Introduction

This chapter is intended to teach you how to use ZEMAX. Each section in this chapter will walk you through a different design problem. The first few design examples are very simple, and may not seem worth the trouble if you are an experienced lens designer. However, if you take the time to go through the lessons you will learn how to run ZEMAX, and then you can move on to your particular design interests.

The first few example sessions do provide some tutorial comments regarding lens design theory to aid those who lack familiarity with the terminology. However this manual in general, and these examples in particular, will not promote the novice designer to an expert. If you cannot follow these examples, or you do not understand the mathematics behind the calculations the program performs, see any of the good books referenced in the chapter "Introduction". You must have properly installed ZEMAX before beginning the lessons.

Lesson 1: a singlet

☞ ***What you will learn: Starting ZEMAX, entering wavelength and lens data, generating fans, and spot diagrams, defining thickness solves and variables, running simple optimizations.***

Suppose you needed to design a F/4 singlet lens with a 100 mm focal length, for use on-axis in the visible spectrum using BK7 glass. How do you start?

First of all, run ZEMAX. The ZEMAX main screen will appear, as will the lens data editor (LDE). You can move and resize the LDE to suit your taste. The LDE consists of various rows and columns arranged like a spreadsheet. The Radius, Thickness, Glass, and Semi-diameter columns are the ones you will use the most, the others will be used only for certain types of optical systems.

One cell in the LDE is highlighted in "reverse video". This means it displays letters on a background in different colors than the other cells. If no cell is highlighted, then click with the mouse on any cell to highlight it. This reverse video bar is referred to as the "cursor" in this tutorial. You can navigate around in the LDE by clicking on the cell you wish to move the cursor to with the mouse, or you can simply use the cursor keys. The operation of the LDE is simple, and with a little practice you will master it.

To begin, we will enter the wavelengths for our system. This does not always have to be done first; we simply elect to do so now. On the main screen menu bar, select System then Wavelengths.

The "Wavelength Data" dialog box will appear in the center of the screen. ZEMAX is full of these dialog boxes; they are used to enter data and to present you with options. Using the mouse, click on the "Use" box on the second and third rows. This will add two more wavelengths to bring the total to three. Now enter in the first "Wavelength" row .486. This is roughly the wavelength, in microns, of the Hydrogen F-line.

ZEMAX always uses microns for wavelength. Now go to the second row, wavelength column, and type .587. Finally, enter .656 in the third row. This is essentially all there is to entering data in ZEMAX; move to the appropriate field and type in the data. On the far right edge of the screen, you can see the primary wavelength indicator column. This indicator points to the primary wavelength, currently .486 microns. Click on the second row of the primary wavelength indicator. The indicator moves down to the .587 position. The primary wavelength is used to calculate the paraxial parameters such as focal length, magnification, pupil sizes, and other properties.

☞ ***ZEMAX always uses microns for wavelength.***

The "Weight" column is used for optimization, and for calculating wavelength weighted data such as RMS spot size and Strehl ratio. For now leave all the weights at 1.0. Click on OK to save the changes and exit the wavelength data dialog box.

Now we need to define an aperture for the lens. This tells ZEMAX how large to make all of the lenses, among other things. Since we wanted a F/4 lens, we will need a 25 mm aperture (a 100 mm focal length divided by F/4). To set this aperture, select System then General. The "General Data" dialog box appears. Select the "Aperture" tab. Click on the cell showing "Aper Value" and enter a value of 25. Note the aperture type is by default "Entrance Pupil Diameter", other types of aperture settings may be selected. The other options listed are not needed yet, so click on OK.

We still do not have a lens. The important surface data still needs to be added. ZEMAX models optical systems using a series of surfaces. Each surface has a radius of curvature, a thickness (the axial distance to the next surface), and a glass. Some surfaces may have other data, we will cover that later. Note three surfaces are shown in the LDE: The object surface, denoted OBJ on the left edge, the stop, denoted STO, and the image plane, denoted IMA. For our singlet, we need a total of four surfaces: The object, the front surface of the lens (which will also be the stop), the back surface of the lens, and then the image plane. To insert a fourth surface, move the cursor on top of the word "Infinity" on the image (the last) surface. Now press the insert key. This inserts a new surface at that row, and moves the image surface down. The new surface is numbered 2. Note that the object is surface 0, and then there is surface 1 (denoted STO because it is the stop), 2, and 3 (denoted IMA).

Now we will enter the glass to be used. Move the cursor over to the "Glass" column of surface 1, which is denoted "STO" on the left hand column. Type "BK7" and press enter. ZEMAX has a very extensive glass catalog online. All we need to do is decide to use BK7; ZEMAX will go look up the glass and calculate the indices at each of the wavelengths we have defined.

Since we have a 25 mm aperture, a reasonable thickness for the lens is 4 mm; so move the cursor to the thickness column of surface 1 (where we just entered BK7) and type "4" and enter. Note the default units are millimeters. Other units (centimeters, inches, and meters) are also available.

Now we need to enter some values for the radius of curvature on each side of the lens. Let’s guess that the front and rear radii are going to be 100 and -100, respectively. Enter these values on surfaces 1 (STO) and 2, respectively. The sign convention is plus if the center of curvature is right of the lens, minus if it is left. These signs (+100, -100) will yield an equi-convex lens. Also, we need to place the image plane at the focus of the lens, so enter a value of 100 for the thickness of surface 2 as well.

How do we know how good the lens is? Probably the most useful diagnostic tool in lens design is the ray fan plot. To generate a ray fan plot, select Analysis then Fans, then Ray Aberration. You should see the plot appear in a small window (if you see any error messages, go back and make sure you entered in all the data exactly as described). The ray fan should look like Figure E1-1. The plot shows transverse ray aberrations (referenced to the chief ray) as a function of the pupil coordinate. The graph on the left is labeled "EY" for epsilon Y. This is the aberration in the Y direction, sometimes called the tangential, or YZ plane. The graph on the right is labeled "EX" for epsilon X, sometimes called the sagittal, or XZ plane. This ray fan exhibits one glaring design error. The tilt through the origin indicates defocus.

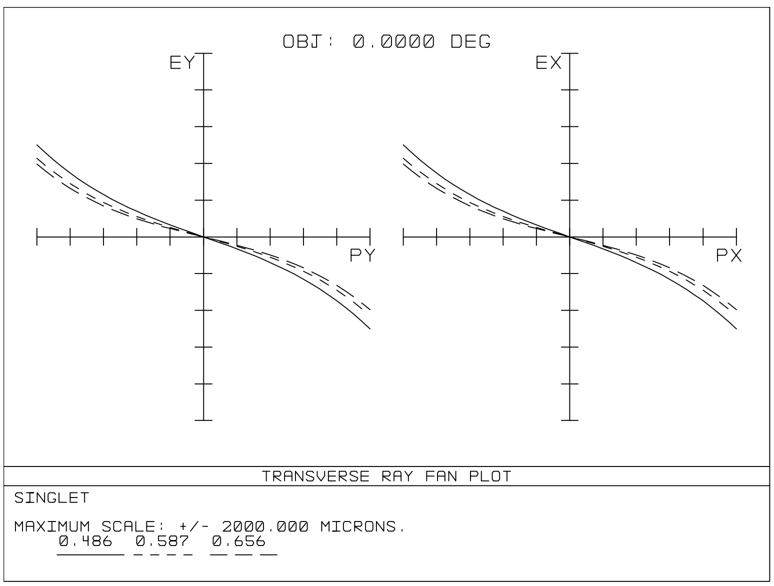

Figure E1-1.

To correct the defocus, we will use a solve placed on the rear side of the lens. Solves (see the chapter "Solves") dynamically adjust certain lens data. To place the image plane in paraxial focus, double click on the thickness of surface 2. The solve dialog box appears; it simply says "Fixed". Click on the drop-down box and change the solve type to "Marginal Ray Height", then click on OK. This solve will adjust the thickness to achieve a marginal ray height of zero, which is paraxial focus. Note the thickness of surface 2 is automatically adjusted to about 96 mm. Now we need to update the ray fan plot to see the change. From the ray fan window menu, click on Update (double clicking anywhere in the window will also update it). The ray fan as shown in Figure E1-2 appears. Now the defocus is gone, and the dominant aberration is spherical; note the change in plot scale.

Is this the best design available? We are going to use optimization to do the rest of the design for us. First we will tell ZEMAX which parameters it is free to design with (these are called variables) and then we will tell it the design requirements (these are called targets or operands). There are three variables here that will help us; the front and back curvatures of the lens, and the thickness of the second surface, which will allow defocus to compensate the spherical. Move the cursor to the radius column of surface 1, and then type Ctrl-Z (if you prefer the menu interface, click once on the radius, and then select Solves then Variable toggle from the LDE menu; you can also double click on the radius for a drop-down list of options, which includes the variable status). Note the "V" appears to indicate a variable parameter. Typing Ctrl-Z works as a toggle. Also set a variable on the radius of surface 2, and the thickness of surface 2. The variable on the thickness of surface 2 overrides the solve placed earlier.

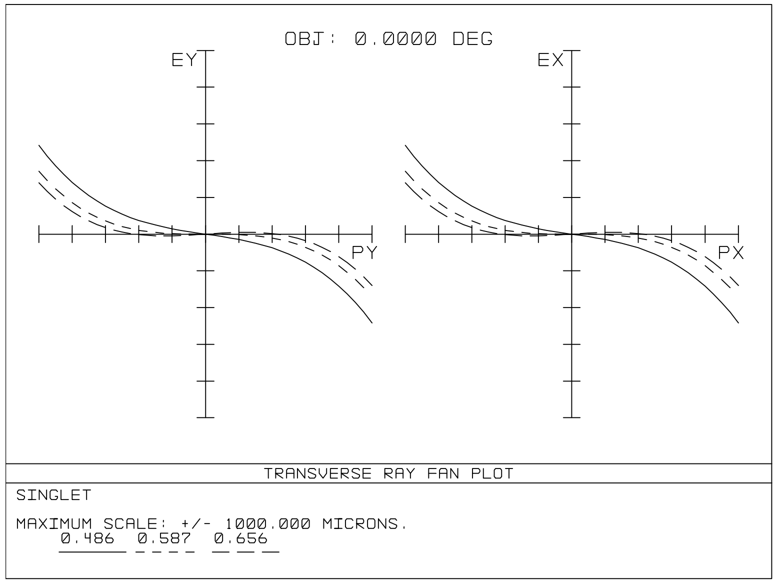

Figure E1-2.

Now we need to define a "Merit Function" for the lens. A merit function defines in a mathematical sense what is a good lens. Merit functions are like golf scores, the lower the better. An ideal lens (for a given application) has a merit function of zero.

To define the merit function, select Editors then Merit Function from the main menu bar. A spreadsheet editor similar to the LDE will appear. From the menu bar of this new window, select Tools then Default Merit Function. On the dialog box that appears, just click on Reset, then OK. You will eventually learn what all the options are for, but for now just accept the defaults. ZEMAX is very good at determining an appropriate default merit function.

ZEMAX has constructed a default merit function for you, consisting of a list of rays to trace which will minimize the RMS wavefront error. This is not quite sufficient, because we also want a 100 mm focal length in addition to minimizing the spot size. Without a specific focal length constraint, ZEMAX will quickly discover that making the focal length infinite (the lens becomes a window) will produce very good wavefront aberration.

Move the cursor to the first row of the Merit Function Editor by a single click of the mouse anywhere in the first row. Now press the insert key to add a new row. Now, underneath the "Type" column, enter "EFFL" and press enter. This operand controls the effective focal length. Move the cursor over to the "Target" column, and enter "100" and press enter. For a "Weight", enter a value of 1. We are done defining the merit function; you can remove the merit function editor from the display by double clicking on the upper left corner of the window. The merit function will not be lost, ZEMAX retains it automatically.

Now select Tools then Optimization from the main menu bar. This brings up the optimization tool dialog box. Note the checkbox labeled "Auto Update". If this option is selected, the windows currently on display (such as the ray fan plot) will be automatically updated as the lens changes during optimization. Select auto update by clicking once in the box, and then click on "Automatic". ZEMAX will decrease the merit function rapidly. Click on exit to close the optimization dialog.

The result of this optimization is a "bending" of the lens. The resulting curvatures of the lens have given us approximately a 100 mm focal length, and as small a RMS wavefront error as possible with this simple system. ZEMAX may not optimize to exactly a 100 mm focal length because the EFFL constraint was a "weighted" target to be considered like any other aberration.

We can now investigate the performance using the ray fan plot. The optimized design has a maximum aberration of about 200 microns, as shown in Figure E1-3.

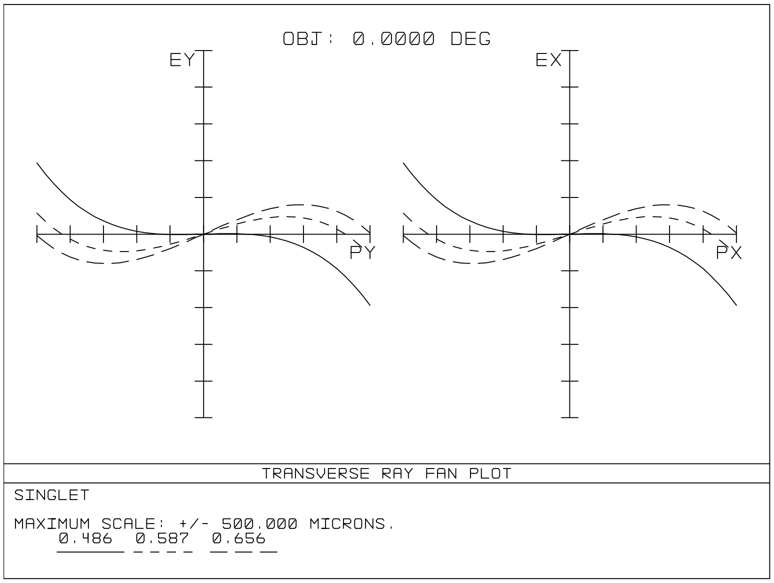

Figure E1-3.

Another way of measuring optical performance is to generate a spot diagram. To see the spot diagram, select Analysis, then Spot Diagrams, then Standard. The spot diagram will appear in another window. This spot is about 400 microns across. For comparison, the Airy diffraction disk is roughly 6 microns across.

Another useful diagnostic tool is the OPD fan. This is a plot of optical path difference (with respect to the chief ray) as a function of the same pupil coordinates used for the rayfan. To see the OPD fan, select Analysis then Fans then Optical Path. You should see the OPD plot as shown in Figure E1-4. This system suffers from roughly 20 waves of aberration, mostly focus, spherical, spherochromatism, and axial color.

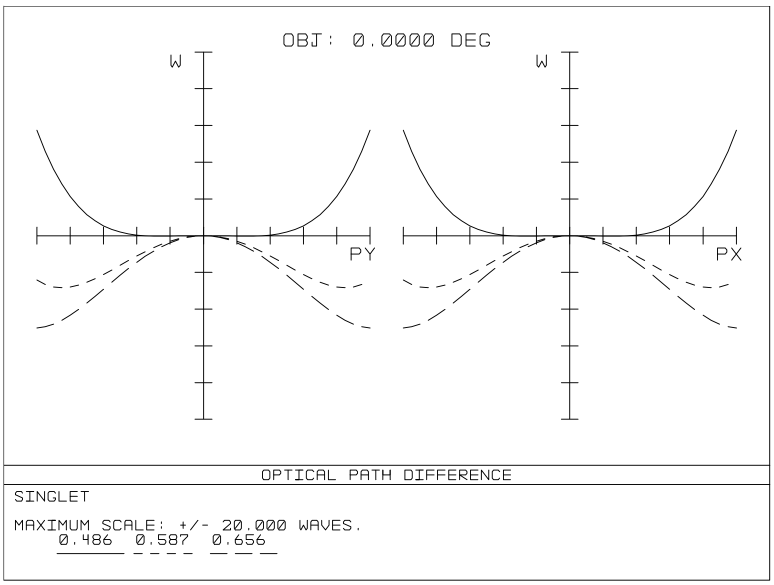

Figure E1-4.

You are probably aware that lenses are considered "diffraction limited" when the wave aberration is roughly one-quarter wave or less (see the references for a more complete discussion of this concept). Clearly our singlet is not diffraction limited. To improve the performance of this (or any) optical system, the designer must determine which aberrations limit the performance, and what options are available for correcting them. From the ray fans (particularly E1-3) it may be apparent that chromatic aberration is the limiting aberration. (see any of the good books available for advice on interpreting ray fans.)

ZEMAX offers another convenient tool for determining the magnitude of the first-order chromatic aberration: the chromatic focal shift plot. This plots back focal length as a function of wavelength, which indicates the variation in paraxial focus. To see the chromatic focal shift plot, select Analysis, Miscellaneous, Chromatic Focal Shift.

You should see the plot shown in Figure E1-5. Note the wavelength scale is vertical, covering the range of defined wavelengths, and that the maximum change in focal length is about 1540 microns. This monotonic type of curve is typical for singlet lenses.

To correct the first-order chromatic aberration, a second glass material is required. This approach leads us to the next example, the design of a doublet.

If you would like to save this lens for later evaluation, select File, Save As. ZEMAX will prompt you for a filename which you can enter.

Any lenses saved in this manner can be retrieved by selecting File, Open. To quit ZEMAX now, select File, Exit.

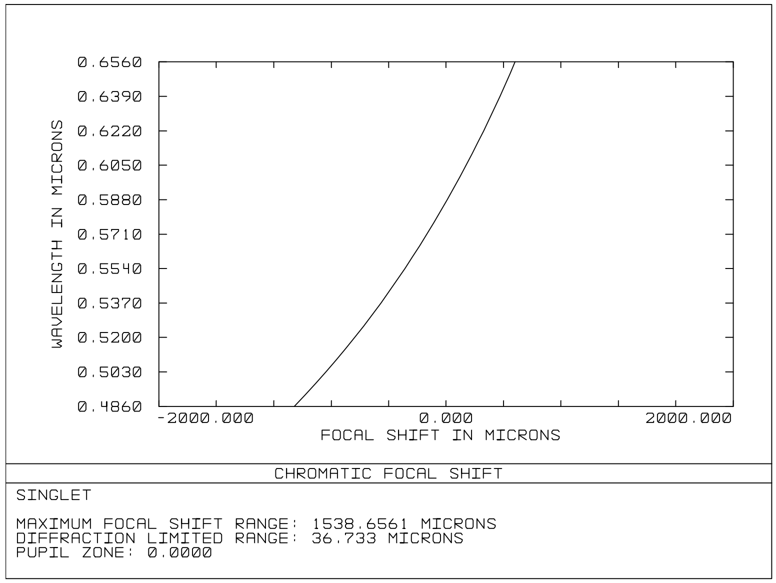

Figure E1-5.

Lesson 2: a doublet

☞ ***What you will learn: Generating layouts and field curvature plots, defining edge thickness solves, defining field angles.***

A doublet lens consists of two glasses, usually cemented (but not always) so they have one common curvature. By using two glasses with different dispersion characteristics, the chromatic aberration may be corrected to first order. This means we should be able to get a parabolic curve instead of a line in the chromatic focal shift plot. This will in turn yield much better imaging. For now we maintain the previous design requirements of 100 mm focal length and on-axis use only; we will add field angles later.

Selecting which two glasses to use requires some finesse; see for example the excellent discussion in Smith, Modern Optical Engineering. Since the purpose of this example is teach you how to use ZEMAX, and not how to design lenses, we will simply suggest the glass choice of BK7 and SF1. If you have just completed the previous lesson, and the singlet lens is still loaded, you do not have to re-enter the wavelengths for this design. Otherwise, enter the wavelengths and apertures according to the instructions in the previous example. Now insert new surfaces as necessary until your lens data editor (LDE) looks like the following table. Not all of the columns are shown for simplicity. If you need to move the stop position so that the first surface is the stop, you can do so by double clicking on the surface type column of the row you wish to make the stop, then choose the "Make Surface Stop" button.

STARTING PRESCRIPTION FOR DOUBLET EXAMPLE

Surf	Radius	Thickness	Glass
OBJ	Infinity	Infinity	
STO	100.000000 V	3.000000	BK7
2	-100.000000 V	3.000000	SF1
3	-100.000000 V	100.000000 V	
IMA	Infinity		

Because there is no separation between the BK7 and the SF1 media, this is a cemented doublet. ZEMAX does not model the cement itself; it simply models the glasses as being in contact.

If you still have the merit function from the previous example loaded, then there is no need to recreate the merit function. Otherwise, recreate the merit function, including the EFFL operand, as described in the previous example.

Now select Tools, Optimization from the main menu bar, and click on "Automatic". The merit function will begin to decrease; click on "Exit" when it stops. To see if we have made any progress, display the chromatic focal shift plot (if it is not already on your screen select Analysis, Miscellaneous, Chromatic Focal Shift). It should look like Figure E2-1.

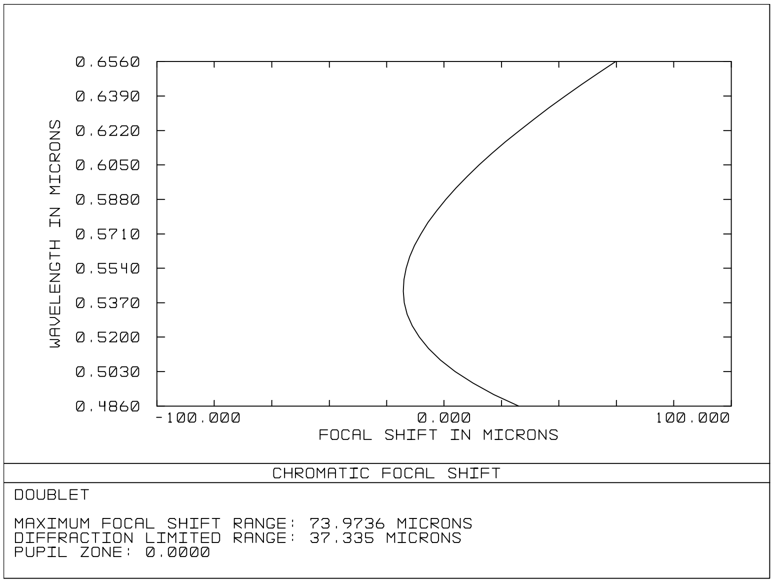

Figure E2-1.

We now have reduced the linear term so that the second-order term dominates, as seen by the parabolic shape. Note also the magnitude of the shift is 74 microns (it was 1540 microns for the singlet).

There are other glass choices that yield better designs. To see the other glasses ZEMAX has in the glass catalog, select Tools, Glass Catalogs. Click on "Exit" when you are done browsing in the catalog.

Now update the rayfan plot by selecting Update from the ray fan window (if the ray fan window is not shown, select Analysis, Fans, Ray Aberration from the main menu bar). The fan is shown in Figure E2-2. The maximum transverse ray aberrations have been reduced to roughly 20 microns. This is a substantial improvement over the 200 microns for the singlet. Note that the slope of the rayfan plot through the origin for each wavelength is roughly the same; this indicates that the relative defocus for each wavelength is small. The slope is not zero, however. This implies that the defocus is being used to balance the spherical aberration. The sideways "S" rayfan curve is typical of a lens with spherical balanced by defocus.

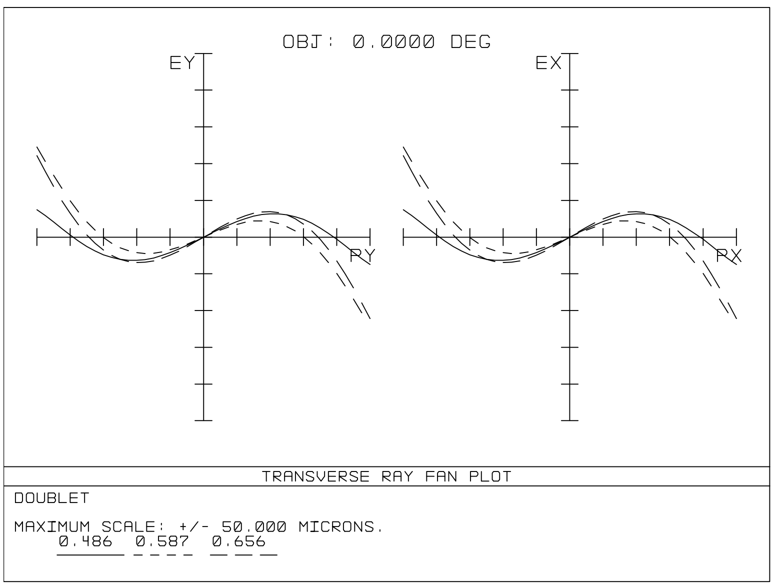

Figure E2-2.

Now that we have designed a lens with good performance characteristics, what does the lens look like? To see a simple, two-dimensional cross section of the lens, select Analysis, Layout, 2D Layout. The layout shown in Figure E2-3 will appear. The layout shows the lens from the first surface to the image plane (by default, other options are available). It also draws three rays (by default) traced from each field at the primary wavelength to the image plane. The rays are at the top, center, and bottom of the entrance pupil, which in this case is surface 1. The first lens has a rather sharp edge, apparently. From the drawing it is difficult to tell if the edge thickness is even positive or negative. Also, it would be nice if the lenses were slightly oversized, so that the useful clear aperture of the lens was smaller than the diameter. This would allow some rim space for polishing and mounting, for example.

We can improve the design with regard to both of these problems. To determine the exact edge thickness, move the cursor to any column on surface 1 (for example, click on the word "BK7" in the LDE). Now select Reports, Surface Data. A window will appear which tells you the edge thickness of that surface. The value given is 0.17, which is a little on the thin side.

Before we fix the thin edge thickness, we will first oversize the lenses. Move the cursor over to the "Semi-Diameter" column of surface 1. Type in "14" over the 12.5 shown. ZEMAX clears away the 12.5, and displays "14.000000 U". The "U" signifies that this aperture is user-defined. If no "U" is shown, then ZEMAX is free to size the aperture as required. You can remove the "U" by typing Ctrl-Z, or by double clicking on the semi-diameter and selecting "Automatic" for a solve type. After making the change, select System, Update to update the apertures. The value 14 is the semi-diameter, which means the full aperture is 28 mm. Enter an aperture of 14 on surfaces 2 and 3 as well.

Update the layout plot. Now the apertures are oversized, but the first edge thickness is negative! Update the surface data window to see the new edge thickness; it should change to a negative number. To provide a more reasonable edge thickness, we could increase the center thickness. However, there is a more powerful method of maintaining the edge thickness at a particular value.

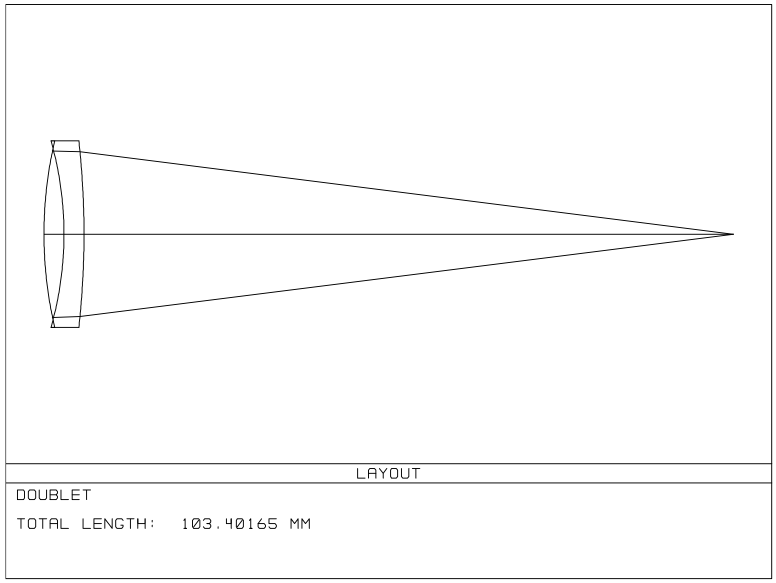

Figure E2-3.

Suppose we wanted to maintain the edge thickness at 3 mm. To do this, double click on the thickness column of surface 1. This brings up the solve control screen. Select "Edge Thickness" from the list of solves that appears. Two values are shown, a "Thickness", and a "Radial Height". Set the thickness to 3 and the radial height to 0 (If the radial height is zero, ZEMAX uses the defined semi-diameter), then click on OK. On the LDE, the thickness of surface 1 has been adjusted. The letter "E" appears in the box to indicate an active edge thickness solve on that parameter.

Update the surface data window again, and the edge thickness of 3 will be listed. You may also update all of the windows at once by selecting System, Update All. This will refresh the layout and ray fan plots. By adjusting the thickness, we have changed the focal length of the lens slightly. If you like, look at the rayfan plot now. Then optimize again (select Tools, Optimization, then select "Automatic". After optimization, click on "Exit" then select System, Update All, to refresh the plots once more.

Now we would like to test the off-axis performance of the doublet. From the main menu, select System, Fields to reach the "Field Data" dialog box. Select three fields by clicking on the "Use" column on rows 2 and 3. In the second row of the y field column below, enter 7 (for seven degrees) and in the third row enter 10. Leave the first row at zero, for on-axis. Leave the x field values at zero as well; for a rotationally symmetric system they have little value. Click on OK to close the box.

Now select System, Update All. The rayfan plot is shown in Figure E2-4. Your plot may be slightly different, depending on how you re-optimized after setting the solve.

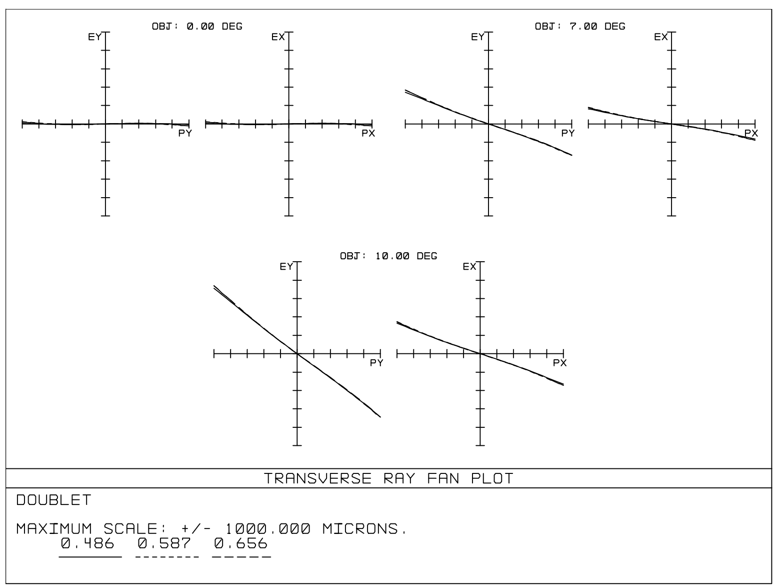

Figure E2-4.

As you may have inferred from these plots, the off-axis performance is very poor. The reason is that we optimized the design for on-axis performance. What aberration limits us now? Studying the rayfan plot identifies the primary aberration as field curvature. This aberration can be evaluated by the field curvature plot. Select Analysis, Miscellaneous, Field Curv/Dist. The field curvature plot shown in Figure E2-5 appears. Note the left plot indicates the shift in paraxial focus as a function of field angle, while the right plot indicates the real ray distortion, referenced to the paraxial ray. All of the information on the field curvature plot is available from the rayfans. The field curvature plot is proportional to the slopes through the origin of the rayfan plot.

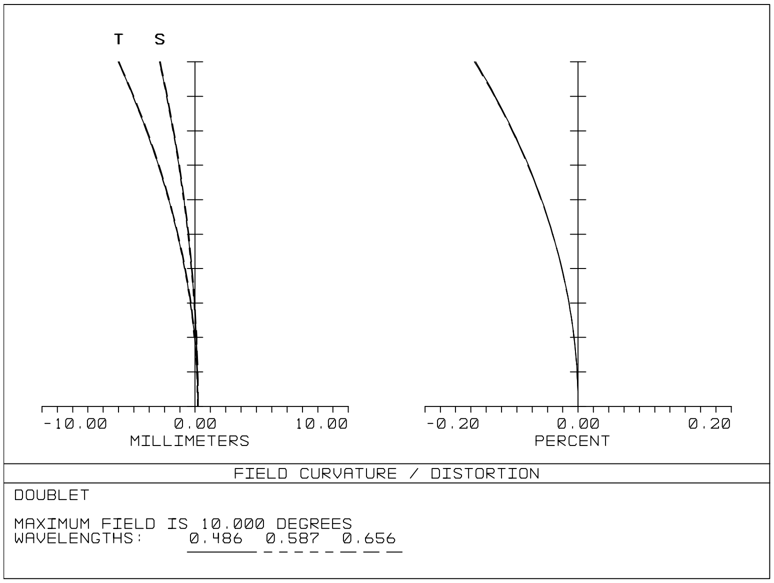

Figure E2-5.

There are techniques for correcting the field curvature, and in fact, the spherical aberration and coma as well. These techniques are also described in Smith, Modern Optical Engineering.

Lesson 3: a Newtonian telescope

☞ ***What you will learn: Using mirrors, conic constants, coordinate breaks, three dimensional layouts, obscurations.***

If you have already worked the previous two examples, you are ready to move on to a more complicated design. The Newtonian is the simplest telescope corrected for all aberrations on axis, and it serves well to illustrate some fundamental ZEMAX operations. First of all, a Newtonian is a telescope consisting of a simple parabolic mirror, and nothing else. The parabola corrects perfectly all orders of spherical aberration, and since we will only use our telescope on axis, there are no other aberrations. To start fresh, close all windows except the LDE, and select File, New.

Assume we want a 1000 mm F/5 telescope. This implies a mirror with a radius of curvature of 2000 mm, and an aperture of 200 mm. Move the cursor to the radius of curvature column on surface 1, which is the stop, and enter -2000.0. The minus sign indicates concave to the object. Now enter a thickness of -1000 on this same surface. The minus sign indicates we are moving "backwards" due to the reflection off the mirror surface. Now enter "MIRROR" for the "Glass" column on this same surface. Select System, General, then enter an aperture value of 200 on the general data dialog box, and click on OK.

ZEMAX uses one default wavelength of .550, and one field angle of 0, and this is acceptable for our purposes. Now open up a layout window. The rays are drawn from the first surface to the image plane, which now lies to the left of the mirror. If you now perform a standard spot diagram (pull down Analysis, Spot Diagrams, Standard; or type Shift+Ctrl+S) you will see a large spot diagram of 77.6 microns RMS. One convenient way of assessing image quality is to superimpose the Airy diffraction ring on top of the spot diagram. To do this, select Settings from the spot diagram menu bar, and on the option "Show Scale", select "Airy Disk", then click on OK. The resulting spot diagram is shown in Figure E3-1.

The RMS spot size listed is 77.6 microns. The reason the rays are not diffraction-limited is because we have not yet entered the conic constant. The -2000 radius of curvature we entered earlier just defines a sphere, we need a conic constant of -1 to define a parabola. In the "Conic" column on surface 1, enter -1, and press enter. Now refresh all windows using System, Update All. On the updated spot diagram, you should see the large Airy ring with a tiny cluster of rays in the center. The RMS spot size is zero.

Unfortunately, the image is in a poor location. By being in the incoming beam path, the image is not readily accessible. This is commonly fixed by using a fold mirror placed after the primary mirror. The fold mirror is tipped at 45 degrees, relaying the image up away from the optical axis. To implement the fold mirror, we must first decide where it should go. Since the incoming beam is 200 mm wide, we want the image plane at least 100 mm above the axis. We will select 200 mm, and therefore the fold mirror must be 800 mm from the primary.

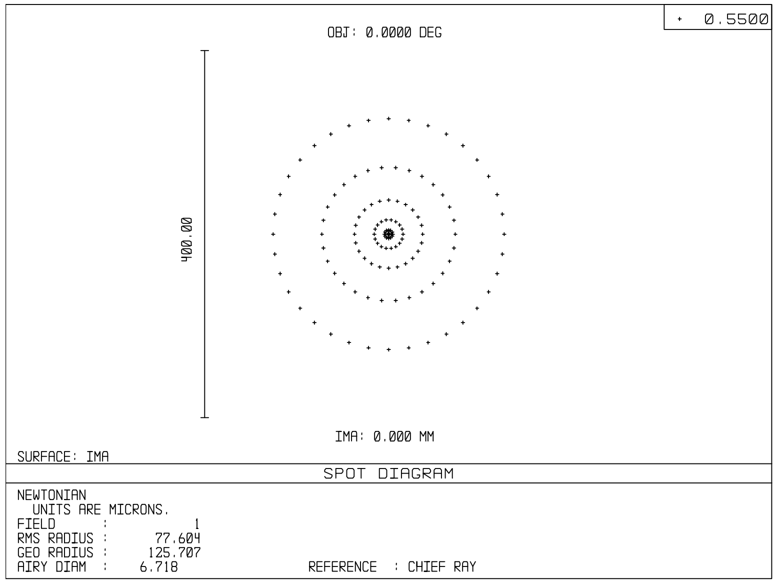

Figure E3-1.

Start by changing the thickness on surface 1 to -800. Now move the cursor to the image surface, and press insert to insert a dummy surface between the primary and the image plane. The new surface will be converted to a fold mirror shortly. The purpose of the dummy surface is simply to locate the fold mirror. Enter a thickness of -200 on the new dummy surface, to maintain the total distance from mirror to image plane at -1000.0.

Now click on Tools, Add Fold Mirror, and set the "fold surface" to 2, and click OK. The resulting spreadsheet display should be similar to the following table (some of the columns have been omitted for clarity).

PRESCRIPTION FOR NEWTONIAN TELESCOPE EXAMPLE

Surf	Surface Type	Radius	Thickness	Glass	Conic	Tilt About X
OBJ	Standard	Infinity	Infinity		0.00000	
STO	Standard	-2000.000	-800.000	MIRROR	-1.00000	
2	Coord Break		0.000			45.00000
3	Standard	Infinity	0.000	MIRROR	0.00000	
4	Coord Break		200.000			45.00000
IMA	Standard	Infinity			0.00000	

Now we would like to view our new folded mirror Newtonian system. The layout used previously will no longer work (it only works for rotationally symmetric systems), instead we use the 3D-layout by choosing Analysis, Layout, 3D Layout. Once the 3D layout appears, use the left, right, up, down, page up, and page down keys to rotate the image around. ZEMAX allows the image to be rotated interactively. One possible projection is shown in Figure E3-2.

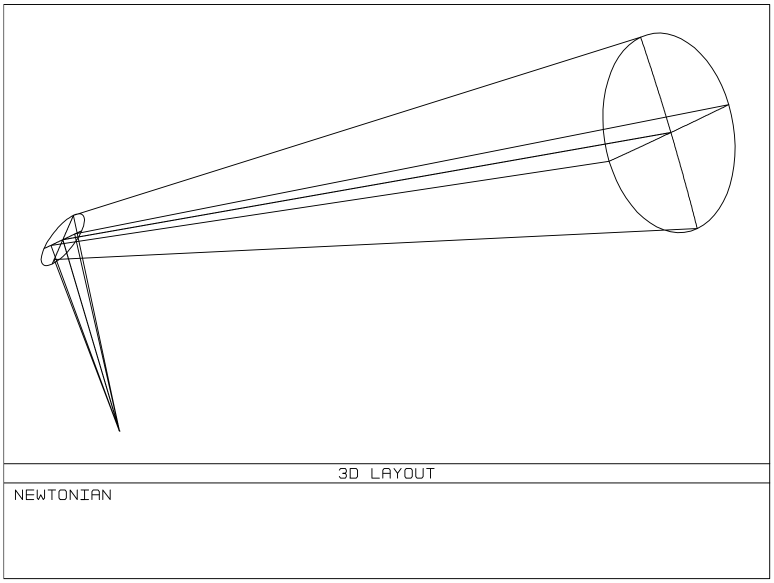

Figure E3-2.

This design projection could be improved several ways. First of all, the rays which are coming from the object to the mirror could be shown. Also, the rays which strike the back of the fold mirror should be vignetted, and not allowed to proceed to the image plane. This is an important effect for real systems, since the rays cannot physically travel through the mirror in usual optical systems.

First, we add a dummy surface in front of the stop by inserting a new surface with the cursor on surface 1. Now, make the thickness of this dummy surface 900. Now, double click on the word "Standard" on surface 1. On the dialog box, select the "Aperture" tab, then select "Circular Obscuration" for an "Aperture Type". This allows the placement of a obscuration in the beam, which accounts for the fold mirror blocking some of the beam. For a "Max Radius" enter 40, then click on OK. Now update the 3D layout. The system now looks more realistic, as shown in Figure E3-3. If not all of the surfaces are visible, select Settings, and change the first and last surface options to 1 and 6, respectively, or click on Reset, then OK.

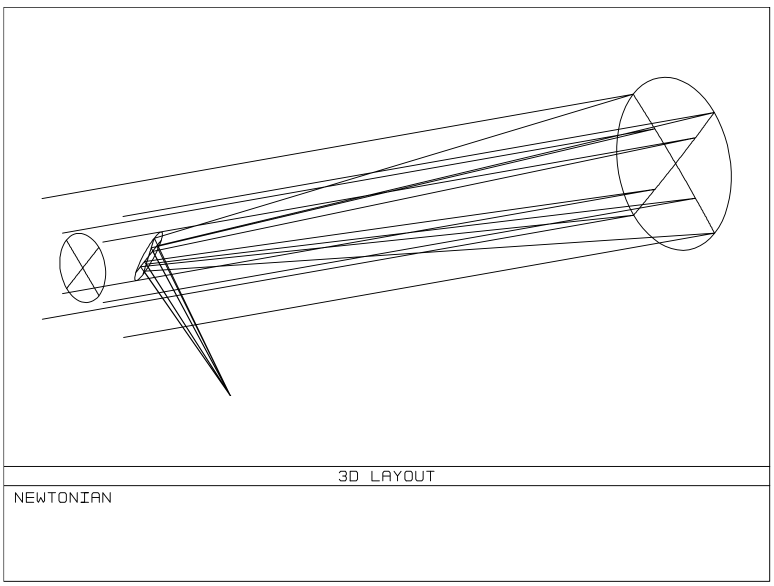

Figure E3-3.

The procedure outlined here is all that is required to use folding mirrors. Coordinate breaks can also be used to tip, tilt, and decenter optical components other than mirrors. Entire optical sub-assemblies may be moved, see some of the example designs included with ZEMAX for sample systems.

Lesson 4: a Schmidt-Cassegrain with aspheric corrector

☞ ***What you will learn: Using polynomial aspheric surfaces, obscurations, apertures, solves, optimization, layouts, MTF plots.***

This lesson is the complete design of a Schmidt-Cassegrain with a polynomial aspheric corrector plate. The design will be for use in the visible spectrum. We would like an aperture of 10 inches, and a back focus of 10 inches (from the back of the primary to focus).

It is easier to start this design with just the corrector and the primary, and so we begin by inserting two surfaces after the stop. Select System, General, and enter 10 for an aperture value. On this same screen, change the units from "Millimeters" to "Inches".

Select System, Wavelengths to reach the Wavelength Data screen, and set the three wavelengths of .486, .587, and .656 with the .587 being the primary wavelength. This can be done with a single step: click on the "Select ->" button on the bottom of the wavelength dialog box.

For now, we will use the default field angle of 0 degrees. Enter the data in the following table on the spreadsheet. The stop is placed at the center of curvature of the primary; this is done to eliminate field aberrations (like coma) and is characteristic of the Schmidt design.

STARTING PRESCRIPTION FOR SCHMIDT CASSEGRAIN

Surf	Radius	Thickness	Glass
OBJ	Infinity	Infinity	
STO	Infinity	1.000000	BK7
2	Infinity	60.000000	
3	-60.000000	-30.000000	MIRROR
IMA	Infinity		

Now perform a layout plot to verify everything is correct. The standard 2D layout will work fine. You should see a plot like Figure E4-1.

Now we will add the secondary mirror, and place the image plane. We will let ZEMAX calculate the correct curvature for the secondary later. For now, modify the spreadsheet to support one new surface as shown in the following table.

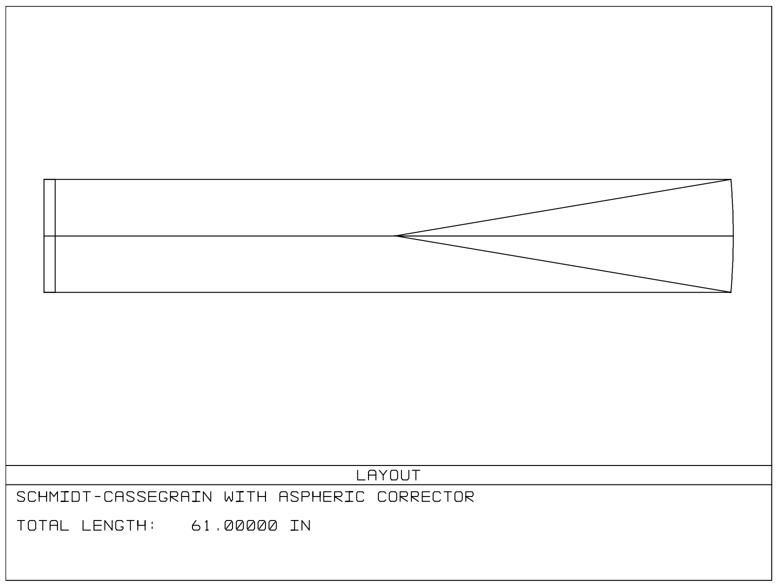

Figure E4-1.

INTERMEDIATE PRESCRIPTION FOR SCHMIDT CASSEGRAIN

Surf	Radius	Thickness	Glass
OBJ	Infinity	Infinity	
STO	Infinity	1.000000	BK7
2	Infinity	60.000000	
3	-60.000000	-18.000000	MIRROR
4	Infinity V	28.000000	MIRROR
IMA	Infinity		

Notice we have decreased the distance from the primary to -18. This will keep the size of the secondary down. The distance to the image plane is now 28, which is exactly 10 inches behind the primary. A variable has been added to the radius of surface 4; we will allow ZEMAX to find the correct curvature. Since no curvature has been entered yet, the image is out of focus. Check your work by updating the layout. It should look like Figure E4-2.

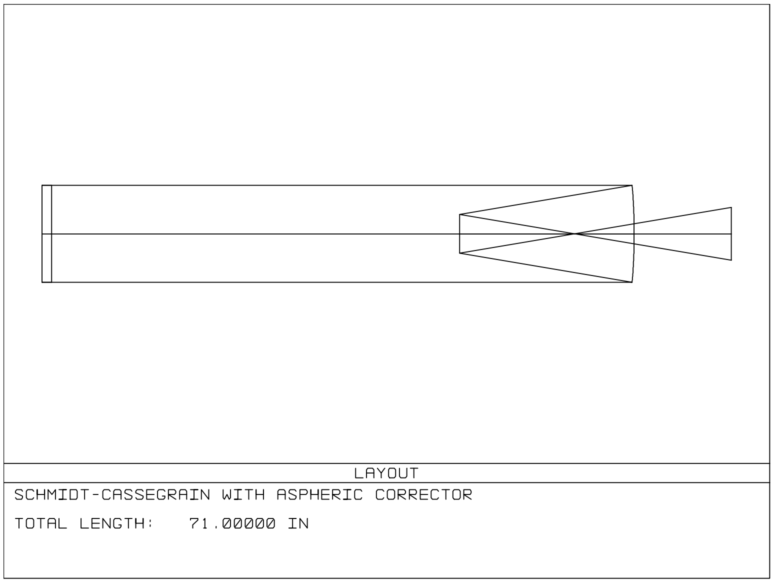

Figure E4-2.

Now select Editors, Merit Function, to display the merit function editor. Select Tools, Default Merit Function from the merit function editor window menu. Click on "Reset", then change the "Rings" option to "5". Now click on OK. The rings option determines the sampling density of the rays, and this design requires more than the default 3.

Select Tools, Optimization. Select "Automatic" and the merit function will quickly drop to about 1.3. This is the residual RMS wave error. Click on "Exit", and then select System, Update All. The radius of the secondary has been changed from infinity to -41.83. Now perform an OPD plot by selecting Analysis, Fans, Optical Path. The OPD plot shows defocus and spherical, and looks like Figure E4-3. Note there is roughly 4 waves of aberration still to correct.

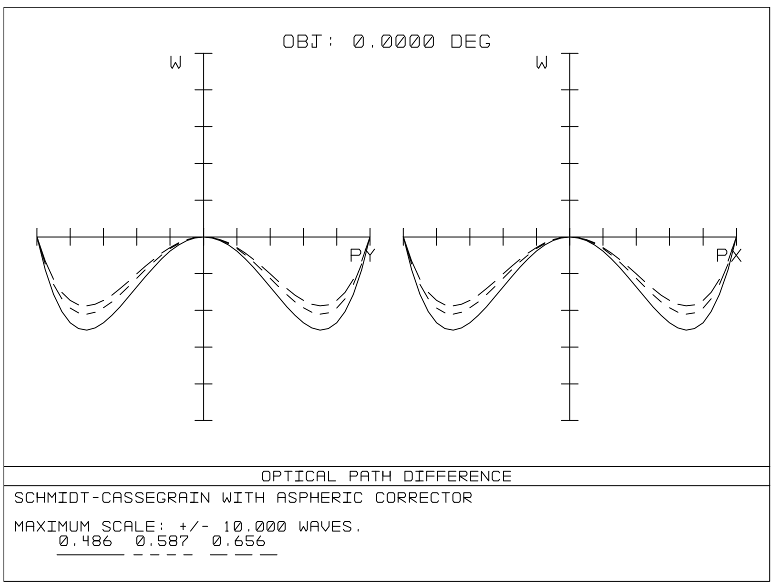

Figure E4-3.

Now click on the "Standard" surface type of surface 1 (the stop surface). From the dialog box that appears, select "Even Asphere". This surface type permits designation of polynomial aspheric coefficients for aspheric correction. Click on OK. Now, move the cursor to the right until you reach the column "4th Order Term" on surface 1, and type Ctrl-Z. This sets a variable on this parameter, currently zero. Also place variables on the "6th Order Term" and "8th Order Term" coefficients. Now select Tools, Optimization, and click on "Automatic". In a few seconds, the merit function will drop substantially as ZEMAX balances the various orders of spherical aberration. Click on Exit.

Now update the OPD plot again, it is shown in Figure E4-4. The spherical aberration has been reduced substantially. Note the limiting aberration now is chromatic aberration; with each wavelength having a different amount of spherical. This is called spherochromatism, and we will correct it shortly.

There is a little bit of experience required now to get this design where we want it. To correct the sphero-chromatism, we need to balance it with axial color. This is a common design approach; balancing higher-order aberrations with lower-order ones in the same family. Here, spherochromatism is the higher-order cousin of first-order axial color. To introduce axial color, we will vary the curvature of surface 1, the front of the corrector plate (this also makes the plate easier to fabricate, for reasons we will not discuss). Set the radius of surface 1 to a variable now.

Now optimize again (Tools, Optimization, Automatic). The merit function will drop again. Now click on Exit, and update the OPD plot. It should look like Figure E4-5.

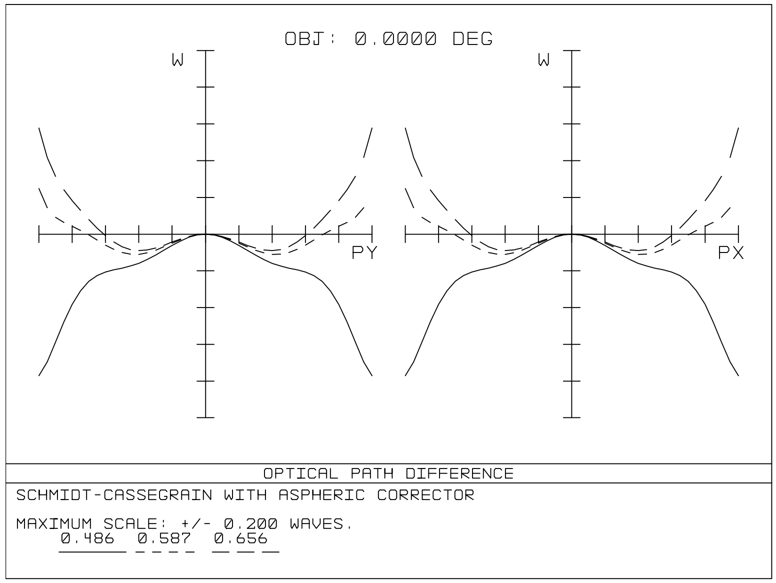

Figure E4-4.

This is the solution we wanted; the residual is less than one-twentieth of a wave! Now we can open up the field angles and fine tune the design. From the main menu, select System, Fields, and set the number of field angles to three. Enter y- angles of 0.0, 0.3, and 0.5 degrees.

If you update and look at the OPD plot now, you will see roughly 1/2 wave of coma at full field. We can easily correct this by re-optimizing. Because we have altered the fields, we must reconstruct the merit function. This is very important! You must appreciate that the default merit function is based upon the fields and wavelengths you have defined; if you change these values, you must reconstruct the merit function.

On the merit function editor, select Tools, Default Merit Function, and change "Rings" to "4". Click on OK. Now select Tools, Optimization, then click on "Automatic". When it has converged, click on Exit, and update the OPD plot once more. The plot is shown in Figure E4-6, and is a well balanced design.

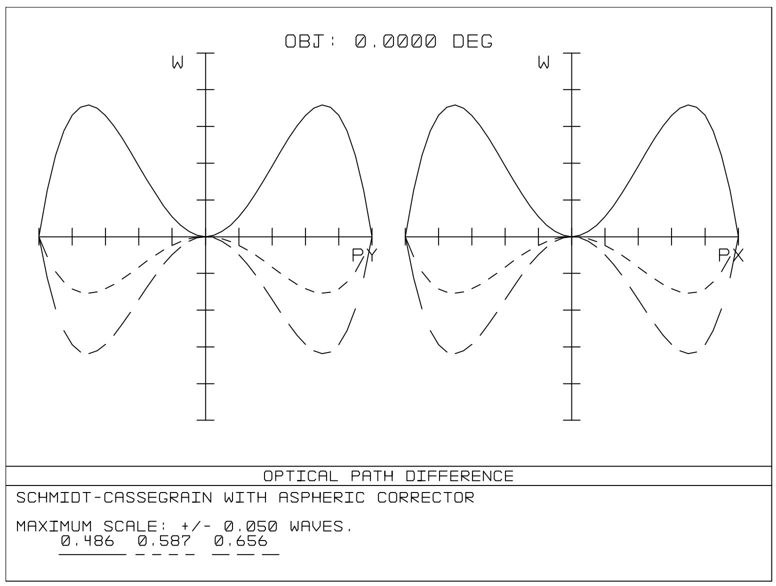

Figure E4-5.

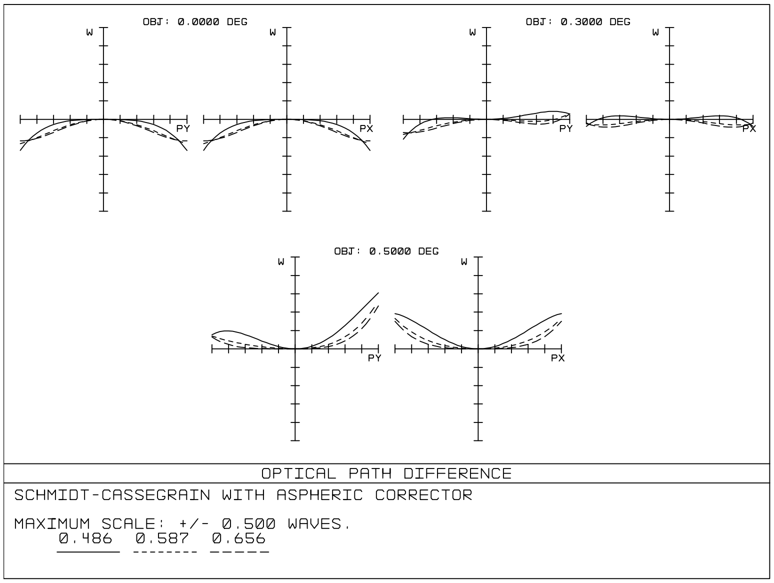

Figure E4-6.

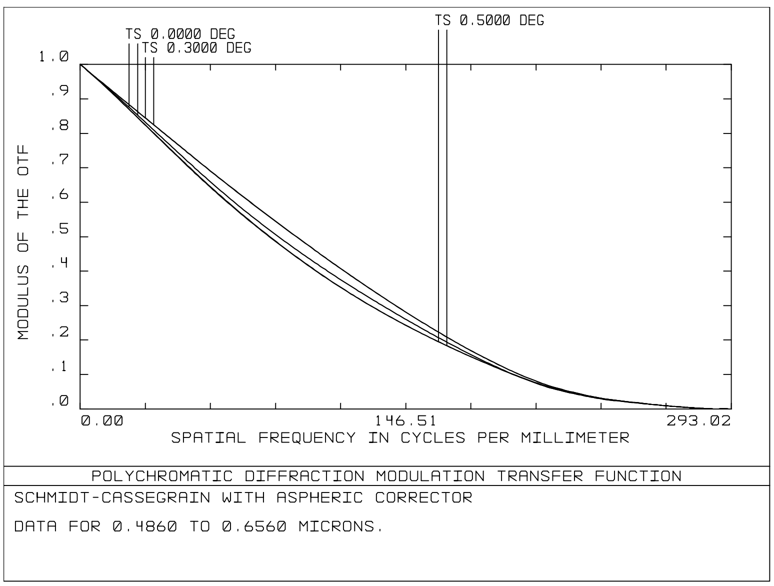

Figure E4-7.

Suppose we are going to use this telescope for taking photographs. We might be interested in the modulation transfer function (MTF), which specifies image contrast as a function of spatial frequency (usually given in inverse millimeters). To see the MTF plot, from the main menu select Analysis, MTF, Modulation Transfer Function. The MTF appears, as shown in Figure E4-7.

The MTF plot is a very powerful analysis tool. The graph shows tangential and sagittal response for all defined fields. There is, however, something wrong with this plot. A perceptive designer will realize that the data shown is the autocorrelation of a circular pupil. The problem lies in the fact that we have not accounted for the several apertures and obscurations in the system. There is the obscuration caused by the secondary, and there is a hole in the primary. If we add these effects, the performance will drop, particularly at the medial spatial frequencies.

To correct this shortcoming in our analysis, return to the LDE, double click on the first column of surface 3, select the "Aperture" tab, and then select "Circular Aperture" from the list of aperture types. Now move to the "Min Radius" and enter 1.7. This says that all rays must be greater than 1.7 inches away from the axis to pass this surface; this is the "hole" in our primary. Change the "Max Radius" to 6.

The obscuration on the secondary is more complex. It needs to be placed optically in front of the secondary. Since ZEMAX traces rays sequentially, we must place it before the primary. This is easier to do than to explain, so have a little faith and try the following.

While still on surface 3, press the insert key. This inserts a new surface between the corrector and the primary. Change the thickness of this new surface (which is now surface 3) from 0 to 20. Move up one row, and change the thickness of surface 2 from 60 to 40. The total corrector to primary is thus unchanged at 60; we have simply added an intermediate surface. Double click on the first column on this new surface 3, and set the aperture type to "Circular Obscuration", and set the "Max Radius" (not the minimum) to 2.5, then click on OK. Set the semi-diameter of surface 3 to be 2.5 as well. Now update the layout plot. If you did all this correctly, you will see the layout shown in Figure E4-8. The slight gap between the obscuration and the secondary is purely a matter of taste; it is easier to see it this way. You could move it on top of the secondary if you prefer.

The MTF is now altered by the obscurations, primarily the secondary. Update the MTF window to see the new MTF, it is shown in Figure E4-9.

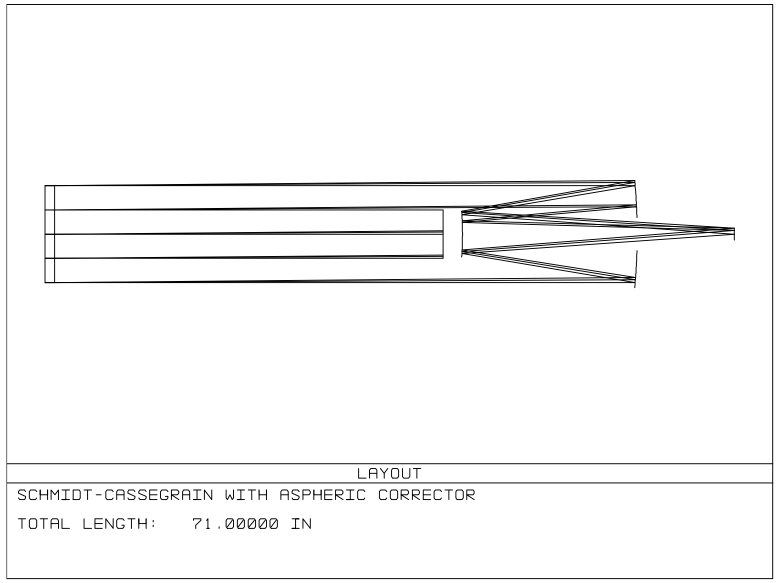

Figure E4-8.

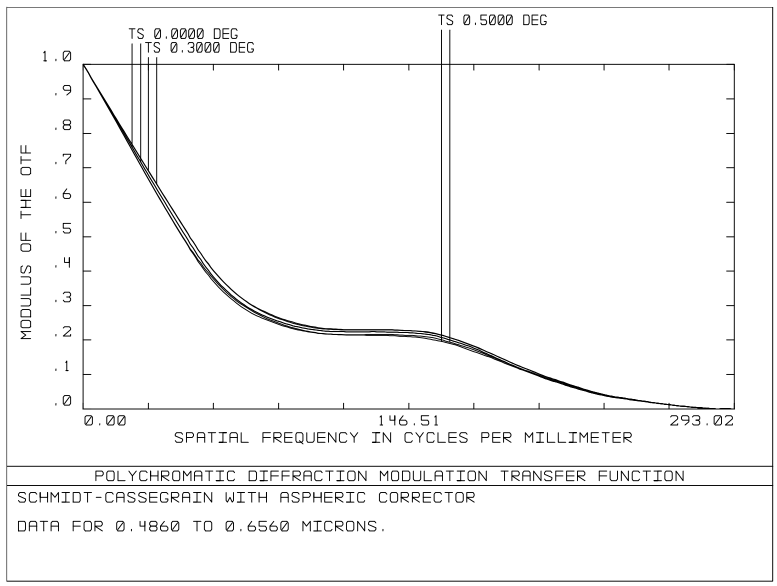

Figure E4-9.

Lesson 5: a multi-configuration laser beam expander

☞ ***What you will learn: Using the multi-configuration capability***

This example assumes you have mastered the operation of ZEMAX, and understand how to perform basic diagnostics such as ray fans and OPD plots.

Suppose you needed to design a beam expander for use with a laser which operates at $\lambda = 1.053\mu$. The input diameter is 100 mm, and the output diameter is 20 mm. Both the input and output are collimated. This is an easy design to do if there is no constraint on the overall length, however, to make it difficult, we will add several constraints:

1) Only two lenses may be used.

2) The design must be Galilean in form (no internal focus).

3) The separation between the lenses must be no more than 250 mm.

4) Only 1 aspheric surface is permitted.

5) The system must be tested at $\lambda = 0.6328\mu$.

The design task involves not only correcting the aberrations, but doing so at two different wavelengths. However, the system is not used at both wavelengths simultaneously, and therefore, we can shift the conjugates during testing. To begin the design, run ZEMAX. Insert several surfaces, and place variables on them until your lens data editor looks like the following table. Note that the "Focal Length" column is several columns to the right of "Glass". The heading "Focal Length" will only appear after you have changed the surface type from "Standard" to "Paraxial". Not all columns are shown for clarity.

STARTING PRESCRIPTION FOR LASER BEAM EXPANDER

Surf	Surface Type	Radius	Thickness	Glass	Focal Length
OBJ	Standard	Infinity	Infinity		
STO	Standard	Infinity V	10.000	BK7	
2	Standard	Infinity V	250.000		
3	Standard	Infinity	5.000	BK7	
4	Standard	Infinity V	10.000		
5	Paraxial		25.000		25.000
IMA	Standard	Infinity			

Note the use of the paraxial lens to bring collimated light to focus. Set both the thickness and the focal length to 25.00. Also, set the entrance pupil diameter to 100, and the wavelength (just one) to 1.053 microns. DO NOT enter any other wavelength yet.

The lens thicknesses were set arbitrarily, but will be sufficient for our purposes. The 250 mm is due to our requirement #3. Now select Editors, Merit Function. The merit function should be empty, with just a "BLNK" (for blank, meaning unused) operand shown. At the first line, change the operand type to "REAY". This real ray Y constraint will be used to control the 5:1 beam compression required. Enter "5" for the "Srf#" (this is the surface on which we want to control the ray height) and 1.00 for Py. Enter a target value of 10. This will give us a collimated output beam of 20 mm diameter. For the weight, enter a value of 1.0. Now select Tools, Update; you should see a value of 50 appear in the value column. This is just the entrance pupil radius because we only have parallel plates at this point.

Now from the editor menu bar select Tools, Default Merit Function. Select "Reset", then change the "Start At" field value to 2, then click on OK. This will add operands starting at row 2 in the spreadsheet, which will prevent loss of the REAY operand already entered.

Now from the main menu bar select Tools, Optimization, then click on Automatic. When the optimization is finished, click on Exit. Now from the main menu select Analysis, Fans, Optical Path. You should see the OPD plot shown in Figure E5-1. The performance is poor at roughly 7 waves.

The limiting aberration is spherical (ZEMAX has added defocus in an attempt to compensate it), and fortunately, we have a very effective way of eliminating spherical. Move the cursor up to the conic on surface 1, and make it variable via Ctrl-Z. Return to the optimization tool and click on Automatic. The merit function should drop dramatically. Now click on Exit, and update the OPD plot. The performance is easily diffraction limited now, with a reasonable conic. Remove the variability on the three curvatures and the conic, by typing Ctrl-Z at each cell.

Before we go any further, save the file by selecting File, Save As. Enter the name MC1.ZMX for the lens, and click on OK. You can open the file later if you make a mistake in the next few steps. Be sure you have removed the variability of the conic as well as the three curvatures.

Go to the Wavelength Data dialog box by selecting System, Wavelengths. Change the wavelength from 1.053 to .6328, and click on OK. Update the OPD plot again. The performance is terrible due to the dispersion of the glass. The aberration shown is simple defocus.

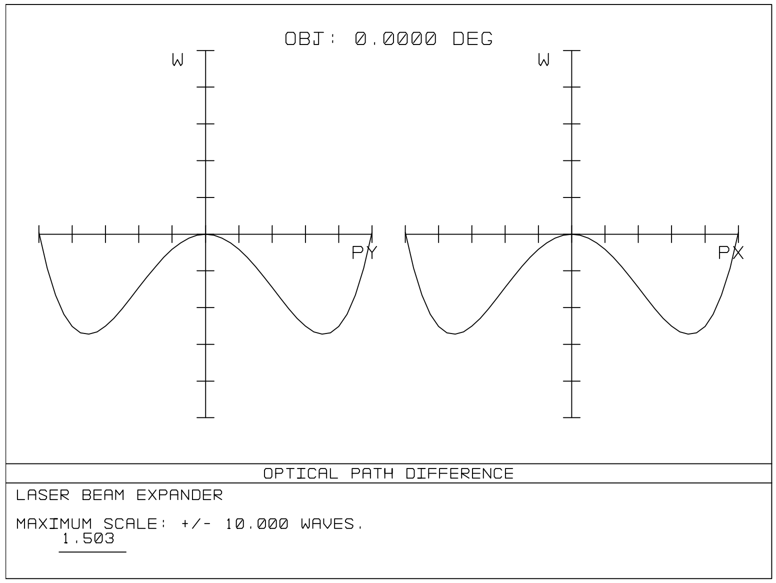

Figure E5-1.

To correct it, we could adjust the lens spacing. Make the 250 mm thickness on surface 2 variable, and then select Tools, Optimization. You should see just one variable listed. Select Automatic. The merit function should decrease. Click on Exit, and then update the OPD plot again. The system has about one wave of aberration at this new wavelength and conjugate. Remove the variable on the thickness of surface 2 by using Ctrl-Z again.

We will now use the multi-configuration capability. From the main menu, select Editors, Multi-configuration. Insert a new configuration by selecting Edit, Insert Config. Now double click on the first column of the first row, and select "WAVE" from the drop-down box which appears. On this same dialog box, select "1" for "Wavelength #", then click on OK. This will allow us to define different wavelengths for each configuration. Enter 1.053 under "Config 1" and .6328 under "Config 2". Now press insert to add a new row to the Multi Configuration Editor. Double click on the first column, on the new row 1, then select "THIC" for an operand type. The "THIC" operand will allow us to define different thickness for each configuration. Select "2" from the "Surface" list, and click on OK. Now enter 250 under "Config 1", and 250 under "Config 2". The "2" refers to surface 2, so we are defining the thickness of surface 2 as a multi-configuration value. Make the thickness of surface 2 under configuration 2 a variable by using Ctrl-Z.

Now return to the merit function editor. Select Tools, then Default Merit Function. On the dialog box which appears, change the "Start At" value to 1. This will cause the default merit function to begin at row 1. Now click on OK. This will reconstruct the merit function for the multi-config case.

Now the REAY constraint entered earlier needs to be added to the new multi-config merit function. On the first row of the merit function editor, note there is a CONF operand with a 1 in the "Cfg#" column. This operand changes the active configuration to number 1. Under this line, 3 OPDX operands follow. Between the CONF and the first OPDX, insert a new row. Change the operand type on this new row to "REAY". Enter "5" for Srf# (this is the surface on which we want to control the ray height) and 1.00 for Py. Enter a target value of 10. This will give us a collimated output beam of 20 mm diameter. Any operand listed under the CONF 1 operand will be enforced in that configuration. Under CONF 2, no operand is needed, since we cannot have exactly a 5:1 beam compression at both wavelengths.

Now go back to the lens data editor, and make the curvatures of surfaces 1, 2, and 4 variable, like at the beginning of the session. Also make the conic of surface 1 variable. Go to the optimization screen by selecting Tools, Optimization. Note 5 variables are active (3 curvatures, 1 conic, 1 multi-config thickness). Now click on Automatic, and when finished, click on Exit.

Now double click on the "Config 1" column heading of the multi-configuration editor, and update the OPD plot, and note the performance is excellent at a wavelength of 1.053. Now double click on the "Config 2" column heading, and update the OPD plot (this time for .6328). It is also well corrected. Note that the multi-configuration editor displays the two thicknesses to use for the two wavelengths. The keyboard shortcut Ctrl-A is handy for quickly changing between the two configurations.

More complex multi-configuration applications are possible, but the procedure is the same.

Lesson 6: fold mirrors and coordinate breaks

☞ ***What you will learn: A better understanding of coordinate breaks, sign conventions for tilted and decentered systems, implementing fold mirrors. Most of the techniques described in this tutorial are automated by the "Add Fold Mirror" tool, however, a detailed explanation is provided for manual entry of coordinate breaks for completeness.***

A previous lesson showed how to design a Newtonian telescope. That lesson introduced the concept of mirrors as well as the coordinate break surface. The important points of that lesson are:

1) Thicknesses always change sign after a mirror. After an odd number of mirrors, all thicknesses should be negative. This sign convention is independent of the number of mirrors, or the presence of coordinate breaks.

2) Coordinate breaks usually come in pairs, and "sandwich" fold mirrors.

This lesson will show how to manually add fold mirrors to a simple converging beam. Start by selecting File, New to clear out any current lens data. The New function will set the number of fields to one, and the number of wavelengths to one, which suits our purpose. On the Lens Data Editor (LDE), there are three surfaces shown: OBJ, STO, and IMA, which are surfaces 0, 1, and 2. Change the surface type on the STO surface to a paraxial lens by double clicking on the surface type column, and then select "paraxial" from the drop down list. Next, set the thickness of the STO surface to 100, which is the default focal length for the paraxial lens. Next, select System, General, and on the dialog box which appears enter an aperture value of 20 (this will yield an F/5 lens). Click on OK to close the dialog box. Now perform a 3D layout by selecting Analysis, Layout, 3D Layout. You should see a plane surface on the left, and rays converging to a point focus on the right. Any optical system could have been used to generate the converging beam; a paraxial lens surface was used for simplicity.

Now we will add a single fold mirror to direct the converging beam upward. The fold mirror will initially be oriented at 45 degrees. Suppose we want the fold mirror to be 30 mm away from the paraxial lens. Three new surfaces are required: a coordinate break to rotate the coordinate system 45 degrees, then a mirror surface, and finally another 45 degree rotation to follow the reflected beam. This is a crucial point: three surfaces are required to implement a single fold mirror.

To add the three surfaces, click anywhere on the image surface row to relocate the cursor, then press the insert key three times. Change the thickness of surface 1 (the STO surface) to 30. Enter in "MIRROR" for the glass column on surface 3. Change the thickness of surface 4 (the surface prior to IMA) to -70. Note the 70 is negative because after an odd number of mirrors all thicknesses change sign.

Now update the 3D layout window. The graphic will be redrawn, and you will see the light begin to focus, hit the mirror, and bounce backward to a focus 40 mm to the left of the paraxial lens. The fold mirror is not yet tilted.

To tilt the fold mirror 45 degrees, change surfaces 2 and 4 to coordinate breaks by double clicking on the surface type column of those surfaces, and select "Coordinate Break" from the drop down list. Now scroll to the right (using the cursor keys or the scroll bars at the bottom of the LDE) until the parameter columns appear. On surfaces 2 and 4 a series of zero values will appear. Click on the parameter 3 column of surface 4, and the column heading should then indicate "Tilt About X". Double click on this cell (make sure you are on surface 4) and select "Pickup" for a solve type on the drop down list. Set the "From Surface" to 2 and the "Scale Factor" to 1.0. This will cause the second coordinate break rotation angle to always be the same as the first. Click on OK. Note a "P", indicating a pickup solve, appears next to the cell value.

Now move up to surface 2, and enter a value of 45 in the "tilt about x" column. From the main menu select System then Update All, and you should see the layout shown in Figure E6-1.

Note that the thickness of the paraxial lens, 30, locates the vertex of rotation for the first coordinate break. The thickness of the coordinate break is 0, which means the mirror is located at the same point. However, the coordinate break has rotated the coordinate system 45 degrees. The mirror itself is not rotated, it is the coordinate system in which it lies that has been rotated. The mirror also has a zero thickness because we want to rotate another 45 degrees before moving on to the next surface. The second coordinate break first rotates another 45 degrees, and then moves the -70 units to focus. Note all tilts and decenters precede the thickness step.

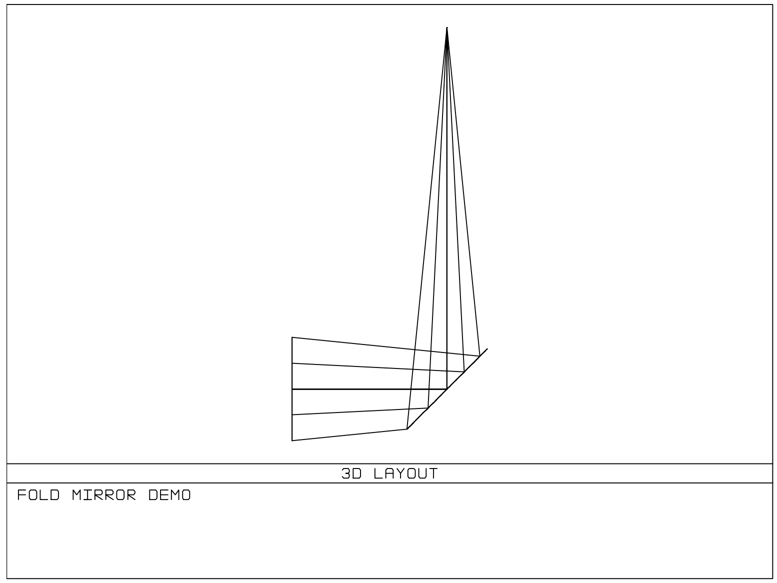

Figure E6-1.

To implement another fold mirror, click on the image surface to locate the cursor there, and press the insert key three times. Change the thickness of surface 4 from -70 to -30, the glass type of surface 6 to MIRROR, and the thickness of surface 7 to +40 (note again the sign change after a mirror). Change the surface types of surfaces 5 and 7 to coordinate breaks, and enter a tilt about x of -45 on surface 5. On surface 7, double click on the tilt about x and place a pick up solve on that parameter. Use a pick up from surface 5, with a scale factor of 1. Update the 3D Layout. It should look like Figure E6-2.

The second series of break-mirror-break folds the beam another 90 degrees, so it is parallel with the original axis. Since we have added pickup solves on the second coordinate break in each series, it is easy to tilt the beam by changing just two numbers. Try entering 30 and -60 on the tilt about x on surfaces 2 and 5, respectively, then choose System, Update All to see the effects on the 3D Layout.

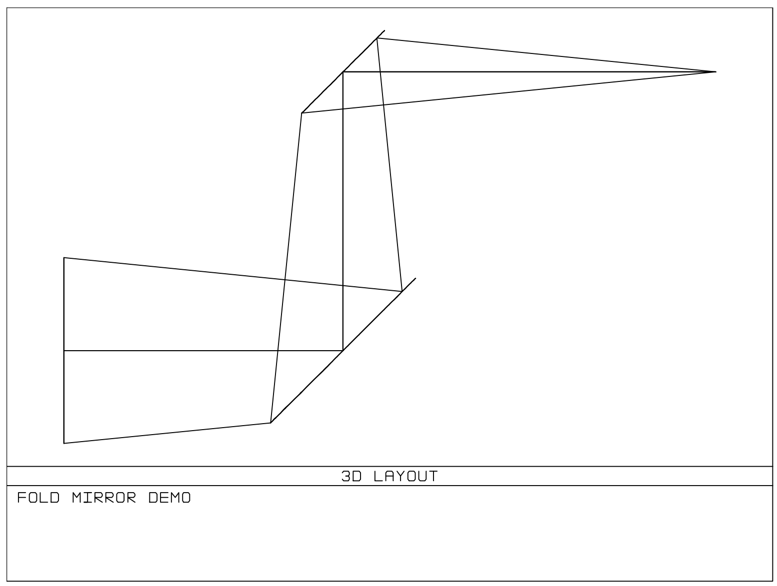

Figure E6-2.

Lesson 7: the achromatic singlet

☞ ***What you will learn: Using the Extra Data Editor, optimizing with Binary surfaces. The features used in this lesson are only available in ZEMAX-EE. This lesson assumes you have successfully completed Lessons 1 and 2.***

If you have been designing refractive optics exclusively, you may not believe there is such a thing as an "achromatic singlet". Of course, a mirror is an achromatic singlet, but is also possible to design a hybrid refractive/diffractive component which is corrected for first-order chromatic aberration. The trick is to use a conventional refractive singlet which has a diffractive surface etched on one side. The curvatures on the faces of the singlet provide the bulk of the focusing power, while the weak diffractive component provides enough dispersion to compensate for the dispersion of the glass.

To review, a singlet lens of focal length f has an optical power of $\varphi = f^{-1}$. The variation in power over the $\lambda_F - \lambda_C$ wavelength range is given by the Abbe number V of the glass of which the singlet is composed:

$$\Delta\varphi = \frac{\varphi}{V}.$$

Note that the dispersion is relatively weak for most glasses; for example, BK7 has a V value of 64.2. The variation in power is therefore about 2% of the total power.

Diffractive optics use the direct manipulation of the phase of the wavefront to add optical power to the beam. For a diffractive surface with a quadratic phase profile, the phase is given by

$$\Psi = Ar^2,$$

where A has units of radians per unit length squared and r is the radial coordinate. It is easy to show the power of a surface with this phase profile is given by

$$\varphi = \frac{\lambda A}{\pi}.$$

Note that the power of this surface varies linearly with wavelength! Over the same wavelength range that the refractive singlet power varies by 2%, the diffractive optic power varies by nearly 40%. Furthermore, the sign of the dispersion can be adjusted by changing the sign of the constant A. This property can easily be exploited by adding a slight amount of positive power to the refractive component, and then compensating by adding negative power to the diffractive component. The amount of power added can be selected to balance the axial color.

To see how easily this can be done, start ZEMAX and choose File, New. Then in the Lens Data Editor (LDE) change the Standard STO surface to a Binary 2 by double clicking on the word "Standard", choose "Binary 2" from the drop down list of surface types, and then click on "OK". Move the cursor down to the IMA row and press insert to add one more surface. Change the thickness of the new surface 2 to 100, and the thickness of surface 1 (the STO surface) to 10. Enter in "BK7" for a glass type on surface 1. Then select System, General and enter an Aperture Value of 20, and click on "OK". Finally, choose System, Wavelengths and enter in 3 wavelengths: .486, .587, and .656. Make the .587 wavelength the primary wavelength.

First we will see how good the performance is if we design a convex-plano singlet. Make the radius of surface 1 variable using Ctrl-Z. Then choose Editors, Merit Function. On the Merit Function Editor (MFE) choose Tools, Default Merit Function. The default is fine, so click on "OK". Close the MFE window.

Now select Tools, Optimization. Click on "Automatic", and it will drop down. Click on "Exit" and select Analysis, Fans, Optical Path. The plot will appear, and it should show about 8 waves of aberration. Note the axial color completely dominates this design. There is also considerable spherical aberration and defocus.

That is about as good as it gets for a simple convex-plano singlet. To improve the design, select Editors, Extra Data. On the EDE, enter in a "1" for the "Max Term #", and a "10" for the "Norm Aper". Make the third "Coeff on P^2" column variable using Ctrl-Z. Now from the main menu select Tools, Optimization, and it should show two variables (the first radii and the diffractive power). Click on "Automatic" and the merit function will drop quickly as ZEMAX uses the diffractive power to correct the axial color. Click on "Exit".

Now choose System, Update All, and the OPD fan will be redrawn with a maximum aberration of about 1 wave. Most of what remains is secondary spectrum and spherical aberration. What about that spherical aberration? We can correct it using a higher order diffractive term. Return to the EDE, change the maximum term number to 2, make the new fourth order term a variable, and reoptimize. Update the OPD plot, and see the wavefront aberration is well below 1 wave.