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 geomet-

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.

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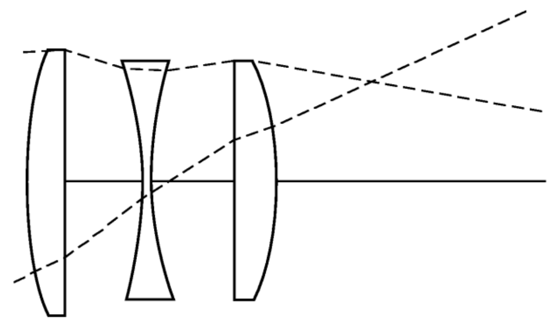

1. Curvatures
2. Thickness
3. Indices
4. Stop size and location
5. Field Angle

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.

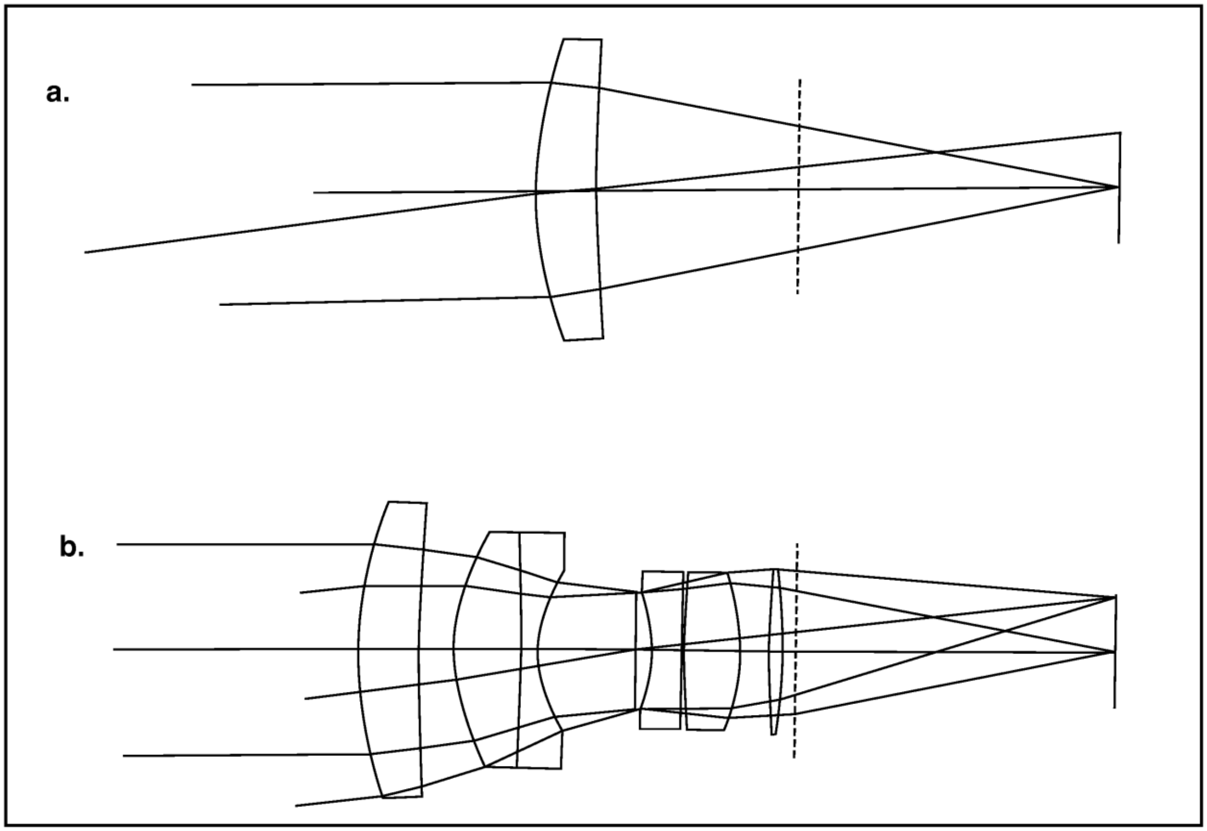

Fig. 1.2 Two lenses that give the same image size but with quite different quality.

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).

1.2.3 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

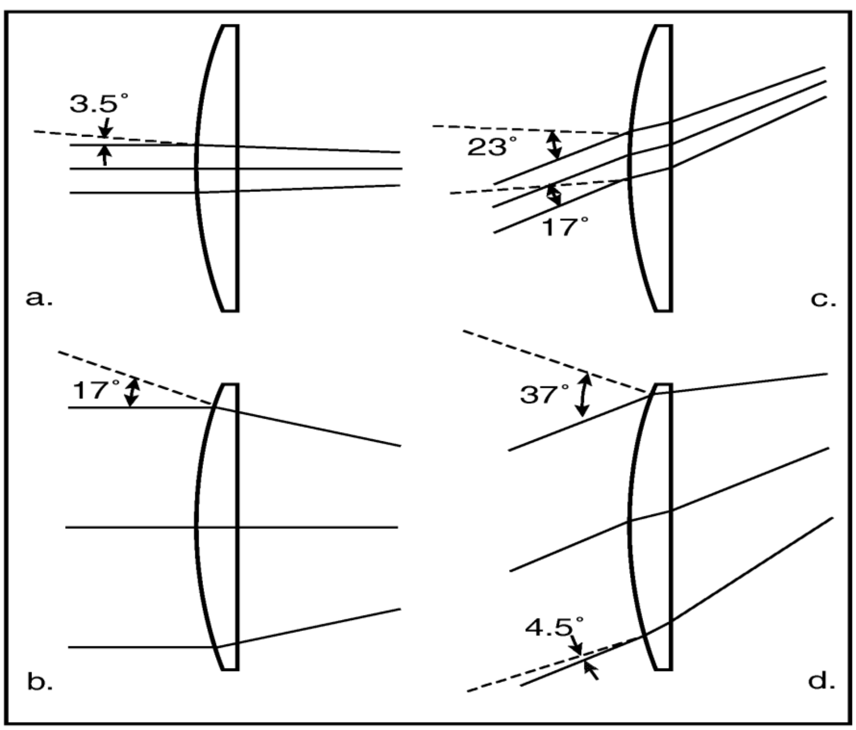

Fig. 1.5 Angle of incidence change with ray height and field angle.

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 1.5b). 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 1.5a to 37° in Figure 1.5d). For the lower ray in c and J, 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 (jc-axis) and field angle (j-axis). For a .25 ° field at f/10, a simple parabolic mirror would suffice. However, for a field of 20° atf/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 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 x 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.

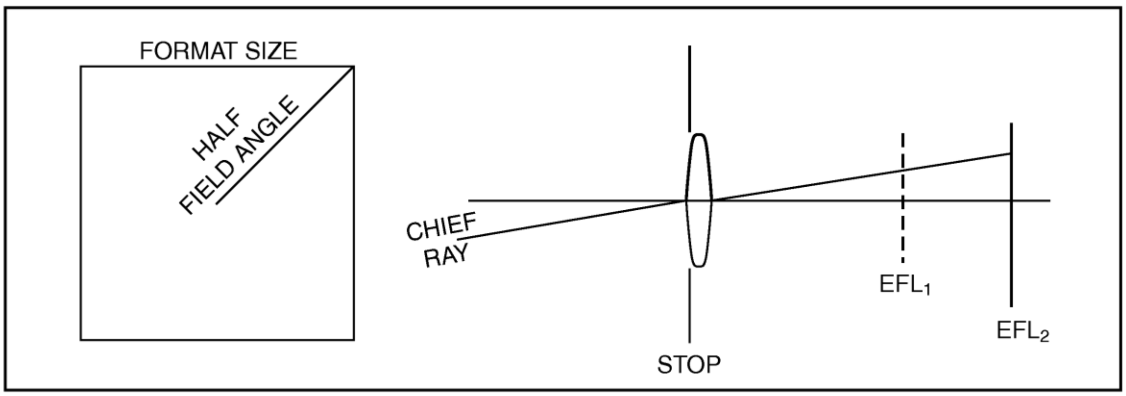

Fig. 1.7 *Dependence of EFL on format size and field coverage.*

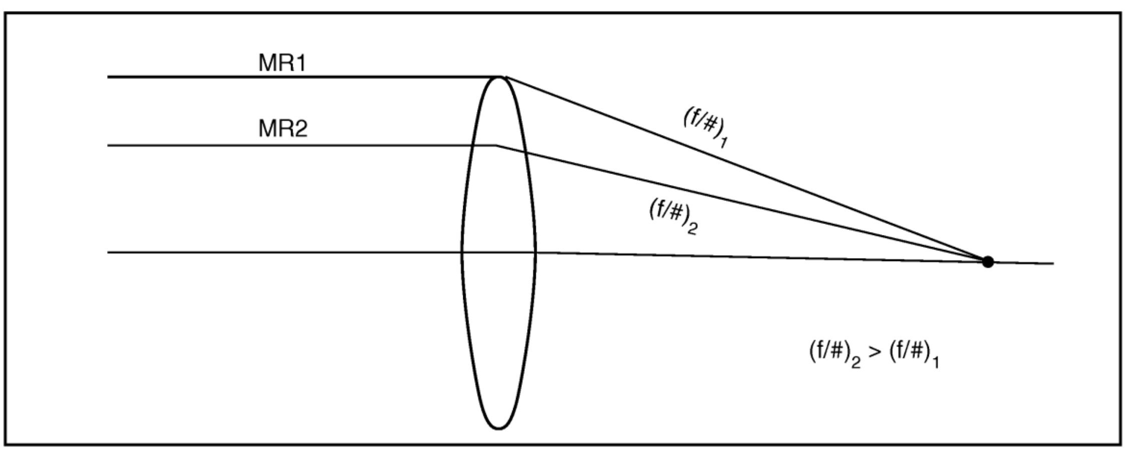

Fig. 1.8 A lower f-number means bigger diameter optics.

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.

1.1 Homework

With the information provided in Figure 1.9, find:

a. the effective focal length (EFL),

b. the lens power ϕ,

c. surface curvatures Cx and C2 (assume equiconvex),

d. radius of curvatures Rx and R2,

e. format size (assume square), and

f. Airy disk diameter.

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

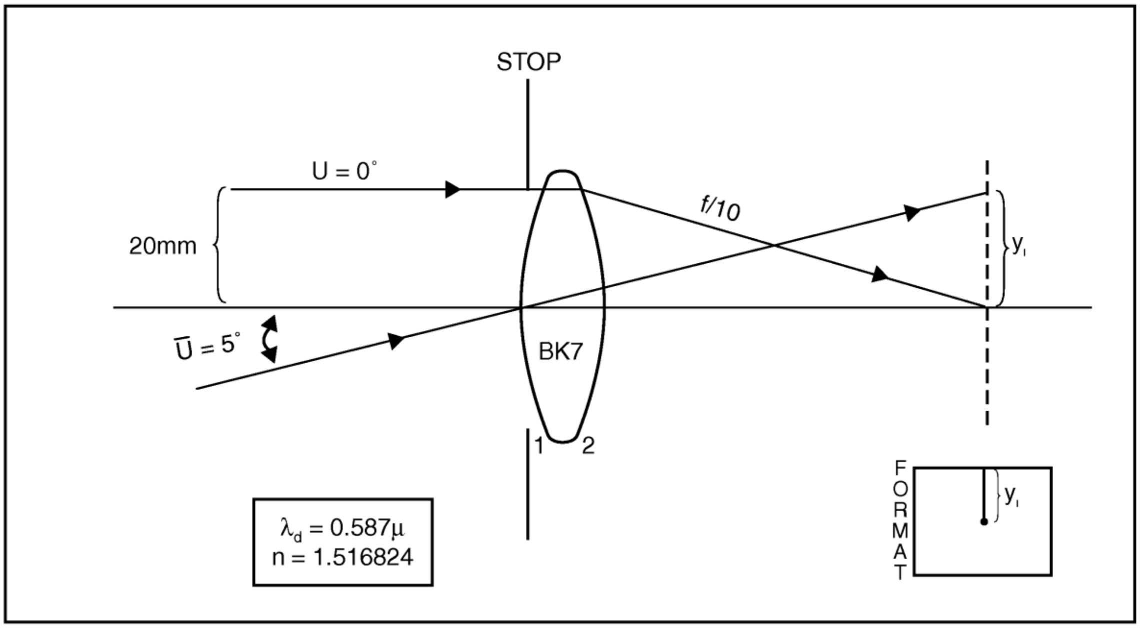

Fig. 1.9 *Illustration for Homework.*