Chapter 1

Agenda

1.1 Introduction

1.1.1 Why Lens Design?

Lens design used to be a skill reserved for a few professionals. They employed company proprietary optical design and analysis software which was resident on large and expensive mainframes. Today, with readily available commercial design software and powerful personal (and portable) computers, lens design tools are accessible to the general optical engineering community. Consequently, some rudimentary skill in lens design is now expected by a wide range of employers who utilize optics in their products. Lens design is, therefore, a strong component of a well-rounded education in optics, and a skill valued by industries employing optical engineers.

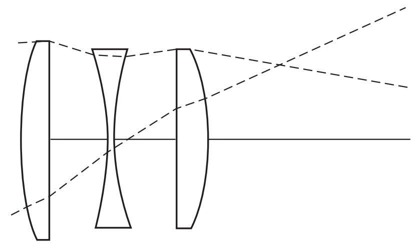
1.1.2 Type of Course

This is an introductory lens design course at the first-year graduate level. It is a nuts and bolts, hands-on oriented course. A good working knowledge of geometric optics (as may be found in such texts as Hecht and Zajac's *Optics* or Jenkins and White's *Fundamentals of Optics*) is presumed. Photographic lenses will form the backbone of the course. We will follow an historic progression (which also has correspondence from simpler to more complex systems). The code used is Focus Software's ZEMAX® and the student must have access to a PC running ZEMAX. The math level required is not taxing: algebra, trigonometry, geometry (plane and analytic), and some calculus. A book list of references is provided in Appendix A.

1.1.3 Acquired Skills

This course will provide you with three basic skills: manual, design code, and design philosophy. The manual skills will include first and third order hand calculations and thin lens pre-designs. (Analysis skills are illustrated in Figure 1.1). The code skills will include prescription entry, variable selection, merit function construction and optimization, and design analysis. The design philosophy includes understanding specifications, selecting a starting point, and developing a plan of attack.

GIVEN
1. Curvatures
2. Thickness
3. Indices
4. Stop size and location
5. Field Angle



USING
1. Paraxial ray trace equations
2. Seidel aberration formulas

FIND

First order

Effective and back focal lengths
F-number
Image location
Image size
Location of principal planes
Separation between vertex and principal plane
Entrance pupil size and location
Exit pupil size and location
Lagrange invariant
Axial and lateral color

Third order

Spherical aberration
Location and size of minimum blur
Coma
Astigmatism
Location and size of medial focus
Petzval curvature
Distortion
Wavefront variance
Strehl ratio
Required conic constant

Fig. 1.1 *Summary of manual skills to be acquired.*

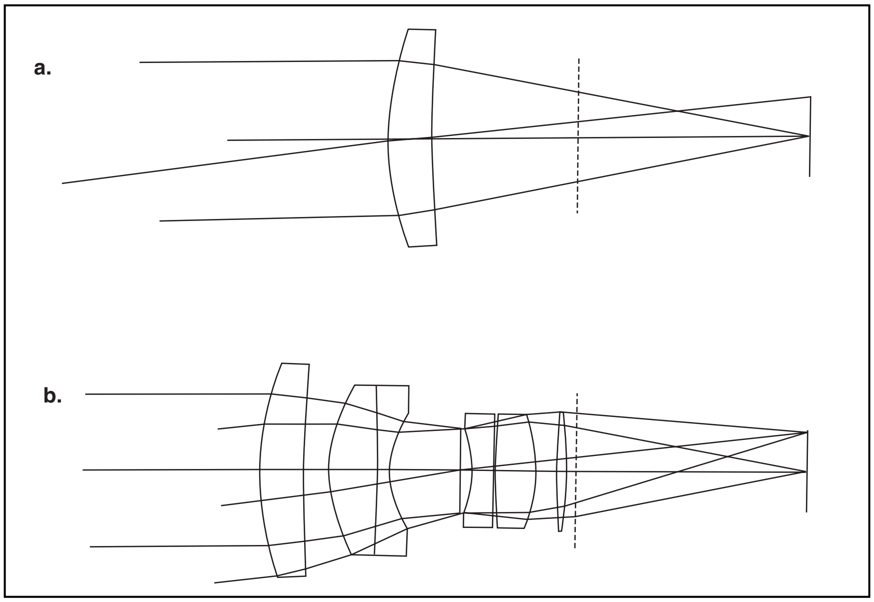


Fig. 1.2 *Two lenses that give the same image size but with quite different quality.*

1.2 Setting the Stage

1.2.1 A Comparison

Consider the two optical systems in Figure 1.2. Both are viewing the same distant object. Both have the same focal length (so the image is the same size). System *a* is simple, while system *b* is complex. If both systems yield the same image size, why not use the simpler system? Why does system *b* have extra lenses? Aside from image size, we assume that you want good, crisp, uniformly bright images across the entire field-of-view (FOV) over a flat recording format. System *b* will give that. System *a* will not. The latter's images will be of poor quality because there is inadequate correction for:

1. color
2. spherical aberration
3. off-axis aberrations
4. field curvature

The extra lenses in *b* are made from different kinds of glass to correct for color. The glass curvatures and thicknesses, and the air-spaces between them, help correct aberrations over the FOV. The result will be high-quality imagery over a flat recording surface (whether that be film or a CCD).

1.2.2 Aberration and Imagery

Figure 1.3 a shows a resolution target being imaged by a "perfect" optical system.

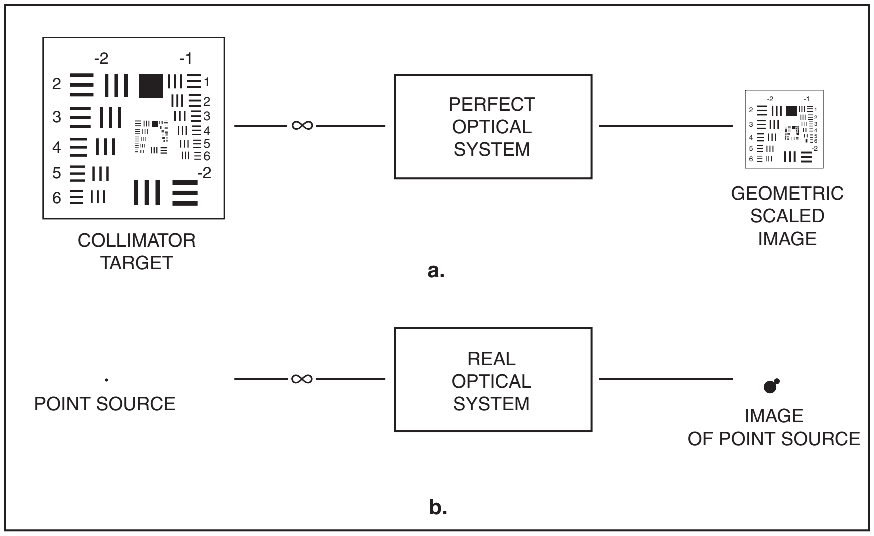


Fig. 1.3 *A resolution target perfectly imaged (***a***); a poorly imaged point source (***b***).*

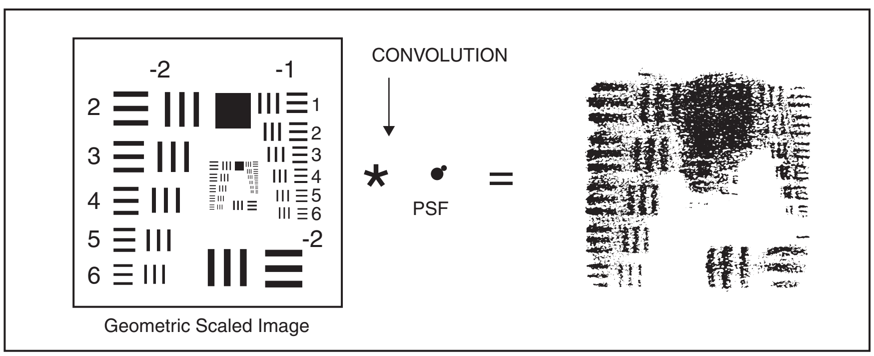


Fig. 1.4 *Degradation of the resolution target image due to convolution with blob point image.*

The image is simply a scaled version of the object. In Figure 1.3*b* we have a point source being imaged by an imperfect optical system. The resulting image is a fuzzy blob instead of a point. If we now combine the two so that we image the resolution target with the imperfect system, the image is of poor quality, as illustrated in Figure 1.4. What has happened is that we have essentially replaced every *image point* in Figure 1.3*a* with the *blob image* in Figure 1.3*b*.

1.2.3 Lens Size and FOV

Fundamentally, aberrated point images that degrade image quality are caused by the nonlinear behavior of Snell's Law. Aberrations arise when the angle of incidence of a ray with the normal of an optical surface starts getting large. This can happen in two ways for a given radius of curvature. For a ray parallel to the optical

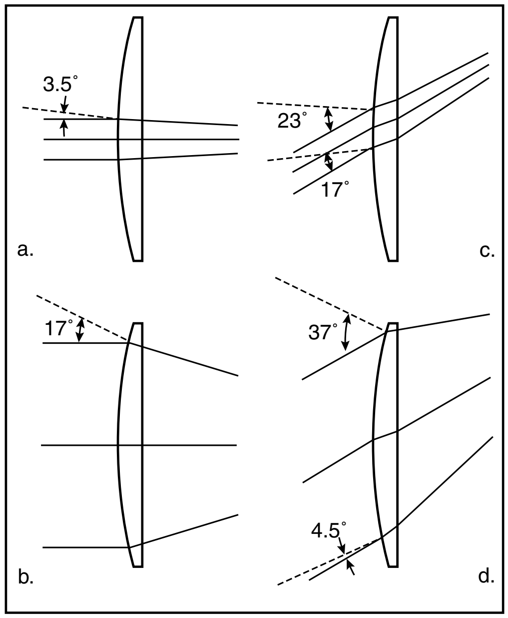


Fig. 1.5 *Angle of incidence change with ray height and field angle.*

axis, as per Figure 1.5*a* and *b*, the angle of incidence increases as the ray height increases (from 3.5° in Figure 1.5*a* to 17° in Figure 1.5*b*). If the ray strikes at the same height but from a different field angle, the angle of incidence can increase (as shown for the upper ray from 3.5° in Figure 1.5*a* to 23° in Figure 1.5*c*). When both conditions happen at the same time, the angle of incidence is even larger (from 3.5° in Figure 1.5*a* to 37° in Figure 1.5*d*). For the lower ray in *c* and *d*, the angle of incidence decreases. But now there is an asymmetry between upper and lower rays, which is indicative of off-axis aberrations.

As a system f-number decreases and field angles (and spectral bandwidth) increase, the complexity of optical systems (required to maintain good image quality) also increases. Figure 1.6 shows a qualitative plot of optical system types as a function of f-number (*x*-axis) and field angle (*y*-axis). For a ¼° field at *f*/10, a simple parabolic mirror would suffice. However, for a field of 20° at *f*/2, a six-element double-Gauss lens might be employed.

1.2.4 Specifications

Before any design can commence, the designer must have a clear understanding of the customer's requirements. This is not as straightforward as it seems. There are times when the customer is not sure of the requirements. This may lead to unexpected specification changes after much design work has already been done. In this case, the designer must take an active role in helping the customer solidify the requirements. At the other extreme is over-specification. Here the customer has placed unrealistic constraints on the design. For example, tolerances may be

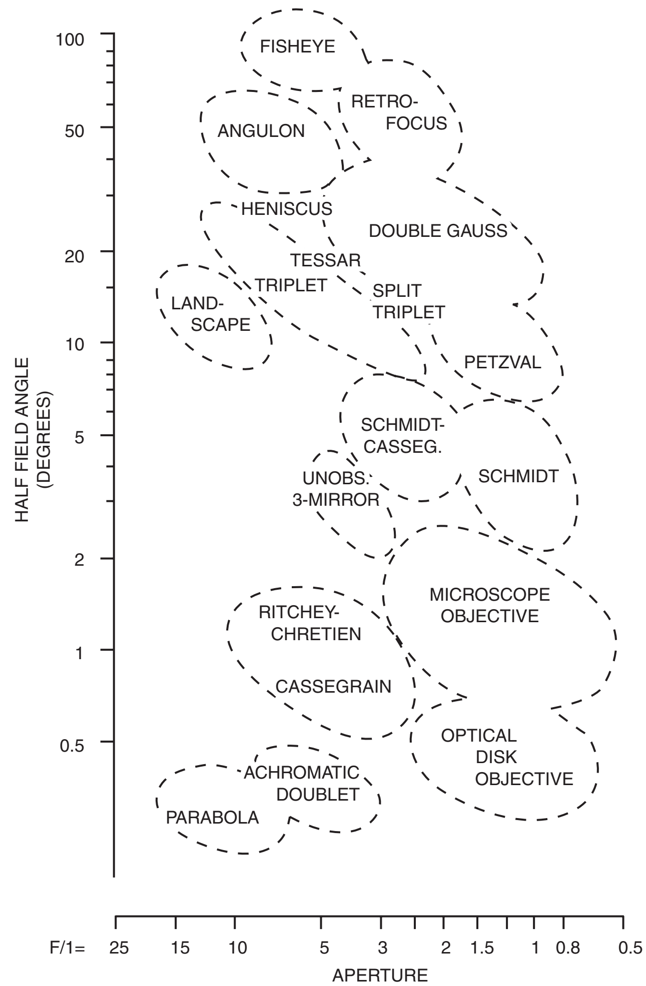


Fig. 1.6 *Map showing the design types which are commonly used for various combinations of aperture and field of view. (From W. Smith,* Modern Lens Design *(McGraw-Hill, 1992). Reprinted with permission of the McGraw-Hill Companies.)*

beyond current fabrication or metrology capabilities. Here again the designer must interact with the customer to arrive at realistic specifications.

Field coverage depends on the format size and effective focal length (EFL) of the optics. For example, the format size may be fixed by the use of 35 mm film, or an 8 × 6 mm CCD chip. The customer will say how much of the outside world or scene is to fit on the given format. This defines a certain FOV or field angle which then dictates an EFL.

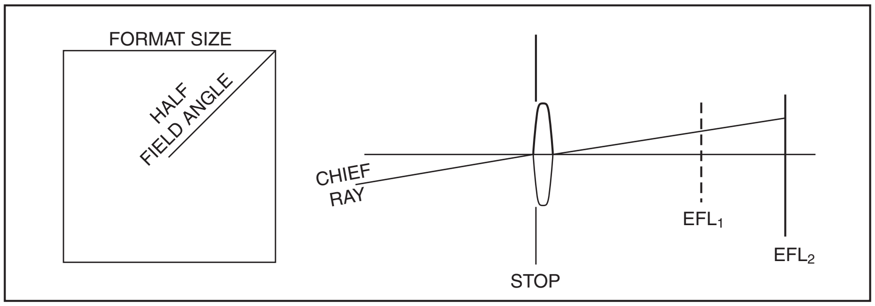


Fig. 1.7 *Dependence of EFL on format size and field coverage.*

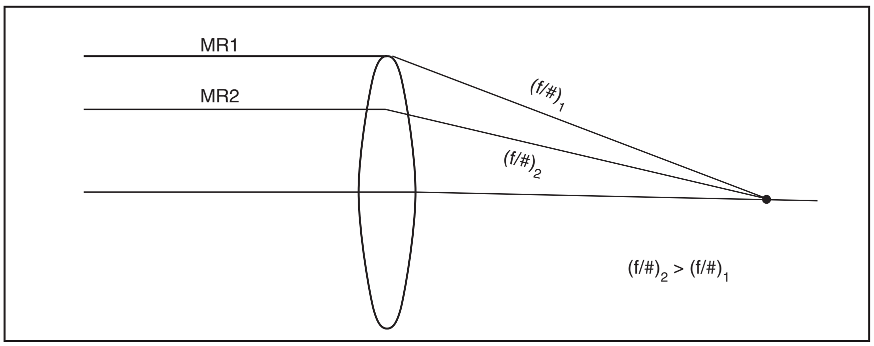


Fig. 1.8 *A lower f-number means bigger diameter optics.*

Figure 1.7 shows, for a given scene or angular coverage, the EFL needed for two different format sizes. The half-field angle is taken at the corner of the format.

The sensor employed will operate over a certain irradiance range. This will help define the f-number range of the objective. For example, on a cloudy day the f-number will be smaller than that used on a sunny day. Figure 1.8 shows how the usable diameter of a singlet is related to the f-number.

The next important specification is resolution. For a given scene, how much detail do we wish to see? Resolution is usually given as line pairs per millimeter. For example, a 100 lp/mm will present more of a design challenge than 50 lp/mm. We also have to distinguish between aerial resolution (i.e., the amount of detail in the image formed by the objective in air) and system resolution (which folds in the limitations imposed by the sensor). For example, black and white Tri-X film has poorer resolution than Pan-X because the silver halide grain sizes are bigger in the former.

Resolution may be specified as an average over the entire format, or specific targets may be given at certain field points. The design task becomes harder as the field angle increases, the f-number decreases, and resolution requirement increases.

Detectors have sensitivity over certain color ranges, hence the next important specification concerns spectral bandwidth and location. Monochromatic designs or designs where color does not matter are generally easier than polychromatic designs. As the bandwidth of a polychromatic design increases, the design task gets harder. Designs can also become more difficult if the location of the bandwidth lies outside the visible spectrum. Here there are fewer choices of materials for color correction.

The above mentioned design specifications are those of primary interest. However, there are several other constraints on designs. There may be volume, packaging, and/or weight constraints. There are constraints imposed by the thermal environment in which the optics will function. There may be constraints imposed by atmospheric or oceanic pressures. There may be constraints on glass choice imposed by humidity (or salinity) in the operational environment.

Finally, there are fabrication, alignment, metrology, and cost constraints. It is preferable to design refractive systems with spherical surfaces rather than aspheric surfaces. The latter are harder to make and test, and thus cost more. You do not want to design a system whose tolerances are so tight that it cannot be made. Again, tighter tolerances increase fabrication, assembly, and metrology costs. If possible, you want to avoid systems that will be difficult to align; e.g., off-axis systems are harder to align than on-axis systems. They are also harder to test. You usually will have to find a compromise between what the customer wants and what he can afford.

1.3 Homework

With the information provided in Figure 1.9, find:

- **a.** the effective focal length (EFL),
- **b.** the lens power ϕ,
- **c.** surface curvatures C_1 and C_2 (assume equiconvex),
- **d.** radius of curvatures R_1 and R_2,
- **e.** format size (assume square), and
- **f.** Airy disk diameter.

Note: The lens can be considered as a thin lens.

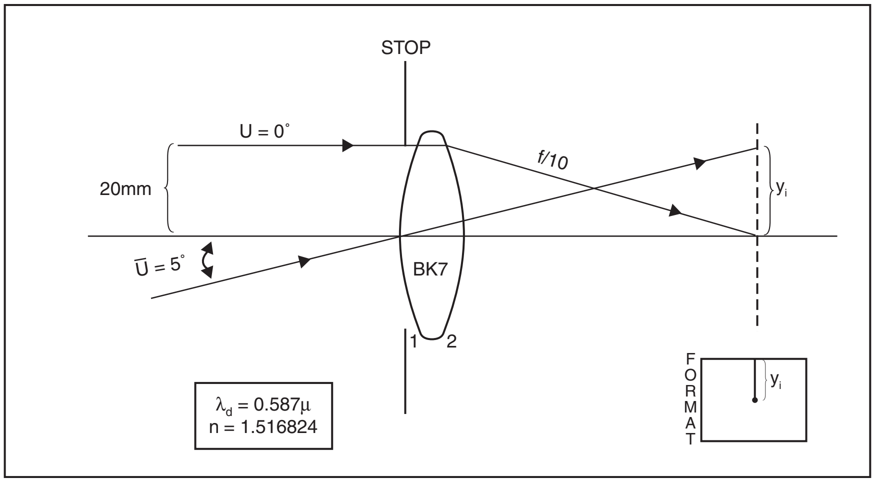


Fig. 1.9 *Illustration for Homework.*

Chapter 2

ZEMAX

2.1 Introduction to ZEMAX

The optical design and analysis code ZEMAX® from Focus Software will be used as the main workhorse throughout this course. This user-friendly software is both powerful and cost effective. In addition, the code is one used extensively in today's workplace. There are other major codes you will encounter in your professional career such as Code-V®, Synopsis®, and SuperOslo®. However, it is important for the student to become adept in at least one major program. This chapter will provide a general introduction and basic orientation to ZEMAX. More detailed information can be found in the ZEMAX manual.

2.2 Data Entry

Before you can begin your design and analysis work, you need to enter an initial prescription into the code. There are four areas requiring input of basic information about the lens, aperture, field, and wavelength. As an example, we will enter a biconvex lens.

2.2.1 Inserting a Prescription in the Lens Data Editor

The main ZEMAX screen (Figure 2.1) shows a toolbar at the top with File, Editor, System, etc. Below that is a row of buttons designated as Upd, Gen, Fie, Wav, etc. Beneath that is the Lens Data Editor (LDE).

Under Surface Type is a column on the extreme left with OBJ, STO, and IMA. With the mouse, move the arrow to the box just to the right of STO and click. The box (Standard) will be highlighted. (You can also do this using the arrow keys.) Now press the Insert key. You have just added a surface designated as 1. Go to Standard next to the IMA row, click, and then press Insert twice. You have now added two more surfaces designated as 3 and 4.

To the right of the Surface Type row are columns labeled Comment, Radius, Thickness, Glass, Semi-Diameter and Conic. Under the Radius column, move the cursor to Surface 3 and enter 100. Drop down to Surface 4 and enter –100.

Under the thickness column, move the cursor to Surface 1 and enter 25. Drop down to Surface 3 and enter 10. Drop down to Surface 4 and double click on the box to the immediate right of the data entry line. A submenu will appear. On the

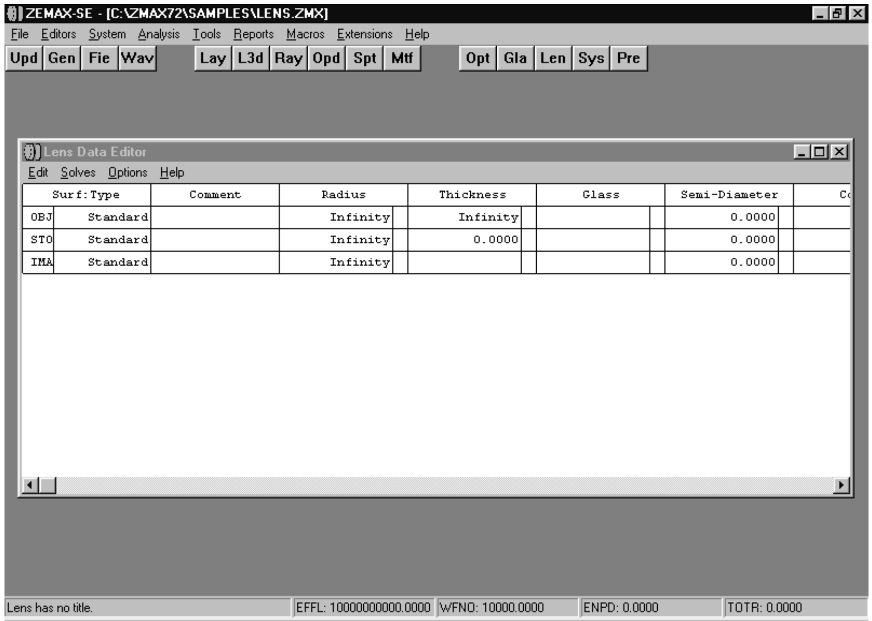


Fig. 2.1 *Main ZEMAX menu as it initially appears.*

line labeled Solve Type, click on the arrow. Several options will appear. Select Marginal Ray Height. (On the height and pupil zone lines the number 0 should also appear.) Click on OK to exit this submenu. The letter M will appear in the little box. This solve will automatically locate the paraxial back focal length since the object is at infinity.

Go to the Glass column. Drop down to Surface 3 and insert BK7.

Go to the Semi-Diameter column. Drop down to Surface 3 and enter 25. Do the same on Surface 4. (Note that the letter U appears in the narrow column on the right. This indicates a user-defined quantity.) The semi-diameter specified here defines the actual size of the lens and how it is drawn. It does *not* define the system aperture. This will be done in the dialog boxes.

This completes the information needed in the Lens Data Editor.

2.2.2 Dialog Boxes

Click on the Gen button. A submenu will appear. This is where the *system* aperture size is defined, glass catalogs are selected, and units are chosen. Click the arrow on the line Aper Type. Another submenu will appear. Click on Entrance Pupil Diameter. On the line Aper Value insert 40. This defines the system aperture. Note that the default units are millimeters. Leave this as it is.

Had we not specified lens size in the LDE, all surface aperture sizes would be automatically defined by the EPD just inserted. Also note that the default glass

SURFACE DATA SUMMARY:

Surf	Type	Comment	Radius	Thickness	Glass	Diameter	Conic
OBJ	STANDARD		Infinity	Infinity		0	0
1	STANDARD		Infinity	25		48.81635	0
STO	STANDARD		Infinity	0		40	0
3	STANDARD		100	10	BK7	50	0
4	STANDARD		-100	95.0681		50	0
IMG	STANDARD		Infinity			43.61104	0

Fig. 2.2 *Hard copy prescription of biconvex lens.*

catalog is Schott. Click on OK to exit this submenu.

Click on the Fie button. A new submenu appears through which field angles are selected. The zero field (on-axis) is already activated. Click on the little box on the extreme left to activate fields 2 and 3. Under the Y-Field column, move the cursor to field 2 and click. Enter 7.07. Go to field 3, click, and enter 10. We have active field angles now at 0°, 7.07°, and 10°. Click OK.

Click on the Wav button. A new submenu will appear. One wavelength is already activated, but this is not the one we want. Move the cursor to row 1 under wavelength, click on the box, and enter 0.486. Activate two more wavelengths by clicking on the little boxes to the extreme left. Under wavelength, click on row 2 and enter 0.587. For row 3 enter 0.656. You have just inserted the three classic wavelengths (in microns)[1] used to define the visible spectrum. They are also designated as the F, d and C lines. In the column marked Primary, click on the button on row 2. This designates the reference wavelength that will be used in the calculation of all first and third order properties.

It may seem confusing at first, but with a little practice it will become second nature. The Lens Data Editor should look like that shown in Figure 2.2. (To get a hard copy of the prescription click on the Pre button → Settings → surface data → OK → Print.)

2.3 Layout

To see what the system looks like, click on the Lay button. The diagram is shown in Figure 2.3. To obtain the scale for this diagram click on Settings. In the Scale Factor box insert 1. Click on OK. The drawing reappears with a scale bar illustrated below it. Note that the Settings box allows you to choose the number of rays and also what fields and wavelengths to display. Explore these to gain a better understanding of these options.

Our object is at infinity, so we have collimated light coming in at the three selected field angles. But we are only seeing 25 mm of collimated space in front of the lens. The stop lies in the plane of the vertex of the first lens surface. The stop diameter (40 mm) is smaller than the 50 mm diameter of the lens. Recall that the semi-diameter column in the LDE designates how big the surfaces are drawn on the

[1] SI units use micrometer.

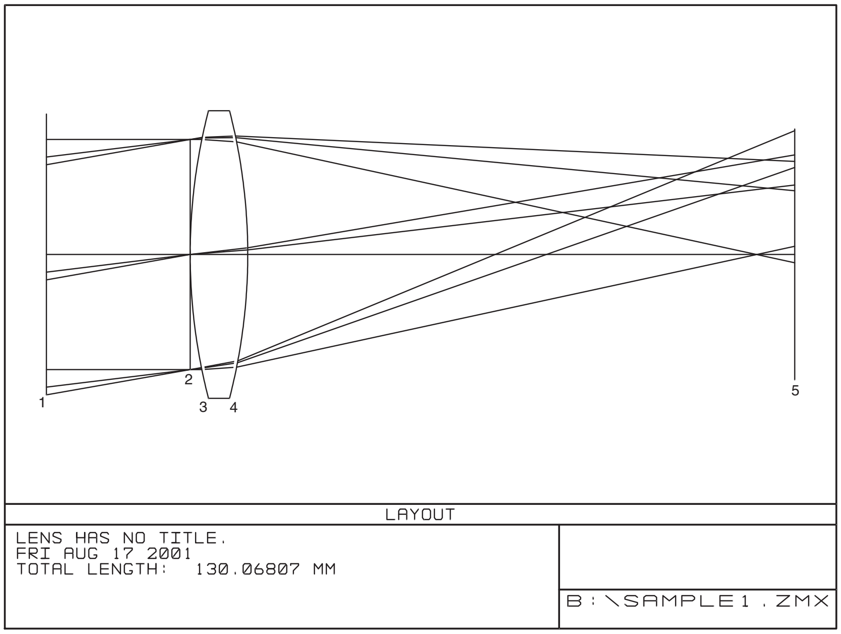


Fig. 2.3 *Layout of example prescription of a biconvex lens.*

```
GENERAL LENS DATA:

Surfaces        :                5
Stop            :                2
System Aperture : Entrance Pupil Diameter = 40
Ray aiming      : Off
Apodization     :Uniform, factor =   0.00000E+000
Eff. Focal Len. :        98.42156 (in air)
Eff. Focal Len. :        98.42156 (in image space)
Back Focal Len. :        95.06807
Total Track     :        130.0681
Image Space F/# :        2.460539
Para. Wrkng F/# :        2.460539
Working F/#     :        2.361136
Image Space N.A.:        0.203207
Obj. Space N.A. :          2e-009
Stop Radius     :              20
Parax. Ima. Hgt.:               0
Parax. Mag.     :               0
Entr. Pup. Dia. :              40
Entr. Pup. Pos. :              25
Exit Pupil Dia. :        41.41099
Exit Pupil Pos. :       -101.8934
Field Type      : Angle in degrees
Maximum Field   :              10
Primary Wave    :           0.587
Lens Units      :   Millimeters
Angular Mag.    :               0
```

Fig. 2.4 *List of system level first-order properties.*

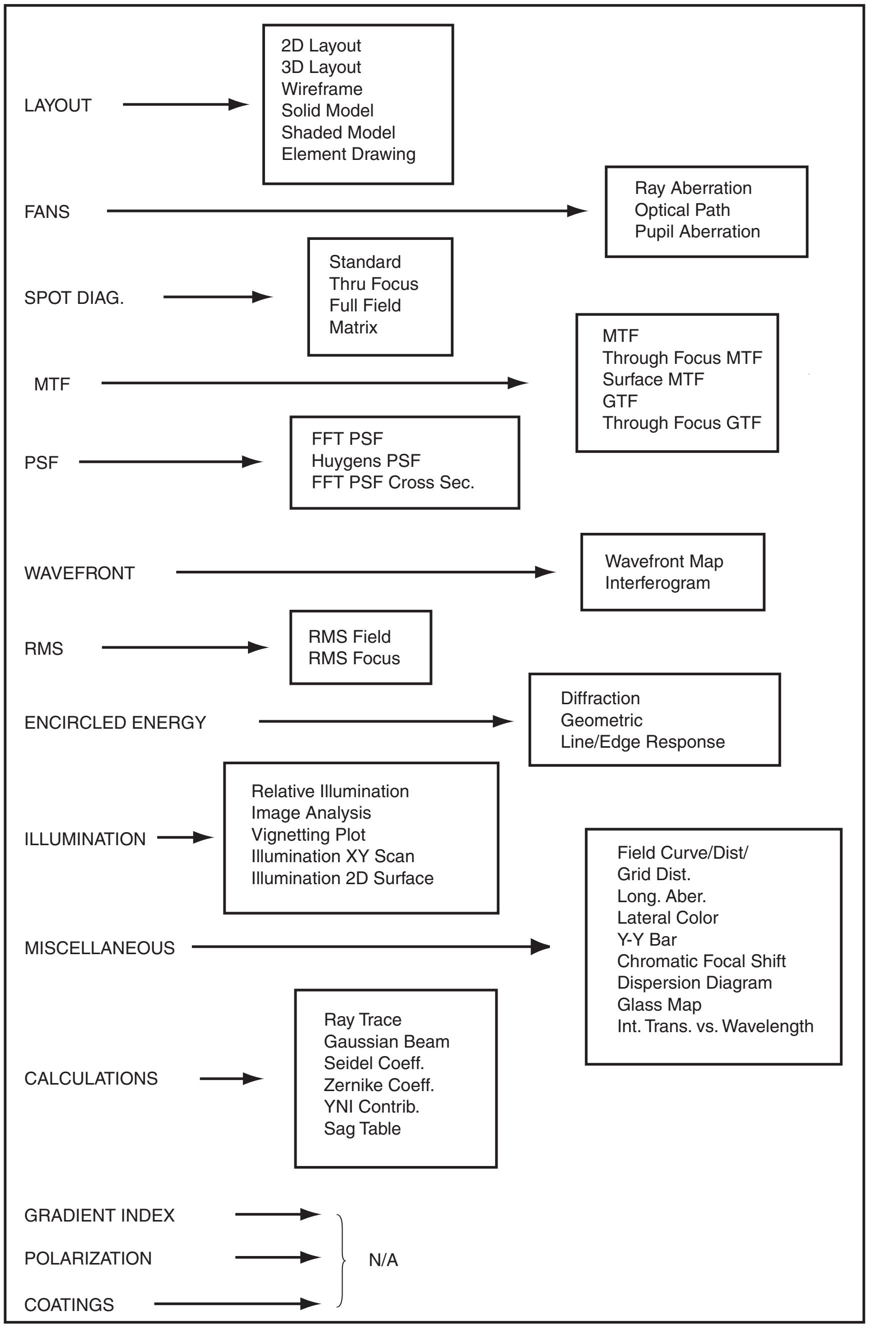


Fig. 2.5 *List of analysis options in ZEMAX.*

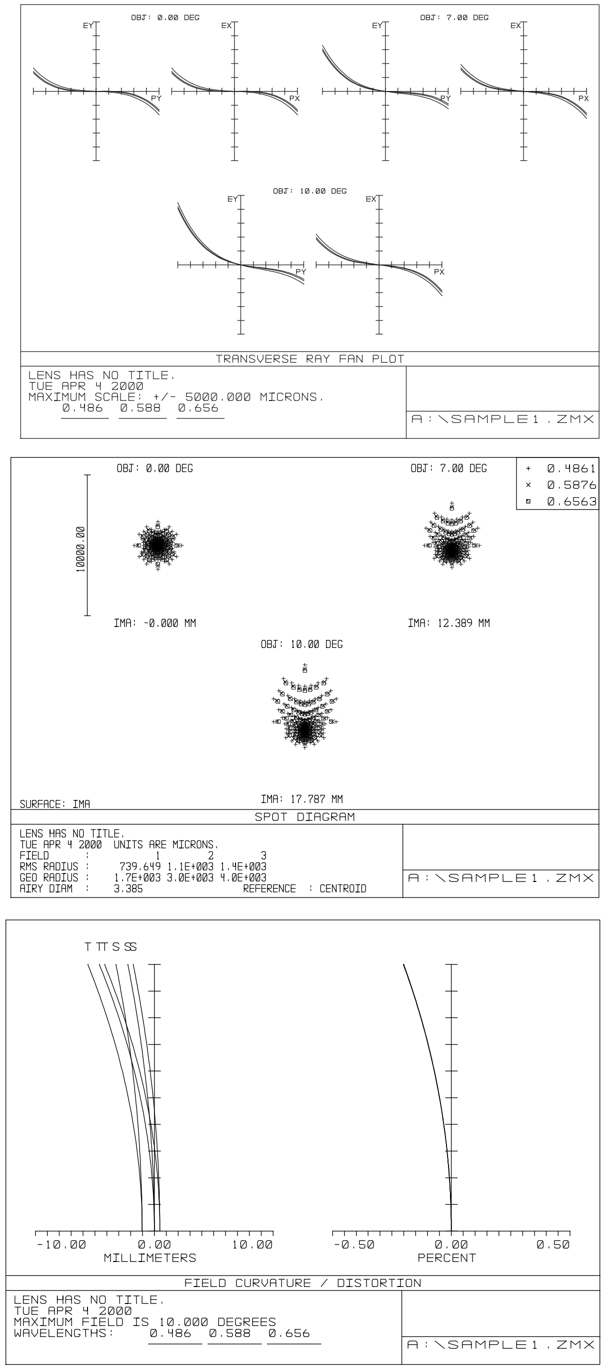


Fig. 2.6 *Illustration of several plot options.*

layout and nothing more. The image plane designated in the plot is where the paraxial marginal ray height is zero (defined by the M-solve). The back focal length is found in the LDE in the thickness column on Surface 4 and is 95.068 mm.

2.4 First Order Properties

We are left with the question, "What is the effective focal length (EFL) and f-number of the system?" To find out what these are as well as other first order properties, click on the Sys button. This will bring up a chart with all the system information listed as shown in Figure 2.4. We see that the EFL is 98.42 mm. The total track = 130.07 mm and is the sum of thicknesses as measured from the first surface to the image plane. Note that there are three f-numbers listed. The first, image space f-number, is *f*/2.46 or EFL divided by EPD (object at infinity). The others will be discussed in Section 2.8.

2.5 Analysis

At the main menu, clicking on Analysis provides the user with options for calculations, plots and graphs that cover nearly every aspect of design analysis. What is available is summarized in Figure 2.5.

For example, to find ray trace information, click on Calculations. Another menu box will appear to the right. Click on Ray Trace. Information on the marginal ray for both the real and paraxial rays is then displayed. Ray selection can be made by clicking on Settings. You can choose the object point's field location (H) and the ray pierce location in the entrance pupil (ρ). Both are given in normalized coordinates; i.e., they have values between 0 and 1.The more frequently used analysis plot options can be accessed either through Analysis or by using the buttons Ray, Opd, Spt, and Mtf. As an example, Figure 2.6 shows ray fan, spot diagram, and field curvature and distortion plots.

2.6 Keeping Track of Designs

In the heat of doing battle with aberrations, many different things are tried to optimize a design. It is very easy to lose track of how you got to a certain point. Therefore, documentation of each step of your design process is extremely important. This documentation should include not only what variables were manipulated and what merit function structure was used, but also the step-by-step file names. For this course, all design homework will be handed in on a 3.5″ floppy disk. The following character file name protocol will be used:

- the first four characters will be letters which will identify the type of system with which we are working;
- the fifth character will be a number (1–9) which will either identify separate designs within the same type or different optimization approaches for the same design problem;

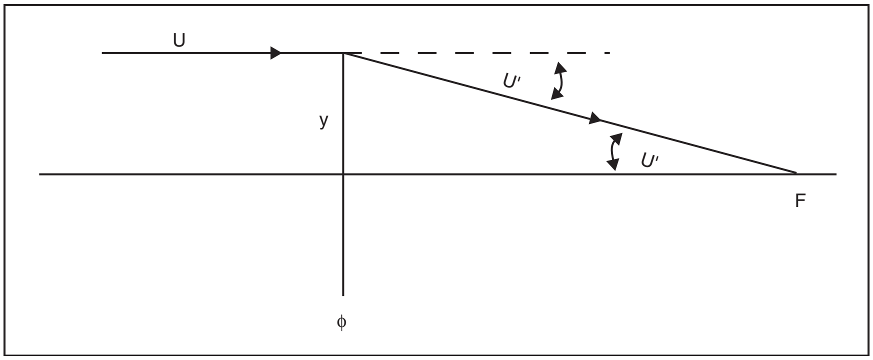


Fig. 2.7 *How f-number is related to image space U′.*

- the sixth character will always be the letter o which stands for the optimization path;
- the next character(s) will be a number which designates a particular step in the optimization path;
- the last character will be either the letter b or a, indicating the condition of the design *before* and *after* the optimization step.

For example, TRIP2o4b indicates a second triplet design at the fourth step of the optimization process just prior to the new optimization run. It is also recommended that each design problem be kept in a separately named folder. For example, the folder containing TRIP2o4b would be called "Triplet."

The naming protocol also serves another important and practical function. It allows the instructor to keep his sanity. It is much easier to grade homework when every student follows the same protocol. When homework is handed in on disk, a script should accompany it. The script should describe what is being done at each optimization step. An example of scripting will be found in your second homework assignment (in Chapter 3). All subsequent ZEMAX assignments should be scripted in a similar manner.

2.7 ZEMAX Glass Catalog

When you insert data under the parameter heading Glass in the LDE you will usually do so using a designation supplied by the manufacturer, e.g., Schott, Ohara, or Corning. ZEMAX has a library of glass designations in folders identified by the company name. Different folders are accessed by ZEMAX *only* when the manufacturer is identified in the Gen menu. There is also a folder which contains commonly used IR transmissive materials such as zinc selenide. Finally, there is a miscellaneous folder that is a mixed bag of different materials including air, water, and plastics.

Glass in ZEMAX is *not* stored as a refractive index versus wavelength lookup table. Rather, glass is stored as a polynomial function; it is the first six coefficients of this polynomial that are stored. If you click on the Gla button, the glass catalog menu will appear. The coefficients for any particular glass are represented by the numbers just to the right of the A0–A5 alpha-numerics. ZEMAX uses these coefficients to calculate the refractive index at any selected wavelength within the valid domain of the polynomial. Of course these coefficients are based on a polynomial fit to *measured* data over a certain spectral range.

The ZEMAX glass catalog provides explicit index data only for "*d*" light (λ = 587 nm). If you want to find out what the indices are for the wavelengths you have selected, you must click on Pre → Settings → Index Data → OK.

2.8 Odds and Ends

2.8.1 More on f-number

We saw that there are three distinct f-numbers shown in ZEMAX's General Lens Data list. The traditional f-number is given by the "image space f-number." What about the other two? Consider a ray parallel to the optical axis incident on a thin singlet at a height *y* as shown in Figure 2.7.

$$\text{image space f-number: } f/\# = \frac{\text{EFL}}{\text{EPD}} \tag{2.1}$$

$$f/\# = \frac{\text{EFL}}{2y} \tag{2.2}$$

$$f/\# = \frac{1}{2y/\text{EFL}} \tag{2.3}$$

$$\text{paraxial working } f/\# = \frac{1}{2\tan U'} \tag{2.4}$$

Here we see that f-number is related to the bend angle on the ray coming to a focus in image space. We'll call this the "paraxial working f-number." It will be the same as the "image space f-number" *only* when the object is at infinity. If the object is at some finite distance, then the bend angle U' will be different resulting in a different *effective* f-number.

The last f-number ZEMAX uses is called the "working f-number." It is defined as:

$$\text{working } f/\# = \frac{1}{2\sin U'} . \tag{2.5}$$

This f-number applies to real aberrated systems where U' departs from its ideal unaberrated path.

We will talk more about paraxial and real rays in Chapter 4.

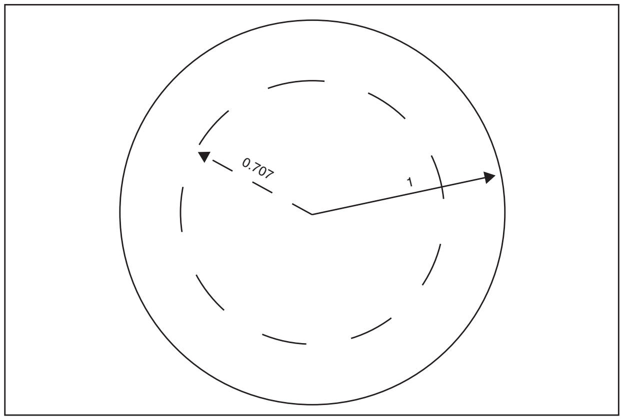


Fig. 2.8 *Zone selection for rays either in object field or in pupil.*

2.8.2 Ray Selection

Consider a unit circle as shown in Figure 2.8. Its area is 3.1416 units. What is the subradius that will enclose *half* this value?

$$\text{subradius} = \sqrt{\frac{3.1416}{2\pi}} = 0.7071 \tag{2.6}$$

The subradius 0.7071 divides the unit circle into two regions (an inner circle and an outer annulus) having the *same* area. There are two traditional applications of this in lens design and in ZEMAX. The first is in selecting where in a circular object field rays emanate; the second, where in the circular entrance pupil rays are incident. When we use the *default* merit function in ZEMAX to set up the ray ensemble for tracing through the system for optimization, you'll see that use is made of this subradius. Back in Section 2.2.2 we selected fields of 0°, 7.07°, and 10°. The middle value was not an arbitrary selection; it was 0.707 times the maximum field angle.

Chapter 3

Conventions and Aspheres

3.1 Introduction

In the last chapter you gained some familiarity with ZEMAX. In this chapter you will start using it. The problem assignment in Section 3.6 will walk you through an extensive exercise set involving the singlet from the first homework. Part of that exercise will involve bending the lens, while maintaining power, to minimize spherical aberration. You will also be using an aspheric surface to drive the spherical aberration to zero. Much of this chapter provides background material for this ZEMAX exercise.

3.2 Sign Conventions

The prescription information fed into ZEMAX and the data for manual calculations will follow a specific sign convention. Figure 3.1 will serve as a guide and reminder of those conventions. Radius of curvature, R, and curvature, C [= $1/R$], are positive if the center of curvature lies to the right of the surface vertex; negative if the center is to the left of the vertex. Shown in the figure are the front and rear principal planes. The former lies to the right of the first surface vertex and the separation (δ) is positive; the latter (δ') is negative. The effective focal length, f', (measured from the rear principle plane) is positive. The front focal length, f, is negative. The object distance (l), measured from the front principal plane, is negative. The image distance (l'), measured from the rear principal plane, is positive. A ray angle is positive if it has an upward slope; negative if downward.

3.3 Shape Factor

Figure 3.2 shows five lenses, all of which have the same focal length or power. The shape of the lens is defined by the shape factor, X. It is defined as:

$$X = \frac{(C_1 + C_2)}{(C_1 - C_2)} \tag{3.1}$$

An equi-biconvex lens has a zero shape factor. A plano-convex lens has a –1 shape factor while a convex-plano lens is +1. In the exercise, the lens shape will be

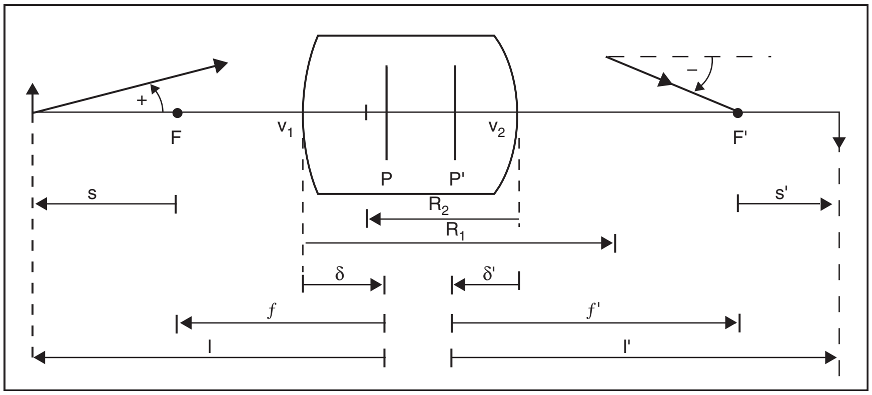


Fig. 3.1 *Sign conventions as used in this book.*

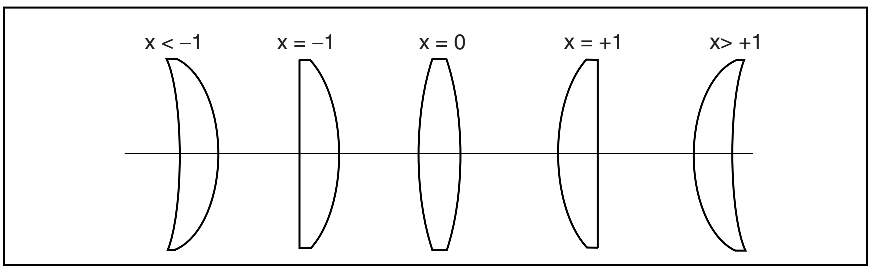


Fig. 3.2 *Lenses have identical power but different shapes.*

changed, and the amount of spherical aberration in image space will also change. Also note that the principal planes will shift position relative to the lens for different bendings.

3.4 Surface Sag

An important property of an optical surface is surface sag, which is illustrated in Figure 3.3. In optical shops, the radii of curvatures specified in your design will be verified by measuring their sags (using a device called a spherometer). Sag will also show up in our discussion on aspheric surfaces.

The exact definition of sag is:

$$\text{sag} = R - \sqrt{R^2 - y^2} \tag{3.2}$$

A convenient approximation is now derived. Rewriting Eq. 3.2:

$$\text{sag} = R - R\left[1 - \left(\frac{y}{R}\right)^2\right]^{\frac{1}{2}} \tag{3.3}$$

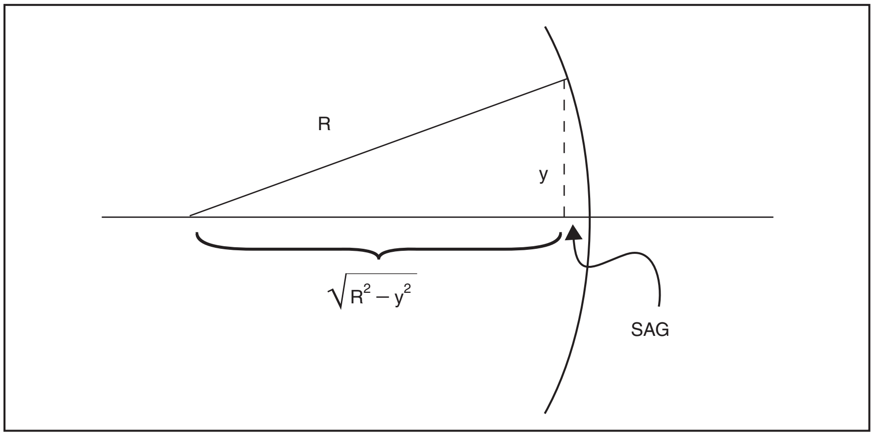


Fig. 3.3 *Illustration of surface sag.*

After taking a binomial expansion and keeping the first two terms:

$$\text{sag} \cong R - R\left[1 - \frac{y^2}{2R^2}\right] \tag{3.4}$$

$$\text{sag} \cong R - R + \frac{y^2}{2R}$$

$$\text{sag} \cong \frac{y^2}{2R} \tag{3.5}$$

Equation 3.5 is the parabolic approximation of the sag of a sphere.

3.5 Aspheric Surfaces

All of the optical surfaces we have dealt with thus far have been either flat or spherical. We must now enter the realm of aspherics. Such optics play a very important role in optical systems. For example, almost all reflective astronomical telescopes have at least one aspheric component, either on the primary or secondary. In most cases both components are aspheric. Closer to earth, the Kodak disc camera uses injection-molded glass elements, some of which are aspheric. The primary reason for using aspheric components is to eliminate spherical aberration (especially when there is a constraint on the number of optical surfaces and indices allowed). However, most designers still prefer to use spherical rather than aspherical surfaces. The reason has more to do with fabrication issues than anything else. Aspherics are much harder to make and measure. More time and skill are required of the optician and metrologist, thereby driving up costs. Consequently, the use of

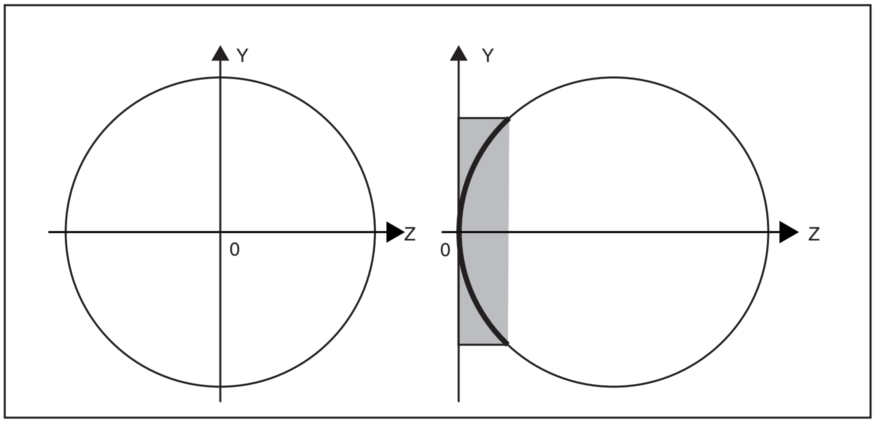


Fig. 3.4 *Unshifted and shifted circles.*

aspherics is limited to cases where (a) there is no other way, or (b) a trade-off study has shown it to be cost effective in the long run. Finally, it should be noted that the use of an aspheric does not change any of the first order design characteristics (cardinal points). All paraxial data remains the same.

The modification made to an optical surface designating it as aspheric is the presence of the conic constant. We will begin by deriving the standard form employed in geometrical optics. Consider the diagrams in Figure 3.4.

On the left we have a circle concentric with the origin of the coordinate system. The equation describing the circle is:

$$z^2 + y^2 = R^2 \tag{3.6}$$

Now we translate the coordinate system as shown on the right. The origin of the coordinate system is now coincident with the vertex of the optical surface. The equation for this translated circle is given by:

$$z^2 - 2zR + y^2 = 0 \tag{3.7}$$

The region of the surface we are interested in is the darkened arc passing through the vertex.

The equation describing a conic asphere is given by:

$$Pz^2 - 2zR + y^2 = 0 \tag{3.8}$$

where $P = 1 + K$, and $K = -e^2$, and e is the numerical eccentricity. (Note that $e^2 = (a^2 - b^2)/a^2$, where a is the semimajor, and b the semiminor axis of the conic respectively.) The conic constant is identified with P by some authors (Kingslake), and K by others (Malacara). One must be careful to ascertain which author is using which constant. This text uses K as does ZEMAX.

We now use the quadratic equation to solve Equation 3.8 for z (where

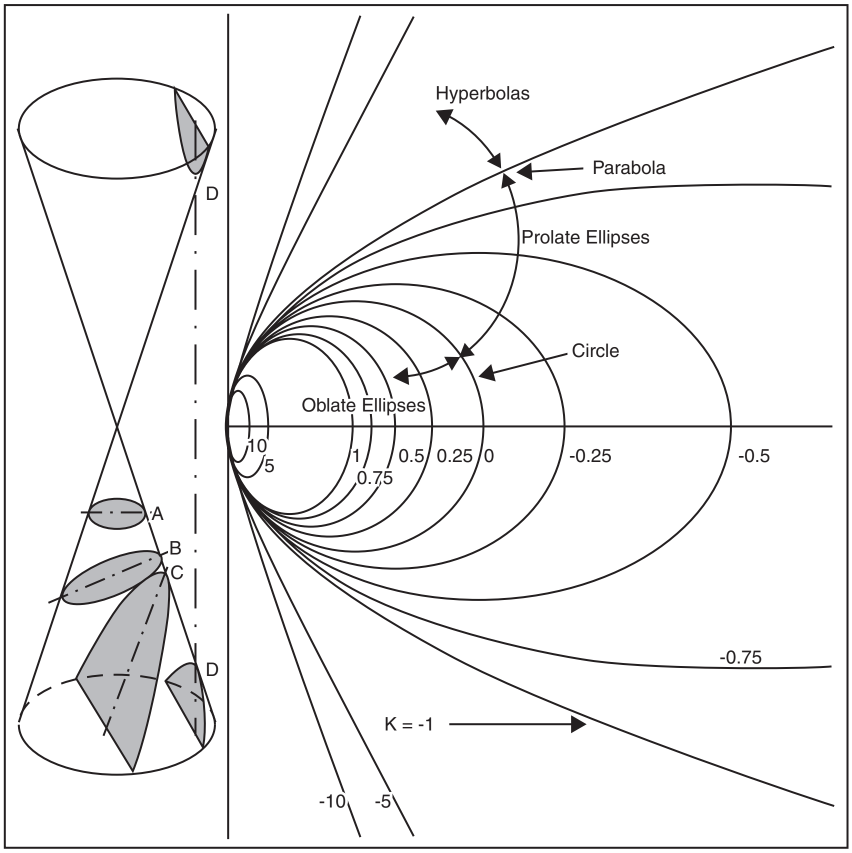


Fig. 3.5 *Various conic constants. Reprinted with permission from Rutten and van Venrooij,* Telescope Optics *(Willmann-Bell, 1988).*

$a = P$; $b = -2R$; $c = y^2$).

$$z = \frac{\left[2R \pm \sqrt{4R^2 - 4Py^2}\right]}{2P} \tag{3.9}$$

$$z = \frac{R \pm \sqrt{R^2 - Py^2}}{P}$$

Now select z_- (which makes $z \to 0$ when $y \to 0$).

$$z_- = \frac{R - R\sqrt{1 - P\left(\frac{y}{R}\right)^2}}{P}$$

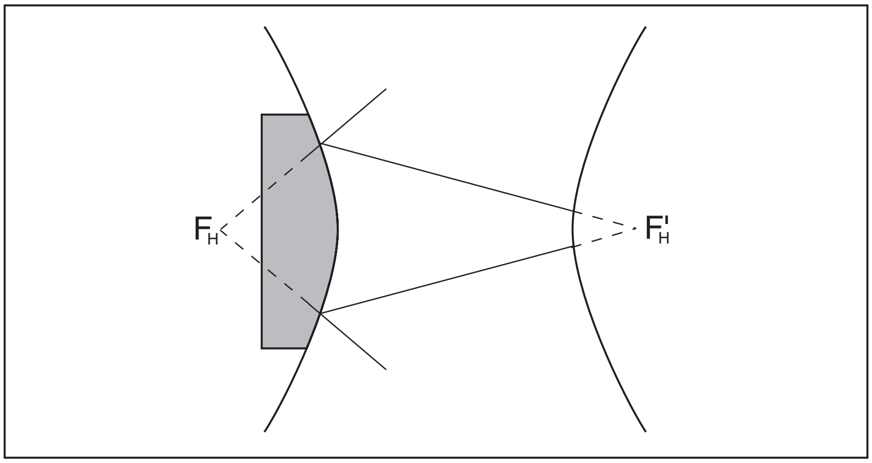


Fig. 3.6 *Ray behavior with hyperbolic surfaces.*

Table 3.1
Conic constant associated with different surface types.

Surface Type	**Conic constant (*K*)**	***P* = 1 + *K***
Circle	0	1
Parabola	–1	0
Hyperbola	< –1	< 0
Prolate Ellipse	–1 < K < 0	0 < P < 1
Oblate Ellipse	> 0	> 1

$$z_{-} = \left(\frac{R}{P}\right)\left[1 - \sqrt{1 - P\left(\frac{y}{R}\right)^2}\right] \quad \textbf{(3.10)}$$

Using the binomial expansion on the square root, and letting z_A replace z_{-}:

$$z_A \sim \left(\frac{R}{P}\right)\left\{1 - \left[1 - \left(\frac{P}{2}\right)\left(\frac{y}{R}\right)^2 - \left(\frac{P^2}{8}\right)\left(\frac{y}{R}\right)^4 - \left(\frac{P^3}{16}\right)\left(\frac{y}{R}\right)^6 - \text{etc.}\right]\right\} \quad \textbf{(3.11)}$$

$$z_A \sim \frac{y^2}{2R} + \left(\frac{P}{8}\right)\left(\frac{y^4}{R^3}\right) + \left(\frac{P^2}{16}\right)\left(\frac{y^6}{R^5}\right) + \left(\frac{5P^3}{128}\right)\left(\frac{y^8}{R^7}\right) + \text{etc.} \quad \textbf{(3.12)}$$

Note that the first term is simply the approximate sag of a spherical surface (as per Equation 3.5). The higher order terms represent the aparabolic departure. The particular aspheric associated with various values of the conic constant are shown in Figure 3.5 and tabulated in Table 3.1.

The image of very distant source (e.g., a star) contains spherical aberration

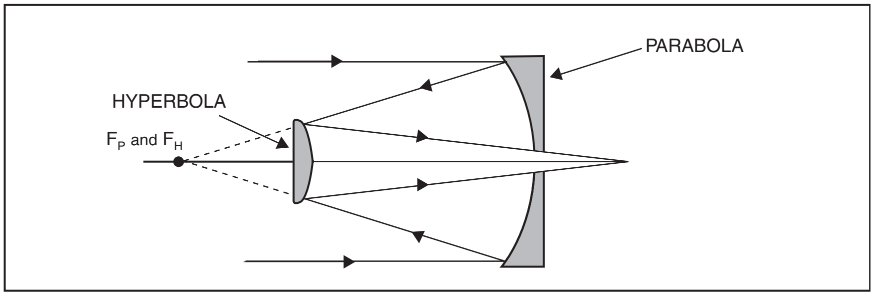


Fig. 3.7 *Cassegrain telescope.*

when its light is reflected from a spherical mirror. This reduces the detail in the image. A parabolic mirror, on the other hand, introduces no spherical aberration. Imagery is sharper. In the classical Cassegrain telescope, the primary mirror is parabolic. The secondary mirror is also aspheric and hyperbolic. A hyperbola has two foci. As illustrated in Figure 3.6, a ray directed toward the focus behind a hyperbolic reflector will be redirected toward the primed focus. In the Cassegrain telescope configuration, the parabolic focus coincides with the hyperbolic focus F_H as shown in Figure 3.7.

3.6 Departure From Sphere

As a designer you must have a good feel for the manufacturability and metrology of your optics. It may be the best diffraction-limited design ever—but if it can not be built what's the point. Also, it may prove difficult, or impossible, to align and test. Meeting spec is not the only criteria of a good design. Consequently, when aspherics are employed, be mindful of the fabrication and testing issues that arise, as well as the added costs and increased delivery times such surfaces usually entail.

When discussing an aspheric design with people in the optics shop, be prepared to provide information on how far the aspheric surface departs from a spherical surface at full aperture (or marginal ray height). This is illustrated in Figure 3.8.

The mathematical description of a spherical surface, Equation 3.7, can be recast into an expansion as was done for the aspheric surface in Equation 3.12. (The form can be quickly obtained by setting $P = 1$ in Equation 3.12.)

$$z_s \sim \frac{y^2}{2R} + \frac{1}{8}\left(\frac{y^4}{R^3}\right) + \frac{1}{16}\left(\frac{y^6}{r^5}\right) + \frac{5}{128}\left(\frac{y^8}{R^7}\right) + \text{etc.} \tag{3.13}$$

Of interest is the difference between Equation 3.13 and Equation 3.12 which, is the departure from sphere:

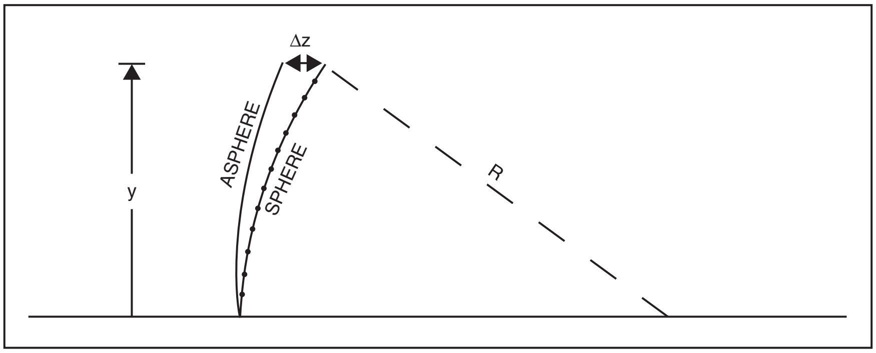


Fig. 3.8 *Departure from sphere.*

$$\Delta z = z_A - z_s \tag{3.14}$$

$$\Delta z \sim \left(\frac{1}{8}\right)(P-1)\left(\frac{y^4}{R^3}\right) + \left(\frac{1}{16}\right)(P^2-1)\left(\frac{y^6}{R^5}\right) + \left(\frac{5}{128}\right)(P^3-1)\left(\frac{y^8}{R^7}\right) + \text{etc.} \tag{3.15}$$

As an example, let's find Δz for a 31.25 cm focal length $f/1.25$ parabola. This means that the parameter values used in Equation 3.15 are: $P = 0$; $y = 12.5$ cm; $R = 62.5$ cm. Calculating the first two terms in Equation 3.15:

$$\Delta z = -0.0125 - 0.00025$$

$$\Delta z = -0.01275 \text{ cm} = -127.5 \text{ microns} = -201\lambda \text{ (for } \lambda = 0.6328\text{)}$$

This is a significant departure from sphere and means that a null lens (Chapter 35) would have to be designed to test this parabola interferometrically at its center of curvature.

3.7 Homework

This exercise consists of 11 parts. Its purpose is to give you some initial experience in the use of ZEMAX as a design and analysis tool. You will also start learning how to select variables and build a merit function for optimization. You will start by entering the lens used in the Homework for Chapter 1 and the radii calculated there. Use the same wavelength and dimensional unit (namely mm). Also, use the M-solve on the thickness after the second lens surface. Surface No.1 will be the first glass surface of the lens. (So initially you will have lines OBJ, STO [which is surf no.1], 2, and IMA.) The merit function editor (MFE) is accessed by clicking on Editors → Merit Function. Get in the habit of inserting all the Seidel operands as a means of keeping track of their values. (While on the first operand row, hit Insert several times for more rows to appear.) Whether operands are used in the optimization will be determined by the number under the weight column (keep moving cursor to right until you see the Weight, Value, and % Contribution

Table 3.2
Initial MFE

Operand	Target	Weight
EFFL	400	0
SPHA	0	0
COMA	0	0
ASTI	0	0
DIST	0	0
PETC	0	0
BLNK		

column headings). Initially your MFE should look like Table 3.2.

Currently, all operands in the above table are turned off. The EFL and Seidels will be computed for wavelength 1 (the only one we're using). Insert 1 under the wavelength column for all operands.

3.7.1 Singlet

1. Load the lens from Homework for Chapter 1. That was a thin lens computation. Now use a real thickness: 4 mm. Field angles are: 0°, 3.5°, 5°, and λ = 0.587. Units are mm. Put M-solve on thickness of the second glass surface.

   SING1o1b

   Note: EFL and f-number are not quite the paraxial values. This is due to the insertion of real thickness.

2. Use f-number solve on R_2 to tweak back to paraxial.

   Double click (DC) on R_2

   Select f-number

   Insert 10

   SING1o1a

   Check out spherical aberration: look at the ray fan plot; spot diagram; Seidel value.

3. Bend lens to reduce spherical. Remove F-solve on R_2. (DC on R_2, select variable). Make R_1 variable.

	Oper	T	W
	Oper	T	W
Go to MFE:	EFFL	400	1
	SPHA	0	1

   SING1o2b → OPT → SING1o2a

   Note: SPHA has dropped from 1.716 to 1.09λ!

4. Go back to SING1o1a. Remove F-solve on R_2. Variables on R_1 and R_2.

	Oper	T	W
Go to MFE:	EFFL	400	1
	COMA	0	1

SING1o3b → OPT → SING1o3a

Note: coma has dropped from – 4.88λ to 0.

5. Go back to SING1o1a. Remove F-solve on R_2. Variables on R_1 and R_2 .

	Oper	T	W
Go to MFE:	EFFL	400	1
	ASTI	0	1

SING1o4b → OPT → SING1o4a

Note: ASTI has dropped from 6.40λ to 0λ

SPHA increased to 325λ

COMA increased to –68λ

Look at layout—this lens is unusable.

6. Go back to SING1o2b. Remove variables on R_1 and R_2. Place variable on *conic constant* of surf no. 2.

SING1o5b → OPT → SING1o5a

Note: SPHA is 0 without affecting coma or astigmatism.

7. Go back to SING1o2b. Set field to zero (this is important.). Go to MFE. Set weight on SPHA to 0. Go to the BLNK surface below all the other operands. Set cursor on BLNK. Go to:

Tools → Default Merit Function → RMS/Spot Radius/Centroid → OK

TRAC will now show up in MFE.

SING1o6b → OPT → SING1o6a

Note: SPHA 1.716 → 1.09λ!

8. Start with SING1o6a. Remove variables on radii. Insert surf no.3. This will be a dummy surface. Put a variable on its thickness. Change semi-diam on surf no. 3 and IMA to 2.

SING1o7b → OPT → SING1o7a

What this does is SHIFT our dummy plane to find the “BEST RMS FOCUS” location. This should be about – 0.682. Use Zoom on Layout to look at image region more closely.

9. Start with SING1o7a. Restore 3.5° and 5° fields. Put variables on R_1 and R_2. Go to MFE:

Tools → Default Merit Function → OK

This adds more TRAC terms to account for off-axis field points. Now we want to find the best RMS spot size compromise over *entire* field.

SING1o8b → OPT → SING1o8a

The shift should be about – 2.7.

10. Start with SING1o8a. Add lens thickness as a variable.

SING1o9b → OPT → SING1o9a

Note that the lens is thicker. Astigmatism is considerably improved. Spherical and coma have gone up a bit.

11. Such a thick lens is impractical. If lens thickness is to be used as a variable, we must put constraints on it. The operands used for this are:

MNCG minimum center glass thickness

MXCG maximum center glass thickness

Go back to SING1o9b. Insert two lines between PETC and the first TRAC line in the MFE.

	Surf no.	Surf no.	T	W
MNCG	1	2	3.0	1
MXCG	1	2	10.0	1

SING1o10b → OPT → SING1o10a

Spherical is better. So is coma. Not much happened to astigmatism.