ZEMAX Users' Knowledge Base - http://www.zemax.com/kb
How To Design a Singlet Lens
http://www.zemax.com/kb/articles/20/1/How-To-Design-a-Singlet-Lens/Page1.html
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This article explains:

- Modifying system settings, including System Aperture, Lens Units, Fields and Wavelengths
- Entering lens prescription data
- Using solves to enforce design contraints
- Analyzing system performance prior to optimization
- Determining degrees of freedom and setting variables
- Setting up a default merit function
- Optimizing and analyzing final design performance

Introduction, Lens Prescription and Design Constraints
The singlet (a single lens) is arguably the simplest imaging system modeled in ZEMAX. Nevertheless, the design of this simple imaging system can help introduce you to the interface of ZEMAX, touch on fundamental design concepts and strategies, and demonstrate how to use some of the basic analysis features for optimizing and determining optical performance.

In this particular exercise, we will design and optimize an F/4 singlet lens made of N-BK7 glass. The final design solution shall meet the following specifications and constraints:

- Focal Length = 100mm
- Semi-Field-Of-View (SFOV) = 5 degrees
- Wavelength: 632.8nm (HeNe)
- Center Thickness (*c.t.*) of the singlet: 2mm < *c.t.* < 12mm
- Edge Thickness (*e.t.*) of the singlet: *e.t.* > 2mm
- The singlet shall be optimized for smallest RMS Spot Size averaged over the field of view at the given wavelength
- Object is at infinity

Given ZEMAX's user-interface and available tools, the singlet can be modeled and optimized easily!

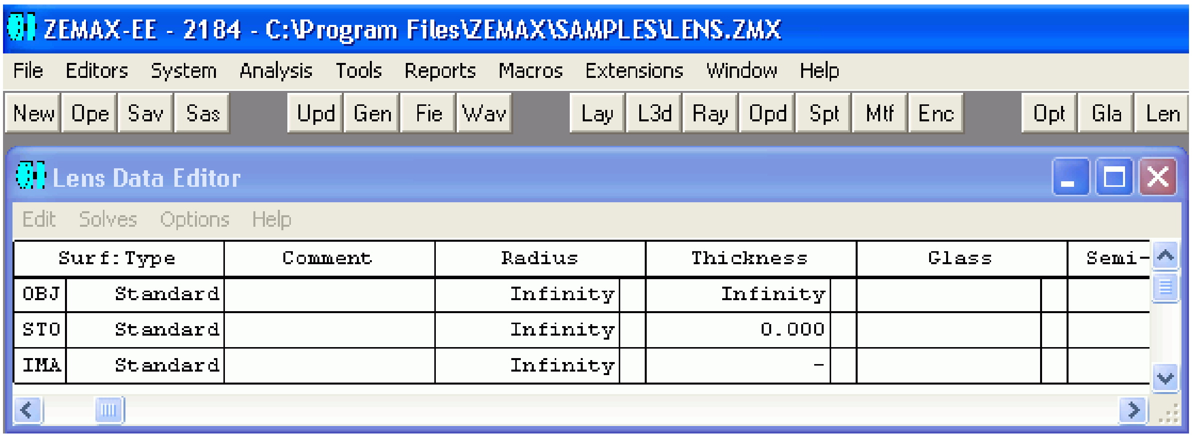
The Lens Data Editor

In computer-aided sequential lens design, rays are traced from one surface to the next in the order in which they are listed. To do this, ZEMAX uses a spreadsheet format called the Lens Data Editor (LDE).

Upon opening ZEMAX, a blank LDE will appear within the main ZEMAX window. The main ZEMAX window has a large blank area, with a title bar, menu bar, and toolbar at the top. The LDE is the primary spreadsheet where the majority of the lens data is entered. Some of the main entries include the following

Surf: Type	the type of surface (Standard, Even Asphere, Diffraction Grating, etc)
Comment	an optional field for typing in surface specific comments
Radius	surface radius of curvature (the inverse of curvature) in lens units

Thickness	the thickness in lens units separating the vertex of the current surface to the vertex of the following surface
Glass	the material type (glass, air, etc.) which separates the current surface and the next surface listed in the LDE
Semi-Diameter	the half-size of the surface in lens units



Each row within the LDE represents a single surface. In sequential ZEMAX, each optical system begins at the object (OBJ) and ends at the image (IMA). In addition to the object and image planes, one of the surfaces must be defined as the aperture stop (STO).

Data can be entered into the LDE by typing in the required values in the highlighted cell. The cursor keys or the mouse may move the highlighted bar to whichever column is desired.

Defining System Settings

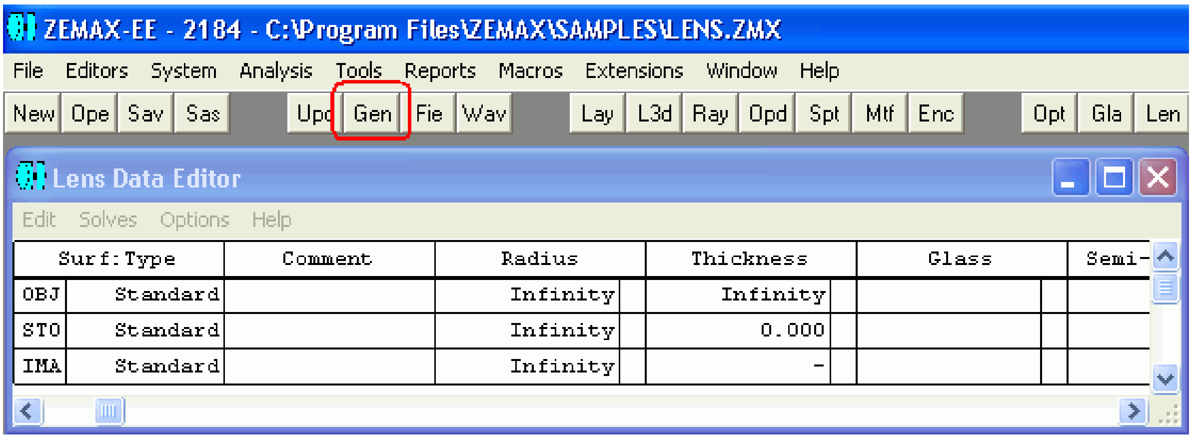
Most frequently, the system aperture is the first parameter which is defined when starting a new design. The system aperture not only defines the size of the beam which ZEMAX will trace through the optical system, but it also determines the initial direction cosines of the rays launched from each field point in the OBJ plane. The system aperture can be defined by a number of different types, including Entrance Pupil Diameter (EPD), Image Space F/#, Object Space NA, Float By Stop Size, etc. Each of these types are defined in more detail in the following section of the ZEMAX User's Guide: “Chapter 6: System Menu > General > Aperture.”

Entrance Pupil Diameter is perhaps the most commonly used system aperture type and is the most convenient definition for the current example. In ZEMAX, the EPD is defined as *the diameter of the pupil in lens units as seen from object space*.

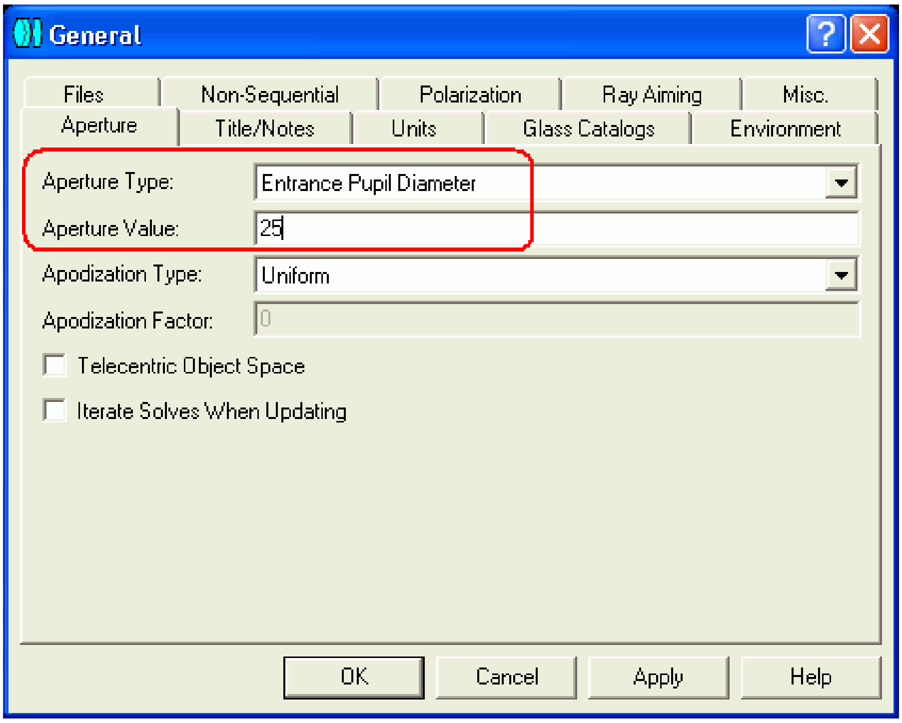
We can easily determine the EPD required for the singlet lens. As was outlined earlier, the singlet lens must have an F/# equal to 4 and an effective focal length of 100mm. Since the F/# is the ratio of the paraxial effective focal length at infinite conjugates over the paraxial entrance pupil diameter, the appropriate EPD is 25mm:

$$F/\# = \frac{efl}{EPD}$$

Where is this value entered into ZEMAX? The system aperture, as well as other system specific settings, are controlled by the System General dialog. To access the System General dialog, select System > General from the main menu in ZEMAX, or click the “Gen” button on the toolbar (often referred to as the “button” bar).

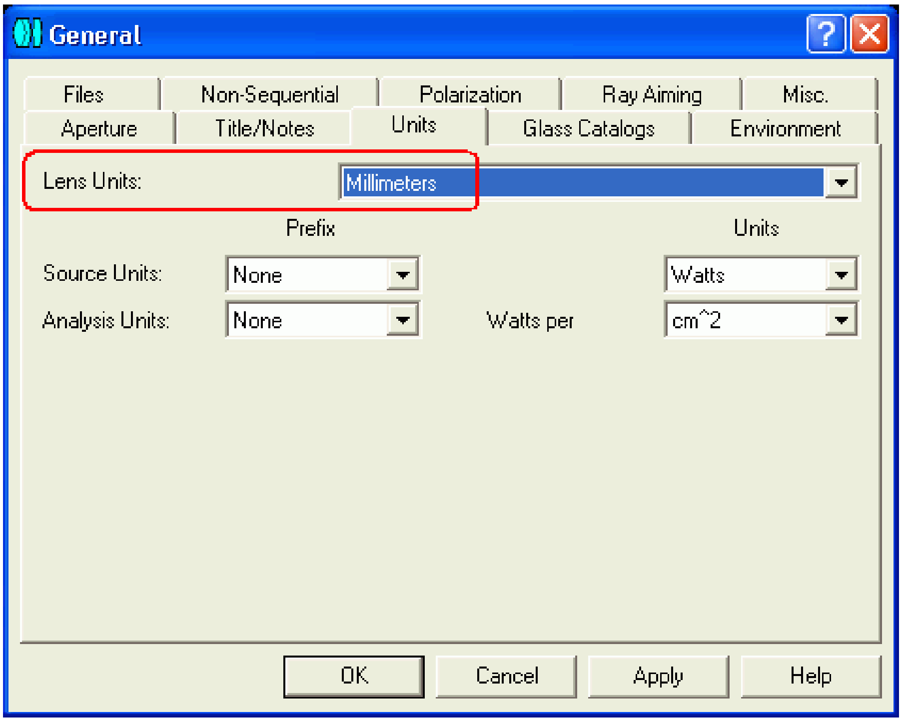


Once the System General dialog is opened, we can now enter in the appropriate system aperture type and value for current design. Under the Aperture tab of the System General dialog, select *Entrtance Pupil Diameter* as the "Aperture Type", and enter in a value of *25* for the "Aperture Value."



The Aperture Value is considered to be in *Lens Units*. The lens units define the units of measure for dimensions in most of the spreadsheet editors in ZEMAX. These dimensions apply to data such as radii, thicknesses, EPDs, and most other parameters in ZEMAX. It is very important that the system units be defined prior to starting the design. Always check to verify that the system lens units are what you expect them to be!

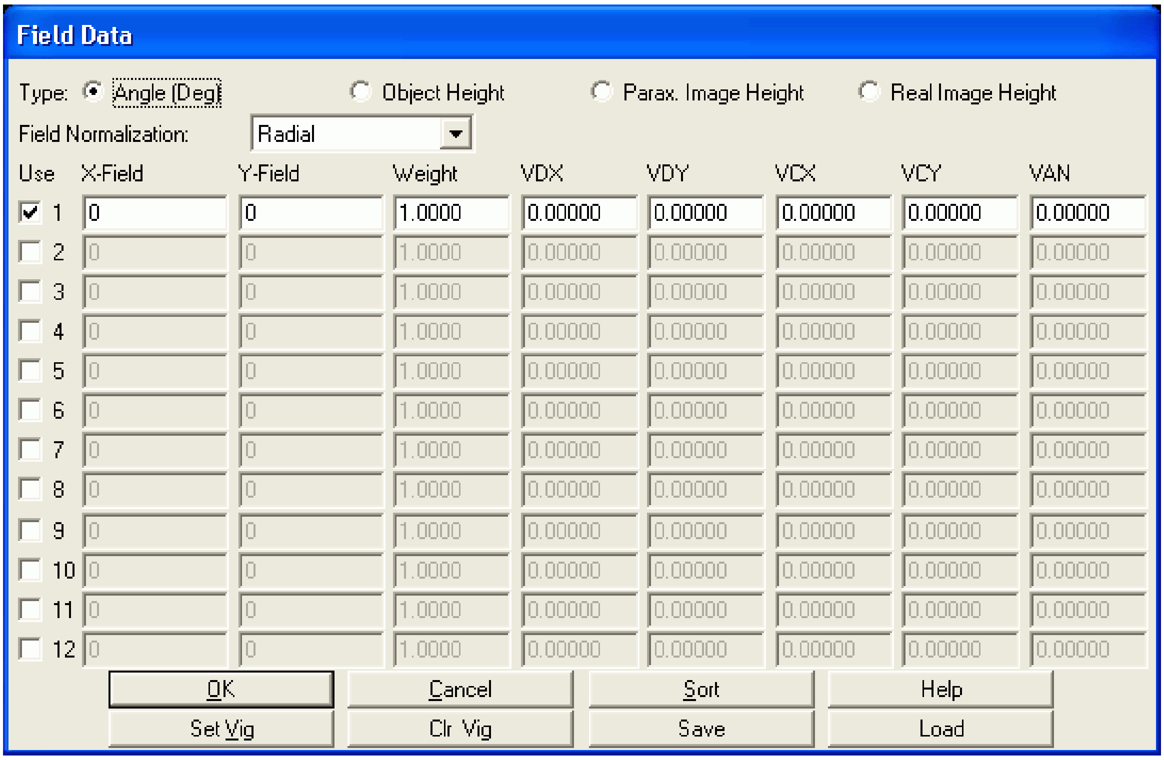
There are four choices for lens units in ZEMAX: millimeters, centimeters, inches, or meters. For the purposes of this design, millimeters will be used. Under the Units tab of the System General dialog, select *Millimeters* as the "Lens Units."



Click "OK" to close the System General dialog. For the time being, other system settings can be ignored and left as the defaults.

Defining Fields in ZEMAX

Field points from within ZEMAX are defined in the Field Data dialog. To access the Field Data Dialog, select System > Fields from the main menu, or click on the “Fie” button on the button bar.



ZEMAX supports 4 different models for defining fields:

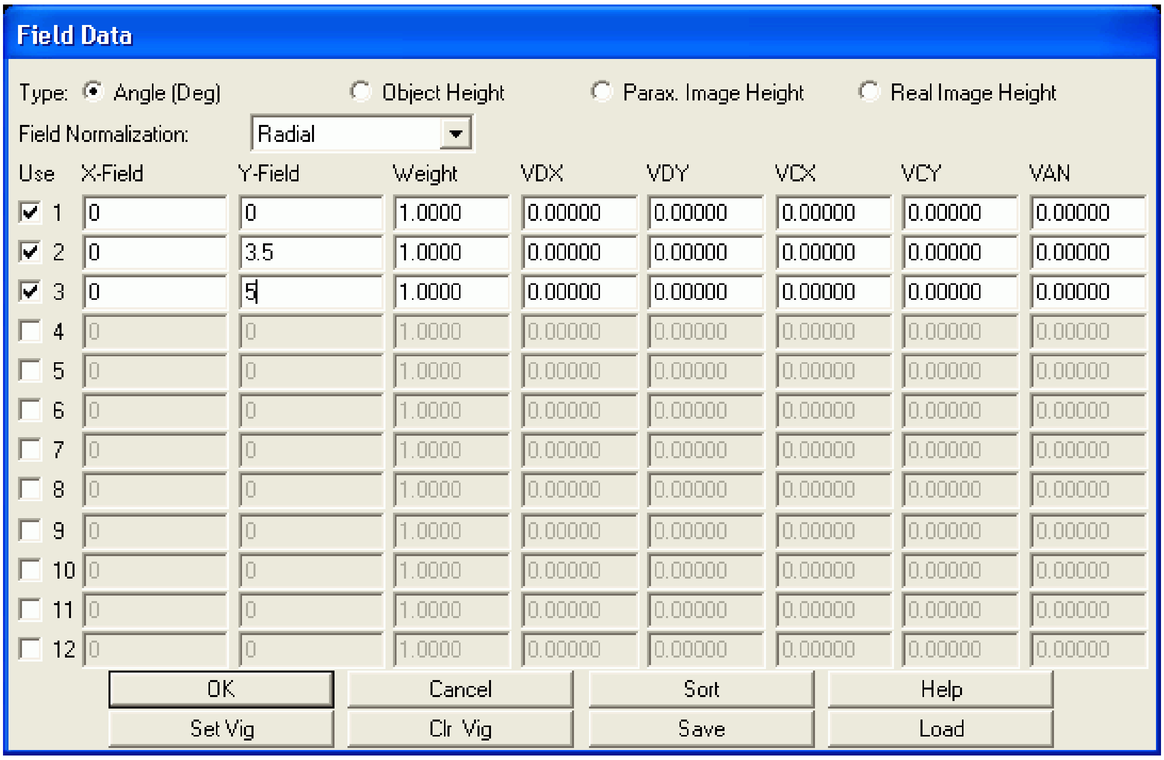
Angle (Deg) the angle in degrees that the chief ray makes with respect to the object space

Z axis. Note that by definition, the chief ray passes through the center of the entrance pupil, so the field angles are measured with respect to the center of the entrance pupil. Positive field angles imply positive slope for the ray in the direction of propagation, and thus refer to negative object coordinates. This option is most useful when at infinite conjugates.

Object Height	the X and Y heights directly on the location of the object (OBJ) surface. The heights are measured in lens units. This option cannot be used when at infinite conjugates.
Paraxial Image Height	the paraxial image height location on the image surface. This option is useful for fixed-frame size designs, such as photographic film in camera systems. This option only works well with systems which are well described by paraxial optics.
Real Image Height	the REAL image height on the image surface. This option is also useful for fixed frame designs. However, ray tracing with this option is slightly slower since ZEMAX must use an iterative approach to determine the proper real ray coordinates of the chief ray on the IMA plane.

For the purposes of the singlet design, we will define the fields in terms of angle. Rather than having a single field representing the HFOV, three fields will be defined within the requirement of 5 degrees: (0, 0), (0, 3.5), and (0, 5).

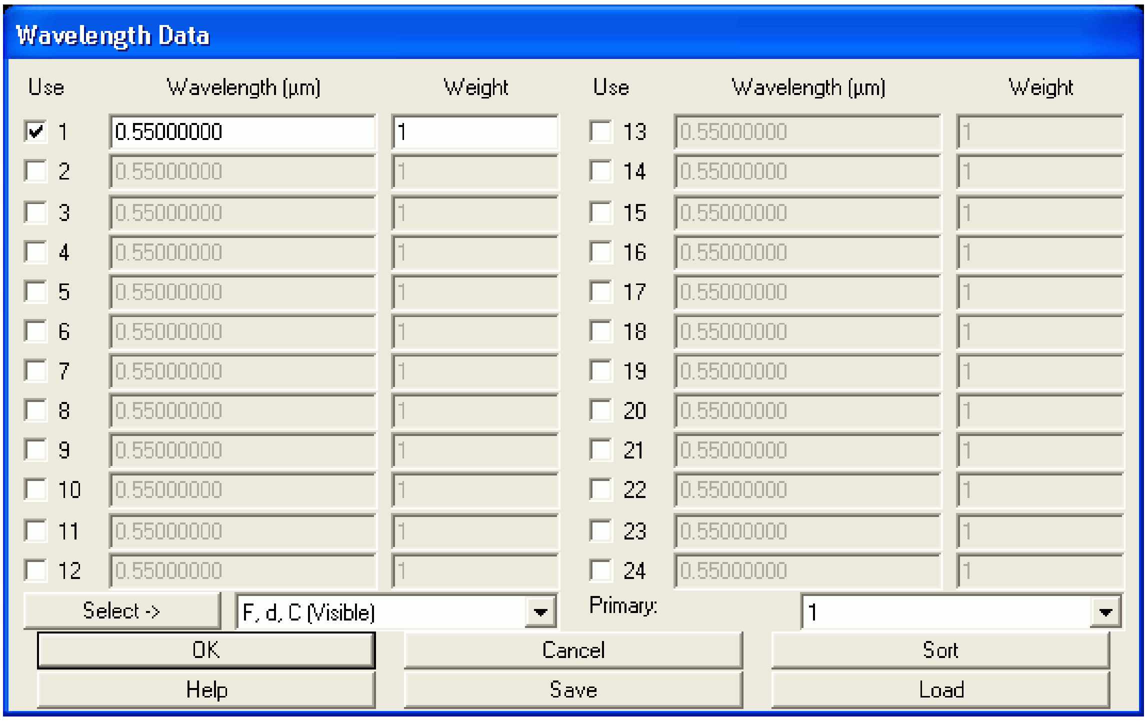
Currently, 12 fields can be entered into the Field Data dialog. Each of these fields can be given a weight, which is primarily useful in optimization. However, for the purposes of this design, all field weights will be left at 1. Enter the three fields into the first three entries in the Field Data dialog, as is shown below:



Select "OK" to close the Field Data dialog.

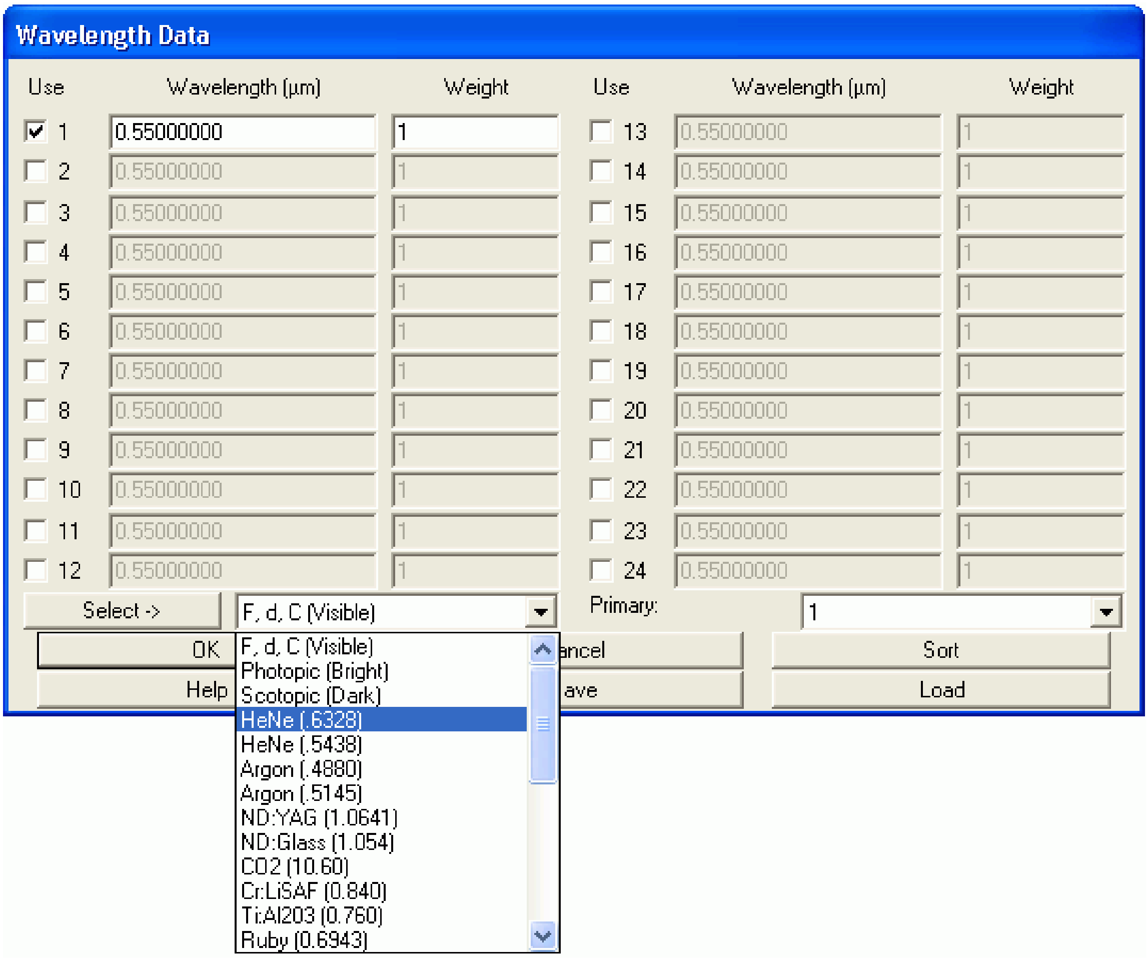
Setting the Wavelengths

Wavelength data is entered into ZEMAX much like field data, only the wavelengths are entered into the *Wavelength Data* dialog. You may access the Wavelength Data dialog by selecting System > Wavelengths from the main menu, or by pressing the “Wav” button on the button bar.

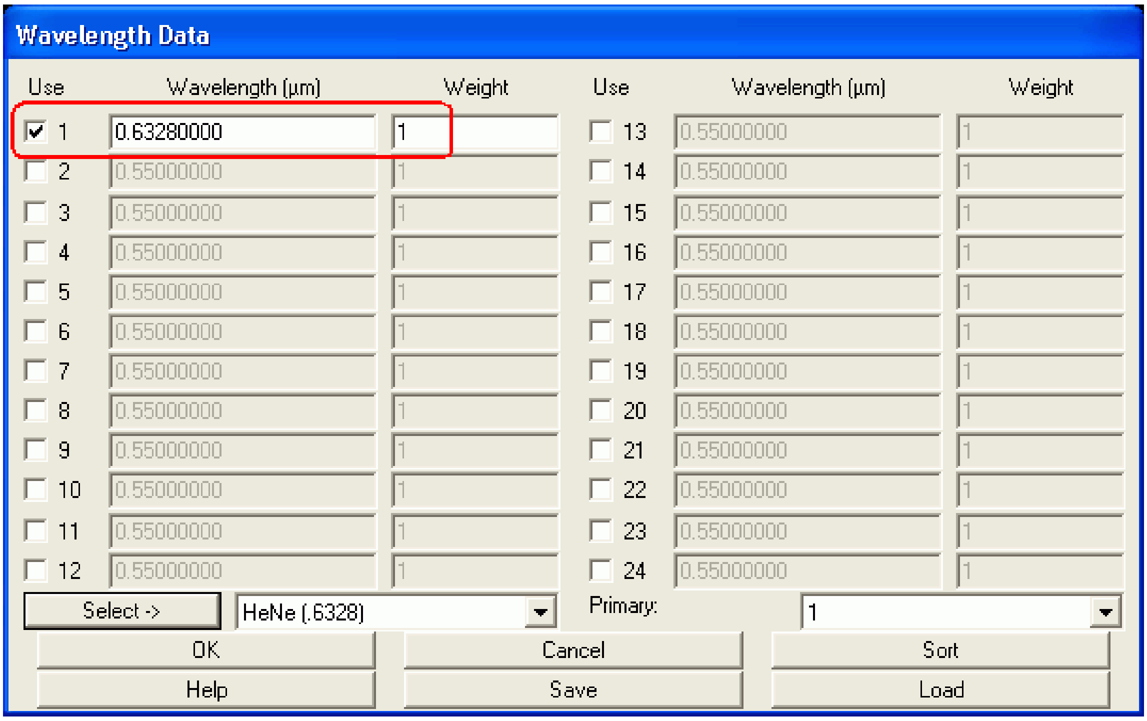


This singlet design is purely monochromatic (pertaining to a single wavelength). From the inital design specifications, the wavelength which will be used is 0.6328mm...the wavelength of a HeNe (Helium Neon) laser.

This wavelength may be manually typed into the Wavelength Data dialog, or it may be entered by selecting one of the pre-programmed wavelength options in the pull down menu near the bottom of the Wavelength Data dialog:



F, d, C (Visible) is the first option by default. However, choose the current design wavelength by first selecting *HeNe (.6328)* from the pull-down menu, and then pressing the "Select ->" button which is next to the pull-down menu. ZEMAX will automatically place this wavelength into the first entry:



Note that wavelengths in ZEMAX are always entered in microns, regardless of the system lens units!

Click "OK" to close the Wavelength Data dialog and apply the defined wavelengths.

Note that wavelength weights are also supported, and are used for various purposes within ZEMAX. However, for the scope of this design, all wavelength weights will remain unity.

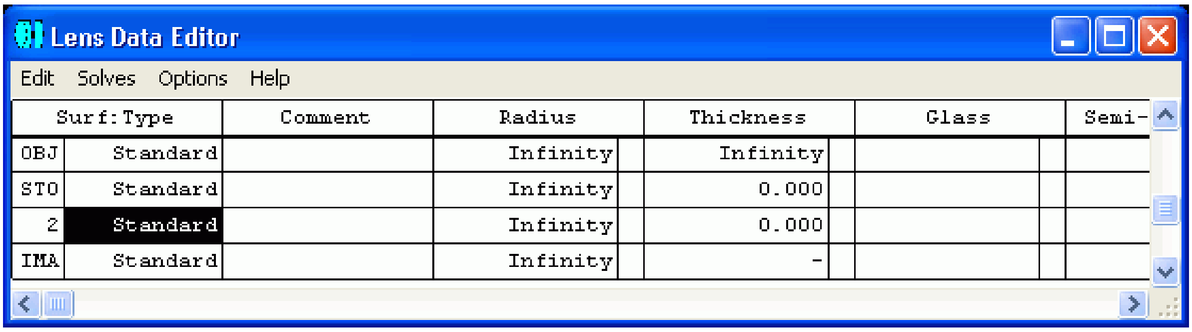
Inserting Surfaces

Once the system settings have been defined, information specific to each surface can be entered into the Lens Data Editor. To reiterate, each row in the LDE represents a single surface. Therefore, two surfaces separated by glass comprise a single element. So, for the purposes of the singlet, a total of 4 surfaces are needed:

1. **The object surface (OBJ):** the location where rays are launched
2. **The front surface of the lens:** where the rays enter the lens. For this design, this will also be the lcation of the stop (STO).
3. **The back surface of the lens:** where the rays exit the lens back into air
4. **The image surface (IMA):** the location where the ray trace stops. No surfaces can be located after the image surface in the LDE. Note that this surface does not necessarily have to be at an acutal image location.

By default, only three surfaces are included in the LDE. Surfaces may be added to the LDE using the "Insert" key on the keyboard, or by selecting Edit > Insert Surface on the menu bar of the LDE. When using this method, a surface will be added prior to the row in which the highlighted cursor is currently located. To add another surface *after* the current surface, "Ctrl + Insert" or Edit > Insert After may be used.

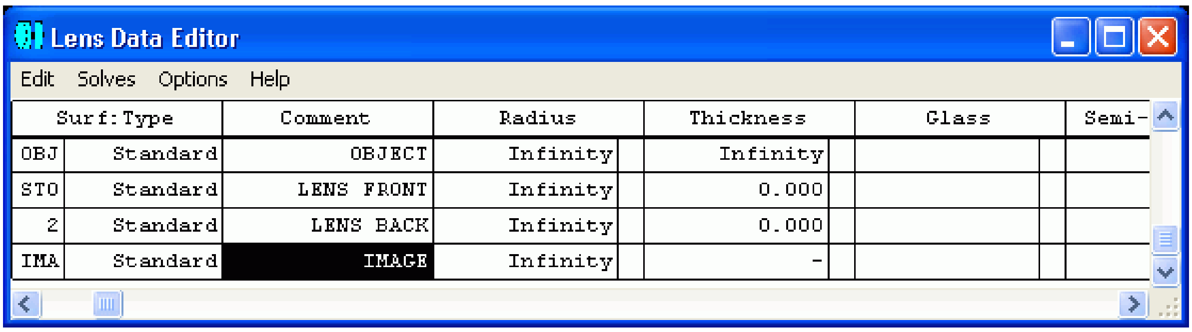
Since the stop will be located at the front surface of the singlet lens, insert another surface (representing the back face of the lens) by placing the highlighted cursor in the row of the IMA surface, and pressing the "Insert" key:



Surf:Type		Comment	Radius	Thickness	Glass	Semi-
OBJ	Standard		Infinity	Infinity		
STO	Standard		Infinity	0.000		
2	Standard		Infinity	0.000		
IMA	Standard		Infinity	-		

The Comment column in the LDE can be very helpful in keeping track of what each surface represents. To enter a comment for a surface, highlight the appropriate cell, and type in the desired text. Once finished, hit the "Enter" key or move the cursor to another cell by using the arrow keys.

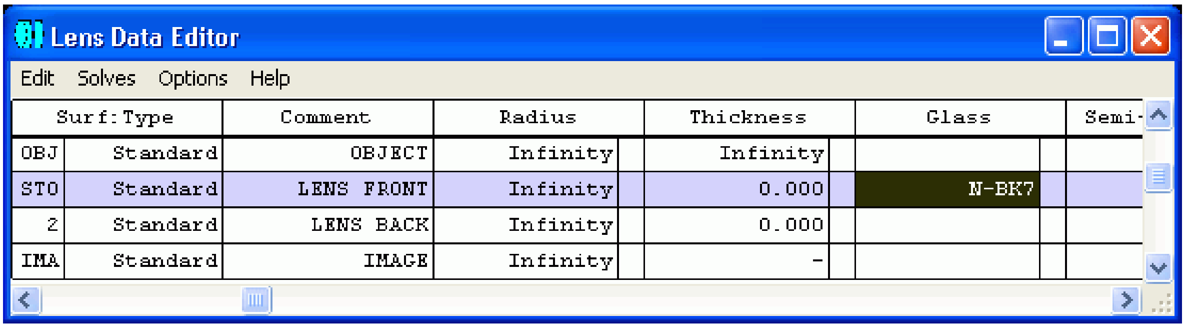
Entering comments as you move along is a very good habit to get into. For the singlet, identify each surface by typing the following text into each appropriate cell in the LDE.



Surf:Type		Comment	Radius	Thickness	Glass	Semi-
OBJ	Standard	OBJECT	Infinity	Infinity		
STO	Standard	LENS FRONT	Infinity	0.000		
2	Standard	LENS BACK	Infinity	0.000		
IMA	Standard	IMAGE	Infinity	-		

Entering Lens Data

The singlet will be made of N-BK7 glass. In ZEMAX, this is the material separating the front and back surfaces of the lens. Enter the glass type separating these two surfaces by simply typing the name of the glass (N-BK7 in this example) in the appropriate cell in the LDE.

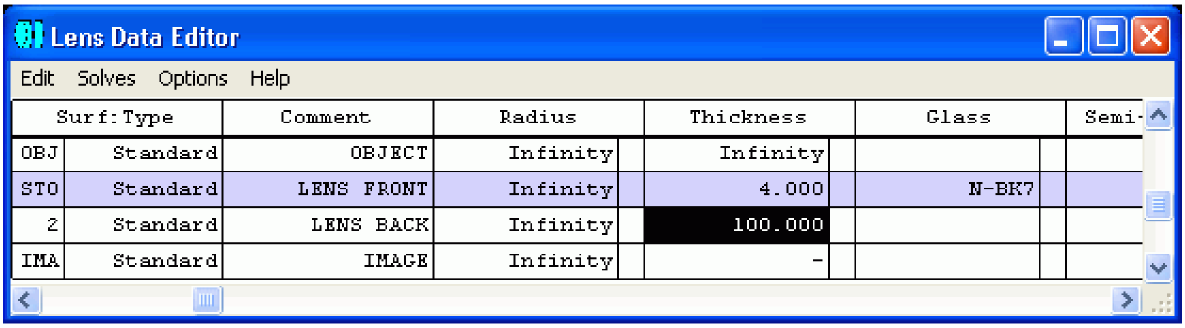


Surf:Type		Comment	Radius	Thickness	Glass	Semi-
OBJ	Standard	OBJECT	Infinity	Infinity		
STO	Standard	LENS FRONT	Infinity	0.000	N-BK7	
2	Standard	LENS BACK	Infinity	0.000		
IMA	Standard	IMAGE	Infinity	-		

ZEMAX automatically recognizes this glass type as one of the many glasses which are compiled into the built-in Glass Catalog. The Glass Catalog contains all of the necessary information for hundreds of glasses provided by manufacturers around the world. ZEMAX will automatically look up this glass in its database to determine the index of refraction of the material at each design wavelength.

Once the glass type is entered into the LDE, the lens thickness for the singlet may be typed into the Thickness column for Surface 1. Since the thickness is the distance along the optical axis to the next surface, this becomes the center thickness of the lens element. As a starting point, a thickness of 4mm may be applied as it is a reasonable center thickness for an aperture of 25mm. Type in a value of *4* into the Thickness column for Surface 1. Note that this parameter will later be set as a variable for optimization.

Similarly, the radius of the first surface and the thickness between the back of the lens and the image need not be pre-determined since they will be set as a variables for optimization. For the time being, we will leave the Radius of Surface 1 as *Infinity* and change the Thickness of Surface 2 to 100mm. Type in the value of *100* into the Thickness column of Surface 2.



Surf:Type		Comment	Radius	Thickness	Glass	Semi-
OBJ	Standard	OBJECT	Infinity	Infinity		
STO	Standard	LENS FRONT	Infinity	4.000	N-BK7	
2	Standard	LENS BACK	Infinity	100.000		
IMA	Standard	IMAGE	Infinity	-		

Solves

When given constraints on an optical design, there are two possible methods of upholding these constraints:

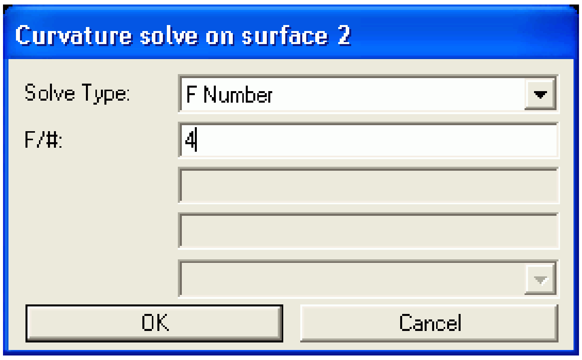
1. Make the parameters which affect these constraints variables and add boundary constraints into the Merit Function Editor (to be introduced shortly) ***OR***
2. Use special solves to enforce the constraints, eliminating unnecessary variables.

The latter of these two is far superior. Though both provide a method of adjusting lens parameters to maintain a specified constraint, boundary constraints can slow down execution of the merit function.

There are many different solves available within ZEMAX, each of which has a specific purpose. However, the performance specifications for this design calls for the use of only one of these solves: one to set the system F/# to maintain the desired focal length.

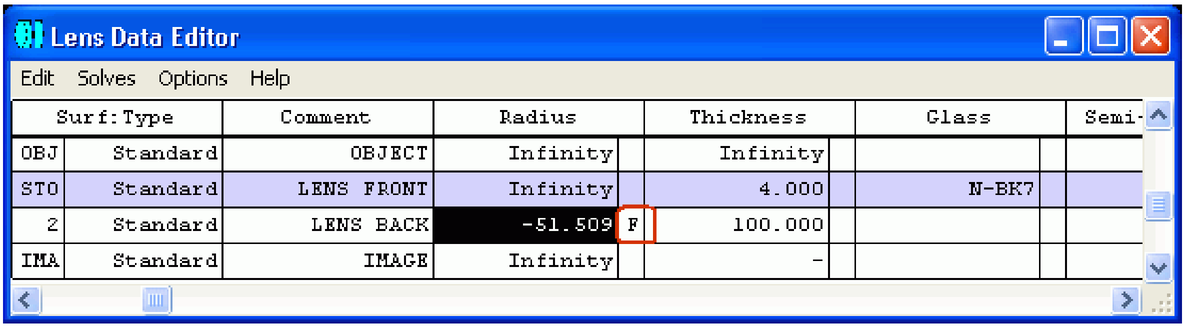
To activate a solve dialog, right-mouse-click on the desired cell, or highlight the cell and press "Enter" on the keyboard. Depending upon which parameter the solve is activated, different solves are available.

To maintain the system F/#, an *F Number* solve can be placed on the radius of Surface 2. The F Number solve adjusts the final optical surface curvature to maintain the system focal length. Right-mouse-click on the Radius cell for Surface 2 to activate the Curvature solve on surface 2 dialog. Select *F Number* from the "Solve Type" pull-down menu and type in a value of *4* into the "F/#" entry below.



Click "OK" to close the solve dialog.

Once the F Number solve is set, ZEMAX will automatically adjust the radius to maintain the desired F/#. In other words, anytime a lens parameter is altered, the solve will be automatically re-calculated. The letter "F" next to the radius is indicative of the F Number solve in place.



Evaluating System Performance Prior to Optimization

There are many different analysis features included in ZEMAX, each of which can be used to evaluate the performance of a design. In this exercise, we will use four of the more fundamental, commonly known types of analyses of system performance to evaluate the singlet prior to optimization:

Layout A layout may be opened by selecting a Analysis > Layout > 2D Layout from the main menu, or by pressing the "Lay" button on the button bar. The 2D Layout option plots a YZ cross section through the lens, and is only valid for rotationally symmetric, axial systems. A layout diagram of the current system is always a useful visual representation of the current optical system.

Spot Diagram A spot diagram may be accessed by selecting "Analysis > Spot Diagrams > Standard" from the main menu, or by pressing the "Spt" button on the button bar. The spot diagram gives indication of the image of a point object. In the absence of aberrations, a point object will converge to a perfect image point. By default, ZEMAX plots the spot diagram for each field point.

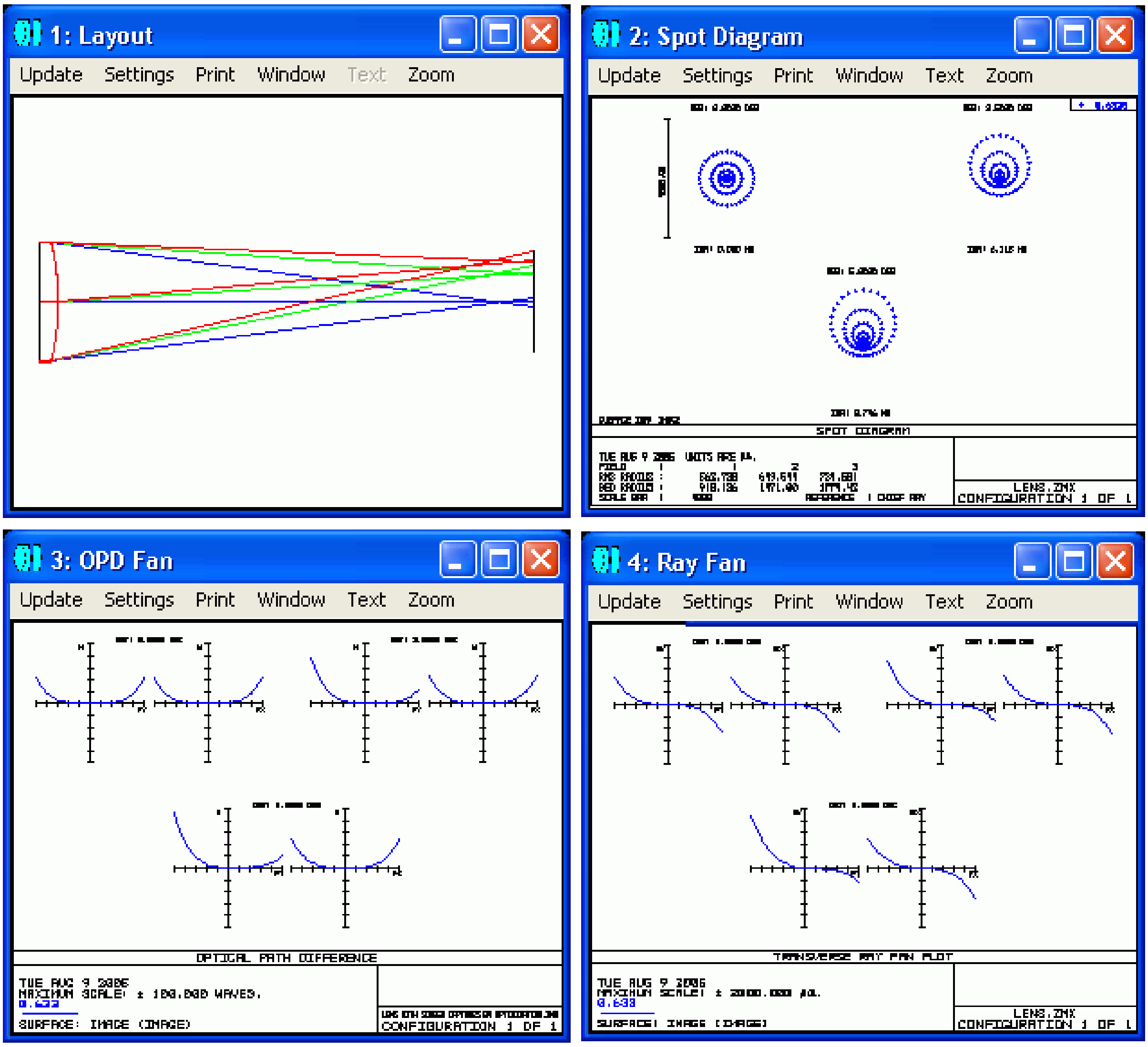
OPD Fan The Optical Path Difference (OPD) fan can be opened by selecting "Analysis > Fans >

Optical Path," or by pressing the "Opd" button on the button bar. The OPD fan is a plot of the optical path difference as a function of pupil coordinate. In a perfect optical system, the optical path of the wavefront will be identical to that of an aberration-free spherical wavefront in the exit pupil.

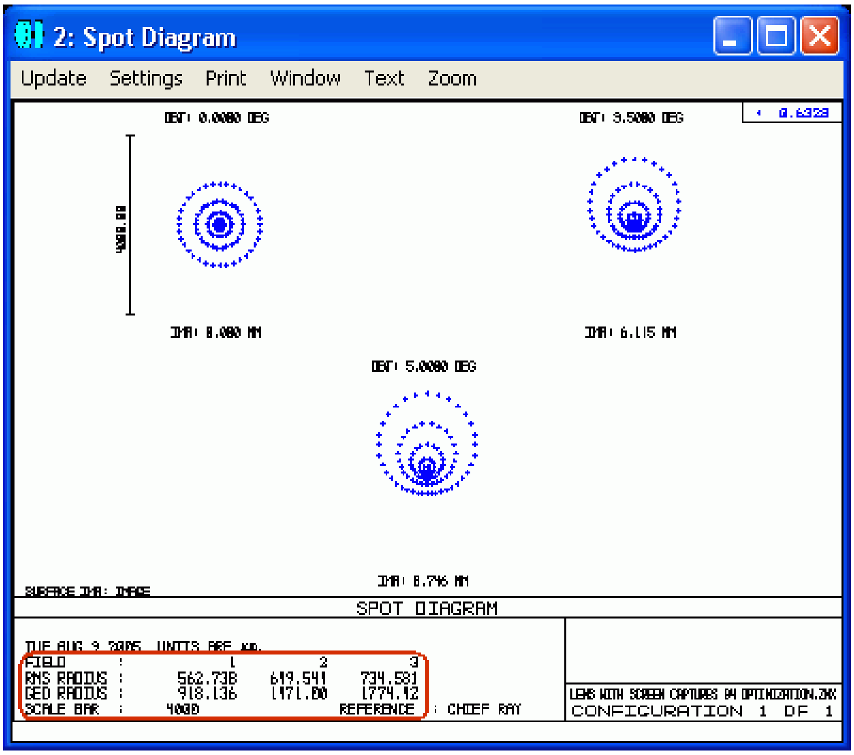
Ray Fan The Ray Fan plot in ZEMAX may be opened by selecting "Analysis > Fans > Ray Aberration" from the main menu in ZEMAX, or by selecting the "Ray" button on the button bar. The Ray Fan plots ray aberrations as a function of pupil coordinate. Generally, a given ray which passes through the optical system an onto the image surface, its point of intersection falls on some small but nonzero distance away from the chief ray. Once again, in a perfect optical system, the ray aberrations should be zero across the pupil.

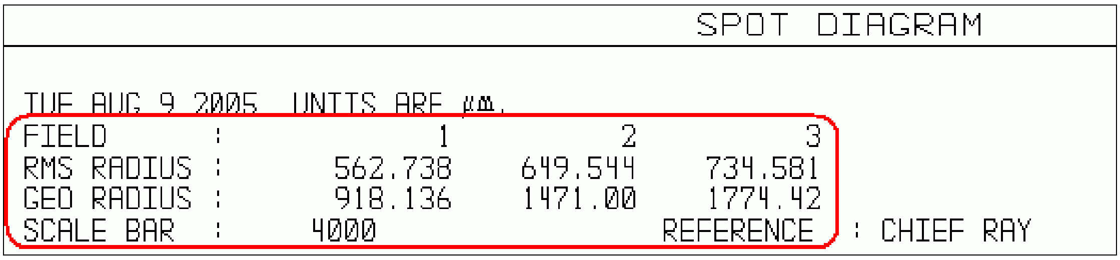
Note that the Spot Diagram, OPD Fan, and Ray Fan Plot are some of the most important tools that a lens designer has available for determining the different types and magnitudes of aberrations present in an optical system. However, the process by which a designer can determine the aberrations present in his/her deisgn from these analysis features goes beyond the scope of this exercise. Instead, these concepts are covered in great detail in several of the references mentioned in Chapter 1 of the ZEMAX User's Guide.

Given the arrangement of the design we have constructed so far, open each one of the above analysis features to review the current lens performance.



From evaluation of the four plots above, it is obvious that the singlet design has a significant number of aberrations, including but not limited to spherical, coma, distortion, defocus, field curvature, and astigmatism. In addition, the geometrical and RMS radii (as is reported at the bottom of the Spot Diagram) at the maximum field are roughly 734.581 and 1774.42µm, respectively.



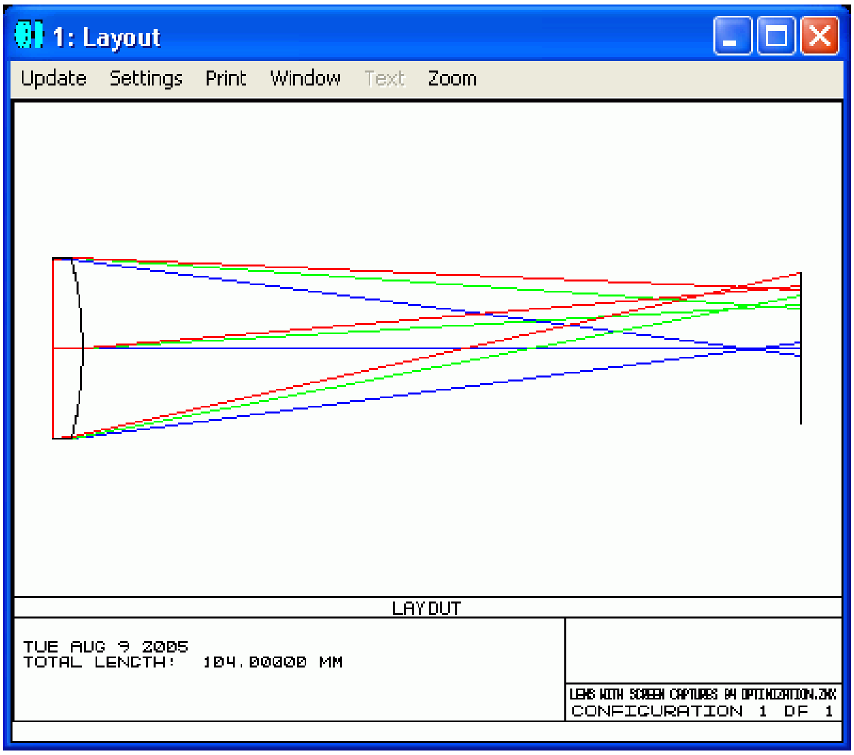

SPOT DIAGRAM

TUE AUG 9 2005 UNITS ARE µm.

FIELD	:	1	2	3
RMS RADIUS	:	562.738	649.544	734.581
GEO RADIUS	:	918.136	1471.00	1774.42
SCALE BAR	:	4000		REFERENCE : CHIEF RAY

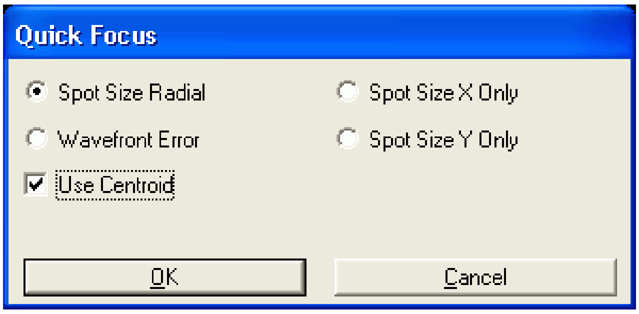
Using the Quick Focus Tool

As could be seen from the four analysis features, the performance of the singlet at this point is certianly not optimal. A big factor in this fairly poor performance was the random selection of the location of the image plane. Even from the Layout, it is obvious that the currently selected image plane is not at "best focus."



Even prior to optimization, we can use a tool within ZEMAX to better position the current image plane location. The tool is known as the *Quick Focus* tool. Quick Focus is a feature in ZEMAX which adjusts the thickness of the surface prior to the image plane to minimize the RMS aberrations.

Open the Quick Focus dialog by selecting Tools > Miscellaneous > Quick Focus or by pressing "Shift+Ctrl+Q" on the keyboard. The "best focus" position which this tool will choose depends upon the criterion which is selected. For the singlet design, we will use radial spot size with respect to the centroid. Select *Spot Size Radial* and place a check next to the "Use Centroid" box.



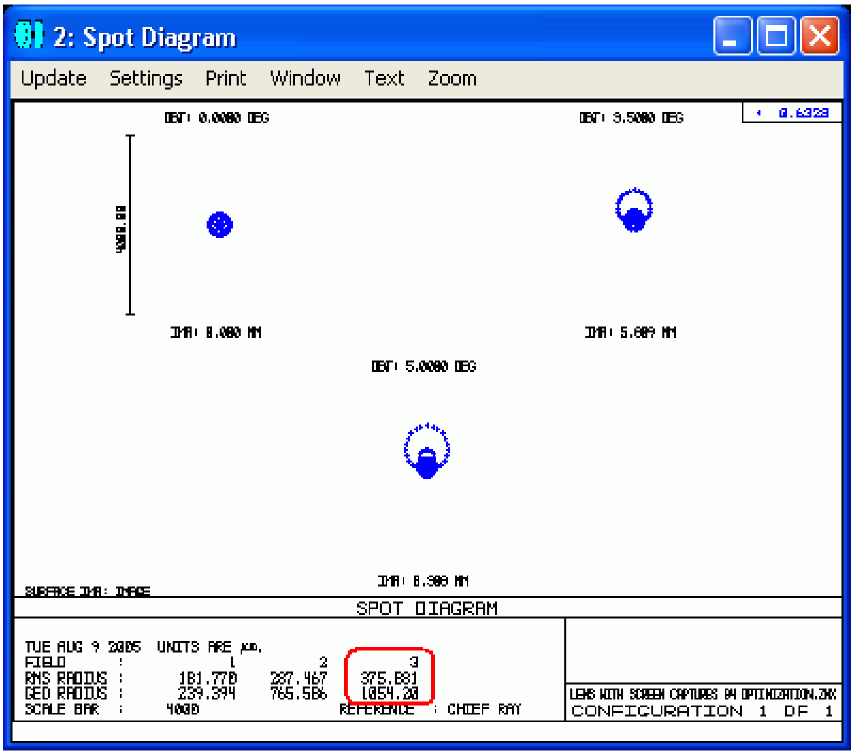
Click "OK" to close the Quick Focus tool dialog.

Note the automatic change to the thickness of the surface prior to the image plane. Update each of the opened analysis windows by selecting "Update" in the upper-left hand corner of each individual analysis window. Note the fairly significant changes in performance simply due to the new selection of the image plane location. Most importantly, the RMS and Geometrical spot sizes at the maximum field decreased by nearly a factor of 2!

Lens Data Editor

Edit Solves Options Help

Surf:Type		Comment	Radius		Thickness		Glass		Semi-
OBJ	Standard	OBJECT	Infinity		Infinity				I
STO	Standard	LENS FRONT	Infinity		4.000		N-BK7		
2	Standard	LENS BACK	-51.509	F	94.864				
IMA	Standard	IMAGE	Infinity		-				



Even though the design is undoubtedly better than before, there is still room for improvement.

Setting Variables and Constructing the Default Merit Function

There are certainly limits as to how well a singlet can perform, but ZEMAX can still be used to find a better solution than the one which currently exists. In doing so, it is important to first determine how many degrees of freedom the current design has. That is, how many parameters are free to adjust? For the singlet in this exercise, one of the parameters (the Radius on Surface 2), can no longer be considered a freely varying parameter since it is controlled by a solve to meet a specific design constraint. However, the center thickness of the lens (the Thickness on Surface 1), the radius of curvature of the front surface (Radius on Surface 1), and the distance from the back of the lens to the image plane (the Thickness on Surface 2) can all be varied in attempt to minimize the RMS spot radius of the singlet.

To allow ZEMAX to consider a parameter as a degree of freedom during optimization, a *Variable* solve type must be placed on the cell in the LDE which represents that parameter. You may set the solve type by right-mouse-clicking on the desired cell or by highlighting the appropriate cell and pressing Ctrl+Z on the keyboard. In the solve dialog which appears, select *Variable* as the "Solve Type" and press "OK." The letter "V" next to the parameter is indicative of a variable in place. Place a variable solve on all three of the parameters which are free to vary during optimization:

Lens Data Editor

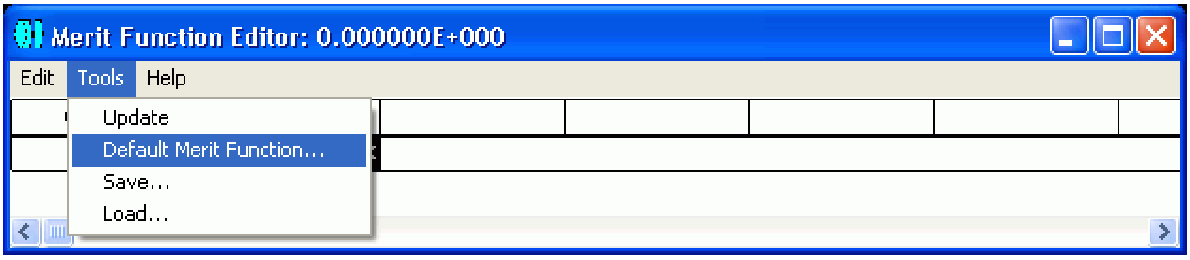
Edit Solves Options Help

Surf:Type		Comment	Radius		Thickness		Glass		Semi-
OBJ	Standard	OBJECT	Infinity		Infinity				I
STO	Standard	LENS FRONT	Infinity	V	4.000	V	N-BK7		
2	Standard	LENS BACK	-51.509	F	94.864	V			
IMA	Standard	IMAGE	Infinity		-				

Once the variables are set, we can now construct the *Default Merit Function*. The merit function is constructed in a completely separate editor from the LDE, called the Merit Function Editor (MFE). Open the MFE by selecting Editors > Merit Function from the main menu in ZEMAX.

The merit function is a numerical representation of how closely an optical system meets a specified set of goals. From within the MFE, ZEMAX uses a list of operands which individually represent different constraints or goals for the system. Once the Merit Function is complete, the optimization algorithm in ZEMAX will attempt to make the value of the merit function as small as possible.

Although it is possible to construct a merit function by hand, it is much easier to have ZEMAX construct one for you. A default merit function can be constructed by selecting Tools > Default Merit Function from the menu bar in the MFE.



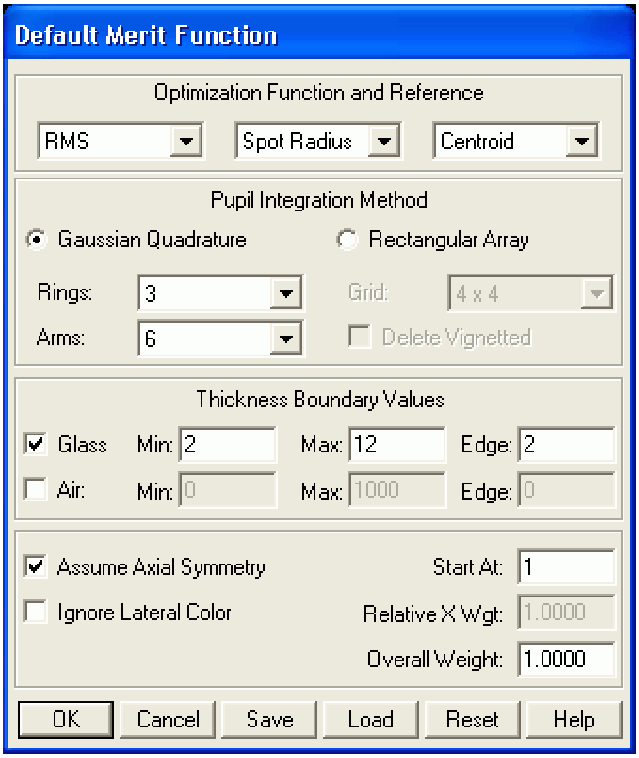
Upon selecting this option, the Default Merit Function dialog will appear, from which various options may be selected for defining the default merit function. Each of the options available in this dialog is discussed in detail in Chapter 14 of the ZEMAX User's Guide.

For the current exercise, the singlet is to be optimized for RMS Spot Radius with respect to the centroid, all of which are options already built-in to ZEMAX's default merit function capabilities. Select *RMS*, *Spot Radius*, and *Centroid* under the Optimization Function and Reference portion of the Default Merit Function dialog.

To prevent the singlet from becoming too thick or to thin, it is important that we set boundary constraints on the thickness of this element. The default merit function has options to set boundary constraints on both glass and air thicknesses. By checking the "Glass" option, minimum, maximum, and edge thickness values can be manually typed into the appropriate entries.

As was described in the system requirements, the singlet center thickness shall be no larger than 12mm, no *smaller* than 2mm, and shall have an edge thickness greater than 2mm. Type the appropriate values into the Default Merit Function dialog for the "Min", "Max", and "Edge" glass thickness entries.

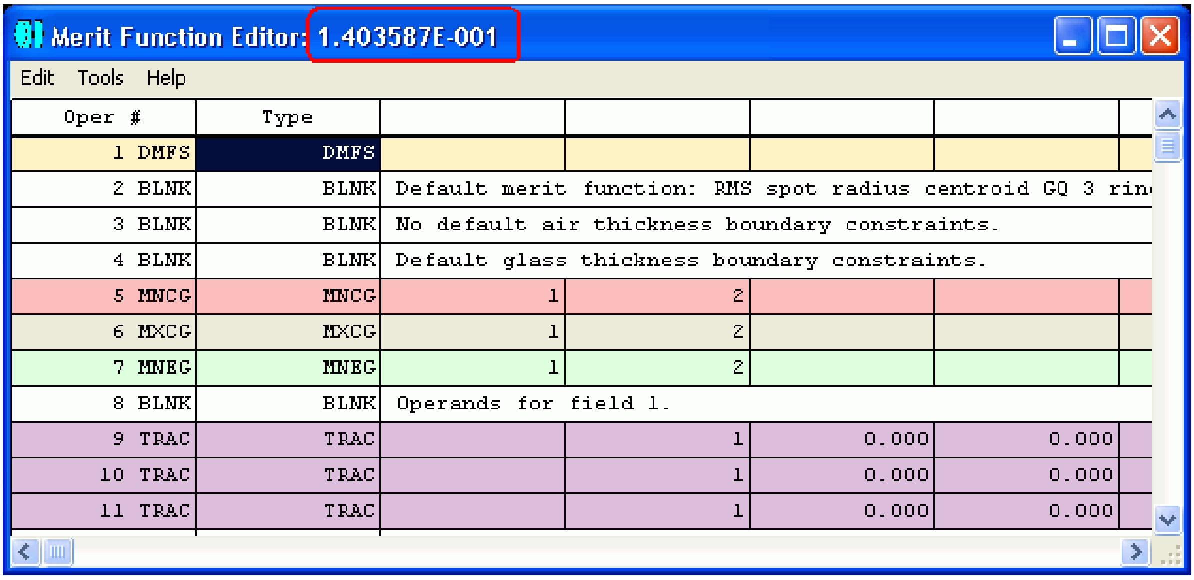
Other than the selection of the appropriate Optimization Function and Reference and the Thickness Boundary Values modification, all other parameters may be left as the default for the purposes of this exercise.



Click "OK" to close the dialog.

Performing Optimization

After selecting "OK" in the Default Merit Function dialog, note the operands which are automatically inserted into MFE. Each of these operands have a particular Target, Weight, and Value which contributes to the value of the merit function, located in the upper left hand corner of the MFE.

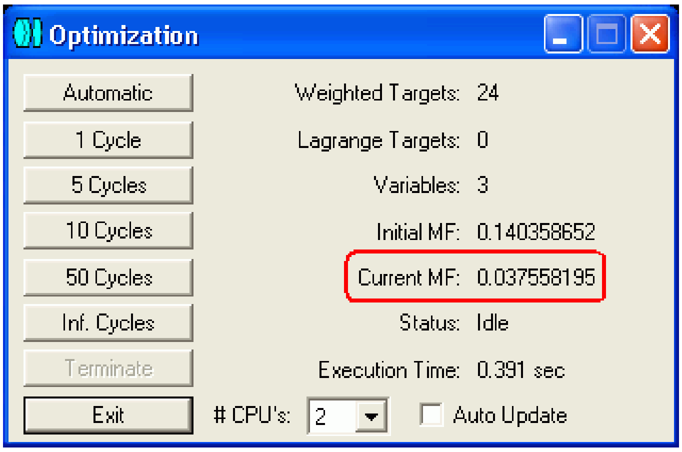


During optimization, ZEMAX attempts to lower this merit function value, which means the design is closer to the goal described in the Merit Function Editor.

To perform Optimization, select "Tools > Optimization > Optimization from the main menu, or press on the "Opt" button located on the button bar. Either of these actions will open the Optimization dialog box. Note that within the Optimization dialog, there are a number of different cycles to choose from. Selecting "Automatic" will ask ZEMAX to run the optimization routine until it has found a local minimum, a solution to the current merit function.

Note that ZEMAX reports both the Initial MF as well as the Current MF values. Run the optimization by pressing the "Automatic" button, and note the change in the merit function value:

BEFORE

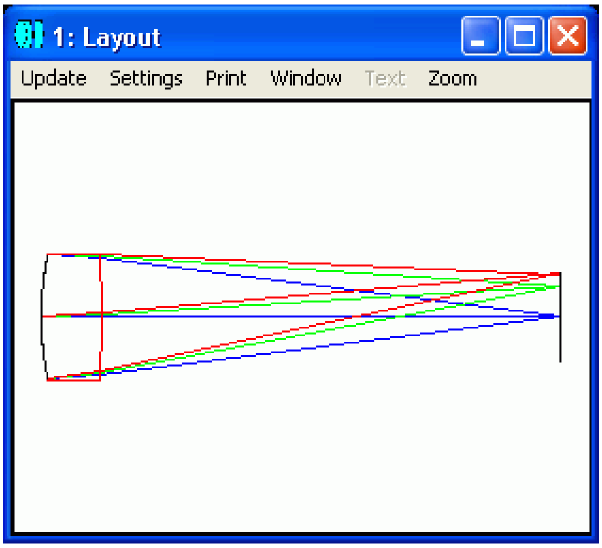


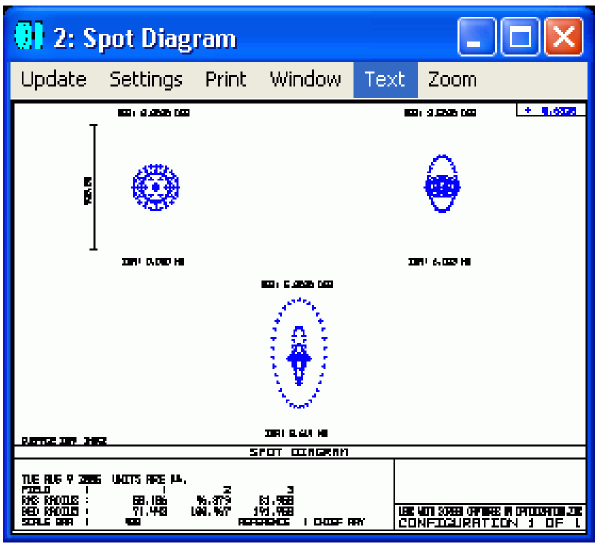
AFTER

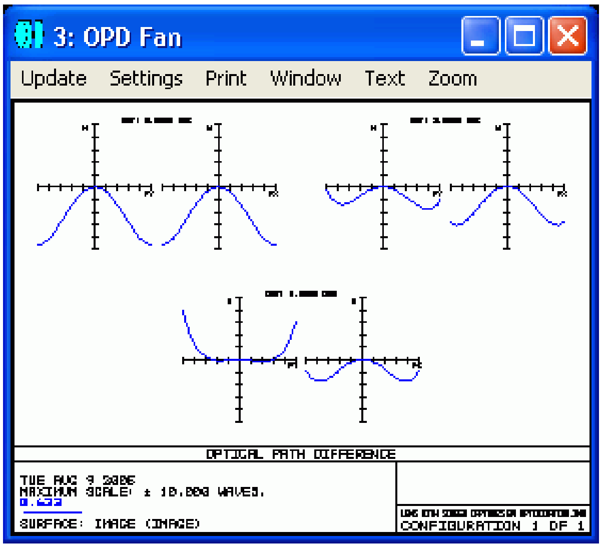
Click "Exit" to close the Optimization dialog.

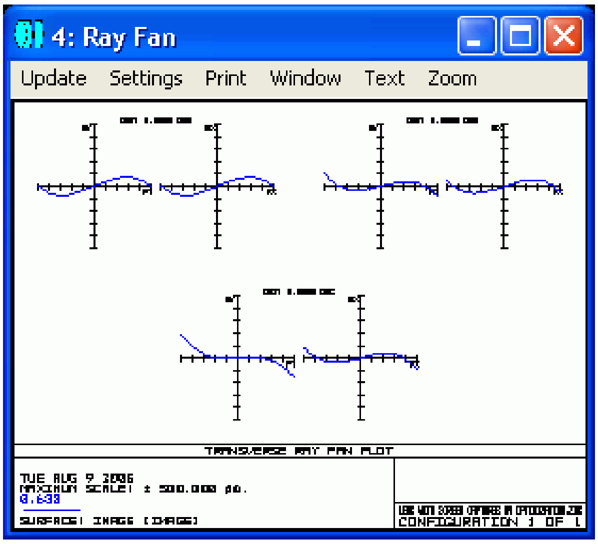
Evaluating Final System Results

Now the that optimization routine is complete, we can evaluate the final design performance and ensure that all of the initial design contraints are met. Each of the previously opened analysis windows can be updated by selecting "Update" from the menu bar of each individual graphics window.









SPOT DIAGRAM

TUE AUG 9 2005 UNITS ARE µm.

FIELD	:	1	2	3
RMS RADIUS	:	50.106	46.379	81.950
GEO RADIUS	:	71.443	100.467	191.958
SCALE BAR	:	400		REFERENCE : CHIEF RAY

Ultimately, ZEMAX has optimized a singlet lens under the constraints which were given in the initial system requirements. Compared to the initial performance analysis, the RMS and Geometrical Spot radii have dropped by nearly a factor of 10! It is also important to note that ZEMAX's chosen thickness for the lens falls within the desired range, and the edge thickness is certainly greater than 2mm; each of which meet the initial system requirements.

Though the performance of the singlet not diffraction limited, the process by which the final design was achieved can be applied to much more complex, more-desirable optical systems!

Summary and References
This tutorial has outlined the basic process of designing a lens, analyzing its performance, and optimizing under certain design contraints. In summary:

- Given certain design criteria, it is important to begin the design by entering in the appropriate system settings, such as Aperture Type, Wavelengths, Fields, and Lens Units.
- Once system related settings are complete, the lens prescription data can be entered into the Lens Data Editor. Educated guesses may be made to those unkown parameters to define a starting point for optimization.
- Use solves to enforce design contraints if at all possible.
- Prior to optimization, the system performance may be analyzed by any number of availalbe features in ZEMAX.
- Determine the degrees of freedom and select the appropriate variables for optimization.
- You may use the built in tools to create a default merit function. Remember, the operands within the merit function define the goal which you are attempting to achieve by optimization. The lower the merit function value, the closer you are to your target.
- Once optimization is complete, ensure that the final design measures up to the inital contraints and requirements. Otherwise, more optimization techniques may be required.

References

There were no external references used for this article.