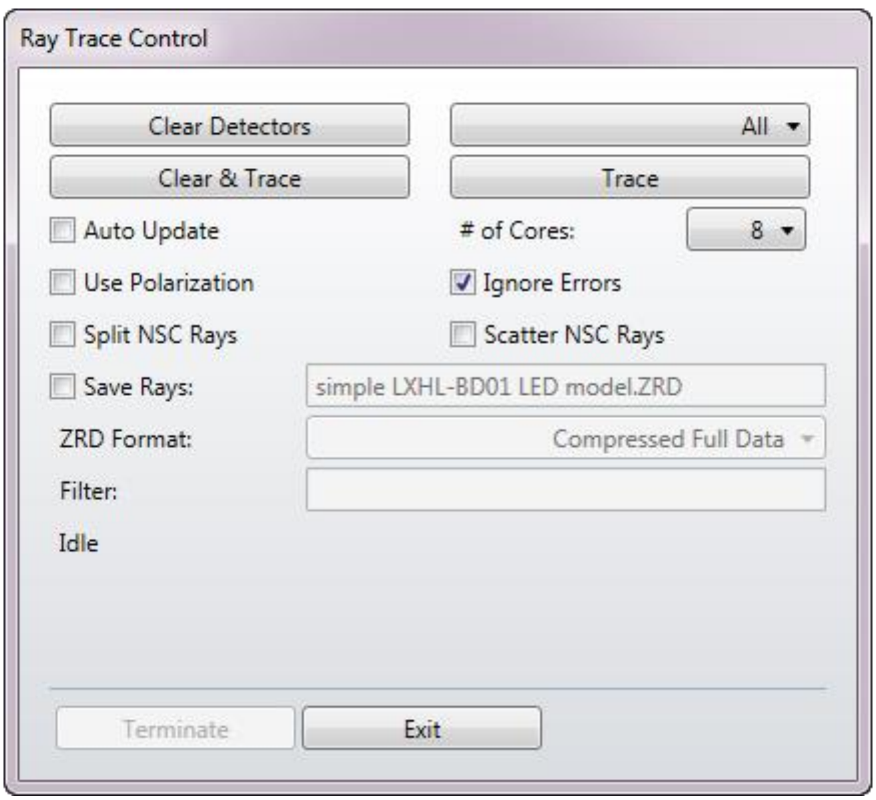
The most common type of detector object is the Detector Rectangle. This is a two-dimensional array of pixels, similar to a CCD array. It is most commonly used with the material ABSORB, so that rays terminate upon being detected, but it can also be set as a MIRROR (with coating, if required, to be discussed later), or its material may be left blank to indicate air. Note that when the material is left blank, rays are not perturbed in any way by being detected. This can be useful, but care must be taken as the detector may appear to not conserve energy if a ray interacts with it multiple times without losing any energy!

Tracing Analysis Rays

Open the sample file Samples\Non-sequential\Sources\Simple LXHL-BD01 LED model.ZMX. This file contains just two objects, a Source Radial set with data taken from the LumiLeds LXHL-BD01 LED datasheet, and a Detector Rectangle set to 100 by 100 pixels.

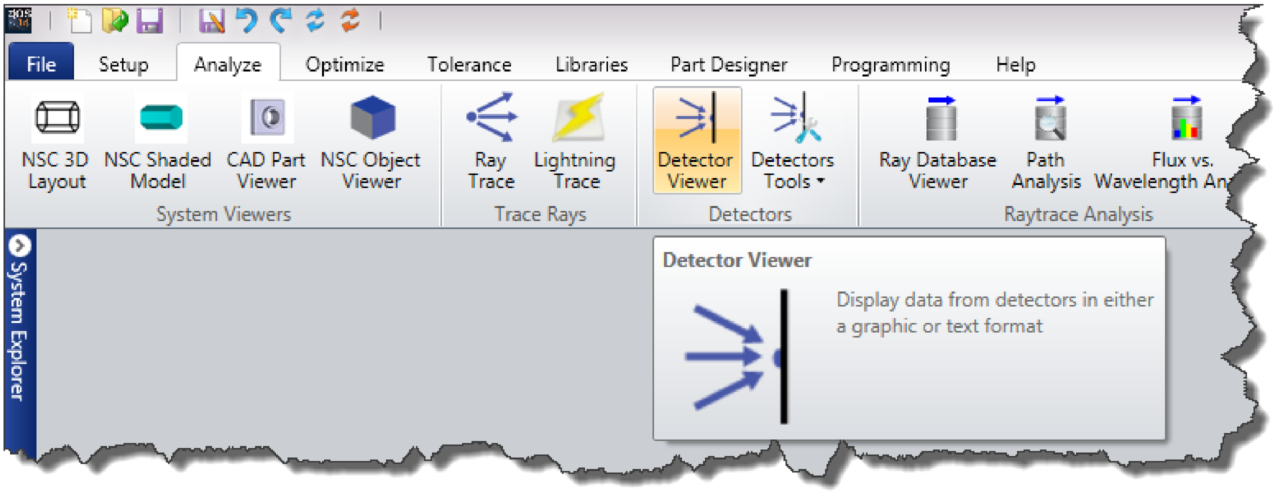
Note that the source object has a total power of 27 Lumens, uses 30 layout rays for drawing purposes, and uses 1 million Analysis rays. In the Analyze tab, click the Ray Trace icon:



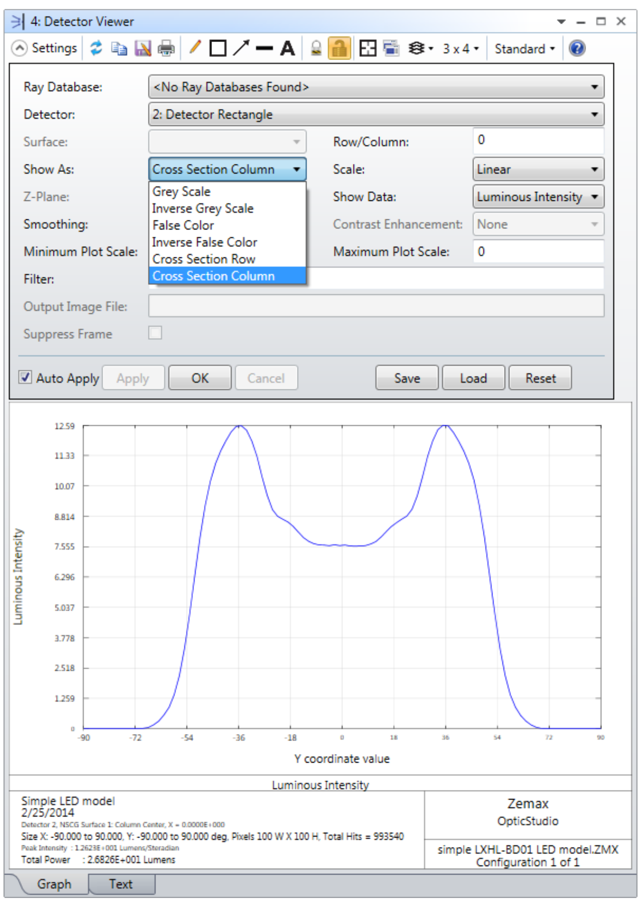


Click Clear and Trace to trace the million Analysis rays, then click Exit. If you have more than one CPU in your computer, the calculation will be automatically split up over all available CPUs.

Click on Analyze...Detector Viewer to see the data inside the Detector.



The Settings dialog for the Detector Viewer is very powerful, and allows you to select incoherent illuminance, Luminous intensity, coherent illuminance and phase (not meaningful in this case) and luminance. Multiple Detector Viewer windows can be open simultaneously to display multiple views of the same data.

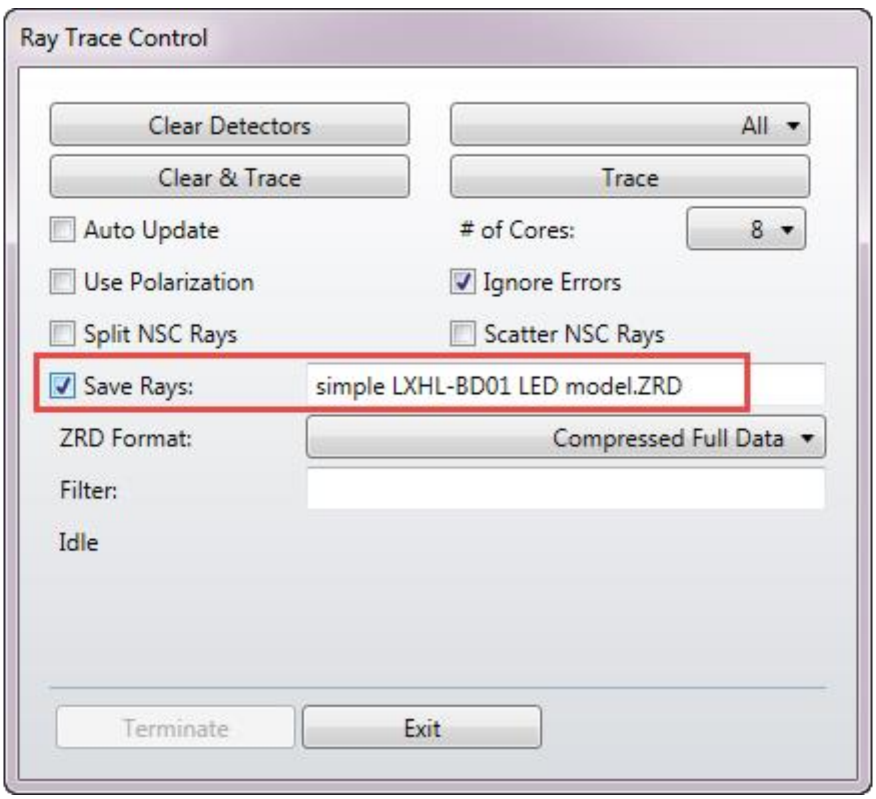


You can also show the data in false color, grey scale or look at cross-sections through the data using the 'Show As' control. When using cross-section views, row or column 0 always means the central row/column. Data can be scaled linearly or logarithmically.

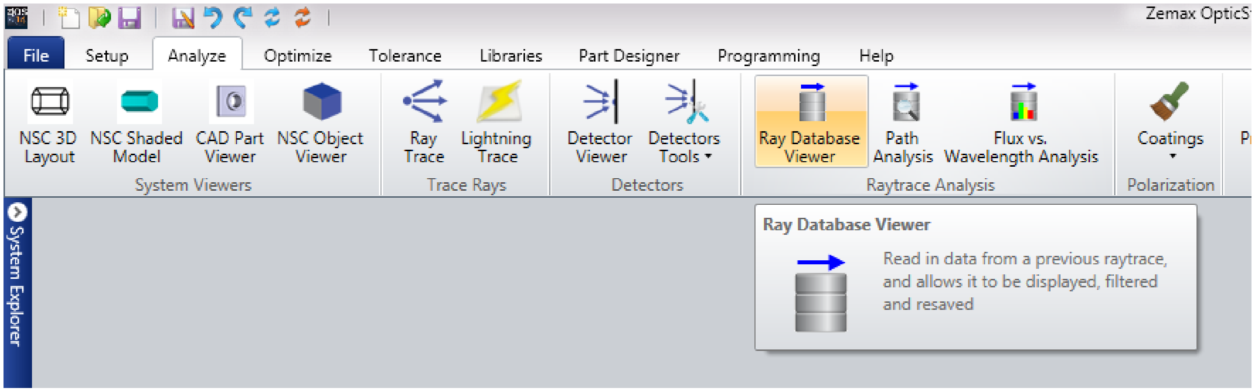
The data can also be smoothed by averaging the data in each pixel and its neighboring pixels. The operation can be repeated the number of times specified by the smoothing parameter. This improves signal/noise at the expense of spatial or angular resolution.

Ray Databases

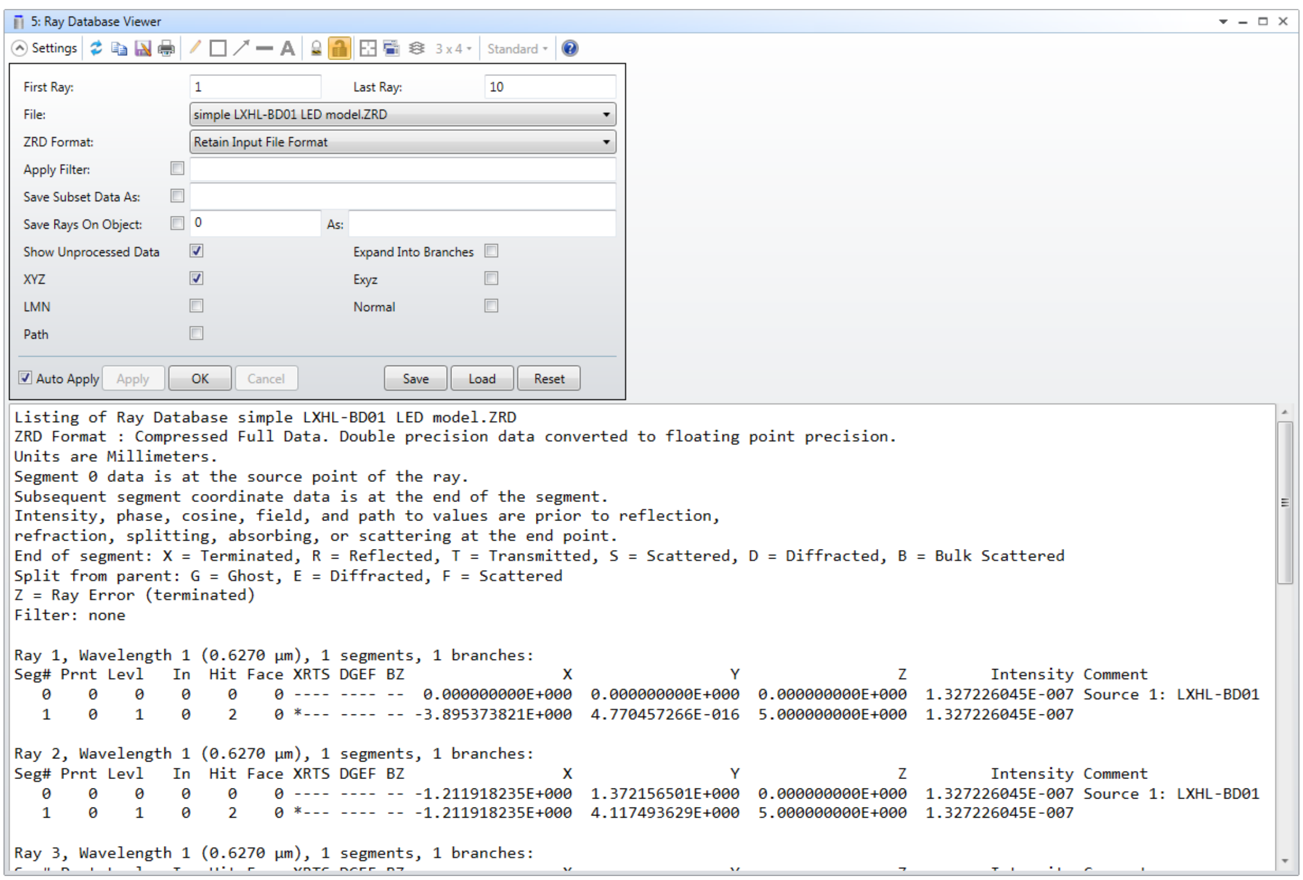
The Detector Viewers are very useful, but sometimes you will want access to the ray data directly. Repeat the ray trace (press the Rtc button) and select 'Save Rays'



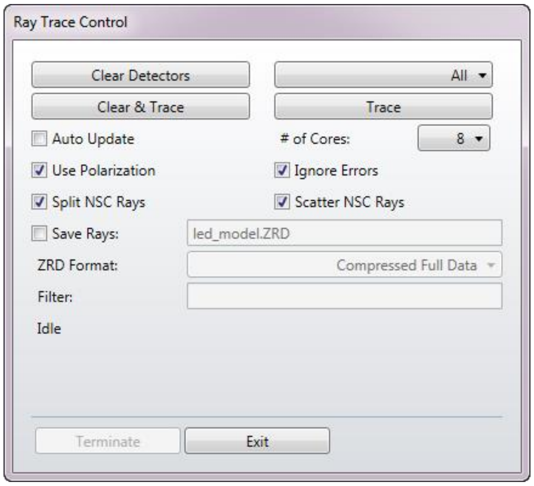
Note that the ray-trace takes a little longer now because of the time taken to write one million ray-histories out to disk. Then press Analyze…Ray Database Viewer:



The Ray Database Viewer shows the history of every ray traced. The intensity position, direction cosines, normals, path length and polarization data of every ray can be shown, although only intensity is shown here. The ray is broken down into segments, where each segment is a single ray-object intersection. Segment 0 is the ray data at the source. Various parameters XRTS etc. show what happened at the end of the segment (X= terminated, R= reflected, etc.). This example is very simple in that rays are launched, traced once and terminated:



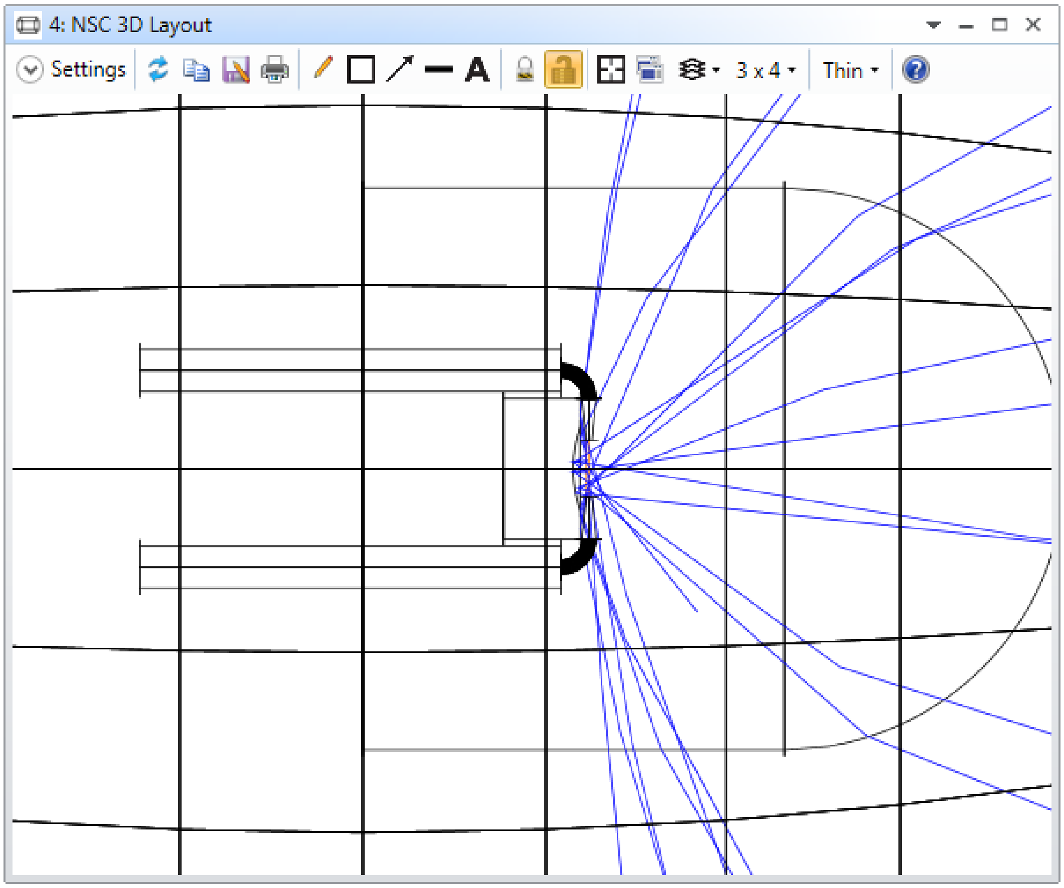
In a more realistic system, there are many more segments, of course. Load the sample file led_model.zmx (in the same folder as the file we are currently using), trace Analysis rays using these settings:



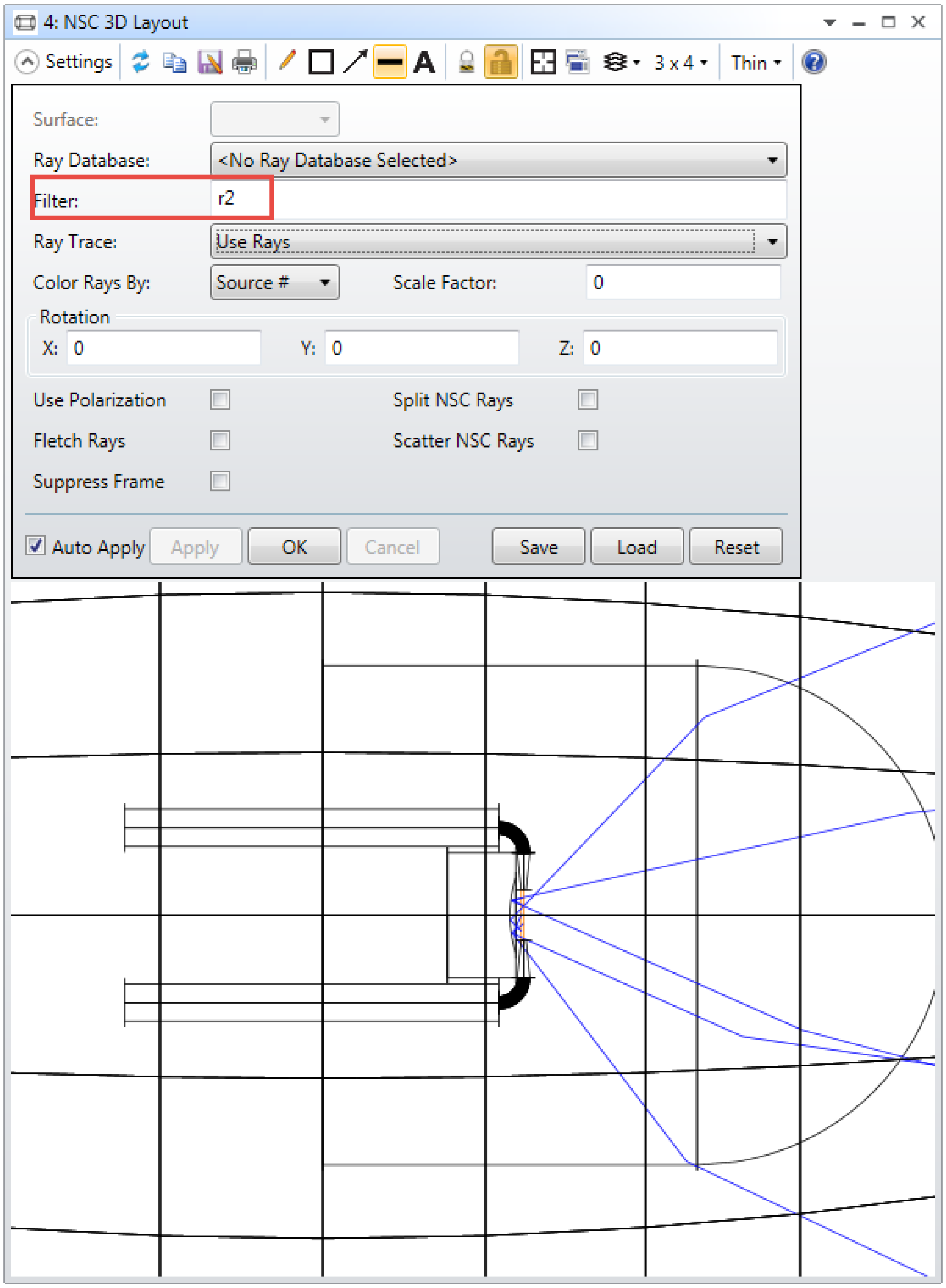
Use the Ray Database Viewer to view the ray histories. Note that as ray splitting is on, you can use the option 'expand into branches' to identify each child ray separately.

Filter Strings

Because OpticStudio knows the history of every ray it has traced, we can use filter strings to identify rays that meet specific conditions easily. For example, in the led model.zmx file, object 2 is a reflector behind the source. Some rays are fired forwards, and never see this mirror, while others move in the opposite direction, hit the reflector, and then travel forwards:



Using the filter string R2 means that only rays that reflect from object 2 will be shown:



!R2 will show those rays that do NOT reflect from object 2, i.e. rays that propagate forwards initially. You can AND, OR, NOT, XOR, etc., multiple filters to produce a filter string that identifies exactly the conditions you want to investigate. For example, to select rays that must have either a) hit object 7 and object 9, but did not reflect off object 6, OR b) missed object 2, the filter string would be `(H7 & H9 & !R6) | M2.`

Filter strings are your most important tool for detailed system analysis. They can also be used with ray databases, both prior to saving the ray-database and with the saved data. For example, in stray-light simulations you may have to trace millions of rays to get one that finds its way to the detector. By saving to disk only those rays that hit the detector, you can produce a manageable data set for further study.

You can replay ray databases through the ray-database viewer, the layout plots, and the detector viewers, and add further filters to the filtered data. The ray database viewer will also let you filter a ray database and save the sub-set data into a new file.

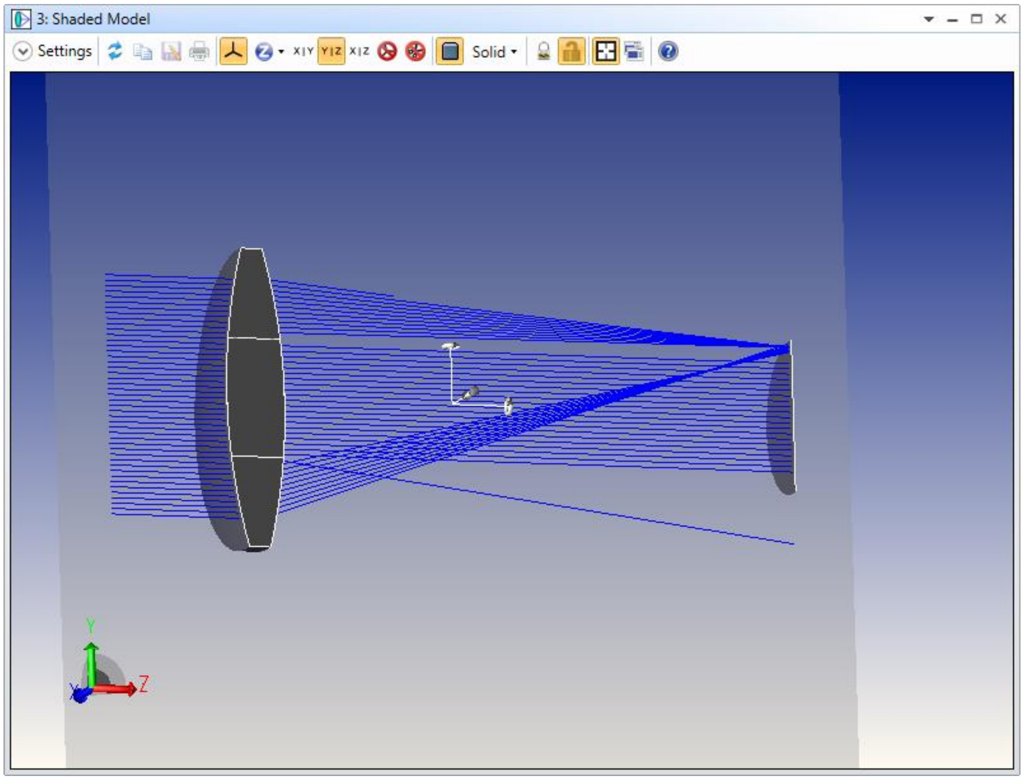
Tutorial 6.5: Complex Object Creation

No matter how many objects we add to OpticStudio, you may still sometimes need an object that is not directly available. There are, however, ways to manipulate existing objects so as to create precisely what you need.

The Overlapping Objects Rule

When two or more objects occupy the same region of space, a simple rule applies. The properties of the common region are defined by whichever object is listed last in the Non-Sequential Component Editor.

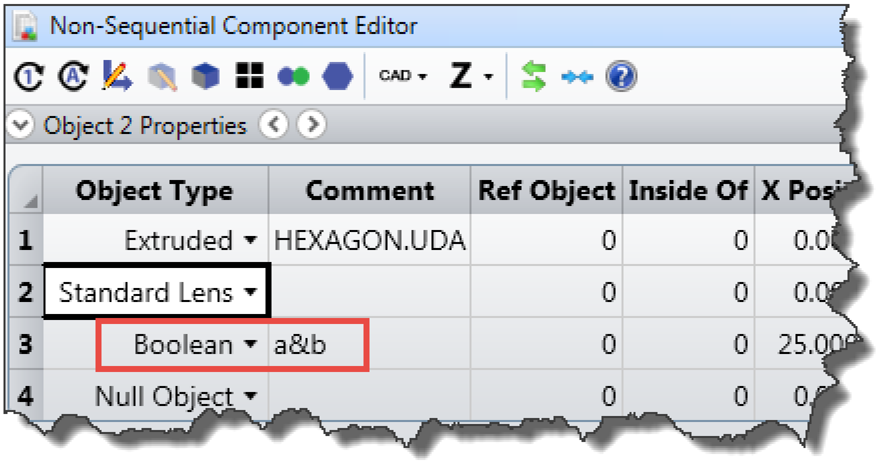
Open the sample file Non-sequential\Diffractives\Diffraction grating lens with hole.zmx. This mixed sequential/non-sequential design shows a lens with diffractive power, and a central region with no diffractive power:

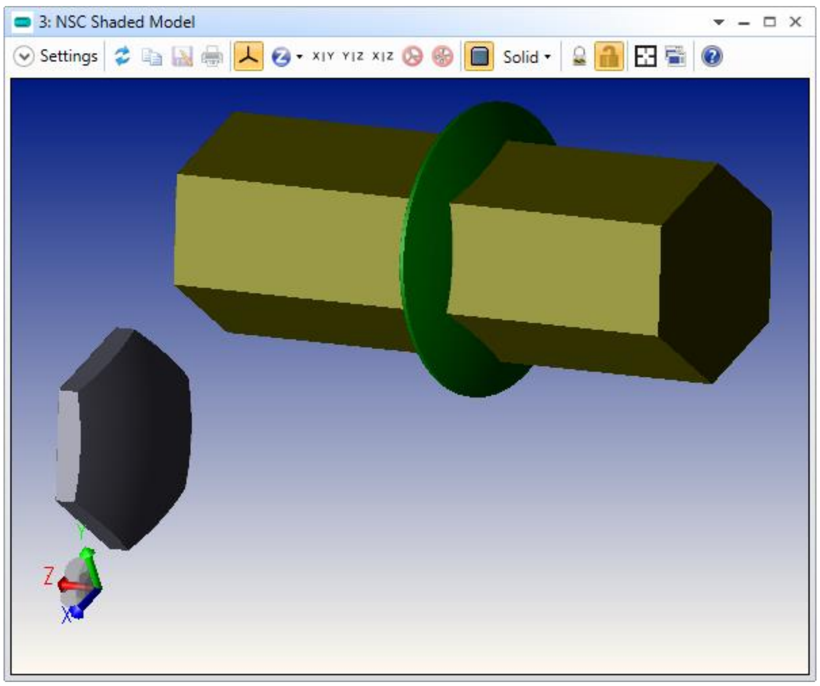


This is easily achieved by placing the non-diffractive element after the diffractive element in the editor, and co-locating them. There is no need to use the 'Inside Of' flag when geometry objects are nested inside each other, unless a source object is inside one of the nested objects. Geometry objects may fully or partially overlap, but source objects must always be entirely inside of any object they are co-located with. The 'Inside of' flag must be used for all nested geometry objects as well as sources in this case.

The Boolean Object

Up to eight objects may be combined in any order by the Boolean object, and Boolean objects may be combined with other objects, including other Boolean objects. For example, the sample file Samples\Non-sequential\Geometry Creation\Boolean Example 2- a lens with a hexagonal edge.ZMX shows how a hexagonal lens can be formed by the Boolean intersection of a lens and a hexagonal bar:

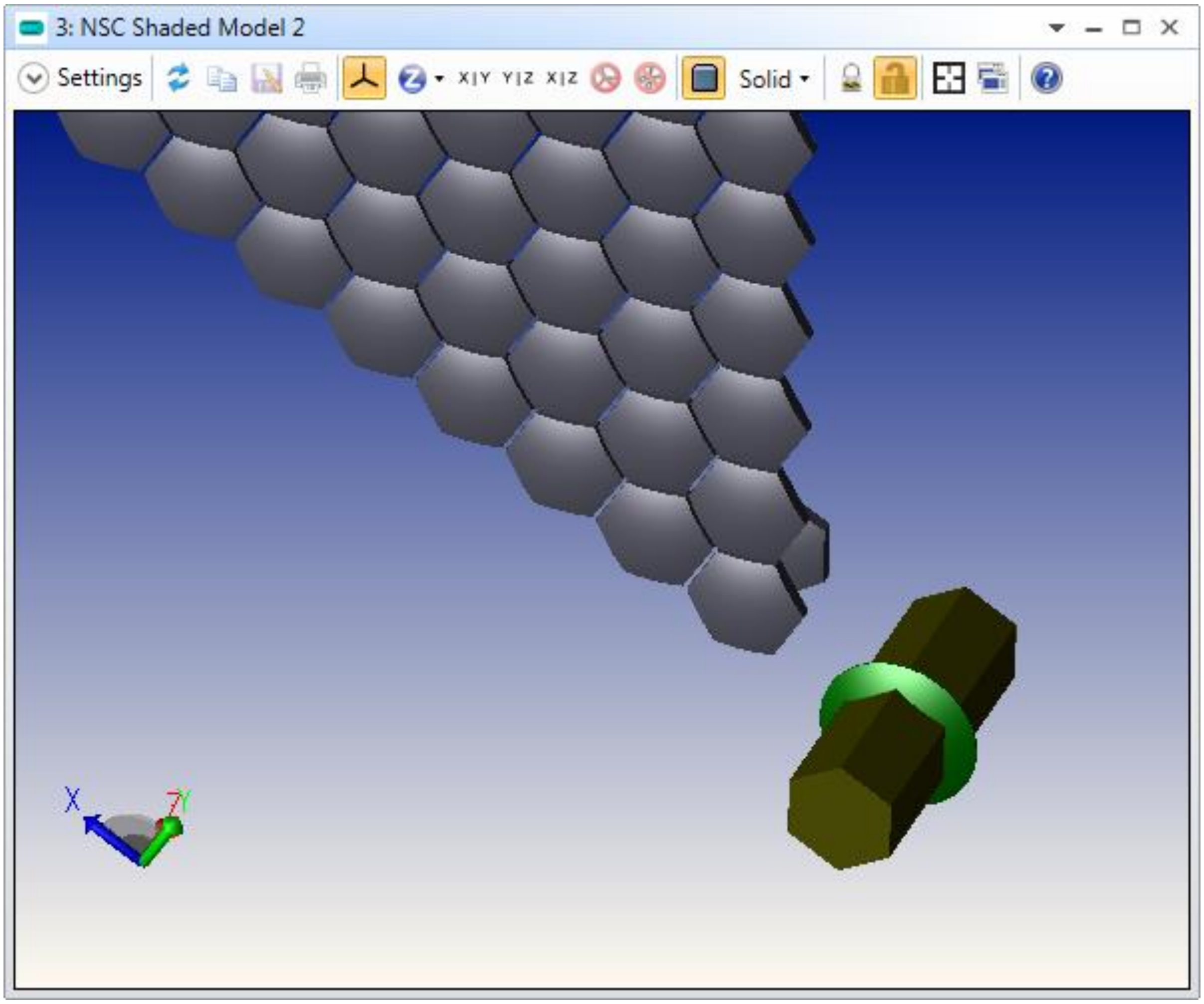




See any of the sample files in Non-sequential\Geometry Creation for further examples.

The Array Object

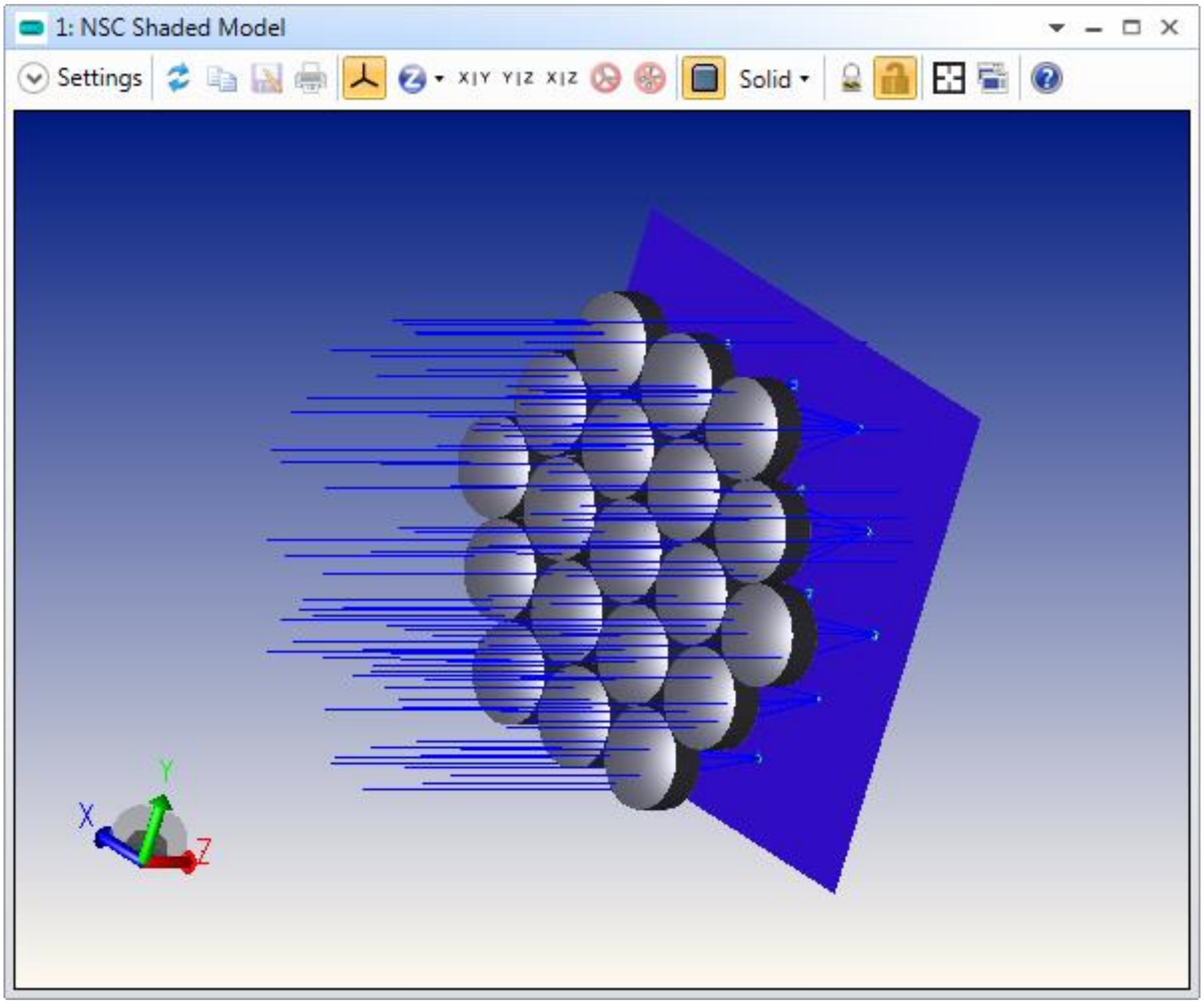
The Array object allows you to make one, two or three-dimensional arrays of any object, for example an array of Boolean objects (Samples\Non-sequential\Geometry Creation\Array Example 3-an array of Boolean objects.ZMX)



Using the Array object is highly recommended over the alternative method of multiple object definitions for several reasons:

- It uses much less memory than the equivalent number of individual objects: typically only slightly more than one instance of the parent object
- It employs sophisticated ray-trace acceleration techniques to trace orders of magnitude faster than the equivalent number of individual objects
- It is less error-prone than entering multiple objects, and only one object needs to be updated or optimized to update or optimize the whole array

The Array Ring can also be used to create circular, hexapolar, and spiral arrays. It has the same advantages as the Array object, outlined above. The sample below is Samples\Non-sequential\Geometry Creation\Ring Array Example 3- Hexapolar Array.ZMX

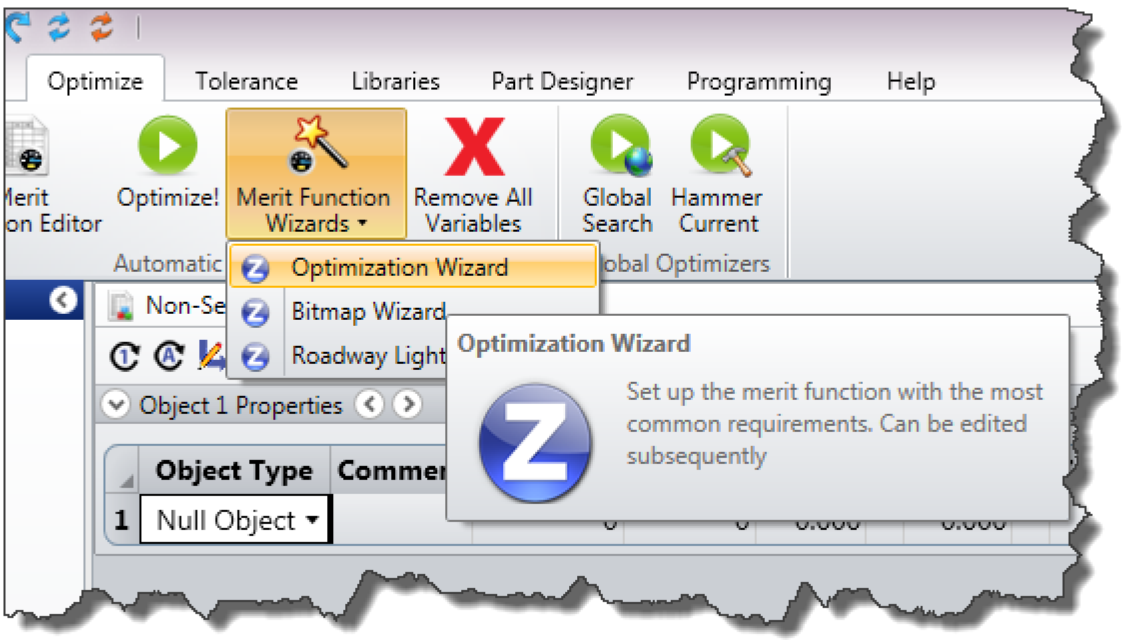


The Source Object

Any geometry object may be used as a source by using the Source object. This is ideal for infra-red and Narcissus analysis, where the emissivity of opto-mechanical components must be accounted for.

Tutorial 7: Optimizing Non-Sequential Systems

Optimization is fully supported in both pure non-sequential and hybrid non-sequential/sequential optical systems. The most common way to optimize a pure non-sequential system is via the Optimization Wizards, which can then be modified with specific requirements. OpticStudio supports three Wizards for non-sequential designs:

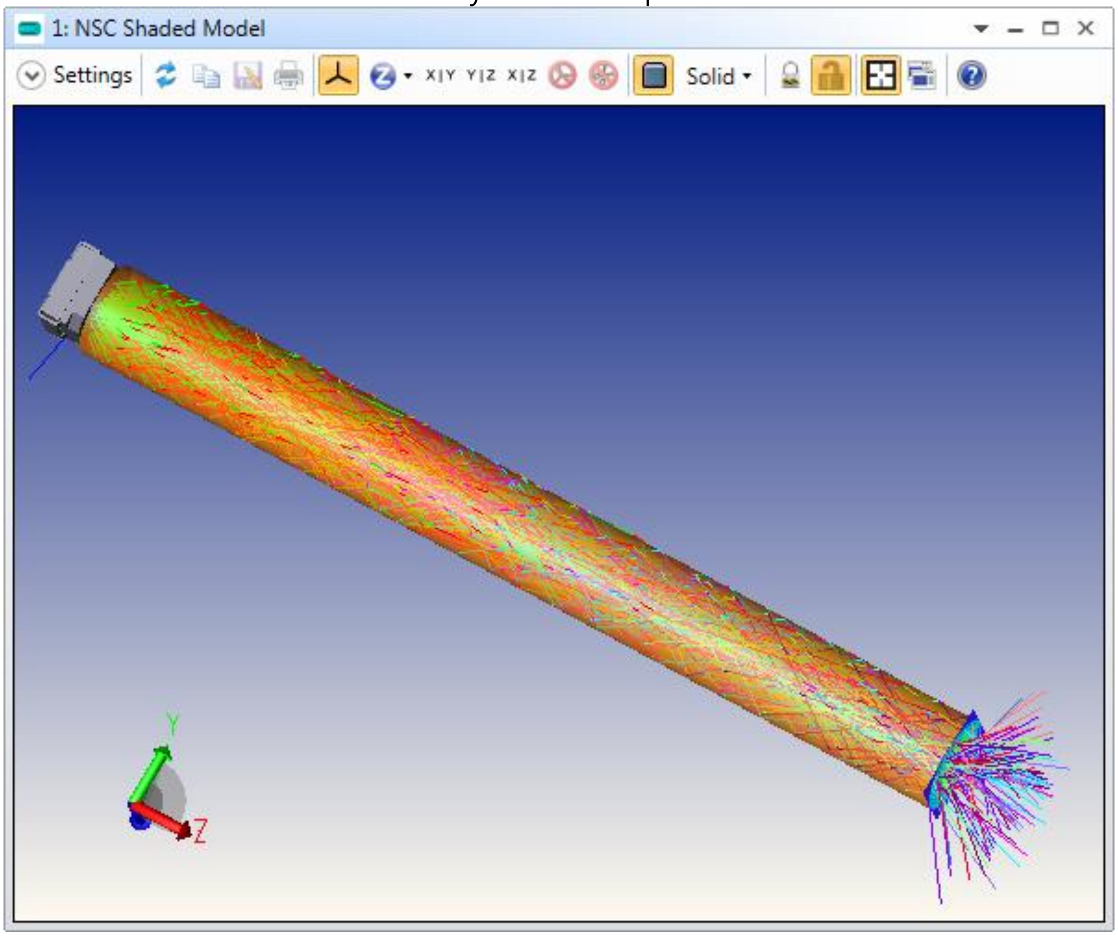


The most common operands used in non-sequential ray tracing are the NSTR and NSDD operands, although other operands are also available. NSTR is used to trace rays, and it acts exactly like the Ray Trace Control dialog.

NSDD is used to clear detectors and to read out detector data. Any pixel can be read out directly, but for optimization it is usually more useful to optimize on aggregate ray data, like centroid location or effective widths in the spatial or angular domains. By using negative pixel numbers in the NSDD operand, OpticStudio will compute data like the average and standard deviation of all pixel data, and spatial or angular centroids and RMS widths.

Open the sample file in the Samples\Non-sequential\Miscellaneous folder called Freeform Optimization.zmx. This file contains a CAD part and source ray file supplied by Osram for their LB_T67c LED. It also contains a lightpipe, the shape of which we wish to optimize.

Note that although the data file for the LED contains 50.7 lm (lumen) of power, we have set the Source power to be 1 lm. This has no effect on the rays traced other than a scaling of intensity, but it makes it easier to discuss efficiency as the total power is now 1 lm.

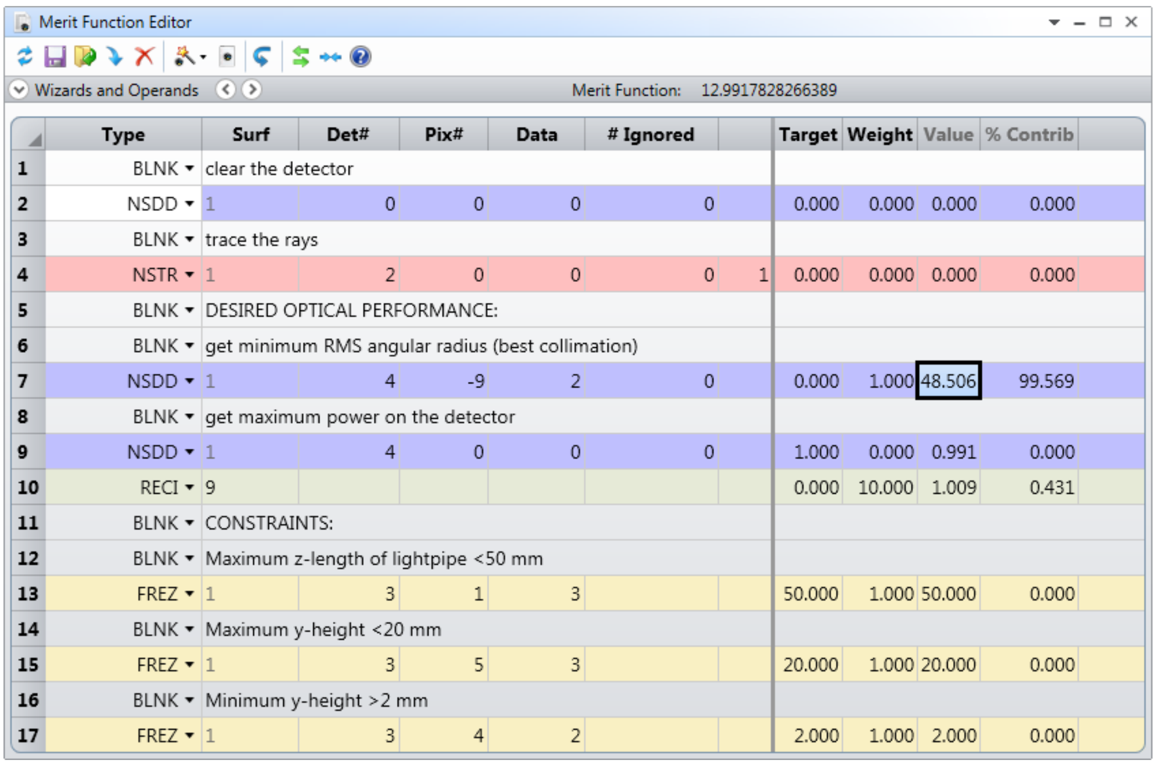


The lightpipe is a Freeform-Z object, which is defined by a set of (y, z) data points. OpticStudio fits a smooth curve through these data points, and then rotates the curve around the z-axis to form a rotationally symmetric pipe. The pipe is currently just a cylinder, but note that the (y,z) data is set to be variable.

Note also that the z-position, and x, y halfwidths of the detector object are locked to the Freeform-z object by pickup solves. These ensure that the detector will always be just in front of the output face of the lightpipe, as the pipe's length is varied during optimization, and adjust the width of the detector so it always captures all the light from the output face as the width of the output face changes.

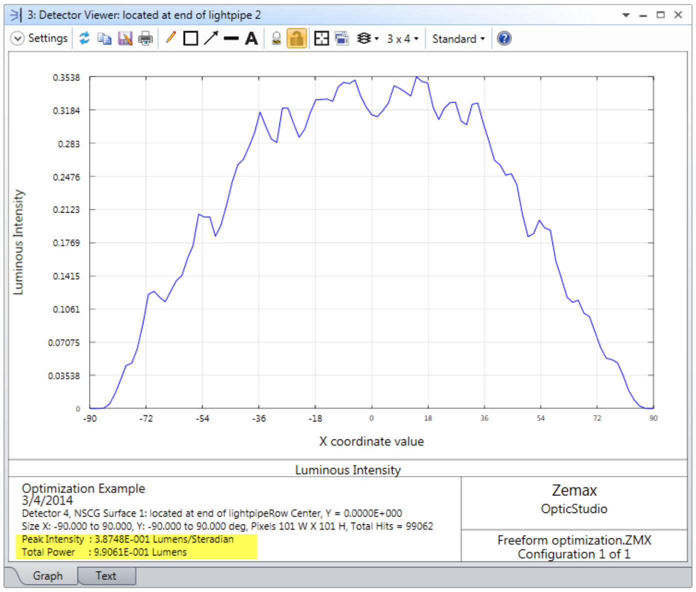
The primary goal for this light pipe is that it should give the highest brightness in the forward direction. Therefore its luminous intensity should be as high as possible and the width (in angle space) of the luminous intensity plot should be as small as possible. In addition, there are some mechanical constraints on the maximum and minimum widths and length of the lightpipe that must be met.

Open the Merit Function Editor and examine the merit function. First the detectors are cleared, and then rays are traced. Then we compute the RMS angular width of the detector data by using pixel -9 (which is RMS width) and Data = 2 (power/unit solid angle). The starting beam has an RMS angular width of 48.5°:



	Type	Surf	Det#	Pix#	Data	# Ignored		Target	Weight	Value	% Contrib
1	BLNK	clear the detector									
2	NSDD	1	0	0	0	0		0.000	0.000	0.000	0.000
3	BLNK	trace the rays									
4	NSTR	1	2	0	0	0	1	0.000	0.000	0.000	0.000
5	BLNK	DESIRED OPTICAL PERFORMANCE:									
6	BLNK	get minimum RMS angular radius (best collimation)									
7	NSDD	1	4	-9	2	0		0.000	1.000	48.506	99.569
8	BLNK	get maximum power on the detector									
9	NSDD	1	4	0	0	0		1.000	0.000	0.991	0.000
10	RECI	9						0.000	10.000	1.009	0.431
11	BLNK	CONSTRAINTS:									
12	BLNK	Maximum z-length of lightpipe <50 mm									
13	FREZ	1	3	1	3			50.000	1.000	50.000	0.000
14	BLNK	Maximum y-height <20 mm									
15	FREZ	1	3	5	3			20.000	1.000	20.000	0.000
16	BLNK	Minimum y-height >2 mm									
17	FREZ	1	3	4	2			2.000	1.000	2.000	0.000

and a peak luminous intensity of 0.38 lm/sr, although this is clearly a noisy number:

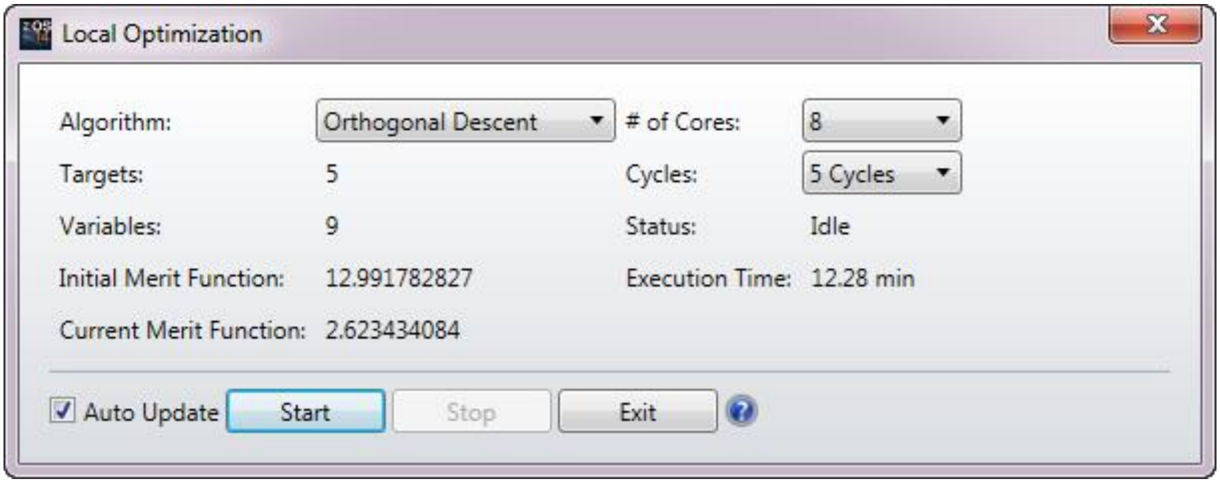


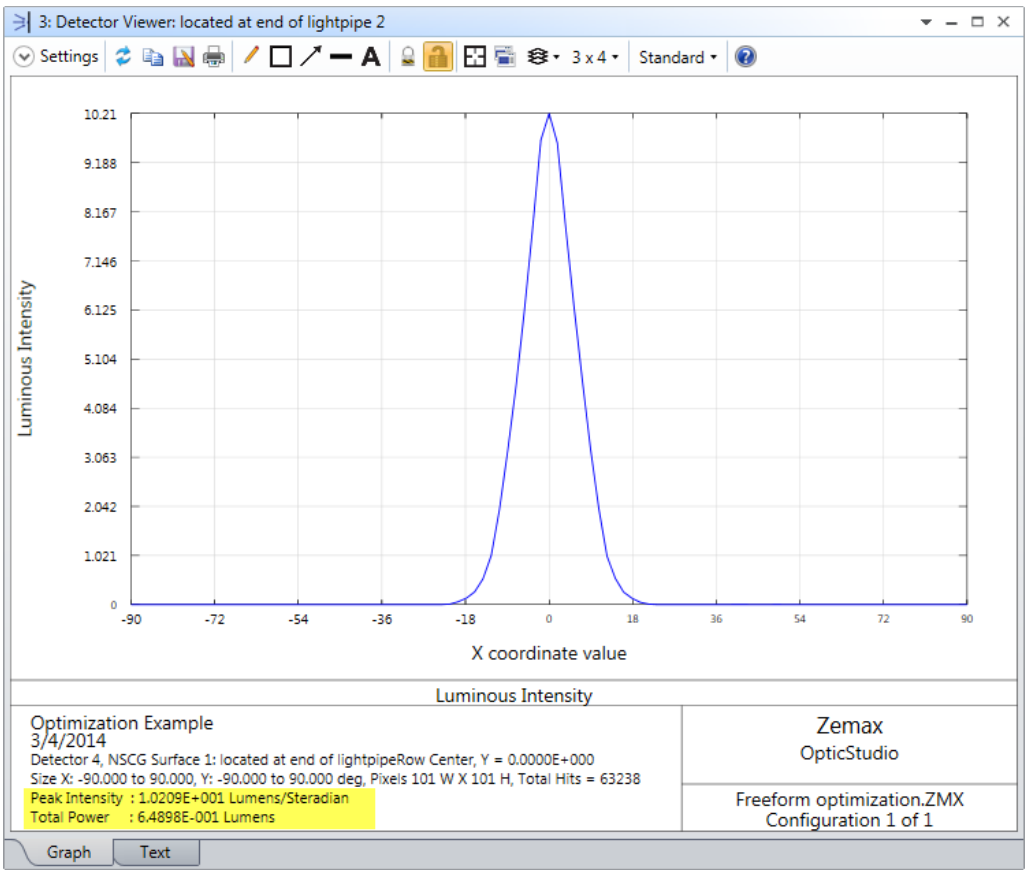
In addition, we also target the total power detected to be as large as possible. This is an important constraint, because if no rays land on the detector, the RMS angular width is identically zero! This is not a solution we want, so we are optimizing for maximum received power and minimum angular width.

There are also some constraints on the shape of the pipe, and you should consult the full description of the FREZ operand for full details in the Help Files Optimize Tab chapter. These constraints prevent the lightpipe from becoming unfeasibly thick or thin.

Run the optimizer, and select the 'Orthogonal Descent' optimization operand. This alternative local optimizer is very good at making big improvements quickly, especially in non-sequential systems, although the Damped Least Squares optimizer can usually make further improvements on it.

After five cycles of optimization, the lightpipe's shape has evolved to produce a peak luminous intensity of 102 lm/sr, which is over 200 times brighter than the starting design, and an RMS angular radius of less than 9°:



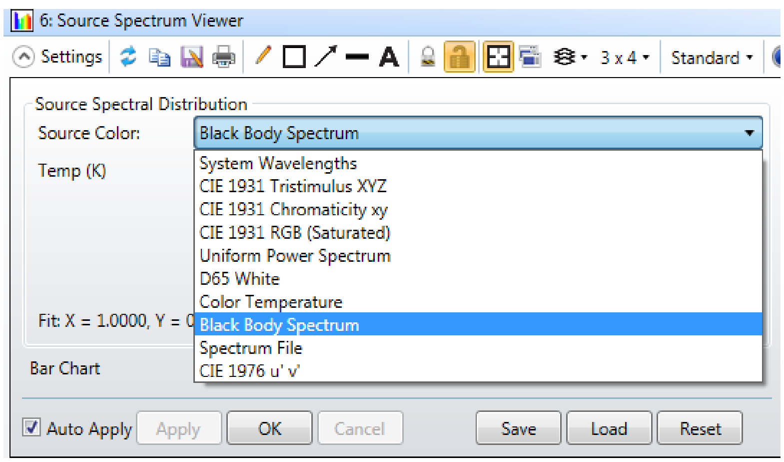


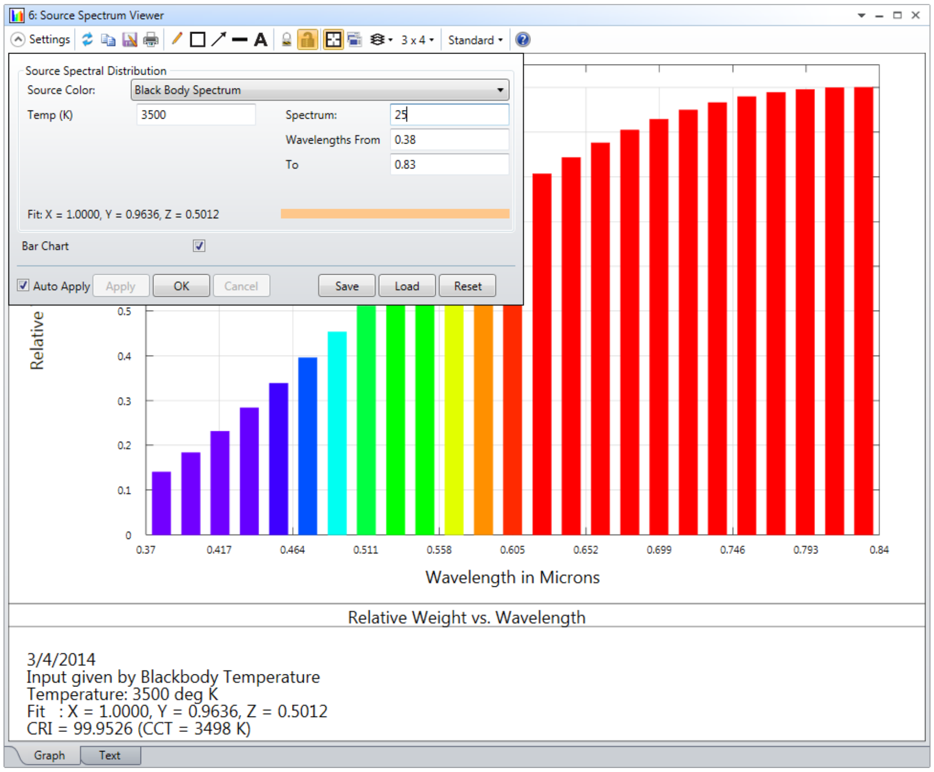
Note also that the detector object has shifted position and increased in size because of the pick-up solves used, and that the pipe is ~65% efficient (check the total power above and compare to our 1 lm launch power)

Tutorial 8: Colorimetry

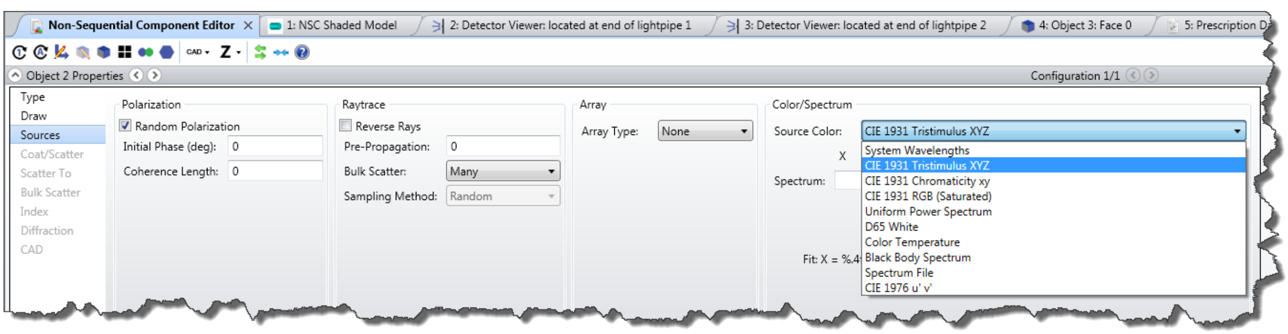
Colorimetry is the study of color, which is the response of the human eye to optical radiation in the wavelength range 0.38 to 0.83 microns. The color of any non-sequential source object can be defined in many ways.

If the wavelength spectrum of a source is known, and there is only one such spectrum it can be entered directly in the System Explorer's Wavelength section (up to 24 data points). However, this is uncommon in colorimetry are other methods are more commonly used. In the Libraries tab, Source Viewers group, select the Source Spectrum Plot and look at its Settings:

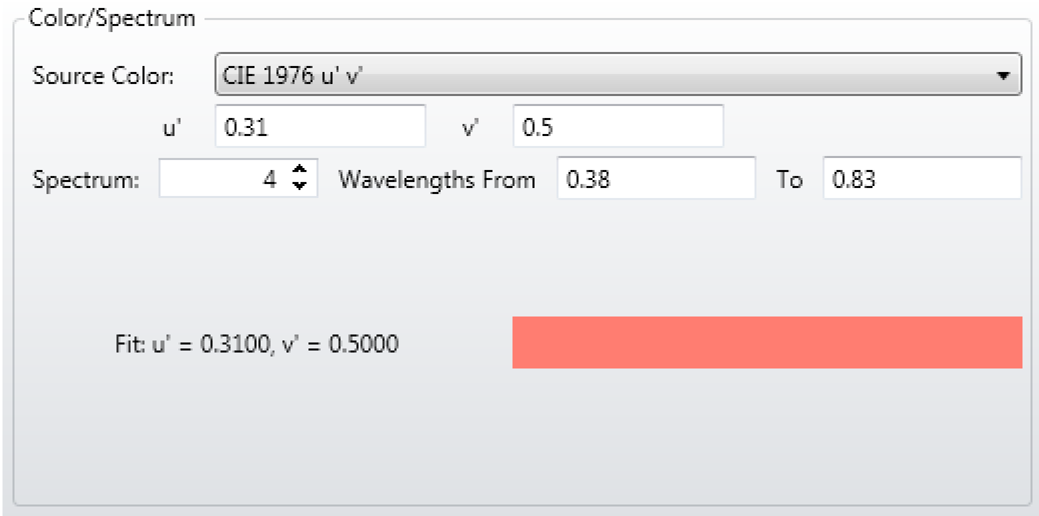




The viewer is useful for investigating all the color models that OpticStudio supports, including those fitted from CIE color coordinates. Once you know how to define the colors you want, you enter this data within the Sources section of the Object Property Inspector:

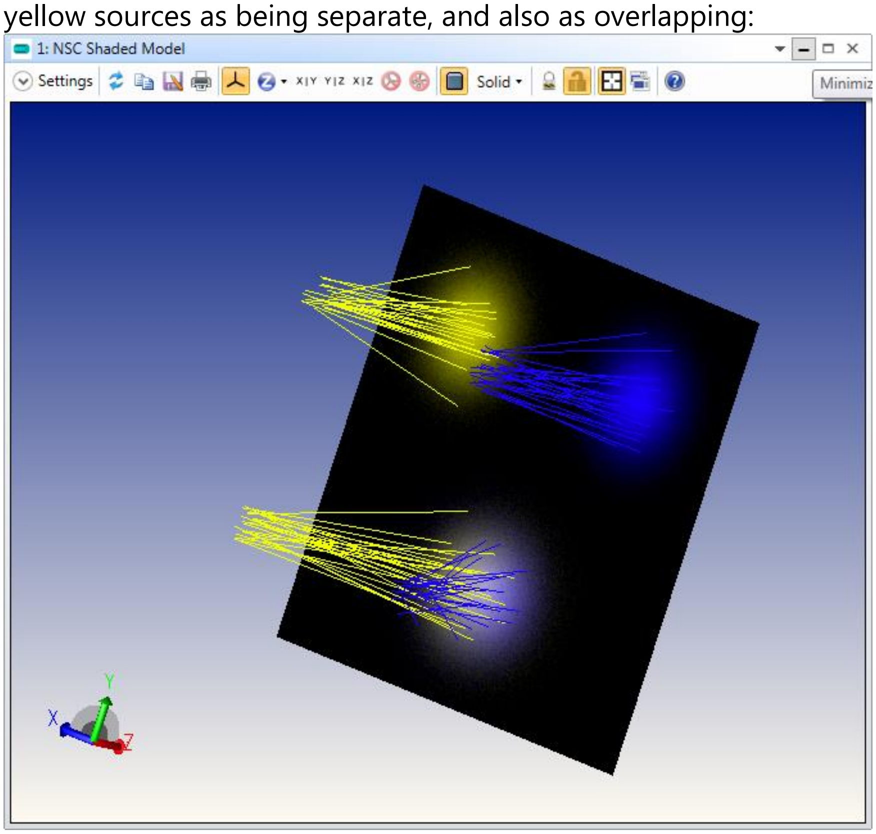


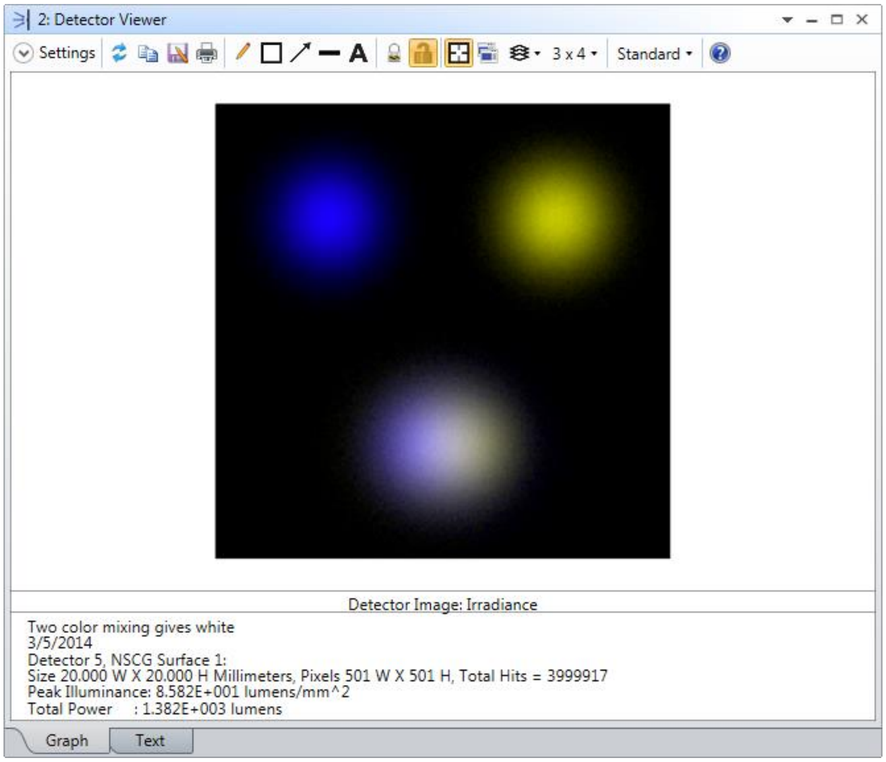
Any number of sources, each with its own unique color, can be defined. For example, if you have CIE 1976 u'v' data for a source where u' = .31 and v' = 0.5, OpticStudio can fit this color exactly using just four wavelengths:



In general, you should use the minimum number of wavelengths that gives adequate color rendering. Rays are then traced using either the specified or synthesized spectra of each source, until they are detected by a Detector Color or Detector Polar object which can provide either True Color (photometric) or False Color (radiometric) data as required by the user.

For example, open the sample file sub-folder \Colorimetry in the non-sequential samples folder, and open Example 1, two color mixing gives white. White LEDs can be produced by using two phosphors in the LED die, giving spectra in the blue and yellow. For simplicity, in this file we show the blue and yellow sources as being separate, and also as overlapping:





Note that because the two beams do not overlap perfectly, you can see a blue tinge on one side of the white spot, and a yellow tinge on the other. Optimization operands are available to allow each pixel's color to be analyzed and targeted in the merit function, so that you can optimize for a desired color or CRI.

Tutorial 9: Polarization, Coatings & Scattering

Ray tracing programs generally treat rays as purely geometric entities, which have only a position, orientation, and phase. For example, a ray is completely described at a surface by the ray intercept coordinates, the direction cosines which define the angles the ray makes with respect to the local coordinate axes, and the phase, which determines the optical path length or difference along the ray.

At the boundary between two media, such as glass and air, refraction occurs according to Snell's law. Usually, the effects at the interface which do not affect beam direction are ignored. These effects include amplitude and phase variations of the electric field which depend upon the angle of incidence, the incident polarization, and the properties of the two media and any optical coatings at the interface.

Polarization analysis is an extension to conventional ray tracing which considers the effects that optical coatings and reflection and absorption losses have on the propagation of light through an optical system. It is available for sequential and non-sequential systems.

Further, scattering at the interface can also be considered. Scattering is due to micro-structure of the surface texture: at a sufficiently fine resolution, the surface of a 'smooth', polished glass is really a rough surface, with the result that the departing direction cosines are perturbed, or scattered, about their specular values. Scattering can also occur during ray-tracing through an optical material, due to inclusions in the material. This is referred to as 'bulk scattering'.

Tutorial 9.1: Polarization

In addition to position and direction, the amplitude and polarization state of a ray can be described by a vector **E** with complex valued components (E_x, E_y, E_z). Since the **E** vector must be orthogonal to the ray direction vector **k**, (given by the (l, m, n) direction cosines of the ray) then **k**.**E** = 0 and

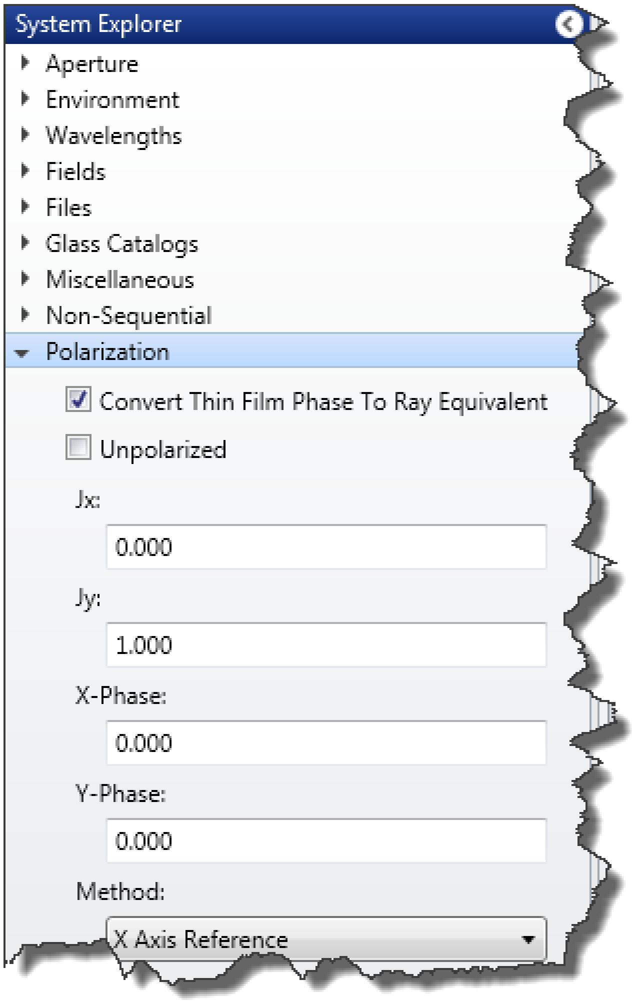
$$E_x.l + E_y.m + E_z.n = 0$$

Since we know the direction cosines, we only need to specify the complex values of E_x and E_y, as E_z is then defined. The polarization can then be defined using a 2D Jones vector **J** = (J_x, J_y) where J_x and J_y are measured *along the direction of the ray* and have both a magnitude and a phase. The 3D **E** vector is then constructed from the 2D **J** vector and the direction cosines of the ray.

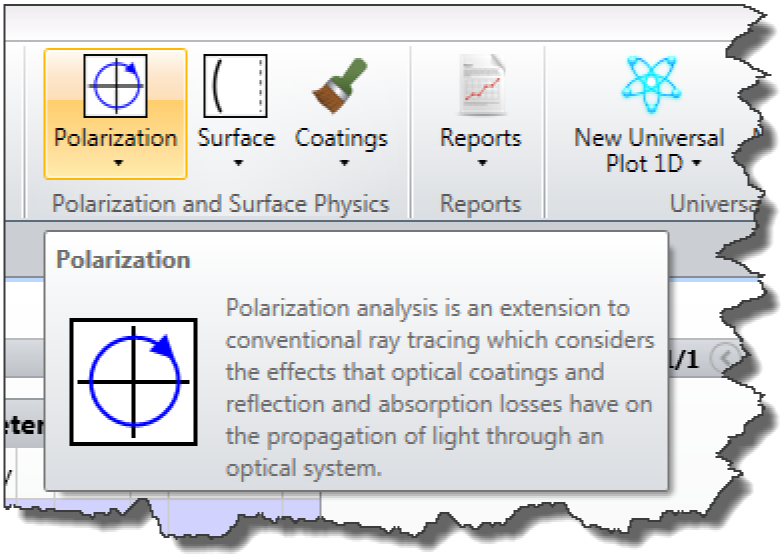
The method used to define the initial polarization of a ray then depends on whether we are working with a sequential or non-sequential system.

Defining Polarization in a Sequential System

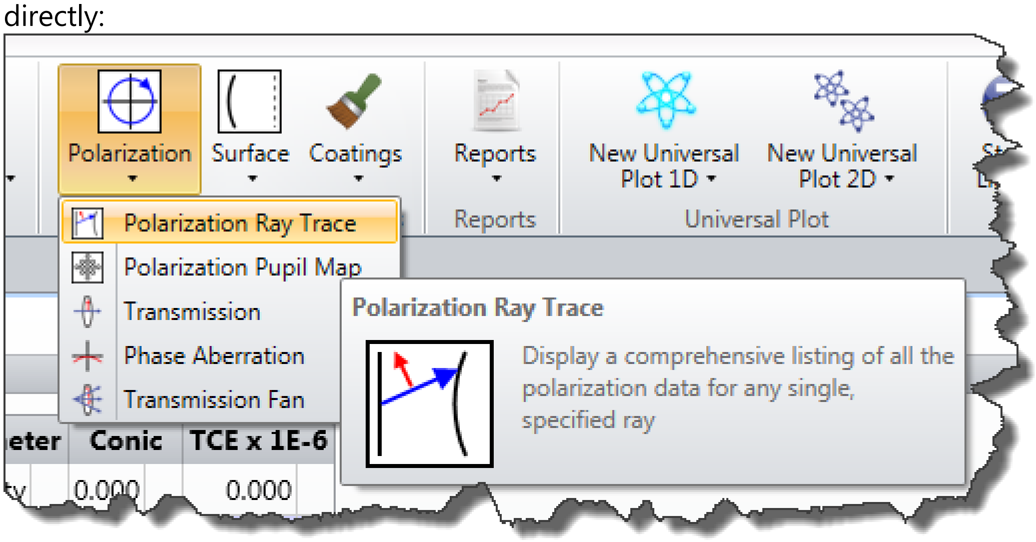
The default polarization state of rays is defined in the General dialog box's Polarization section:

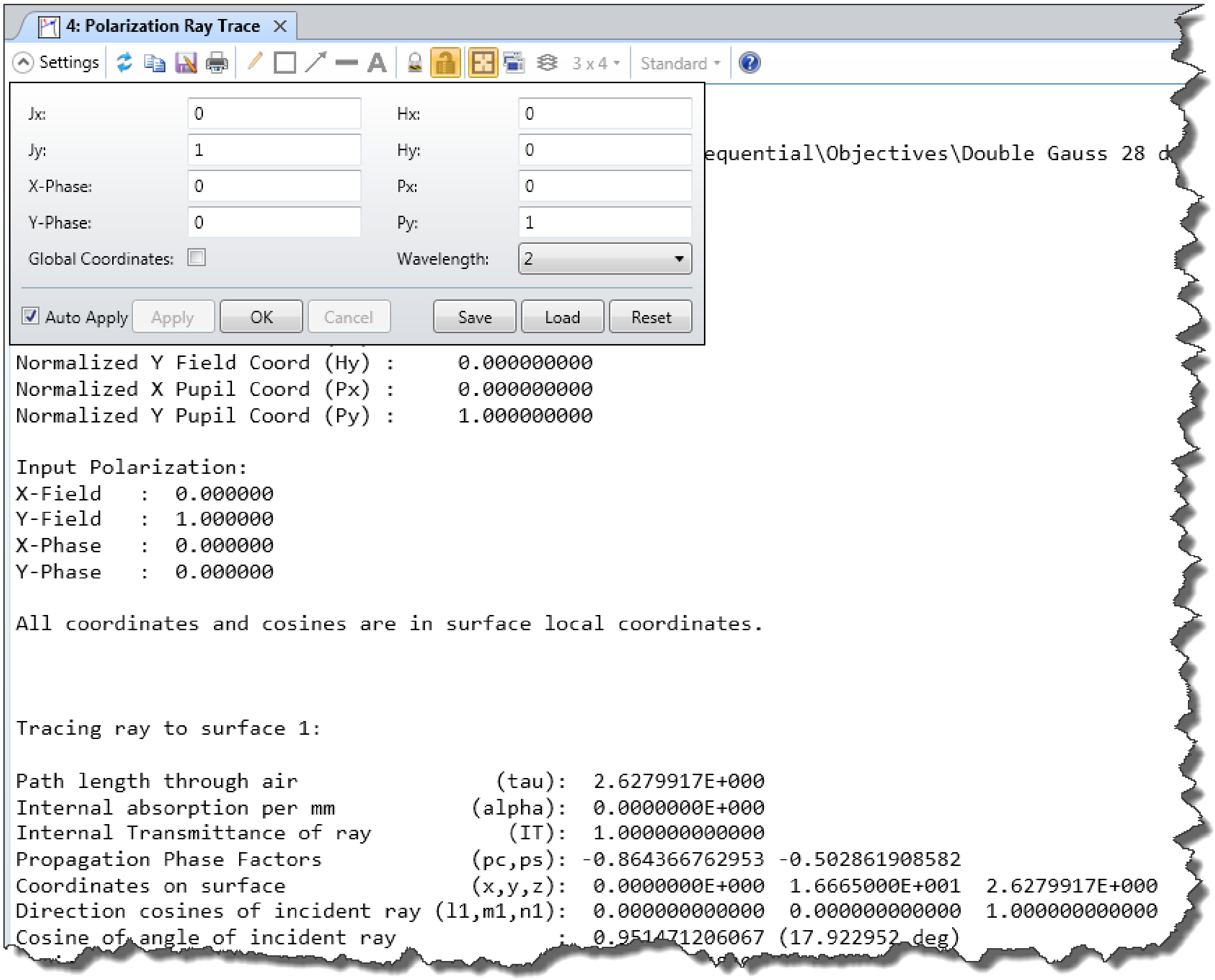


If an Analysis feature uses polarization, but its Settings do not allow for the definition of the polarization, then that calculation will use the settings here. However, many Analysis windows do allow the direct definition of the polarization state. These are the ones in the special 'Polarization and Surface Physics' group:



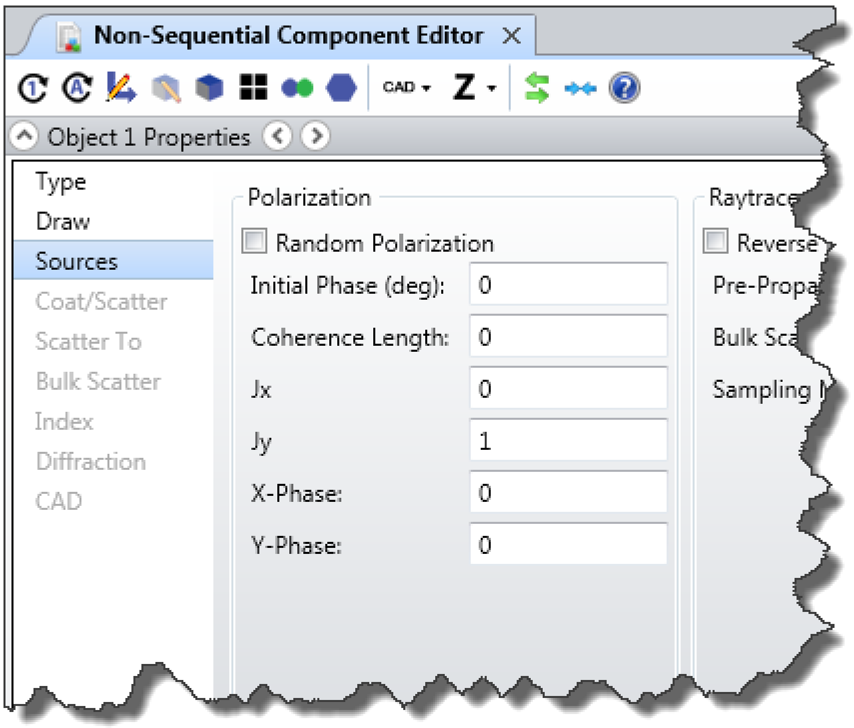
These windows *default* to the setting in the System Explorer, but allow direct modification. For example, the Polarization Ray Trace lets you can define the ray coordinates and polarization state directly:




4: Polarization Ray Trace
Settings
3 x 4
Standard
Jx: 0
Jy: 1
X-Phase: 0
Y-Phase: 0
Global Coordinates:
Hx: 0
Hy: 0
Px: 0
Py: 1
Wavelength: 2
Auto Apply
Apply
OK
Cancel
Save
Load
Reset
equential\Objectives\Double Gauss 28 d
Normalized Y Field Coord (Hy) : 0.000000000
Normalized X Pupil Coord (Px) : 0.000000000
Normalized Y Pupil Coord (Py) : 1.000000000
Input Polarization:
X-Field : 0.000000
Y-Field : 1.000000
X-Phase : 0.000000
Y-Phase : 0.000000
All coordinates and cosines are in surface local coordinates.
Tracing ray to surface 1:
Path length through air (tau): 2.6279917E+000
Internal absorption per mm (alpha): 0.0000000E+000
Internal Transmittance of ray (IT): 1.000000000000
Propagation Phase Factors (pc,ps): -0.864366762953 -0.502861908582
Coordinates on surface (x,y,z): 0.0000000E+000 1.6665000E+001 2.6279917E+000
Direction cosines of incident ray (l1,m1,n1): 0.000000000000 0.000000000000 1.000000000000
Cosine of angle of incident ray : 0.951471206067 (17.922952 deg)

Defining Polarization in a Non-Sequential System

Non-Sequential source objects can have their polarization state defined in the Property Inspector Sources section:



Every source can have separate polarization properties specified for it.

Tutorial 9.2: Thin-Film Coatings

OpticStudio has an extensive thin film modeling capability to support the polarization analysis. Multilayer film dielectric and metallic coatings may be defined, from either a predefined or user defined material database. Many thin-film codes, like The Essential Macleod, TFCalc and Film-Star, export coating designs directly in OpticStudio format.

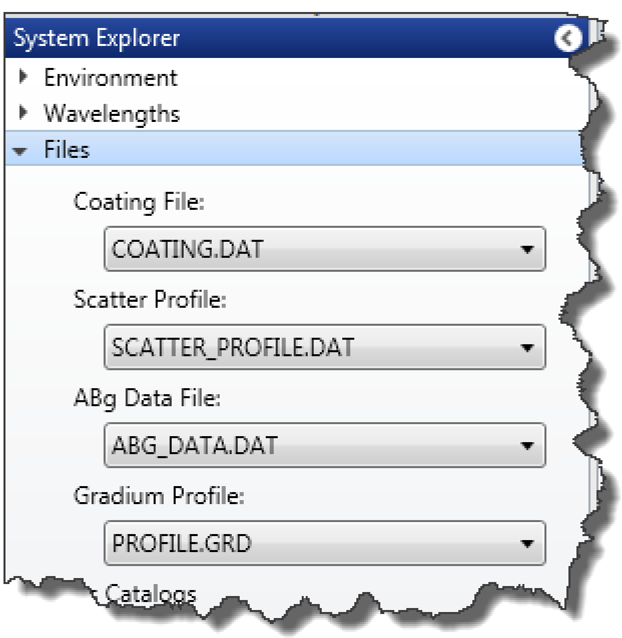
Coatings may be applied to either dielectric or metallic substrates. Coatings may be composed of arbitrary layers of arbitrary material, each defined with a complex index of refraction, with full dispersion modeling in the coating materials. Substrates may be glass, metallic, or user defined. Coating layers may be of uniform or varying thickness, and loops of replicated coating stacks can be easily created.

OpticStudio automatically reverses the coating layer order if surfaces go from air to glass then glass to air, so the same coating may be applied on many surfaces without the need to define “mirror image” coatings.

Coatings are defined in a file with the .dat extension. This file is located in the coatings folder, which by default is My Documents\Zemax\Coatings. This folder can be modified by clicking on Project Preferences in the Setup tab. OpticStudio is shipped with a file called coating.dat, which contains sample data.

Note: You should not edit coatings.dat, as it is provided by the OpticStudio installer and will be overwritten when you next install an update.

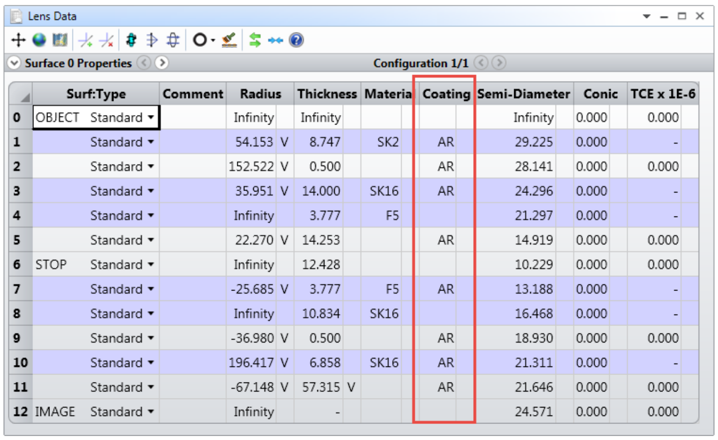
Always place your own coating data in your own .dat file, and load it via the System Explorer Files section:



With the coating data in place, OpticStudio computes the diattenuation, phase, retardance, reflection, transmission, or absorption of any coating as a function of wavelength or angle.

Adding Coatings to Sequential Surfaces

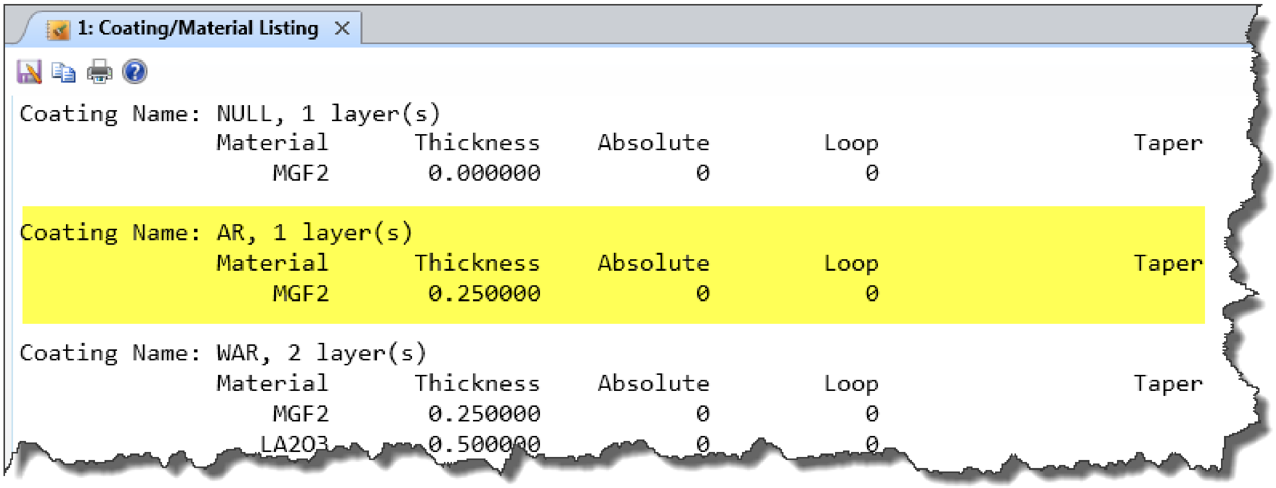
Open the sample file Sequential\Objectives\Double Gauss 28 degree field.zmx again. This uses the supplied coatings.dat file. Note the Coatings column in the Lens Data Editor:



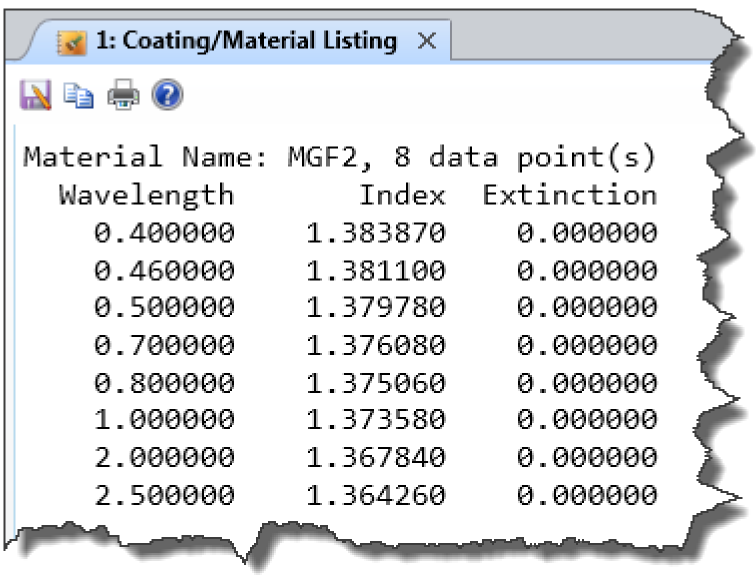
	Surf:Type	Comment	Radius	Thickness	Material	Coating	Semi-Diameter	Conic	TCE x 1E-6
0	OBJECT Standard		Infinity	Infinity			Infinity	0.000	0.000
1	Standard		54.153 V	8.747	SK2	AR	29.225	0.000	-
2	Standard		152.522 V	0.500		AR	28.141	0.000	0.000
3	Standard		35.951 V	14.000	SK16	AR	24.296	0.000	-
4	Standard		Infinity	3.777	F5		21.297	0.000	-
5	Standard		22.270 V	14.253		AR	14.919	0.000	0.000
6	STOP Standard		Infinity	12.428			10.229	0.000	0.000
7	Standard		-25.685 V	3.777	F5	AR	13.188	0.000	-
8	Standard		Infinity	10.834	SK16		16.468	0.000	-
9	Standard		-36.980 V	0.500		AR	18.930	0.000	0.000
10	Standard		196.417 V	6.858	SK16	AR	21.311	0.000	-
11	Standard		-67.148 V	57.315 V		AR	21.646	0.000	0.000
12	IMAGE Standard		Infinity	-			24.571	0.000	0.000

Now go to the Libraries tab, and select the Coating Catalog icon from

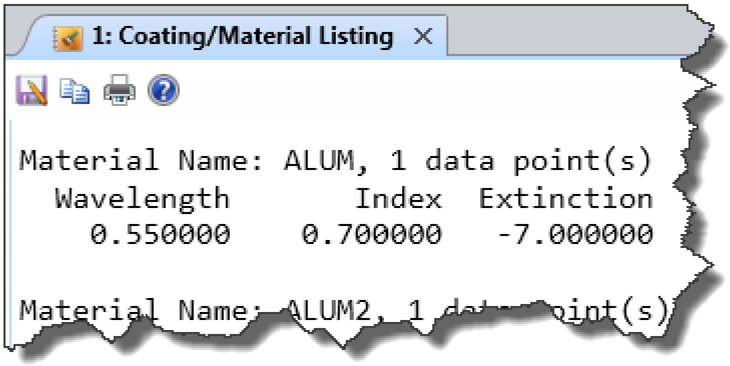
Scroll down to find the coating AR:



Coating thickness is given in units of waves at the primary wavelength unless the "Absolute" flag is non-zero; in which case the coating thickness is in μm independent of wavelength. The coating AR is, therefore, a λ/4 thick layer of the material MGF2, which is defined earlier in the coating.dat file:



This listing gives the complex refractive index, defined as η = n + ik, where n is the usual index of refraction, and k is the extinction coefficient. As the material MGF2 is defined as having positive n and zero k, it is a pure dielectric. The material ALUM however:

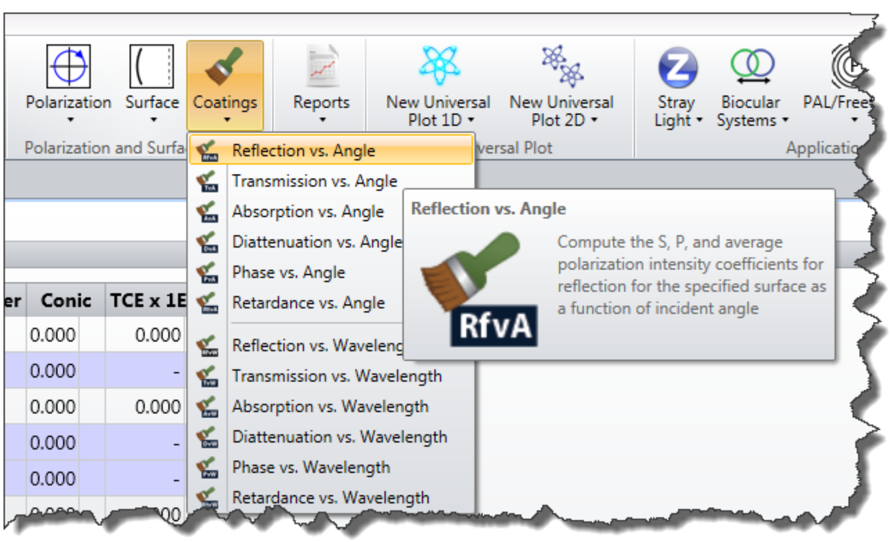


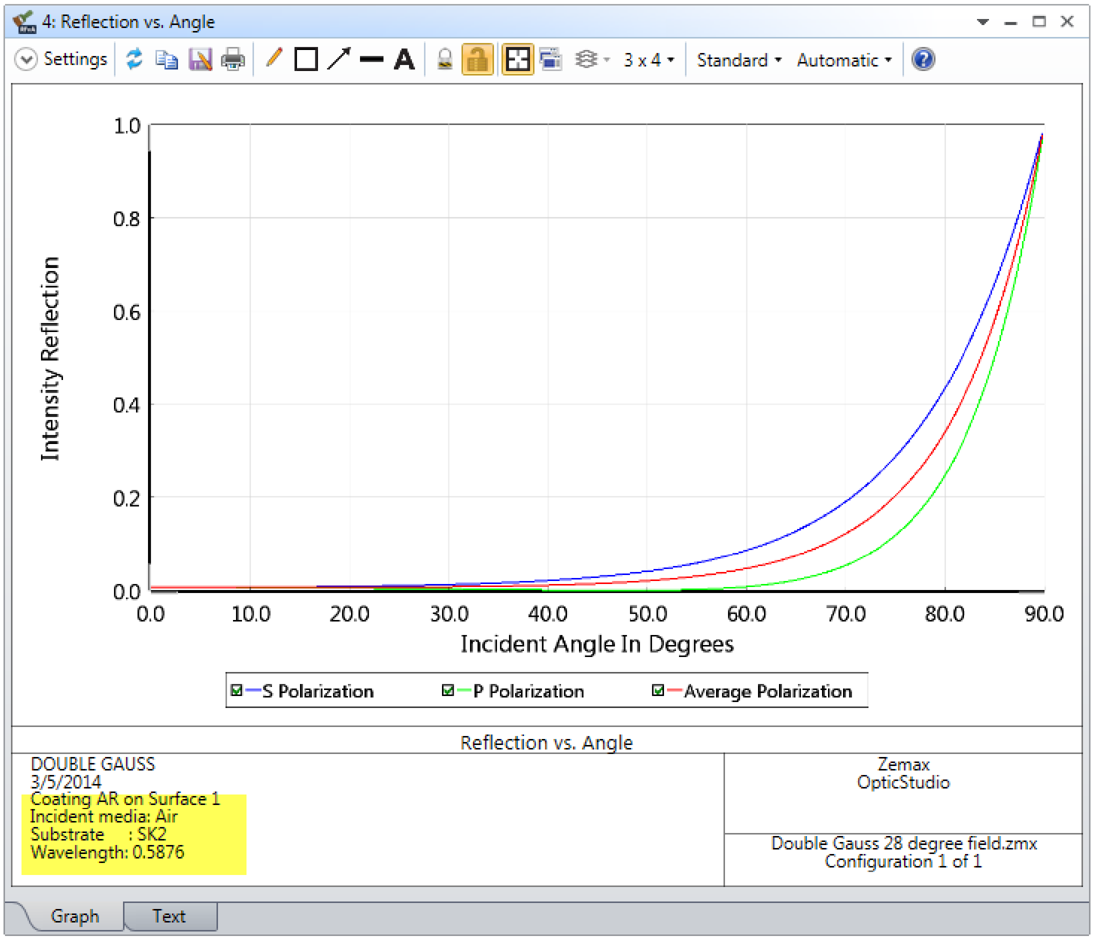
has index <1 and negative extinction, and so is a metal (the OpticStudio convention is that extinction is negative for an absorbing medium). Coatings can be made up of any number of dielectric and metallic layers, the layer thickness can be constant or tapered, and repetitive loops of coatings can be easily defined.

If you do not have the coating prescription, OpticStudio supports several IDEAL coatings which allow you to just specify reflection and transmission, and also TABLE coatings that are similar to IDEAL coatings, except the transmission and reflection may be a function of incident angle and wavelength and may be specified separately for S and P polarizations.

Note: See the Polarization section of the Technical Reference for full details of the coating file syntax.

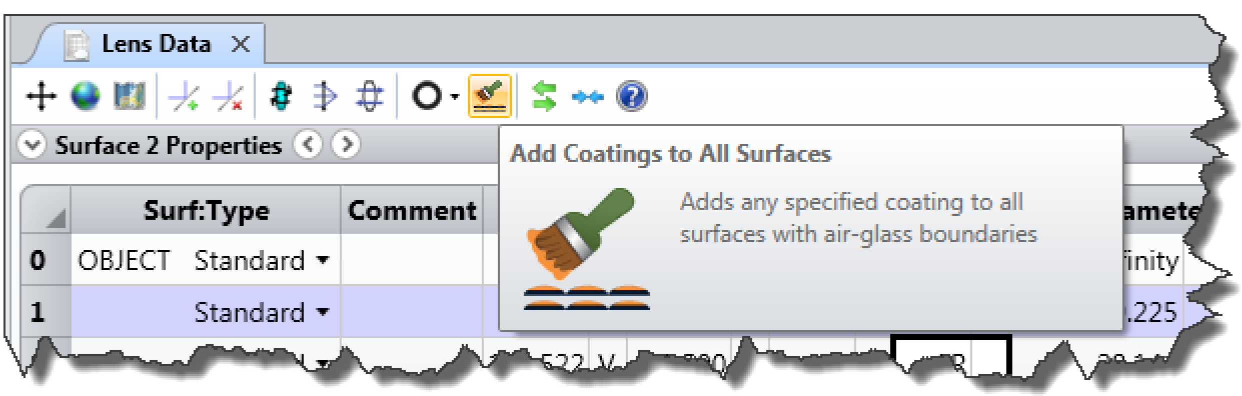
Now click on Coatings…Reflection vs Angle in the Analyze tab to see the performance of this coating on an SK2 substrate:





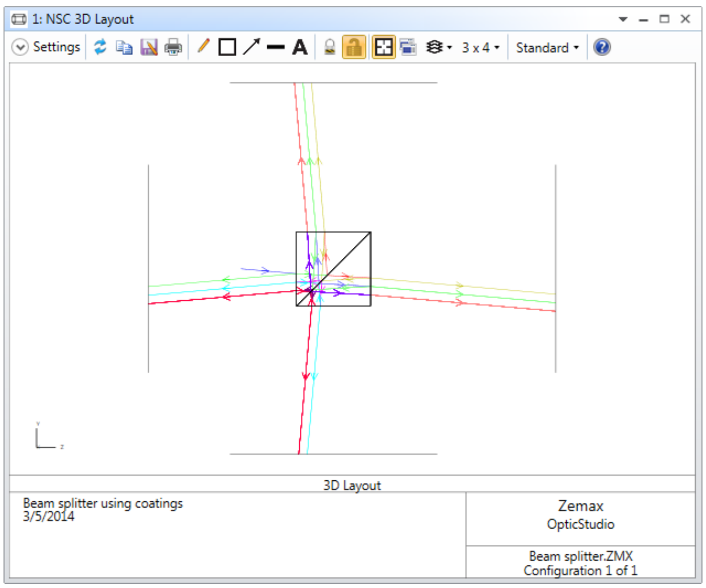
Other plots in the same menu let you see transmission, diattenuation, phase, retardance, etc. In the coating column of surface 1, press the spacebar to delete the coating, and note how the reflection vs. angle plot changes.

Coating names can be typed directly into the coating column to apply the coating to the surface, and the Apply Coating to All Surfaces tool in the Lens Data Editor toolbar lets you quickly add a coating to all surfaces of the system.

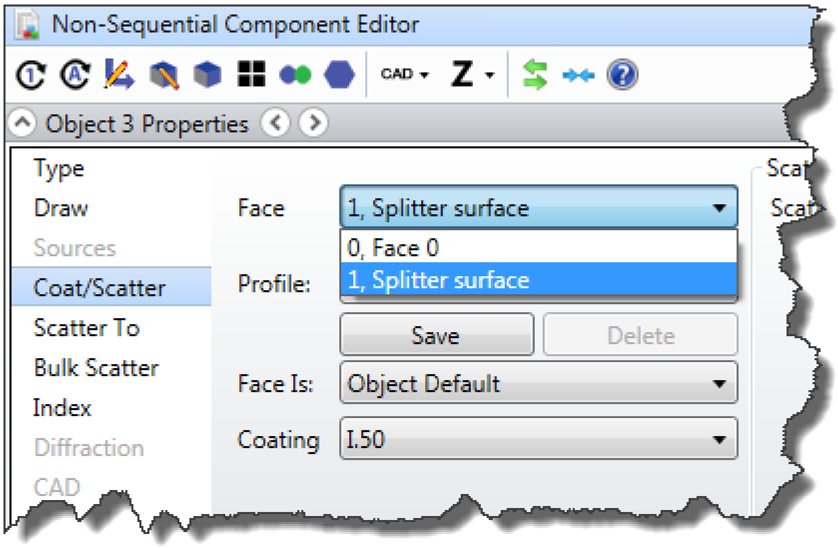


Adding Coatings to Non-Sequential Objects

It is only a little more complex to add coatings to non-sequential objects. Because objects are volumes and not surfaces, one object may have several faces that can take different coatings. Open the sample file Non-sequential\Ray splitting\Beam Splitter.zmx to demonstrate this:

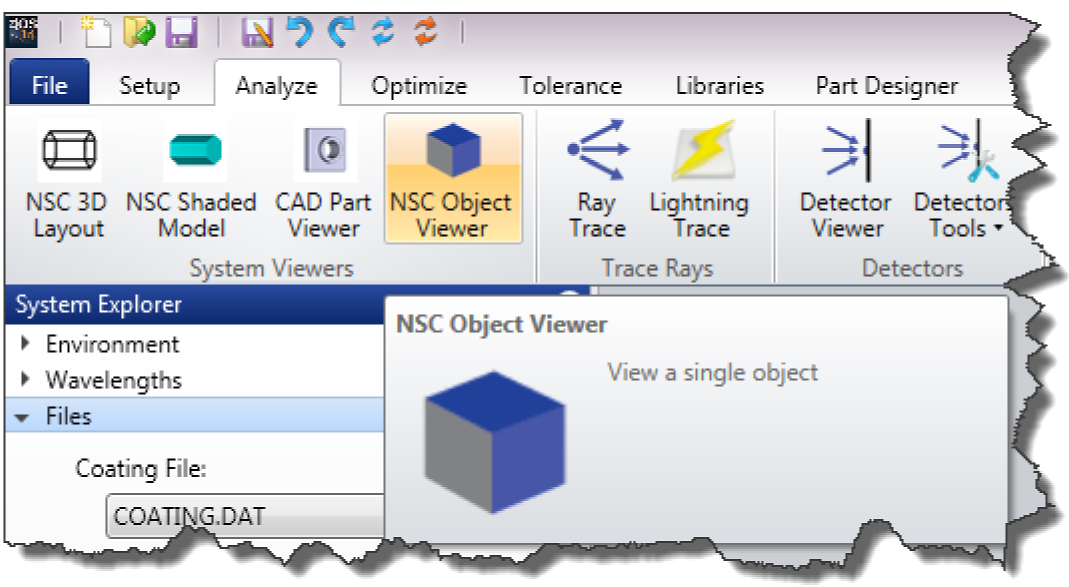


Double-click on the second prism object, object 3, to open the Property Inspector and go to the Coat/Scatter tab. This object has two faces: face 1 which is the splitter face (the hypotenuse of the prism) and face 0 is everything else.

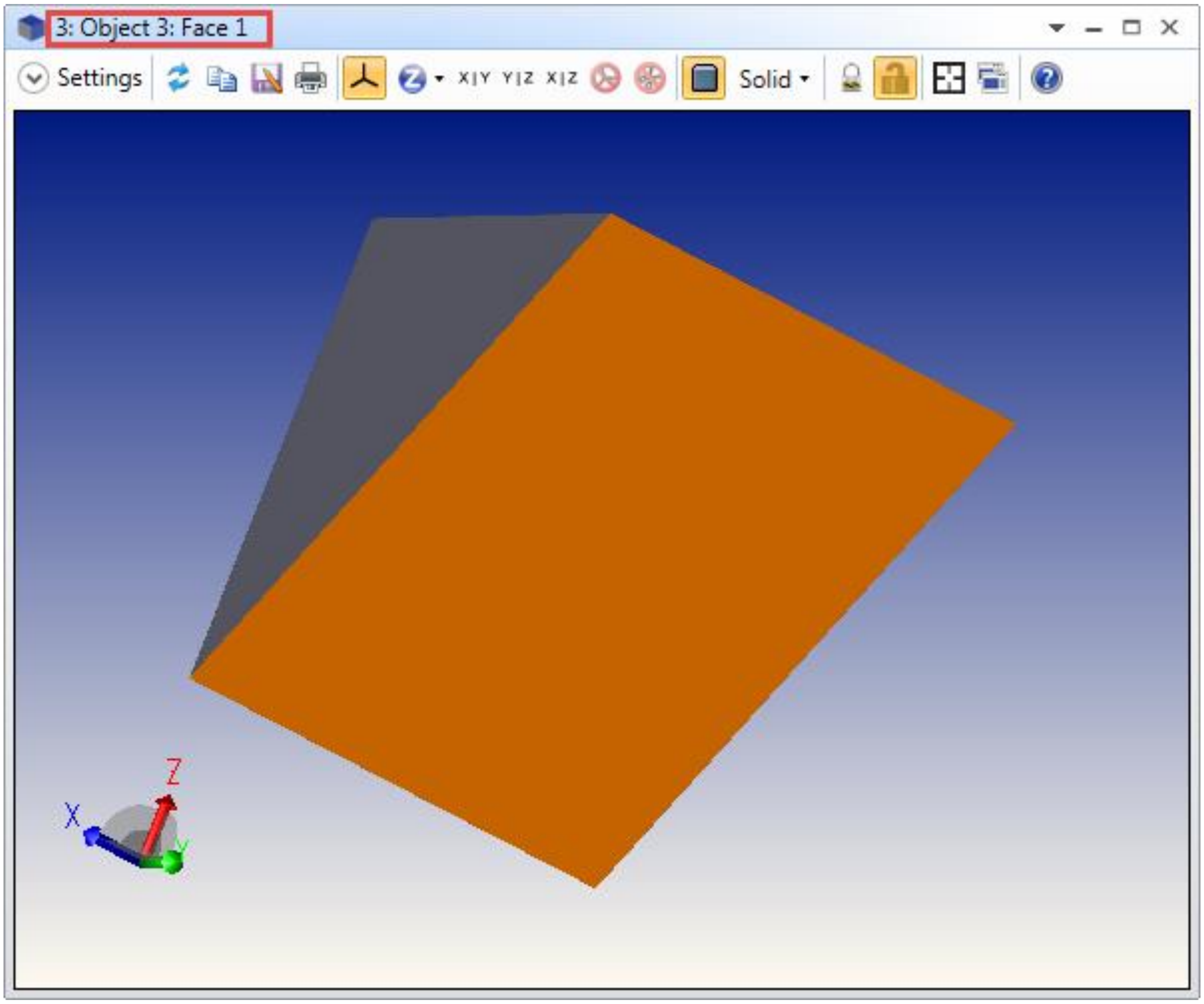


Face 1 is coated with an IDEAL coating I.5, which transmits 50% and reflects 50% of the ray energy, and face 0 is coated with I.95 which transmits 95% and reflects 5% of energy.

All native OpticStudio objects use *faces* to define the various regions of optical interest in the object, and these are documented in the object definition section of the manual. Alternatively, you can use the NSC Object Viewer in the Analyze tab to view individual objects.



If you click on a face of the object with the mouse, that face will highlight and will be identified in the title bar of the window:



Defining the Faces of CAD objects

OpticStudio uses the several different CAD objects to load STL, STEP, IGES and SAT format files, and also to work dynamically with SolidWorks™, AutoDesk Inventor™ and Creo Parametric™ (formerly Pro/Engineer) parts and assemblies. These are defined by a potentially huge number of NURBS surfaces. Some CAD programs create data files that have many more small surfaces than is useful for optical analysis.

For example, a simple cylinder may be described in the CAD file by hundreds of small surfaces, while for optical analysis only two or three different optical properties are applied to the entire object. Rather than assign optical properties to each of the many surfaces, it is usually more convenient to group CAD surfaces by assigning a single face number to all surfaces that form a continuous smooth portion of the object.

CAD objects support a 'Face Mode' parameter to simplify the allocation of optical faces to an arbitrary CAD part, as follows:

- Face Mode = 0: All surfaces are assigned face number 0. The entire object will have just one face. This is ideal if a single optical finish, like anodized aluminum, will be applied to the whole object

- Face Mode = 1: All surfaces whose edges meet along a non-zero length curve, and whose normal vectors along the curve of contact are parallel within a user defined angle tolerance are assigned a common face number. The angle tolerance is defined by the Face Angle (parameter 8). This mode allows control over how finely the faces are numbered. If the Face Angle is set to a large value (such as 180) then all faces that touch will share a common number. Larger Face Angles yield fewer unique faces. This is useful with faces that are at say 90° have different optical properties.

- Face Mode = 2: All surfaces are uniquely numbered. This mode yields the largest number of unique faces.

- Face Mode = 3: Retains the face numbers defined in the imported file. Some CAD files, such as those created by Zemax, have face numbers already defined. If Zemax recognizes the face numbers, they will be used. If Zemax does not detect the face numbers, the surfaces will be numbered as for Face Mode = 2.

- Face Mode = 4: All surfaces on each separate object defined in the CAD file are assigned a common face number. This option is useful for applying one property to all surfaces on each object when more than one object is defined with a single CAD file.

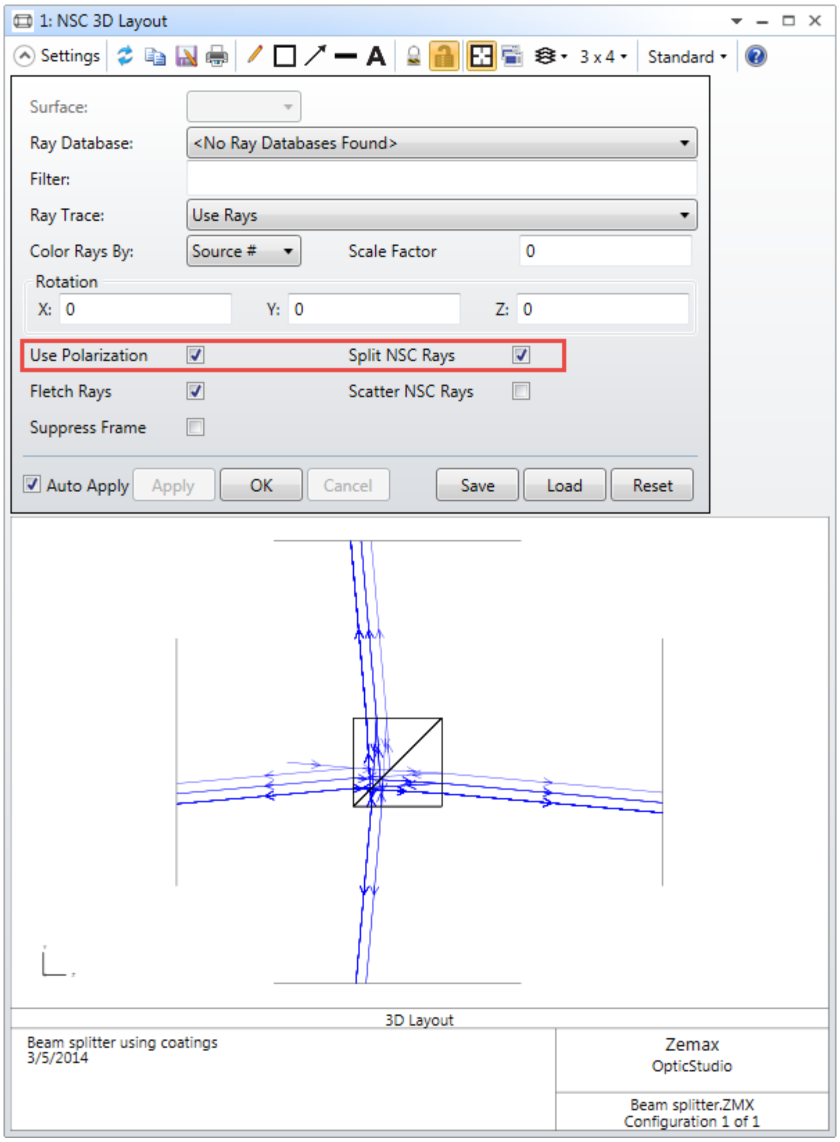
OpticStudio also supports manual assignment of face numbers to imported object surfaces using the "CAD" section of the Object Properties.

Tutorial 9.3: Ray Splitting

Either sequential or non-sequential ray-tracing may be done while accounting for polarization effects, or polarization may be ignored. If polarization ray-tracing is being used, transmission, reflection, and absorption of optical energy is accounted for at all surfaces, and bulk absorption by the optical media is also accounted for.

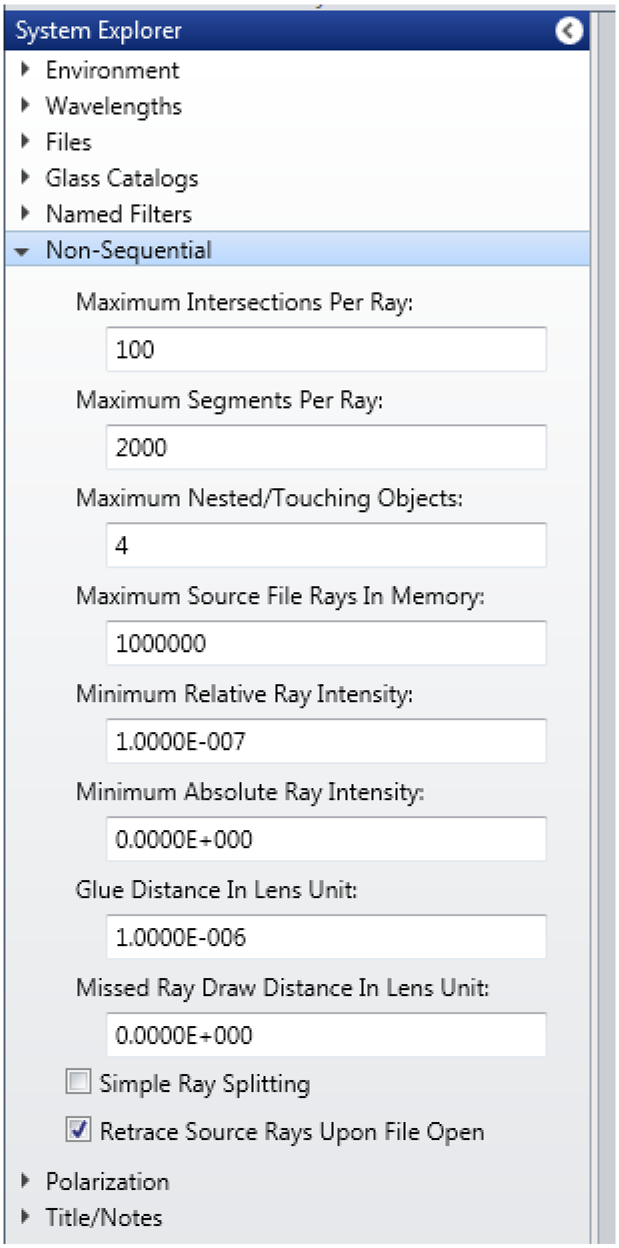
In pure non-sequential ray-tracing, rays may also be split at interfaces. In this case, reflection losses are not just accounted for, but a new ray is launched that takes the reflected energy away.

Because accurate reflection and transmission computation requires polarization information, ray splitting is only allowed when performing polarization ray-tracing.



Ray splitting can be turned off, and in this case the transmitted path is always taken at a refractive interface unless the ray totally internally reflects. The reflected path is of course always taken if the object is a mirror.

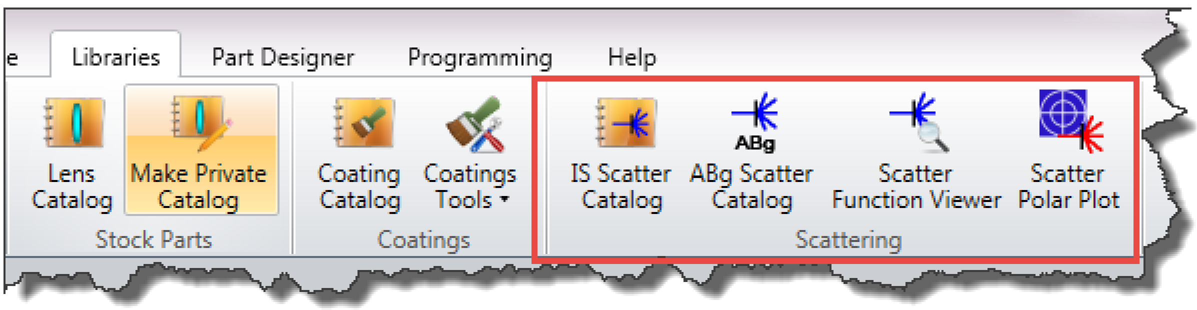
The layout above shows some of the ray paths possible in the beamsplitter example when rays are split. There is only 1 input ray drawn! The ray termination criteria defined in the System Explorer's Non-Sequential section are essential for efficient calculation when ray splitting is on. It is advisable to set the relative ray transmission reasonably high, around 0.001, until the model is working well and more detailed results are needed.



OpticStudio also supports an option to randomly choose either the reflected or the refracted path rather than split the ray into two and trace both. This is controlled by the 'Simple Ray Splitting' shown above. The decision to trace the reflected or the refracted ray is random; with the reflection and transmission coefficients being interpreted as a relative probability of taking that path.

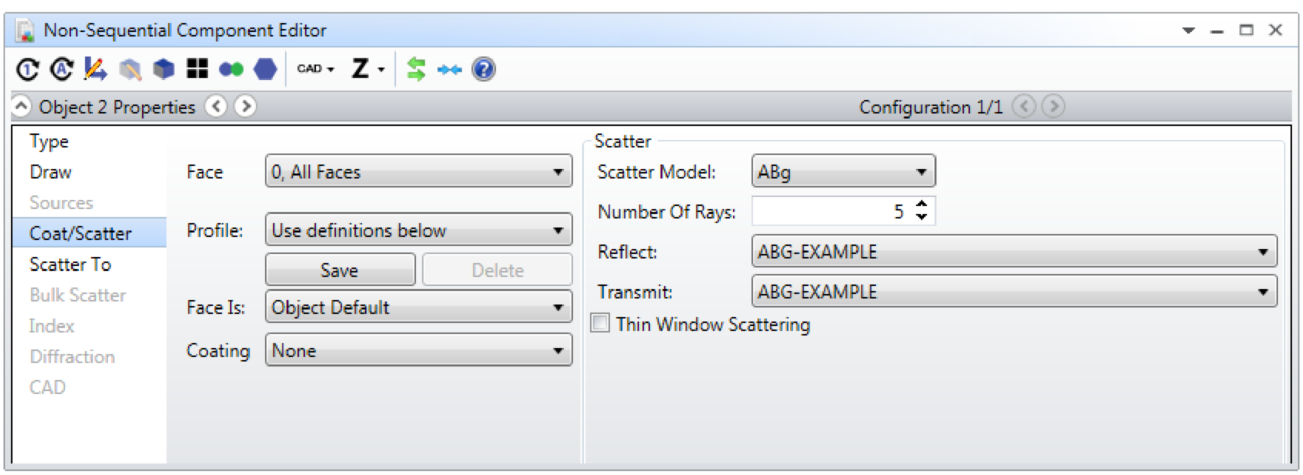
Tutorial 9.4: Ray Scattering

In addition to partial reflections at the surfaces of optical components, rays can also scatter due to microscopic roughness of the surface. OpticStudio supports many detailed models of scattering from optical surfaces, including Lambertian (used for very rough, highly scattering surfaces), Gaussian (typically used for modeling the scattering of a well-polished surface, ABg, K-correlation and more. In addition, OpticStudio can import scattering data in a simple ASCII file format, and the Premium edition contains a library of measured scatter profiles. See the Scattering group in the Libraries tab for details

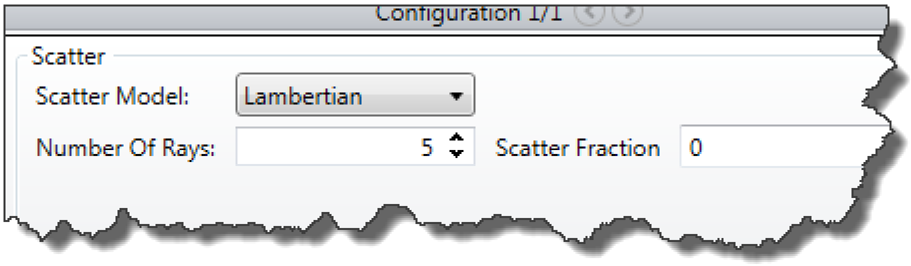


Although scattering can be used in sequential ray-tracing (see the Scattering tab Properties Inspector dialog), it is most useful in non-sequential ray-tracing, where rays can go wherever they want to. Scattering functions are applied to the faces of non-sequential objects in the same way as thin-film coatings are: on the Coat/Scatter tab of the Object Properties tab.

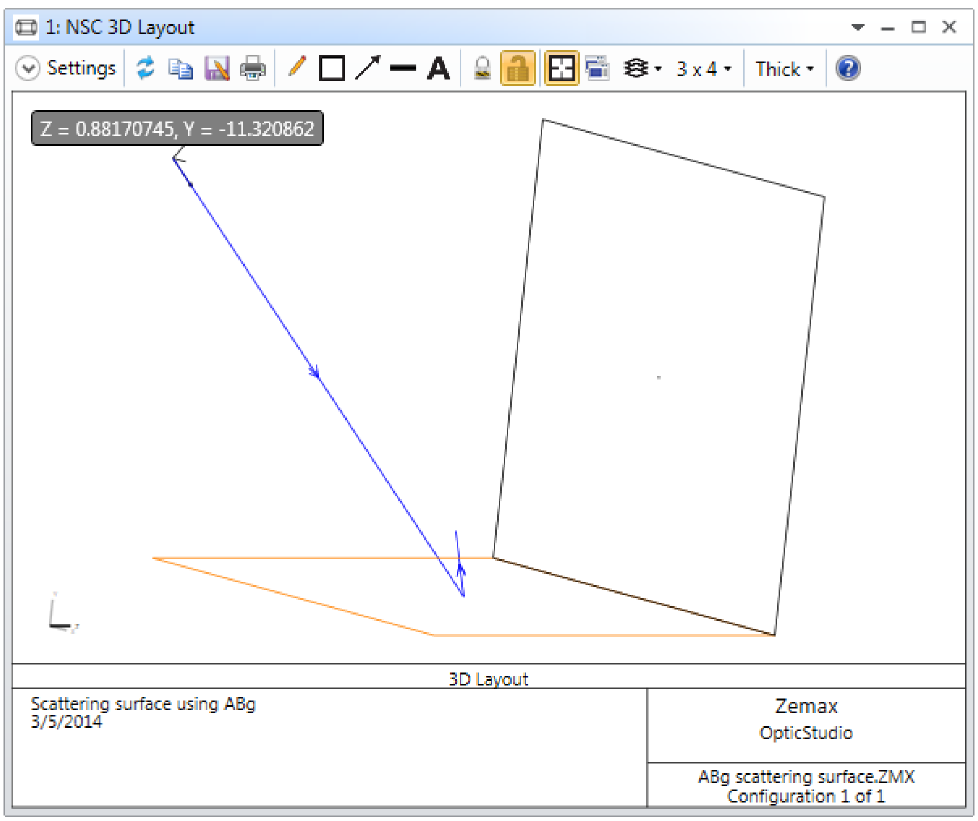
Open the sample file in Non-sequential\Scattering called ABg scattering surface.zmx. This file uses the ABg scattering model on Object 2, which is commonly used with measured scattering data:



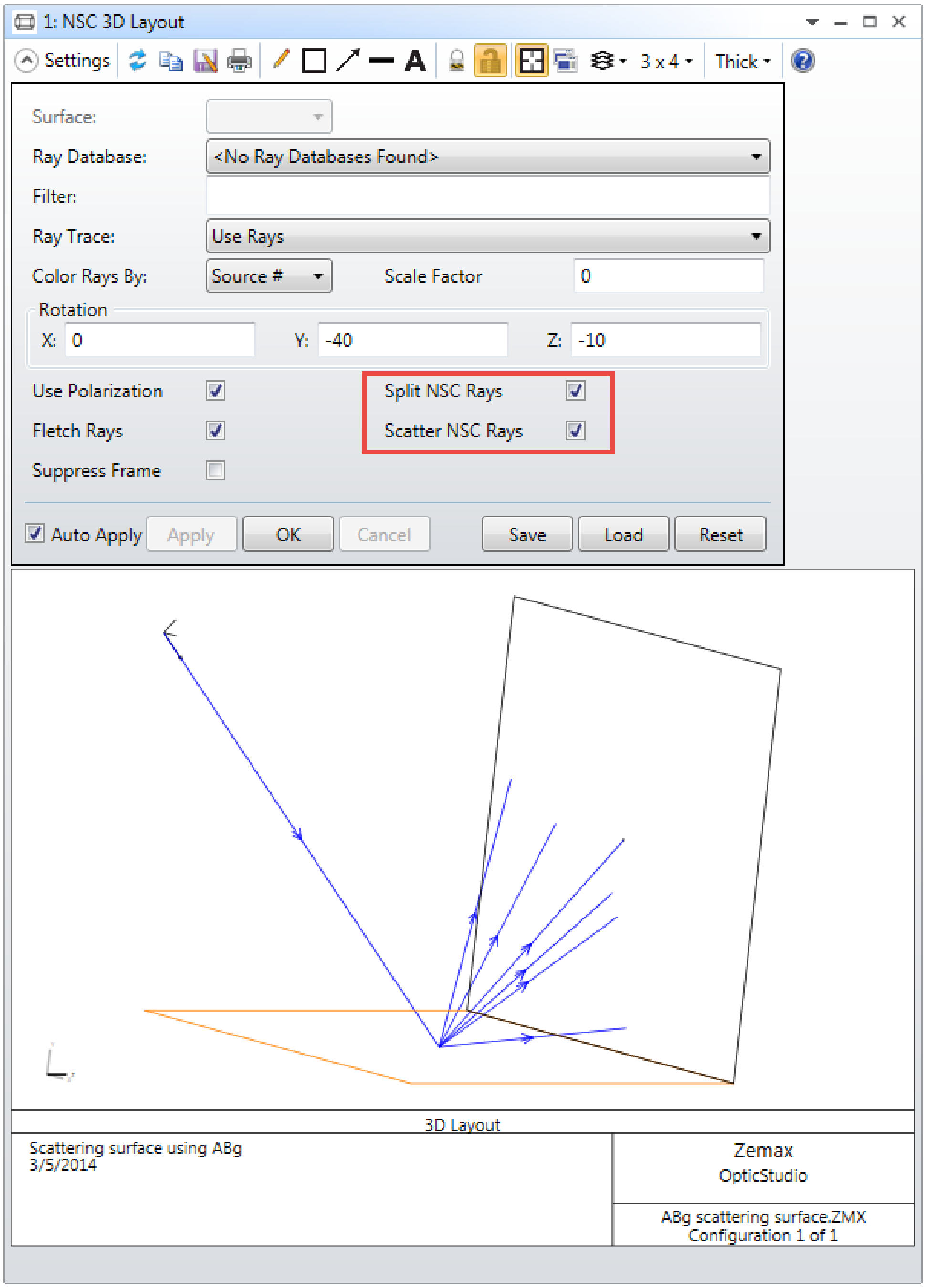
As it is based on measured data, the total amount of energy scattered by the surface is defined by the data file. Other scattering models, like the Lambertian model, require you to tell OpticStudio how much energy to scatter using the "Scatter Fraction" parameter on this dialog, which will appear if a scattering mode that requires it is chosen:



If ray splitting is turned off, the ray will either scatter or not, depending on the value of the 'Scatter Fraction' parameter (or equivalent measured data) and a random number OpticStudio generates for each ray-object intersection. Update the NSC 3D layout, and note that *the ray either scatters or does not scatter*:



On the Settings dialog, select "Split Rays' as well as "Scatter Rays":



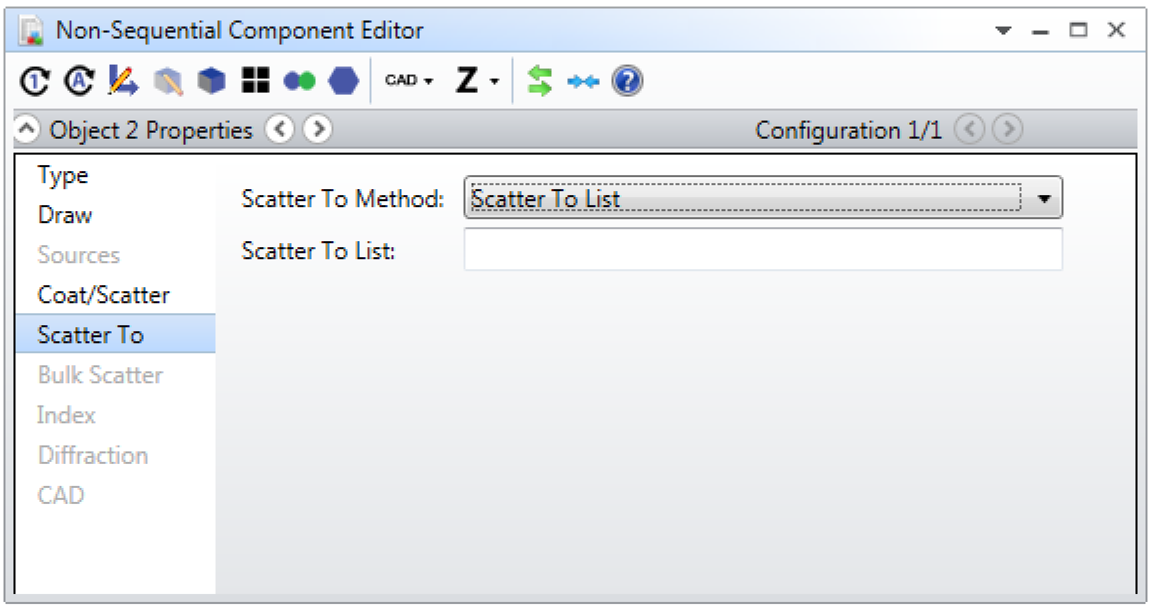
The ray will now be split into the unscattered ray, and five scattered rays.

Update this layout a few times, and note that you always get the unscattered ray, and five randomly scattered rays. The number of scattered rays is defined by the 'Number of Rays' parameter in the Coat/Scatter tab of the Object properties.

Tutorial 9.5: Importance Sampling

A very large number of rays may need to be traced to find a relatively small number of scattered rays that strike an object of interest, such as a detector. OpticStudio supports two powerful ways to improve the efficiency of the scattering analysis.

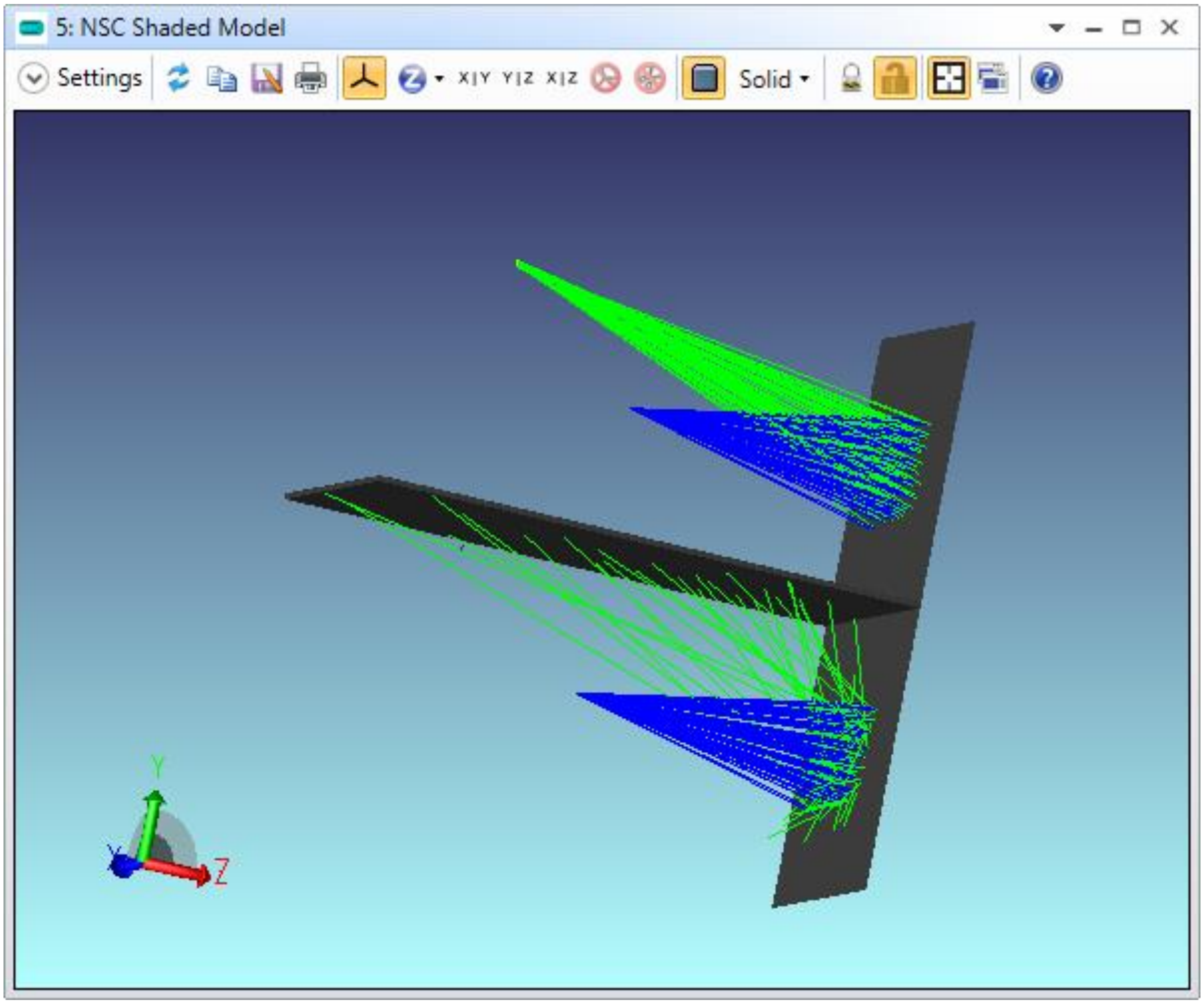
The first method is to scatter a ray according to the scatter distribution, but only trace the ray if the ray propagates towards an object of interest. This method may be implemented by defining a 'Scatter To' list of objects using the 'Scatter To' tab in the Property Inspector.



The Scatter To method works well for wide angle scatter (such as Lambertian scatter) and when the object of interest subtends a relatively large angle as seen from the scattering surface.

The second method is to always scatter the ray towards the object(s) of interest, and then to normalize the energy the ray carries to account for the probability the ray would have actually scattered in that direction. This method is called "Importance Sampling". Importance Sampling is generally superior to the Scatter To method if the scatter is narrow angle or the object of interest subtends a relatively small angle as seen from the scattering surface.

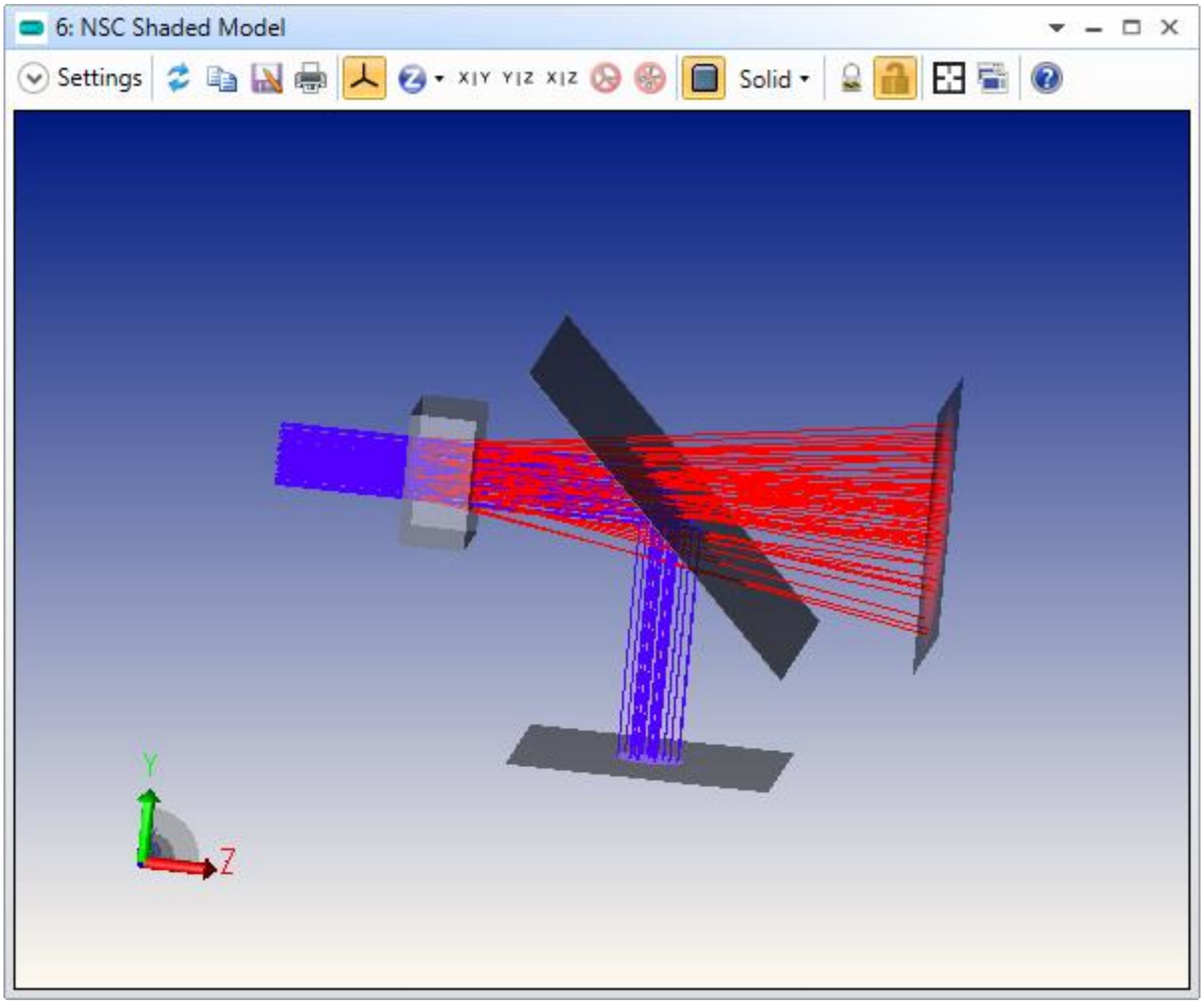
Open the sample file in Non-sequential\Scattering called Importance Sampling Demonstration.zmx. This shows directly the benefit of using Importance Sampling. Rays are always scattered to the desired object, in this case a detector, and the resulting signal/noise ratio is therefore far superior.



Tutorial 9.6: Bulk and Fluorescent Scattering

Bulk scattering models the random scattering of rays while propagating through a solid object. This may be a very rare event (like scattering from inclusions in optical-quality glass) or a very common event (like scattering in biological tissue samples). OpticStudio includes several bulk scattering models, including Henyey-Greenstein and Rayleigh scattering.

In addition, rays may change wavelength when bulk scattered, usually to longer wavelengths. Open the sample file in Non-sequential\Scattering called Fluorescence Example.zmx. This file uses two wavelengths, 1 (blue) and 2 (red). The source radiates only in the blue, and this light enters a medium that scatters the light in angle and wavelength. A beamsplitter transmits the red and reflects the blue:



Bulk scattering properties are defined on the 'Bulk Scatter' tab of the Property Inspector dialog:

The "Wavelength Shift" control allows definition of wavelength transitions during bulk scatter events. The syntax is "in, out, prob" where "in" is the input wavelength number, "out" is the output wavelength number, "prob" is the relative probability that this shift will occur when tracing the in wavelength. Multiple transitions may be defined using a semi colon separator.

For example, if a single input wavelength (#1) will shift to wavelength #2 50% of the time, wavelength #3 40% of the time, and the remaining 10% of the time will remain at the input wavelength, then the wavelength shift string is

```
1, 2, 50.0; 1, 3, 40.0; 1, 1, 10.0
```

What's Next?

Well done on working through this guide! This guide is by necessity brief, and has only scratched the surface of what you can achieve with OpticStudio.

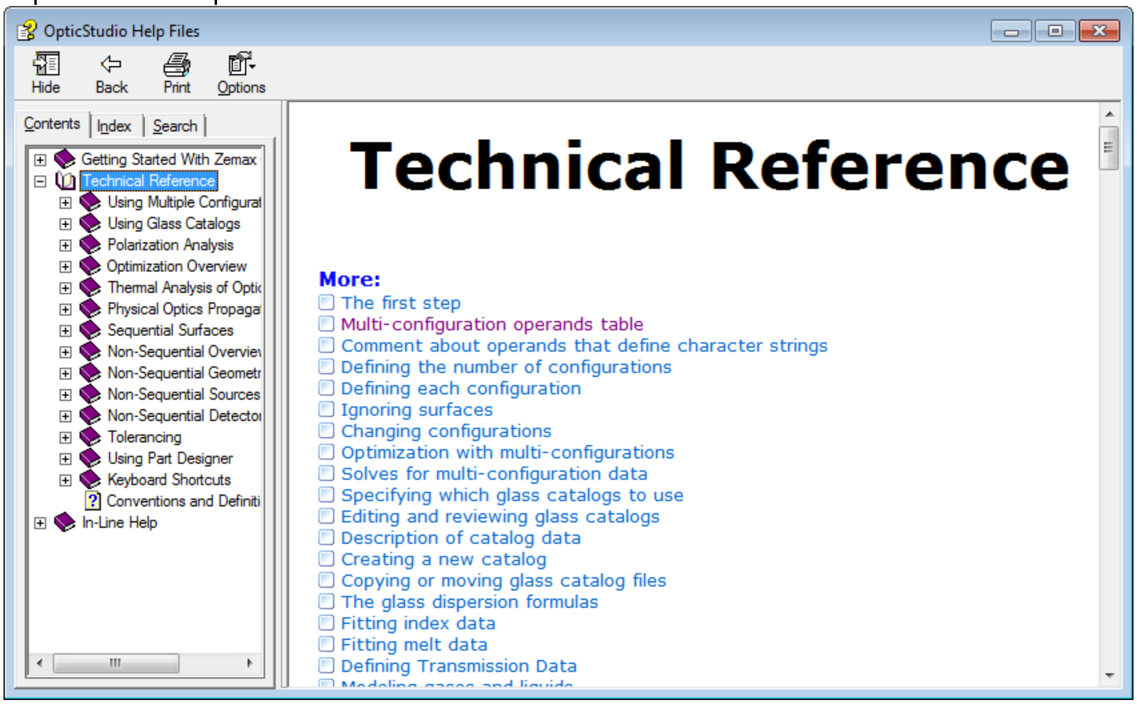
The goal was to get you started using OpticStudio in just an hour or two. There is plenty that is not covered. For example, it does not discuss Tolerancing, Physical Optics, thermal analysis, multi-beam interference in non-sequential mode, and many of the powerful analysis and optimization capabilities of OpticStudio.

Note: Just because it is not covered here does not mean that it's not in OpticStudio!

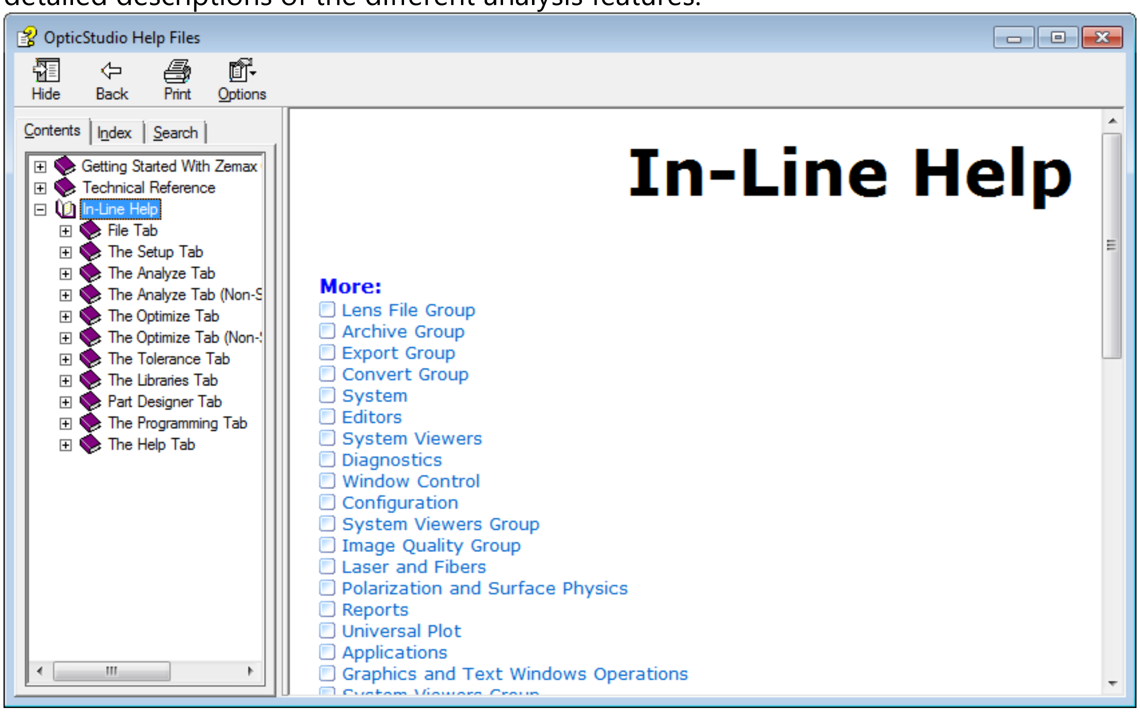
Here are some other resources that will help you:

- The OpticStudio Knowledge Base. This is an indispensable resource for OpticStudio users, and contains hundreds of articles including tutorials, answers to frequently-asked questions, and examples. It is structured into categories, and has a powerful search engine to help you find articles of interest easily.

- The Technical Reference files in the Help system give detailed discussions of the underlying capabilities of OpticStudio



- The In-Line Help files are accessed by clicking the Help "?" button in dialog boxes, and give detailed descriptions of the different analysis features.



- Zemax LLC and its team of international distributors offer dedicated training classes on the use of OpticStudio. Courses are held from introductory to advanced level, and cover all aspects of sequential lens design, illumination, stray light, programming OpticStudio and more. See www.zemax.com/training for more details.

Getting Technical Support

Please contact support@zemax.com, or your local distributor, if you need help in using OpticStudio! For help in the Chinese language, use china@zemax.com.

Note: It is vastly easier to resolve a technical problem with a sample file that demonstrates it. Of course, many customers are concerned about the confidentiality of their designs. We do not undertake any product development contract work. Therefore, if you have a technical question, you can be sure that you are not explaining your work to someone who may be working for a competitor, or bidding against you for the same job! Our goal is simply to help you use OpticStudio most effectively.

If you are still uncomfortable about sharing your design file, try simplifying it to the bare essentials necessary to show the problem, or use one of the >100 sample files supplied with OpticStudio instead.

Then please follow these steps:

- Make sure you are running the current version. Check For Updates in the Help tab. If you are eligible for technical support then you are eligible to run the current version. Make sure you can reproduce your problem with the current version as it contains fixes for all known bugs.
- Run System Check in the Setup tab to test your file for common setup errors.
- Email a full description of the problem to support@zemax.com or your local distributor. Please be sure you include:
    - Your name, organization, email address and phone number in case we need to talk directly with you.
    - The serial number of your OpticStudio key (run Help...About in OpticStudio to get this).
    - A clear description of your problem. Include the sample file that demonstrates the issue if you can.
    - Use File...Backup to Archive and send the resulting .ZAR file. This single file contains everything we need to reproduce your design exactly as you have it on your computer.

You will get a response within a maximum of one working day, and usually a lot sooner.

If support for your key is not current, you can renew it easily by sending an email to sales@zemax.com or your local distributor and requesting a quotation for support renewal.

References on Lens Design

Neither the Zemax program nor the Zemax documentation will teach you how to design lenses or optical systems. Although the program will do many things to assist you in designing and analyzing optical systems, you are still the designer. The Zemax documentation is not a tutorial on optical design, terminology, or methodology. Technical support available to Zemax users includes assistance in using the program, but does not include tutoring on fundamental optical design principles. If you have little or no experience in optical design, you may want to read up on any of the many good books available on the subject. The following table lists some (but by no means all) of the books which will aid in your education.

REFERENCES

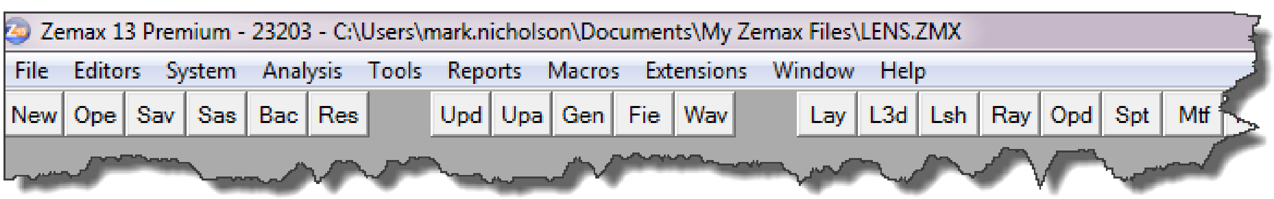
Author	**Title**	**Publisher**
Bass	Handbook of Optics	McGraw-Hill
Born & Wolf	Principles of Optics	Pergamon Press
Fischer & Tadic-Galeb	Optical System Design	McGraw-Hill
Geary, Joseph M.	Introduction to Lens Design: With Practical Zemax Examples	Willmann-Bell
Hecht	Optics	Addison Wesley
Kingslake, Rudolph	Lens Design Fundamentals	Academic Press
Laikin, Milton	Lens Design, Third Edition	Marcel Dekker
Mahajan, Virendra	Aberration Theory Made Simple	SPIE Optical Engineering Press
O' Shea, Donald	Elements of Modern Optical Design	John Wiley and Sons
Rutten and van Venrooij	Telescope Optics	Willmann-Bell
Shannon, Robert	The Art and Science of OpticalDesign	Cambridge University Press
Smith, Gregory Hallock	Practical Computer-Aided Lens Design	Willmann-Bell, Inc.
Smith, Warren	Modern Optical Engineering	McGraw-Hill
Smith, Warren	Modern Lens Design	McGraw-Hill
Welford	Aberrations of Optical Systems	Adam Hilger Ltd.
Welford	Useful Optics	University of Chicago Press

Most importantly, Zemax is not a substitute for good engineering practices. No design should ever be considered finished until a qualified engineer has checked the calculations performed by the software to see if the results are reasonable. This is particularly important when a design is to be fabricated and significant costs are involved. It is the engineers responsibility to check the results of Zemax, not the other way around.

Converting from Zemax13 and Older

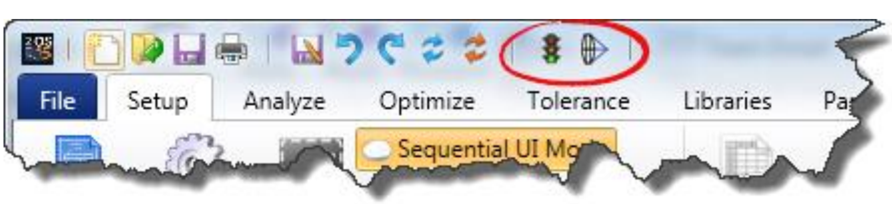
This section of the Getting Started Using Zemax OpticStudio guide is aimed at those users upgrading from earlier versions of Zemax (Zemax 13 and earlier). In this section we map the user interface of the previous versions of Zemax to their current locations, and highlight any changes of significance.

We also recommend you read the Navigating the OpticStudio Interface section for full instructions on how to use the new UI.

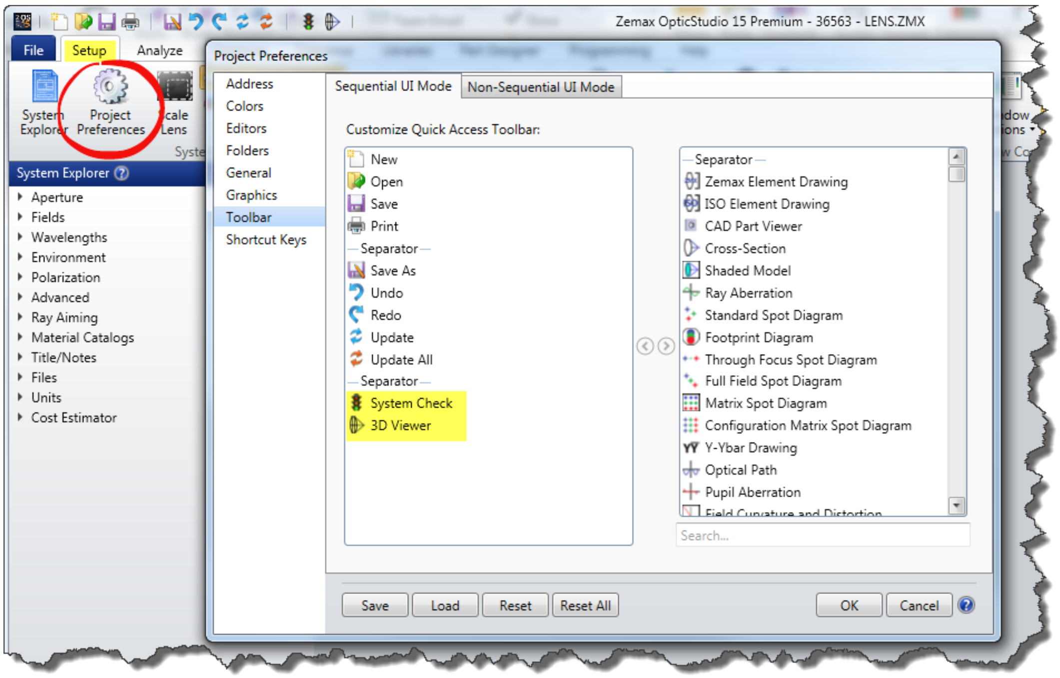


In the following section we will look at each Z13 menu and see where its contents have now moved to.

Note that the button bar used in Z13 is obsolete, and instead you place any feature you want directly onto the Quick-Access toolbar in OpticStudio:

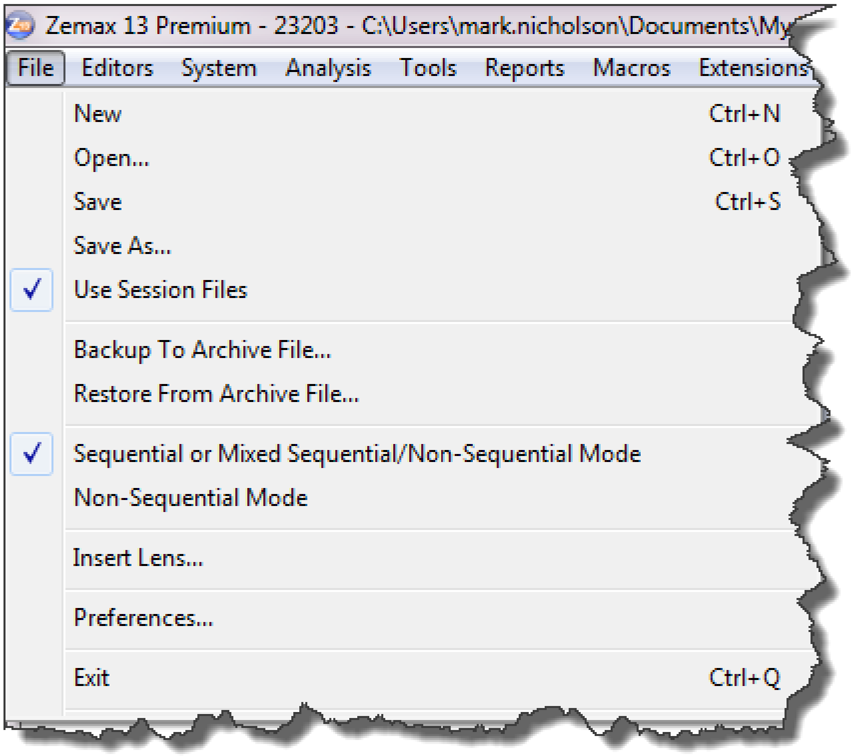


In the Setup tab, click on the Project Preferences icon and simply drag and drop the features you want onto the Quick-Access toolbar.

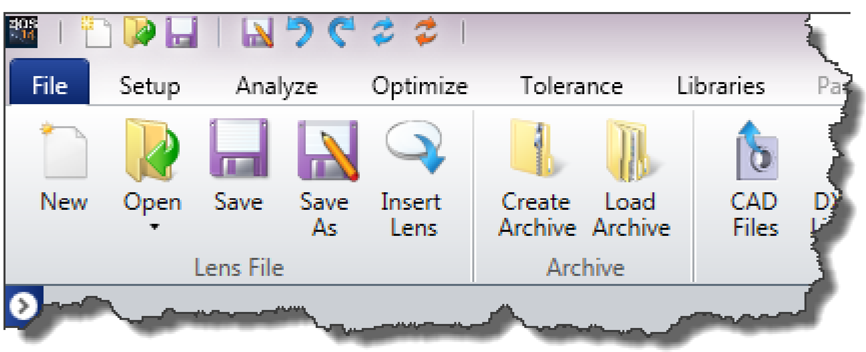


All keyboard shortcuts used by Z13 still work in OpticStudio!

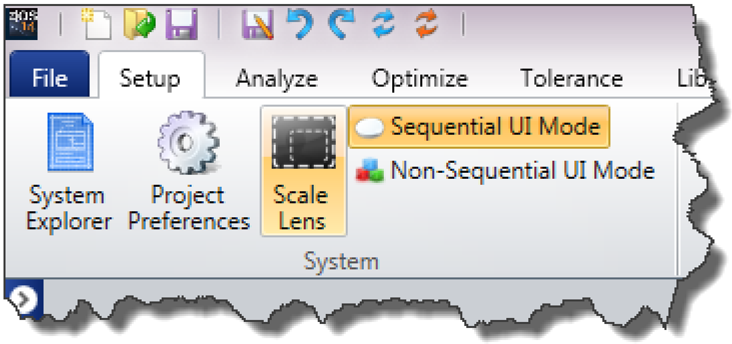
Zemax 13 File Menu



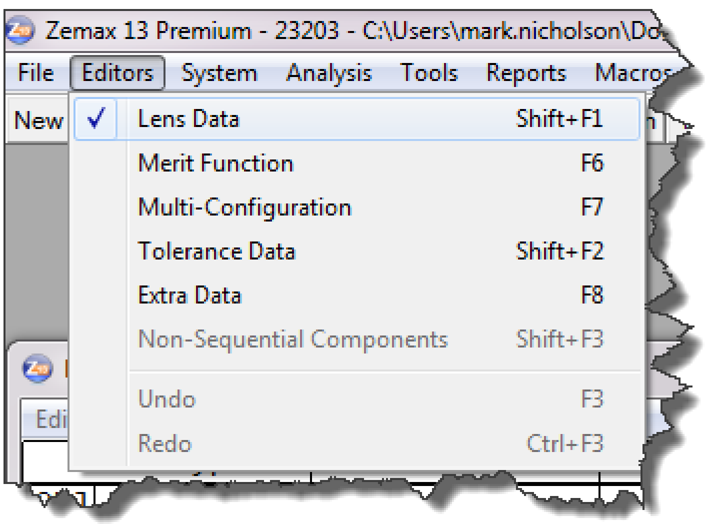
Almost all of these features have moved to the File tab in OpticStudio



Except for the Program Mode and Preferences, which are now on the Setup tab:



Zemax 13 Editors menu

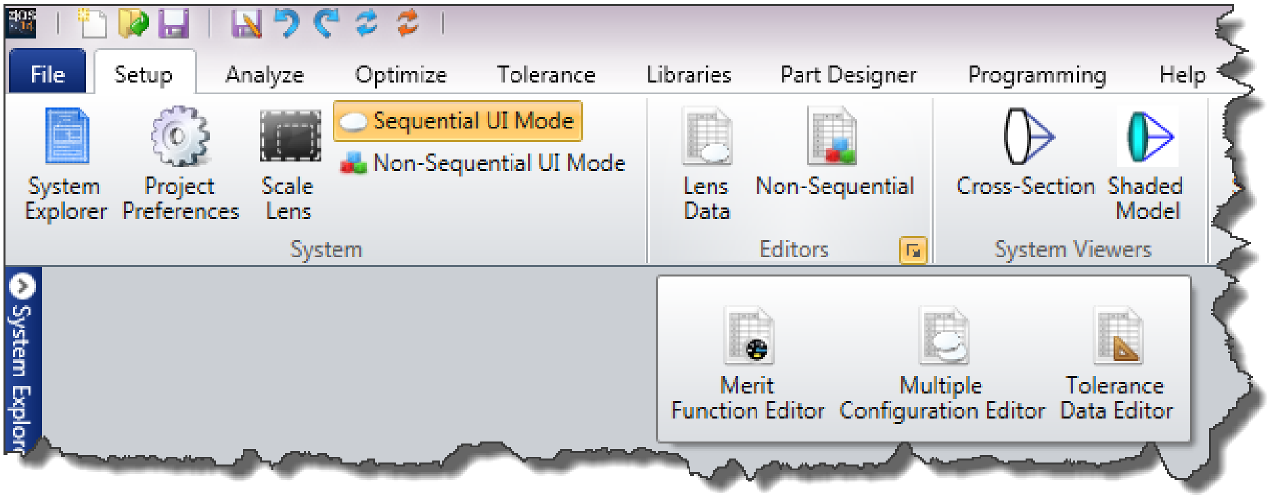


The biggest change here is that the Extra Data Editor is now obsolete. Extra Data is now appended onto the Lens Data Editor. The Lens Data Editor in Z13 uses parameters 0 through 12. In OpticStudio, extra data now appears from Parameter 13 onwards, and ther LDE simply scales in size to accommodate however much data you need.

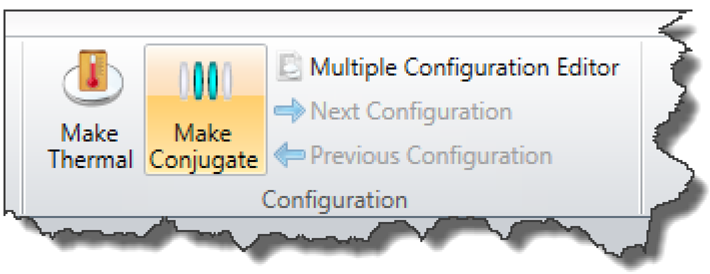
All Z13 and older files are read and remapped automatically by OpticStudio. Tolerance operands, multiconfiguration operands and optimization operands that referred to Extra Data parameter numbers are now remapped to use parameter data operands instead. As a result, .zmx files produced by OpticStudio can not be read successfully by older versions if the file contains extra data operands in the merit, multi-configuration or tolerance editors.

In Extensions and ZPL macros you can address (previously) Extra Data items using either extra data operands or parameter operands with the parameter number >12.

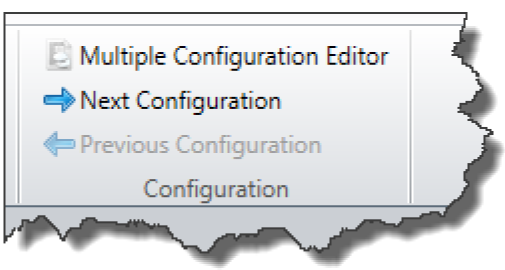
Editors can be found in the Setup tab in the Editors group, which shows the two main editors and can expand to show all editors:



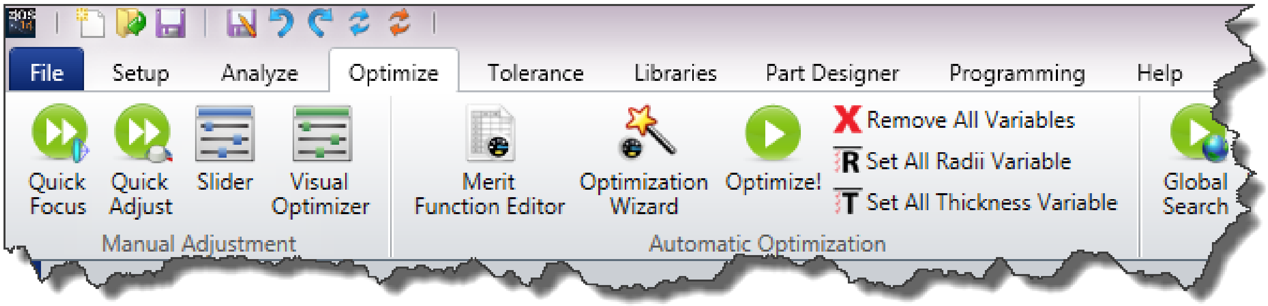
The Multi-Configuration Editor is also available from the Configuration group of the Setup tab:



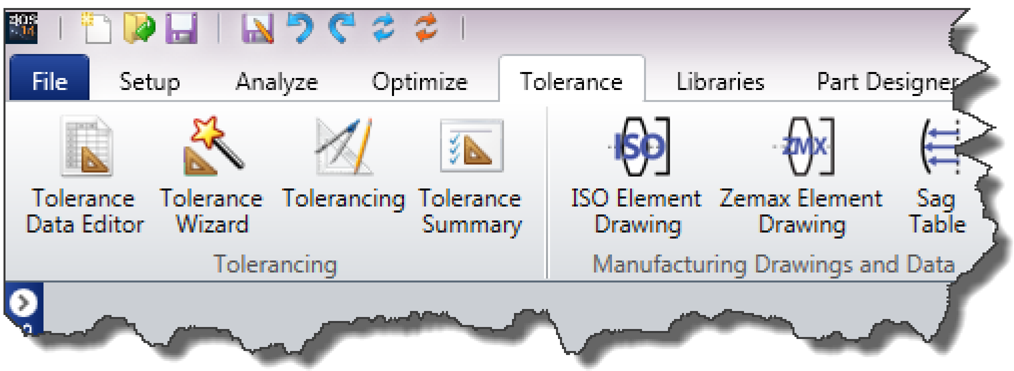
If more than one configuration exists in the MC editor, a smaller Configuration group appears on the Analyze, Optimize and Tolerance tabs also:



The Merit Function Editor is also available in the Optimize tab, and the Default Merit Function tool is renamed the Optimization Wizard:

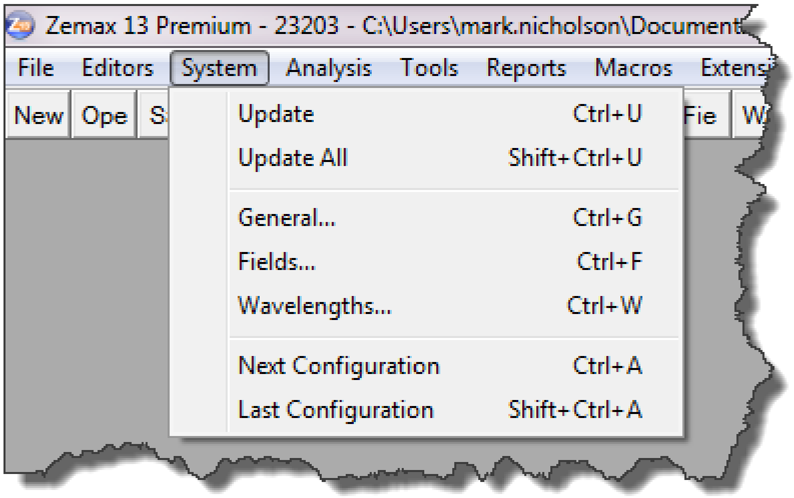


The Tolerance Data Editor is also available in the Tolerance tab, and the Default Tolerances tool is now called the Tolerance Wizard:

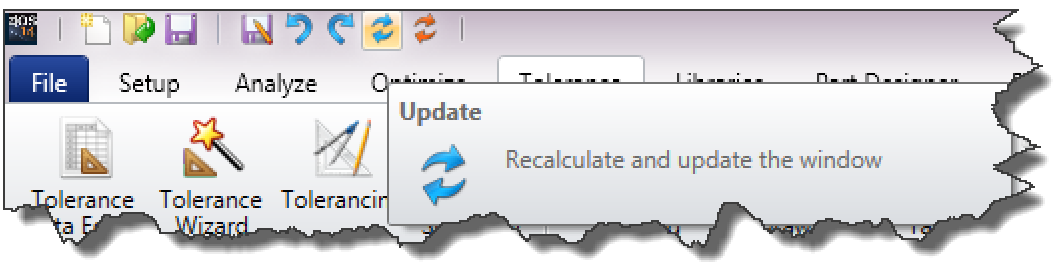


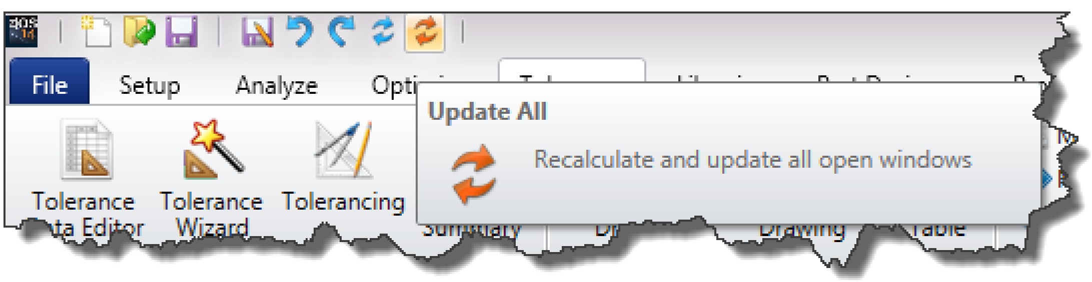
The Editors have been completely re-written to provide a modern, intuitive spreadsheet capability. See the Navigation guide for full details.

Zemax 13 System Tab

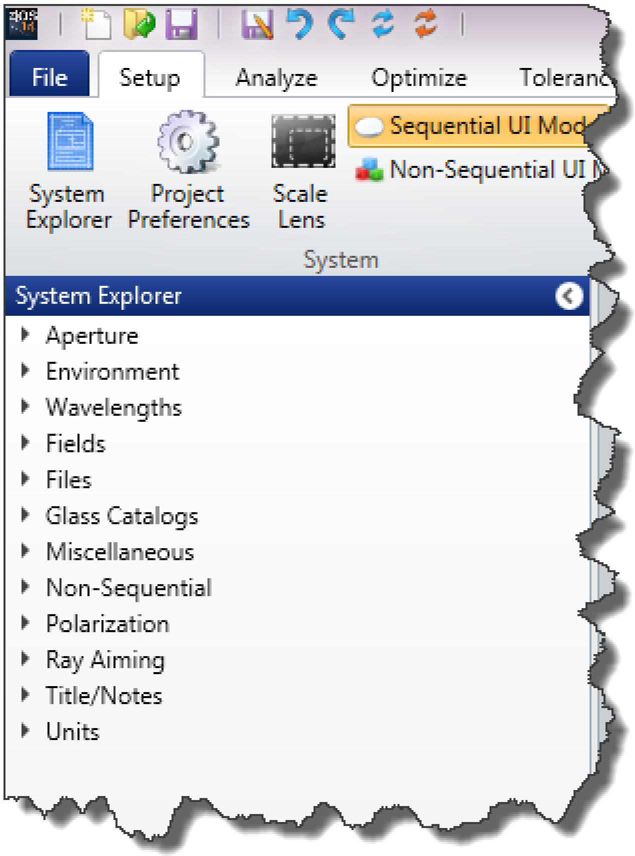


Update and Update All are moved to the Quick-Access toolbar:

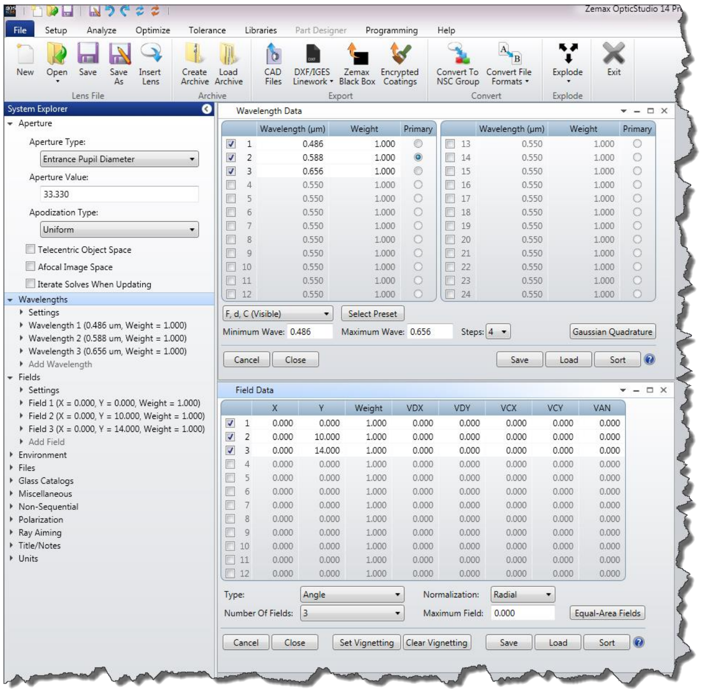




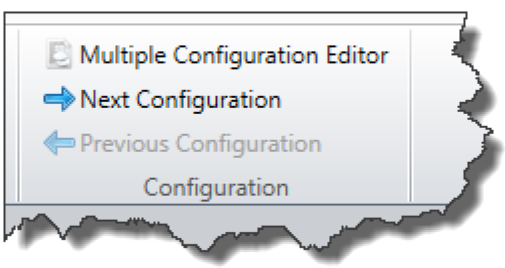
The General, Fields and Wavelengths menu items are now combined in the System Explorer, which is available via the sidebar or the System Explorer icon in the Setup tab:



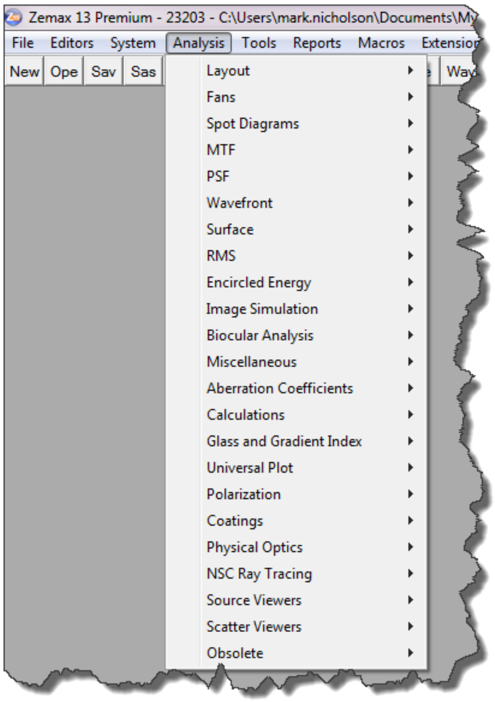
Filed and Wavelength data can be entered directly in the System Editor, or their older-style dialogs can be invoked by double-clicking on the top lines of either the Fields or Wavelengths group:



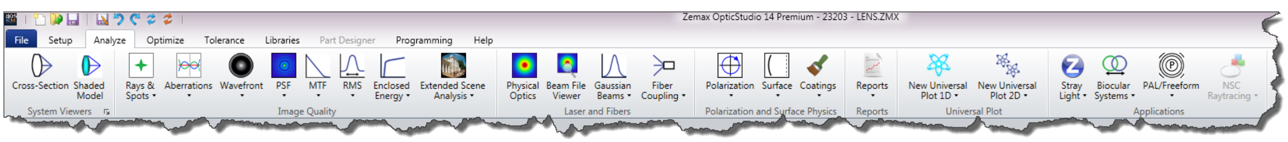
The Next and Last Configuration controls are on the Configuration group of the Setup tab, and if the design has more than one configuration are also available on the Analyze, Optimize and Tolerance tabs.



Zemax 13 Analysis Menu

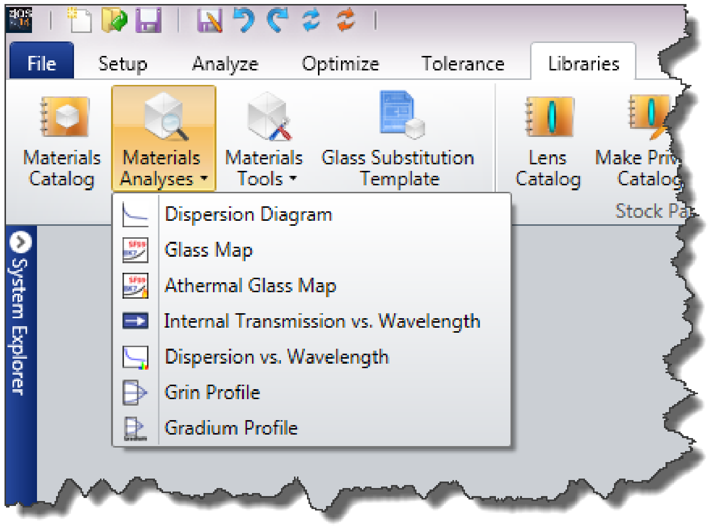


Almost everything on this menu has moved to the Analyze tab:

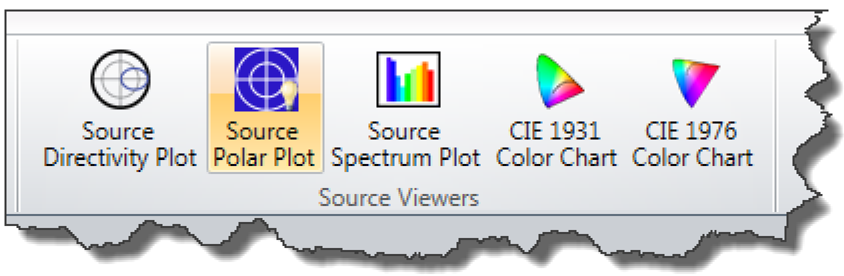


With the following exceptions:

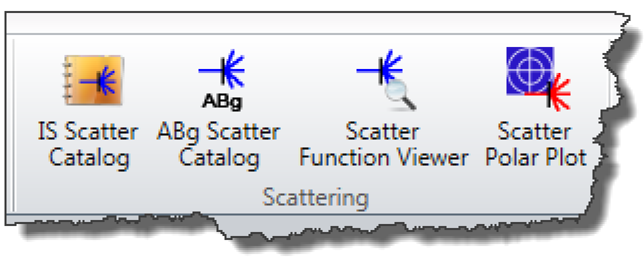
- Glass and Gradient Index now appears in the Optical materials group of the Libraries tab



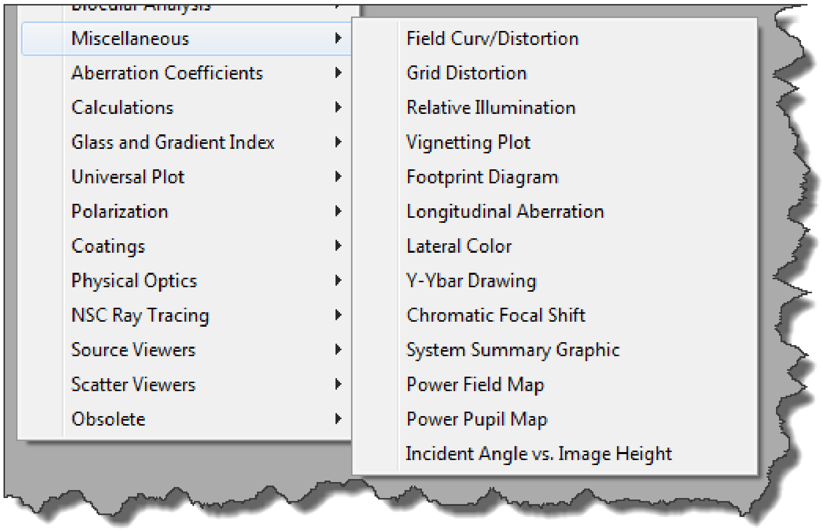
- Source Viewers have moved to the Source Viewers group in the Libraries tab

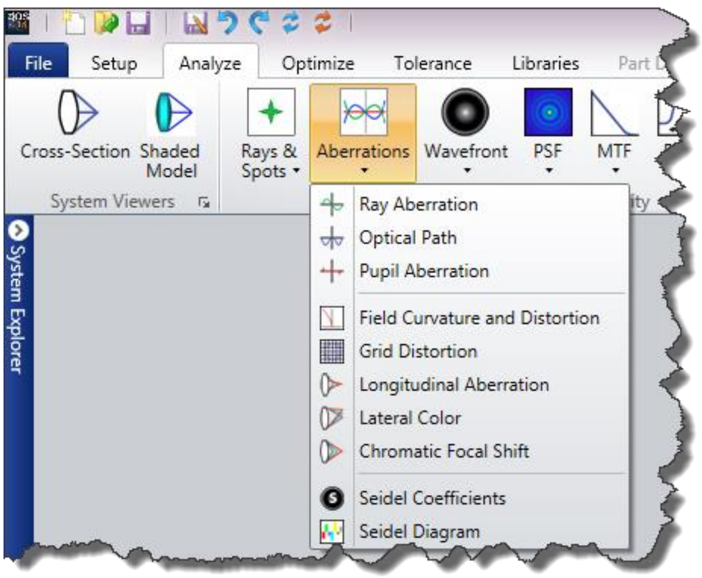


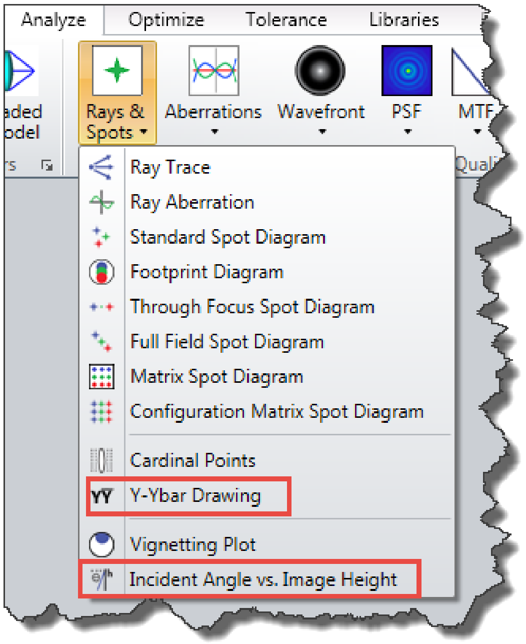
- Scatter Viewers have moved to the Scatter Viewers group in the Libraries tab:

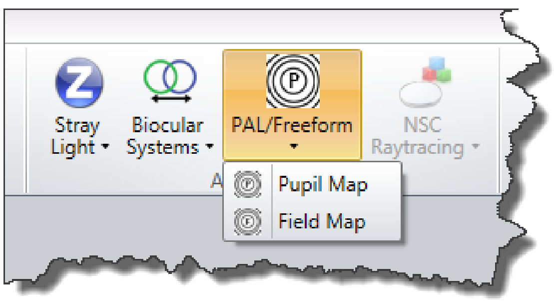


- The items under Miscellaneous have been placed in more meaningful locations:

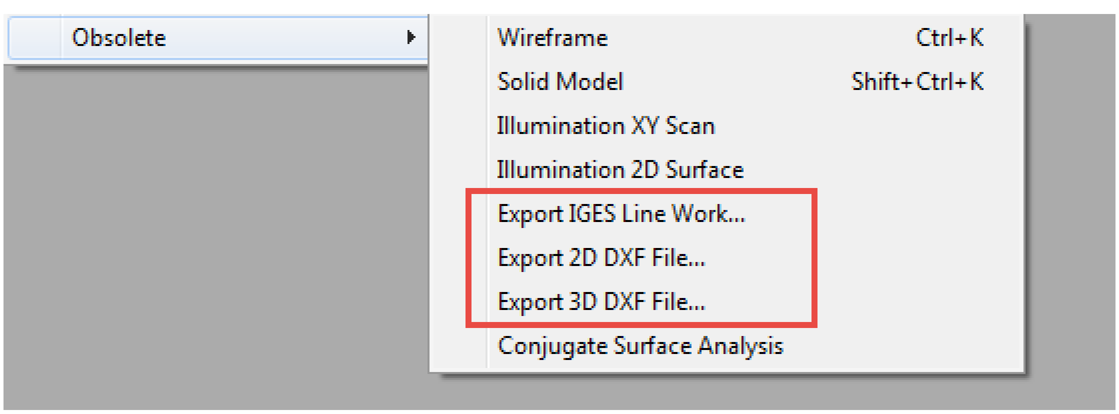

Miscellaneous
Aberration Coefficients
Calculations
Glass and Gradient Index
Universal Plot
Polarization
Coatings
Physical Optics
NSC Ray Tracing
Source Viewers
Scatter Viewers
Obsolete
Field Curv/Distortion
Grid Distortion
Relative Illumination
Vignetting Plot
Footprint Diagram
Longitudinal Aberration
Lateral Color
Y-Ybar Drawing
Chromatic Focal Shift
System Summary Graphic
Power Field Map
Power Pupil Map
Incident Angle vs. Image Height


File
Setup
Analyze
Optimize
Tolerance
Libraries
Cross-Section
Shaded Model
Rays & Spots
Aberrations
Wavefront
PSF
MTF
System Viewers
System Explorer
Ray Aberration
Optical Path
Pupil Aberration
Field Curvature and Distortion
Grid Distortion
Longitudinal Aberration
Lateral Color
Chromatic Focal Shift
Seidel Coefficients
Seidel Diagram

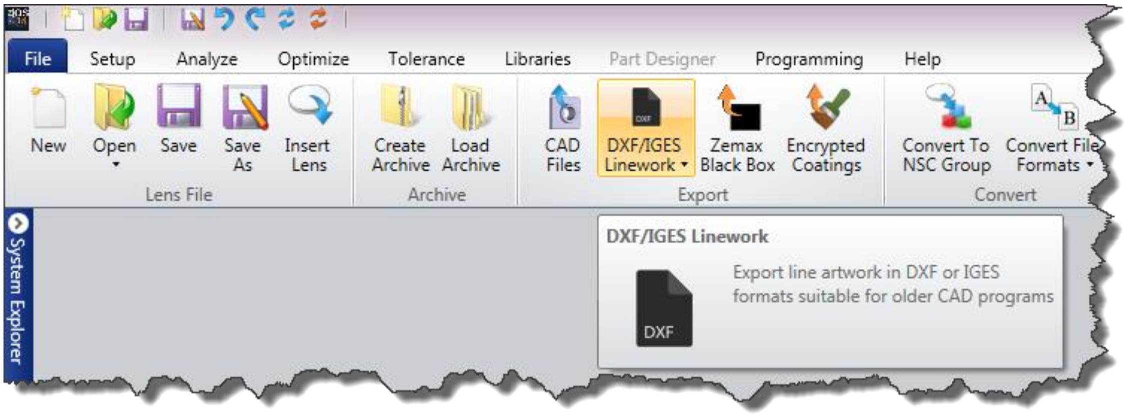




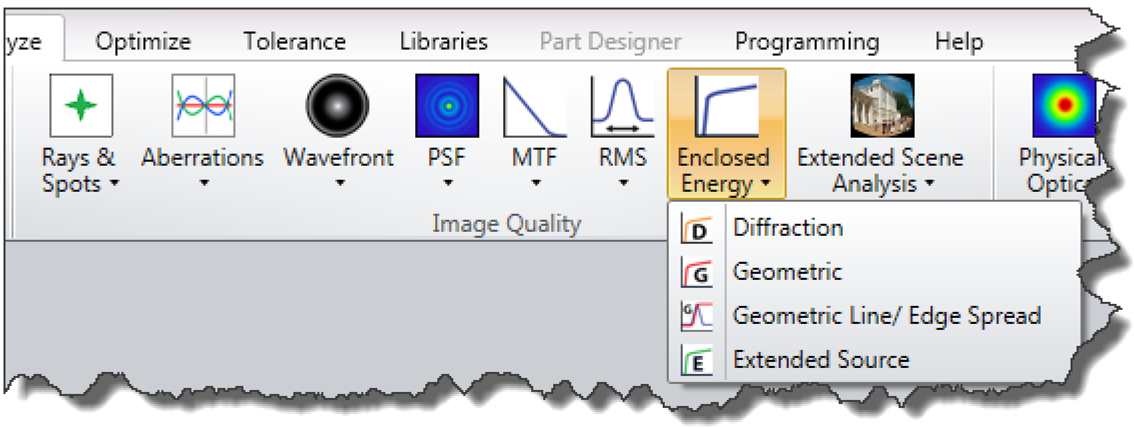
- The items under Obsolete have been removed, except for



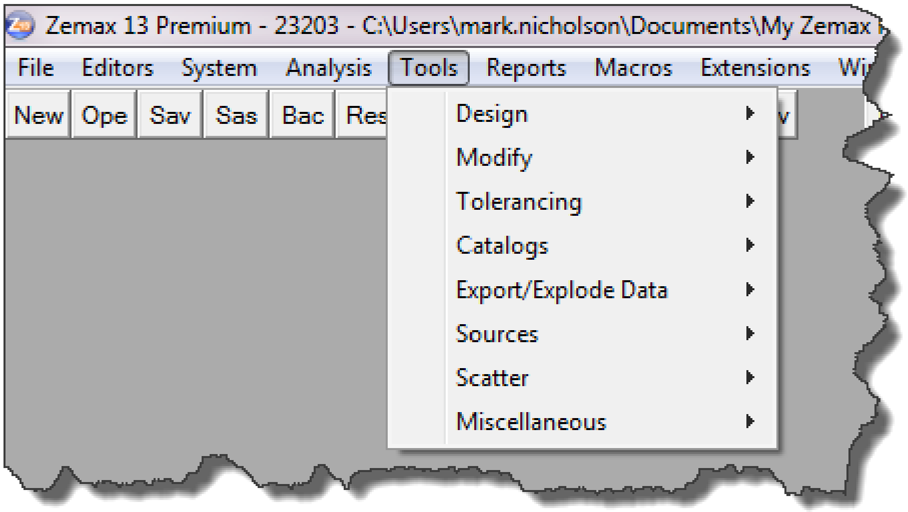
which now appear in the Export group of the File tab:



- Encircled Energy is now called Enclosed Energy as circles are not the only option ☺

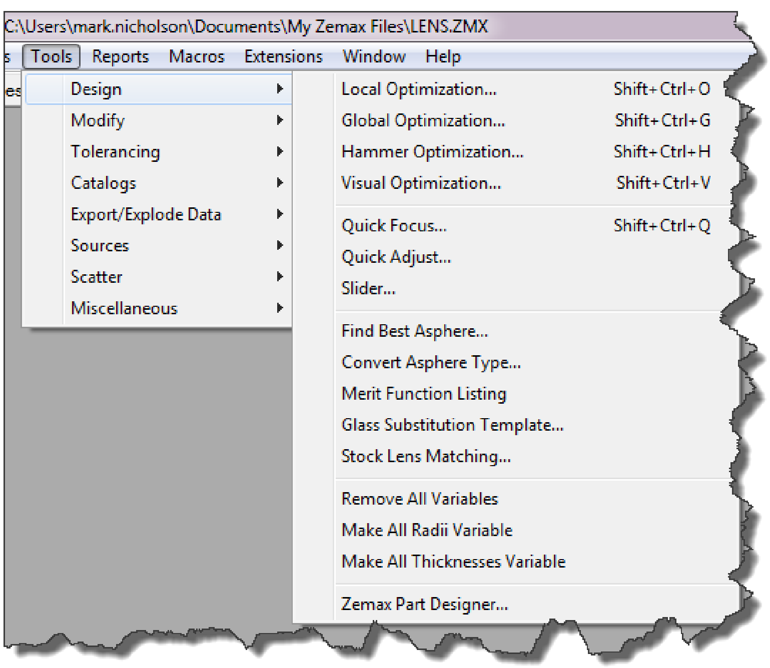


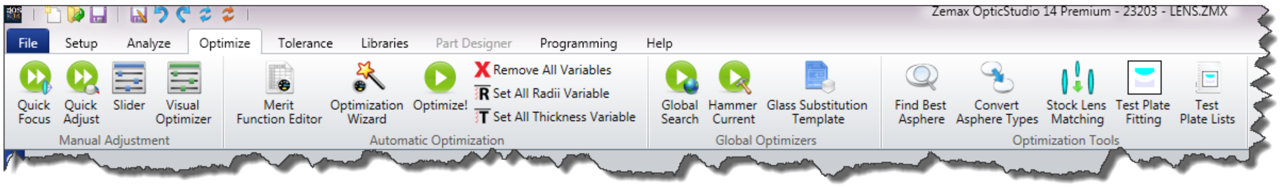
Zemax 13 Tools Menu



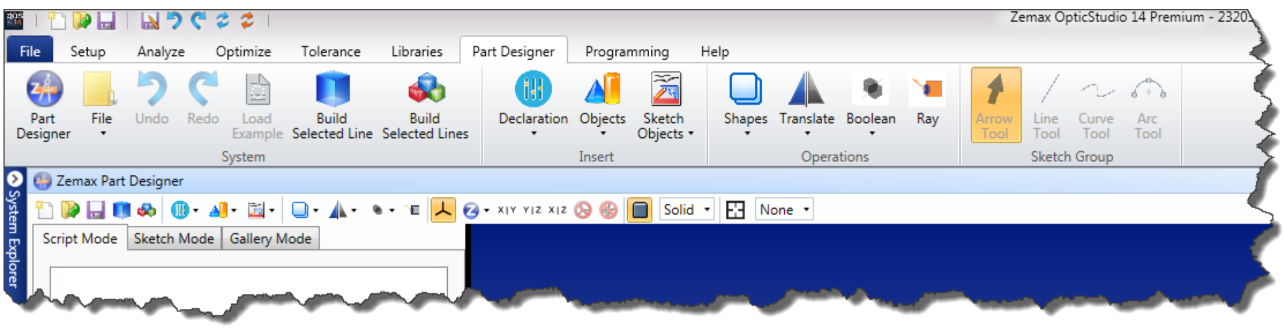
This entire menu is now obsolete, and items have either been moved to their own tabs or to the toolbars of the appropriate editor.

Tools...Design is now the Optimize tab

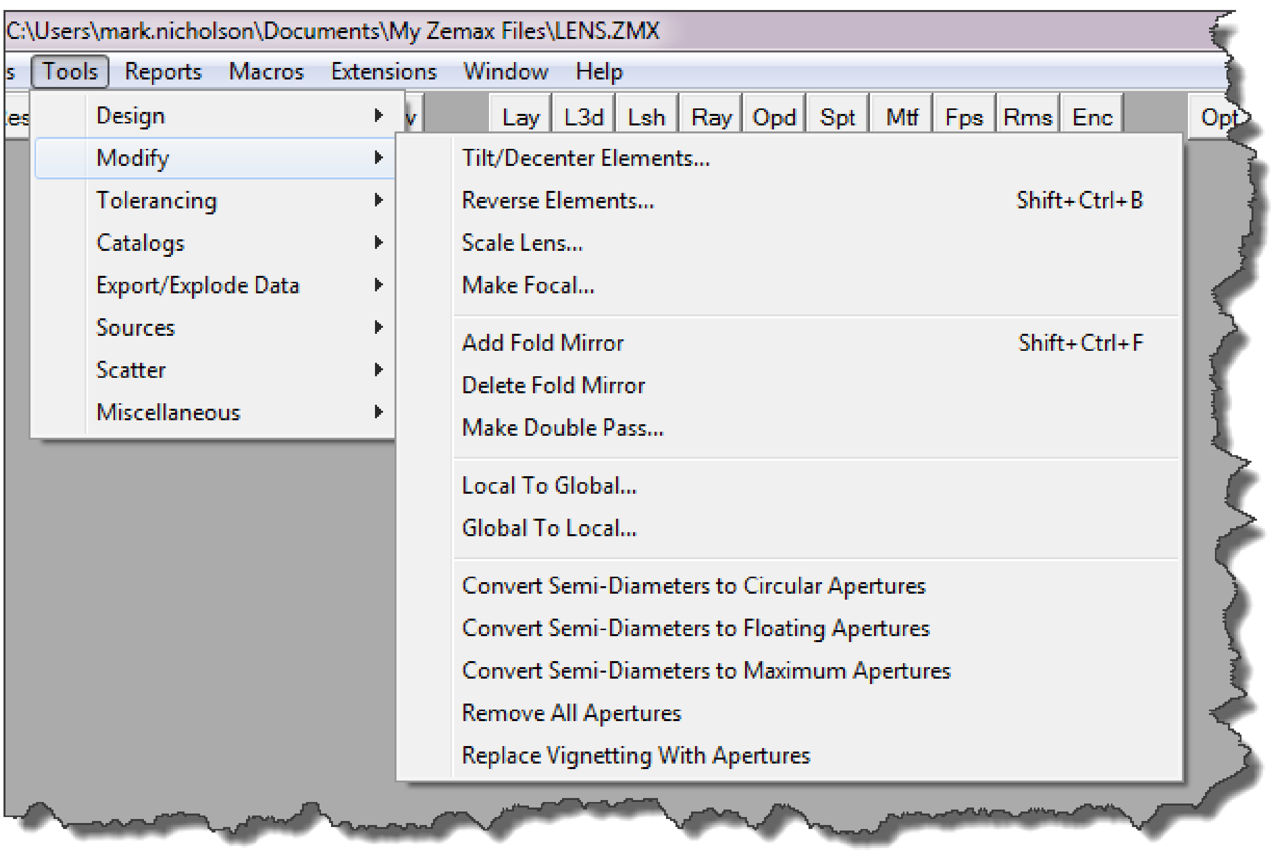


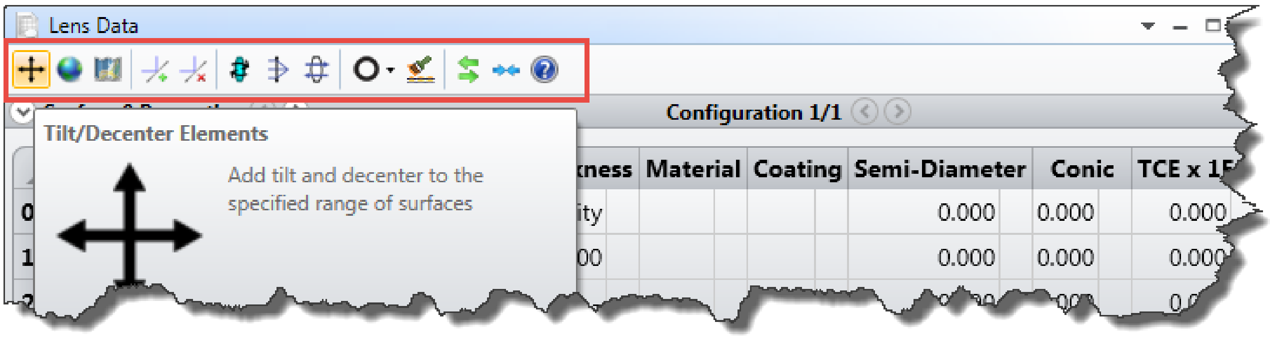


And the Zemax Part Designer is now a built-in capability with its own tab, which is available only in non-sequential mode, or if you have the Premium version of OpticStudio:

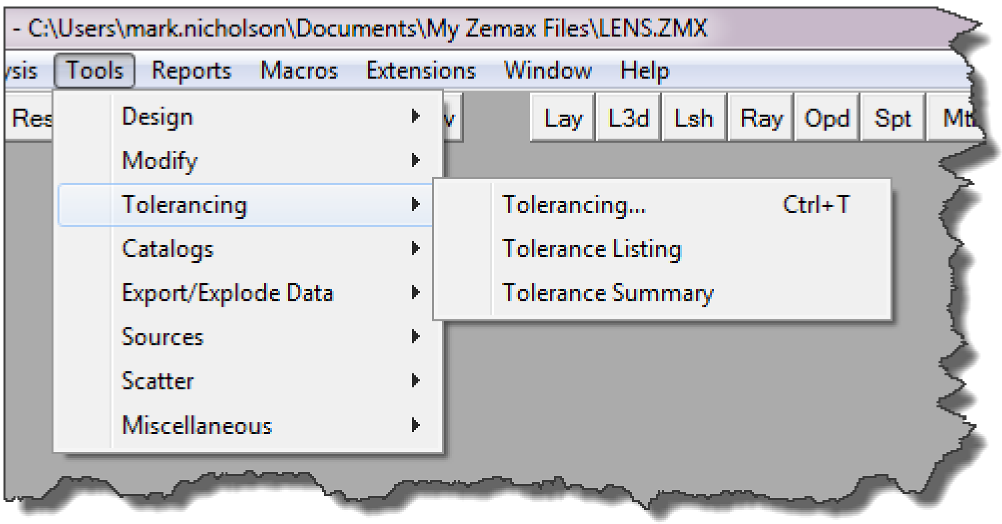


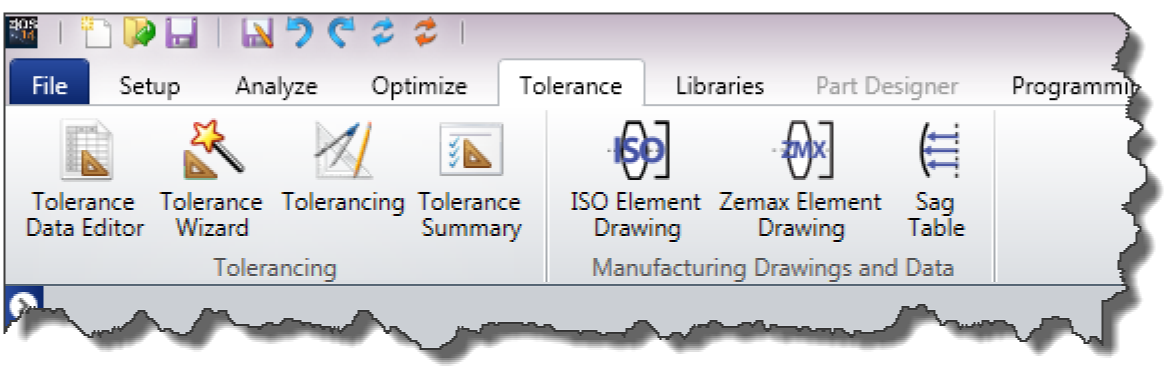
Tools...Modify has moved to the toolbar of the Lens Data Editor:



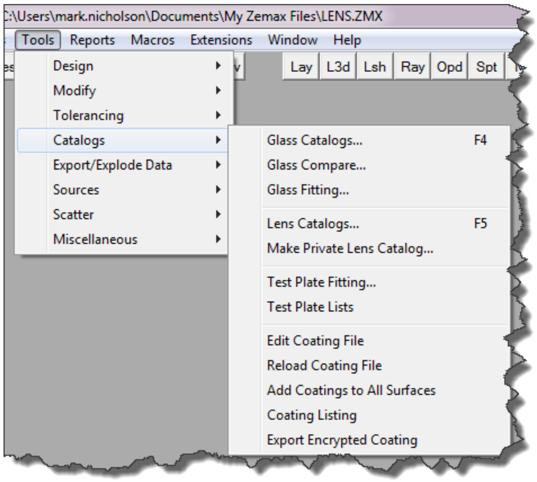


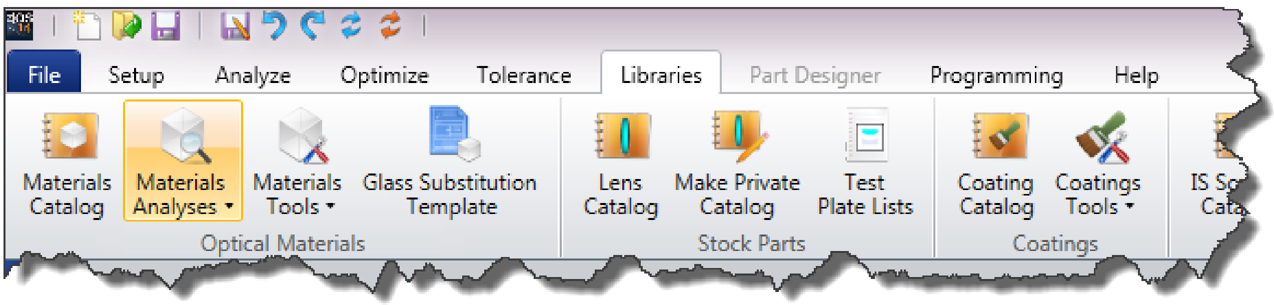
Tools…Tolerancing has become the Tolerance tab:



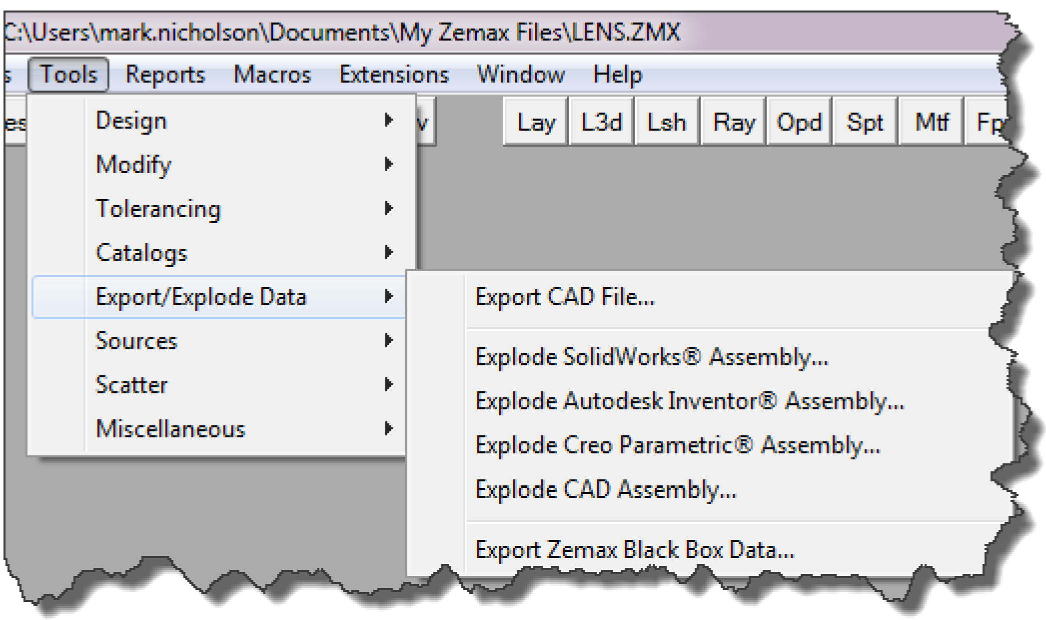


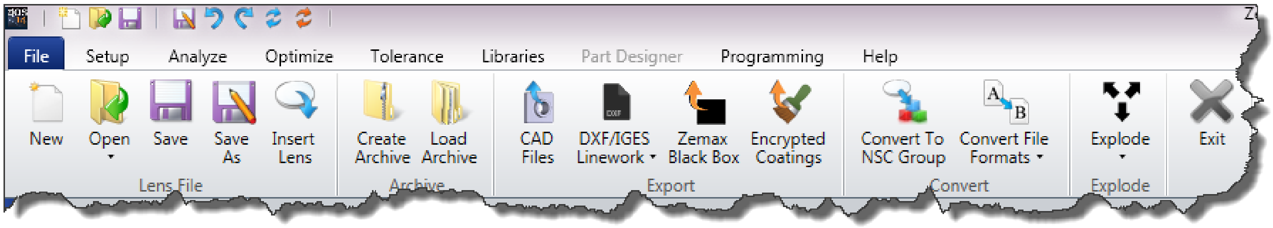
Tools…Catalogs has become the Libraries tab:



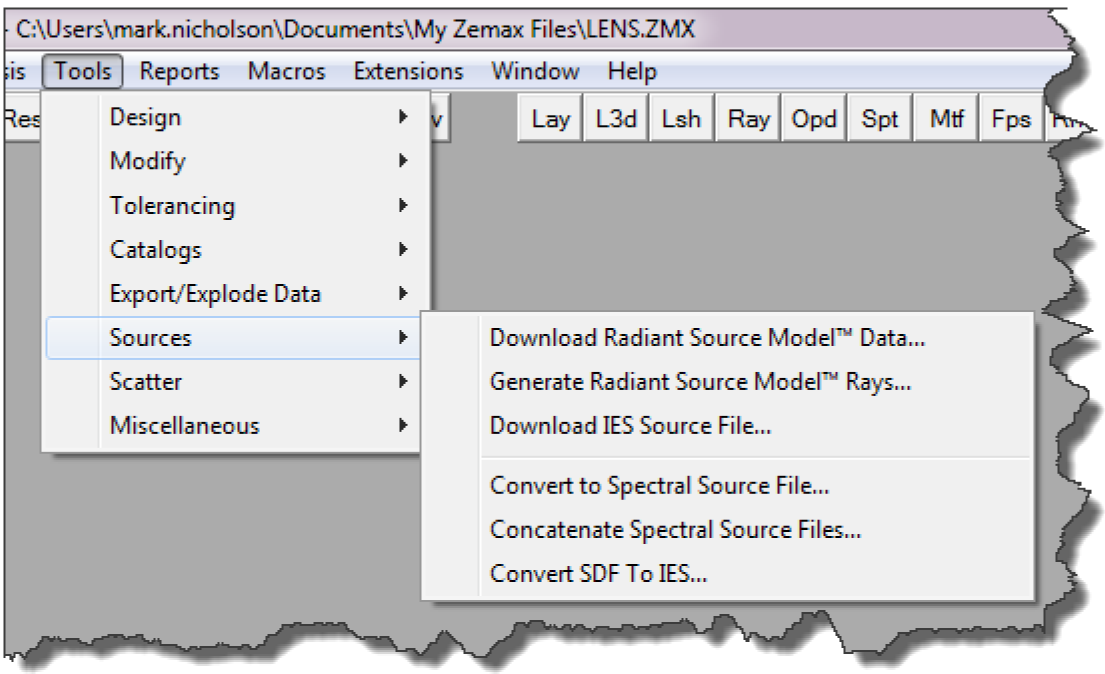


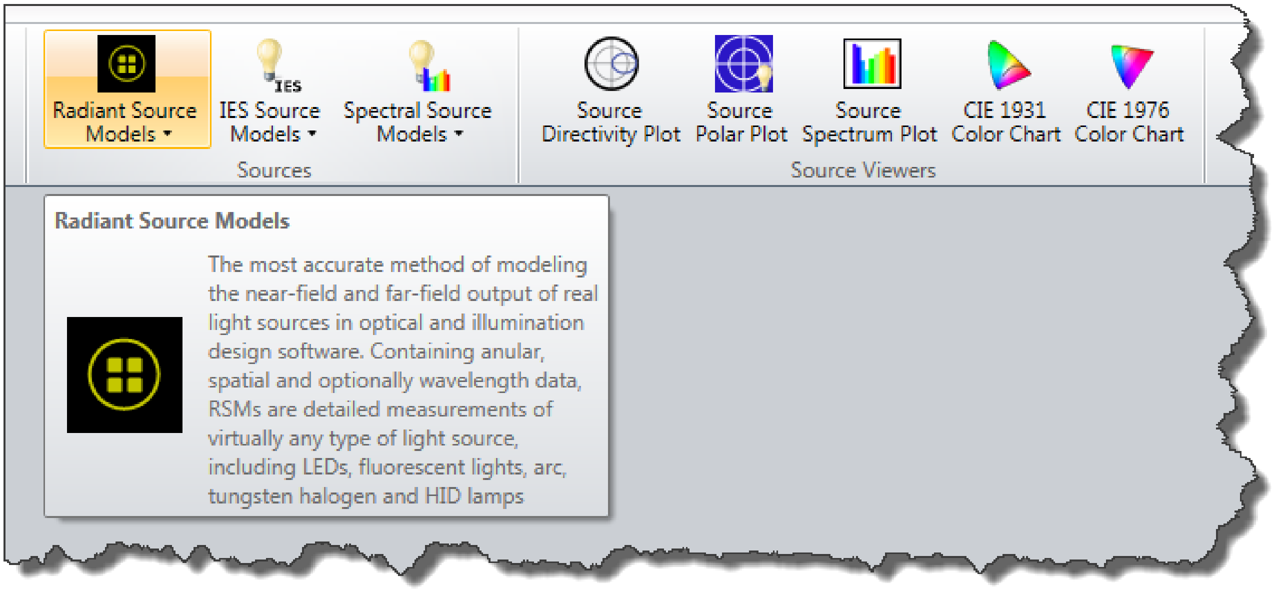
Tools...Export/Explode has moved to the Export and Explode groups on the File tab



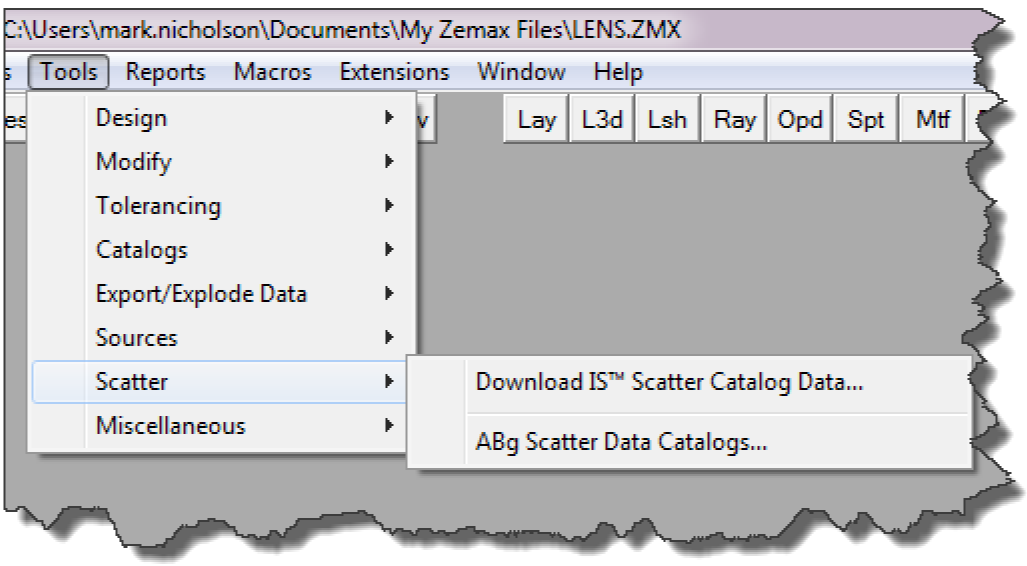


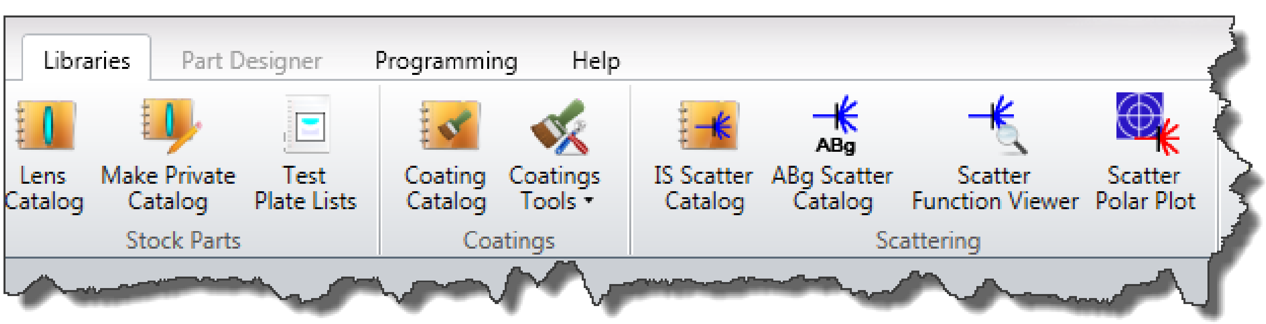
Tools…Sources has moved to the Sources group on the Libraries tab:



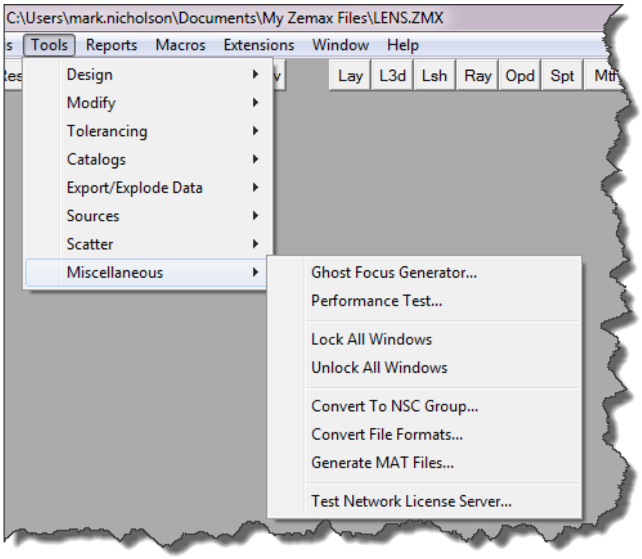


Tools...Scatter has moved to the Scatter group of the Libraries tab

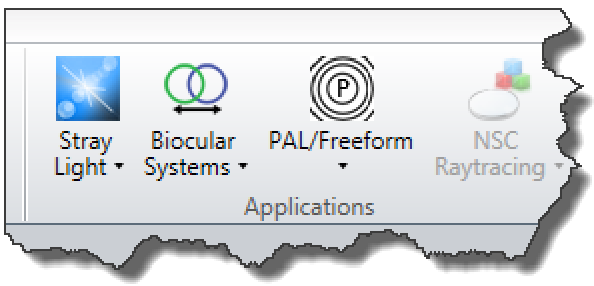


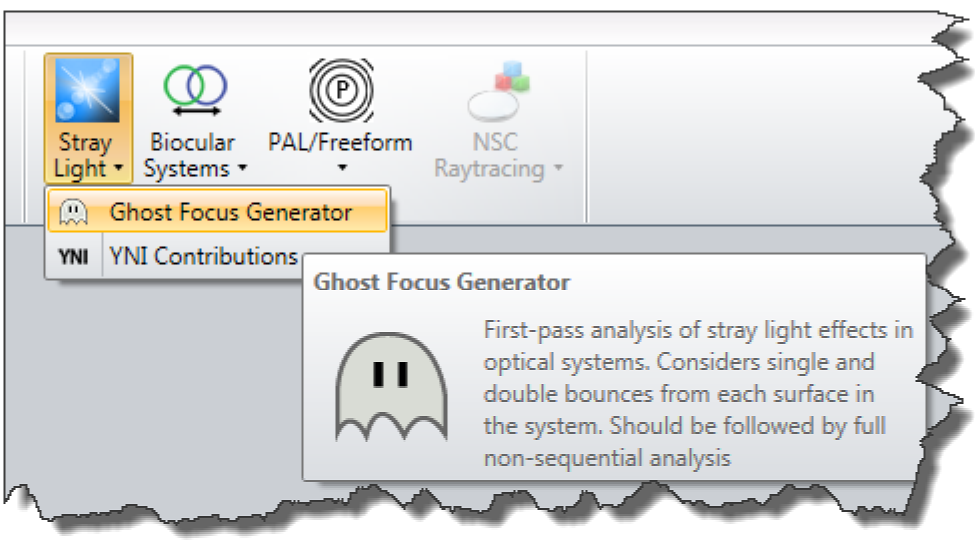


Tools...Miscellaneous is obsolete and its features have been placed in more meaningful locations:

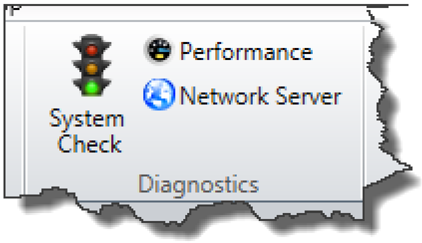


The Ghost Focus Generator is now on the Analyze tab, in the Applications Group

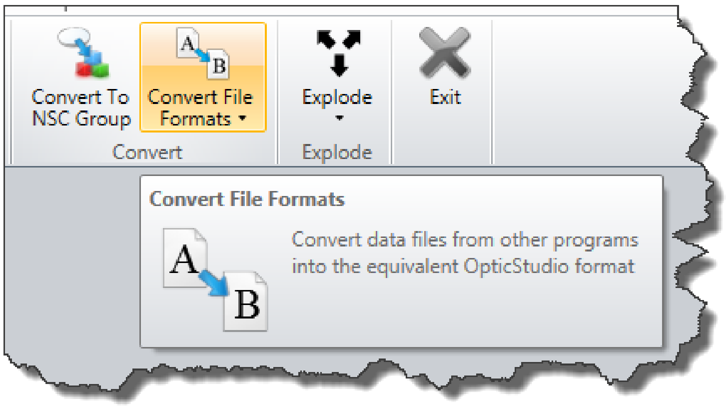


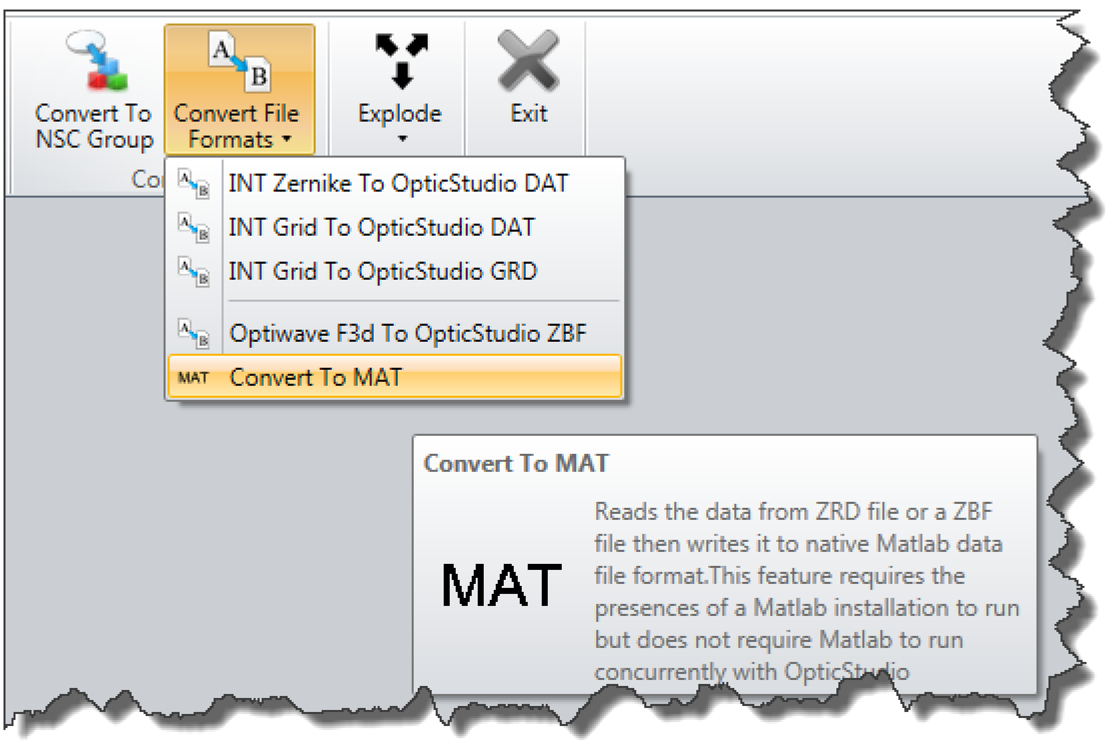


The Performance Test and Test Network Server are now in the Diagnostics group of the Setup tab:

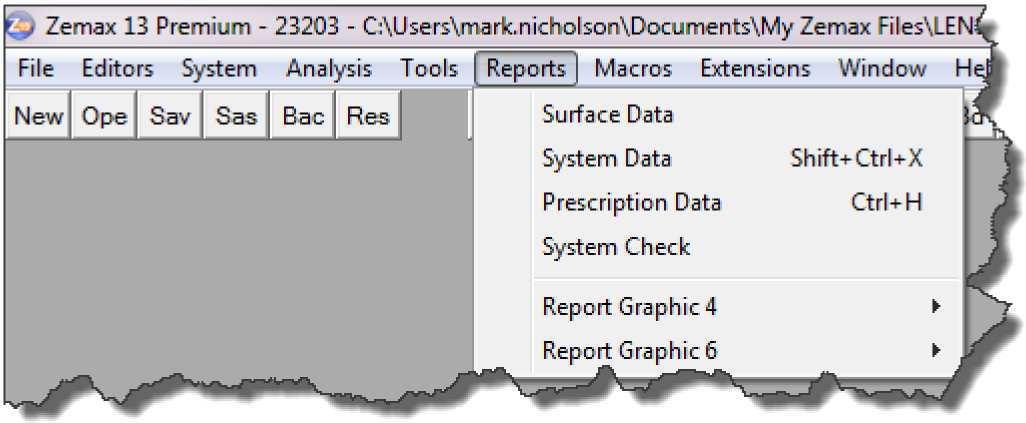


The file conversion and MatLab® export tools are now on the File tab Convert group:

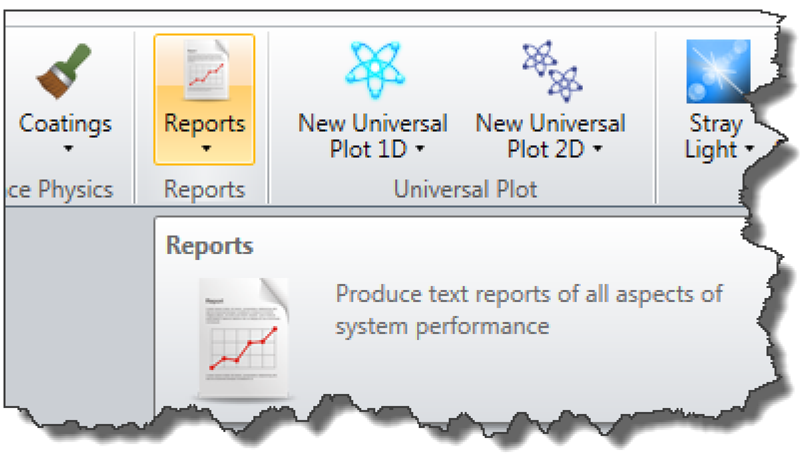


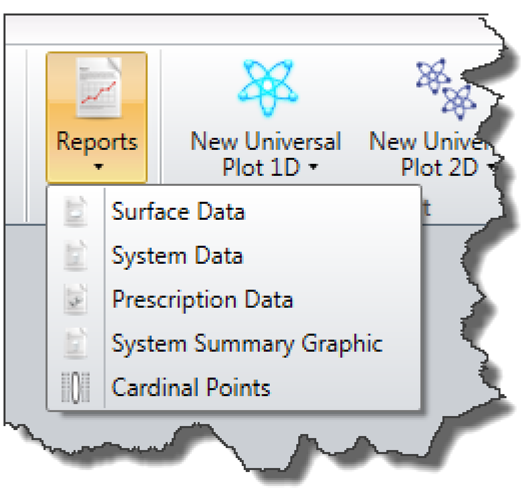


Zemax 13 Reports Menu



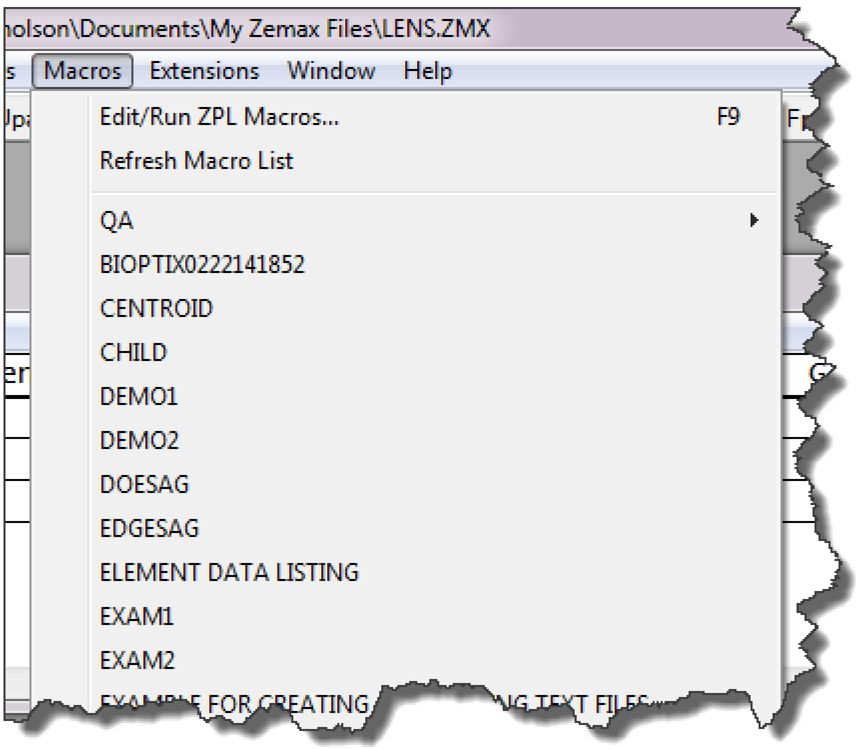
These are now in the Reports group on the Analyze tab:



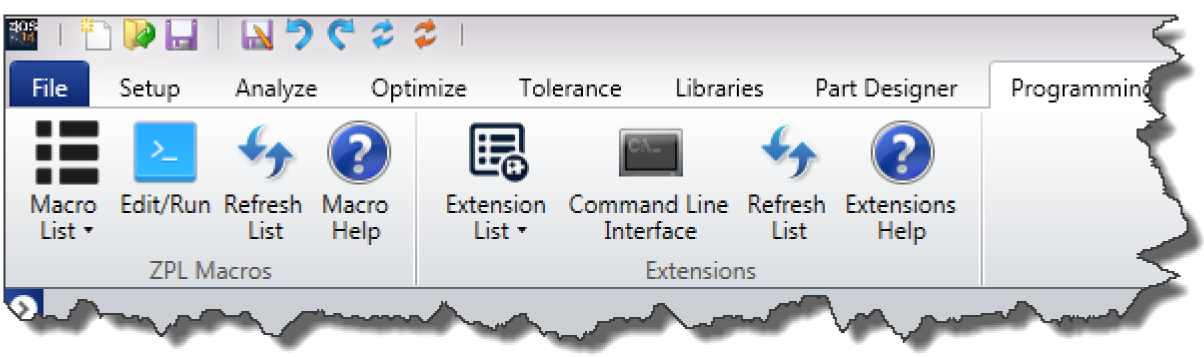


Note that the Report Graphic 4 and Report Graphic 6 have no equivalent in OpticStudio. These features were only supported by the Z13 graphics engine. A replacement feature will be incorporated in a future release.

Zemax 13 Macros Menu

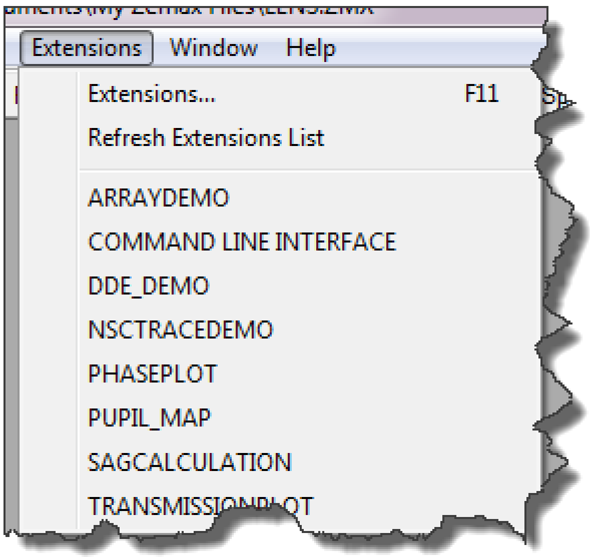


This is now in the ZPL Macros group of the Programming tab

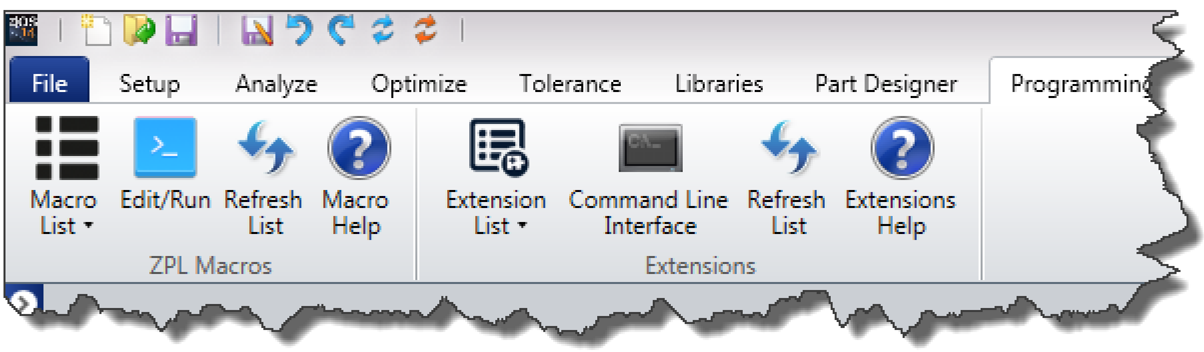


A built-in macro editor is now provided.

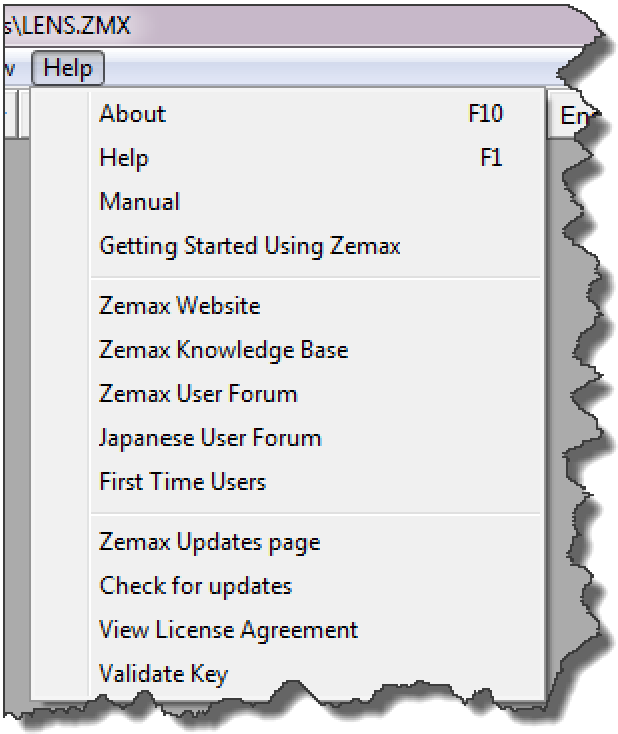
Zemax 13 Extensions Menu



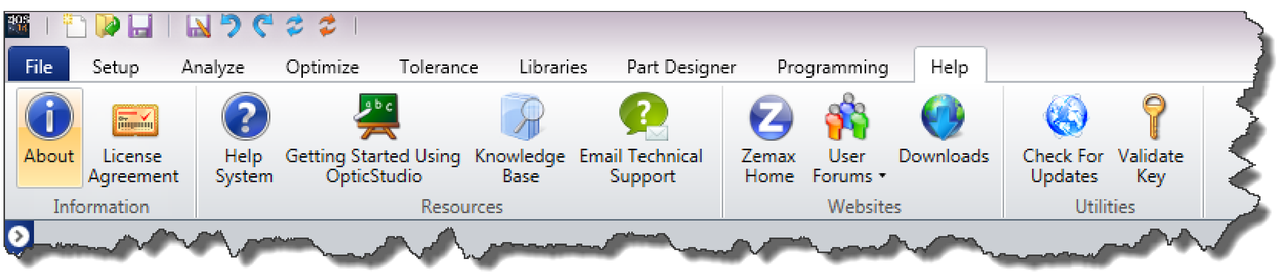
This is now in the Extensions group of the Programming tab



Zemax 13 Help Menu



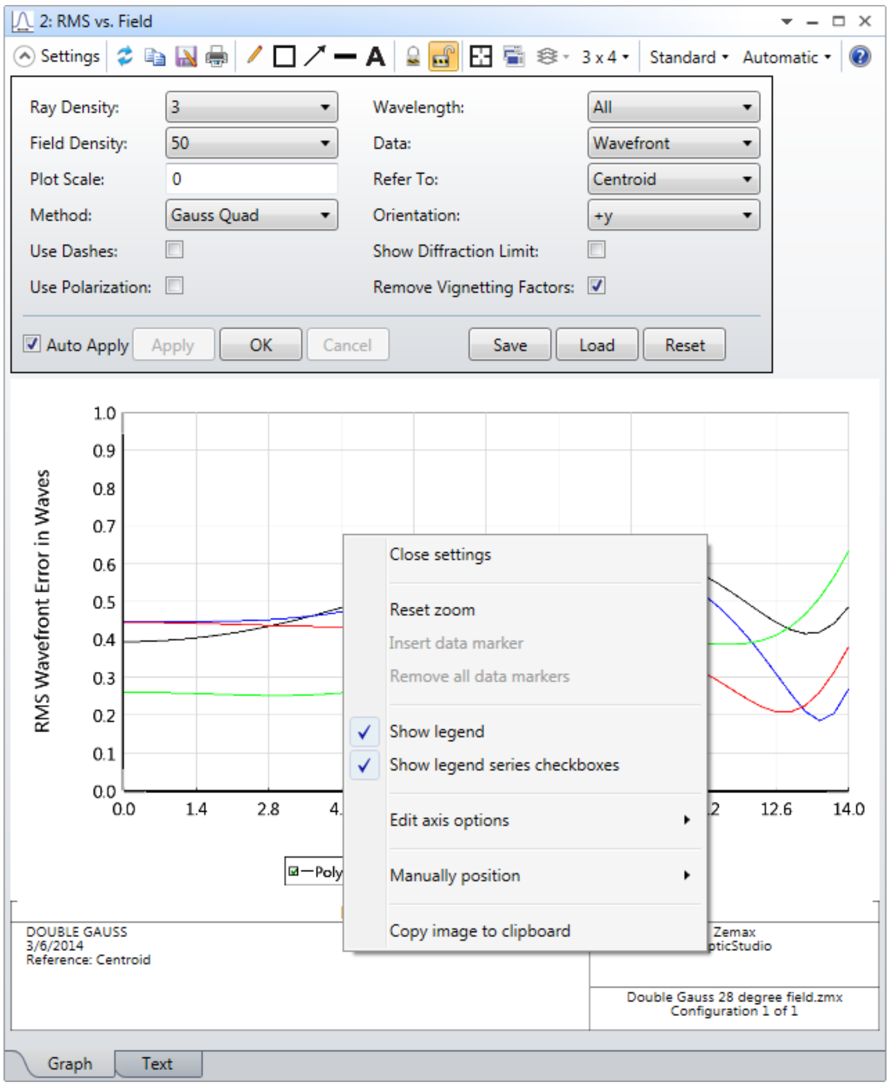
Now on the Help tab



The Help system is now a searchable hyperlinked document, organized by the tabs in the main ribbon bar of the OpticStudio UI.

2D Analysis Windows

The Settings dialog may now be left open and changes may be auto-applied. Right-mouse-clicking now brings up a context menu. Data markers may be set on most windows, and the interactivity of all windows is greatly improved. Data is no longer recalculated when displayed differently: data is only recalculated if the calculation settings change.



There is a wider range of options available via right-mouse-click, and a toolbar provides access to all tools associated with the window. The scale of the axes can be changed by selecting the sliders on each end of the axes. See the full discussion of Analysis windows in the Navigation section.

3D Analysis Windows

All the benefits of the 2D Analysis windows, plus the 3D projection can be rotated by holding down the left mouse button and dragging, zoomed by holding down the scroll wheel and panned by holding down the right mouse button. Again, see the full discussion of Analysis windows in the Navigation section.

Shaded Model

This has been completely re-written to provide a CAD-like user experience. See the full discussion in the Navigation section.

Editors

The editors have been completely re-written to make them more intuitive spreadsheets. Each editor how has a toolbar with all its associated tools on it. For more information, see the "Using the Editors" section of the Help Files under The Setup Tab > Editors Group.

Conventions and Definitions

This chapter describes the conventions and defines terminology used throughout this manual. Most of the conventions and terms Zemax uses are common in the optics industry, however there may be some important differences.

Active configuration

The active configuration is the configuration currently being displayed in the lens data editor. For details see the Help Files chapter about the Multiple Configuration Editor.

Angular magnification

The ratio of the paraxial image space chief ray angle to the paraxial object space chief ray angle. The angles are measured with respect to the paraxial entrance and exit pupil locations.

Apodization

Apodization refers to the uniformity of illumination in the entrance pupil of the system. By default, the pupil is always illuminated uniformly. However, there are times when the pupil should have a non-uniform illumination. For this purpose, Zemax supports pupil apodization, which is a variation of amplitude over the pupil.

Three types of pupil apodization are supported: uniform, Gaussian, and tangential. For each type (except uniform), an apodization factor determines the rate of variation of amplitude in the pupil. See the discussion on apodization types and factors in the Aperture section of the Help Files chapter about the System Explorer.

Zemax also supports user defined apodizations, which may be placed on any surface. Surface apodizations behave differently than pupil apodizations, because surfaces need not be located at a pupil. For more information on surface apodizations, see the Help Files chapter about the Lens Data Editor and the User Defined surface.

Back focal length

Zemax defines the back focal length as the distance along the Z axis from the last surface made of glass to the paraxial image surface for the object at infinite conjugates. If no surfaces are made of glass, the back focal length is the distance from surface 1 to the paraxial image surface for the object at infinite conjugates.

Cardinal planes

The term cardinal planes (sometimes called cardinal points) refers to those special conjugate positions where the object and image surfaces have a specific magnification. The cardinal planes include the principal planes, where the lateral magnification is +1, the anti-principal planes, where the lateral magnification is -1, the nodal planes, where the angular magnification is +1, the anti-nodal planes, where the angular magnification is -1, and the focal planes, where the magnification is 0 for the image space focal plane and infinite for the object space focal plane.

Except for the focal planes, the cardinal planes are conjugates with each other, that is, the image space principal plane is conjugate with the object space principal plane, etc. If the lens has the same index in both object space and image space, the nodal planes are identical to the principal planes.

Zemax lists the distance from the image surface to the various image space planes, and lists the distance from the first surface to the various object space planes.

Chief ray

If there is no vignetting, and there are no aberrations, the chief ray is defined to be the ray that travels from a specific field point, through the center of the entrance pupil, and on to the image surface. Note that without vignetting or aberrations, any ray passing through the center of the entrance pupil will also pass through the center of the stop and the exit pupil.

When vignetting factors are used, the chief ray is then considered to be the ray that passes through the center of the vignetted pupil, which means the chief ray may not necessarily pass through the center of the stop.

If there are pupil aberrations, and there virtually always are, then the chief ray may pass through the center of the paraxial entrance pupil (if ray aiming is off) or the center of the stop (if ray aiming is on), but generally, not both.

If there are vignetting factors which decenter the pupil, then the chief ray will pass through the center of the vignetted entrance pupil (if ray aiming is off) or the vignetted stop surface (if ray aiming is on).

The common convention used is that the chief ray passes through the center of the vignetted pupil, while the principal ray passes through the center of the unvignetted stop. Zemax never uses the principal ray. Most calculations are referenced to the chief ray or the centroid. Note the centroid reference is generally superior because it is based upon the aggregate effect of all the rays that actually illuminate the image surface, and not on the arbitrary selection of one ray which is “special”.

Coordinate axes

The optical axis is the Z axis, with the initial direction of propagation from the object being the positive Z direction. Mirrors can subsequently reverse the direction of propagation. The coordinate system is right handed, with the sagittal X axis being oriented "into" the monitor on a standard layout diagram. The tangential Y axis is vertical.

The direction of propagation is initially left-to-right, down the positive Z axis. After an odd number of mirrors the beam physically propagates in a negative Z direction. Therefore, all thicknesses after an odd number of mirrors should be negative.

Diffraction limited

The term diffraction limited implies that the performance of an optical system is limited by the physical effects of diffraction rather than imperfections in either the design or fabrication. A common means of determining if a system is diffraction limited is to compute or measure the optical path difference. If the peak to valley OPD is less than one quarter wave, then the system is said to be diffraction limited.

There are many other ways of determining if a system is diffraction limited, such as Strehl ratio, RMS OPD, standard deviation, maximum slope error, and others. It is possible for a system to be considered diffraction limited by one method and not diffraction limited by another method.

On some Zemax plots, such as the MTF or Diffraction Encircled Energy, the diffraction limited response is optionally shown. This data is usually computed by tracing rays from a reference point in the field of view. Pupil apodization, vignetting, F/#'s, surface apertures, and transmission may be accounted for, but the optical path difference is set to zero regardless of the actual (aberrated) optical path.

For systems which include a field point at 0.0 in both x and y field specifications (such as 0.0 x angle and 0.0 y angle), the reference field position is this axial field point. If no (0, 0) field point is defined, then the field coordinates of field position 1 are used as the reference coordinates instead.

Edge thickness

Zemax defines the edge thickness of a surface as:

$$E_i = Z_{i+1} - Z_i + T_i$$

where is the sag of the surface, is the sag of the next surface, and is the axial thickness of the surface. The sag values are computed at the +y semi-diameter of their respective surfaces; Note that edge thickness is computed for the +y radial aperture, which may be inadequate if the surface is not rotationally symmetric, or if surface apertures have been placed upon either of the surfaces.

Edge thickness solves use a slightly different definition of edge thickness. For edge thickness solves only, the sag of the i+1 surface is computed at the semi-diameter of surface i. This method avoids a possible infinite loop in the calculation, since changing the thickness of surface i may alter the semi-diameter of surface i+1, if the latter semi-diameter is in "automatic" mode and the value is based upon ray tracing. See "Thickness: Edge thickness" and "Entering semi-diameter data" for more information.

Effective focal length

The distance from the rear principal plane to the paraxial image surface. This is calculated for infinite conjugates. Principal plane calculations are always based upon paraxial ray data. The effective focal length is always referenced to an index of refraction of 1.0, even if the image space index is not unity.

Entrance pupil diameter

The diameter in lens units of the paraxial image of the stop in object space.

Entrance pupil position

The paraxial position of the entrance pupil with respect to the first surface in the system. The first surface is always surface 1, not the object surface, which is surface 0.

Exit pupil diameter

The diameter in lens units of the paraxial image of the stop in image space.

Exit pupil position

The paraxial position of the exit pupil with respect to the image surface.

Field angles and heights

Field points may be specified as angles, object heights (for systems with finite conjugates), paraxial image heights, or real image heights. Field angles are always in degrees. The angles are measured with respect to the object space z axis and the paraxial entrance pupil position on the object space z axis. Positive field angles imply positive slope for the ray in that direction, and thus refer to negative coordinates on distant objects. Zemax converts x field angles (α_x) and y field angles (α_y) to ray direction cosines using the following formulas:

$$\tan\alpha_x = \frac{l}{n}$$

$$\tan\alpha_y = \frac{m}{n}$$

$$l^2 + m^2 + n^2 = 1$$

where l, m, and n are the x, y, and z direction cosines.

If object or image heights are used to define the field points, the heights are measured in lens units. When paraxial image heights are used as the field definition, the heights are the paraxial image coordinates of the primary wavelength chief ray on the paraxial image surface, and if the optical system has distortion, then the real chief rays will be at different locations. When real image heights are used as the field definition, the heights are the real ray coordinates of the primary wavelength chief ray on the image surface.

Zemax uses normalized field coordinates for many features. For information on how field coordinates are normalized, see the “Normalized field coordinates” definition. To set the field type and values, see Help Files chapter about the Setup Tab > System Explorer > Fields.

Float by stop size

Float by stop size is one of the system aperture types supported by Zemax. This phrase refers to the fact that the entrance pupil position, object space numerical aperture, image space F/#, and stop surface radius all are specified if just one of them is specified. Therefore, setting the stop radius, and then allowing the other values to be whatever they are, is a perfectly valid way of defining the system aperture. It is particularly handy when the stop surface is a real, unchangeable aperture buried in the system, such as when designing null corrector optics.

Ghost reflections

Ghost reflections are spurious, unwanted images formed by the small amount of light which reflects off of, rather than refracts through a lens face. For example, the multiple images of the aperture stop visible in photographs taken with the sun in the field of view are caused by ghost reflections. Ghost images can be problematic in imaging systems and in high power laser systems.

Glasses

Glasses are entered by name in the glass column. Available glasses may be reviewed, and new ones entered using the glass catalog tool. See the Chapter "Using Glass Catalogs" for details.

Blanks are treated as air, with unity index. Mirrors can be specified by entering "MIRROR" for the glass type, although this name will not appear in the glass catalog. The index of refraction of the mirror space is always equal to the index of refraction of the media before the mirror.

For information on the effect of temperature and pressure on index of refraction data, search the Help Files for "Defining temperature and pressure".

Hexapolar rings

Zemax usually selects a ray pattern for you when performing common calculations such as spot diagrams. The ray pattern refers to how a set of rays is arranged on the entrance pupil. The hexapolar pattern is a rotationally symmetric means of distributing a set of rays. The hexapolar pattern is described by the number of rings of rays around the central ray. The first ring contains 6 rays, oriented every 60 degrees around the entrance pupil with the first ray starting at 0 degrees (on the x-axis of the pupil). The second ring has 12 rays (for a total of 19, including the center ray in ring "0"). The third ring has 18 rays. Each subsequent ring has 6 more rays than the previous ring.

Many features which require a sampling parameter to be specified (such as the spot diagram) use the number of hexapolar rings as a convenient means of specifying the number of rays. If the hexapolar sampling density is 5, it does not mean that 5 rays will be used. A sampling of 5 means 1 + 6 + 12 + 18 + 24 + 30 = 91 rays will be used.

Image space F/#

Image space F/# is the ratio of the paraxial effective focal length calculated at infinite conjugates over the paraxial entrance pupil diameter. Note that infinite conjugates are used to define this quantity even if the lens is not used at infinite conjugates.

Image space numerical aperture (NA)

Image space NA is the index of image space times the sine of the angle between the paraxial on-axis chief ray and the paraxial on-axis +y marginal ray calculated at the defined conjugates for the primary wavelength.

Lens units

Lens units are the primary unit of measure for the lens system. Lens units apply to radii, thicknesses, apertures, and other quantities, and may be millimeters, centimeters, inches, or meters.

Marginal ray

The marginal ray is the ray that travels from the center of the object, to the edge of the entrance pupil, and on to the image surface.

If there is vignetting, Zemax extends this definition by defining the marginal ray to be at the edge of the vignetted entrance pupil. If ray aiming is on, then the marginal ray is at the edge of the vignetted stop.

See also the definition of the chief ray.

Maximum field

The maximum field is the minimum radial coordinate that would enclose all the defined field points if the x and y values of each field point were plotted on an Cartesian XY plot. The maximum field is measured in degrees if the field type is angles, or in lens units for object height, paraxial image height, or real image height. To set the field type and values, go to the Setup Tab > System Explorer > Fields. For more information on the field type, search the Help Files for "Field angles and heights".

Non-paraxial systems

The term non-paraxial system refers to any optical system which cannot be adequately represented by paraxial ray data. This generally includes any system with tilts or decenters, strong aspheres, axicons, holograms, gratings, cubic splines, ABCD matrices, gradient index, diffractive components, or non-sequential surfaces.

A great deal of optical aberration theory has been developed for systems with conventional refractive and reflective components in rotationally symmetric configurations. This includes Seidel aberrations, distortion, Gaussian beam data, and virtually all first order properties such as focal length, F/#, and pupil sizes and locations. All of these values are calculated from paraxial ray data.

If the system being analyzed contains any of the non-paraxial components described, then any data computed based upon paraxial ray tracing cannot be trusted. Zemax will generally use exact real rays rather than paraxial rays for ray tracing through these surfaces and components.

A system which is well described by paraxial optics will have the general property that the real and paraxial marginal ray data converge as the radial entrance pupil coordinate of the rays being traced tends toward zero.

Non-sequential ray tracing

Non-sequential ray tracing means rays are traced only along a physically realizable path until they intercept an object. The ray then refracts, reflects, or is absorbed, depending upon the properties of the object struck. The ray then continues on a new path. In non-sequential ray tracing, rays may strike any group of objects in any order, or may strike the same object repeatedly; depending upon the geometry and properties of the objects.

See also the definition of "Sequential ray tracing".

Normalized field coordinates

Normalized field coordinates are used in both the Zemax program and documentation. There are two normalized field coordinates: Hx and Hy. Normalized field coordinates are convenient because useful field locations may be defined in a manner that does not change with the individual field definitions or field of view of the optical system. For example, the normalized field coordinate (0, 1) is always at the top of the field of view, whether the field points are defined as angles or heights, and regardless of the magnitude of the field coordinates.

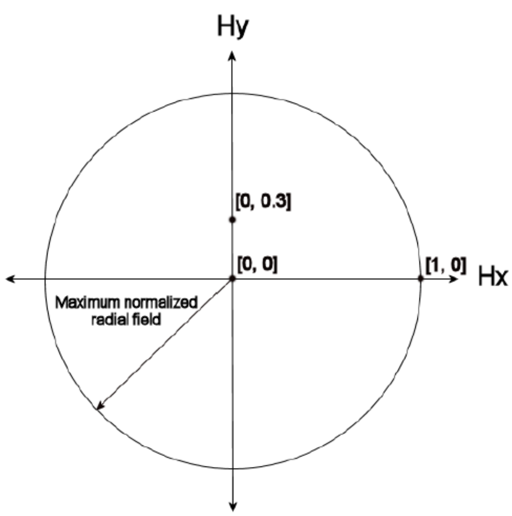
There are two methods used to normalize fields: radial and rectangular. The choice of field normalization method is made on the Field Data dialog; for a description see the "Field angles and heights" definition.

Radial field normalization

If the field normalization is radial, then the normalized field coordinates represent points on a unit circle. The radius of this unit circle, called the maximum radial field, is given by the radius of the field point farthest from the origin in field coordinates. The maximum radial field magnitude is then used to scale all fields to normalized field coordinates. Real field coordinates can be determined by multiplying the normalized coordinates, H_x and H_y, by the maximum radial field magnitude:

$f_x = H_x F_r$, and $f_y = H_y F_r$,

where F_r is the maximum radial field magnitude and f_x and f_y are the field coordinates in field units.



For example, suppose 3 field points are defined in the (x, y) directions using object height in lens units at (0.0, 0.0), (10.0, 0.0), and (0.0, 3.0). The field point with the maximum radial coordinate is the second field point, and the maximum radial field is therefore 10.0. The normalized coordinate (Hx = 0, Hy = 1) would refer to the field coordinates (0.0, 10.0). The normalized coordinate (Hx = 1, Hy = 0) would refer to the field coordinates (10.0, 0.0). Note the normalized field coordinates can define field coordinates that do not correspond to any defined field point. The maximum radial field is always a positive value.

If a fourth field point at (-10.0, -3.0) were added in the above example, the maximum radial field would become

$$F_r = \sqrt{3^2 + 10^2},$$

or approximately 10.44031. Normalized coordinates should always be between -1 and 1, and should also meet the condition:

$$H_x^2 + H_y^2 \le 1 .$$

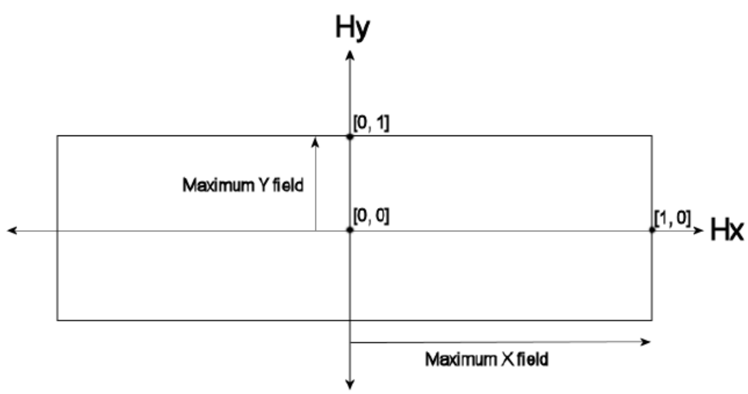
Otherwise, the field point lies outside of the maximum radial field.

Rectangular field normalization

If the field normalization is rectangular, then the normalized field coordinates represent points on a unit rectangle. The x and y direction widths of this unit rectangle, called the maximum x field and maximum y field, are defined by the largest absolute magnitudes of all the x and y field coordinates. The maximum x and y field magnitudes are then used to scale all fields to normalized field coordinates. Real field coordinates can be determined by multiplying the normalized coordinates, H_x and H_y, by the maximum x and y field magnitudes:

$f_x = H_x F_x$, and $f_y = H_y F_y$,

where F_x and F_y are the maximum x and y field magnitudes, and f_x and f_y are the field coordinates in field units.



For example, suppose 3 field points are defined in the (x, y) directions using object height in lens units at (0.0, 0.0), (10.0, 0.0), and (0.0, 3.0). The field point with the maximum x coordinate is the second field point, and the maximum x field is therefore 10.0. The field point with the maximum y coordinate is the third field point, and the maximum y field is therefore 3.0. The normalized coordinate (Hx = 0, Hy = 1) would refer to the field coordinates (0.0, 3.0). The normalized coordinate

(Hx = 1, Hy = 0) would refer to the field point (10.0, 0.0). The normalized coordinate (Hx = 1, Hy = 1) would refer to the field coordinates (10.0, 3.0). Note the normalized field coordinates can define field coordinates that do not correspond to any defined field point. The maximum x and y field are always positive values.

If a fourth field point at (-10.0, -3.0) were added in the above example, the maximum x and y field values would not change. Normalized rectangular coordinates should always be between -1 and 1.

Normalized pupil coordinates

Normalized pupil coordinates are often used in both the Zemax program and documentation. There are two normalized pupil coordinates: Px and Py. Normalized pupil coordinates are convenient because useful pupil locations may be defined in a manner that does not change with the aperture size or position. For example, the normalized pupil coordinate (0.0, 1.0) is always at the top of the pupil, and therefore defines a marginal ray. The normalized pupil coordinate (0.0, 0.0) always goes through the center of the pupil, and therefore defines a chief ray.

The normalized pupil coordinates represent points on a unit circle. The radial size of the pupil is defined by the radius of the paraxial entrance pupil, unless ray aiming is turned on, in which case the radial size of the pupil is given by the radial size of the stop. For more information on ray aiming see the Help Files chapter called the Setup tab > System Explorer > Ray Aiming.

For example, if the entrance pupil radius (not diameter) is 8 mm, then (Px = 0.0, Py = 1.0) refers to a ray which is aimed to the top of the entrance pupil. On the entrance pupil surface, the ray will have a coordinate of (x = 0.0 mm, y = 8.0 mm).

Note that the normalized pupil coordinates should always be between -1 and 1, and that

$$P_x^2 + P_y^2 \le 1 .$$

A significant advantage of using normalized pupil coordinates is that rays defined in normalized coordinates remain meaningful as the pupil size and position changes. Suppose prior to optimizing a lens design, a ray set is defined to compute the system merit function. By using normalized coordinates, the same ray set will work unaltered if the entrance pupil size or position or object size or position is changed later, or perhaps even during the optimization procedure.

Object space numerical aperture

Object space numerical aperture is a measure of the rate of divergence of rays emanating from the object surface. The numerical aperture is defined as the index of refraction times the sine of the paraxial marginal ray angle, measured in object space. The marginal ray defines the boundary of the cone of light diverging from an object point.

Parameter data

Parameter data values are used to define certain non-standard surface types. For example, parameter data may include aspheric coefficients, grating spacings, or tilt and decenter data. For a complete discussion of the parameter data values see the Sequential Surfaces section under Lens Data Editor in the Help Files.

Paraxial and parabasal rays

The term paraxial means "near the axis". Paraxial optics are optics that are well described by the linear form of Snell's law. Snell's law is:

$$n \sin\theta = n' \sin\theta' .$$

For small angles this becomes

$$n\theta = n'\theta' .$$

Many definitions in optics are based upon this assumption of linearity. Aberrations are deviations from this linearity, and so the paraxial properties of optical systems are often considered the properties the system has in the absence of aberrations. Paraxial rays are traced using formulas which assume the optical surface power is based only upon the vertex radius of curvature, ignoring local linear tilts and higher order curvature of the surface.

Paraxial data is computed on a plane tangent to the surface vertex, assuming the vertex radius of curvature is an acceptable approximation to the surface power over the entire aperture of the surface. Certain unusual surface types do not have a paraxial analog, so the real ray tracing calculations are made at these surfaces, even for a paraxial ray.

Zemax computes many paraxial entities, such as focal length, F/#, focal position, entrance pupil diameter, and others. These values should be used with caution when the optical system has components which violate the assumption that the vertex curvature is an acceptable approximation to the surface power over the entire aperture of the surface.

For many analysis features, paraxial data is required, typically as a reference against which real rays are measured. To ensure these features work properly, even for optical systems that do not meet the paraxial assumption above, Zemax traces "parabasal" rays which are real (real means using Snell's law explicitly) that make small angles with respect to a reference ray, which is usually an axis or chief ray. The parabasal rays are used to compute the limiting properties of the system as the stop size is decreased, which provides a good estimate of the paraxial properties.

The reason Zemax uses parabasal rays rather than paraxial formulas is because many optical systems include non-paraxial components. Non-paraxial means these components are not well described by conventional axial first-order theory. This includes tilted or decentered systems, systems using holograms, diffractive optics, general aspheres, and gradient index lenses.

In summary, paraxial ray data is computed using first order approximations to the surface power for tracing rays, while parabasal rays are real, exact ray traces close to a chief or reference ray. Most paraxial data, such as EFL, F/#, and magnification, use paraxial rays and the data is invalid if the optical system is not well described by the vertex power of every surface. Most analysis features in Zemax use parabasal rays, to allow these features to work with a greater range of optical systems, including those with optical surfaces not well described solely by their vertex surface power.

Paraxial image height

The paraxial radial size of the image in lens units of the full field image at the paraxial image surface.

Paraxial magnification

The radial magnification, being the ratio of paraxial image height to object height. The paraxial magnification is measured at the paraxial image surface. The value is always zero for infinite conjugate systems.

Paraxial working F/#

The paraxial working F/# is defined as

$$W = \frac{1}{2n\tan\theta},$$

where θ is the paraxial marginal ray angle in image space and n is the index of refraction of image space. The paraxial marginal ray is traced at the specified conjugates. For non-axial systems, this parameter is referenced to the axis ray and is averaged over the pupil. The paraxial working F/# is the effective F/# ignoring aberrations. See also the definition for “working F/#”.

Primary wavelength

The primary wavelength in micrometers is displayed. This value is used for calculating most other paraxial or system values, such as pupil positions.

Radii

The radius of curvature of each surface is measured in lens units. The convention is that a radius is positive if the center of curvature is to the right (a positive distance along the local z axis) from the surface vertex, and negative if the center of curvature is to the left (a negative distance along the local z axis) from the surface vertex. This is true independent of the number of mirrors in the system.

Real propagation

A real propagation means the rays are propagated in the direction energy would actually flow. See also the definitions for “Virtual propagation” and “Thicknesses”.

Sagittal and Tangential

The term "tangential" refers to data computed in the tangential plane, which is the plane defined by a line and one point: the line is the axis of symmetry, and the point is the field point in object space. The sagittal plane is the plane orthogonal to the tangential plane, which also intersects the axis of symmetry at the entrance pupil position.

For typical rotationally symmetric systems with field points lying along the Y axis, the tangential plane is the YZ plane and the sagittal plane is the plane orthogonal to the YZ plane which intersects the center of the entrance pupil.

The problem with this definition is that it is not readily extended to non-rotationally symmetric systems. For this reason, Zemax instead defines the tangential plane to be the YZ plane regardless of where the field point is, and tangential data is always computed along the local y axis in object space. The sagittal plane is the orthogonal to the YZ plane, and intersects the center of the entrance pupil in the usual way, and sagittal data is always computed along the x axis in object space.

The philosophy behind this convention is as follows. If the system is rotationally symmetric, then field points along the Y axis alone define the system imaging properties, and these points should be used. In this case, the two different definitions of the reference planes are redundant and identical. If the system is not rotationally symmetric, then there is no axis of symmetry, and the choice of reference plane is arbitrary.

One feature, the computation of Fast Semi-Diameters (see the Advanced section of the System Explorer), does use the "true" tangential plane, which Zemax defines as the plane that contains the actual field point and the z axis in object space.

Semi-diameters

The size of each surface is described by the semi-diameter setting. The default setting is the radial distance to the aperture required to pass all real rays without clipping any of the rays. Typing a value for the semi-diameter column results in the character "U" being displayed next to the value. The "U" indicates that the semi-diameter is user defined. When a user-defined semi-diameter is placed on a surface with refractive power (which is done by typing in a value in the appropriate column), and no surface aperture has been defined, Zemax automatically applies a "floating" aperture to the surface. A floating aperture is a circular aperture whose radial maximum coordinate is always equal to the semi-diameter of the surface. For more information on surface aperture types, see the Aperture section of the Surface Properties (in the Lens Data Editor).

Semi-diameters on any surface for axial symmetric systems are computed very accurately, as long as the surface does not lie within the caustic of the ray bundle (note this usually occurs at or near the image surface). Zemax estimates semi-diameters for axial systems by tracing a few marginal pupil rays. For non-axial systems, Zemax estimates the required semi-diameters using either a fixed number of rays or by an iterative technique, which is slower but more accurate. See the explanation of "Fast Semi-Diameters" in the Advanced section of the System Explorer for details. It is important to note that the "automatic" semi-diameter computed by Zemax is an estimate, although it is generally a very good one.

Some surfaces may become so large in aperture that the surface z coordinate becomes multiple valued; for example, a very deep ellipse may have more than one z coordinate for the same x and y coordinates on the surface. For the case of spherical surfaces, this condition is called "hyperhemispheric" and Zemax uses this term even if the surface is not a sphere. Hyperhemispheric surfaces are denoted by an asterisk "*" in the semi-diameter column. The indicated semi-diameter is of the outer edge of the surface, which will have a smaller radial aperture than the maximum radial aperture.

Sequential ray tracing

Sequential ray tracing means rays are traced from surface to surface in a predefined sequence. Zemax numbers surfaces sequentially, starting with zero for the object surface. The first surface after the object surface is 1, then 2, then 3, and so on, until the image surface is reached. Tracing rays sequentially means a ray will start at surface 0, then be traced to surface 1, then to surface 2, etc. No ray will trace from surface 5 to 3; even if the physical locations of these surfaces would make this the correct path.

See also the “Non-sequential ray tracing” definition.

Special characters

There are many places in Zemax where user defined file, material, glass, or other names may be provided. Generally, Zemax allows any characters to be used in these names, except for a few reserved “special characters” The special characters are space, semi-colon, single quote, and tab.

Strehl ratio

The Strehl ratio is one commonly used measure of optical image quality for very high quality imaging systems. The Strehl ratio is defined as the peak intensity of the diffraction point spread function (PSF) divided by the peak intensity of the diffraction point spread function (PSF) in the absence of aberrations. Zemax computes the Strehl ratio by computing the PSF with and without considering aberrations, and taking the ratio of the peak intensity. The Strehl ratio is not useful when the aberrations are large enough to make the peak of the PSF ambiguous, or for Strehl ratios smaller than about 0.1.

Surface apertures

Surface apertures include circular, rectangular, elliptical, and spider shaped apertures which can vignette rays. There are also user defined shapes for surface apertures and obscurations; and a “floating” aperture that is based upon the current semi-diameter value. Surface apertures do not affect ray launching or tracing, except for the termination of a ray if it does not pass the surface aperture. Surface apertures have no effect on the system aperture. For more information, see the Aperture section of the Surface Properties

System aperture

The system aperture is the overall system F/#, Entrance Pupil Diameter, Numerical Aperture, or Stop Size. Any of these 4 quantities is sufficient to define the other 3 for a particular optical system. The system aperture is used to define the object space entrance pupil diameter, which in turn is used to launch all rays. The system aperture is always circular. Rays may be vignetted after being launched by various surface apertures. There is only one system aperture, although there may be many surface apertures.

Thicknesses

Thicknesses are the relative distance to the next surface vertex in lens units. Thicknesses are not cumulative, each one is only the offset from the previous vertex along the local z axis. The orientation of the local z axis can change using coordinate breaks (see the Coordinate Break surface in the Lens Data Editor section of the Help Files) or surface tilts and decenters (see the Tilt/Decenter section of the Surface Properties).

Thicknesses corresponding to real propagation (see “Real propagation”) always change sign after a mirror. After an even number of mirrors (including zero mirrors), thickness are positive for real propagations and negative for virtual propagations (see “Virtual propagation”). After an odd number of mirrors, thicknesses are negative for real propagations and positive for virtual propagations. This sign convention is independent of the number of mirrors, or the presence of coordinate breaks. This fundamental convention cannot be circumvented through the use of coordinate rotations of 180 degrees.

Total internal reflection (TIR)

TIR refers to the condition where a ray makes too large an angle with respect to the normal of a surface to meet the refraction condition as specified by Snell's Law. This usually occurs when a ray with a large angle of incidence is refracting from a high index media to a lower index media, such as from glass to air. When doing sequential ray tracing, rays which TIR are considered errors, and are terminated. Physically, the ray would reflect rather than refract from the boundary, but Zemax does not consider this effect when doing sequential ray tracing. For non-sequential ray tracing, rays which TIR are properly reflected.

Total track

Total track is the length of the optical system as measured by the vertex separations between the “left most” and “right most” surfaces. The computation begins at surface 1. The thickness of each surface between surface 1 and the image surface is considered, ignoring any coordinate rotations. The surface which lies at the greatest z coordinate defines the “right most” surface, while the surface with the minimum z coordinate defines the “left most” surface. Total track has little or no value in non-axial systems.

Vignetting factors

Vignetting factors are coefficients which describe the apparent entrance pupil size and location for different field positions. Zemax uses five vignetting factors: VDX, VDY, VCX, VCY, and VAN. These factors represent decenter x, decenter y, compression x, compression y, and angle, respectively. The default values of all five factors are zero, which indicates no vignetting.

Both the field of view and the entrance pupil of an optical system can be thought of as unit circles. The normalized field and pupil coordinates, defined in “Normalized field coordinates”, are the coordinates on these two unit circles. For example, the pupil coordinates (px = 0, py = 1) refer to the ray which is traced from some point in the field to the top of the entrance pupil. If there is no vignetting in the system, Zemax will trace rays to fill the entire entrance pupil during most computations.

Many optical systems employ deliberate vignetting. This means a portion of the rays are intentionally "clipped" by apertures other than the stop surface. There are two common reasons for introducing vignetting in an optical system. First, vignetting decreases the size of the lenses, particularly in wide angle lenses. Second, vignetting may remove a portion of the beam which would be excessively aberrated. Vignetting usually increases the F/# as a function field angle (which darkens the image), but the image quality may improve if the most severely aberrated rays are clipped.

Vignetting factors redefine the entrance pupil for a specific field position. The normalized pupil coordinates are modified using two successive transformations. First, the coordinates are scaled and shifted:

$P'_x = VDX + P_x(1 - VCX)$, and

$P'_y = VDY + P_y(1 - VCY)$, .

The scaled and shifted coordinates are then rotated by the vignetting angle:

$P''_x = P'_x \cos\theta - P'_y \sin\theta$, and

$P''_y = P'_x \sin\theta + P'_y \cos\theta$,

where θ is the vignetting angle VAN. The VDX term can shift the apparent pupil left and right, while VCX makes the pupil larger or smaller in the x direction. Similar results hold for the VDY and VCY values. Note that if the vignetting factors are all zero, the pupil coordinates are left unmodified. Vignetting factors provide a convenient way of designing optics which employ vignetting. However, there are restrictions to using vignetting factors that must be understood.

Some Zemax features are capable of tracing rays from arbitrary field positions where no vignetting factors have been assigned. These features may not provide completely accurate results for data computed at field positions other than the defined fields. Some features will remove the vignetting factors for these computations by placing a clear aperture on each surface that vignettes the rays an equivalent amount. Features that automatically remove the vignetting factors are described in the Analysis chapter.

Some features in Zemax do not automatically remove vignetting factors for intermediate field positions, such as ray operands in the merit function (operands like REAX that can launch a single ray, for example) or ZPL macros. If the vignetting factors are not removed, Zemax will attempt to interpolate the vignetting factors. For rotationally symmetric systems, or systems with field points entirely along the y axis, Zemax interpolates between adjacent field points to estimate the vignetting factors to use at intermediate field points. For more general optical systems with X field values, Zemax uses the closest defined field point for determining the vignetting factors for an arbitrary field point.

Once a vignetting factor is defined, it is up to the designer to ensure that rays beyond the apparent pupil are in fact vignetted! If the vignetting factor is used to shrink the size of the lenses, then the lenses should be made no larger than is required to pass the rays which are at the edge of the apparent pupil. If rays from beyond the vignetted aperture are allowed to pass in the real optical system, then the lens performance will not correlate with the computer model.

Identical or nearly identical field coordinates may not be defined with different vignetting factors. Field coordinates must be different by roughly 1E-06 times the maximum field coordinate if two neighboring fields use different vignetting factors. This is required because Zemax must determine vignetting factors for any field coordinates, not just those at defined field positions; and identical field coordinates with different vignetting factors have no physical interpretation. The proper way to set up this sort of system is to use multiple configurations, and change the vignetting factors via the multi-configuration editor.

The vignetting factors work with and without ray aiming turned on. If ray aiming is off, then the paraxial entrance pupil is remapped according to the equations given earlier. If ray aiming is turned on, then the remapping is done at the stop surface.

One possible application of vignetting factors is to account for pupil aberration without using the ray aiming feature. This is an advanced trick which can be used to speed up ray tracing in wide angle systems.

Vignetting factors may be defined on the “Field Data” dialog box. See the Fields section of the System Explorer for more information. Vignetting factors may also be zoomable parameters; see the Chapter “Multi-Configurations”. For more information on the use of vignetting as a design tool, see any of the good books referenced in the first chapter.

Virtual propagation

A virtual propagation means the rays are propagated in a direction opposite to the direction energy would actually flow. Virtual propagations are often useful for placing virtual sources or pupils. See also the definitions for “Real propagation” and “Thicknesses”.

Wavelength data

Wavelength data are always measured in micrometers referenced to “air” at the current system temperature and pressure. The default system temperature is 20 degrees Celsius, and the default air pressure is 1.0 atmospheres. If the system temperature and/or pressure is modified, or under the control of multi-configuration operands, care must be taken to adjust the wavelengths to the new air temperature and pressure.

Wavelength data is entered in the Wavelengths section of the System Explorer.

Wavelength data are always measured in micrometers referenced to “air” at the system temperature and pressure.

Working F/#

Working F/# is defined as

$$W = \frac{1}{2n\sin\theta},$$

where θ is the real marginal ray angle in image space and n is the index of refraction of image space. The marginal ray is traced at the specified conjugates. Working F/# ignores surface apertures but considers vignetting factors.

For off axis field points or non-axial systems, working F/# is determined by the average of the square of the numerical aperture between the axis ray and four marginal rays, at the top, bottom, left, and right side of the vignetted pupil. The average of the square of the numerical aperture of the four rays is converted back to equivalent F/#.

Working F/# is generally much more useful than image space F/# because it is based upon real ray data at the actual conjugates of the lens. See also the definition for "Paraxial working F/#".

If the marginal rays cannot be traced (due to ray errors) then a smaller pupil is temporarily used to estimate the working F/#. In this case, Zemax scales the data to estimate the working F/# at the full pupil size, even though rays are not be traceable at the full aperture.

If the marginal rays are nearly parallel to the chief ray, the resulting F/# may become so large as to be inaccurate. Zemax will automatically "cap" the F/# at 10,000 if the calculated F/# becomes larger than 10,000. This result simply means the F/# cannot be calculated accurately using rays. Such a large F/# means the output beam is nearly collimated, and many assumptions Zemax makes are not valid in this case. The two solutions are to bring the nearly collimated beam to a focus using a paraxial lens, or to use the exit pupil size and position to estimate the F/#. For more information, see the explanation of "Method To Compute F/#" in the Advanced section of the System Explorer.

For a generalized definition of F/# useful for evaluating image brightness, see the discussion of "Effective F/#" in the discussion about the Relative Illumination analysis.

Index

2

2D Analysis Windows 203

3

3D Analysis Windows 204

A

Active configuration 205
Adding Coatings to Non-Sequential Objects 161
Adding Coatings to Sequential Surfaces 157
Analyze Tab 19
Analyze Tab (Non-Sequential UI Mode) 20
Angular magnification 205
Apodization 205
Are There Enough Field Points? 98
Arranging Windows 29

B

Back focal length 205

C

Cardinal planes 205
Chief ray 206
Congratulations on your purchase of Zemax OpticStudio! 7
Conventions and Definitions 204
Converting from Zemax13 and Older 177
Coordinate axes 206
Customizing Your Installation 12

D

Defining Polarization in a Non-Sequential System 155
Defining Polarization in a Sequential System 151
Defining the Faces of CAD objects 163
Defining the Merit Function 91
Detector Objects 128
Diffraction limited 206
Don't Optimize Aberration Coefficients Directly 105

E

Edge thickness 207
Editors 204
Effective focal length 207
Entrance pupil diameter 207
Entrance pupil position 207
Exit pupil diameter 208
Exit pupil position 208

F

Field angles and heights 208
File Tab 17
Filter Strings 133
Float by stop size 208

G

Getting Started With OpticStudio™ 7
Getting Technical Support 175
Ghost reflections 209
Glass Optimization 101
Glasses 209

H

Help Tab 25
Hexapolar rings 209

I

Image space F/# 209
Image space numerical aperture (NA) 209
Important notice 8
Installation 9

L

Lens units 210
Libraries Tab 22
License Codes 10

M

Marginal ray 210
Maximum field 210

N

Navigating the OpticStudio Interface 13
Network Keys and Clients 11
Non-paraxial systems 210
Non-sequential ray tracing 210
Normalized Field Coordinates 48, 211
Normalized Pupil Coordinates 49, 213

O

Object Parameters 123
Object Positioning 118
Object space numerical aperture 213
Optimize Tab 21
Optimizing the Lens 94

P

Parameter data 213
Paraxial and parabasal rays 214
Paraxial image height 215
Paraxial magnification 215
Paraxial working F/# 215
Part Designer Tab 23
Primary wavelength 215
Printing Windows 30
Programming Tab 24

R

Radii 215
Ray Databases 131
Real propagation 215
References on Lens Design 176

S

Sagittal and Tangential 215
Semi-diameters 216
Sequential ray tracing 217
Setting Variables 89
Setup Tab 18
Shaded Model 204
Source Objects 126
Special characters 217
Strehl ratio 217
Surface apertures 217
System aperture 217
System Explorer 16

T

The Array Object 139
The Boolean Object 137
The Fields Section 44
The Overlapping Objects Rule 136
The Source Object 140
The Wavelengths Section 47
Thicknesses 218
Tolerance Tab 22
Total internal reflection (TIR) 218
Total track 218
Tracing Analysis Rays 128
Troubleshooting 11
Tutorial 1.1: The Lens Data Editor 39
Tutorial 1.2: Analysis Windows 41
Tutorial 1.3: The System Explorer 43
Tutorial 1.4: The Normalized Coordinate System 47
Tutorial 1: A Walk-Through an OpticStudio Design 32
Tutorial 2.1: Working in Three Dimensions 56
Tutorial 2: Defining, Positioning and Moving Surfaces 52
Tutorial 3: A Multi-Configuration Design 60
Tutorial 4: Exporting To Mechanical CAD Packages 75
Tutorial 5.1: The Lens Specification 79
Tutorial 5.2: Entering the Basic System in the System Explorer 79

Tutorial 5.3: Entering the Basic System in the Lens Data Editor 83
Tutorial 5.4: Tips and Tricks for Successful Optimization 104
Tutorial 5: Optimization 78
Tutorial 6.1: A Simple Example 108
Tutorial 6.2: Object Positioning & Definition 118
Tutorial 6.3: Combining Sequential and Non-Sequential Ray-Tracing 124
Tutorial 6.4: Tracing Rays and Getting Data 126
Tutorial 6.5: Complex Object Creation 136
Tutorial 6: Non-Sequential Ray Tracing (Professional and Premium only) 108
Tutorial 7: Optimizing Non-Sequential Systems 142
Tutorial 8: Colorimetry 147
Tutorial 9.1: Polarization 151
Tutorial 9.2: Thin-Film Coatings 155
Tutorial 9.3: Ray Splitting 164
Tutorial 9.4: Ray Scattering 167
Tutorial 9.5: Importance Sampling 170
Tutorial 9.6: Bulk and Fluorescent Scattering 171
Tutorial 9: Polarization, Coatings & Scattering 150
Tutorials 32

U

Use Adequate Boundary Conditions 106
Use Hammer Often 106
Use Physically Significant Merit Functions 105
Use the Optimization Wizard 106
Use the System Check Utility 107
Using Analysis Windows 27
Using Spreadsheet Editors 25
Using the Normalized Coordinates 49
Using the Shaded Model 29

V

Vignetting factors 218
Virtual propagation 220

W

Wavelength data 220
What’s Next? 173
Working F/# 221

Z

Zemax 13 Analysis Menu 186
Zemax 13 Editors menu 180
Zemax 13 Extensions Menu 201
Zemax 13 File Menu 179
Zemax 13 Help Menu 202
Zemax 13 Macros Menu 200
Zemax 13 Reports Menu 199
Zemax 13 System Tab 182
Zemax 13 Tools Menu 191