1 INTRODUCTION: THE ART AND SCIENCE OF OPTICAL DESIGN

1.1 Science and Art in Optical Design

The process of optical design is both an art and a science. There is no closed algorithm that creates a lens, nor is there any computer program that will create useful lens designs without general guidance from an optical designer. The mechanics of computation are available within a computer program, but the inspiration and guidance for a useful solution to a customer's problems come from the lens designer. A successful lens must be based upon technically sound principles. The most successful designs include a blend of techniques and technologies that best meet the goals of the customer. This final blending is guided by the judgment of the designer.

Let us start by looking at a lens design. Figure 1.1 shows the layout of a photographic type of lens, showing some of the ray paths through the lens. The object is located a long distance (100,000,000 mm) to the left. This is what the computer program considers equivalent to an infinite object distance. The bundles of rays from each object point enter the lens as parallel bundles of rays. Each ray bundle passes through the lens and is focused toward an image point. On the lens shown, the field covered is 21° half width, which defines the size of the object that will be imaged by the lens.

The diameter of the bundles of light rays entering the lens determines the brightness of the image, and is established by the aperture stop of the lens. The aperture stop is represented by a physical aperture placed on a surface within the lens. Because the object is at infinity, the image will be formed in the focal plane of the lens. The focal length of the lens provides a scaling factor between the angular coordinates on the object and the linear coordinates on the image plane of the lens. The lens shown here has a focal length of 50.0 mm, and accepts an incoming bundle in the center of the field which is 26 mm in diameter. Using standard optical designations, this lens is a 50 mm

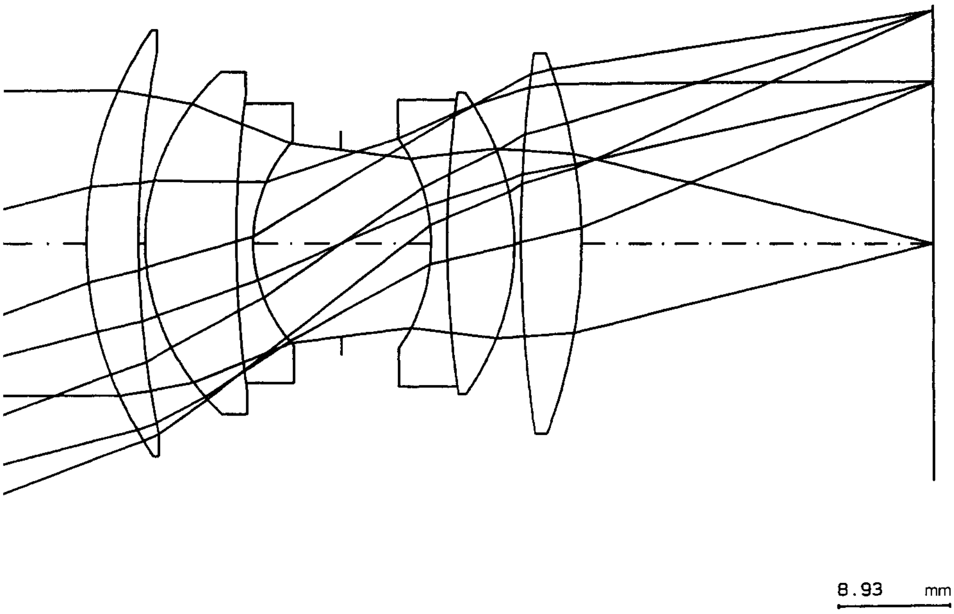

FIGURE 1.1 Layout plot of a double Gauss lens, indicating paths of on- and off-axis ray bundles (CODE V).

effective focal length lens, F/1.92, covering a 21° half field. This is approximately a "normal" lens for a 35 mm camera.

The parameters describing the field size, axial aperture, and image size are first order properties of the lens. In a perfect lens, these properties would be all that is needed to describe the image formation, as each point on the object would be represented as a perfect point in the image. This is as far as simple optics needs to go. If image formation were aberration free once the selection of the image scale, location, and brightness were stated, there would be no difficulty in lens design. Also this book would not have a reason to exist.

The reality is that the laws of geometrical and physical optics do not permit the formation of a perfect image except in a very small number of simple cases. In the lens being considered here, the image formation is not, and cannot be, entirely perfect. The lens shown contains a number of individual elements, chosen by the designer and optimized on the computer to obtain the best possible solution to the customer's requests, within a set of practical boundary conditions.

Image formation will be limited by the aberrations intrinsic to the passage of light through the lens. One measure of the aberration is the size of the blur of rays surrounding the central ray through the aperture stop. Another is the extent to which the optical paths along each ray in a bundle through the lens differs from the optical path along the central ray from the object. The aberrations are also dependent upon the color or wavelength of the light within each ray bundle, and by the distortion in the image, or the extent to which the central ray of each bundle fails to intersect at each image point determined by the first-order optical description of the image.

This lens consists of several elements; the shapes and locations of which are determined by the lens designer to provide the best possible match between the customer's needs and the physical limitations upon image formation. The laws of geometrical optics determine the passage of rays through a lens system. The laws of physical optics determine how the light within each bundle combines to form an image of each object point. The description of a lens in terms of aberrations and image quality can be calculated to any desired accuracy. All of the descriptions are based upon numerical computation, and are only approximately represented by analytic equations. A closed-form analytic description of the image forming process does not exist for a practical lens. This is due to the nonlinearity relating the angles of incidence and refraction of each ray, and because of the complexity in computing the physical image due to diffraction of light.

The lens designer is working with a very complicated system of physical components that can be described in numerical detail. The complexity is such that there are possibly hundreds or even thousands of closely equivalent solutions for each set of parameters provided by the customer for the lens. Thus, although the scientific or technical description of the lens can be expressed to any accuracy by using a computer, the artistry of the lens designer is required to guide the design process and select the best solution from the myriad possible "close fits" to the required lens parameters.

There are explicit parameters, such as the required focal length, but there are also somewhat "hidden" parameters that drive the path of the design. Vignetting, which is the deliberate reduction of irradiance off axis by proper selection of element diameters, is an extremely important tool in eliminating some of the worst parts of off-axis aberrations. This is a tool used frequently by designers in finding the best possible and most economic solution to design problems. This vignetting effect changes with the setting of the working aperture of the lens, and must be agreed to by the designer and the customer as part of the design goals.

Description of image formation requires tracing about five rays at each field, to produce about sixty different aberrations to correct. This amounts to 180 ray surfaces to be computed for each examination of the aberrations in this sample lens. Each step in the optimization requires that each parameter be changed and a finite differential formed of the change in each of the aberrations. This will require 6,480 ray surfaces for each step in the computation. The six-element lens shown contains at least thirty-six possible parameters. Even though a computer can trace rays at a fantastic rate, about 50,000 to 200,000 ray surfaces per second on a high-level personal computer, it is not possible to explore all possible alternatives for a practical lens. If it is assumed that each parameter can take any of 10,000 distinct values, the complete evaluation would require about 10^{108} possible combinations be evaluated. At a rate of about 0.1 seconds per evaluation this would take approximately 10^{99} years. There obviously is a better way to proceed.

The artistic part of design extends beyond the selection of the image quality to include the mechanical layout, selection of materials and minimization of problems with tolerance required for fabricating a successful lens. A high-speed computer permits optimization to proceed very rapidly. In the usual case, hundreds of possible designs can be evaluated in an hour, and the optimum selection of these made by the use of a computer program. Few of these are desirable or acceptable solutions. Only in a very small number of cases can the design be completed without application of the judgment of a designer to guide the outcome of the computer program.

It should be evident by now that successful design is more than computer program manipulation. Conversely, an understanding of how to creatively use the process of computerized optimization is essential to successful designing. The art of the designer begins with definition of the starting point. No matter how effective the optimization process, an inappropriate selection of starting point can lead to a failure in the design.

As the design proceeds, alteration of the requested goals is important. The designer needs to learn from the steps taken by the optimization process what the limitations are for the lens, and how the parameters and the merit function describing the goals can best be altered.

Understanding of the basis of geometrical optics and aberration content in lenses is essential to knowing when to stop. Continuing to attempt to optimize a lens whose image forming capabilities cannot be improved is inefficient, costly, and a bit foolish. Completing the design with a lens that cannot be fabricated is equally foolish.

By now it is obvious that successful optical design is more than mere computer operation and interpretation of ray traces. The successful designer must be aware of many properties of lenses that will affect the eventual outcome of the design. Figure 1.2 shows a short list of many of the items that should be considered by a designer approaching a lens design. It is likely that others can add (but certainly not eliminate) many items to this list.

In this list, the items in bold type are those that are covered in some detail in this book. The items in italics are mentioned or discussed in somewhat less detail and completeness. The ordinary type face lists some of the topics that a designer needs to be aware of that are not discussed in any detail in this book.

Focal length
Field angle or field size
F/number
Numerical aperture
Wavelength and spectral range
Magnification
Magnification range
Type of lens
Back focus
Front focus
Pupil locations
Illumination
Irradiance uniformity
vignetting
transmission
Ghost images
Distortion
Variation with conjugates
Variation with spectral region
Size and configuration
Folding components
Interference with optical path
Zoom range
Zoom mechanization
Focus mechanization
Image quality
Aberrations
Resolution
OTF
MTF
Energy concentration
Effect of aperture stop
Scattered light
Polarization
Veiling glare
Light baffling
Off-axis rejection
Field stop definition
Diffraction effects
Tolerances
Depth of focus
Interface with variable aperture
Interface with autofocus system
Image quality at various apertures
Cost of design
Cost of prototype
Cost of production
Schedule and delivery time
Optical interfacing with instrument
Materials
Availability
Cost
Continued supply
Suitability for processing
Environmental considerations
Hazardous materials
Environment
Temperature range
Storage conditions
Atmospheric pressure
Humidity
Vibration and shock
Availability of subcontractors
Level of technology
Coatings
Transmission
Reflectivity
Absorption
Availability
Risk
Environmental effects
Weight
Moment about mounting
Producibility
Manufacturability
Manufacturing processes
Mounting procedures
Mounting interfaces
Mechanical interface with instrument
Detector
Photographic
Sampling array
Signal to noise
Surface finish, cosmetics
Beam parameters
Radiation damage
Irradiance damage
Prior experience
Track record
Prior art
Patentability
Patent conflict situation
Competitive situation
Marketability
Interface to other products
Lifetime of product
Rate of production
Environmental hazards
Liability issues
Delay to market
Timing of disclosure
Integration with products
Customer view of product
Styling
Financial viability
Investment requirements
Investment risk
Access to funding

FIGURE 1.2 Some of the important topics that a successful lens designer needs to address during the process of designing a lens.

1.2 Starting a Design

The starting point is data supplied by a customer for the lens. The goals for the lens need to be stated in a form that can be translated by a designer into the initial selection of parameters for the lens. Frequently the specifications will be unclear, sometimes redundant or conflicting with physical reality. Sometimes the customer or intended user is not well versed in optics and image formation, leading to some innocently expensive or physically impossible requirements.

The designer has the responsibility of sorting through the specifications and constructing a realistic set of goals for the design. Since the specifications usually include cost and delivery, the refining of lens specifications is not entirely a technical activity.

Figure 1.2 includes most of the properties of a lens that need to be included in a complete set of specifications. The first-order optical specifications, near the beginning of the list, are required to establish the paraxial base set of coordinates in which the image will be evaluated. These quantities should be familiar to anyone who has ever taken an optics course. The image quality requirements describe how faithfully the image reproduces the object. Although radiometry would seem to be a property of the first-order requirements, additional effects such as losses by transmission through the lens and the vignetting that is used to control image quality off axis in some lenses are image quality considerations. In Chapter 2 on basic optics, the fundamental relationship between paraxial coordinates, radiometry of images, and change of image quality across the field are discussed.

Mechanical and fabrication requirements deal with the need to be able to produce a lens if it is to be of any use to the customer. The tolerances break into three parts. The first are the requirements on construction parameters to ensure that the image falls in the proper location and contains aberrations within an acceptable degradation from the base system. The second deals with the need to use the lens in a defined environment. The third specifies the acceptable irregularity and randomness that can be allowed on the surfaces of the lens to control both aberrations and scattered light. Specification of these tolerances requires running an emulation of the design of the lens, in which the computer perturbs the state of the lens according to specific algorithms and calculates the likelihood that any lens assembled within the tolerances will meet the requirements.

The final set of specifications deals with the "other" things about lenses that are important. Significant here are cost and schedule for delivery. Success in meeting these specifications actually is very closely tied to the choice of the parameters and tolerances that are needed for the lens.

The type of lens that is selected needs to be responsive to these requirements. There are many hidden considerations, such as the focal length, weight, spectral range, and actual required image quality that will affect the choice of lens type. The number of elements permitted also influences the type of lens that is used, as available space and cost are two of the perennial difficult-to-express limits that are used in design. The discussion in Chapter 7 on the design of specific types of lenses will indicate how this selection process is developed, and will permit modification of the starting configuration by the designer.

In many cases, the starting point can be obtained from a basic optical layout, beginning with a first-order calculation. In Chapter 7, the discussion of doublets and triplets will be carried out using this approach. For more complicated lenses, such as Double Gauss types, wide-angle and some types of zoom lenses, the best starting point is usually prior art. In most cases this will be from a lens data library or a lens patent.

1.2.1 DETAILED DESCRIPTION OF A LENS

A lens can usually be described in terms of only a few parameters, any of which may become variables in the subsequent optimization process. The basic lens consists of an ordered set of spherical surfaces, separations, or thicknesses, and refractive or reflective materials. The surfaces are stored in sequential numbered order with the curvature, thickness to the next surface, and the index of refraction of the medium after the surface attached to each surface number. Additional information about the surface shape, orientation, and dimension may also be attached to the surface number.

In most designs, the goal is to produce a lens which provides uniform imagery over a two-dimensional image plane. Therefore, most lenses of interest will consist of rotationally symmetric surfaces. Data for the lens shown in the previous section is listed in Figure 1.3. In addition to the surface data, certain other information describing the optical operating conditions of the lens is also listed. Although each lens design program will have its own set of acronyms and format for the lens data, the goal for all is the same.

The specific lens data actually put into a computer will usually appear in a different form, as in Figure 1.4, which is a data input file for the CODE V program. There is a natural flow to this form of input, and each program will have its own set of acronyms and abbreviations that make the job of communication simpler. Most programs also permit interactive input of the lens data in a spreadsheet format as in Figure 1.5. Here the user is prompted for the data necessary to complete the lens data set. In most cases the most likely

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Excerpt
More Information

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Sample Lens
                  RDY            THI              GLA              CCY   THC
> OBJ:         INFINITY       INFINITY                             100   100
     1:        31.79843       4.009367       LAF2_SCHOTT             0   100
     2:        81.76294       0.500000                               0   100
     3:        19.00541       7.206837       LAF2_SCHOTT             0   100
     4:        90.39788       1.303044       SF3_SCHOTT              0   100
     5:        12.41339       7.000000                               0   100
   STO:        INFINITY       7.000000                             100   100
     7:       -15.50210       1.303044       SF64A_SCHOTT            0   100
     8:        91.47280       5.242247       LAF2_SCHOTT             0   100
     9:       -21.41355       0.500000                               0   100
    10:       116.05450       4.800000       LAF2_SCHOTT             0   100
    11:       -43.97434      27.980887                               0   PIM
   IMG:        INFINITY      -0.066048                             100     0

 SPECIFICATION DATA
    EPD        25.00000
    DIM              MM
    WL           656.30     587.60     486.10
    REF               2
    WTW               1          1          1
    XAN         0.00000      0.00000       0.00000
    YAN         0.00000     14.70000      21.00000

 APERTURE DATA/EDGE DEFINITIONS
    CA
    CIR S1                     16.004532
    CIR S2                     15.526973
    CIR S3                     12.769472
    CIR S4                     10.368361
    CIR S5                      8.307168
    CIR S6                      7.578557
    CIR S7                      8.530869
    CIR S8                     10.655071
    CIR S9                     11.220801
    CIR S10                    13.938192
    CIR S11                    14.269285

REFRACTIVE  INDICES
     GLASS  CODE                        656.30       587.60       486.10
    SF3_SCHOTT                        1.732416     1.739997     1.758671
    SF64A_SCHOTT                      1.699097     1.705846     1.722403
    LAF2_SCHOTT                       1.739046     1.743999     1.755690

NFINITE CONJUGATES
    EFL          49.9998
    BFL          27.9809
    FFL         -19.4621
    FNO           2.0000
    IMG DIS      27.9148
    OAL          38.8645
    PARAXIAL  IMAGE
     HT          19.1931
    ANG          21.0000
    ENTRANCE  PUPIL
     DIA         25.0000
     THI         27.1596
    EXIT  PUPIL
     DIA         26.8115
     THI        -25.6419
```

FIGURE 1.3 A sample listing of the data describing a lens (CODE V).

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Excerpt
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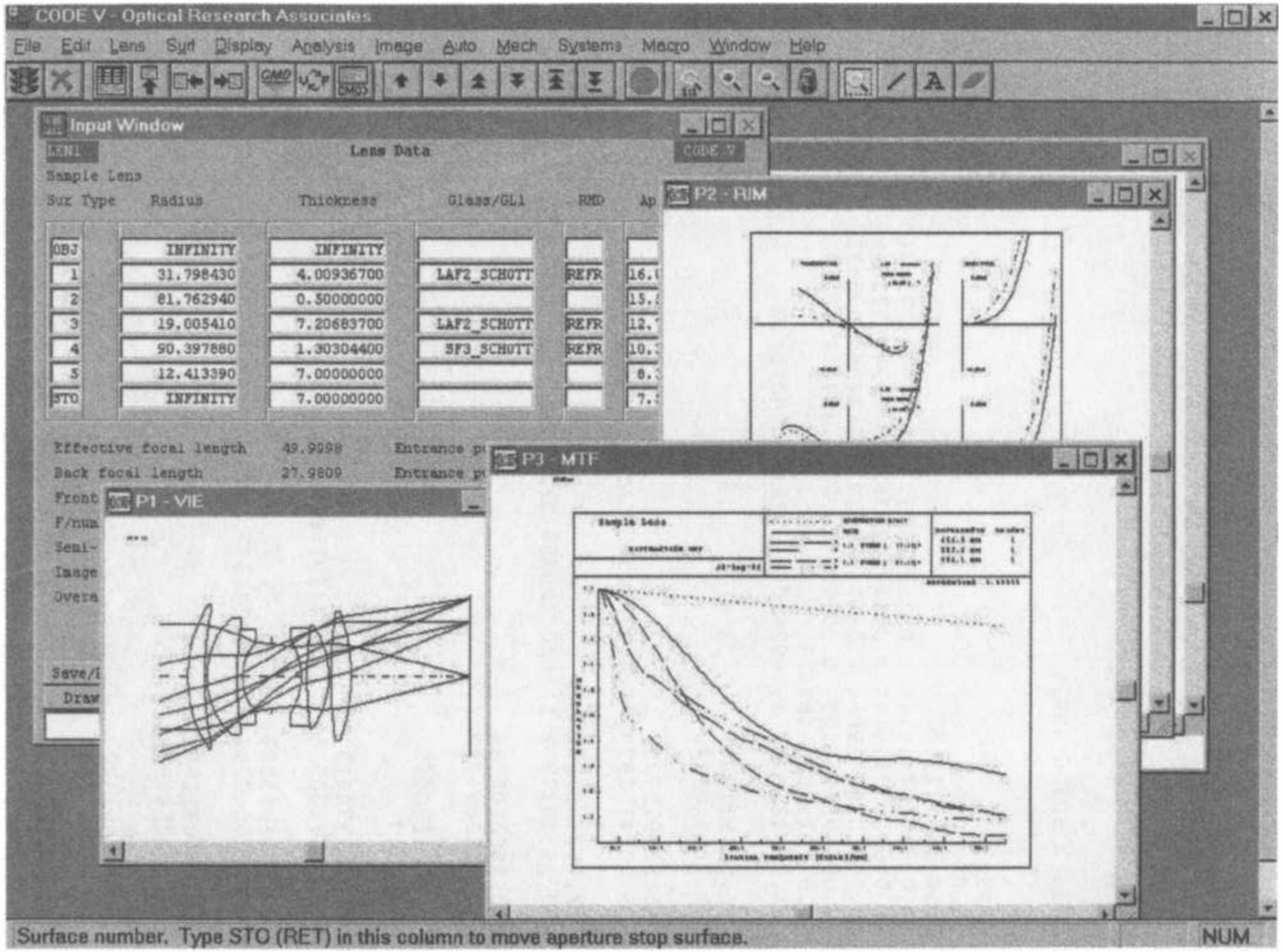
```
RDM;LEN
TITLE 'Sample Lens'
EPD   25.0
NFO   7
FFO   -0.2
IFO   0.05
DIM   M
WL    656.3 587.6 486.1
REF   2
WTW   1 1 1
INI   'RRS'
XAN   0.0 0.0 0.0
YAN   0.0 14.7 21.0
VUX   0.00910997119141 0.0115763173828 0.0994343730469
VLX   0.00910997119141 0.0115763173828 0.0994343730469
VUY   0.00910989619054 0.0461619962916 0.349698303521
VLY   0.00910989619054 0.302554428909 0.497028541314
SO    0.0 5011708836836.3
S     31.7984318367 4.00936706947 LAF2_SCHOTT
  CCY 0
  CIR 16.0045318604
S     81.7629405148 0.5
  CCY 0
  CIR 15.5269727707
S     19.0054101873 7.20683730737 LAF2_SCHOTT
  CCY 0
  CIR 12.7694721222
S     90.3978818762 1.30304429758 SF3_SCHOTT
  CCY 0
  CIR 10.3683605194
S     12.4133854383 7.0
  CCY 0
  CIR 8.3071680069
S     0.0 7.0
  STO
  CIR 7.5785574913
S     -15.5021009259 1.30304429758 SF64A_SCHOTT
  CCY 0
  CIR 8.53086853027
S     91.4728040296 5.24224744333 LAF2_SCHOTT
  CCY 0
  CIR 10.6550712585
S     -21.4135490344 0.5
  CCY 0
  CIR 11.2208013535
S     116.054499482 4.8 LAF2_SCHOTT
  CCY 0
  CIR 13.9381923676
S     -43.974336366 27.9808869798
  CCY 0
  CIR 14.269285202
  PIM
SI    0.0 -0.0660477586985
  THC 0
GO
```

FIGURE 1.4 The same data as in Figure 1.3, but expressed in the serial form used in entering data into a computer program (CODE V).



(a)

FIGURE 1.5 Examples of spreadsheet form of lens data input for three different commercially available lens design programs: (a) CODE V; (b) ZEMAX; (c) OSLO.