

3.1.2-Optical Lens Design

Optical lens design is the science, art of calculating the various lens construction parameters that will meet or at least approach desired performance requirements while staying within required constraint values, and any cost, schedule limitations.

Optical design process

Pre-design: Once the basic factors are set, there are decisions to be made, such as reflecting vs. refracting? Number of elements? Overall size? Pre-design often involves paper and pencil sketching, including rough graphical ray tracing but now some graphical software tools can really help in this stage.

- **Starting Point Selection:** Concept moves toward reality here, often with the help of an existing solution for a similar situations are rich sources. Software comes into play important role here, since access to a database of existing designs can really speed up the selection process. Graphical and approximate methods can also be used to create a starting point.
- **Initial Analysis:** It helps to have a baseline analysis of the starting point so you can gauge improvement. Aberration analysis is useful in the design process, especially in selecting variables for optimization.

- **Optimization:** Once you define a set of variables such as curvature, thickness, index of refraction, etc. that the program can change to try to improve performance, an error function that measure of optical quality, and constraints which are boundary values that restrict possible configurations, you are ready to optimize the lens. Numerical methods are used to alter the variables in systematic ways that attempt to minimize the error function while honoring all constraints. Sometimes it goes smoothly, more often it doesn't, so changes are necessary.

- **Final Analysis:** After optimizing the lens, you need to see if it is actually doing what you want. Optimization error functions may not correlate perfectly with specifications such as MTF or encircled energy (I will mention about these terms in detail in physical performance testing part). If it's not quite there, you may have to go back for some more optimization such as adding variables or changing constraints. You may even have to find a different starting point in some cases.
- **Prepare for Fabrication:** If the lens design meets its requirements, you will still have more work to do to prepare for fabrication such as; illumination analysis, tolerancing, environmental effects, mounts and baffles.

• **3.1.3-Optical Performance Testing**

- Performance requirements can include:

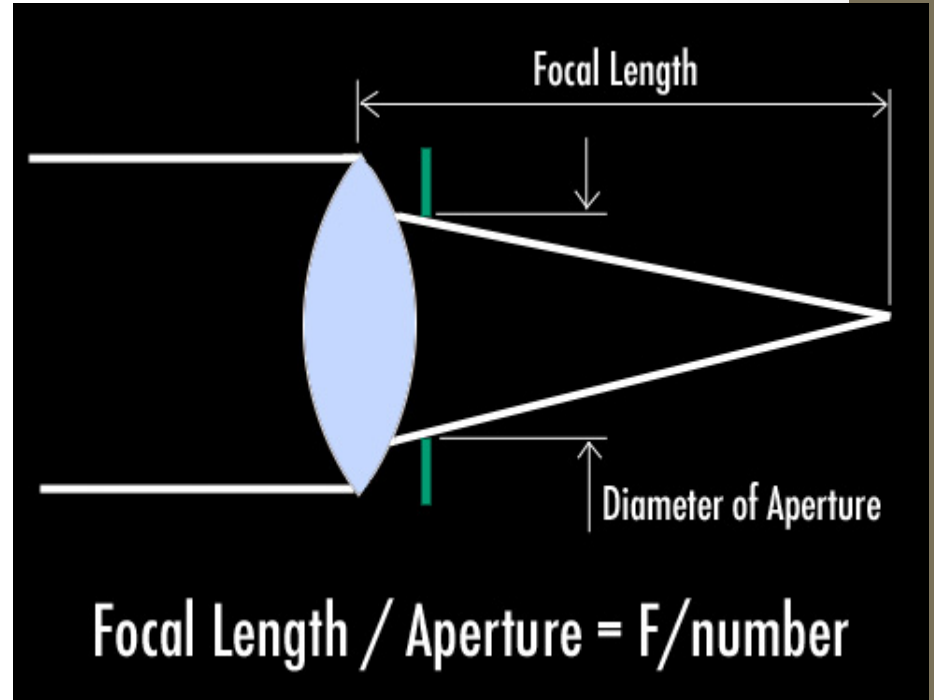
- 1-Optical Performance

- 2-Physical Requirements

- 3-Environmental Requirements

- We focused on optical performance and every system has different performance parameters which depends on what you want. I will mention about most widely used ones.

- **Optical Performance**
- **1- F-Number**
- In optics, the f-number (sometimes called focal ratio, f-ratio, or relative aperture) of an optical system expresses the diameter of the entrance pupil in terms of the effective focal length of the lens; in simpler terms, the f-number is the focal length divided by the aperture diameter. It is a dimensionless number.



- Modern lenses use a standard f-stop scale, which is an approximately geometric sequence of numbers that $f/1, f/1.4, f/2, f/2.8, f/4, f/5.6, f/8, f/11, f/16, f/22, f/32, f/45, f/64, f/90, f/128$, etc.
- For example, $f/16$ means that the pupil diameter is equal to the focal length divided by sixteen; that is, if the camera has an 80 mm lens, all the light that reaches the film passes through a virtual disk known as the entrance pupil that is 5 mm ($80 \text{ mm}/16$) in diameter.

- Depth of field increases with f-number, as illustrated in the photos below. This means that photos taken with a low f-number will tend to have one subject in focus, with the rest of the image out of focus.



f/32



f/5

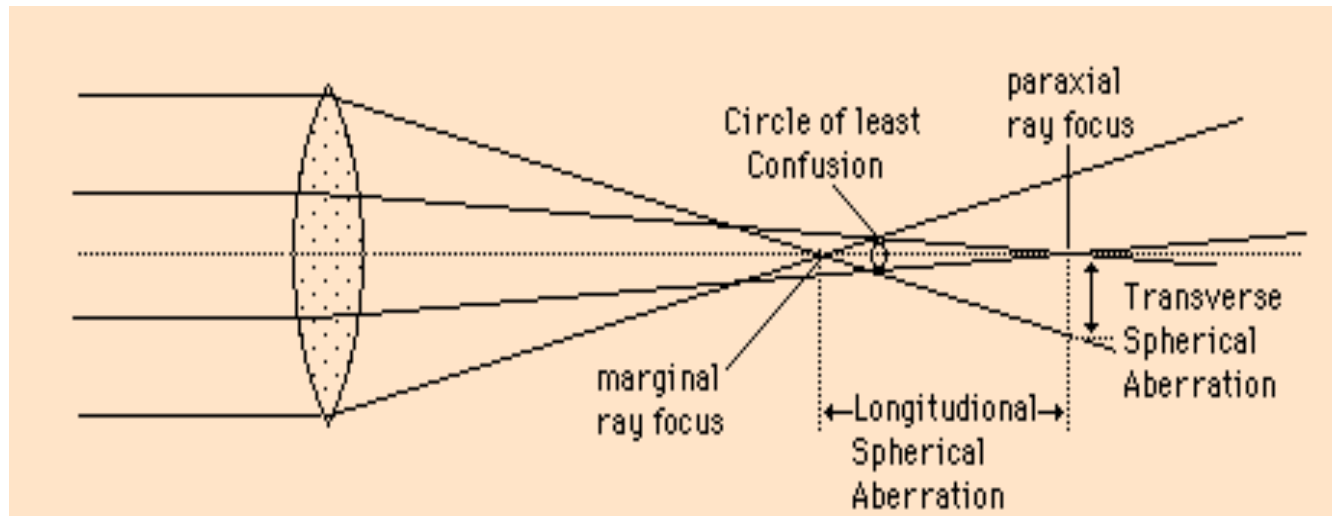
• 8-Aberrations

- In an ideal optical system, all rays of light from a point in the object plane would converge to the same point in the image plane, forming a clear image. The influences which cause different rays to converge to different points are called aberrations.
- For monochromatic light there are five kind of aberrations: *spherical aberration*, *coma*, *astigmatism*, *curvature of field* and *distortion*.
- For chromatic light there are *axial* and *lateral* aberrations

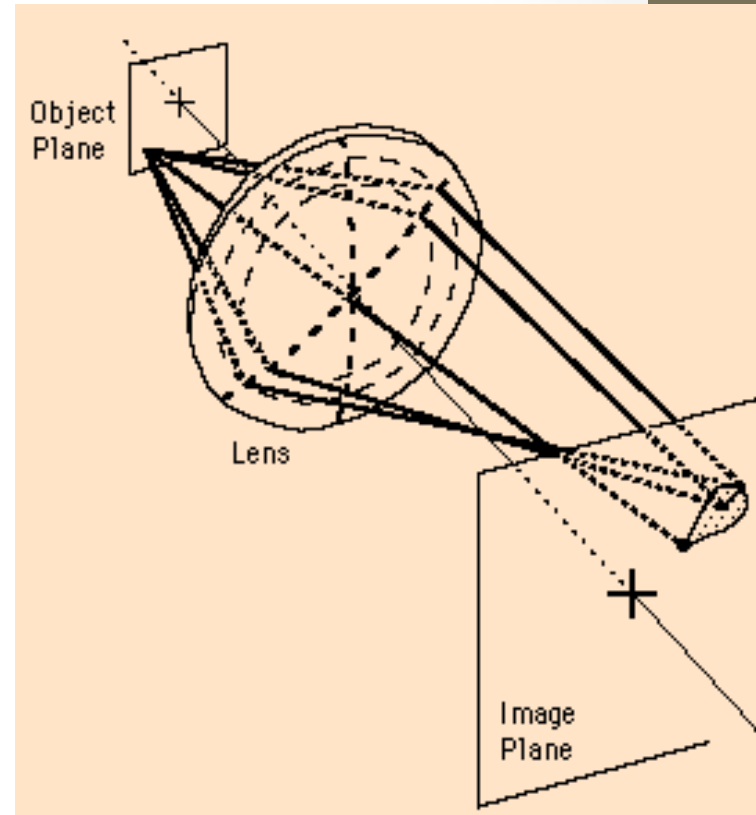
- **Monochromatic Aberration**

- **1-Spherical Aberration**

- For lenses made with spherical surfaces, rays which are parallel to the optic axis but at different distances from the optic axis fail to converge to the same point. For a single lens, spherical aberration can be minimized by bending the lens into its best form. For multiple lenses, spherical aberrations can be canceled by overcorrecting some elements. The use of symmetric doublets greatly reduces spherical aberration.



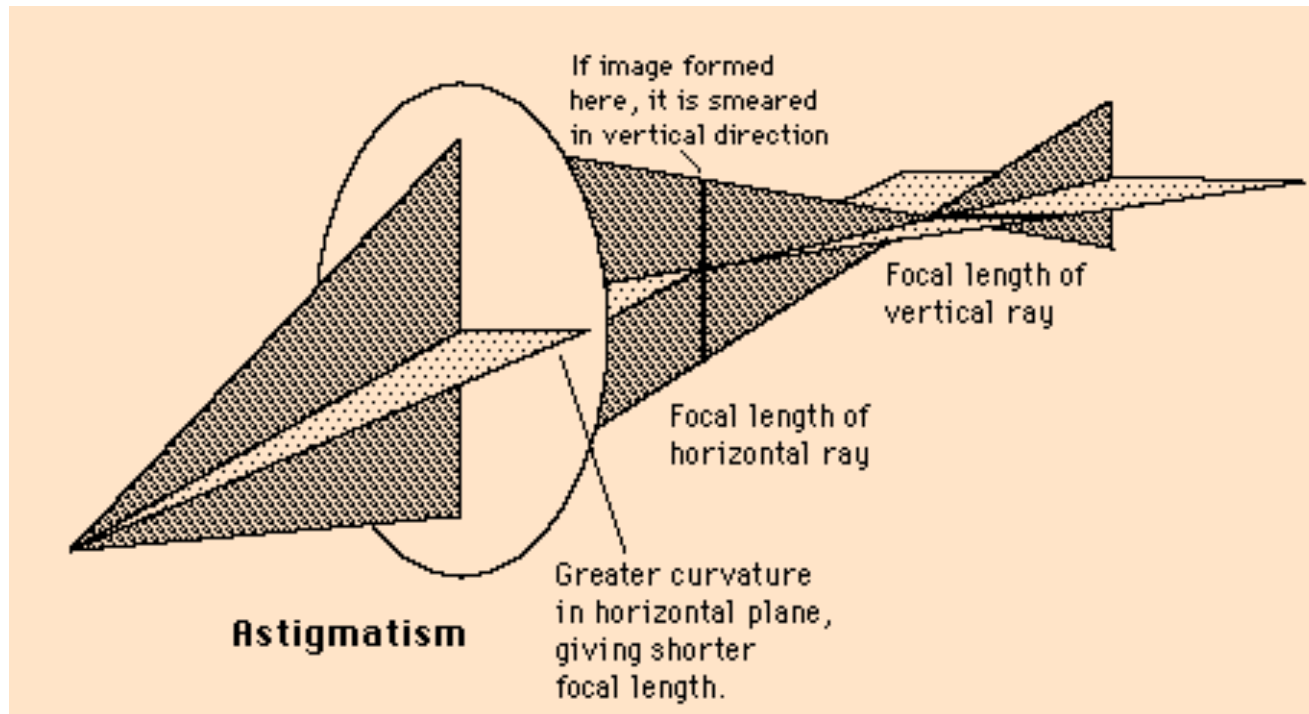
- **2-Coma**
- Coma is an aberration which causes rays from an off-axis point of light in the object plane to create a trailing "comet-like" blur directed away from the optic axis.
- A lens with considerable coma may produce a sharp image in the center of the field, but become increasingly blurred toward the edges. For a single lens, coma can be partially corrected by bending the lens. More complete correction can be achieved by using a combination of lenses symmetric about a central stop.



- **3-Astigmatism**

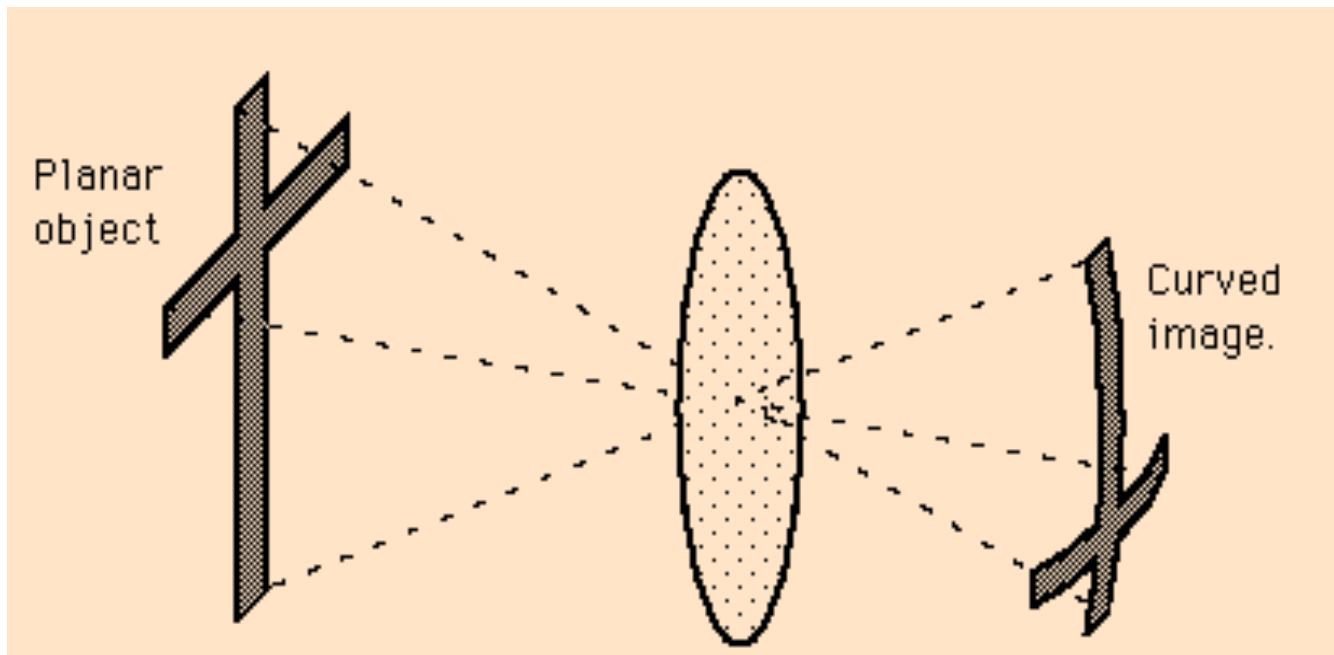
- The kind of astigmatism commonly encountered as a vision defect is a result of different lens curvatures in different planes.

- A more general type of astigmatism, which occurs for off-axis rays through any spherically ground lens, is called oblique astigmatism



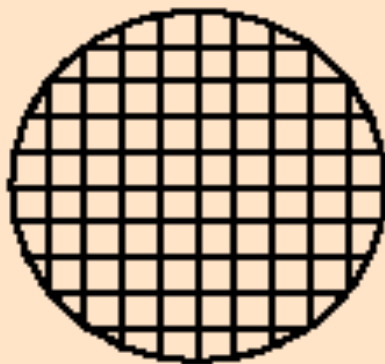
- **4-Curvature of Field**

- Curvature of field causes an planar object to project a curved (nonplanar) image. It can be thought of as arising from a "power error" for rays at a large angle. Those rays see then lens as having an effectively smaller diameter and an effectively higher power, forming the image of the off axis points closer to the lens

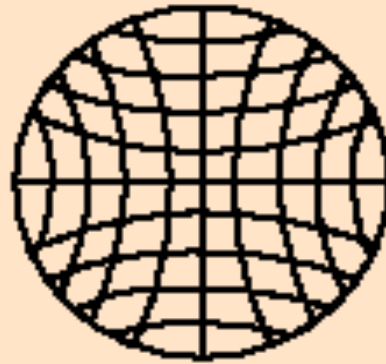


- **5-Distortion**

- Other than distortions from lens imperfections, certain distortions occur from the geometry of the lens. The barrel and pincushion distortions below can be readily seen in the image formed by a thick double convex glass lens. They are the reason for a practical limitation in the magnification achievable from a simple magnifier. These distortions are minimized by using symmetric doublets such as the orthoscopic doublet and eyepieces such as the Ramsden eyepiece.



**Undistorted
Image**



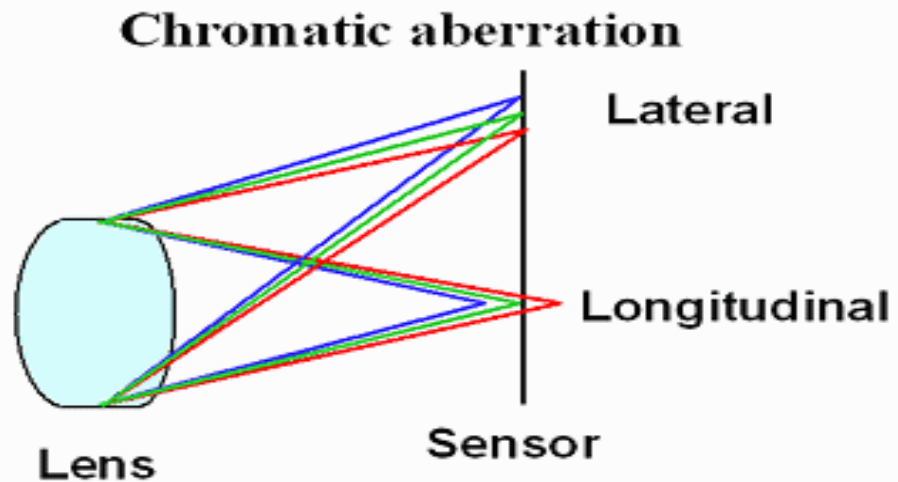
**Pincushion
Distortion**



**Barrel
Distortion**

- **Chromatic Aberration**

- A normal lens will focus the various colors at different locations, thus producing a blurred image. This phenomenon is called **chromatic aberration**. This problem was resolved when they started using objectives made of two lenses with different indices of refraction. These objectives are designed in such a way that the chromatic defect produced by the first lens is compensated by the opposite defect produced by the second lens. This has the result that the various colors are focused at the same location, thereby producing a sharper image.



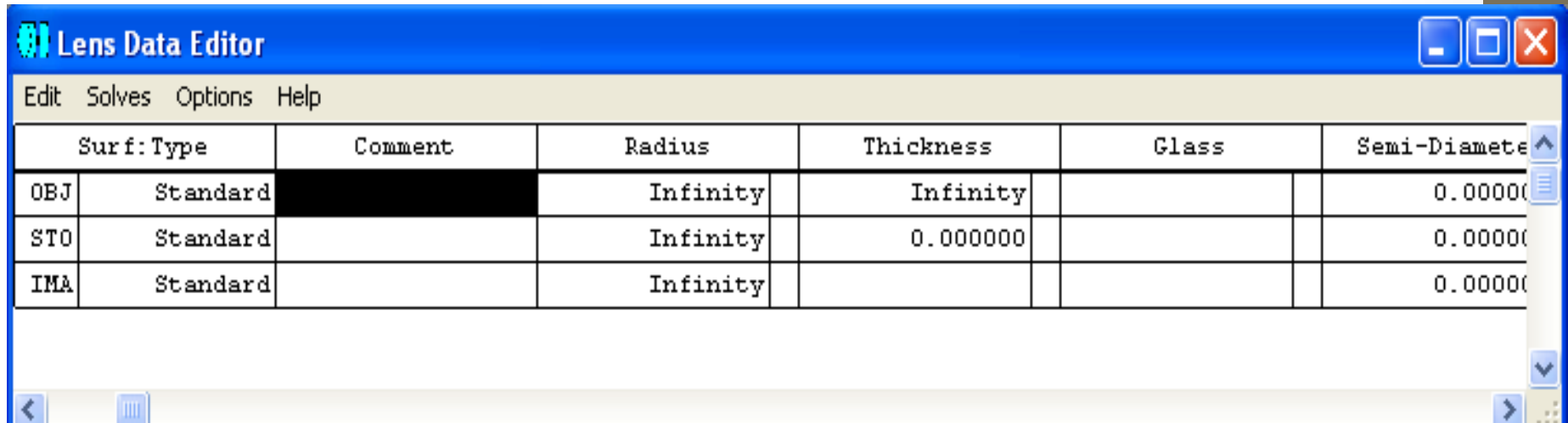
• **3.2 Software**

- The most widely used optical design software are;
 - **Code V** Comprehensive optical design software by "Optical Research Associates"
 - **OpTaliX** Comprehensive Software for optical design and thin film coatings.
 - **OSLO** Comprehensive optical design and analysis software. Now sold by Lambda Research.
 - **ZEMAX** Optical design and analysis software by Focus Software Inc.

- 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: $2\text{mm} < c.t. < 12\text{mm}$
- -Edge Thickness (*e.t.*) of the singlet: $e.t. > 2\text{mm}$
- -The singlet shall be optimized for smallest RMS Spot Size averaged over the field of view at the given wavelength
- -Object is at infinity

• 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).

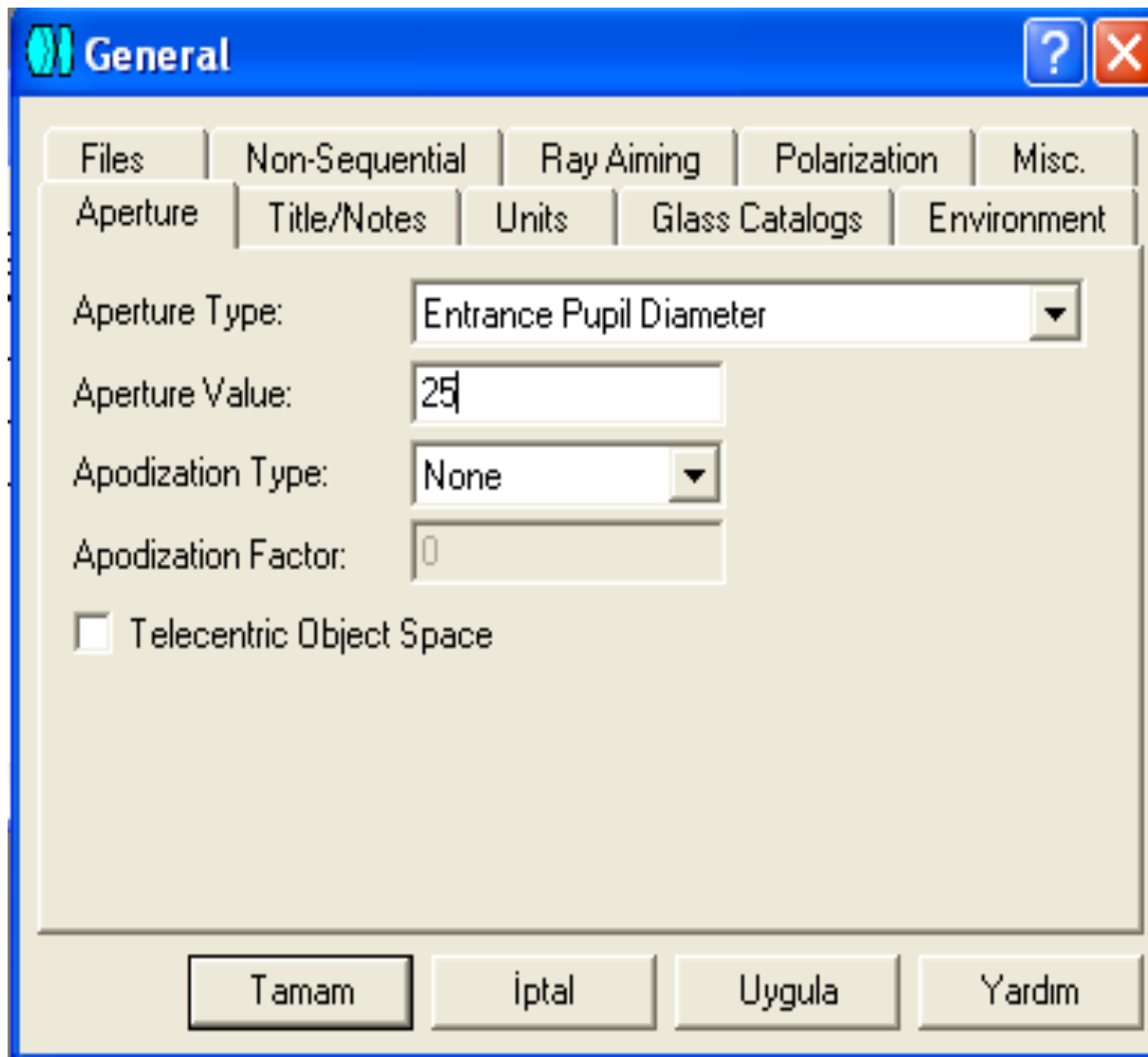


The screenshot shows the Lens Data Editor window with a menu bar (Edit, Solves, Options, Help) and a table of lens data. The table has six columns: Surf: Type, Comment, Radius, Thickness, Glass, and Semi-Diameter. The data is as follows:

Surf: Type	Comment	Radius	Thickness	Glass	Semi-Diameter
OBJ	Standard	Infinity	Infinity		0.00000
STO	Standard	Infinity	0.000000		0.00000
IMA	Standard	Infinity			0.00000

- 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

- We know the f number is 4 and focal length is 100mm then we find entrance pupil diameter EPD as $100/4=25$.



- **Defining Fields in ZEMAX**

- To access the Field Data Dialog, select System > Fields from the main menu, or click on the “Fie” button on the button bar. Currently, 12 fields can be entered into the Field Data dialog. Enter the three fields into the first three entries in the Field Data dialog, as is shown below:

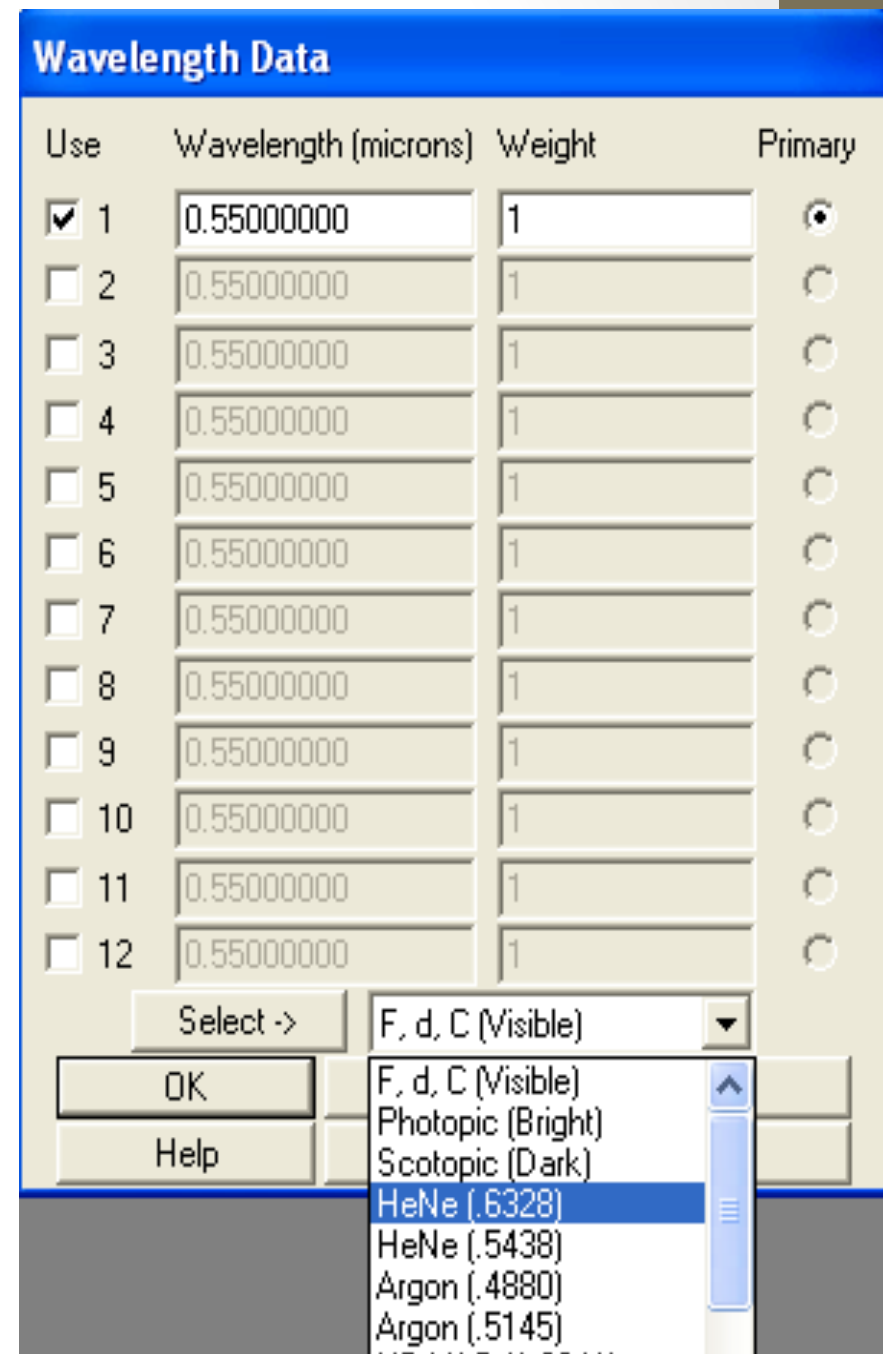
Field Data

Angle (Deg) Paraxial Image Height
 Object Height Real Image Height

Use	X-Field	Y-Field	Weight	VDX	VDY	V CX	V CY	V AN
<input checked="" type="checkbox"/> 1	0	0	1.0000	0.00000	0.00000	0.00000	0.00000	0.00000
<input checked="" type="checkbox"/> 2	0	3.5	1.0000	0.00000	0.00000	0.00000	0.00000	0.00000
<input checked="" type="checkbox"/> 3	0	5	1.0000	0.00000	0.00000	0.00000	0.00000	0.00000
<input type="checkbox"/> 4	0	0	0.0000	0.00000	0.00000	0.00000	0.00000	0.00000
<input type="checkbox"/> 5	0	0	0.0000	0.00000	0.00000	0.00000	0.00000	0.00000
<input type="checkbox"/> 6	0	0	0.0000	0.00000	0.00000	0.00000	0.00000	0.00000
<input type="checkbox"/> 7	0	0	0.0000	0.00000	0.00000	0.00000	0.00000	0.00000
<input type="checkbox"/> 8	0	0	0.0000	0.00000	0.00000	0.00000	0.00000	0.00000
<input type="checkbox"/> 9	0	0	0.0000	0.00000	0.00000	0.00000	0.00000	0.00000
<input type="checkbox"/> 10	0	0	0.0000	0.00000	0.00000	0.00000	0.00000	0.00000
<input type="checkbox"/> 11	0	0	0.0000	0.00000	0.00000	0.00000	0.00000	0.00000
<input type="checkbox"/> 12	0	0	0.0000	0.00000	0.00000	0.00000	0.00000	0.00000

OK	Cancel	Sort	Help
Set Vig	Clr Vig	Save	Load

- **Setting the Wavelengths**
- 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. From the initial design specifications, the wavelength is HeNe (Helium Neon) laser.



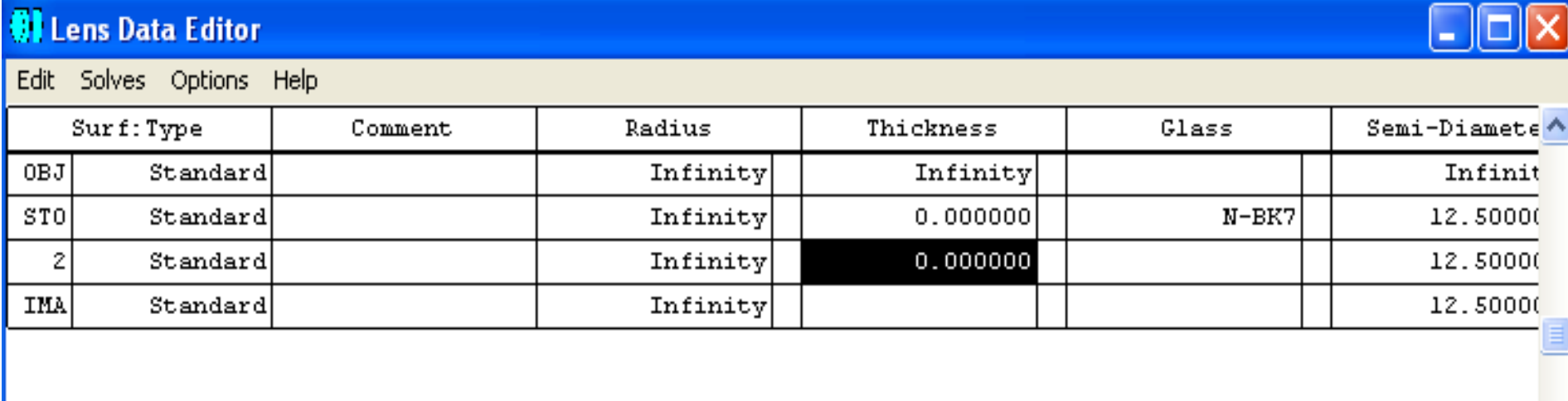
- **Inserting Surfaces**

- Therefore, two surfaces separated by glass comprise a single element. So, for the purposes of the singlet, a total of 4 surfaces are needed. 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.

Surf: Type	Comment	Radius	Thickness	Glass	Semi-Diameter
OBJ	Standard	Infinity	Infinity		Infinity
STO	Standard	Infinity	0.000000		12.50000
2	Standard	Infinity	0.000000		12.50000
IMA	Standard	Infinity			12.50000

- **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.



Lens Data Editor

Edit Solves Options Help

Surf: Type	Comment	Radius	Thickness	Glass	Semi-Diameter
OBJ	Standard	Infinity	Infinity		Infinity
STO	Standard	Infinity	0.000000	N-BK7	12.50000
2	Standard	Infinity	0.000000		12.50000
IMA	Standard	Infinity			12.50000

- 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. 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 variables for optimization. we will leave the Radius of Surface 1 as *Infinity* and change the Thickness of Surface 2 to 100mm.

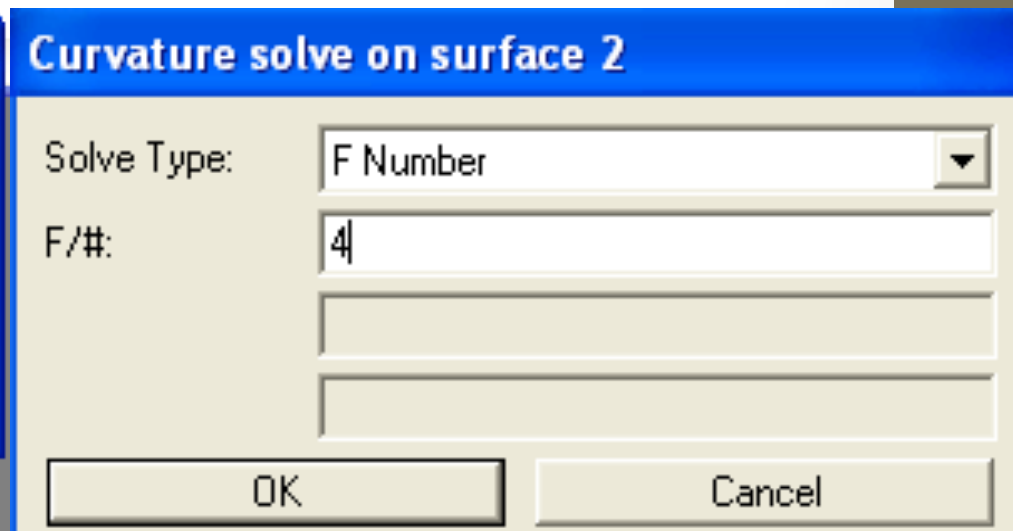
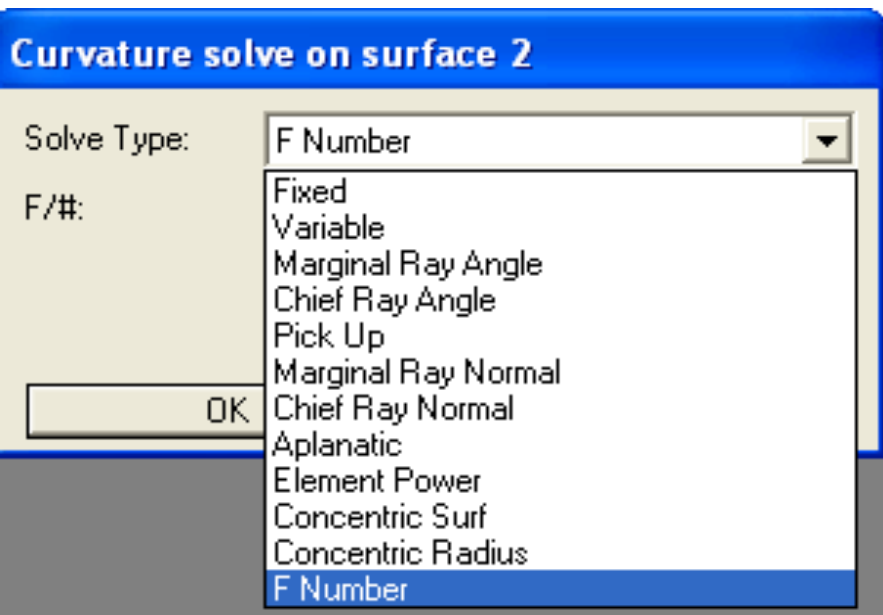
Lens Data Editor

Edit Solves Options Help

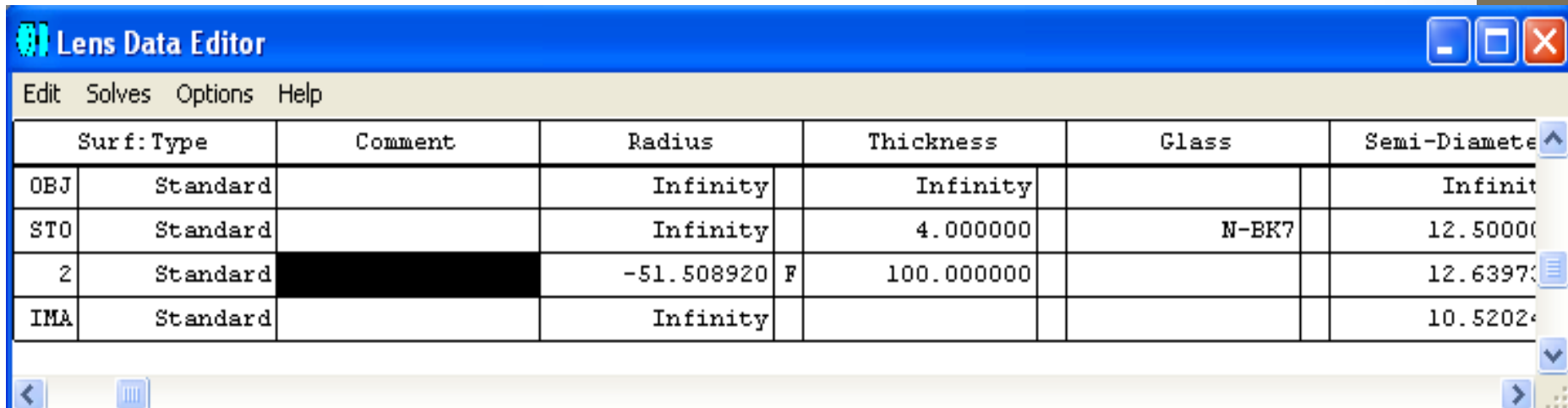
Surf	Type	Comment	Radius	Thickness	Glass	Semi-Diameter
OBJ	Standard		Infinity	Infinity		Infinity
STO	Standard		Infinity	4.000000	N-BK7	12.50000
2	Standard		Infinity	100.000000		12.73040
IMA	Standard		Infinity			21.47930

- **Solves**

- 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.



- 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.



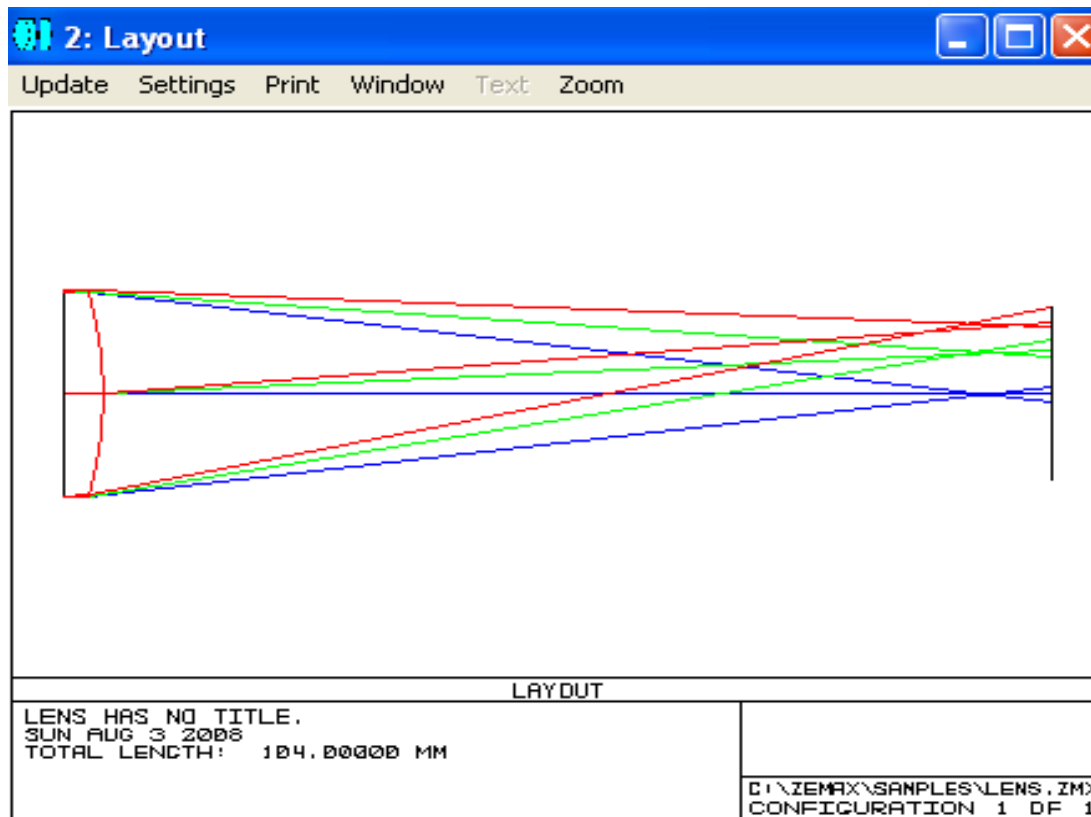
The screenshot shows the 'Lens Data Editor' window with a menu bar (Edit, Solves, Options, Help) and a table of lens data. The table has columns for Surf, Type, Comment, Radius, Thickness, Glass, and Semi-Diameter. The third row (Surface 2) is highlighted in black, and its 'Radius' column contains the value -51.508920 with an 'F' in the adjacent column, indicating a focal length solve.

Surf	Type	Comment	Radius	Thickness	Class	Semi-Diameter
OBJ	Standard		Infinity	Infinity		Infinity
STO	Standard		Infinity	4.000000	N-BK7	12.500000
2	Standard		-51.508920	100.000000		12.639700
IMA	Standard		Infinity			10.520200

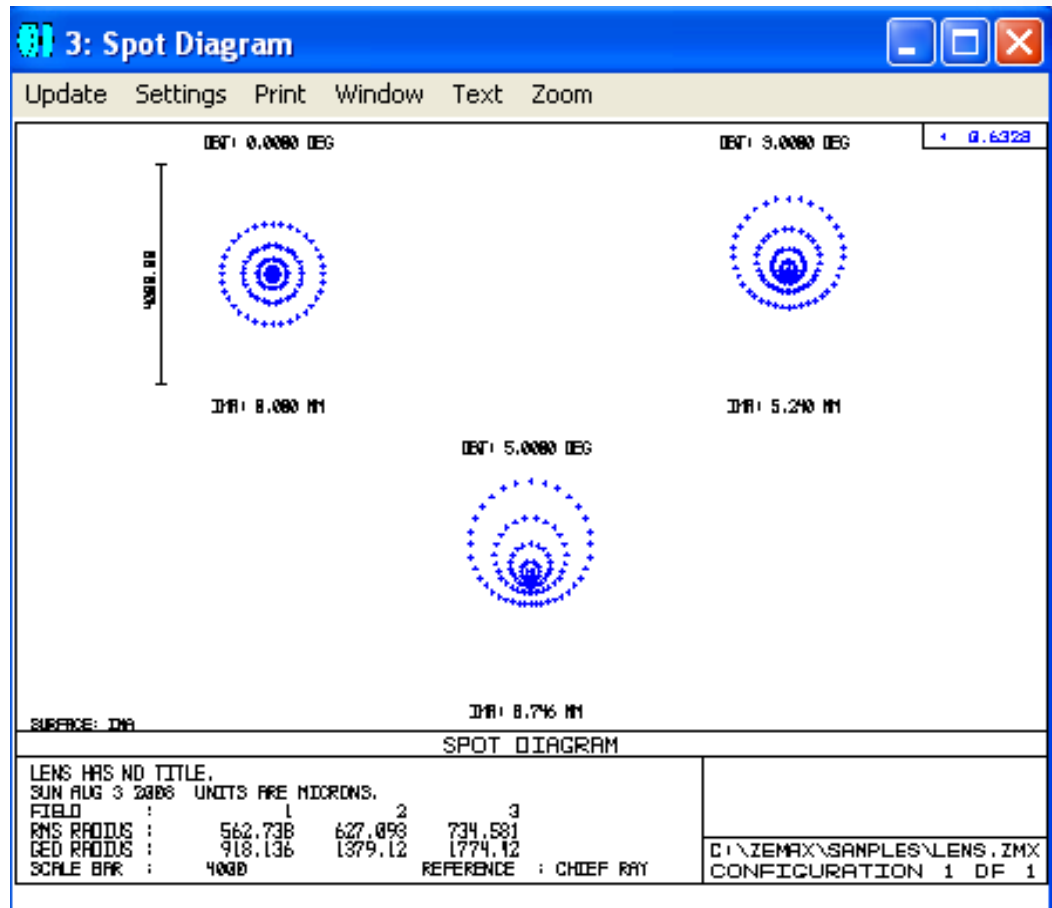
- **Evaluating System Performance**

- 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.

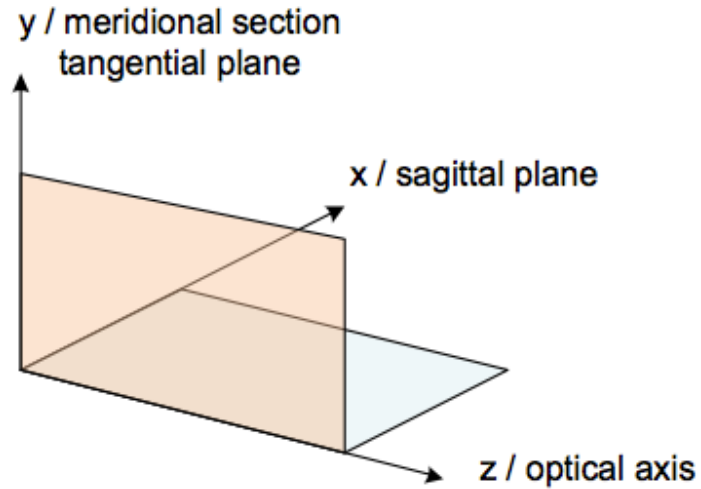
- **Layout** A layout may be opened by selecting a Analysis > Layout > 2D Layout from the main menu, or by pressing the “Lay” button on the button bar. The 2D Layout option plots a YZ cross section through the lens, and is only valid for rotationally symmetric, axial systems.
- A layout diagram of the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



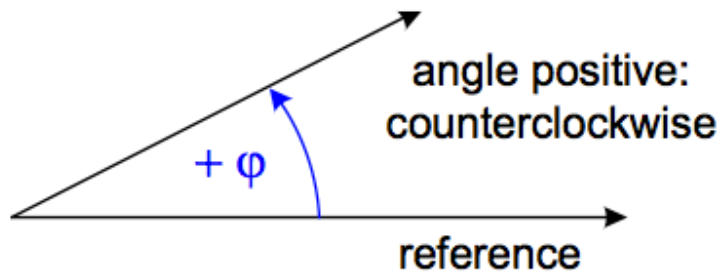
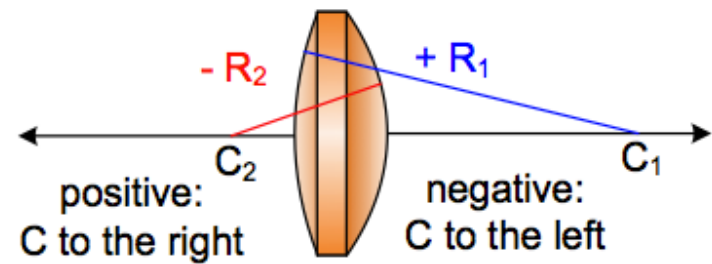
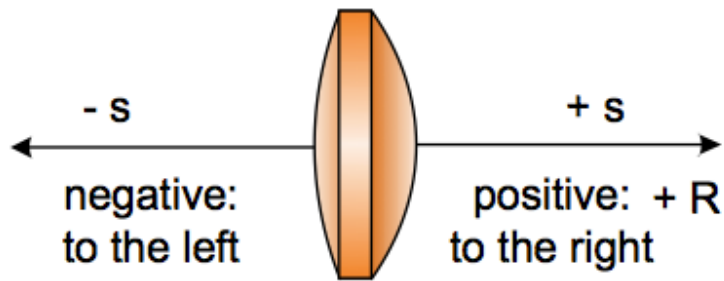
- **Spot Diagram** A spot diagram may be accessed by selecting “Analysis > Spot Diagrams > Standard” from the main menu, or by pressing the “Spt” button on the button bar. The spot diagram gives indication of the image of a point object.
- In the absence of aberrations, a point object will converge to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



- Coordinate systems
2D sections: y-z shown



- Sign of lengths, radii, angles:



- ■ Helpful shortcuts:
- F3: undo
- F2 or BackSpace: edit a cell in the editor
- Cntr+V: variable toggle
- F6: merit function editor
- Cntr+U: update
- Shift+cntr+Q: quick focus