Chapter 25

Tele Lenses

One of the great advantages of 35 mm cameras is their ability to conveniently use lenses having longer-than-normal focal lengths and narrower fields of view. This greater reach makes possible whole new ways of taking pictures. You can get close without being close.

With a large-format camera, such as a 4×5, long-focus lenses quickly become huge and unwieldy, more like big telescopes, and they are rarely seen. With a 35 mm camera, lenses having a typical focal length of 135 mm and a field of 18 degrees are not only practical but they can be used handheld. This capability was recognized early. When in 1931 interchangeable lenses were first introduced for the revolutionary new Leica, one of the first two was a 135 mm long-focus lens (the other was a 35 mm wide-angle lens).

The terminology for long-focus lenses is the subject of some controversy. They might be called telescopic lenses, but more often they are called telephoto lenses. Actually, in optics the term telephoto is quite specific and refers to a particular compact design type where, for convenience, overall physical length is made shorter than effective focal length. As described earlier in Section 8.3, to do this the system must be asymmetric. It must have net positive (converging) optical power in the front part and net negative (diverging) optical power in the rear part (see Fig. 8.5). Thus, strictly speaking, a telephoto lens is not just one with a longer-than-normal focal length. But common usage of favorite words is hard to buck. Here, these narrow-field lenses will be called simply tele lenses.

25.1 Double-Gauss, 105 mm, $f/2.8$

One approach to making a tele lens for a 35 mm camera is to take one of the common design forms and simply increase the focal length while keeping the same 24×36 mm image format dimensions. Thus you can make a tele lens based on the Cooke Triplet, Tessar, or several others. In this example, the Double-Gauss approach has been adopted. Focal length is 105 mm, field of view across the flat format diagonal is 23.2 (± 11.6) degrees, speed is $f/2.8$, and color correction is panchromatic. This focal length was chosen because it is almost exactly twice the focal length of a normal 52 mm lens. Such lenses are very popular with photographers for scenic shots and for head-and-shoulders

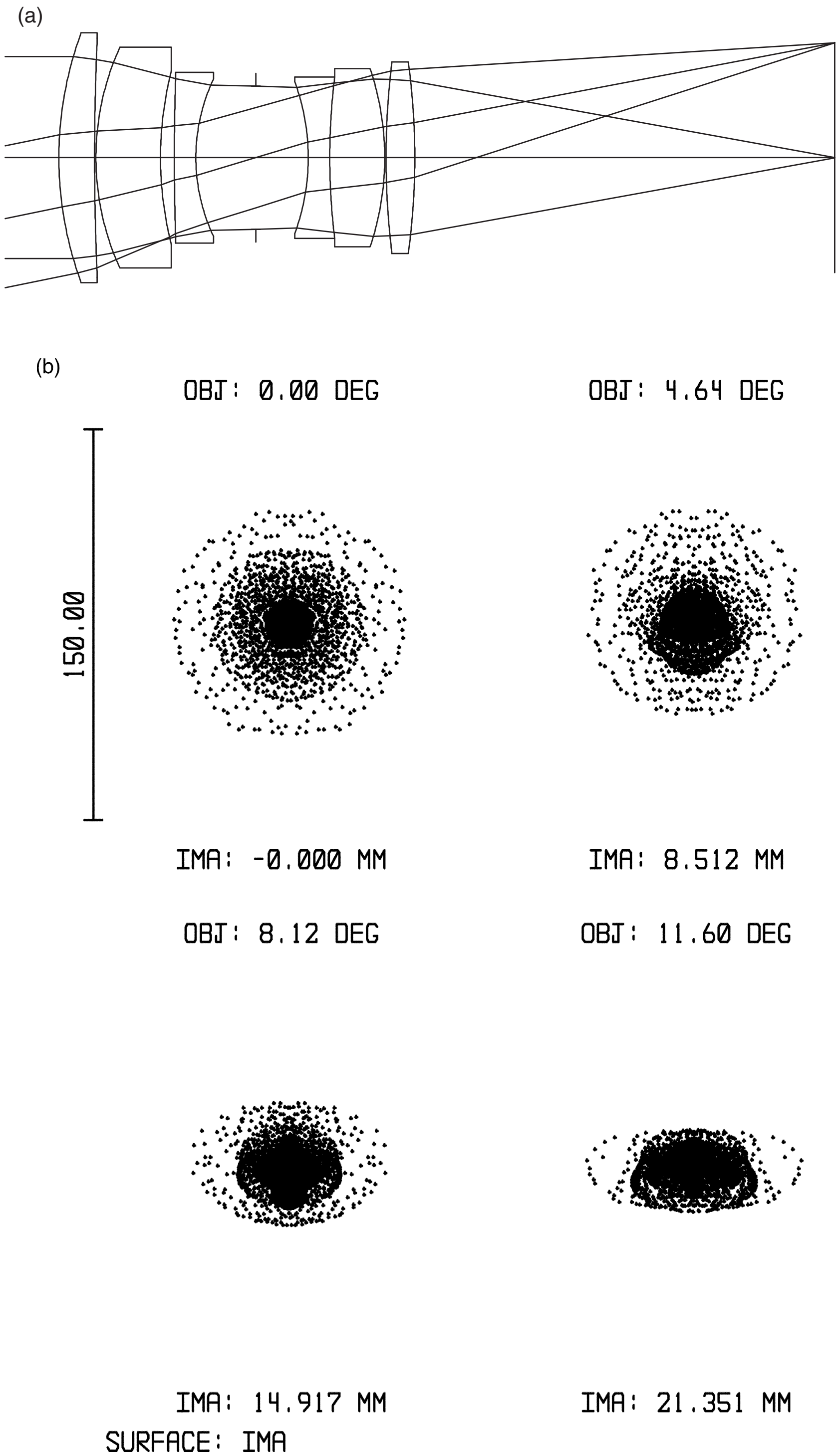

Figure 25.1 (a) Cross-section layout of Double-Gauss: 105 mm, $f/2.8$, ± 11.6 deg and (b) Spot diagram for Double-Gauss. Size measured in microns.

portraits without the perspective exaggeration produced when using a normal lens too close. Figure 25.1(a) is the layout.

The spot diagram is Fig. 25.1(b). Image quality is excellent and remarkably constant all across the field. Both on-axis and off-axis, the main aberration is secondary longitudinal color. As we shall see, secondary color is a very common aberration in longer-focal-length lenses. There is also some oblique spherical aberration off-axis. At the edge of the field, distortion is -0.95% and illumination is 67%. Sharpest opening is $f/11$. The overall length of this lens from its front surface to the image is 144 mm, which is significantly greater than its effective focal length of 105 mm. This is the opposite of a true telephoto lens.

25.2 Sonnar, 105 mm, *f*/2.8

For a 105 mm long-focus lens having an $f/2.8$ speed, the competitor to the Double-Gauss is the Sonnar. This is reminiscent of their rivalry in former decades in high-speed normal lenses. But this time the Sonnar is the winner.

Recall that a Sonnar is a modified and expanded Cooke Triplet. For historical reasons, this version of a Sonnar, which has an added airspace in the center three-element group, is called an Ernostar by some designers.

For this example, focal length is again 105 mm, field of view is 23.2 (± 11.6) degrees, speed is $f/2.8$, the image surface is flat, and color correction is panchromatic. The layout is Fig. 25.2(a) and the spot diagram is Fig. 25.2(b). The aberration mix is very similar to that of the Double-Gauss, with perhaps a bit of coma added. The image quality is not quite as uniform across the field, but it is still excellent. At the edge of the field, distortion is $+0.47\%$ and illumination is 60%. Sharpest opening is between $f/11$ and $f/16$.

The most significant difference from a practical standpoint is overall length, which is now only 118 mm. Although not a true telephoto, the Sonnar is shorter than an equivalent Double-Gauss. And you get this advantage with almost no penalty in image quality. In the marketplace, this compactness is the deciding

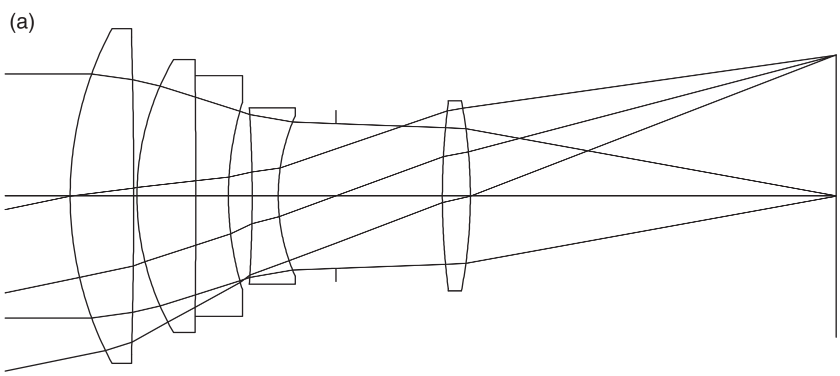

Figure 25.2 (a) Cross-section layout of Sonnar: 105 mm, $f/2.8$, ± 11.6 deg and (b) Spot diagram for Sonnar. Size measured in microns.

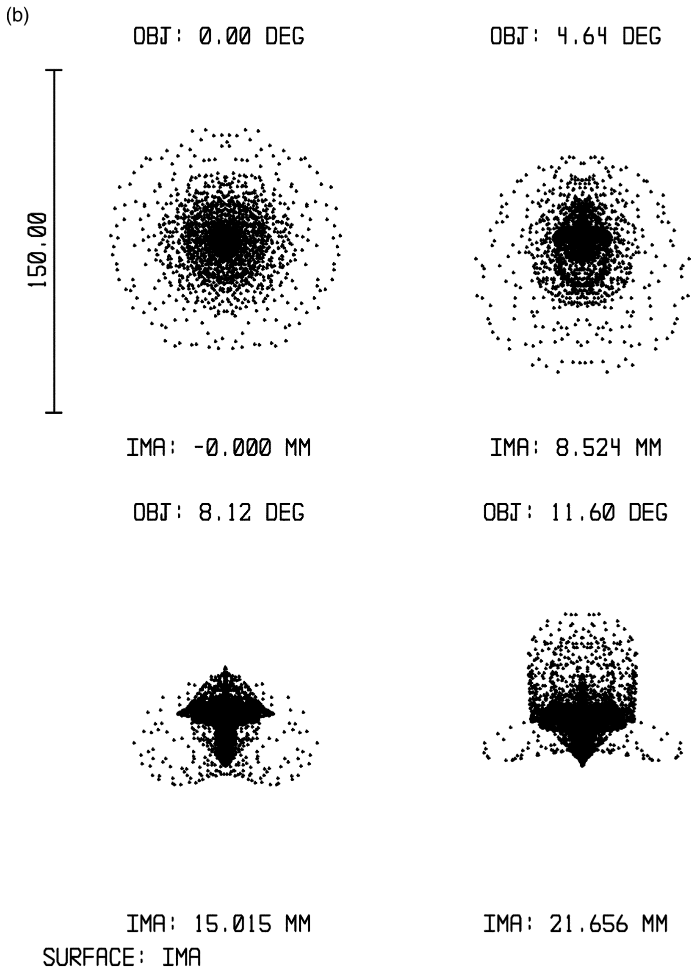

Figure 25.2 *Continued.*

factor. It also has five elements instead of six, which reduces cost. Today for a 24×36 mm film or digital format, most lenses that have focal lengths between 85 mm and 135 mm and a speed of around $f/2.8$ are similar to this Sonnar-Ernostar design.

25.3 True Telephoto, 300 mm, $f/4.0$

When the focal lengths of tele lenses for 35 mm cameras get much beyond 135 mm, the importance of reducing overall length becomes ever greater. Here the true telephoto design approach is especially valuable.

In this example, focal length is 300 mm, but overall physical length has been restricted to be only 250 mm. The three elements in the front have net positive

optical power, and the two elements in the rear have net negative optical power. Astronomers do the same thing when they add a negative Barlow lens to their telescope to increase effective focal length. The front part alone would have a focal ratio of about $f/2.6$, but when the rear part is added, the focal ratio of the combination becomes $f/4.0$. A maximum opening of $f/4.0$ was selected to hold down weight in what is now becoming a rather big lens. Field of view is 8.2 (± 4.1) degrees, the image surface is flat, and color correction, as usual, is panchromatic. To prevent vibrations, a long-focal-length lens such as this is usually mounted on a tripod, although sometimes a special gunstock-type support can be employed. Lenses with roughly this focal length are widely used for sports action photography, nature photography, and for police and military surveillance. The lens is really a little telescope. The layout is Fig. 25.3(a).

The spot diagram is Fig. 25.3(b). Both on-axis and off-axis, the dominant aberration is a rather large amount of secondary longitudinal color. The image surface has been placed at the best compromise location for all wavelengths. Off-axis, there is some secondary lateral color too. Relative to the chromatic aberrations, the monochromatic aberrations are small. As mentioned earlier, this color is typical of all-refractive tele lenses made of normal glasses. The problem is caused by a mismatch of partial dispersions, that is, the shapes of the glasses' refractive-index-versus-wavelength curves are different. At the edge of the field, distortion is +0.39% and illumination is 78%. With its longer focal length scaling up aberrations, sharpest opening is now $f/22$.

There are two ways around this problem. The first way is to make one or more of the elements of glasses having abnormal partial dispersions. Now the crown and flint glasses, which must have different regular dispersions, can have similar partial dispersions, thus making them a better match for each other. Favorite abnormal glasses are the fluoro-crowns and crystal fluorite (calcium fluoride). Others are the short flints, such as KzFSN4. When done carefully, secondary color can be reduced or even eliminated. A lens having no secondary color is called an apochromat. However, apochromats are still not completely color-free; they have a residual aberration called tertiary color. But tertiary color is nearly always much smaller than secondary color.

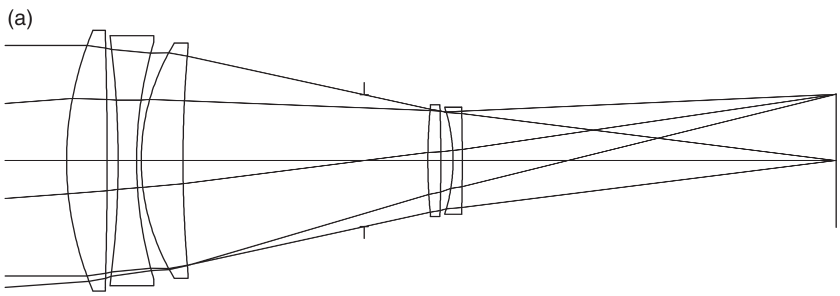

Figure 25.3 (a) Cross-section layout of Telephoto: true telephoto, 300 mm, $f/4$, ± 4.1 deg and (b) Spot diagram for Telephoto. Size measured in microns.

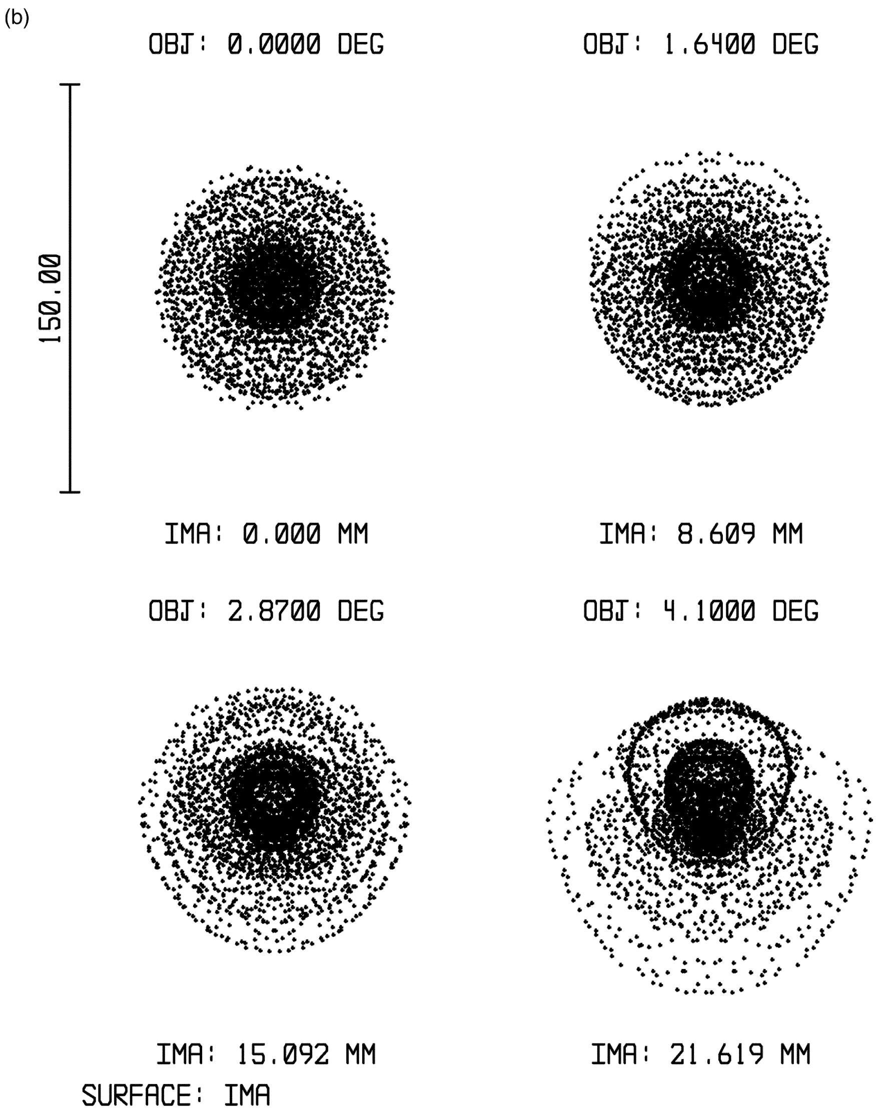

Figure 25.3 *Continued.*

As might be expected, the abnormal-dispersion glasses are expensive and more difficult to work in the optical shop. Thus long tele lenses with less color are expensive. Nevertheless, their cost is coming down somewhat as they are becoming more widely used.

25.4 Catadioptric Telescope, 1200 mm, *f*/8.0

The second way to reduce color in long-focal-length tele lenses is to use reflecting mirrors instead of refracting lenses for much of the major optical power. Mirrors

are useful because all wavelengths are reflected the same amount without chromatic aberrations. Refractive elements can be included with mirrors, but the function of the lenses now becomes more to control aberrations than for heavy-duty ray bending. An optical system incorporating both mirrors and lenses together is called catadioptric, or more colloquially, a "cat-lens" or even a "mirror-lens."

An example of a cat-lens is shown in Fig. 25.4(a). The light passes through a full-aperture singlet corrector lens in front and is then reflected by the large primary mirror. The primary mirror in this case is not a first-surface mirror (reflecting surface on the front side) like those found in most reflecting telescopes. Instead, to give more design variables to help control aberrations, it has its

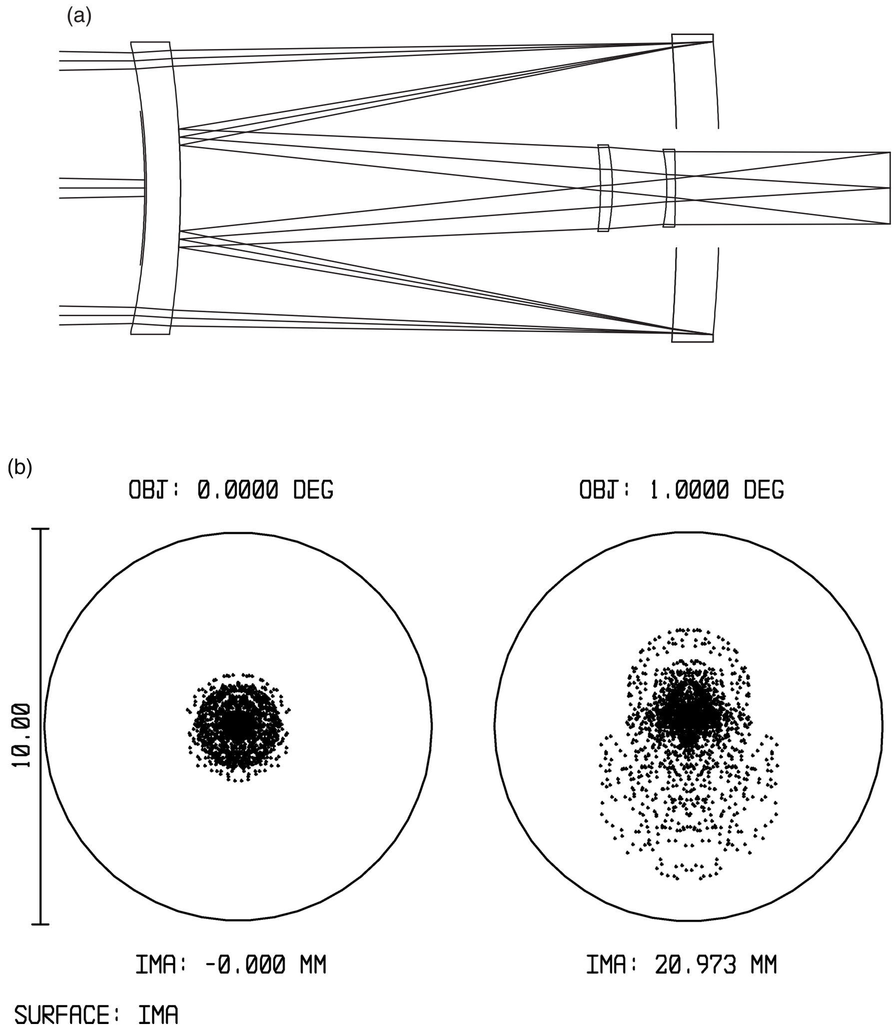

Figure 25.4 (a) Cross-section layout of Cat-Lens: D = 150 mm, $f = 1200$, $f/8$, ± 1 deg and (b) Spot diagram for Cat-Lens. Size measured in microns.

reflecting surface on the back side and the light passes through the mirror substrate twice, once in each direction. Such a second-surface lens-mirror is called a Mangin mirror. The light is next reflected by a smaller secondary mirror, which is formed here by an aluminized spot in the center of the back of the big corrector lens. In the middle of the front side, there is an opaque painted area that serves as a baffle against stray light. The converging beams finally pass through two small lenses that further control aberrations before being focused onto the flat image plane, which is located behind a hole in the middle of the primary mirror. These two small lenses are not an achromat but are rather a nearly-zero-power corrector with both elements made of the same glass type. The result of all these elements is a modification and extension of a classical Cassegrain telescope.

For this cat-lens, effective focal length is 1200 mm, entrance pupil diameter is 150 mm (nearly 6 inches), overall focal ratio on the image surface is $f/8$, corner-to-corner field of view on a 24×36 mm detector is 2.0 (± 1.0) degrees, and color correction is panchromatic. Because this system has an entrance pupil with a central obscuration, it cannot be used stopped down (the middle of each focused light cone is missing due to the shadow of the secondary mirror and baffle).

Note on the layout that the concave primary mirror has positive (converging) optical power, and the convex secondary mirror has negative (diverging) optical power. Thus this cat-lens is a reflecting version of a true telephoto lens. The focal ratio of the light coming off the primary mirror is about $f/2.8$, whereas the overall effective focal ratio on the image surface is $f/8$. The system is also folded twice, once by each reflection, thus making a package about 440 mm long, which is very short considering its 1200 mm focal length.

Figure 25.4(b) is the spot diagram. The large circles represent the size of the Airy diffraction disk on the image surface. All across the field the spots are much smaller than the Airy disk. Thus the exact shape of the spots is unimportant; all that matters is that they are small and will get lost in the diffraction. This system is clearly diffraction-limited. Its performance is limited only by the finite wavelength of light. This is another reason for not stopping down (a smaller entrance pupil would make diffraction worse). Given its first-order parameters, you cannot get image sharpness better than this. Distortion at the edge of the field is a negligible $+0.14\%$.

Cat-lenses are very popular with photographers who need a compact system with a long focal length. However, cat-lenses have that central obscuration. This causes two problems in addition to not being able to stop down. First, some of the light is blocked. In this example, which has no regular vignetting, all across the field only about 63% of the light incident on the entrance pupil gets past the central obscuration and to the focus (not counting any losses by imperfect reflections and transmissions). Thus the final image brightness seems more like $f/10$ (or maybe $f/11$) rather than $f/8$. Second, out-of-focus highlights and glints in a picture appear as bright doughnuts instead of disks. This effect is not aesthetically pleasing and shouts cat-lens. But for many applications, especially nature and astronomical photography, cat-lenses similar to this are the ones to have.