

INTRODUCTION TO **LENS DESIGN**

With Practical ZEMAX® Examples



Joseph M. Geary
Center for Applied Optics

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Preface

This book evolved from an introductory course in lens design sponsored by the Center for Applied Optics for use in the Optical Science & Engineering doctoral program at the University of Alabama in Huntsville. At the inception of this course, I searched for a lens design textbook and found, to my surprise and dismay, that there really were none! Although there were several good books about lens design (see the booklist in Appendix A), these tended to be either monographs or compilations of different designs. None were written with students (or instructors) in mind. Hopefully this book is a step in the pedagogical direction. As I began preparing lectures it also seemed obvious that no modern lens design course could be given without thoroughly integrating one of the commercially available lens design codes into the syllabus. For a variety of reasons (including user friendliness and cost effectiveness) ZEMAX was selected.

This is not a textbook in the traditional sense. It is a formalized embodiment of lectures with assigned homework and exams. The course is designed around a 14-week semester (MWF) with enough material to fill 38 lectures of 55 minutes each. The material is at the first-year graduate level, and is intended as a first course in lens design. It is also structured to be hands-on and engineering oriented. A solid footing in undergraduate geometrical optics (Appendix A) is the only prerequisite. Math requirements are modest: algebra, trig, geometry, and calculus. Although this course is about lens design, I believe its scope is more general in that it can provide optical engineers with important tools and skills that will be useful in their professional careers.

Though written in lecture format and suitable for classroom use, the book is primarily designed for self-study. As such it can be used on three distinct levels. Obviously, the full benefit will be had by those having access to ZEMAX (and the accompanying manual). However, I believe enough information is provided (particularly with the help of Appendices C and E) to allow readers using alternate codes (such as Code-V, SYNOPSIS, and Super OSLO) to work the examples and assignments in a beneficial manner. Finally, for readers who do not have any major code readily available, a great deal can still be learned about design and analysis in conjunction with working the manual calculation problems and by doing the thin lens pre-designs preceding code work.

With a few exceptions, the backbone of the course is the photographic lens, and we follow an almost historic development. There are ten photographic lens design problems from the simple Wollaston landscape lens to the more complex achromatic telephoto. Along the way we visit such things as the Rapid Rectilinear and Cooke Triplet. The design principles covered in the course include: lens bend-

ing, stop shift, symmetry, element splitting, color correction, aberration balancing, field flattening, aspherics, as well as the proper use and construction of the merit function. Though ZEMAX is an integral part of the course, its use will not be blind. Manual thin lens pre-design calculations provide the starting prescriptions for every ZEMAX homework. Paraxial ray tracing, element power computations, and aberration calculations are utilized throughout the course. Consequently, all designs are firmly anchored by theory.

Of equal importance to the design principles covered in the course are the analytical tools used to determine the quality of the design. ZEMAX and its sister codes are built upon a strong tradition of optical analysis, and will provide the user with a rich variety of numbers and plots (such as axial color and ray fan plots, spot diagrams, and MTF). This course will provide the student with a thorough understanding of where these numbers come from and what the plots mean. This understanding is supported by 26 assignments evenly split between “pencil and paper” calculations and ZEMAX code work. The course is structured so that students start using ZEMAX in the very first week, and every week thereafter. This affects the arrangement of material because roughly every third lecture focuses on a specific lens design and provides background for the ZEMAX assignment.

I would like to dedicate this book to Professors Roland Shack and Bob Shannon who were my mentors at the Optical Sciences Center. I also want to include Prof. Rudolph Kingslake in this dedication. All three have provided inspiration for this work, and I thank each for the things I’ve learned from them.

My thanks to Dr. John Dimmock, Director of both the Center for Applied Optics and the Optical Sciences and Engineering program, for his generous support in developing the lens design course upon which this book is based. I also owe a debt of gratitude to all the reviewers of the manuscript. In alphabetical order they are: Dr. Richard Buchroeder, Dr. Qian Gong (Swales Aerospace), Dr. John Loomis (University of Dayton Research Institute), Dr. Malcolm MacFarlane (Goodrich), Mr. Ken Pitalo (University of Alabama in Huntsville), Dr. Pat Reardon (University of Alabama in Huntsville), Dr. Babak Saif (Space Telescope Institute), Dr. José Sasian (University of Arizona), Dr. Lynn Seppala (Lawrence Livermore National Laboratory), Dr. Bob Shannon (University of Arizona), Dr. Greg Smith, Dr. Phil Stahl (Marshall Space Flight Center), Dr. Harold Suiter, Dr. Bill Swantner (BSC Optics), and Dr. Mary Turner (Focus Software Inc.). The constructive criticism provided by these professionals has greatly improved the quality of this work. Finally, I want to thank my daughter, Jennifer, for the fine art work she contributed to this book.

Note on ZEMAX: ZEMAX SE versions 6.0 – 7.2 have been used in the development of this book and in the instruction of this course. I have found that different versions can give slightly different numbers for variables in the lens data editor and for operand values in the merit function editor at the end of an optimization run. The differences tend to be of no significance. I provide many design examples using ZEMAX optimization where specific numerical values are pointed out or tabulated. For those using other versions of ZEMAX, please do not be

surprised if your post-optimization numbers do not agree precisely with mine. They should, however, be reasonably close.

Instructor Note: I found the use of a computer projector absolutely indispensable in teaching this course. I strongly encourage any instructor to employ a computer projector not only for homework reviews but also for live demonstrations of ZEMAX features, and for illustrating design principles.

Joseph M. Geary
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October 15, 2002

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.

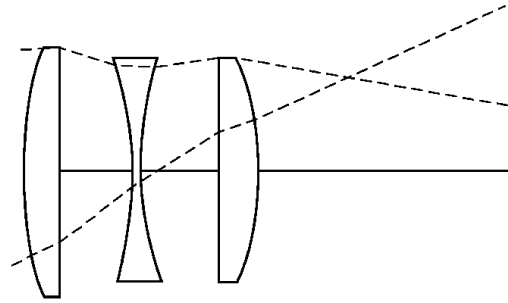
1.1.3 Acquired Skills

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.

2 Chapter 1 Agenda

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.*

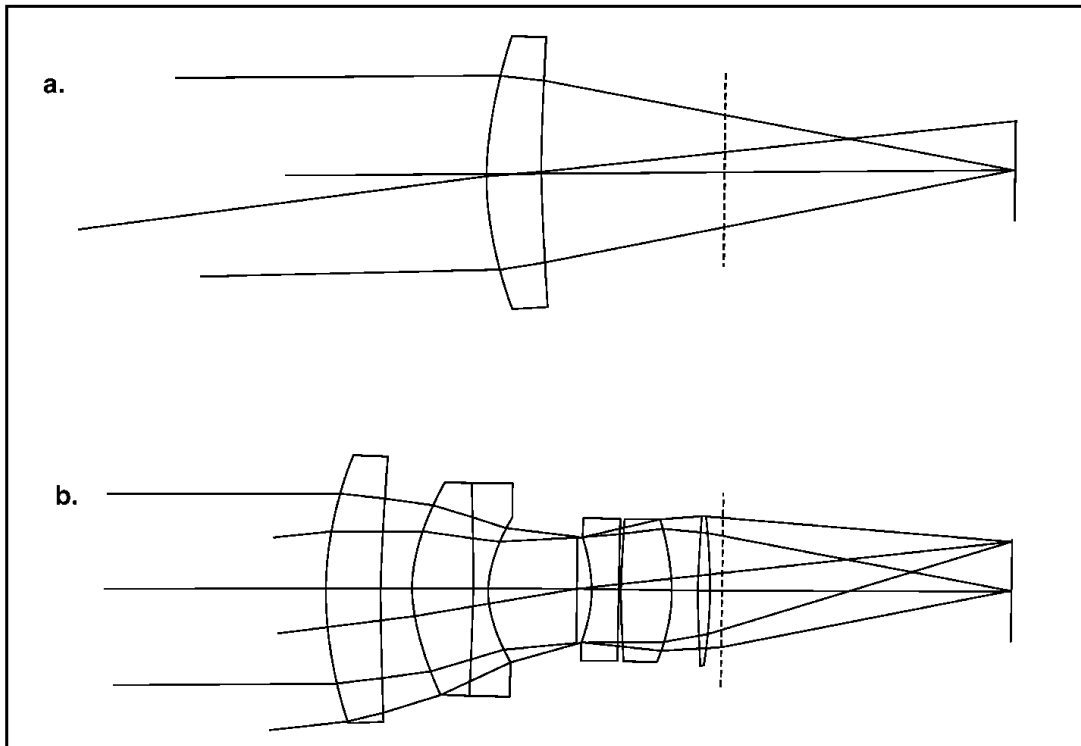


Fig. 1.2 Two lenses that give the same image size but with quite different quality.

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 1.3a shows a resolution target being imaged by a “perfect” optical system.

4 Chapter 1 Agenda

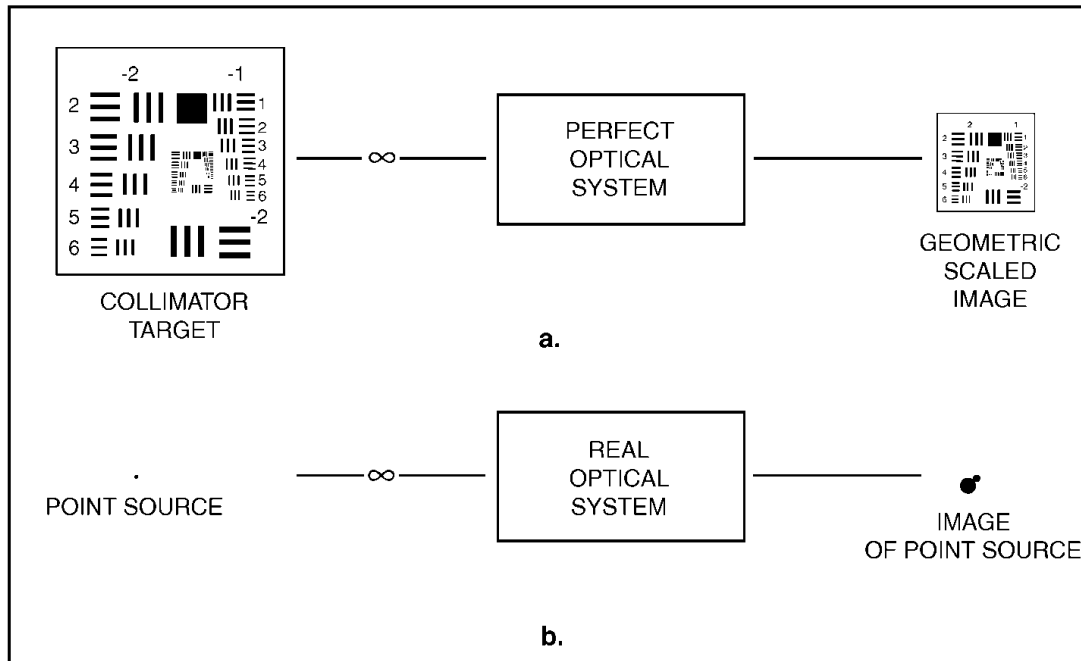


Fig. 1.3 A resolution target perfectly imaged (a); a poorly imaged point source (b).

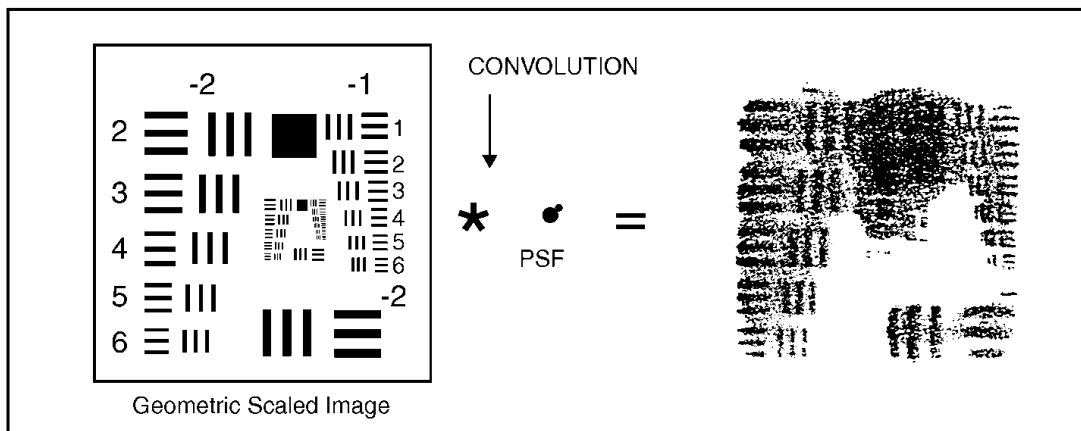


Fig. 1.4 Degradation of the resolution target image due to convolution with blob point image.

The image is simply a scaled version of the object. In Figure 1.3b 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 1.3a with the *blob image* in Figure 1.3b.

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

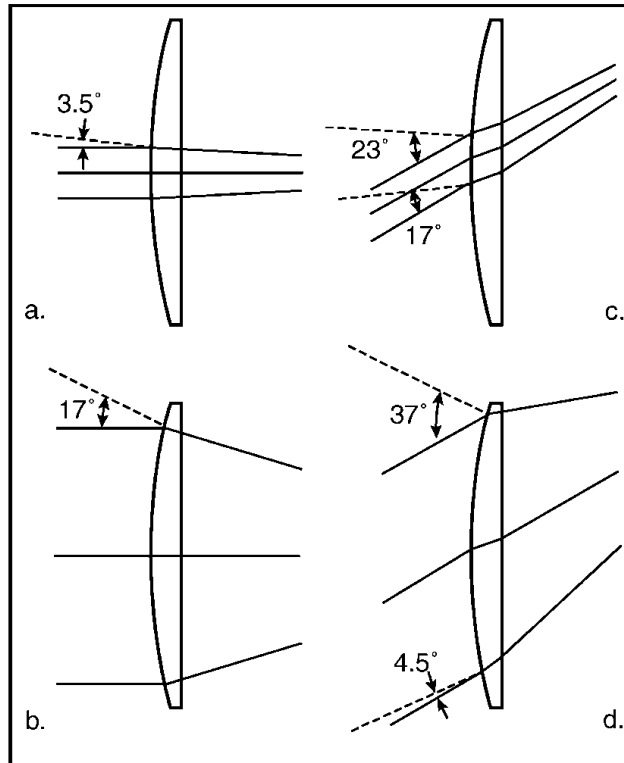


Fig. 1.5 Angle of incidence change with ray height and field angle.

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 $1/4^\circ$ 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

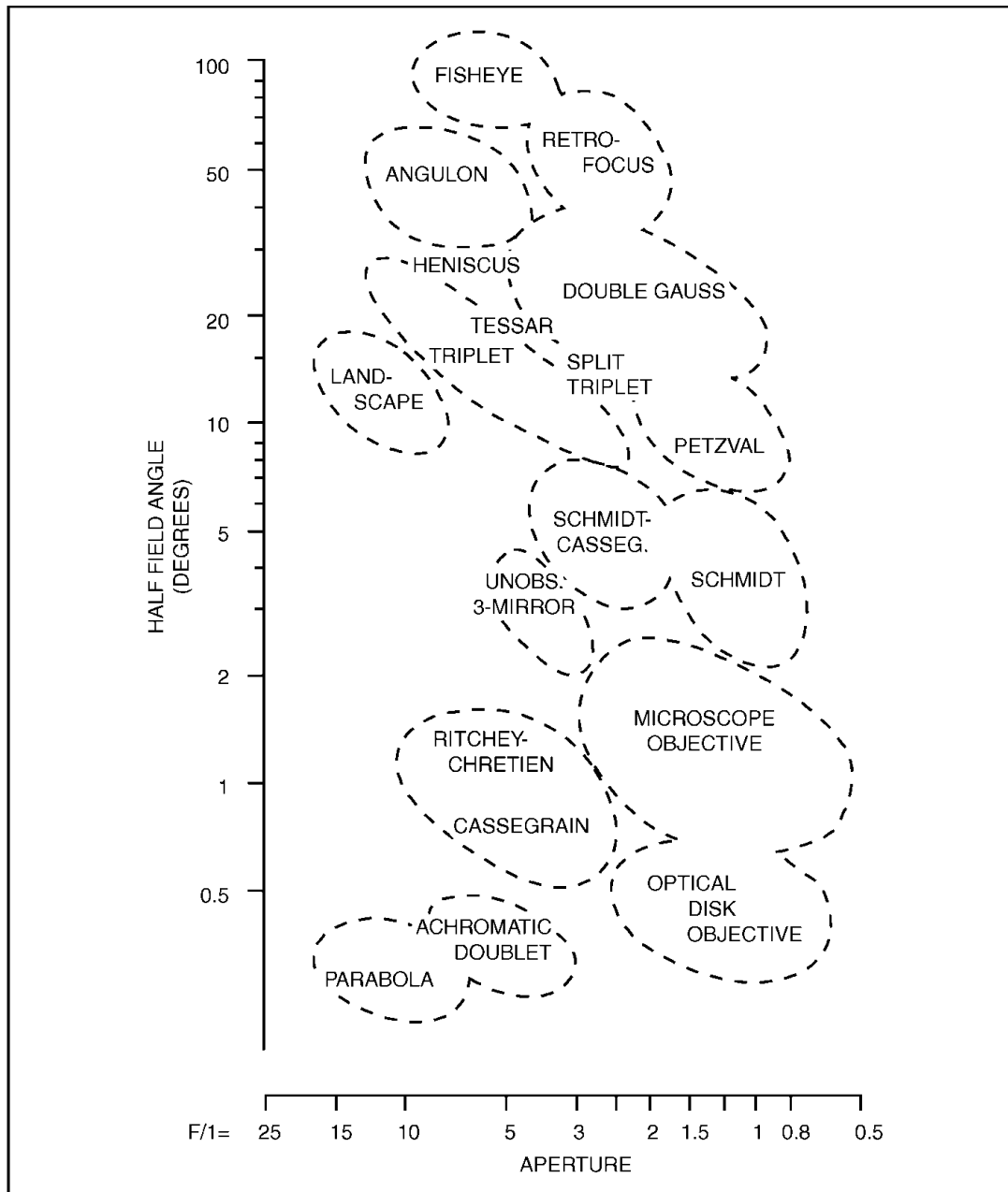


Fig. 1.6 Map showing the design types which are commonly used for various combinations of aperture and field of view. (From W. Smith, *Modern Lens Design* (McGraw-Hill, 1992). Reprinted with permission of the McGraw-Hill Companies.)

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.

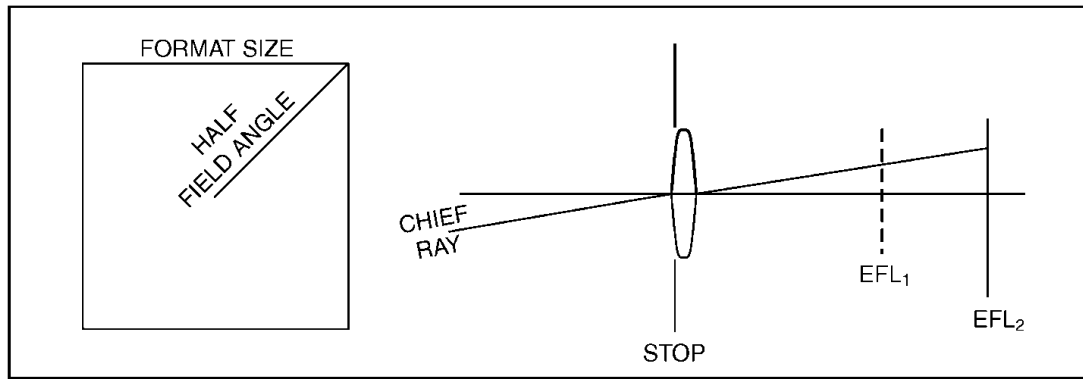


Fig. 1.7 Dependence of EFL on format size and field coverage.

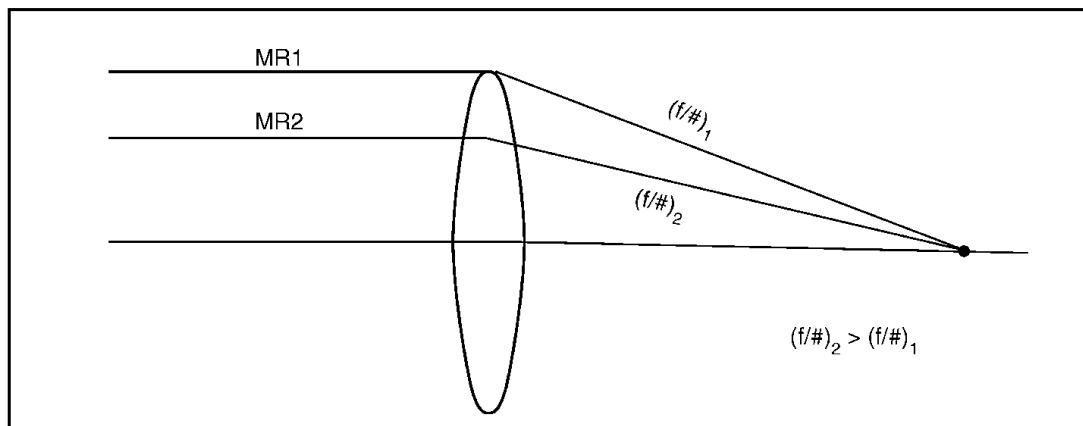


Fig. 1.8 A lower f -number means bigger diameter optics.

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.

8 Chapter 1 Agenda

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.