Metrology of Optical Systems

Figures and Images for Instructors

Module 1

Optical System Parameters and Performance Metrics

Precision Optics Series

National Center for Optics and Photonics Education

This text was developed by the National Center for Optics and Photonics Education (OP-TEC), University of Central Florida, under NSF ATE grant 1303732. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

Published and distributed by
OP-TEC
University of Central Florida
http://www.op-tec.org

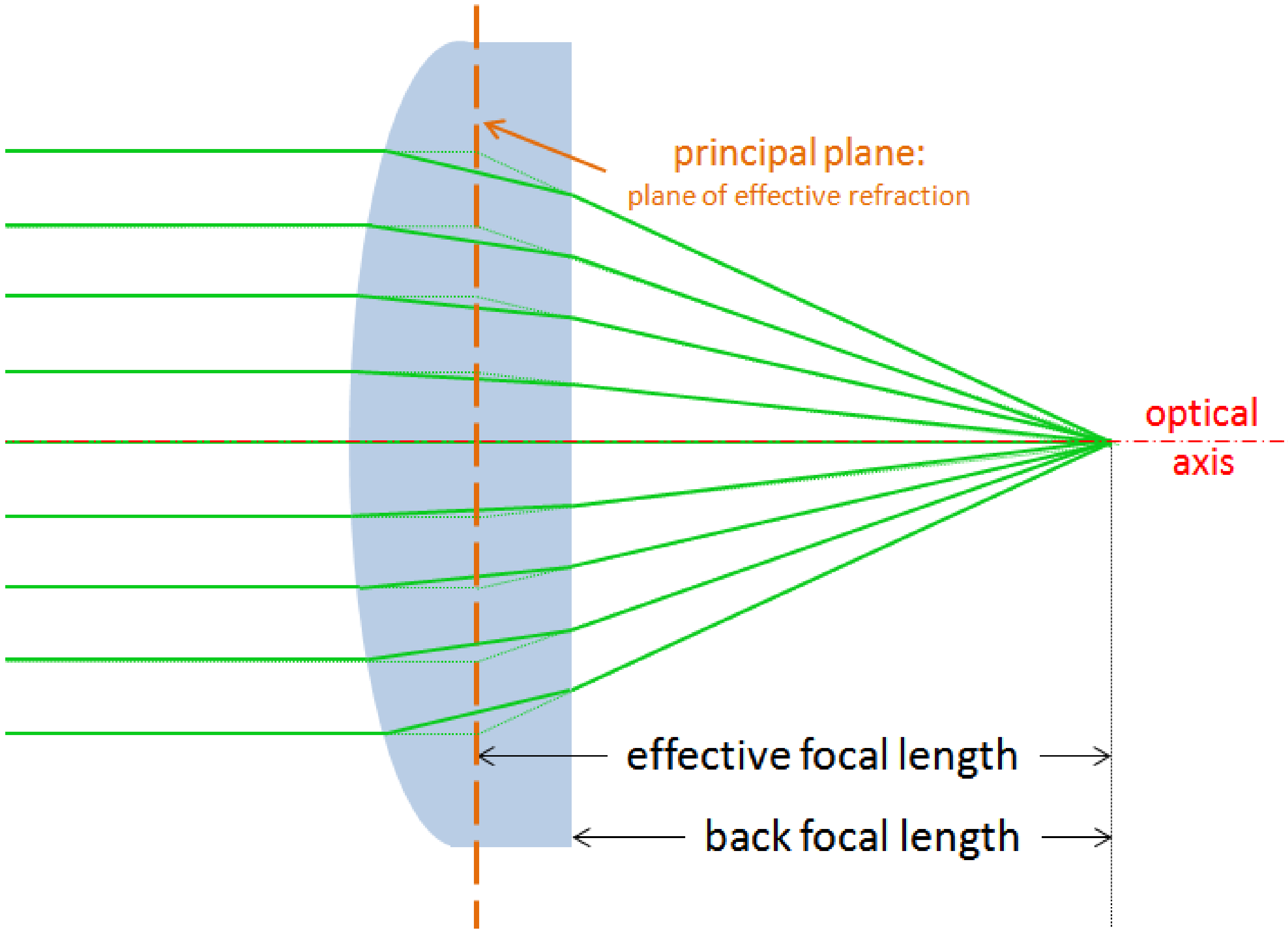


Figure 1-1 *The focal length is measured as the distance along the optical axis not from the back surface of the lens, but from the principal plane to the focal spot.*

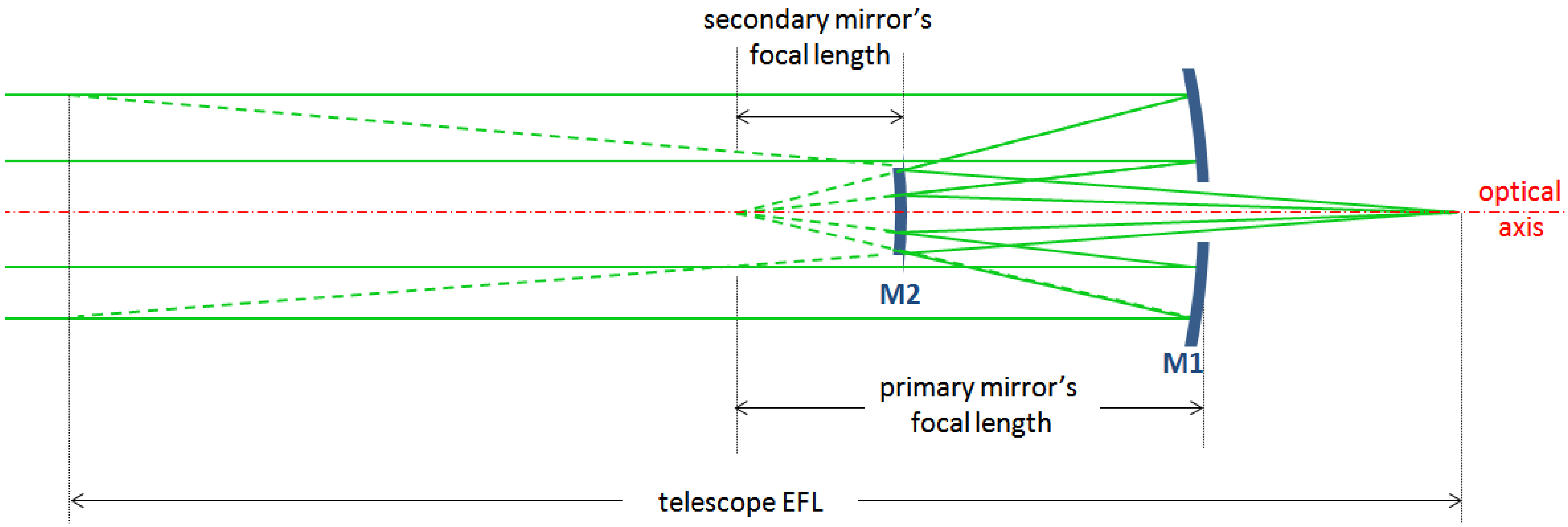


Figure 1-2 *A Cassegrain telescope creates a long effective focal length (EFL) in a short tube using two mirrors with focal lengths that are shorter than the composite EFL*

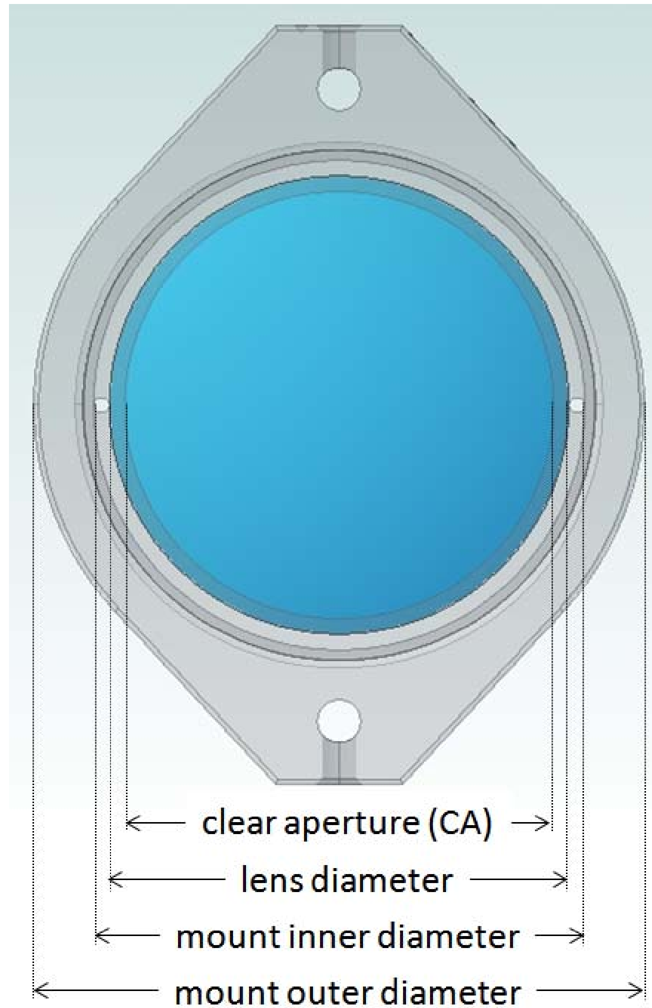


Figure 1-3 *The clear aperture is a diameter over which an optical element meets its design specifications. It is usually slightly smaller than the physical lens diameter.*

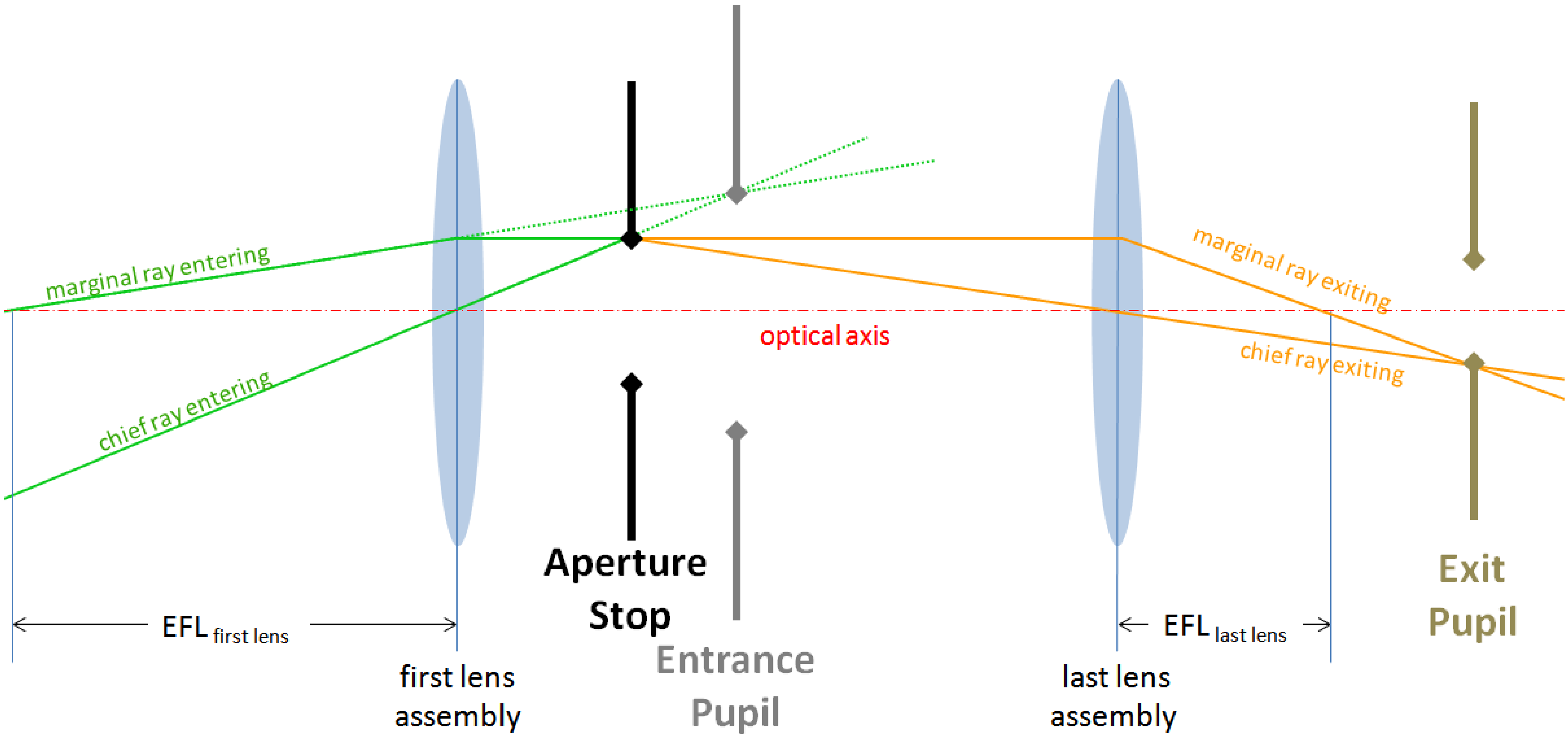


Figure 1-4 *The entrance and exit pupil location and size are determined by imaging the aperture stop.*

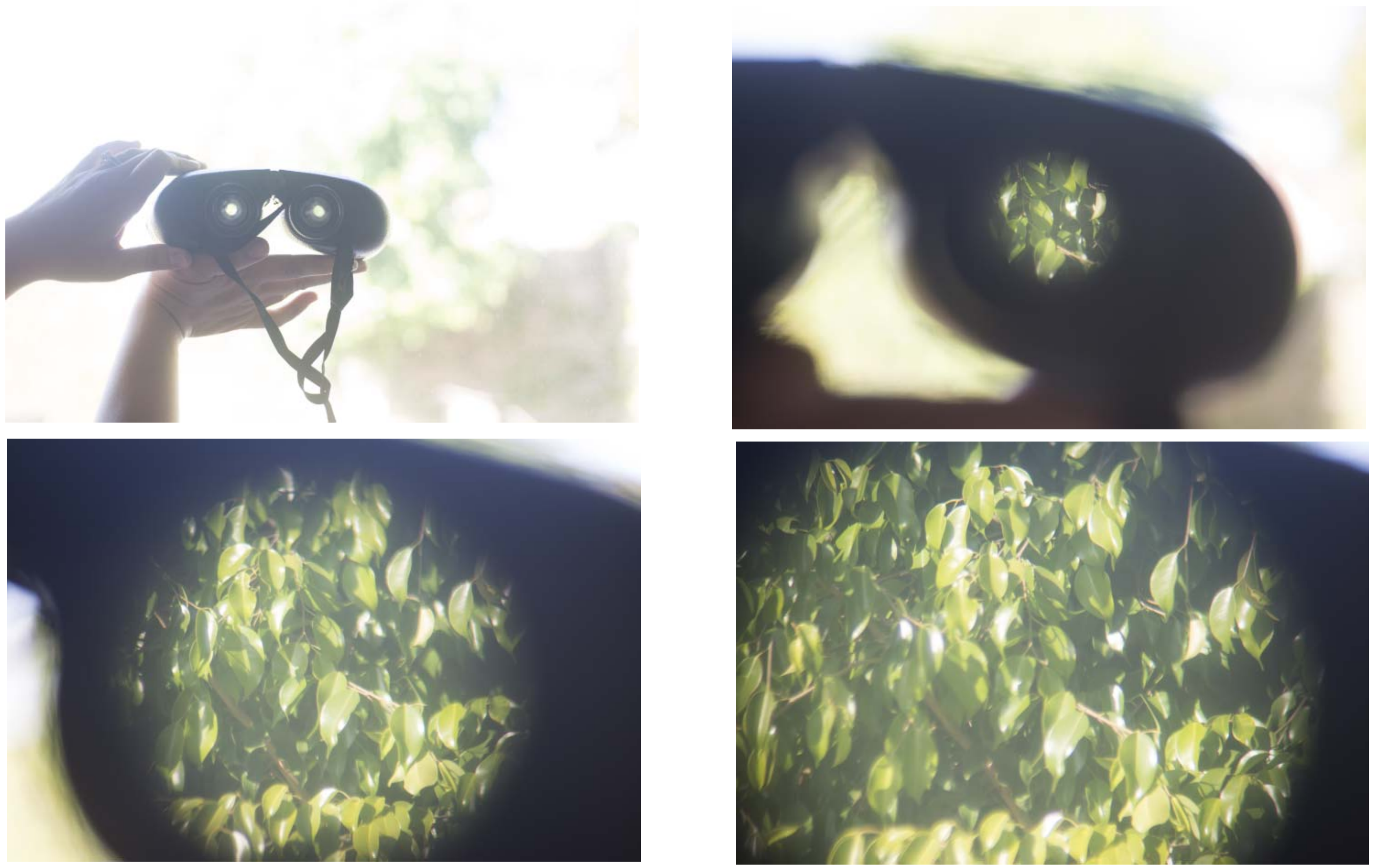


Figure 1-5 *Successive images of this figure are taken as two optical systems, a binocular and a camera (the camera used to take these pictures) are moved closer together. In the first three images, a mismatch exists between the size and location of the exit pupil of the binoculars and the entrance pupil of the camera used to take the picture. The mismatch exists due to incorrect separation of the two optical systems along the optical axis. Therefore, the mismatch is improved by moving the systems (and their pupils) closer together until they overlap and nearly all light through the binocular enters the camera's aperture.*

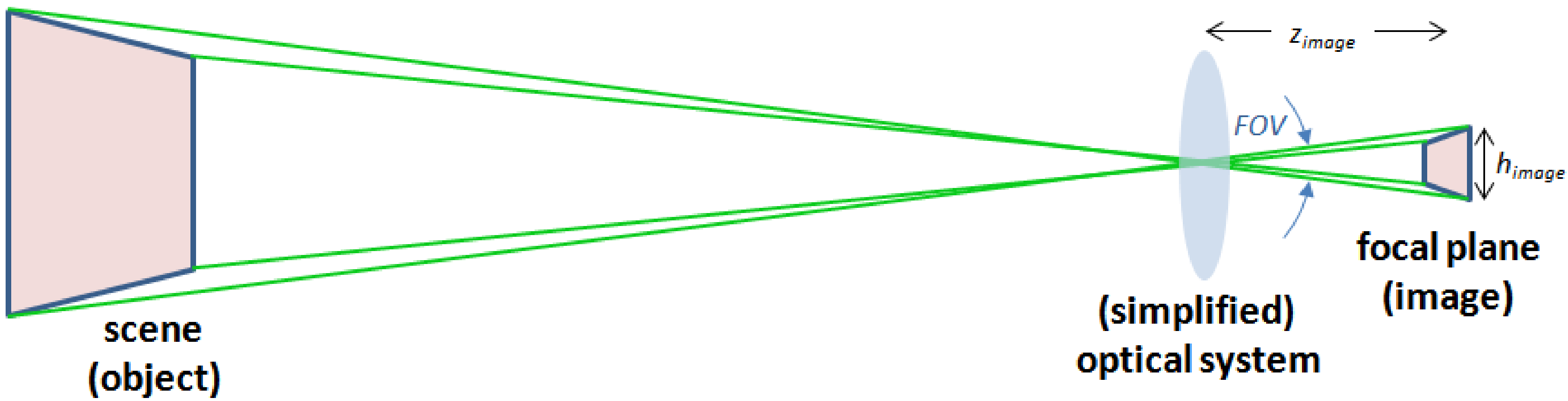


Figure 1-6 *The FOV is proportional to the physical extent of the focal plane (image)*

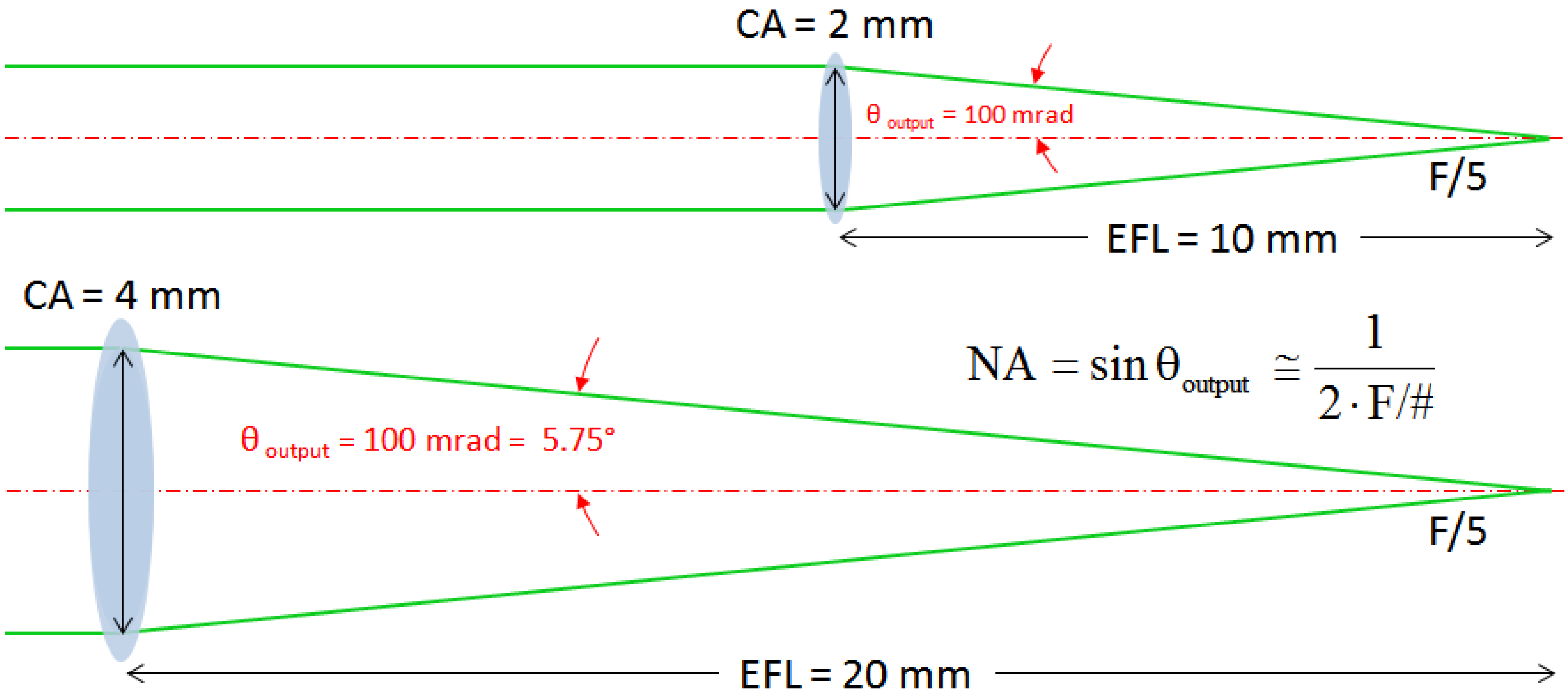


Figure 1-7 *Two F/5 optical systems with different defining parameters are shown. For an F/5 system,* θ_{output} *equals 100 milliradians or 5.75°.*

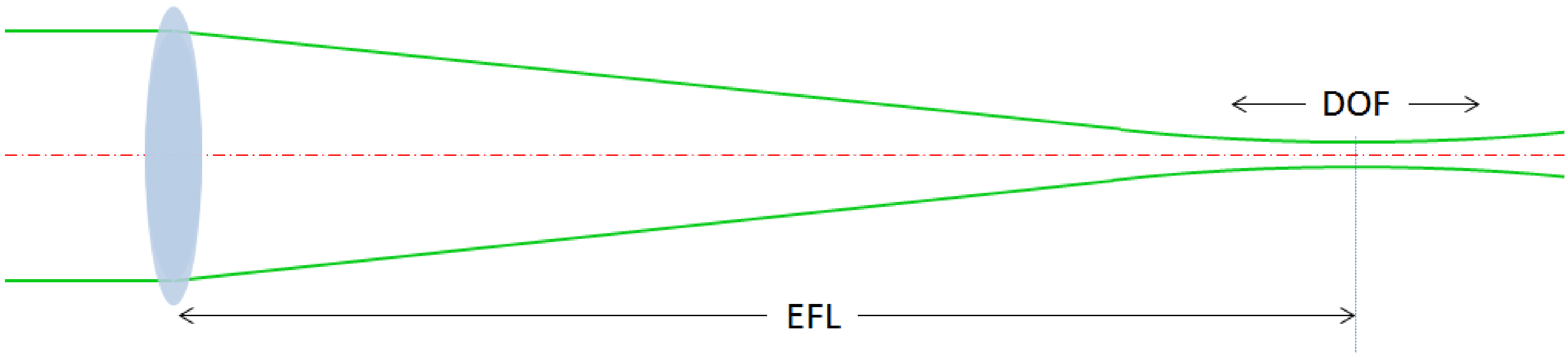


Figure 1-8 *Light is in focus over a focal region known as the depth of focus (DOF). Faster (lower) f-numbers and shorter wavelengths create smaller depths of focus.*

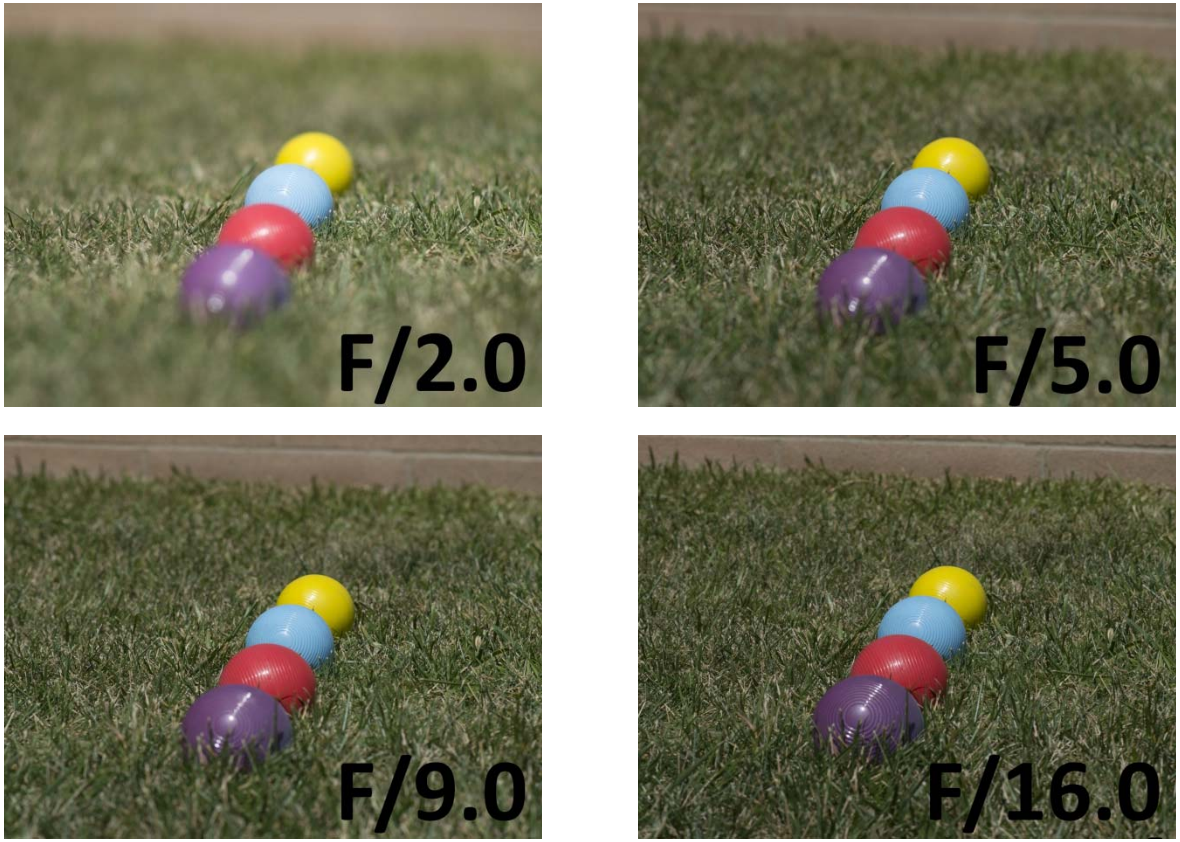


Figure 1-9 *The principal of depth of field (DOF) is illustrated by these four images. When the camera's aperture is stopped down (reduced in diameter), the value of the F/# increases and the DOF increases. The grooves in the blue ball are evident in the image shot at F/2.0, but the other balls' grooves are out of focus. When the aperture is stopped down to F/5.0, the red ball's grooves become apparent. Further stopping down the aperture to F/9.0 makes the red grooves sharply focused and shows some detail in the purple ball's grooves, but only at F/16.0 are all balls in focus. The DOF dependence on the F/# is also seen by observing fact that a deeper patch of grass is in focus for higher f-numbers.*

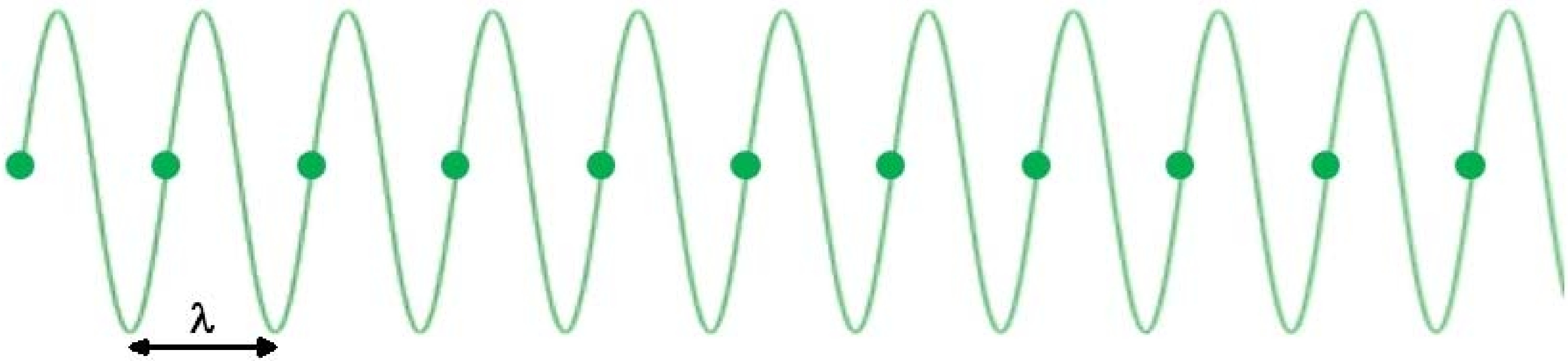


Figure 1-10 *Each dot along this wave represents a point of equal phase.*

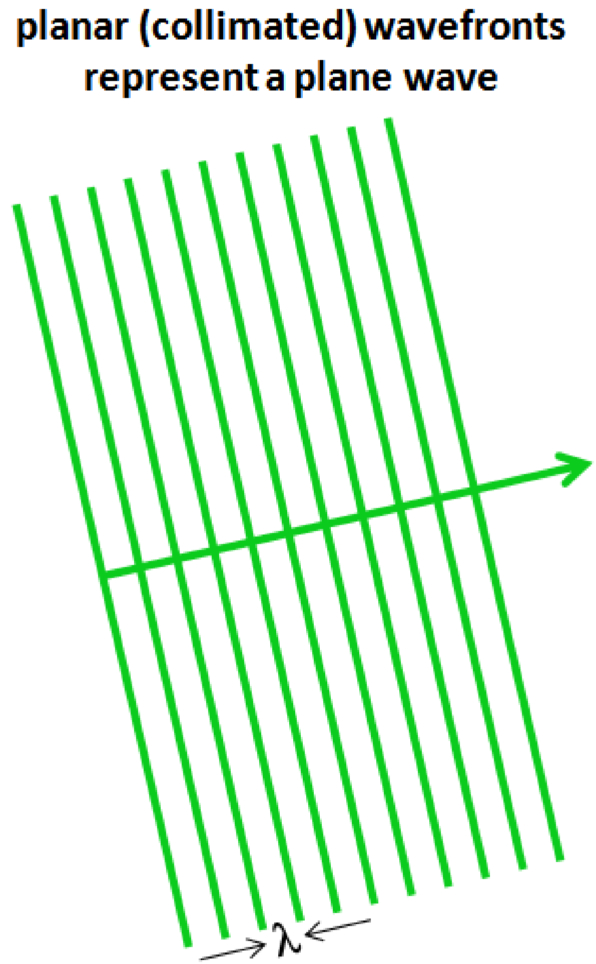


Figure 1-11 *The concept of the plane wave is shown here, along with the propagation vector of the light.*

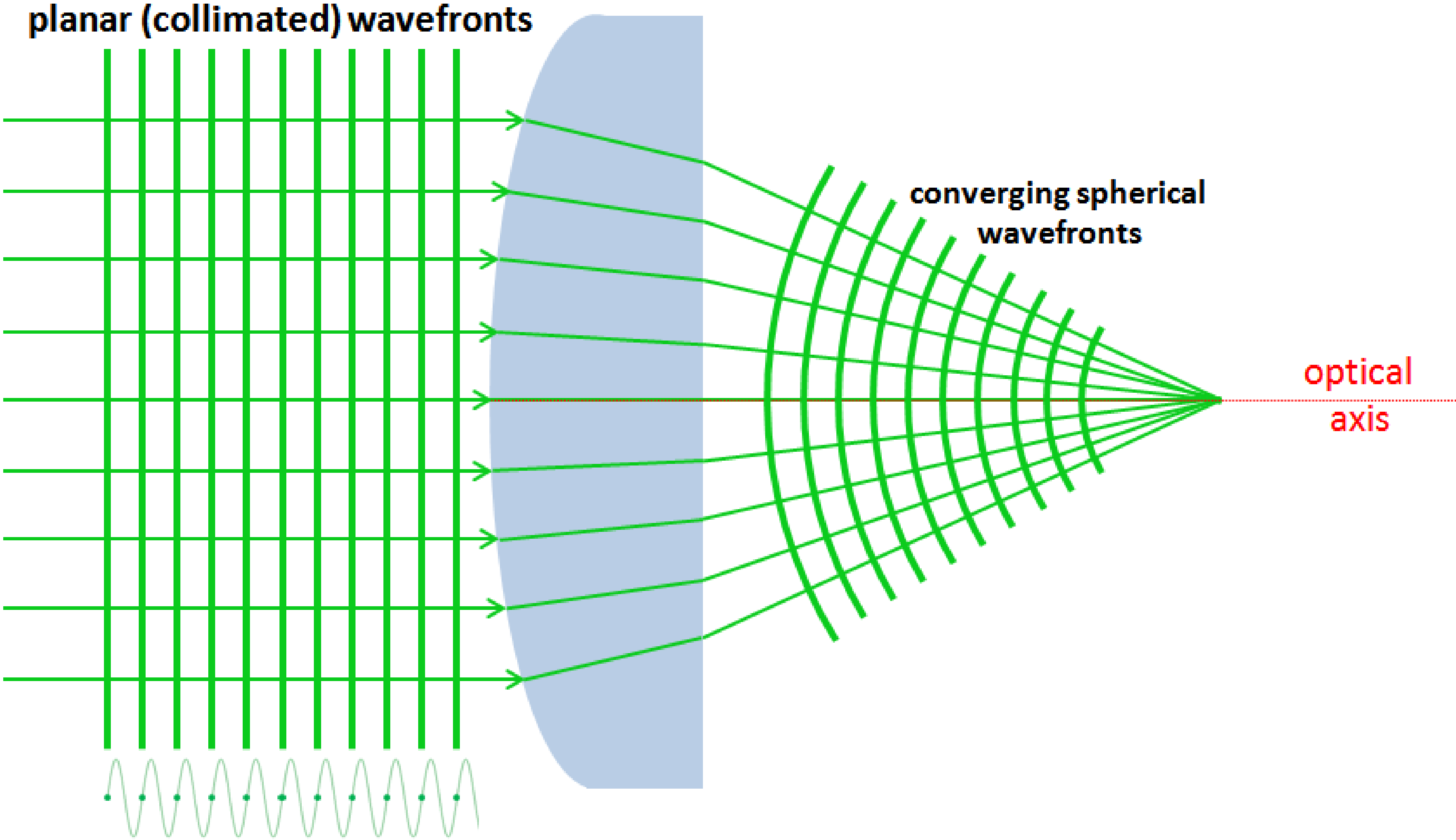


Figure 1-12 *This figure represents an ideal, collimated plane wavefront moving through a converging (focusing) lens.*

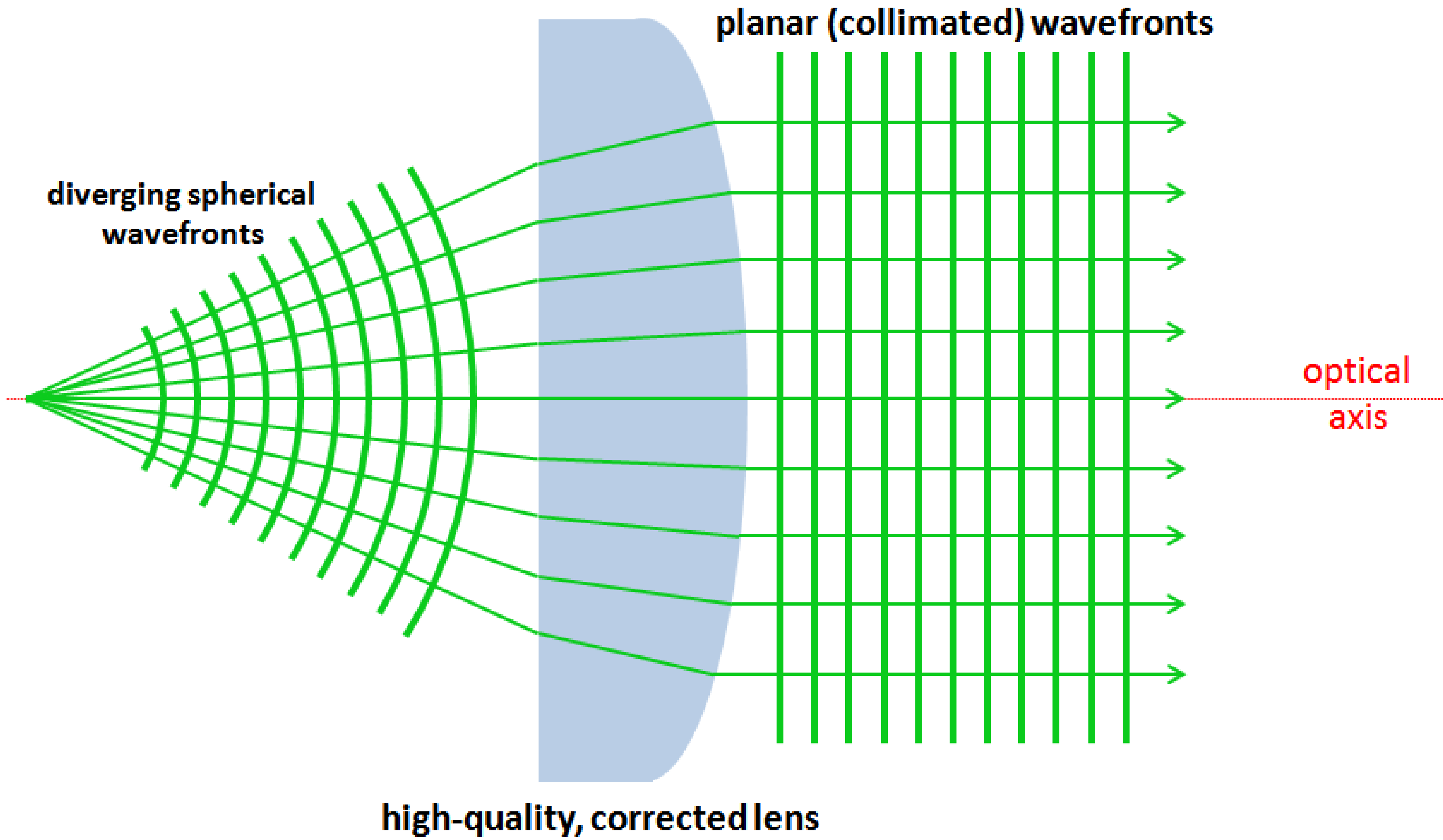


Figure 1-13 *The opposite scenario to Figure 1.12 is shown here, the collimation of a point source to an ideal, flat, collimated wavefront.*

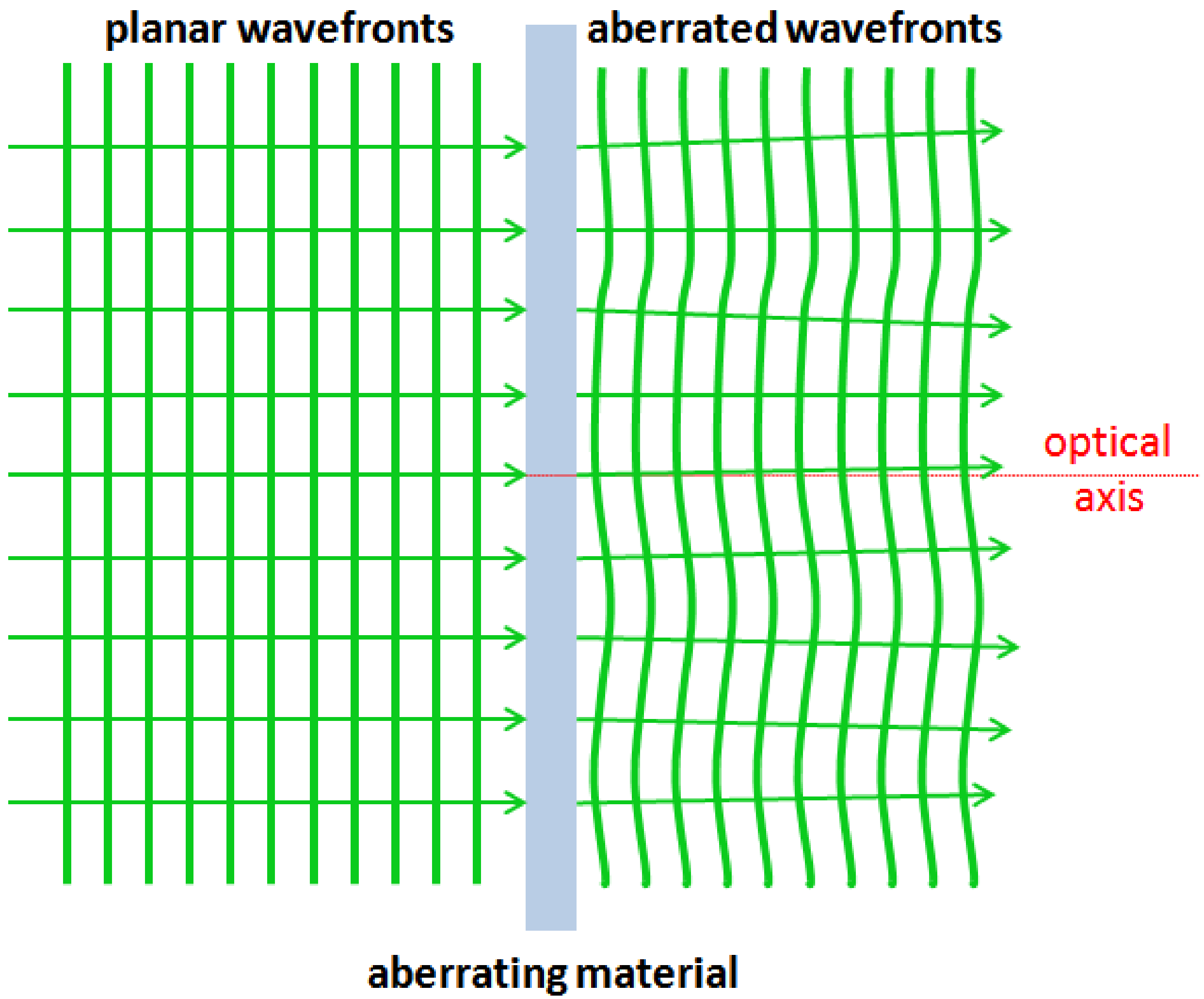
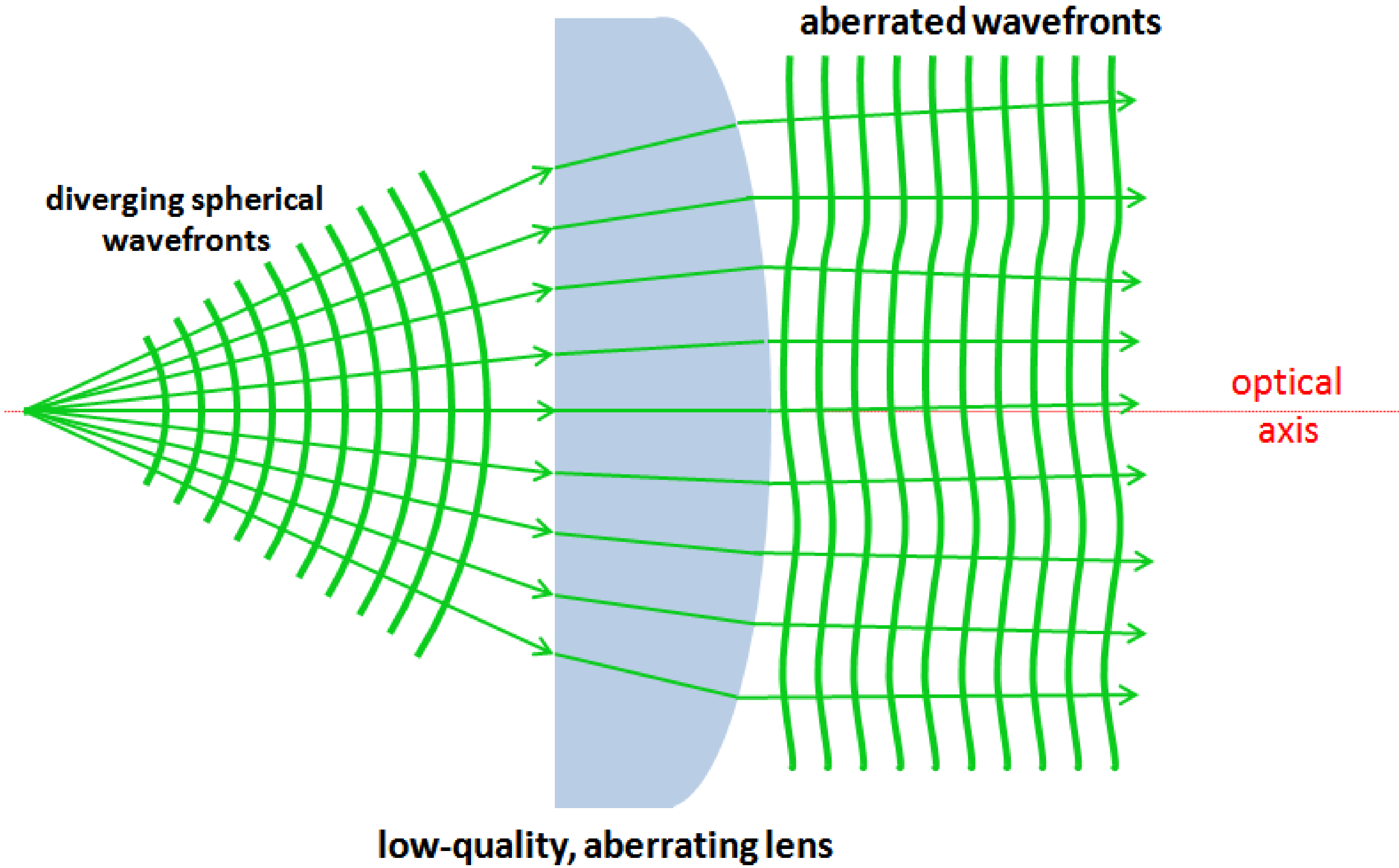

planar wavefronts
aberrated wavefronts
optical
axis
aberrating material

Figure 1-14



aberrated wavefronts
diverging spherical wavefronts
optical axis
low-quality, aberrating lens

Figure 1-15

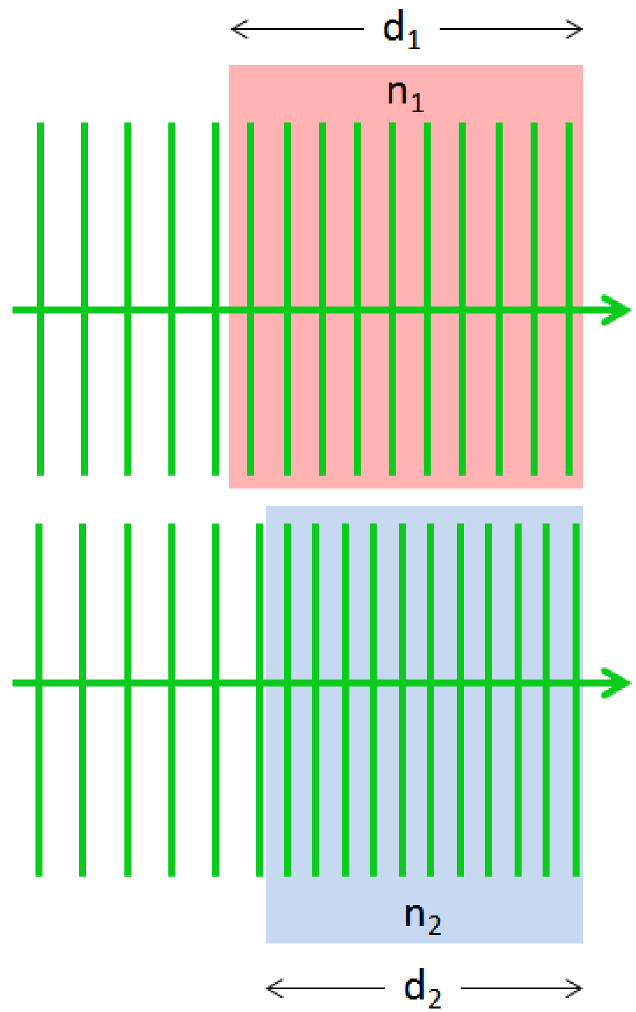


Figure 1-16 *The two rays shown take different physical paths, d_1 and d_2, through different optical materials, n_1 and n_2, resulting in an optical path difference. Even if d_1 was equal to d_2, the refractive index difference still gives the rays an OPD.*

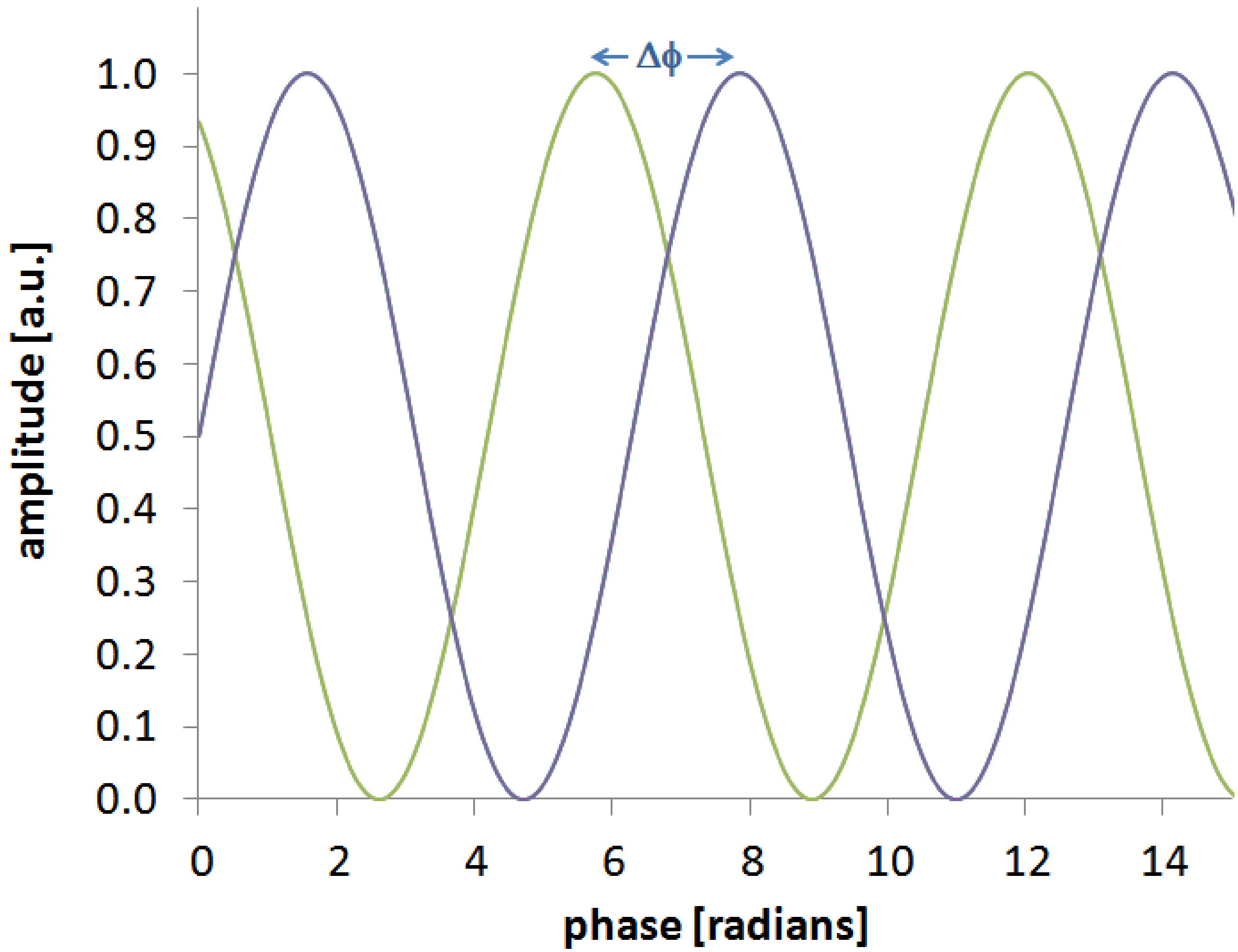


Figure 1-17 *The change in phase between the two waves shown here is indicated by the parameter Δφ. In this example, Δφ equals about 2 radians.*

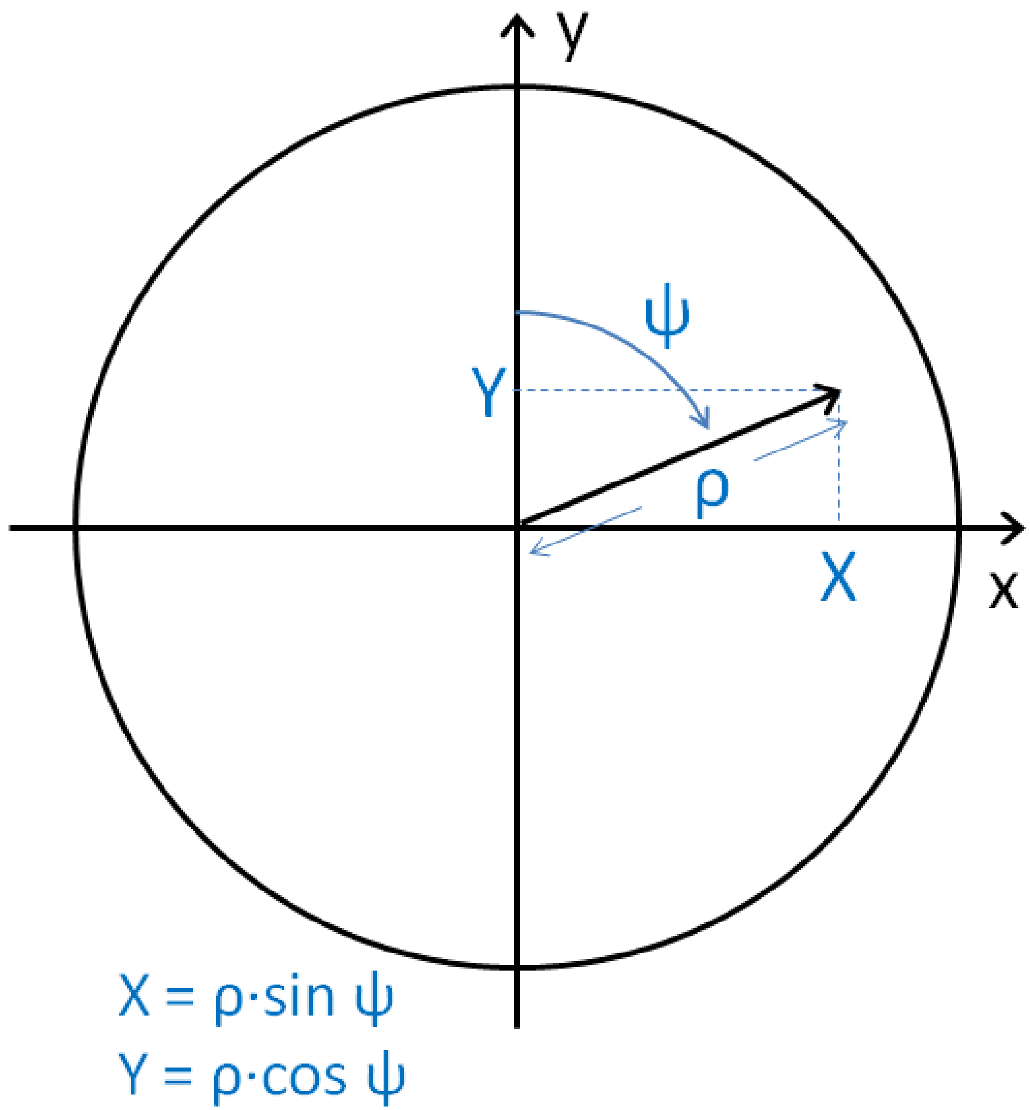


Figure 1-18 *Coordinates aberration function*

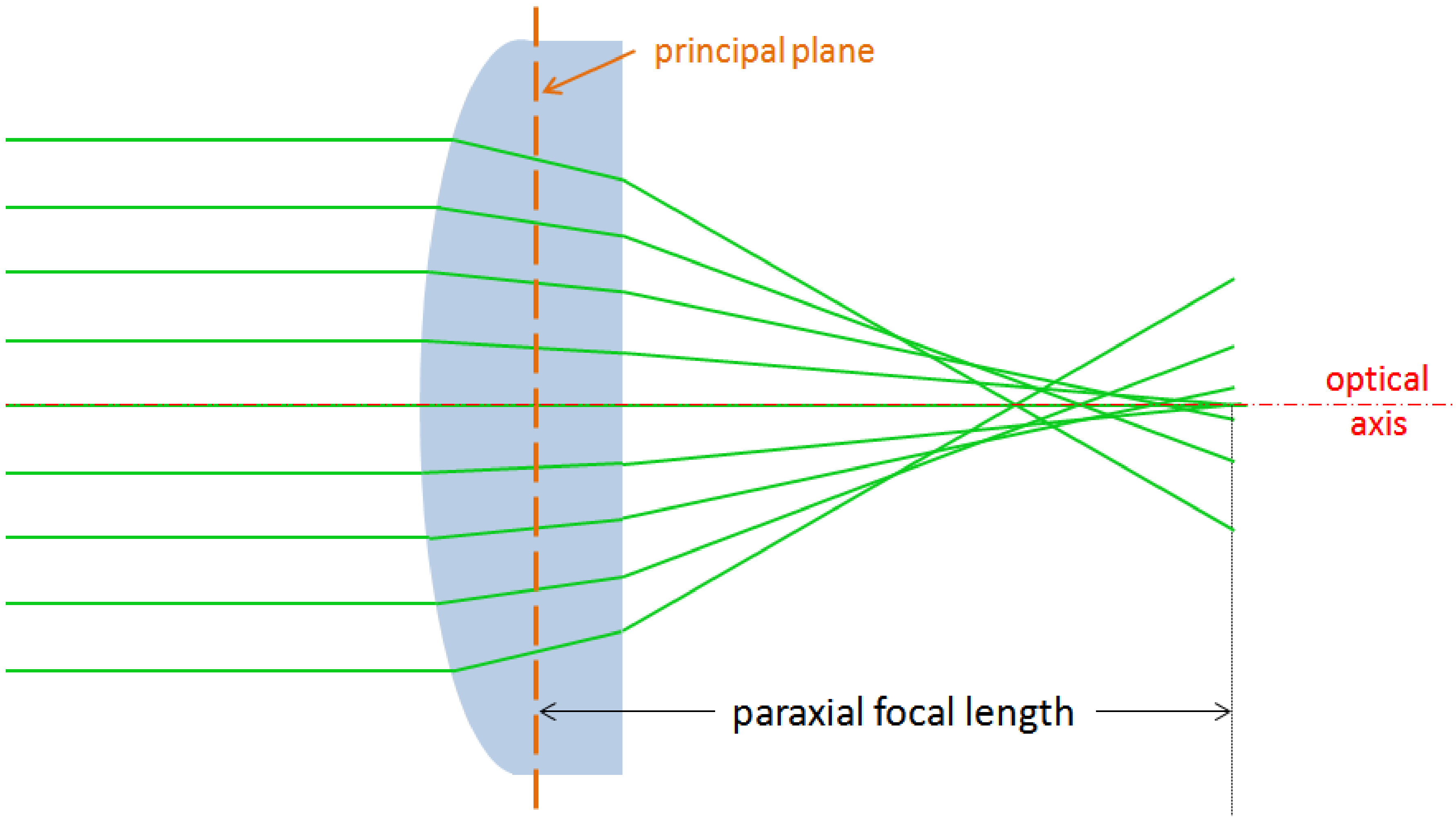


Figure 1-19 *A lens with spherical aberration is shown. The lens itself is the aperture stop, so that rays farther from the optical axis are more aberrated with respect to the paraxial rays, those near the optical axis.*

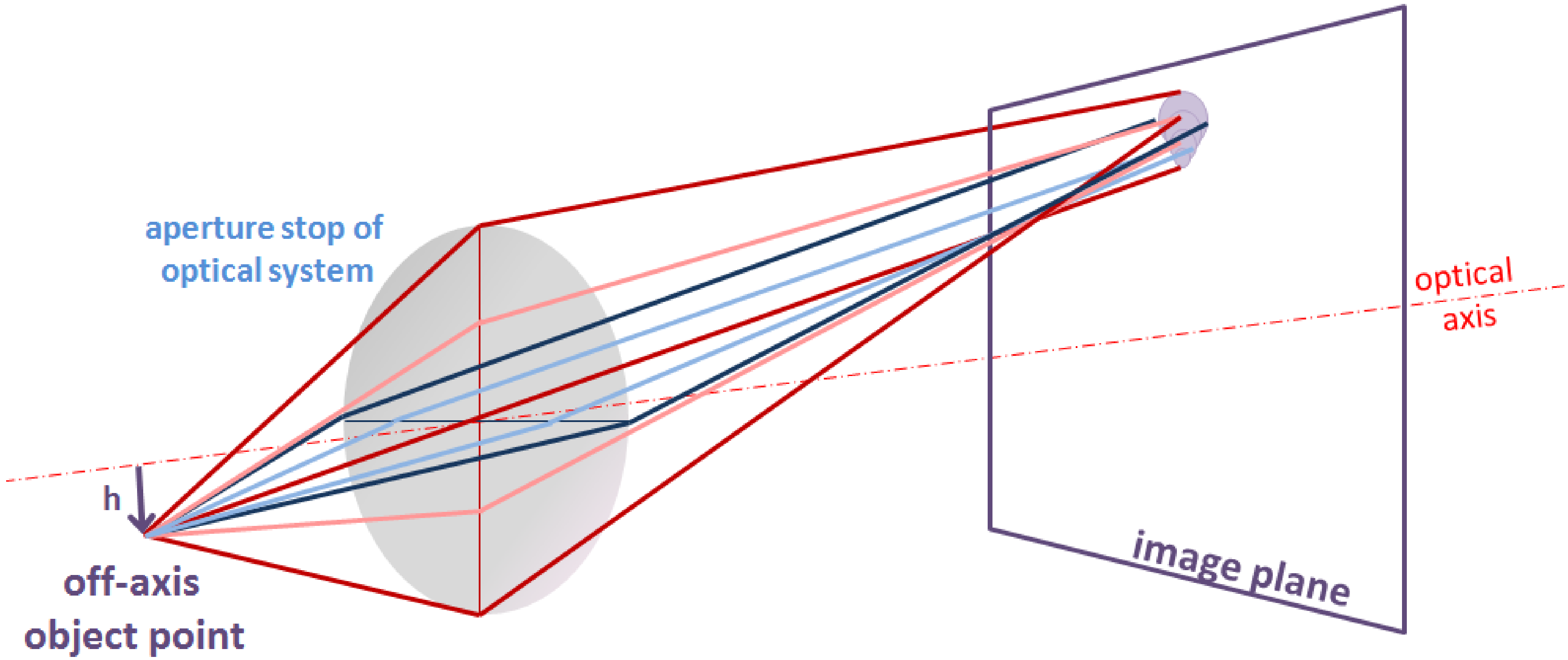


Figure 1-20 *A lens with coma is shown. Rays of different colors represent light in perpendicular planes. The lens itself is the aperture stop, so that rays entering the system at larger distances from the optical axis are more aberrated.*

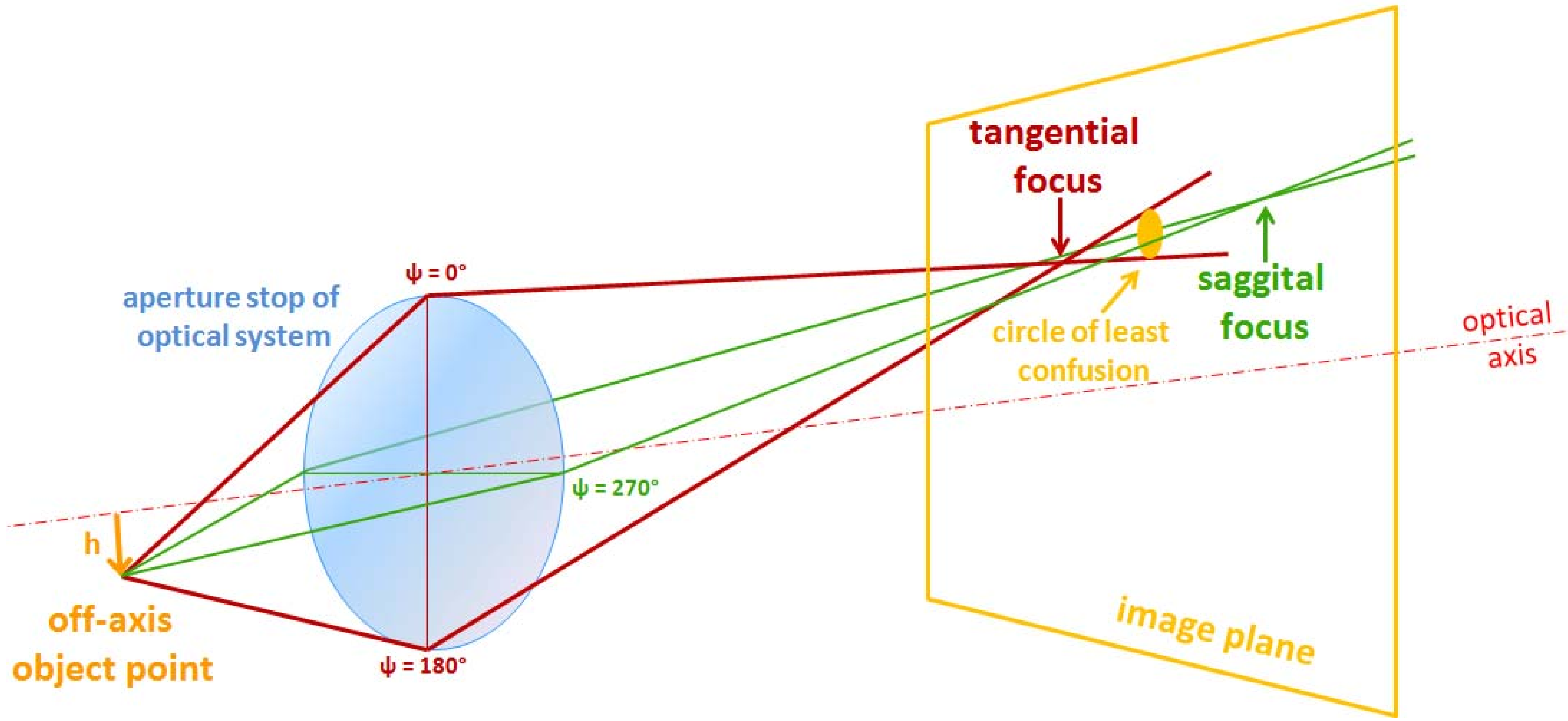


Figure 1-21 *An optical system with astigmatism is shown as an aperture stop. Rays of different colors represent light in different, perpendicular planes. The saggital (green) and tangential (red) line focuses of the off-axis point on the object are evident on either side of the circle of least confusion.*

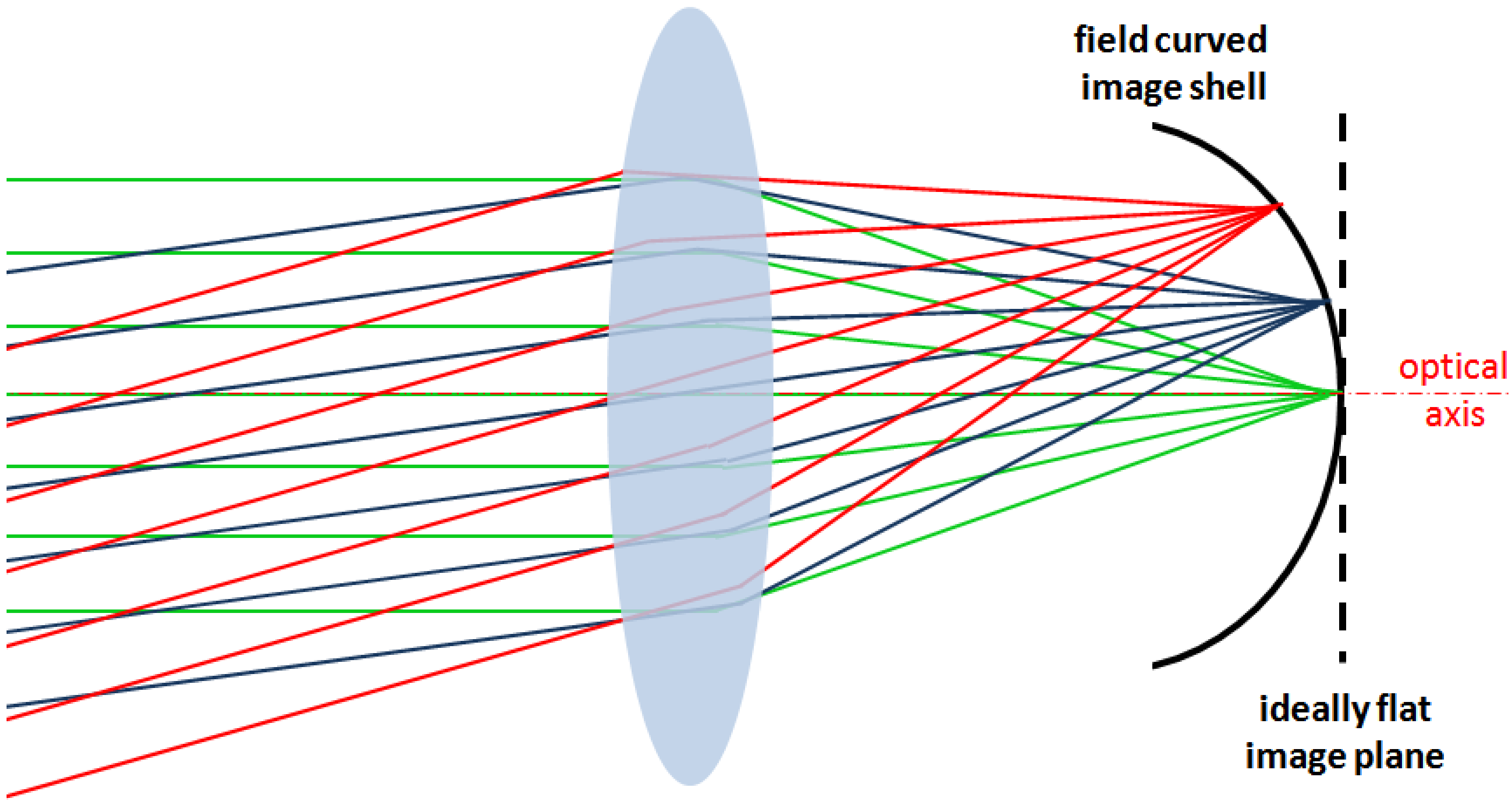


Figure 1-22 *An optical system with field curvature is shown. Different colors represent different field angles in this figure. The curved image plane is evident—larger object heights (that is, larger field angles) are imaged closer to the aperture stop than on-axis object heights.*

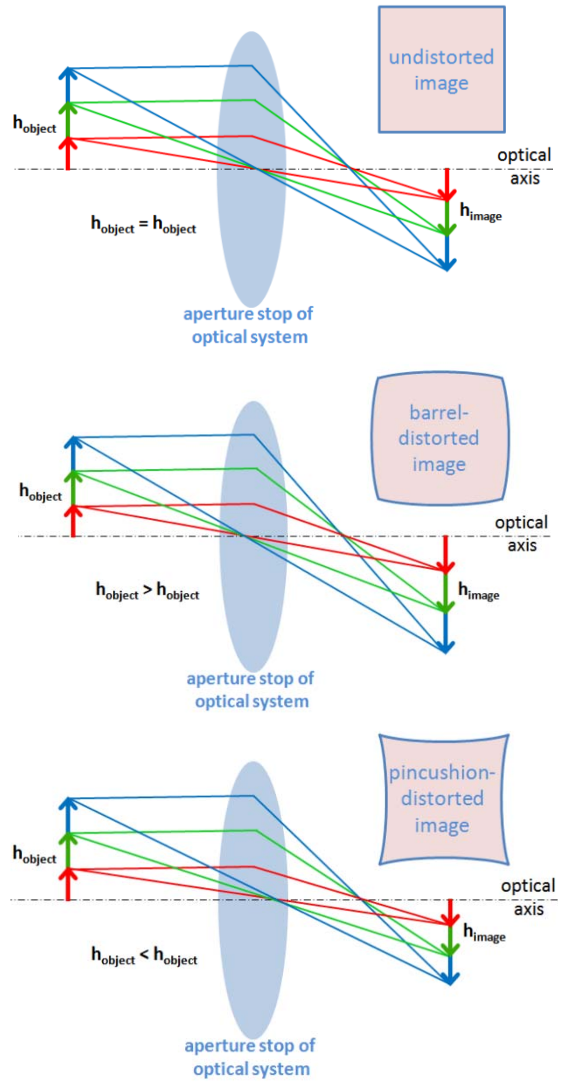


Figure 1-23 *Optical systems with zero distortion, barrel distortion, and pincushion distortion are shown. In this figure, distortion is exaggerated at about 16%. That is, image heights are equal to the object heights in the undistorted optical system, but they are 16% larger in the barrel-distorted image, and 16% smaller in the pincushion-distorted image.*

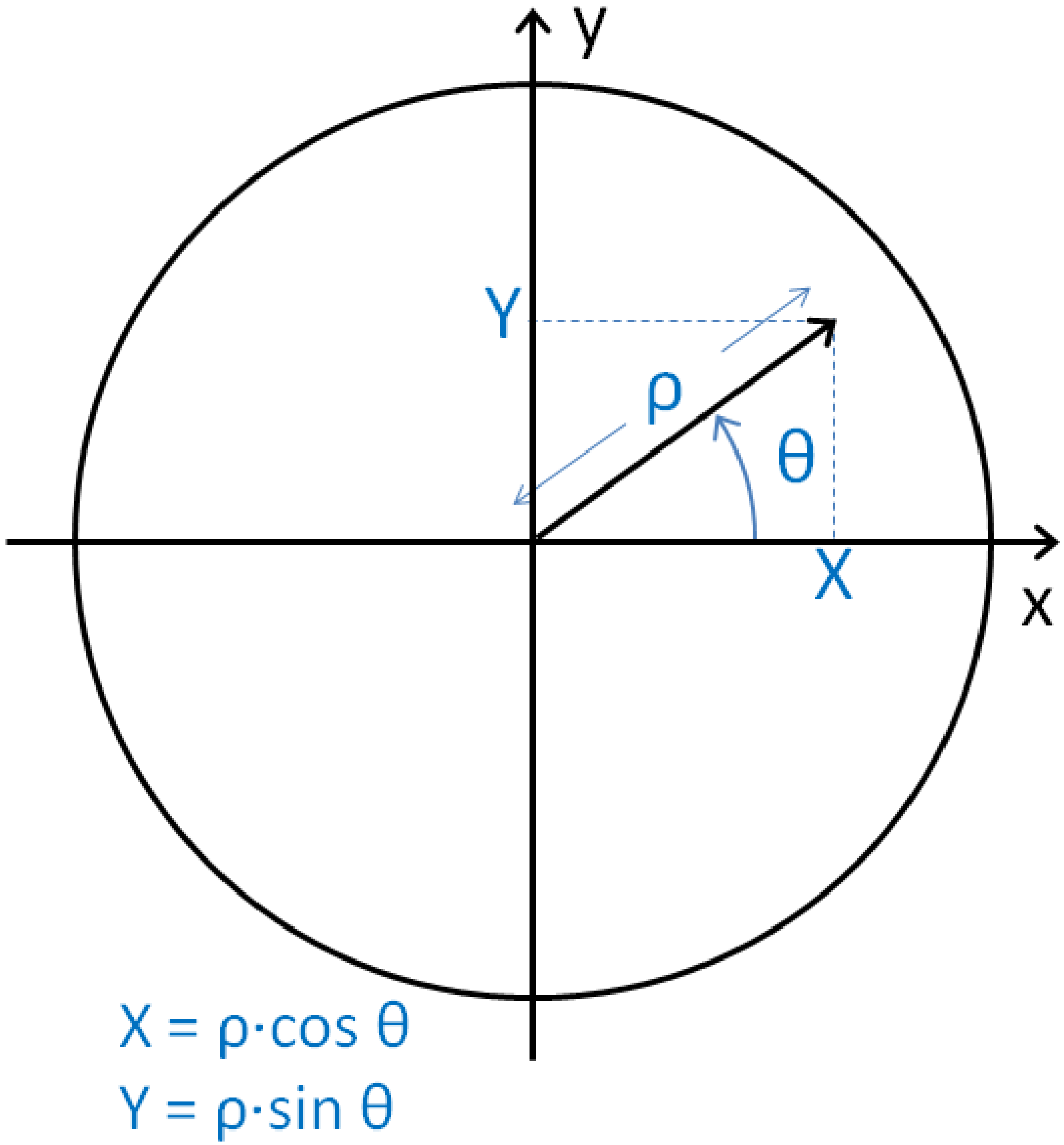


Figure 1-24 *Zernike Coordinates*

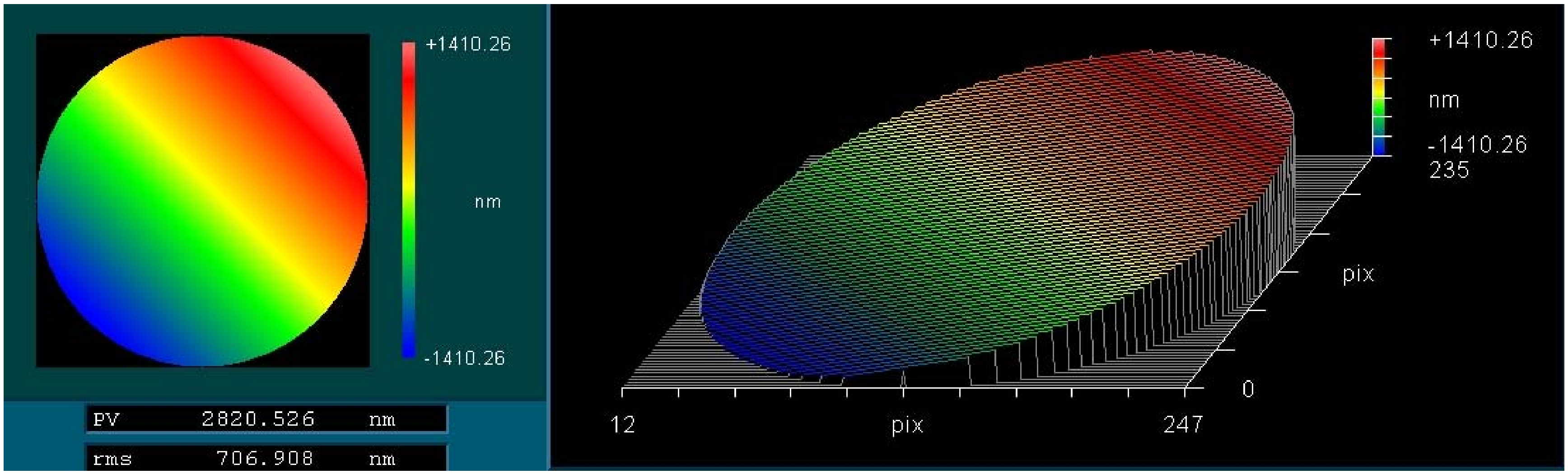


Figure 1-25 *One micrometer of x- and y-tilt are shown here, resulting in an ideally flat wavefront that is tilted at 45°.*

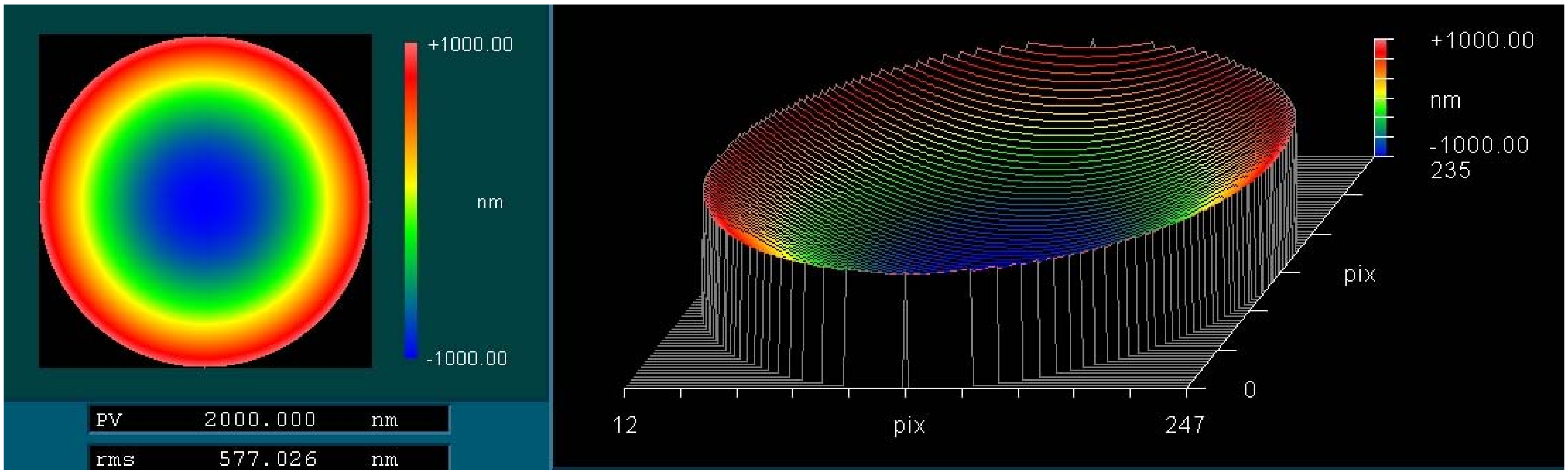


Figure 1-26 *One micrometer of focus is shown here, resulting in a wavefront that is defocused by a total of 2 µm.*

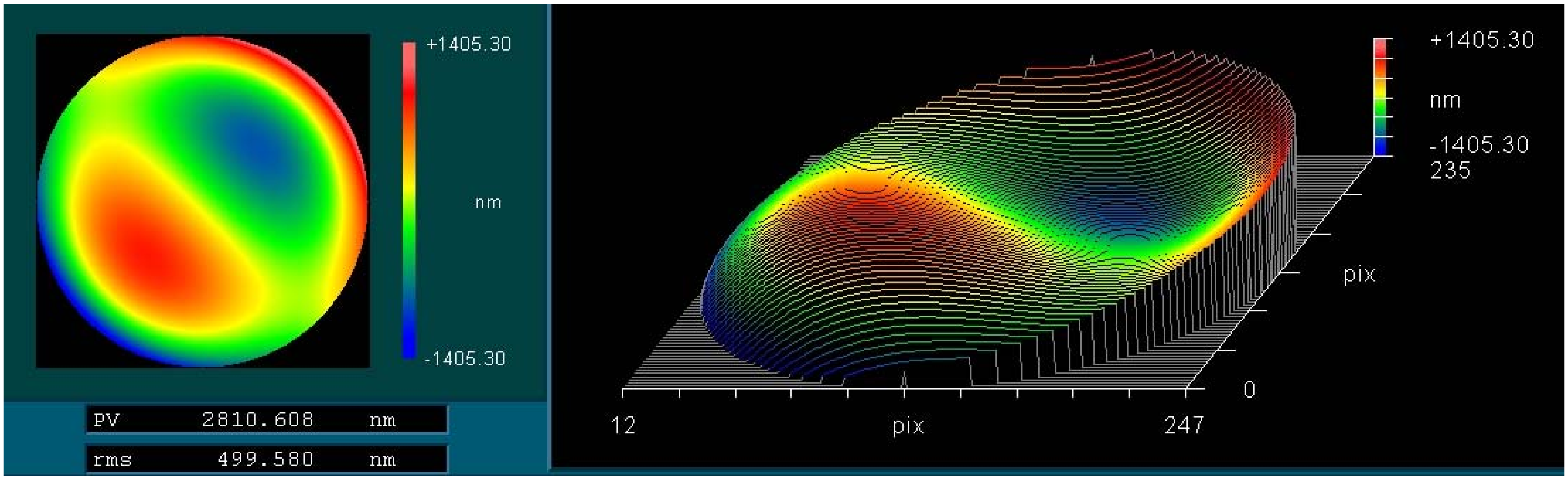


Figure 1-27 *One micrometer of x- and y-coma gives the asymmetric wavefront map shown here.*

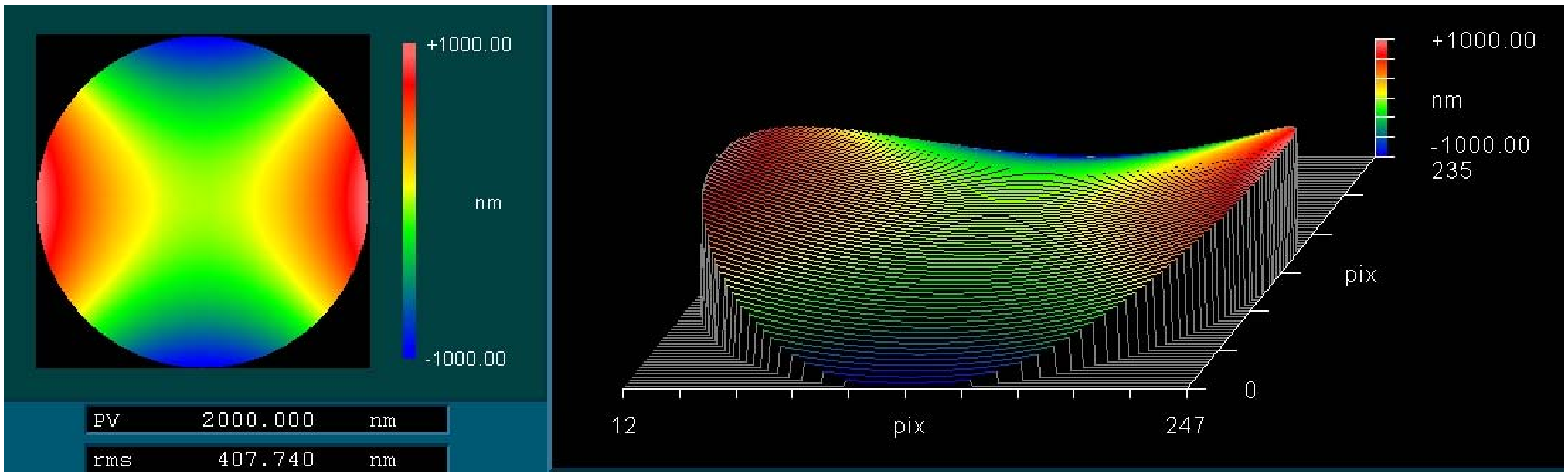


Figure 1-28 *One micrometer of x-astigmatism gives the asymmetric saddle-shaped wavefront map shown here.*

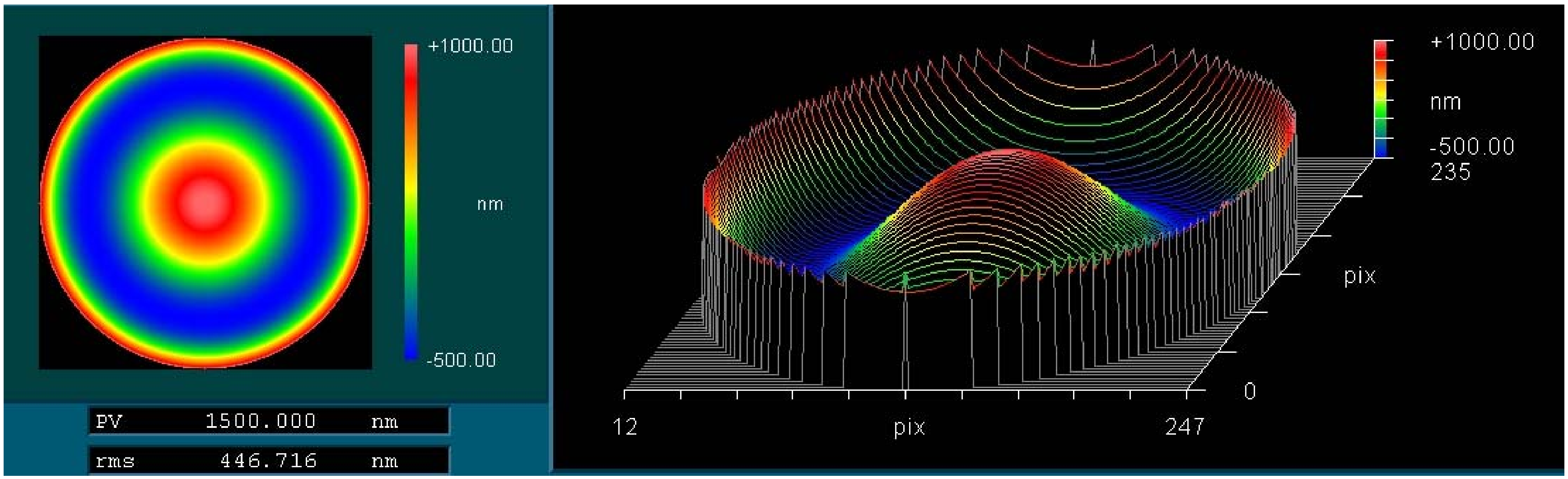


Figure 1-29 *One micrometer of spherical aberration gives the symmetric, sombrero-shaped wavefront map shown here.*

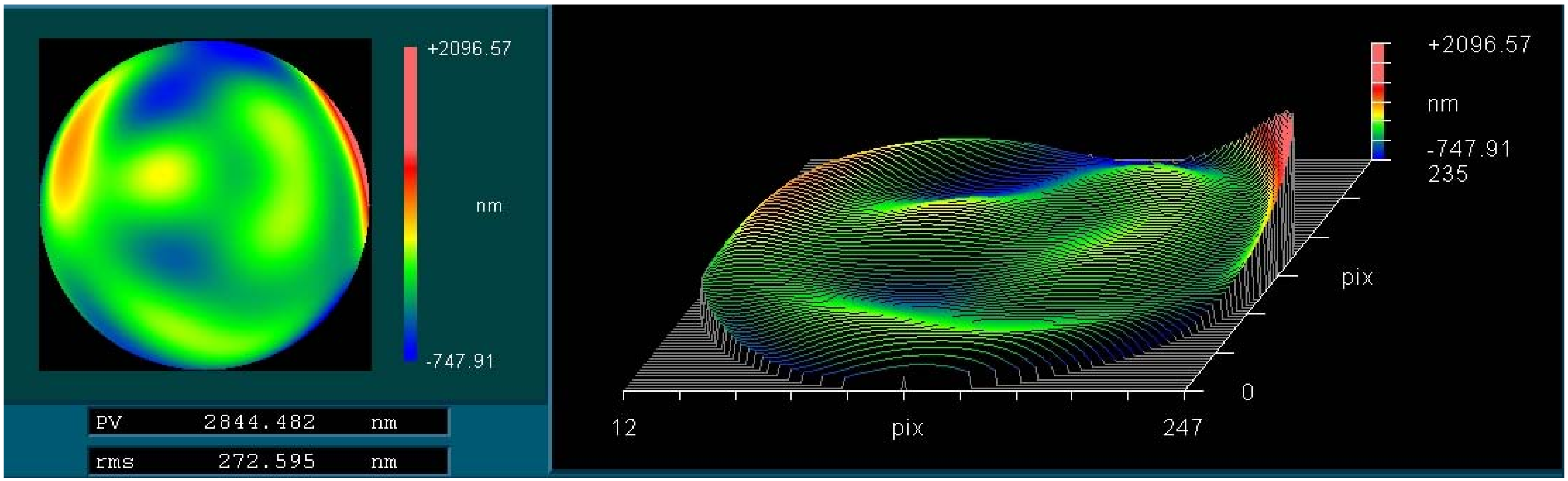


Figure 1-30 *The WFE map is shown for an aberrated optical system.*

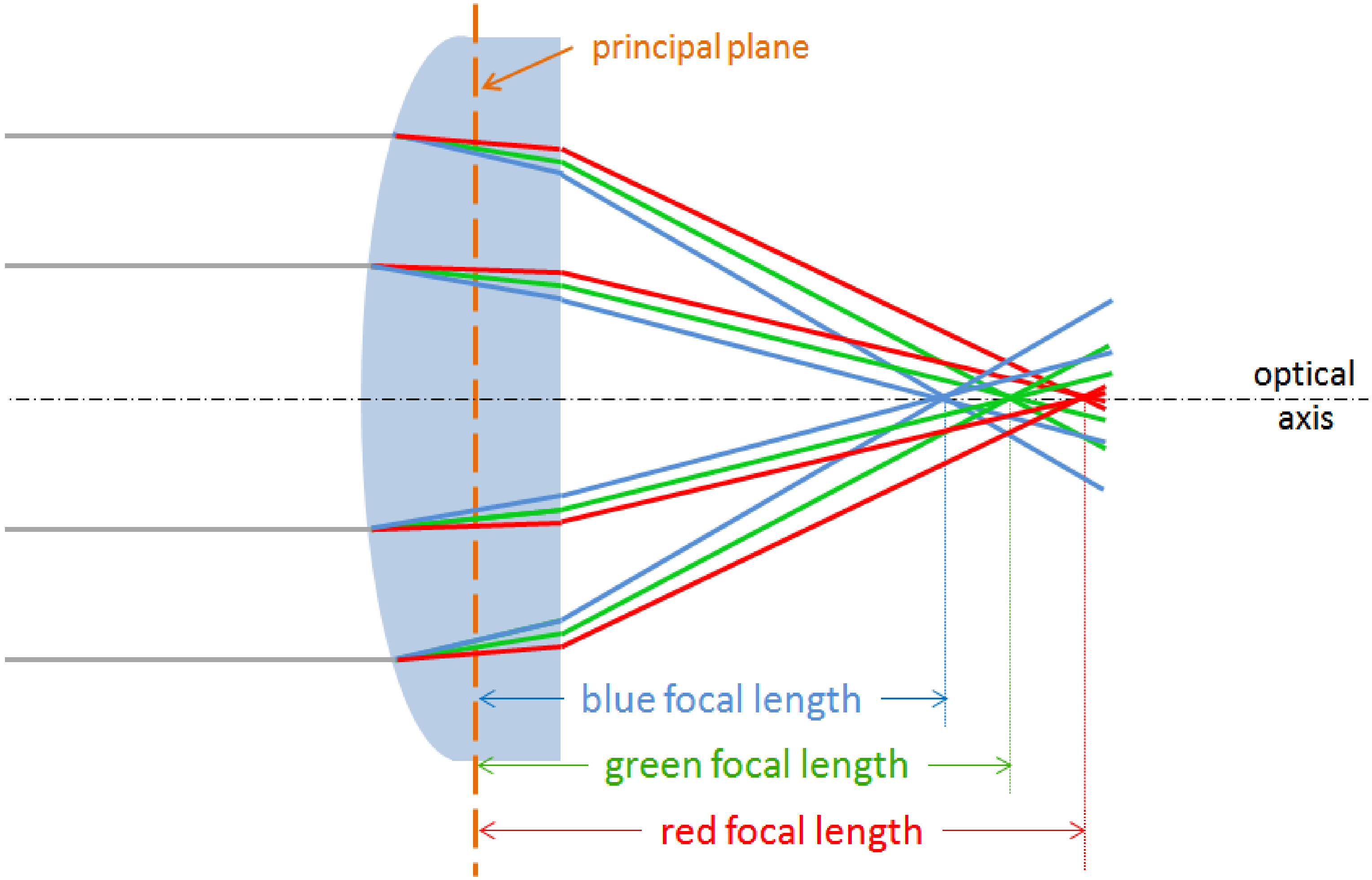


Figure 1-31 *A lens with chromatic aberration is shown. Rays of different colors represent light of those colors. Note the separation of red, green, and blue wavelengths along the optical axis and laterally as a result. This is a typical representation of chromatic aberration in the visible portion of the spectrum, but chromatic aberrations exist for all spectral regions and must be compensated over the optical system's operational spectrum.*

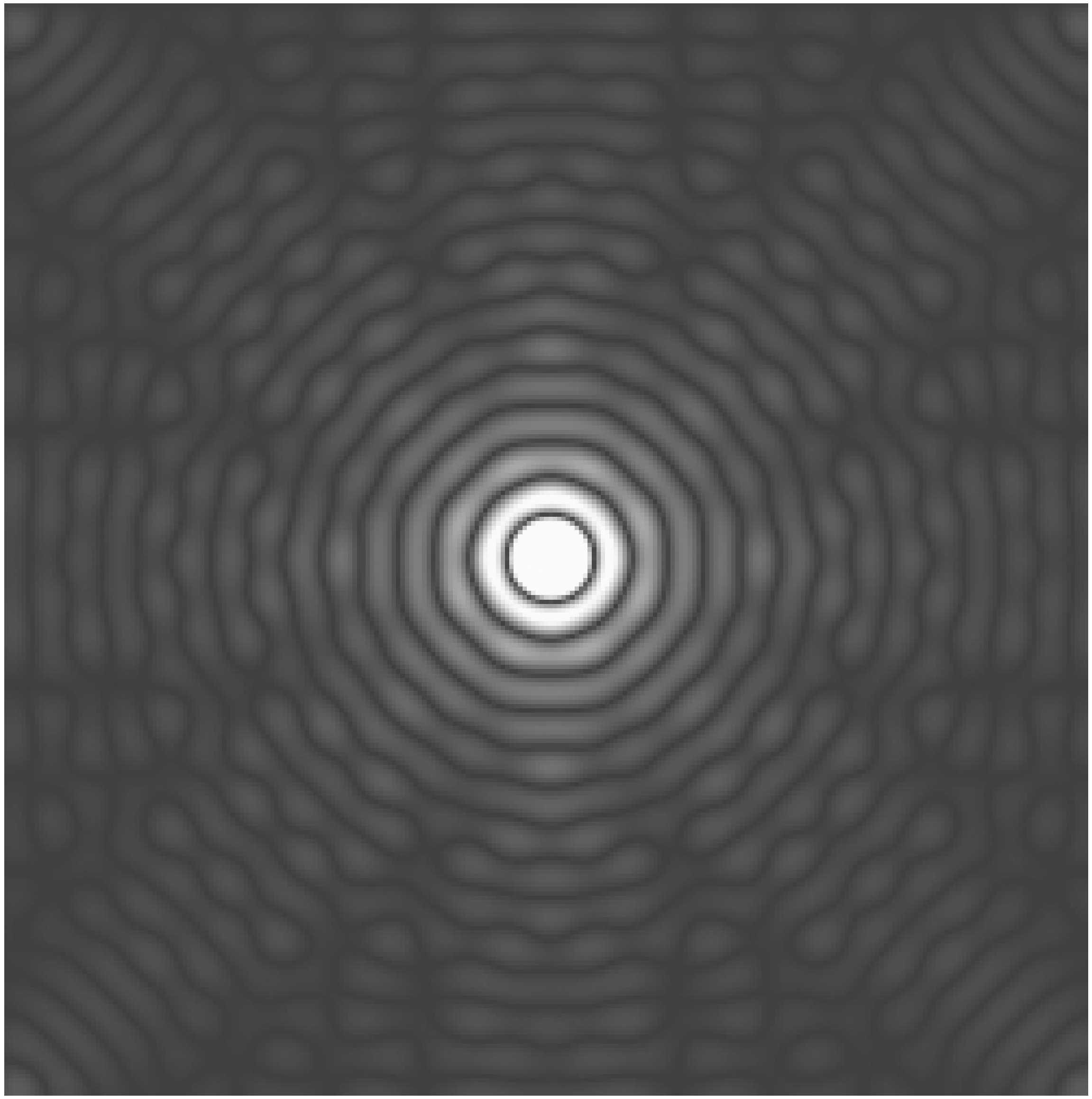


Figure 1-32 *The point-spread function of an ideal, diffraction-limited optical system.*

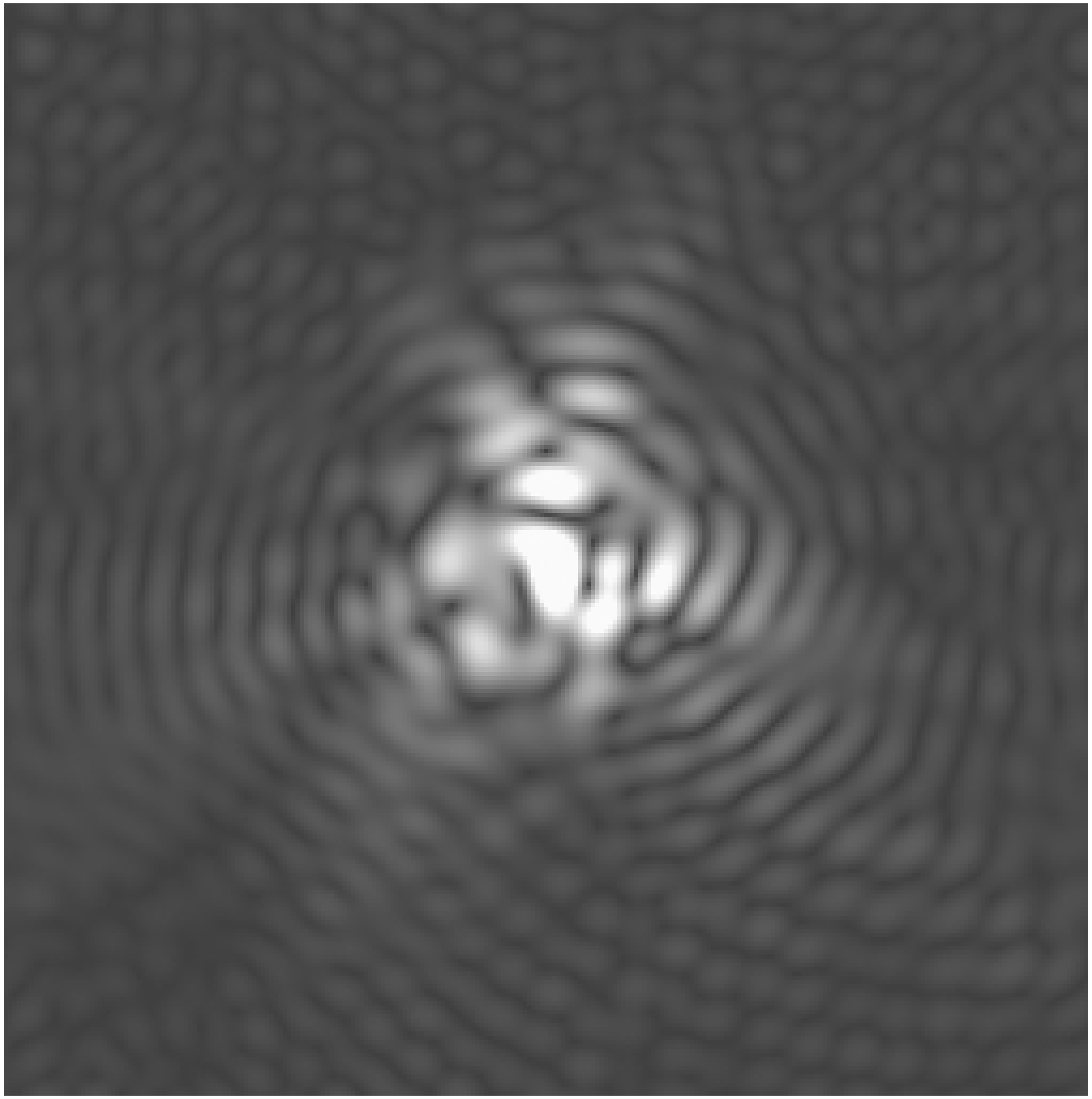


Figure 1-33 The PSF is shown for an aberrated optical system.

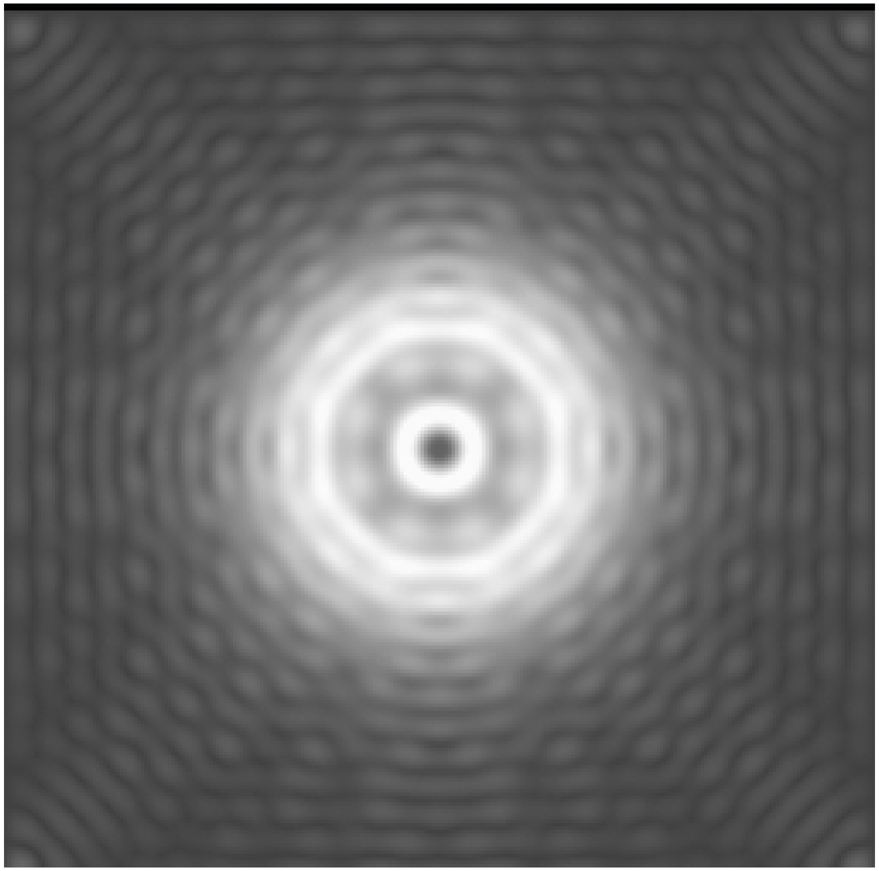


Figure 1-34

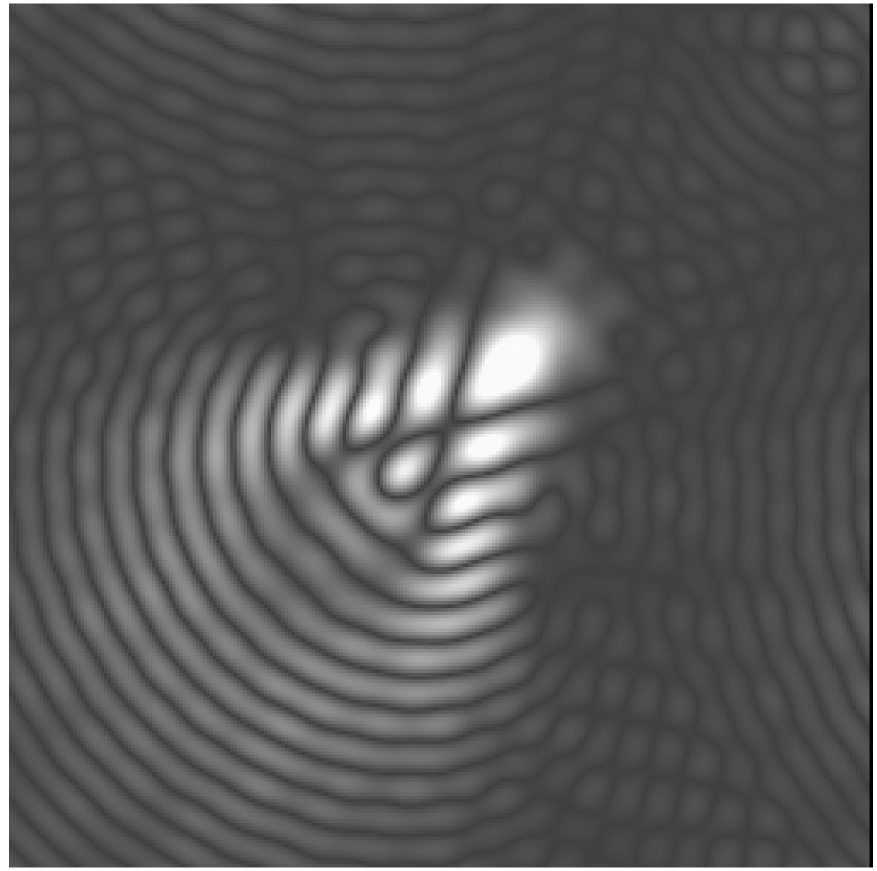


Figure 1-35

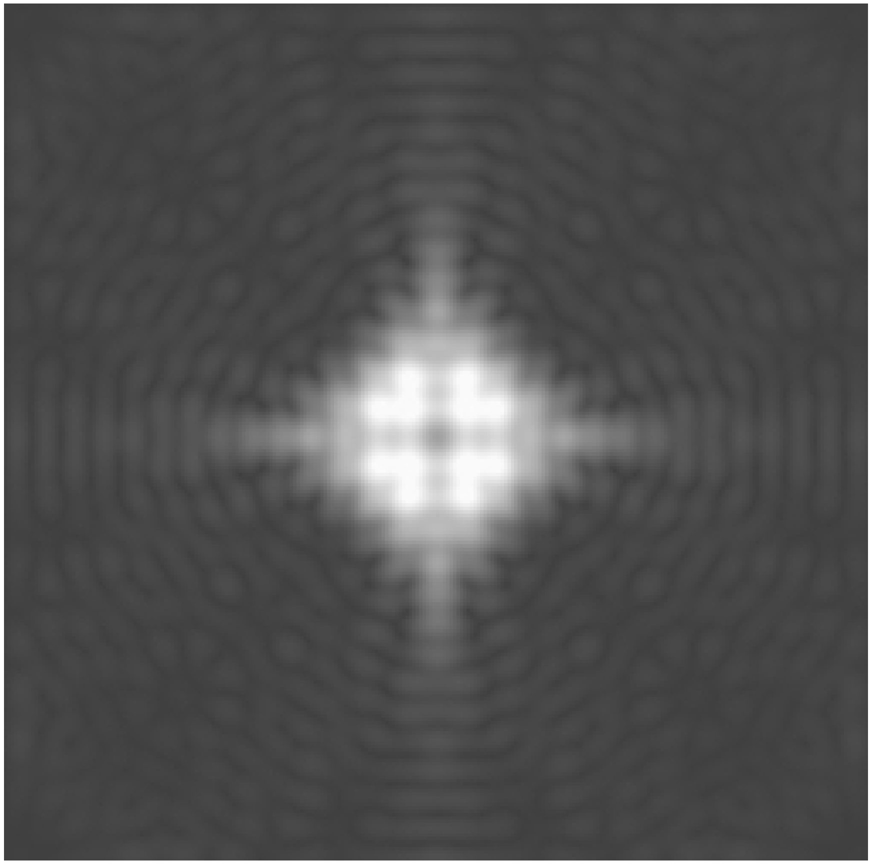


Figure 1-36

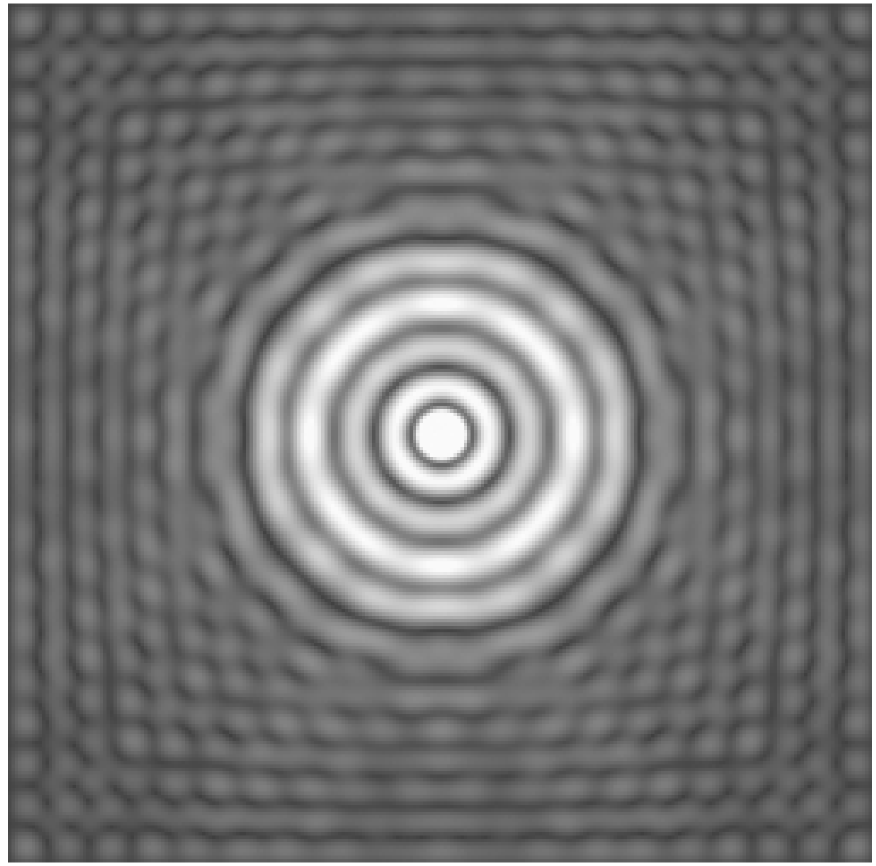


Figure 1-37

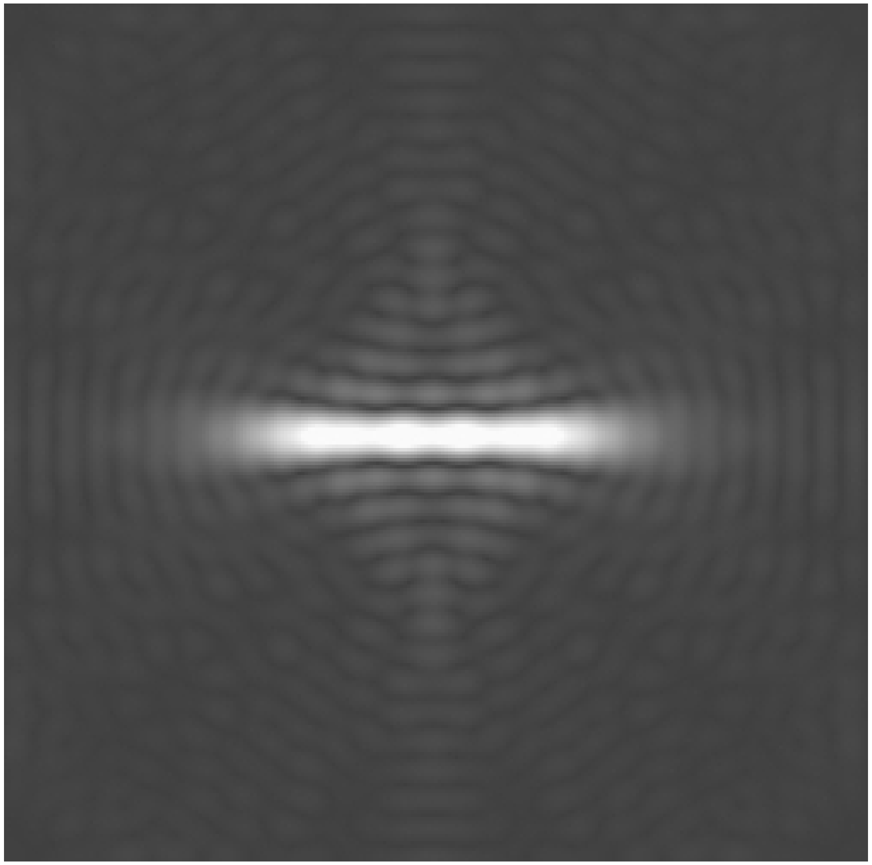


Figure 1-38

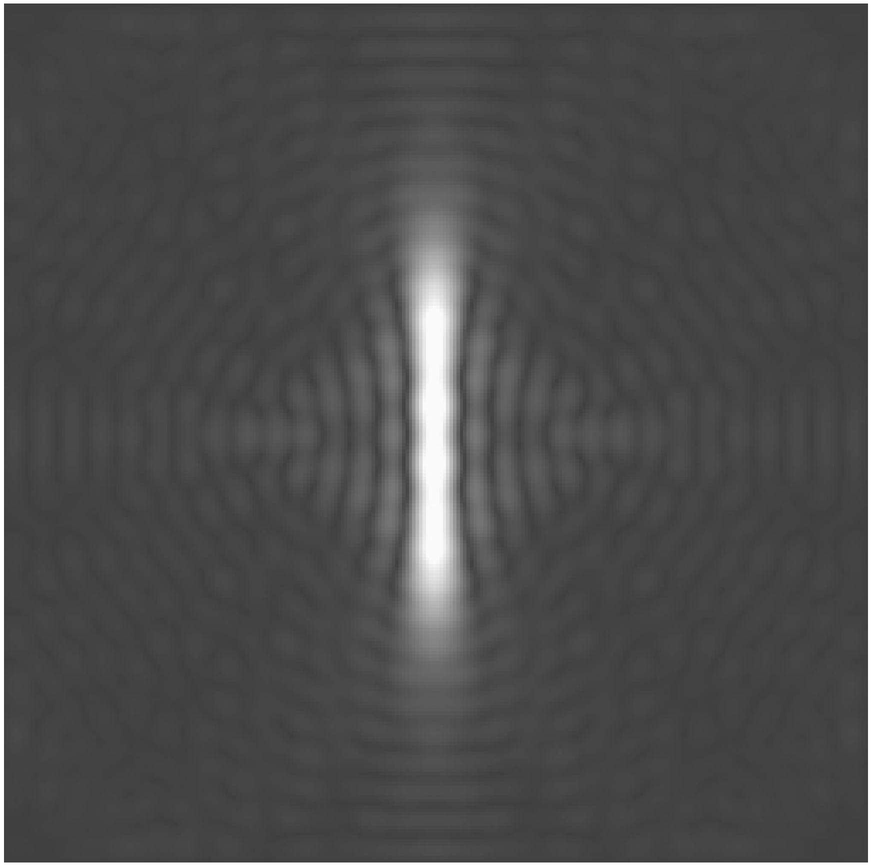


Figure 1-39

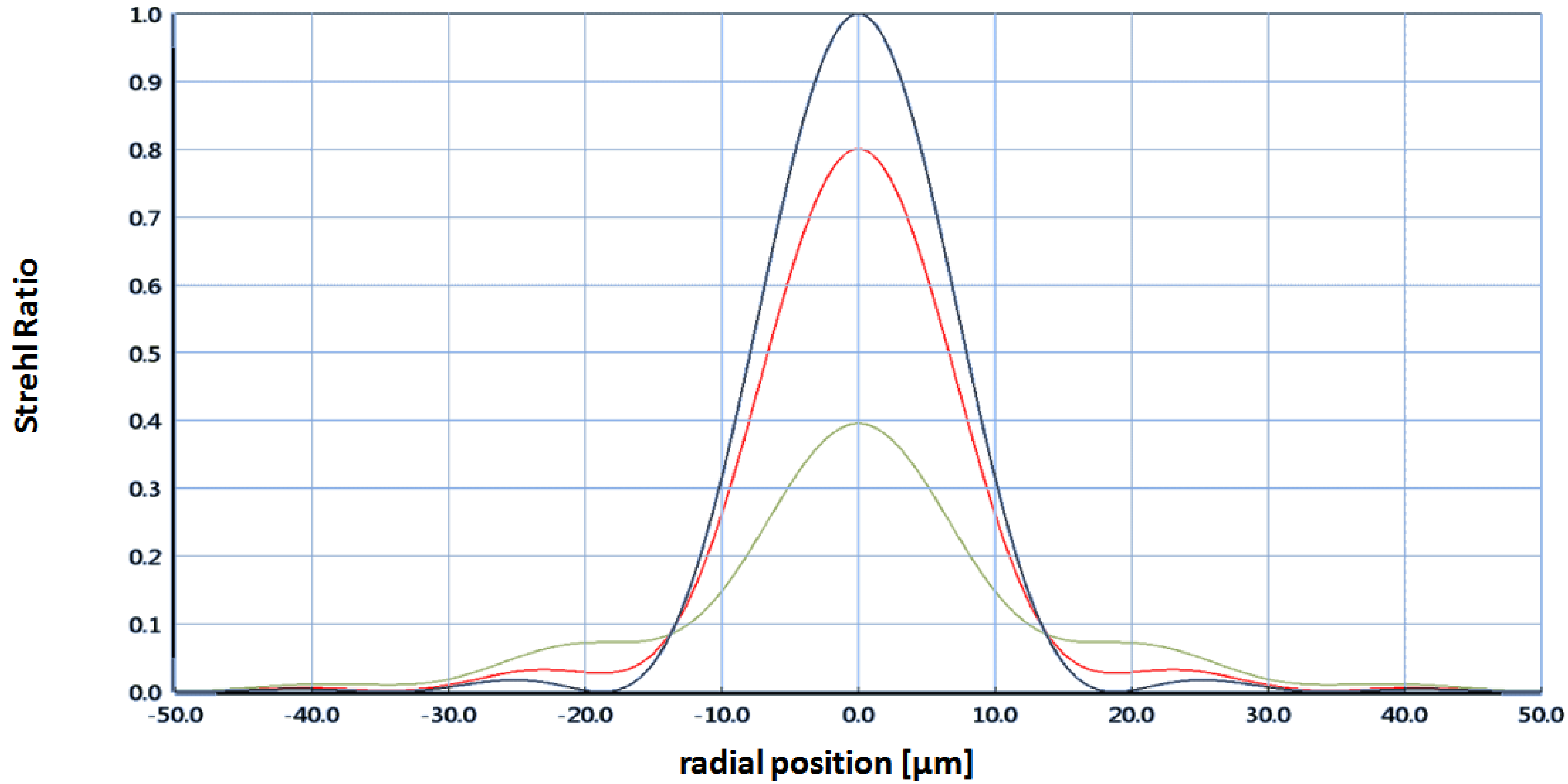
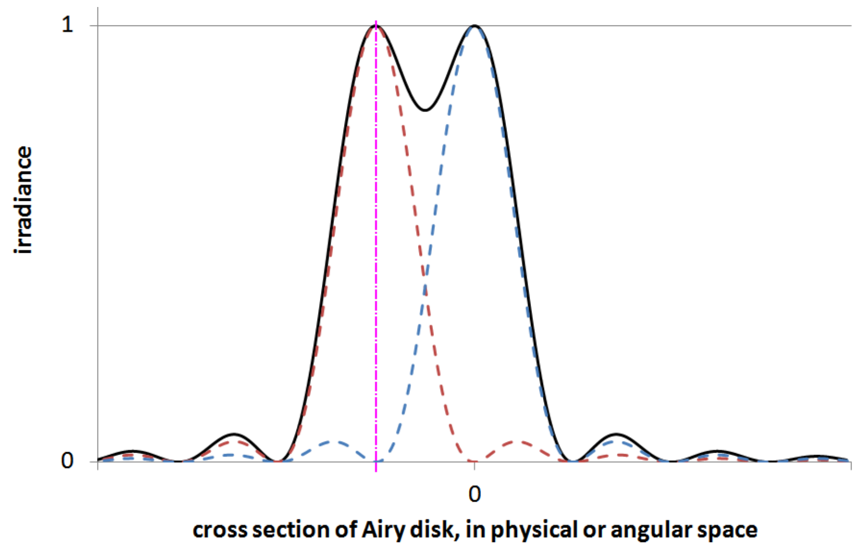


Figure 1-40 *Strehl ratios of 0.4 (green), 0.8 (red), and 1.0 (blue) are shown here. Ratios lower than unity were achieved to create this figure by defocusing the optical system.*



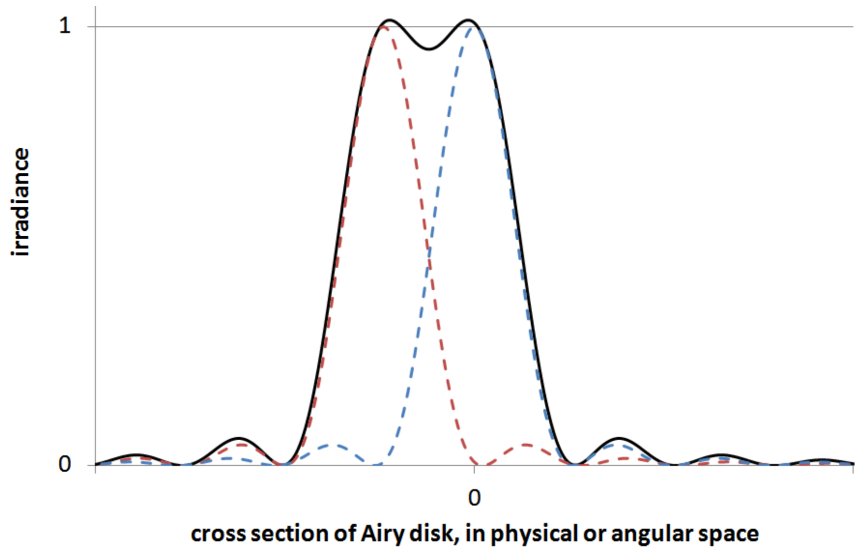


Figure 1-41 *The first figure shows the PSF cross-section of two resolved spots, with the vertical line indicating where the minimum of one spot exactly overlaps the maximum of the other spot—this is the criterion for resolution. The second plot shows two spots that are too close and therefore unresolved.*

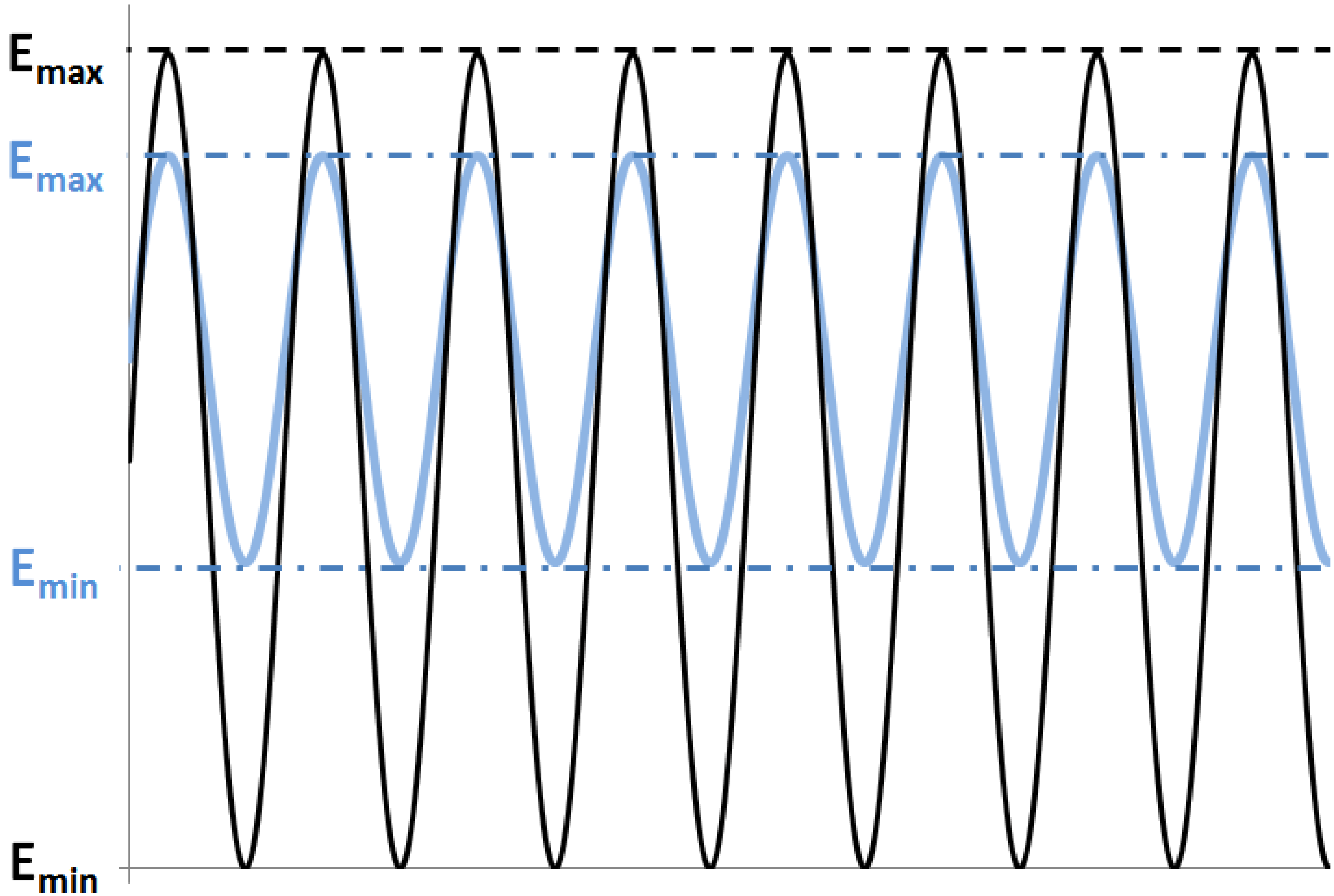


Figure 1-42 *This plots irradiance as the modulation (or contrast or visibility) of features in a sinusoidal image. Crests represent points of maximum irradiance, and troughs are minima in irradiance. The darker curve shows 100% contrast, and the lighter curve is lower, about 50% contrast, wherein both the blackest blacks and the whitest whites appear gray.*

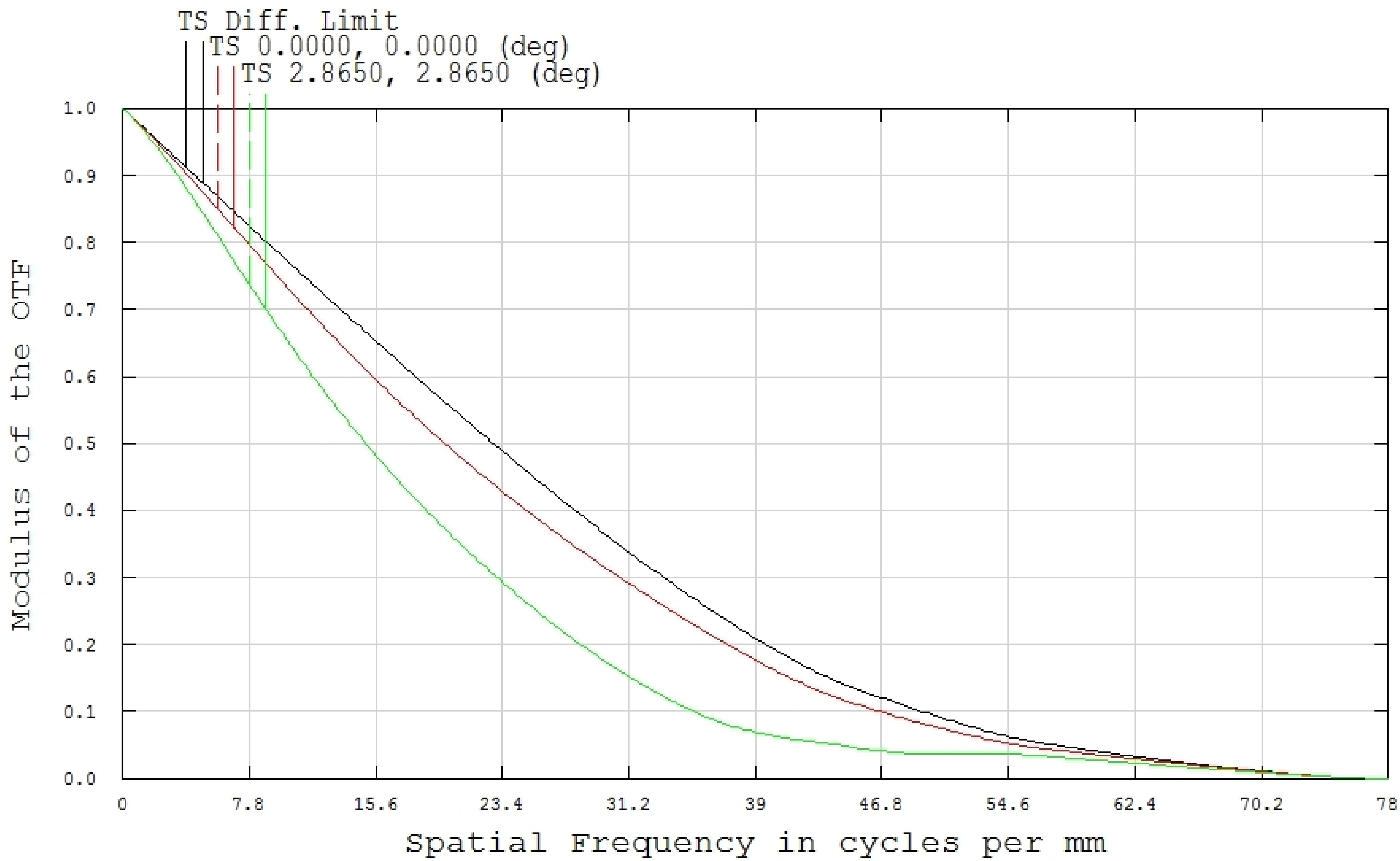


Figure 1-43 *An example of an MTF curve, with the ideal, diffraction-limited performance shown as a solid black curve, an on-axis field curve shown in red, and an off-axis field shown as in green.*

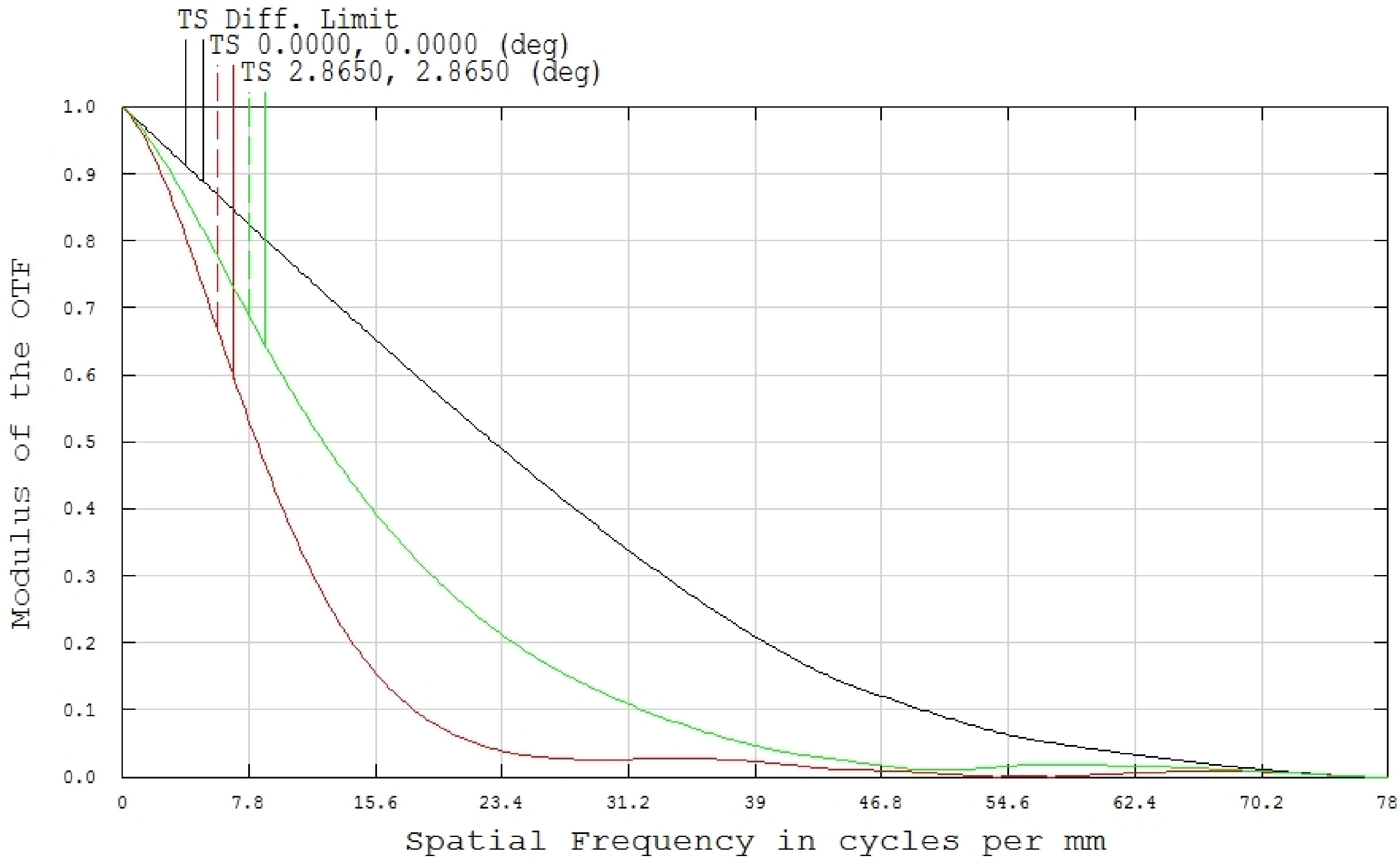


Figure 1-44 *The same plot as shown previously, but defocused by 2 mm.*

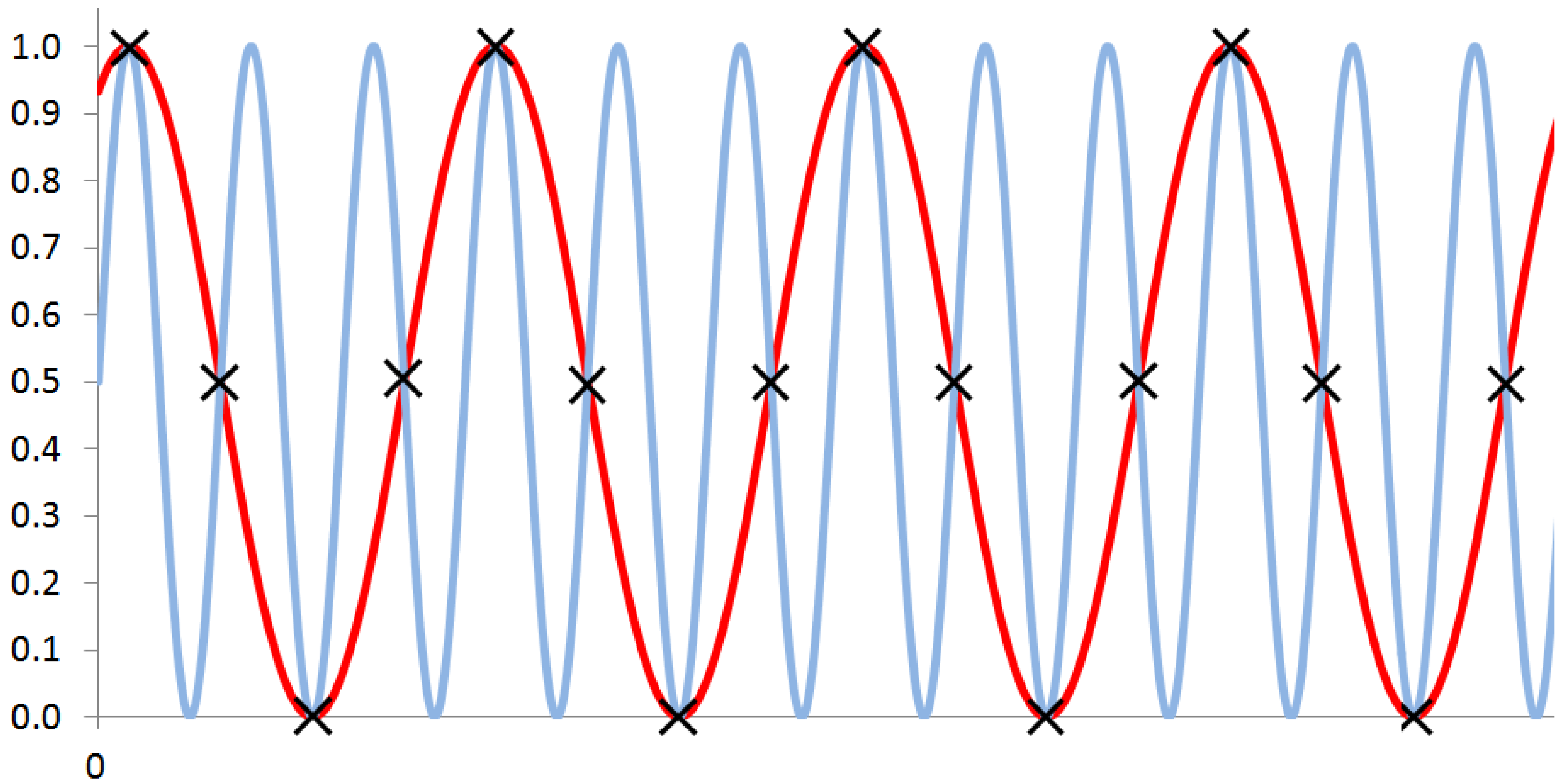


Figure 1-45 *The **X**-marks show a sampling frequency that is appropriate to reconstruct the lower-frequency sine wave (red), but not the higher-frequency sine wave (blue). These two spatial frequencies are aliases.*