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Optical System Design

SECOND EDITION

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Optical System Design

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Second Edition



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CHAPTER 7

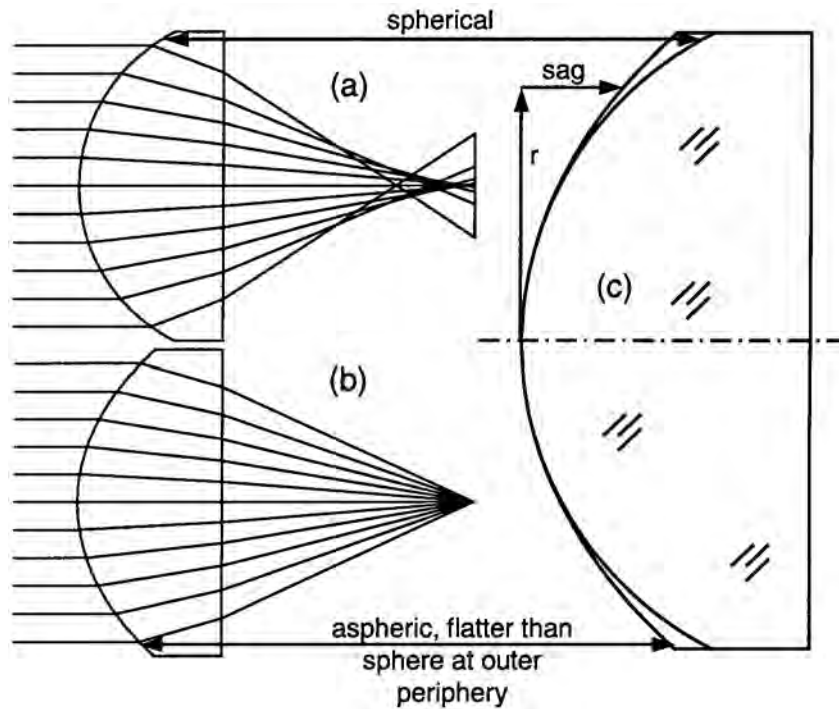
Spherical and Aspheric Surfaces

Definition of an Aspheric Surface

A *spherical* surface is defined by only one parameter, the radius or curvature of the surface. If the surface is refractive, with different indices of refraction before and after the surface, then the power of the surface is defined by the surface radius and the indices of refraction of the two media. *Radius* and *curvature* are reciprocal to one another.

Figure 7.1a shows a plano convex lens element with a spherical radius, imaging an axial point from infinity. The spherical aberration is quite evident. The high angle of incidence of the upper limiting ray of approximately 45° to the surface normal causes this ray to refract very strongly and ultimately to cross the axis significantly closer to the lens than rays closer to the optical axis. A spherical surface has the property that the rate of change of the surface slope is exactly the same everywhere on the surface, and thus the aberration is inevitable. Let us consider reducing the slope of the surface toward the outer periphery of the surface in order to flatten the shape in the region surrounding the outer rays. If we make the surface shape gradually flatter as we proceed outward from the optical axis, we can differentially reduce the refracting ray angle so that the net effect is to bring all of the rays to a common focus position, as shown in Fig. 7.1b. Figure 7.1c compares the spherical surface, which is steeper at its edge, with the aspheric surface, which is flatter at its edge. While correction of spherical aberration is not the only application of aspheric surfaces, it is one of the major application areas.

Figure 7.1
Comparison of a
Spherical and an
Aspheric Lens



Aspheric surfaces cannot be defined with only one curvature over the entire surface because its localized curvature changes across the surface. An aspheric surface is usually defined by an analytical formula, but sometimes it is given in the form of a sag table for coordinate points across the surface. The sag of a surface is shown in Fig. 7.1. The most common form of an aspheric surface is a rotationally symmetric surface with the sag defined as

$$z = \frac{c r^2}{1 + \sqrt{1 - (1 + k)c^2 r^2}} + \sum a_i r^{2i}$$

where c is the base curvature at the vertex, k is a conic constant, r is the radial coordinate measured perpendicularly from the optical axis, and $a_i r^{2i}$ are the higher-order aspheric terms.

When an aspheric surface is not rotationally symmetric, it is given either as a *biconic* surface with two basic curvatures and two conic constants in two orthogonal directions or as an *anamorphic asphere*, which has additional higher-order terms in two orthogonal directions.

Another form of aspheric surface is a *toroid* or *toric*. A toroid has, in effect, the shape of a doughnut. If a doughnut were sitting on the table, we all would agree that it had a basic outer diameter. If we now cut the doughnut vertically into two halves and we look at the cut, we see a circle whose diameter is less than the diameter by perhaps a factor of 5 or thereabouts. These two radii define a toroid, the overall outer radius of the doughnut and the smaller cross-sectional radius. If you work with torics in lens design, it is extremely important that you understand fully and completely the definition used by the computer program you are using, so take the time to study the manual in depth in this regard. In addition, if need be, set up a sample to assure that your understanding is correct. While a doughnut is one form of toroid, a football shape is another, and it is imperative to understand which one your equation is representing, especially if it is to be manufactured.

Conic Surfaces

In the case where the higher-order aspheric terms are zero, the aspheric surface takes the form of a rotationally symmetric conic cross section with the sag defined as

$$z = \frac{c r^2}{1 + \sqrt{1 - (1 + k)c^2 r^2}}$$

where c is the base curvature at the vertex, k is a conic constant, and r is the radial coordinate of the point on the surface. In Table 7.1, it is shown how a conic surface takes on the following surface types as a function of the conic constant, k , in the sag equation.

TABLE 7.1

Conic Section
Types

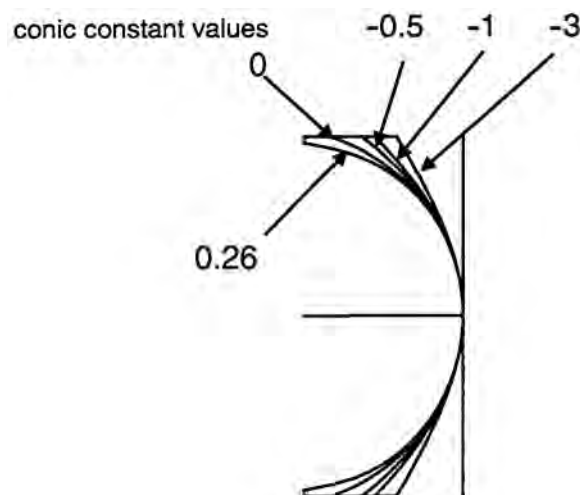
Conic Constant k	Surface Type
0	Sphere
$k < -1$	Hyperboloid
$k = -1$	Paraboloid
$-1 < k < 0$	Ellipsoid
$k > 0$	Oblate ellipsoid

Figure 7.2 shows five surfaces having different conic constants but the same curvature. Most of us are generally familiar with the surface shapes described. One surface we do not come across often is the oblate ellipsoid, sometimes called the oblate spheroid. This can be thought of as the shape of the Earth as it rotates about its axis. Due to centrifugal force, the diameter is greater at the equator than in the polar direction. The oblate ellipsoid has its foci orthogonal to the optical axis.

Conic surfaces, either reflective or refractive, are free of spherical aberration for one particular set of conjugate points. Let us look into a set of different conic surfaces. A spherical surface forms an aberration-free image if the object is at the center of curvature of the surface. An ellipsoid forms an aberration-free image for a pair of real image conjugates on the same side of the surface and a hyperboloid for conjugates on two different sides of the surface. A parabolic mirror forms a perfect image of a point for an axial object at infinity. This is the reason why parabolic mirrors (sometimes combined with hyperbolic mirrors) are widely used in astronomical optics.

When the object point is moved axially from the position of the aberration-free conjugate, a certain amount of spherical aberration is introduced. If the point is moved laterally, other aberrations, such as coma, astigmatism, and field curvature, contribute to image blurring.

Figure 7.2
Conic Surfaces with
the Same Curvature
and Different Conic
Constants



Application of Aspheric Surfaces in Reflective and Refractive Systems

Aspheric surfaces are widely used and often essential in reflective systems due to the small number of surfaces and typically large apertures. While a complex lens may consist of 18 spherical radii in order to minimize the aberrations, a reflective system can only have two surfaces in most cases. A simple spherical reflecting telescope suffers from spherical aberration and coma. A spherical mirror is shown in Fig. 7.3a. A point object at infinity is focused by the spherical mirror at a distance from the mirror equal to the one-half of the mirror radius, and this distance is the focal length. Third-order spherical aberration results, and the wavefront error or OPD is proportional to the (aperture)⁴, as described in Chap. 5.

A parabolic reflecting telescope is shown in Fig. 7.3b. This is a classic example of how spherical aberration can be corrected. An infinitely distant axial point is imaged to a perfect aberration-free image point. Unfortunately, the image quality degrades quickly when the object is moved off axis. Coma is the aberration that restricts the field of view of the parabolic telescope to a very small field.

A very common form of reflecting telescope is the two-mirror *Cassegrain* telescope, with both mirrors being conic surfaces. The *classical Cassegrain* telescope has a paraboloidal primary mirror and a hyperboloidal secondary mirror, as shown in Fig. 7.4. f_1 is the location of the

Figure 7.3
Conic Surfaces for
Reflecting Systems

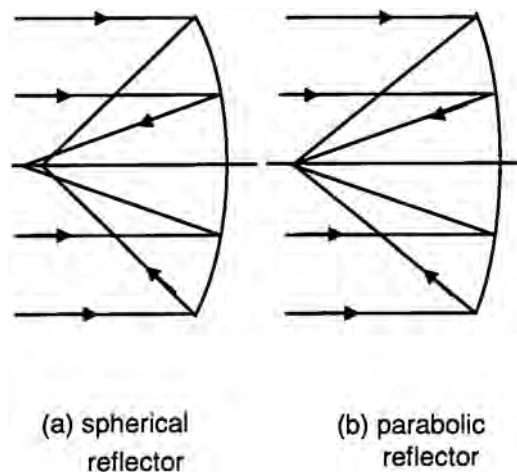


Figure 7.4
Cassegrain Telescope

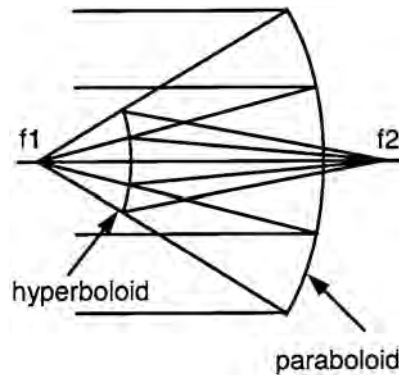
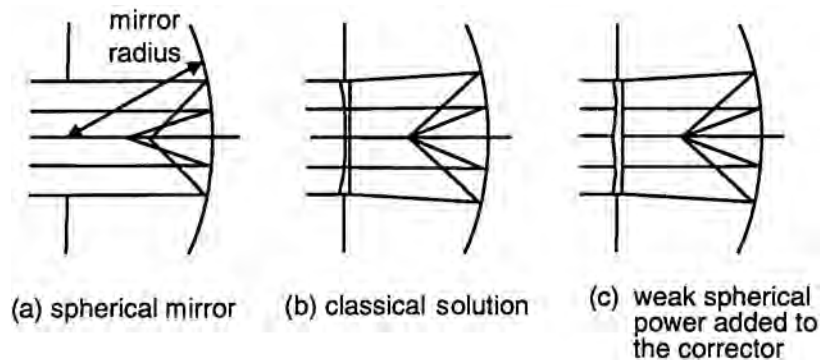


image which would be formed by the large primary mirror, and f_2 is the location of the image of the entire system. Note that the secondary mirror reimages f_1 to f_2 . A similar configuration, called a *Ritchey-Chrétien* Cassegrain telescope, has both primary and the secondary hyperbolic mirrors. The classical Cassegrain performance is limited by off-axis coma while the Ritchey-Chrétien Cassegrain is, in effect, a coma-free Cassegrain. Its limiting aberration is astigmatism.

Another well-known type of telescope is a Schmidt telescope, which is shown in Fig. 7.5. It consists of a spherical mirror with an aspheric corrector plate located at the center of curvature of the mirror. Third-order spherical aberration results in a wavefront aberration function proportional to the (aperture)⁴. If the aperture stop is located at the center of curvature of the mirror, there is symmetry for all field positions. Apart from the aperture stop being obliquely viewed by the

Figure 7.5
Schmidt Telescope



oblique bundle of off-axis rays, the oblique rays are focused in the same manner as the axial bundle. The chief ray is normally incident onto the mirror everywhere in the field of view. The image is formed on a spherical surface, with the image radius equal to one-half the mirror radius.

Without any aberration correction, the rays that are closer to the aperture edge are focused closer to the mirror than the paraxial rays. The wavefront distortion, which is proportional to the fourth power of the aperture radius, can be corrected with a wavefront distortion of the opposite sign introduced by the aspheric corrector plate placed in the aperture stop as in Fig. 7.5*b* to provide effective “parabolization” of the spherical mirror. A fourth-order aspheric deviation from the flat base surface of the glass corrector introduces a negative fourth-order wavefront distortion. The aspheric refractive corrector reduces the spherical aberration. However, some chromatic aberration is introduced by the wedged shape at the outer periphery of the corrector, close to the aperture edge. In order to minimize this chromatic aberration, a very weak positive power is added to the corrector, such that the corrector has zero power at 0.7 of its aperture, as shown in Fig. 7.5*c*. This shape of the corrector is not only the optimum shape for the correction of sphero-chromatism (the variation of spherical aberration with wavelength), it is also best suitable for manufacturing.

The majority of optical systems are based on the use of spherical components because they are easier to manufacture. However, there are cases where aspheric optical components have a significant advantage over spherical ones. In astronomical optics, reflective aspheric components are widely used. Today, with the significant development of new plastic materials, low-cost molded aspheric refractive optics are finding their place in the large consumer market. Precision diamond grinding and compression molding of glass aspheric lenses is also becoming more common.

Refractive aspheric lenses are widely used in many kinds of illumination systems, from the condensers in projection systems and microscopes, to street lamps and searchlights. Since in many cases these are not imaging systems, the manufacturing tolerances on these components are somewhat forgiving. In the case where the optical components are not exposed to the heat from the light source, aspheric optical elements can be injection molded. In projection systems, aspheric condensers are often molded glass lenses, mostly from B270 glass. B270 is a very common low-cost glass similar to BK7, which is used extensively in “float glass” for low-cost windows and mirrors. Glasses that are moldable have a

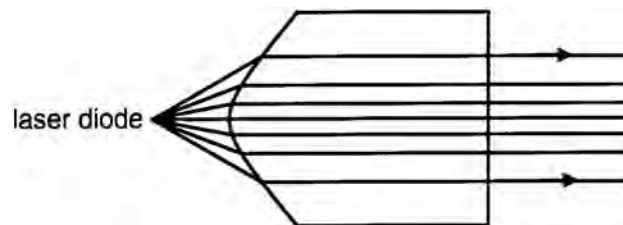
lower temperature at which they become soft than the standard optical glasses. Heat generated by the light source, or by the absorption of light by the optical components themselves, is often a severe problem in optical systems and requires the use of heat-resistant materials such as fused silica or fused quartz.

Another field where aspherics find their place is in systems for focusing of laser beams, for example, in CD players or data storage systems, when coupling light from a laser diode into a fiber, or when collimating light from laser diode arrays. These applications require high-precision optical components, as well as optically stable components in a given temperature range. The small size of these components makes them easier to mold. Optical plastics are used wherever they are acceptable, because of the much lower manufacturing costs. However, accurate lens shape and the very good temperature stability of glass aspheric lenses make them a better solution for applications where high precision is required. Glass aspheric lenses are manufacturable in diameters smaller than 25 mm. At diameters greater than 25 mm, aspheric glass lenses become too expensive for high-volume manufacturing. Single-glass bi-aspheric lenses are used for focusing or collimation of $NA = 0.5$ laser beams with diffraction-limited performance.

An infinitely distant object imaged through a planohyperbolic lens is focused to an aberration-free spot. This feature is used in the case of a planohyperbolic fiber lens (the cross section of the fiber has a planohyperbolic shape) to collimate the fast axis of the laser diode arrays, as shown in Fig. 7.6. The distance of the laser diode from the lens is determined by the index of refraction of the lens.

Improvements in the quality of injection-molded plastic optics make the use of them possible in camera lenses and projection lenses. The optical design of these kinds of lenses is difficult because many parameters have to be considered such as

Figure 7.6
A Planohyperbolic
Collimator



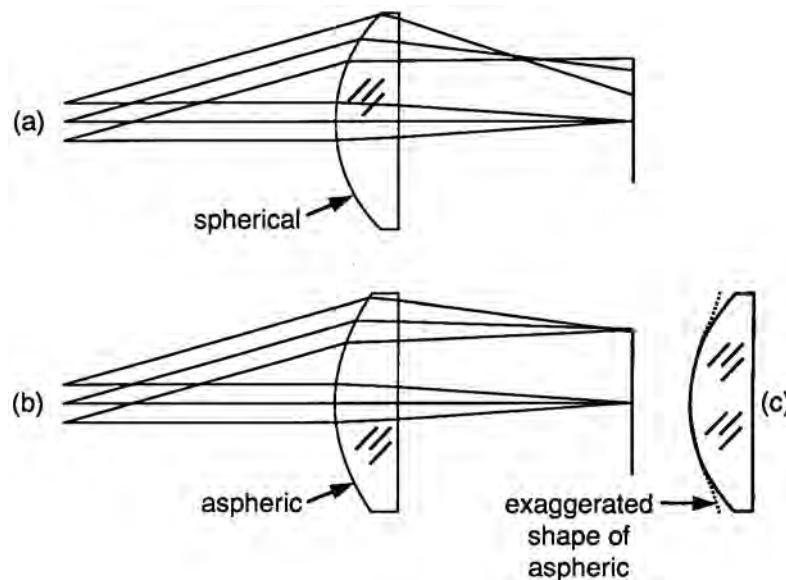
- The location of the component in the lens to minimize the beam size over the plastic component.
- The shape of the lens to keep the molding parting line inside the component.
- Athermalization of the lens.

In high-performance lenses, plastic components should be away from the aperture stop because it is very difficult to achieve diffraction-limited performance with injection-molded plastic components. However, they can be extremely useful in the correction of field aberrations such as astigmatism, field curvature, and also distortion.

Much of the discussion thus far with respect to aspheric surfaces and their benefits has related to the correction of spherical aberration. If an aspheric surface is located at or near the aperture stop of a system, it will primarily affect or benefit spherical aberration, which is an axial aberration which, for the most part, carries across the field of view. As aspheric surfaces are located further from the stop, they can help to minimize some or all of the off-axis aberrations such as coma and astigmatism.

A good example of the application of an aspheric surface used for astigmatism correction is shown in Fig. 7.7. In Fig. 7.7a, we see a single-element lens with its aperture stop located far to the left of the lens. If

Figure 7.7
Correction of Astigmatism with an Aspheric Surface



the curved lens surface is spherical, the oblique rays create a footprint on the surface, which is larger in the plane of the figure than the orthogonal plane in/out of the figure. As we discussed in Chap. 5, this tends to refract and pull the rays in the plane of the figure inward from where they would otherwise focus. We now need to ask ourselves what would it take to push the focus position outward and compensate for this inward focus shift. The answer is to create a more negatively powered surface in the plane of the figure at the outer periphery of the lens. This is shown in proper scale in Fig. 7.7*b* and in an exaggerated form in Fig. 7.7*c*. This more negatively powered surface shape in the plane of the figure has virtually no effect in the orthogonal plane, hence the highly efficient correction of astigmatism by the aspheric surface.

Another common use of aspherics is in the thermal infrared where the cost of materials is extremely high. With the use of aspherics, the number of elements can be reduced to a minimum.

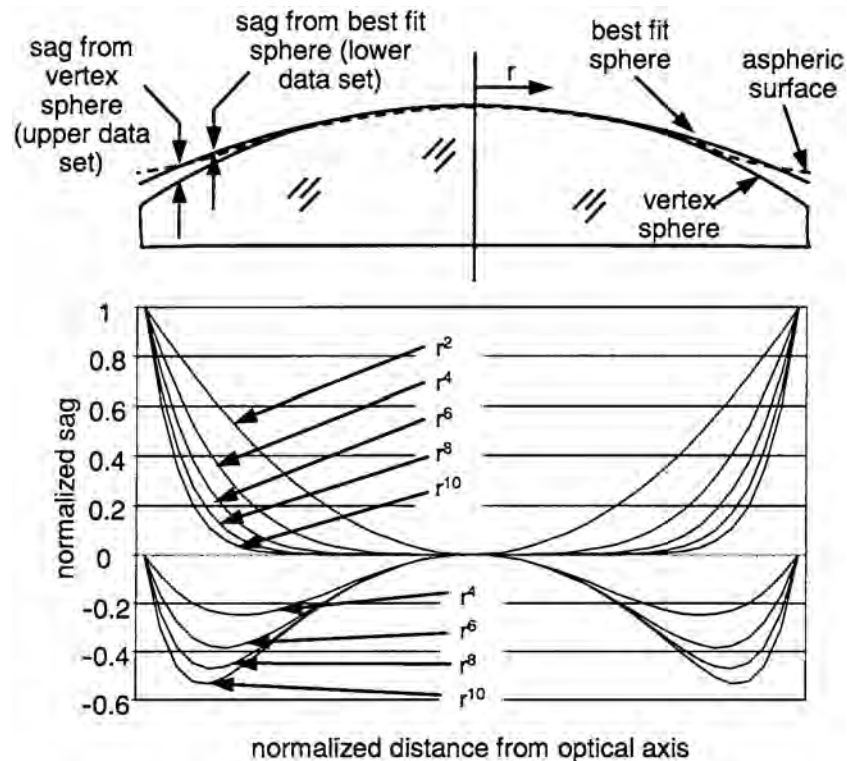
Guidelines in the Use of Aspheric Surfaces

The proper usage of aspheric surfaces is extremely important. This includes which surfaces to make aspheric and whether to use a conic section or, alternatively, a higher-order aspheric. The conic sections include paraboloids, hyperboloids, and ellipsoids, as discussed earlier in this chapter. The higher-order terms are surface departures from conic, which are proportional to r^4 , r^6 , r^8 , r^{10} , and so on, where r is the radial distance from the optical axis. The simpler forms of reflective systems, such as the classical Cassegrain (paraboloidal primary, hyperboloidal secondary) and the Ritchey-Chrétien Cassegrain (two hyperboloids), were discussed earlier. The classical Cassegrain is limited by coma and field curvature, and the Ritchey-Chrétien is, in effect, a coma-free Cassegrain which is limited by astigmatism and field curvature. Once the basic system is set up on your computer, varying the appropriate conic constants is all it takes to reach a viable solution.

But how do we decide which surface, or surfaces, in a lens system should be made aspheric, and how do we decide what form of aspheric to use? To answer this question, first consider Fig. 7.8, where we show: (1) the aspheric surface departures from the base spherical surface and (2) the departures from what we call the “nearest sphere” or “best-fit

Figure 7.8

Aspheric Sags from
Vertex Sphere (Top)
and Best-Fit Sphere
(Bottom)



sphere" to the aspheric surface. The nomenclature is shown in the top of Fig. 7.8 with accurate data below.

If we now compute for our baseline spherical optical system a plot of the optical path difference, we should look for a form matching the basic profile or character of these data. For example, if the axial OPD plot resembles the form of the sag from the nearest sphere for the r^6 case, then varying the r^6 coefficient on a surface near the aperture stop will likely be beneficial. If we find a sharp increase or decrease in the OPD off axis at the edge of the pupil, then varying a higher-order term or two on a surface away from the stop will likely be beneficial. There are some basic guidelines, and these are listed here:

1. Conic surfaces can be used for correcting third-order spherical aberration and other low-order aberrations.
2. If you have a nearly flat surface, then use an r^4 and higher-order terms rather than a conic.

3. If you have at least a somewhat curved surface, then you can use the conic along with higher-order terms if required.
4. It is generally best not to use both a conic and an r^4 surface, as they are mathematically quite similar. This is because the first term of the expansion of a conic is r^4 . While they can both literally be used, the optimization process often tends to beat one against the other, yielding artificially large coefficients, and this may have an effect on the convergence of the optimization.
5. Use aspherics beginning with the lower-order terms and working upward as required. If you can stay with conics, this may make testing more manageable. You should be able to assess the need for adding terms based on the character of the OPD plot.
6. It is very dangerous to use a large number of aspheric surfaces, especially with higher-order terms. This is because they will beat against each other. This means that as one surface adopts a certain aspheric profile or contour, it may increase in its asphericity, with its effect cancelled by adjacent surfaces. For example, if the first of two closely located aspheric surfaces has significant surface departure from sphericity, the neighboring aspheric surface could very likely cancel this effect. While the lens may perform well on paper, we now need to manufacture two highly aspheric surfaces, a difficult and expensive task which may not be necessary.
7. If possible, optimize your design first using spherical surfaces, and then use the conic and/or aspheric coefficients in the final stages of optimization. This may help in keeping the asphericities to a more manageable level.

Specification of Aspheric Surfaces

It is important to specify an aspheric surface sufficiently enough to convey to the shop both what you want and what you need. The following items are most often included in specifying aspheric surfaces:

1. The surface to be aspheric is labeled aspheric on the component drawing.
2. You should include an equation of the surface shape along with the aspheric coefficients. A small sketch indicating the nomenclature and sign convention is recommended.

3. A table listing the sag as a function of the radial distance from the surface vertex normal to the optical axis, r , is imperative. You should list a sufficient number of data points to adequately sample the surface profile.
4. You should list how close the actual surface must come to the ideal design prescription. The form of this can be “surface to match nominal surface to within four visible fringes (or 0.001 mm) over clear aperture.”
5. You may need to call out higher-frequency surface irregularities and/or surface finish. The higher-frequency irregularities can be called out by indicating the maximum slope departure from nominal over the surface. Surface finish is normally called out by indicating the rms surface finish, in nanometers. This latter callout is generally used for diamond-turned surfaces, where surface roughness is sometimes a problem or where scattering and off-axis rejection is of major concern such as in space telescopes.
6. You should, if possible, indicate the form of testing to be used.

Do keep in mind that the more callouts you list and the more extensive the testing, the more costly your optics will be, and they will likely take longer to manufacture. Your callouts should indicate only what you need functionally for your system to work properly.

CHAPTER 9

The Optical Design Process

The optical design process includes a myriad of tasks that the designer must perform and consider in the process of optimizing the performance of an imaging optical system. While we often think primarily of the robustness of the optimization algorithm, reduction of aberrations, and the like, there is much more to do. The designer must be at what we sometimes call “mental and technical equilibrium with the task at hand.” This means that he or she needs to be fully confident that all of the following are understood and under control:

- All first-order parameters and specifications such as magnification, focal length, f /number, full field of view, spectral band and relative weightings, and others.
- Assure that the optical performance is being met, including image quality, distortion, vignetting, and others.
- Assure that the packaging and other physical requirements, including the thermal environment, is being taken into account.
- Assure that the design is manufacturable at a reasonable cost based on a fabrication, assembly, and alignment tolerance analysis and performance error budget.
- Consider all possible problems such as polarization effects, including birefringence, coating feasibility, ghost images and stray light, and any other possible problems.

Once every one of these items has been addressed and is at least recognized and understood, we start with the sketch of the system. First, the system is divided into subsystems if possible, and the first-order parameters are determined for each subsystem. For example, if we are to design a telescope with a given magnification, the entrance pupil diameter should be chosen such that the exit pupil size matches the eye pupil. A focal length of the objective and the eyepiece should be chosen such that the eyepiece can have a sufficiently large eye relief. Now, when the specs for each subsystem are defined, it is time to use the computer-aided design algorithms and associated software to optimize the system, which will be discussed in the rest of this chapter. Each subsystem can be designed and optimized individually, and the modules joined together or, more often, some subsystems are optimized separately and some as an integral part of the whole system.

What Do We Do When We Optimize a Lens System?

Present-day computer hardware and software have significantly changed the process of lens design. A simple lens with several elements has nearly an infinite number of possible solutions. Each surface can take on an infinite number of specific radii, ranging from steeply curved concave, through flat, and on to steeply curved convex. There are a near infinite number of possible design permutations for even the simplest lenses. How does one optimize the performance with so many possible permutations? Computers have made what was once a tedious and time-consuming task at least manageable.

The essence of most lens design computer programs is as follows:

- First, the designer has to enter in the program the starting optical system. Then, each variable is changed a small amount, called an *increment*, and the effect to performance is then computed. For example, the first thickness may be changed by 0.05 mm as its increment. Once this increment in thickness is made, the overall performance, including image quality as well as physical constraints, are computed. The results are stored, and the second thickness is now changed by 0.05 mm and so on for all variables that the user has designated. Variables include radii, airspaces,

element thicknesses, glass refractive index, and Abbe number. If you are using aspheric or diffractive surfaces, then the appropriate coefficients are also variables.

- The measure of performance as used here is a quantitative characterization of the optical performance combined with a measure of how well the system meets its first-order constraints set by the user such as focal length, packaging constraints, center and edge thickness violations, and others. The result of the computation is a single number called an *error function* or *merit function*. The lower the number, the better the performance. One typical error function criteria is the rms blur radius, which, in effect, is the radius of a circle containing 68% of the energy. Other criteria include optical path difference, and even MTF, as described in Chap. 15.
- The result is a series of derivatives relating the change in performance (P) versus the change in the first variable (V_1), the change in performance (P) versus the change in the second variable (V_2), and so on. This takes on the following form:

$$\frac{\partial P}{\partial V_1}, \frac{\partial P}{\partial V_2}, \frac{\partial P}{\partial V_3}, \frac{\partial P}{\partial V_4} \dots$$

- This set of partial derivatives tells in which direction each parameter has to change to reduce the value of the sum of the squares of the performance residuals. This process of simultaneous parameter changes is repeated until an optimum solution is reached.

A lens system consists of a nearly infinite number of possible solutions in a highly multidimensional space, and it is the job of the designer to determine the optimum solution.

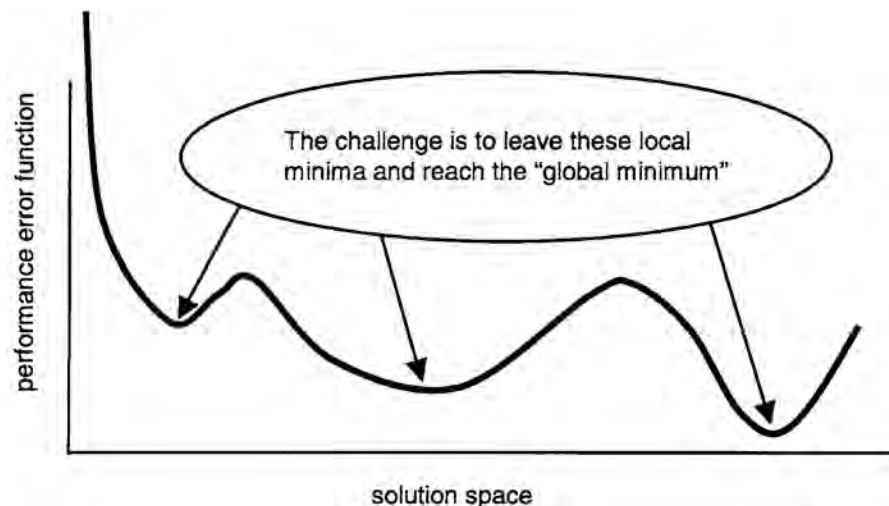
Designers have used the following analogy to describe just how a lens design program works:

- Assume that you cannot see and you are placed in a three-dimensional terrain with randomly changing hills and valleys. Your goal is to locate the lowest elevation or altitude, which in our analogy equates to the lowest error function or merit function. The lower the error function, the better the image quality, with the “goodness” of performance being inversely proportional to the elevation.
- You are given a stick about 2 m long, and you first stand in place and turn around tapping the stick on the ground trying to find which direction to walk so as to go down in elevation.

- Once you determine the azimuth resulting in the greatest drop in elevation, you step forward in that direction by 2 m.
- You now repeat this process until in every direction the elevation goes up or is level, in which case you have located the lowest elevation.
- But what if just over a nearby hill is an even lower valley than you are now in? How can you find this region of solution? You could use a longer stick, or you could step forward a distance several times as long as the length of your stick. If you knew that the derivative or slope downward is linear or at least will continue to proceed downward, this may be a viable approach. This is clearly a nontrivial mathematical problem for which many complex and innovative algorithms have been derived over the years. But the problem is so nontrivial as well as nonlinear that software algorithms to locate the so-called global minimum in the error function are still elusive. Needless to say, the true global minimum in the error function may be quite different or distant from the current location in our n -dimensional terrain.

Figure 9.1 shows a two-dimensional representation of solution space as discussed previously. The *ordinate* is the error function or merit function, which is a measure of image quality, and the *abscissa* is, in effect, solution space. We may initiate a design on the left and the initial

Figure 9.1
Illustration of Solution
Space in Lens Design



optimization brings the error function to the first minimum called a *local minimum* in the error function. We then change glasses and/or make other changes to the design and ultimately are able to move the design to the next lower local minimum. Finally, we add additional elements and make other changes and we may be able to reach the local minimum on the right. But how do we know that we are at, or even close to, a global minimum? Here lies the challenge as well as the excitement of lens design!

It is important here to note that reaching global minimum in the error function is not necessarily the end goal for a design. Factors including tolerance sensitivity, packaging, viability of materials, number of elements, and many other factors influence the overall assessment or “goodness” of a design. Learning how to optimize a lens system is, of course, quite critical to the overall effort, and learning how to reach a viable local or near-global minimum in the error function is very important to the overall success of a project.

How Does the Designer Approach the Optical Design Task?

The following are the basic steps generally followed by an experienced optical designer in performing a given design task. Needless to say, due to the inherent complexity of optical design, the processes often become far more involved and time consuming. Figure 9.2 outlines these basic steps:

1. The first step in the design process is to *acquire and review all of the specifications*. This includes all optical specifications including focal length, f /number, full field of view, packaging constraints, performance goal, environmental requirements, and others.
2. Then we *select a representative viable starting point*. The starting point should, wherever possible, be a configuration which is inherently capable of meeting the specifications for the design. For example, if the specifications are for an $f/10$ monochromatic lens covering a very small field of view and having an entrance pupil diameter of 5 mm, then the lens may very well be a single element. However, if the requirements call for an $f/1.2$ lens over a wide spectral band covering a 40° full field of view, then the solution may very well

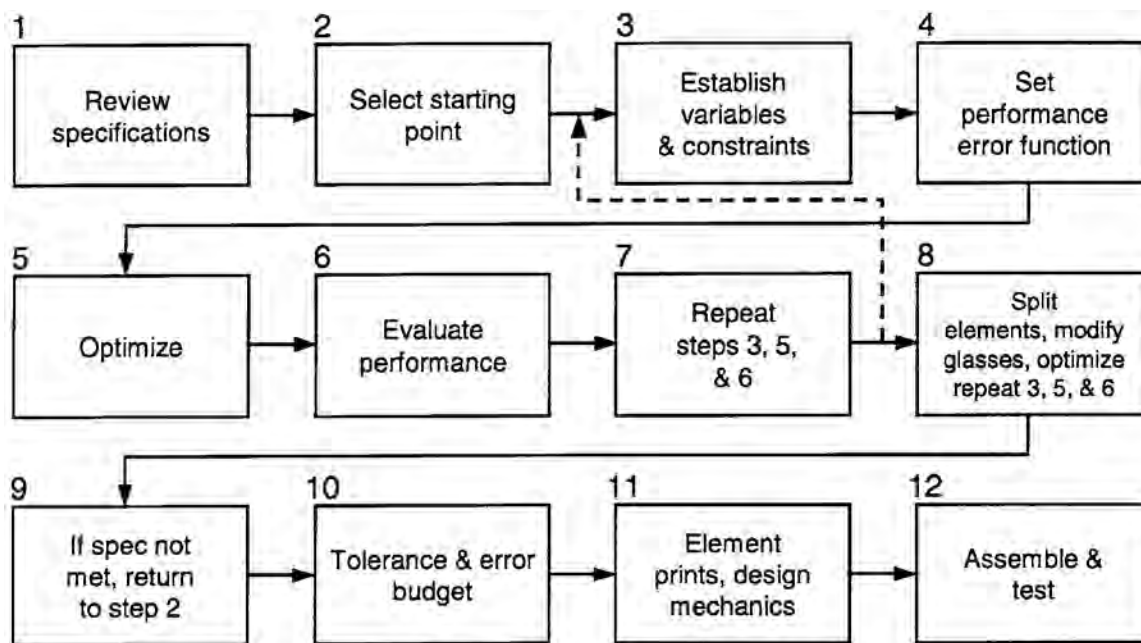


Figure 9.2

Lens Design and Optimization Procedure

be a very complex six- to seven-element double Gauss lens form. If we were to use a single element for this latter starting point, there would be no hope for a viable solution. Finding a good starting point is very important in obtaining a viable solution. The following are viable sources for starting points:

You can use a *patent* as a starting point. There are many sources for lens patents including Warren Smith's excellent book *Modern Lens Design*. There is also a CD-ROM called "LensView," which contains over 20,000 designs from patents. These are all searchable by a host of key parameters. While the authors of this book are not patent attorneys, we can say with confidence that you may legally enter design data from a patent into your computer and work with it in any way that you would like to. If your resulting design is sold on the market, and if the design infringes on the patent you used (or any other for that matter), you could be cited for patent infringement. It is interesting to note that the purpose

of our patent system in this country is to promote inventions and innovation. This is done by offering an inventor a 17-year exclusive right to his or her invention in exchange for *teaching* in the patent how to implement the invention. Thus, you are, in effect, invited to use the design data and work with it with the goal of coming up with a better design, which you can then go out and patent. By this philosophy, inventors are constantly challenged to improve upon an invention, which, in effect, advances technology, which is what the patent process is all about. Needless to say, we urge you to be careful in your use of patents.

You could use a so-called hybrid design. We mean a hybrid to be the combining of two or more otherwise viable design approaches so as to yield a new system configuration. For example, a moderate field-of-view Tessar lens design form can be combined with one or more strongly negatively powered elements in the front to create an extremely wide-angle lens. In effect, the Tessar is now used over a field of view similar to its designed field, and the negative element or elements bend or “horse” the rays around to cover the wider field of view. An *original design* can, of course, be a viable starting point. As your experience continues to mature, you will eventually become comfortable with “starting from scratch.” With today’s computer-aided design software, this works most of the time with simple systems such as doublets and triplets; however, with more complex systems, you may have problems and will likely be better off resorting to a patent or other source for a starting point.

3. Once you have entered your starting point into the software package you are using, it is time to *establish the variables and constraints*. The system variables include the following: radii, thicknesses, airspaces, surface tilts and decenters, glass characteristics (refractive index and Abbe number), and aspheric and/or other surface variables, including aspheric coefficients. The constraints include items such as focal length, f /number, packaging-related parameters (length, diameter, etc.), specific airspaces, specific ray angles, and virtually any other system requirement. Wavelength and field weights are also required to be input. It is important to note that it is not imperative (nor is it advisable) to vary every conceivable variable in a lens, especially early in the design phase. For example, your initial design optimization should

probably be done using the glasses from the starting point, in other words do not vary glass characteristics initially. This will come later once the design begins to take shape and becomes viable. You may also want to restrict the radii or thicknesses you vary as well, at least initially. For example, if adjacent elements have a very small airspace in the starting design, this may be for a good reason, and you should probably leave them fixed. Also, element thicknesses are very often not of great value as variables, at least initially, in a design task, so it is usually best to keep element thicknesses set to values which will be viable for the manufacturer.

4. You now will *set the performance error function and enter the constraints*. Most programs allow the user to define a fully “canned” or automatically generated error function, which, as discussed earlier, may be the rms blur radius weighted over the input wavelengths and the fields of view. In the Zemax program the user selects the number of rings and arms for which rays will be traced into the entrance pupil (rays are traced at the respective intersection points of the designated number of rings and arms). Chapter 22 shows a detailed example of how we work with the error function.
5. It is now time to *initiate the optimization*. The optimization will run anywhere from a few seconds for simple systems to many hours, depending on just how complex your system is and how many rays, fields of view, wavelengths, and other criteria are in the system. Today, a state-of-the-art PC optimizing a six- to seven-element double Gauss lens with five fields of view will take in the order of 5 to 10 s per optimization cycle. Once the computer has done as much as it can and reaches a local minimum in the error function, it stops and you are automatically exited from the optimization routine.
6. You now *evaluate the performance* using whatever criteria were specified for the lens. This may include MTF, encircled energy, rms spot radius, distortion, and others.
7. You now *repeat steps 3 and 5 until the desired performance is met*. Step 3 was to establish the variables and constraints, and step 5 was to run the optimization, and these steps are repeated as many times as necessary to meet the performance goals. You will often reach a solution that simply does not meet your performance requirements. This is very common during the design evolution, so do not be surprised, depressed, or embarrassed if it happens

to you ... it happens to the best of us. When it does happen, you may need to *add or split the optical power of one or more of the lens elements* and/or to *modify glass characteristics*. As we have discussed previously, splitting optical power is extremely valuable in minimizing the aberrations of a lens.

8. There is a really simple way of splitting an element in two, and while it is not “technically robust,” it does work most of the time. What you do is insert two surfaces in the middle of the current element, the first of which will be air and the second is the material of your initial element. The thickness of each “new” element is one-half of the initial element and the airspace should be small, like 0.1, for example. Now simply enter twice the radius of the original element for both s_1 and s_2 of the new elements. You will end up with two elements whose net power sum is nearly the same as your initial element. You can now proceed and vary their radii, the airspace, and, as required, the thicknesses.
9. If you still cannot reach a viable design, then at this point you will need to *return to step 2 and select a new starting point*.
10. Your final task in the design process is to *perform a tolerance analysis and performance error budget*. We will be discussing tolerancing in more depth in Chap. 16. In reality, you should be monitoring your tolerance sensitivities throughout the design process so that if the tolerances appear too tight, you can take action early in the design phase and perhaps select a less sensitive design form.
11. Finally, you will need to *generate optical element prints, contact a viable lens manufacturer, and have your elements produced*. You will also need to work with a qualified mechanical designer who will *design the cell or housing* as well as any required interfaces. It is important to note that while we list the mechanical design as taking place at this point after the lens design is complete, it is extremely important to work with your mechanical designer throughout the lens design process so as to reach an optimum for both the optics as well as the mechanics. Similarly, you should establish a dialog with the optical shop prior to completing the design so as to have time to modify parameters which the shop feels needs attention such as element thicknesses, glass types, and other parameters.
12. Once the components are in house, you will need to *have the lens assembled and tested*. Assembly should be done to a level of precision and cleanliness commensurate with the overall

performance goals. Similarly, testing should be to a criterion which matches or can be correlated with your system specifications and requirements. We discuss testing in Chap. 15.

Sample Lens Design Problem

There was a very interesting sample lens design problem presented at the 1980 International Lens Design Conference. The optimized design for an $f/2.0$, 100-mm focal length, 30° full field-of-view double Gauss lens similar to a 35-mm camera lens was sent out to the lens design community. One of the tasks was to redesign the lens to be $f/5$ covering a 55° full field with 50% vignetting permitted. Figure 9.3 shows the original starting design, as well as the design after changing the f /number and field of view, without any optimization.

Sixteen designers submitted their results, and they spent from 2 to 80 h working on the problem. We will present here three representative solutions in Fig. 9.4. The design in Fig. 9.4a is what we often call a *happy lens*. What we mean is that the lens is quite well behaved with no steep bending or severe angles of incidence. The rays seem to “meander” nicely through the lens. It is a comfortable design. We show to the right of the layout a plot of the MTF. MTF will be discussed in detail in Chap. 10. For the purpose of this discussion, consider the MTF to be contrast plotted in the ordinate as a function of the number of line pairs per millimeter

Figure 9.3
Starting Design for
Sample Lens Design
Problem

