# First Order Ghost Analysis

## INTRODUCTION

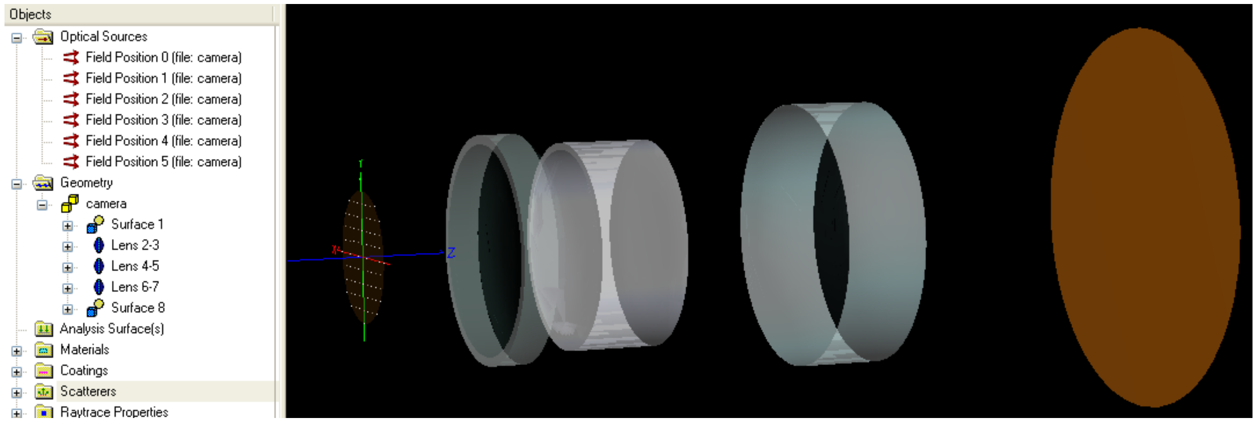
FRED is capable of providing the user with detailed information about arbitrary ghost and scatter paths through an opto-mechanical system. We simply setup the optics and mechanics with physical property attributes (coatings, materials, scatter models, etc.), setup an appropriate source and tell FRED to keep track of all unique paths through the system during the raytrace. When the raytrace completes, we can post-process the raytrace path information to extract out the paths which are relevant to our system.

Suppose, however, that we are interested in characterizing the primary ghost paths within an optical system; perhaps our system isn't completely developed or refined to warrant a lengthy multi-level stray light analysis. This knowledge base article presents a script which automates an analysis of the primary ghost paths in an imported sequential design. We start by discussing the procedure for setting up the imported sequential file appropriately for the analysis and then we discuss the script implementation and procedure for running the analysis.

## SETTING UP THE MODEL

For the purposes of this article, we will be working with a lens design that is included in your FRED installation directory: <installation directory>\Resources\Samples\Optical Design Files\camera.ZMX

Start by first importing the "camera.ZMX" design file in to FRED using Menu > File > Import > Import Optical and accepting the default settings on the import dialog. After import, you should see the lens system in your 3D view and the Object Tree should be shown as below. The design is a simple three element lens with an aperture stop in front of the first lens.

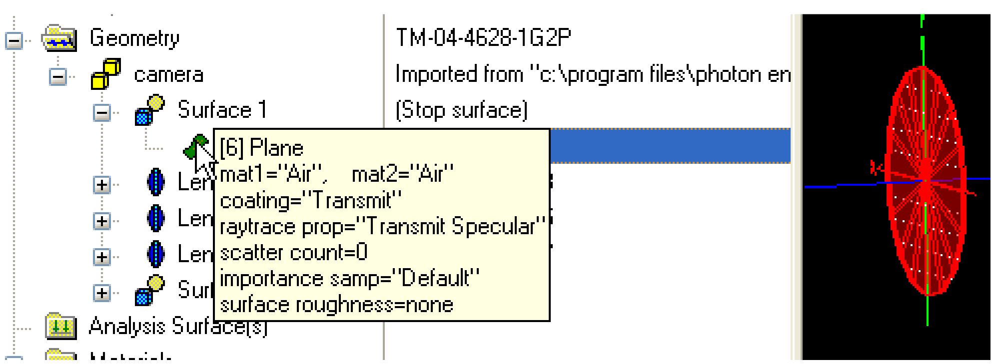



Before we do any raytracing and analysis we need to prepare the surfaces and geometry in a manner which is suitable for the first order ghosting calculation we wish to perform. There are six items that we need to address in our design:

1. Creating a "FRED" aperture stop
2. Specifying surface coating properties which allow ghosting to occur
3. Specifying surface raytrace control properties which allow ghosting to occur
4. Modification of the source position specification
5. Addition of an analysis surface
6. Modification of the sequential raytrace path

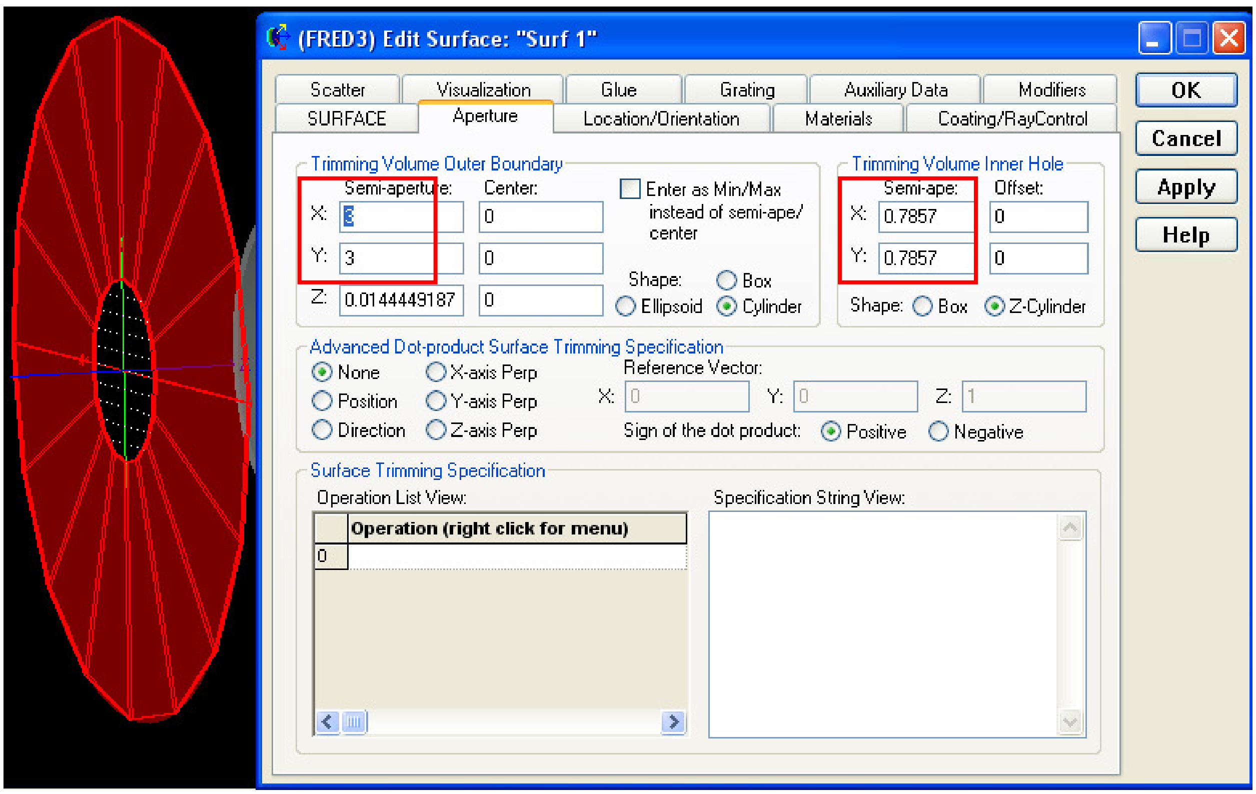
## Creating a "FRED" Aperture Stop

Note that after importing our lens system the aperture stop surface is a simple Air/Air transmitting planar surface.

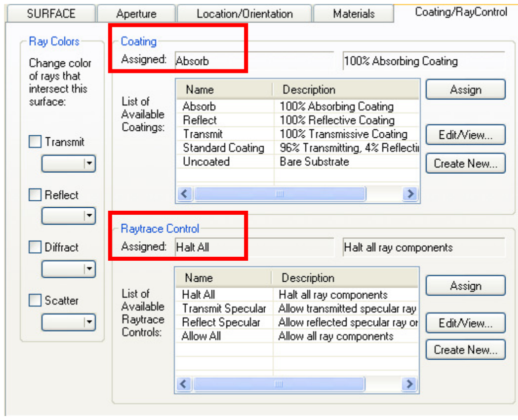


Although this type of specification is meaningful for a lens design program, FRED has no knowledge of what a stop is supposed to mean. In FRED, we simply setup the geometry with the correct physical properties and the physics of the surfaces govern where rays are allowed to propagate. In this sense, we need to turn our sequential “stop” surface into a real “physical” stop surface which is suitable for FRED.

We start by opening up the dialog for Surf 1 and going to the Aperture tab. We’re going to turn the planar surface into an annulus, with inner aperture equal to the current outer aperture of the disk. This is easily done by copying the existing value of the “Trimming Volume Outer Boundary” and pasting this value in to the “Trimming Volume Inner Hole”. Then, we make the Trimming Volume Outer Boundary larger (as large as makes sense for the lens housing and mechanics).



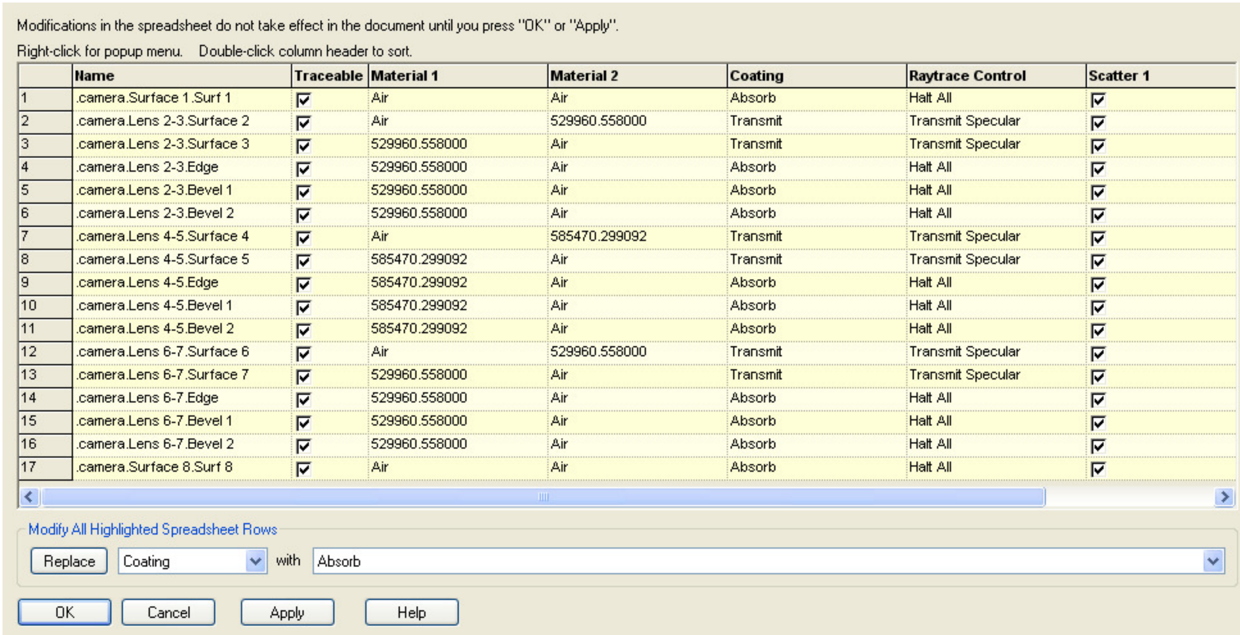

Now that we have an annulus surface, we need to make it optically relevant. On the Coating/RayControl tab of the surface dialog, apply the Absorb coating and the Halt All raytrace control.




## Specifying Surface Coating Properties

The point of this analysis is to find out how much power (and the distribution of that power) reaches our focal plane due to a specular series of events between our lens surfaces which are not “design” paths. For example, an internal bounce within our first lens element may make its way out to the detector and we wish to quantify it’s contribution.

In order for the ghost paths to occur, our lenses need to have coatings on them which allow some fraction of the incident energy to propagate in reflection and transmission. By default, the lens surfaces are imported with 100% transmitting coatings and we will never get any ghosts to be generated. We could visit each optical surface of our lens and apply a non-ideal coating model to each one, but FRED does provide an interface which makes this process a little less tedious. Go to Menu > Edit > Edit/View Multiple Surfaces. This interface provides a mechanism for making multiple surface property assignments quite easily.

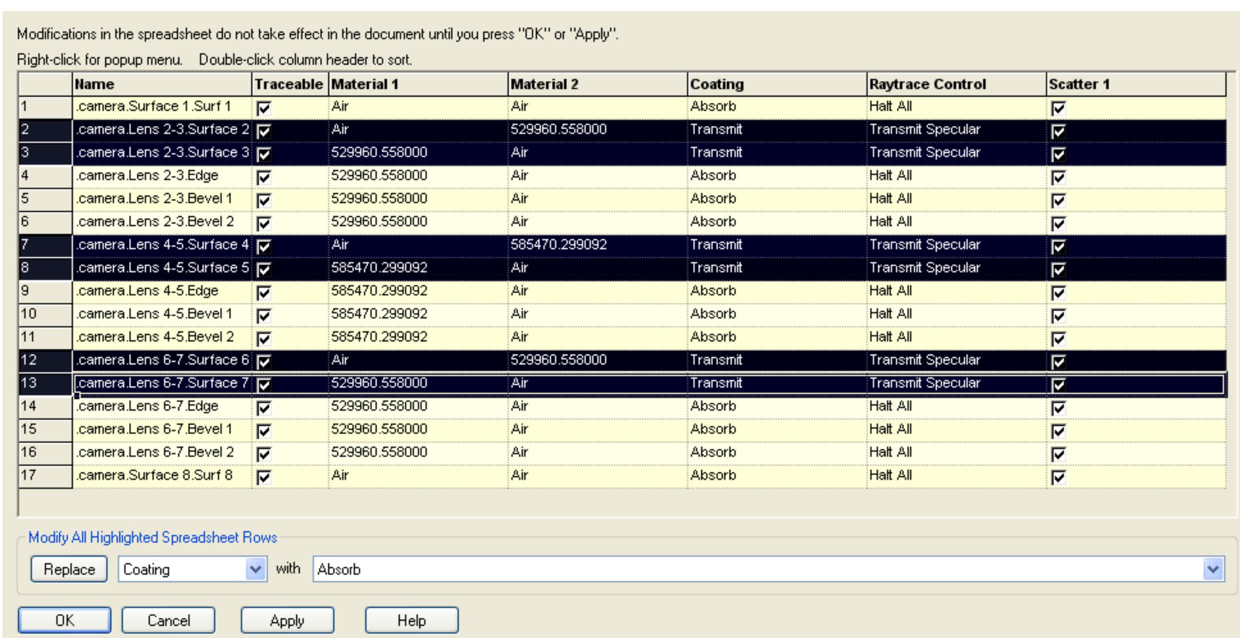


Modifications in the spreadsheet do not take effect in the document until you press "OK" or "Apply".
Right-click for popup menu. Double-click column header to sort.

| | Name | Traceable | Material 1 | Material 2 | Coating | Raytrace Control | Scatter 1 |
|---|---|---|---|---|---|---|---|
| 1 | .camera.Surface 1.Surf 1 | ☑ | Air | Air | Absorb | Halt All | ☑ |
| 2 | .camera.Lens 2-3.Surface 2 | ☑ | Air | 529960.558000 | Transmit | Transmit Specular | ☑ |
| 3 | .camera.Lens 2-3.Surface 3 | ☑ | 529960.558000 | Air | Transmit | Transmit Specular | ☑ |
| 4 | .camera.Lens 2-3.Edge | ☑ | 529960.558000 | Air | Absorb | Halt All | ☑ |
| 5 | .camera.Lens 2-3.Bevel 1 | ☑ | 529960.558000 | Air | Absorb | Halt All | ☑ |
| 6 | .camera.Lens 2-3.Bevel 2 | ☑ | 529960.558000 | Air | Absorb | Halt All | ☑ |
| 7 | .camera.Lens 4-5.Surface 4 | ☑ | Air | 585470.299092 | Transmit | Transmit Specular | ☑ |
| 8 | .camera.Lens 4-5.Surface 5 | ☑ | 585470.299092 | Air | Transmit | Transmit Specular | ☑ |
| 9 | .camera.Lens 4-5.Edge | ☑ | 585470.299092 | Air | Absorb | Halt All | ☑ |
| 10 | .camera.Lens 4-5.Bevel 1 | ☑ | 585470.299092 | Air | Absorb | Halt All | ☑ |
| 11 | .camera.Lens 4-5.Bevel 2 | ☑ | 585470.299092 | Air | Absorb | Halt All | ☑ |
| 12 | .camera.Lens 6-7.Surface 6 | ☑ | Air | 529960.558000 | Transmit | Transmit Specular | ☑ |
| 13 | .camera.Lens 6-7.Surface 7 | ☑ | 529960.558000 | Air | Transmit | Transmit Specular | ☑ |
| 14 | .camera.Lens 6-7.Edge | ☑ | 529960.558000 | Air | Absorb | Halt All | ☑ |
| 15 | .camera.Lens 6-7.Bevel 1 | ☑ | 529960.558000 | Air | Absorb | Halt All | ☑ |
| 16 | .camera.Lens 6-7.Bevel 2 | ☑ | 529960.558000 | Air | Absorb | Halt All | ☑ |
| 17 | .camera.Surface 8.Surf 8 | ☑ | Air | Air | Absorb | Halt All | ☑ |



We are going to use this interface to replace all of our Transmitting surfaces with the default "Standard Coating", which allows 96% power transmitted and 4% power reflected, and the default "Allow All" raytrace control, which allows rays to be split into reflected and transmitted components at an interface. While holding down the "Ctrl" key on your keyboard, select the rows in the spreadsheet which have the "Transmit" coating.



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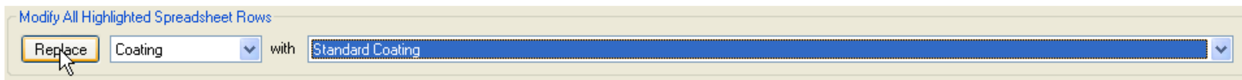
Right-click for popup menu. Double-click column header to sort.

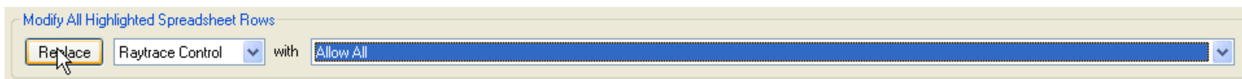
| | Name | Traceable | Material 1 | Material 2 | Coating | Raytrace Control | Scatter 1 |
|---|---|---|---|---|---|---|---|
| 1 | .camera.Surface 1.Surf 1 | ☑ | Air | Air | Absorb | Halt All | ☑ |
| 2 | .camera.Lens 2-3.Surface 2 | ☑ | Air | 529960.558000 | Transmit | Transmit Specular | ☑ |
| 3 | .camera.Lens 2-3.Surface 3 | ☑ | 529960.558000 | Air | Transmit | Transmit Specular | ☑ |
| 4 | .camera.Lens 2-3.Edge | ☑ | 529960.558000 | Air | Absorb | Halt All | ☑ |
| 5 | .camera.Lens 2-3.Bevel 1 | ☑ | 529960.558000 | Air | Absorb | Halt All | ☑ |
| 6 | .camera.Lens 2-3.Bevel 2 | ☑ | 529960.558000 | Air | Absorb | Halt All | ☑ |
| 7 | .camera.Lens 4-5.Surface 4 | ☑ | Air | 585470.299092 | Transmit | Transmit Specular | ☑ |
| 8 | .camera.Lens 4-5.Surface 5 | ☑ | 585470.299092 | Air | Transmit | Transmit Specular | ☑ |
| 9 | .camera.Lens 4-5.Edge | ☑ | 585470.299092 | Air | Absorb | Halt All | ☑ |
| 10 | .camera.Lens 4-5.Bevel 1 | ☑ | 585470.299092 | Air | Absorb | Halt All | ☑ |
| 11 | .camera.Lens 4-5.Bevel 2 | ☑ | 585470.299092 | Air | Absorb | Halt All | ☑ |
| 12 | .camera.Lens 6-7.Surface 6 | ☑ | Air | 529960.558000 | Transmit | Transmit Specular | ☑ |
| 13 | .camera.Lens 6-7.Surface 7 | ☑ | 529960.558000 | Air | Transmit | Transmit Specular | ☑ |
| 14 | .camera.Lens 6-7.Edge | ☑ | 529960.558000 | Air | Absorb | Halt All | ☑ |
| 15 | .camera.Lens 6-7.Bevel 1 | ☑ | 529960.558000 | Air | Absorb | Halt All | ☑ |
| 16 | .camera.Lens 6-7.Bevel 2 | ☑ | 529960.558000 | Air | Absorb | Halt All | ☑ |
| 17 | .camera.Surface 8.Surf 8 | ☑ | Air | Air | Absorb | Halt All | ☑ |

Now that we have selected the rows we wish to modify, we use the "Modify All Highlighted Spreadsheet Rows" area of the dialog to replace the properties of interest. In this case, choose "Coating" from the property type dropdown list, choose "Standard Coating" from the available properties dropdown list, and then hit the "Replace" button.




## Specifying Surface Raytrace Control Properties

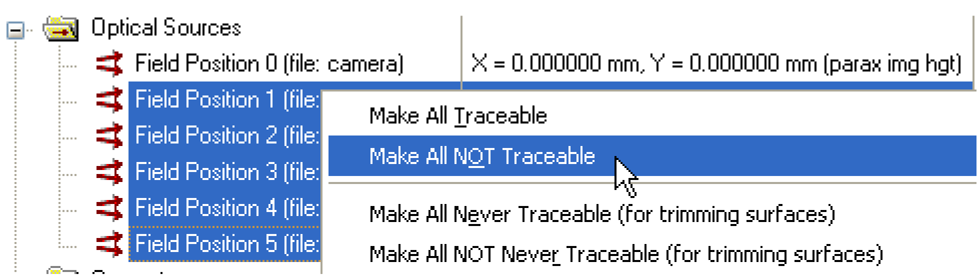
Repeat this procedure for the Raytrace Control, using the Allow All property.



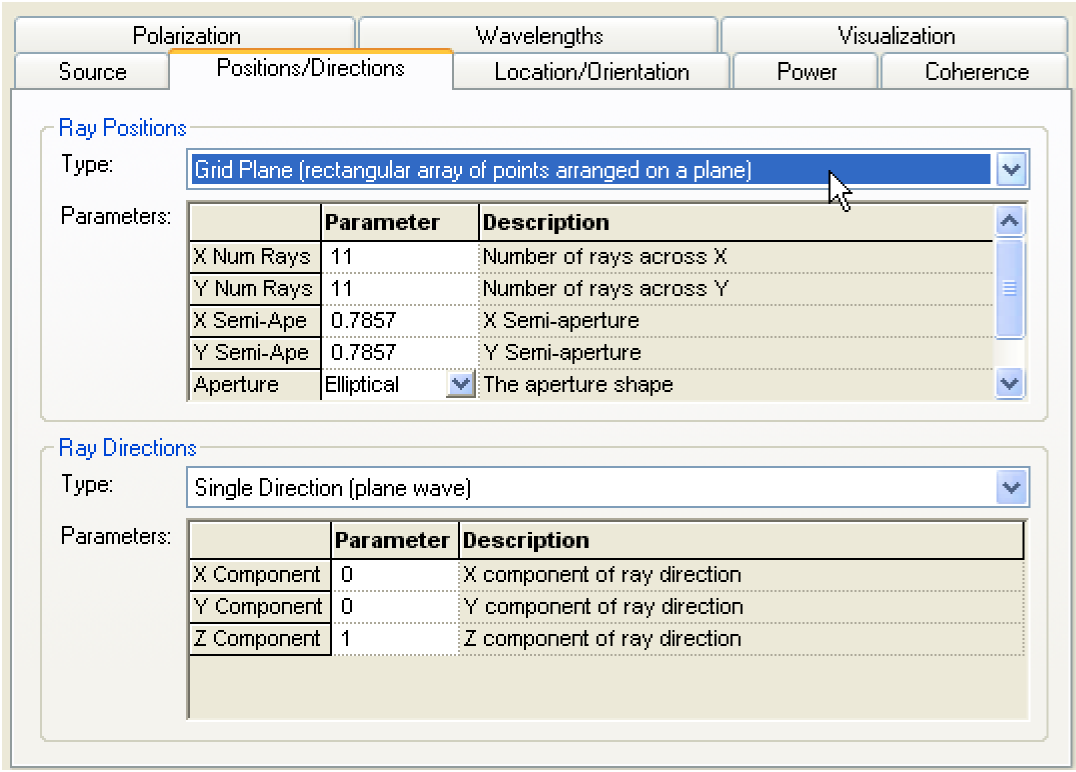

Once you have replaced the Coating and Raytrace Control for the selected surfaces, you can press the OK button to commit the changes back to the document and close the Edit/View Multiple Surfaces dialog.

## Setting up the Source

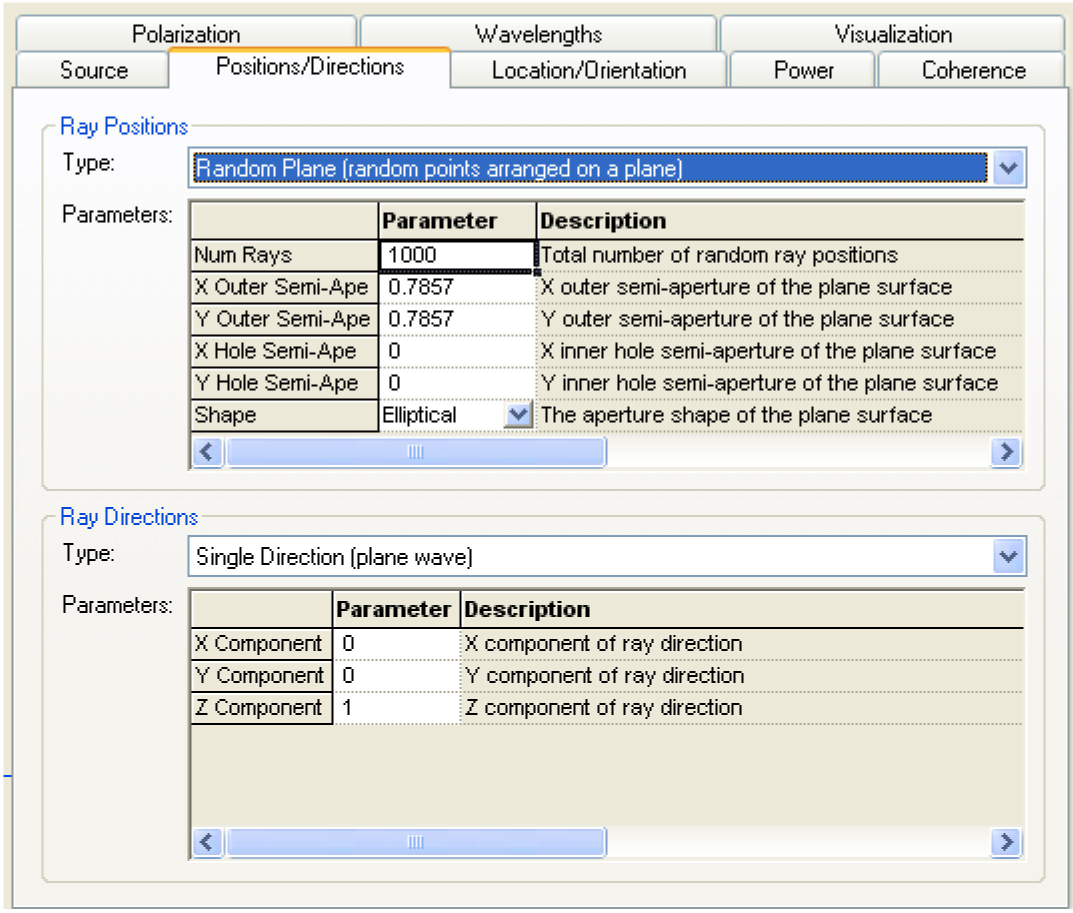
The geometry properties will now support first level ghosting to occur within the lens elements and we should now setup our optical source. Note that FRED did create multiple field sources as specified in your design file but we will perform our analysis with the on-axis field. Expand out your Optical Sources folder, select field sources 1-5 on the tree, right mouse click and toggle the "Make All NOT Traceable" option to turn these sources off.




When tracing incoherent sources it is generally a good idea to remove any "grid-ness" of the source definition. Double click on the Field Position 0 source to open its dialog and then move to the Positions/Directions tab. Note that the Ray Positions specification is set to “Grid Plane”.



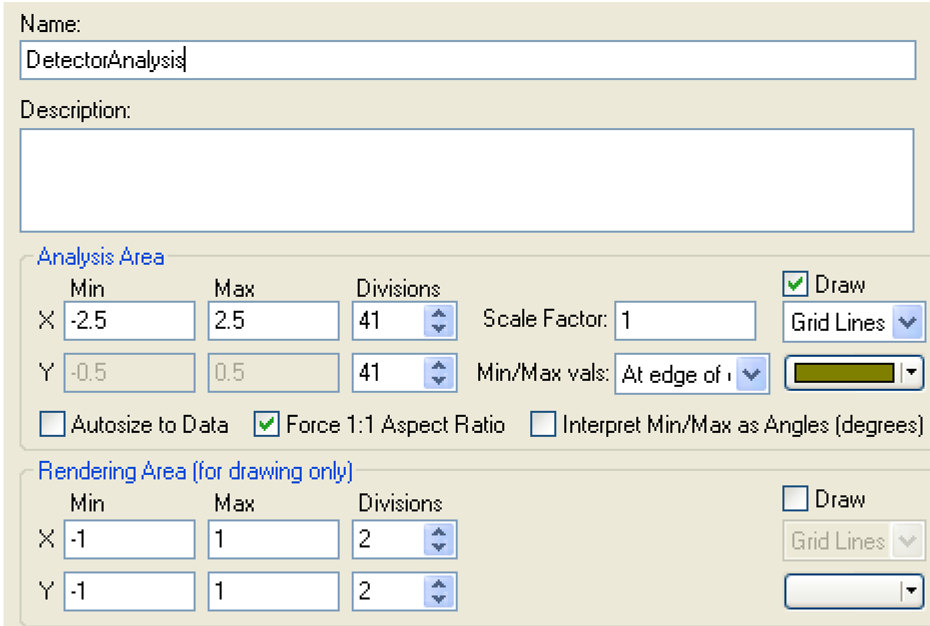

With incoherent sources, having grid positions and directions specifications can cause aliasing artifacts in the calculated energy distributions (source grid overlapping with an analysis grid). To remove the potential of this occurring, we change the ray positions type from Grid Plane to “Random Plane” while maintaining the same aperture size and shape.



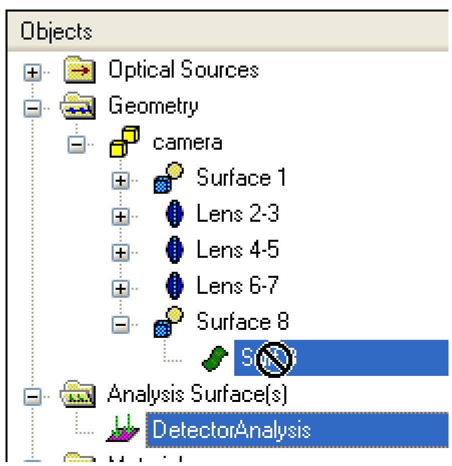

After you have changed the ray positions specification of your source as described above, hit OK to accept the changes and close the dialog.

## Adding an Analysis Surface

Although we have a surface for our focal plane, we need to add an Analysis Surface to it in order to calculate an irradiance distribution. First, we determine that the aperture size of our focal plane is about 2.5 mm. Next, we right mouse click on our Analysis Surface(s) folder and choose “New Analysis Surface”. For now, it is sufficient to specif the name, the size of the analysis area, and the number of divisions in the grid. We will put the analysis surface into position after it has been created.

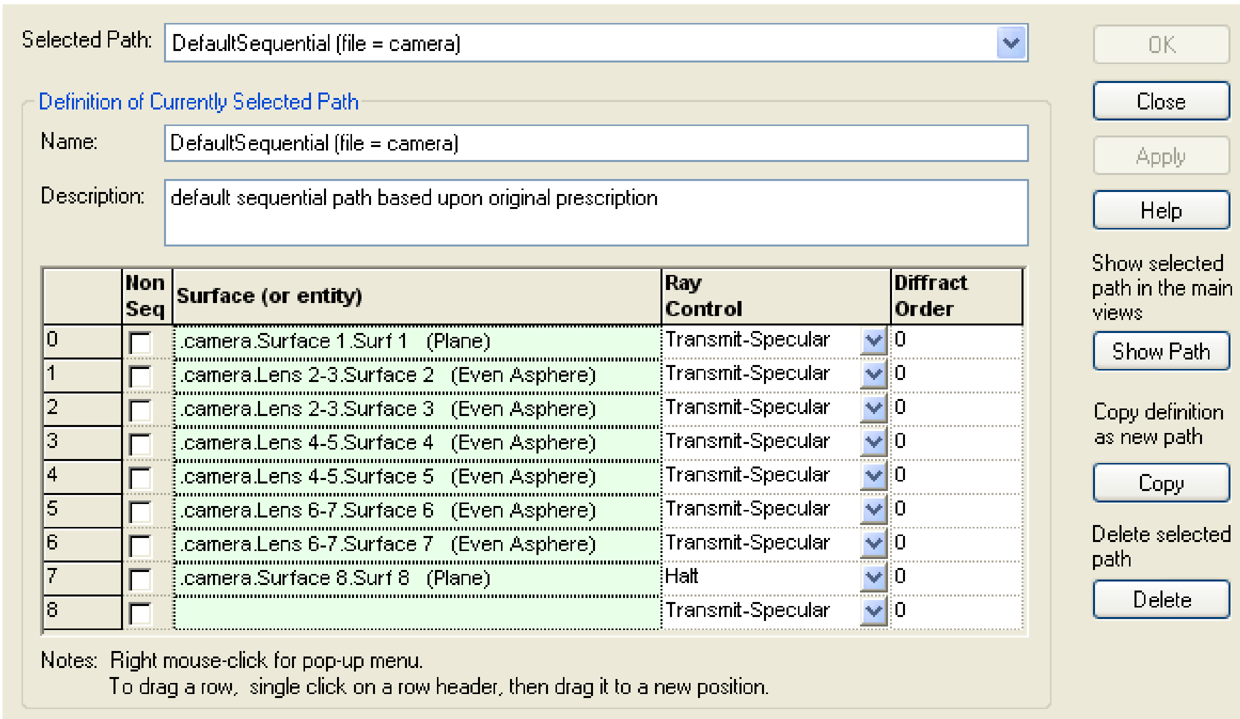



After completing the specifications above, hit the OK button to create the new analysis surface. We can assign this analysis surface to our detector by expanding out the Analysis Surface(s) folder and our geometry tree (so that we can see "Surf 8") and then dragging and dropping the DetectorAnalysis node onto Surf 8.

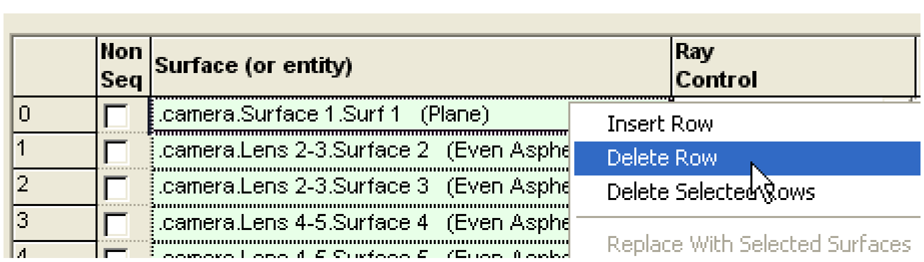



## Modifying the Default Sequential Path

As we will see shortly, the basis of our scripted analysis is the default sequential path of the lens design which is automatically created on file import. To view the sequential paths available, navigate to Menu > Raytrace > User-defined Ray Paths. In the "Selected Path" drop down list, choose "DefaultSequential" to display the path listing. Although FRED's native raytracing mode is non-sequential, it can be instructed to perform sequential raytracing (i.e. an explicit ordered list of intersection events). The DefaultSequential raytrace path (shown below) instructs FRED to perform this exact sequence of intersection events.




Notice, however, that the first event in the DefaultSequential path is a transmission through "Surf 1". When we first imported our lens design, this event made sense because the "stop" was actually an Air/Air transmitting disk. However, we have modified our stop surface to be suitable for a FRED model by making it an absorbing annulus surface. Changing the stop surface in this way means that we should remove it from our DefaultSequential path (after all, we actually want rays which *don't* hit the aperture stop). To remove an event from a sequential path, right mouse click on the row you wish to remove and select the "Delete Row" option.



Hit the OK button on the dialog to accept this change and commit it to the document.

## RUNNING THE SCRIPT

The idea behind the automated script is to start with the DefaultSequential path and then use it to generate all possible 1st order ghost paths in the system. For a system with *n* optical surfaces, the number of ghosts can be determined from:

$$n_{ghosts} = \sum_{m=1}^{n-1} m$$

Algorithmically, the script automates the following steps:
1. Find and store the default sequential path events
2. Construct a list of all ghost surface combinations
3. Loop over each ghost surface combination and
   - 3a. Construct the sequential path corresponding to the ghost
   - 3b. Raytrace the sequential path
   - 3c. Perform an irradiance on the focal plane and calculate statistics
   - 3d. Report the ghost path information to the output window

After running the script, the document will contain:

1. A unique sequential path for each first order ghost path in the system
2. An Analysis Results Node (ARN) for each ghost path in the system containing the irradiance distribution for each ghost path.
3. A summary of each ghost path in the output window

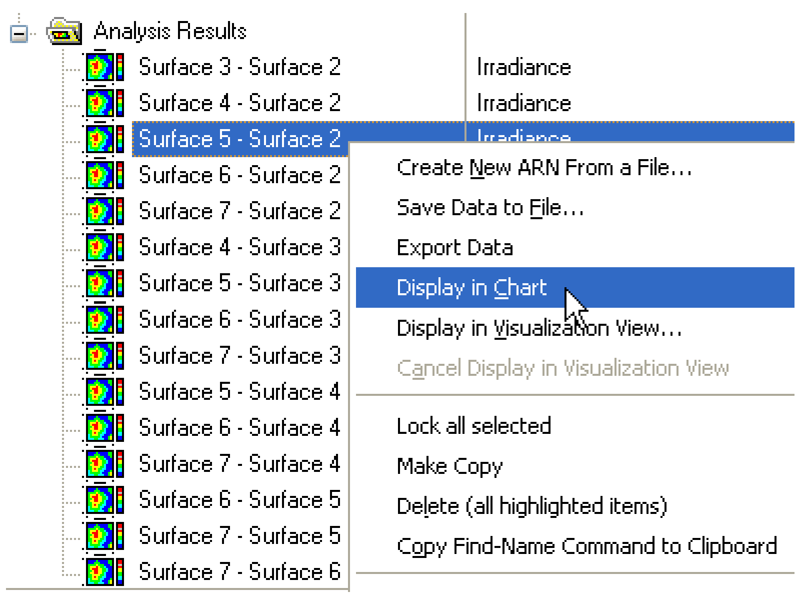
In order to prepare the script to be run on our example system, there are two lines we need to modify.

1. Line 19: Fill in the appropriate FindFullName command for the analysis surface being used to calculate the irradiance distribution on our focal plane
2. Line 24: Fill in the appropriate name of the default sequential path that was created on file import (you can copy this from the user defined path dialog)

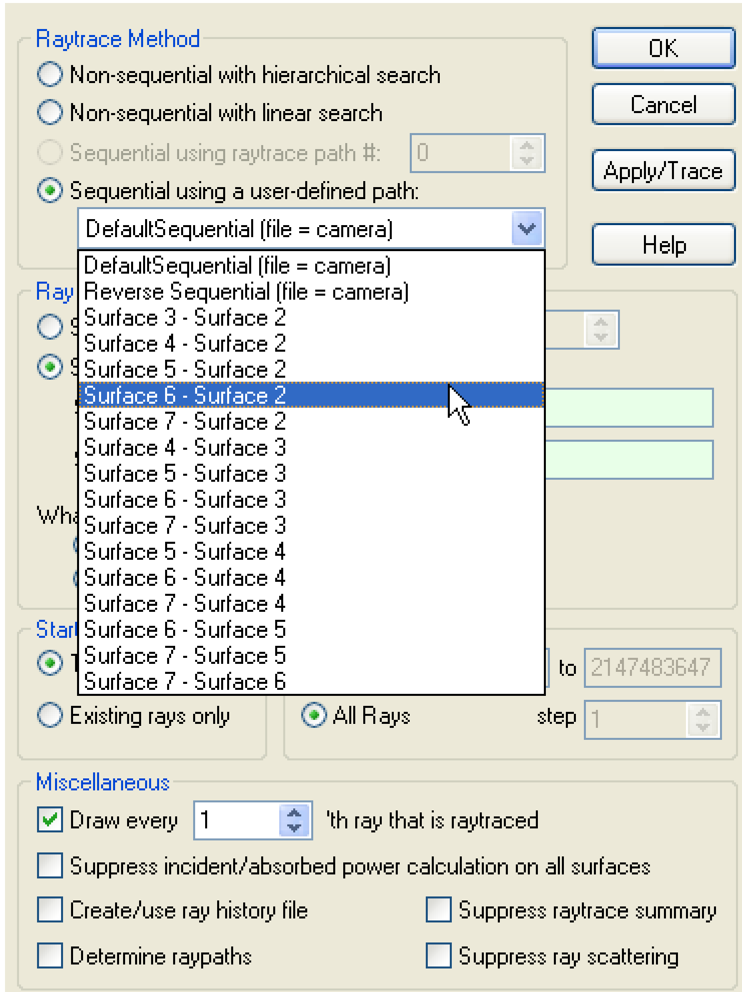
The following output should be printed to the output window after running the script and provides an overview of each ghost path through the system by listing the ghost surface pairs, the number of rays included in the result, the total power in that ghost path on the detector and the peak irradiance value in that ghost path's distribution.

| Ghost 1 | Ghost 2 | Rays | Power | Peak Irrad |
|---|---|---|---|---|
| Surface 3 | Surface 2 | 426 | 1.77842569818944E-04 | 1.68424428093321E-04 |
| Surface 4 | Surface 2 | 945 | 3.63580347807876E-04 | 2.32829929396206E-04 |
| Surface 5 | Surface 2 | 1501 | 5.32397974902029E-04 | 2.6822007866443E-04 |
| Surface 6 | Surface 2 | 554 | 1.79401416946168E-04 | 2.14232741230853E-04 |
| Surface 7 | Surface 2 | 861 | 2.59297985033487E-04 | 1.8224944090925E-04 |
| Surface 4 | Surface 3 | 1097 | 4.58069858530129E-04 | 3.36848856186641E-04 |
| Surface 5 | Surface 3 | 3000 | 1.15422332637421E-03 | 4.26854870559712E-04 |
| Surface 6 | Surface 3 | 66 | 2.34021087869024E-05 | 7.15253543105145E-05 |
| Surface 7 | Surface 3 | 378 | 1.2352228707769E-04 | 1.3183553306514E-04 |
| Surface 5 | Surface 4 | 1077 | 4.4992917751729E-04 | 2.52636642139981E-04 |
| Surface 6 | Surface 4 | 42 | 1.6159126569239E-05 | 7.76099764654021E-05 |
| Surface 7 | Surface 4 | 213 | 7.55249874486396E-05 | 1.43050708621029E-04 |
| Surface 6 | Surface 5 | 1054 | 4.3990987780918E-04 | 2.94742749163311E-04 |
| Surface 7 | Surface 5 | 3000 | 1.15422332637421E-03 | 8.92514729352124E-04 |
| Surface 7 | Surface 6 | 3000 | 1.25241246351369E-03 | 6.31591605349952E-04 |

Additionally, the Analysis Results folder on your object tree should contain one irradiance distribution for each of the ghost paths. You can view these results in the chart viewer by right mouse clicking on the ARN:




Lastly, you can re-trace any of the specific ghost paths using the Advanced Raytrace dialog and selecting the "Sequential using a user-defined path" option and then selecting the desired ghost path:




## SUMMARY

This article and the corresponding example files demonstrates a procedure for preparing your optical design file for a ghosting analysis in FRED and presents a script utility to help automate a first order ghost analysis. The script leaves the FRED document in a state which contains the results for all first order ghost paths in the system, provides a summary of all first order ghost paths and additionally creates unique user-defined ray paths for each ghost surface pair that can be traced upon request.