

# Lens Combinations

## INFINITE CONJUGATE RATIO

As shown in the previous discussion, the best-form singlet lens for use at infinite conjugate ratios is generally nearly plano-convex. Figure 1.24 shows a plano-convex lens (LPX-15.0-10.9-C) with incoming collimated light at a wavelength of 546.1 nm. This drawing, including the rays traced through it, is shown to exact scale. The marginal ray (ray f-number 1.5) strikes the paraxial focal plane significantly off the optical axis.

This situation can be improved by using a two-element system. The second part of the figure shows a precision achromat (LAO-21.0-14.0), which consists of a positive low-index (crown glass) element cemented to a negative meniscus high-index (flint glass) element. This is drawn to the same scale as the plano-convex lens. No spherical aberration can be discerned in the lens. Of course, not all of the rays pass exactly through the paraxial focal point; however, in this case, the departure is measured in micrometers, rather than in millimeters, as in the case of the plano-convex lens. Additionally, chromatic aberration (not shown) is much better corrected in the doublet. Even though these lenses are known as achromatic doublets, it is important to remember that even with monochromatic light the doublet's performance is superior.

Figure 1.24 also shows the f-number at which singlet performance becomes unacceptable. The ray with f-number 7.5 practically intercepts the paraxial focal point, and the  $f/3.8$  ray is fairly close. This useful drawing, which can be scaled to fit a plano-convex lens of any focal length, can be used to estimate the magnitude of its spherical aberration, although lens thickness affects results slightly.

## UNIT CONJUGATE RATIO

Figure 1.25 shows three possible systems for use at the unit conjugate ratio. All are shown to the same scale and using the same ray f-numbers with a light wavelength of 546.1 nm. The first system is a symmetric biconvex lens (LDX-21.0-19.2-C), the best-form singlet in this application. Clearly, significant spherical aberration is present in this lens at  $f/2.7$ . Not until  $f/13.3$  does the ray closely approach the paraxial focus.

A dramatic improvement in performance is gained by using two identical plano-convex lenses with convex surfaces facing and nearly in contact. Those shown in figure 1.25 are both LPX-20.0-20.7-C. The combination of these two lenses yields almost exactly the same focal length as the biconvex lens. To understand why this configuration improves performance so dramatically, consider that if the biconvex lens were split down the middle, we would have two identical plano-convex lenses, each working at an infinite conjugate ratio, but with the convex surface toward the focus. This orientation is opposite to that shown to be optimum for this shape lens. On the other hand, if these lenses are reversed, we have the system just described but with a better correction of the spherical aberration.

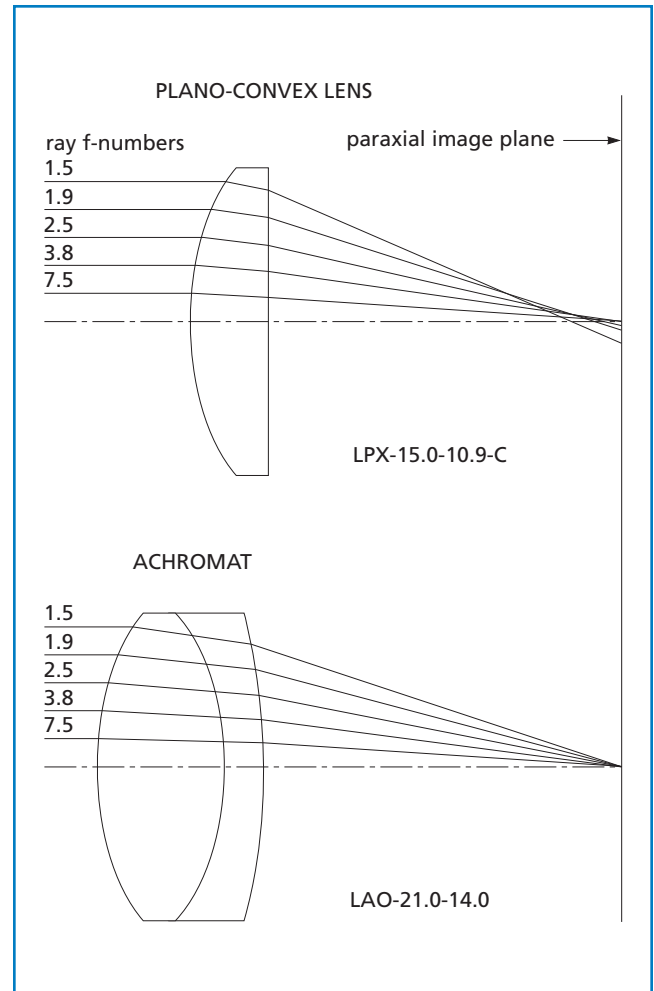


Figure 1.24 Single-element plano-convex lens compared with a two-element achromat

Previous examples indicate that an achromat is superior in performance to a singlet when used at the infinite conjugate ratio and at low f-numbers. Since the unit conjugate case can be thought of as two lenses, each working at the infinite conjugate ratio, the next step is to replace the plano-convex singlets with achromats, yielding a four-element system. The third part of figure 1.25 shows a system composed of two LAO-40.0-18.0 lenses. Once again, spherical aberration is not evident, even in the  $f/2.7$  ray.

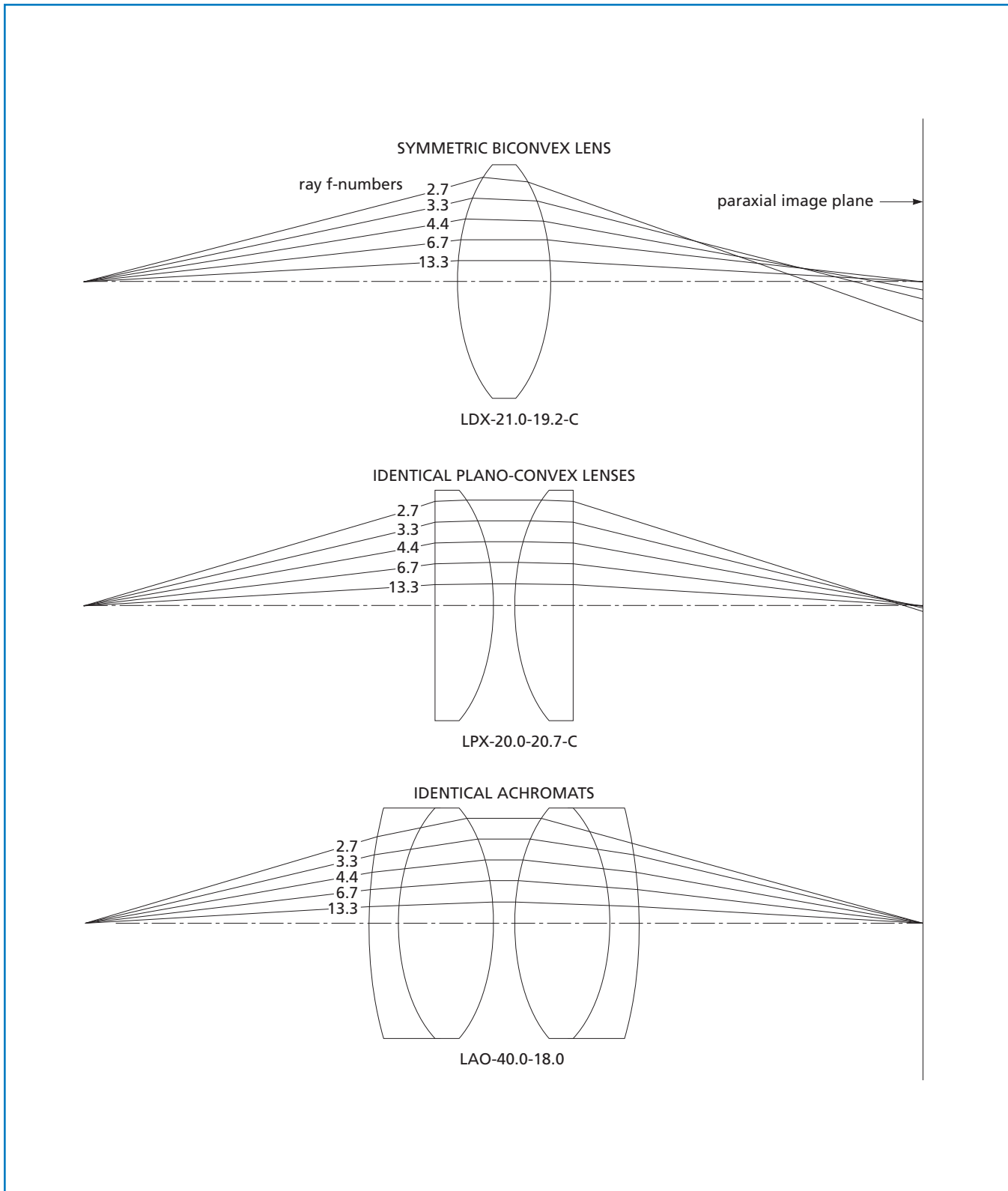


Figure 1.25 Three possible systems for use at the unit conjugate ratio