

Understanding astigmatism

MAS450/854
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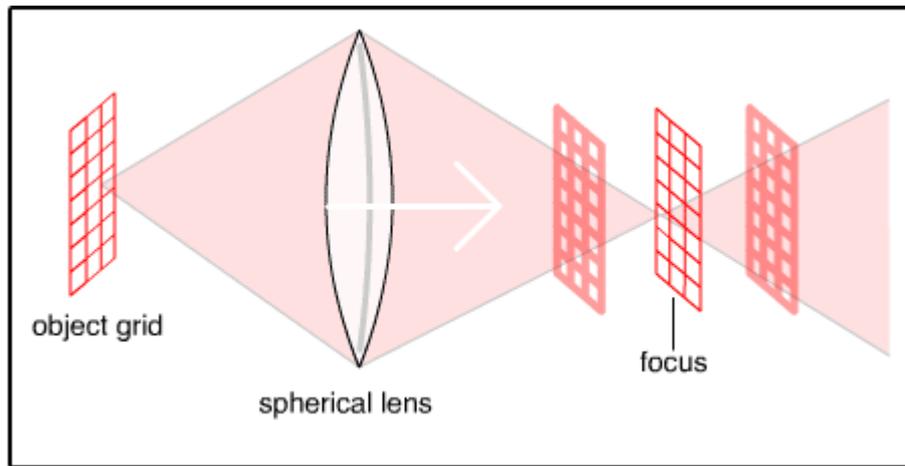
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Introduction

Astigmatism is an aberration that results when an optical system focuses two orthogonal axes of light at two different distances in space. Holograms and holographic optical elements intentionally produce, or unintentionally suffer, from astigmatism. To explain the basic properties of astigmatism, though, we choose a simpler optical model using spherical and cylindrical refractive lenses.

Spherical lens with no astigmatism

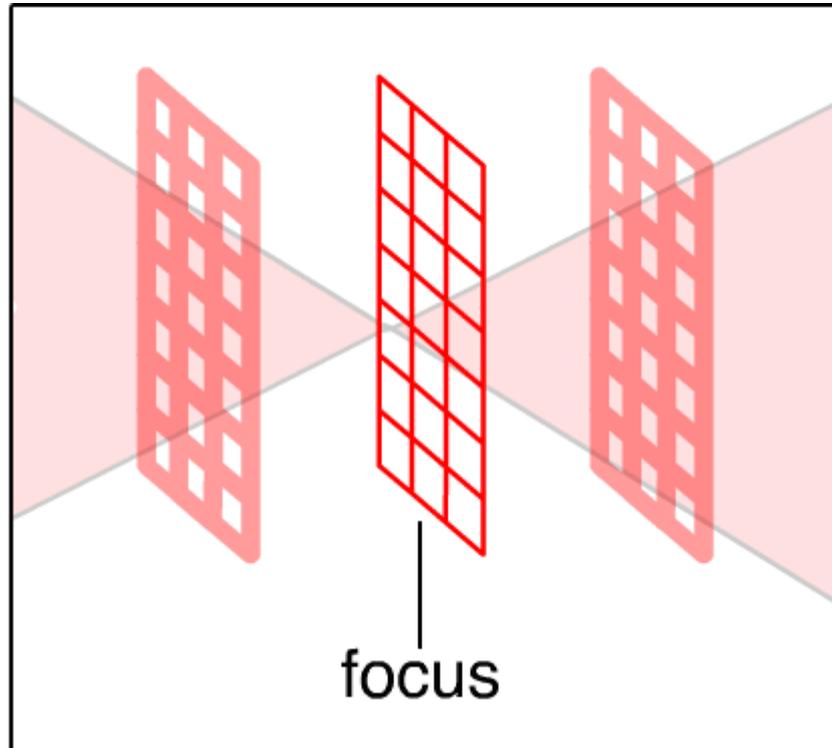
The ideal version of the common spherical lens, of which a typical magnifying glass is an example, exhibits no astigmatism. The lens is symmetric in the horizontal and vertical directions (indeed, all directions), and thus has an optical power that doesn't vary depending on whether the angle that light strikes the lens is in the vertical or horizontal plane. With regard to focus, that means that light emitted from a single point on an object and captured by different parts of the lens is redirected by lens refraction and comes together at a single point. The following diagram shows this process of symmetric focus schematically.



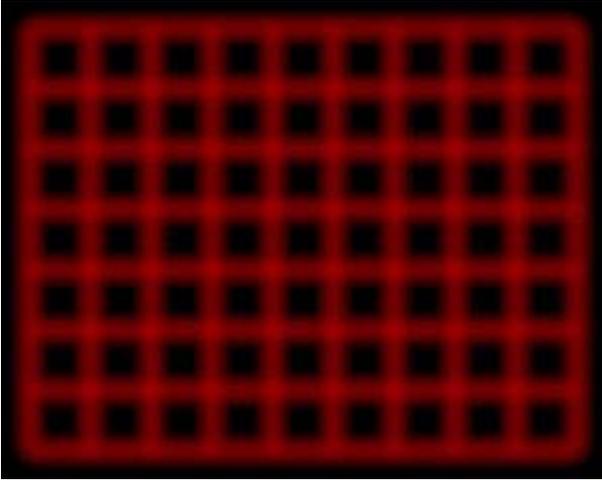
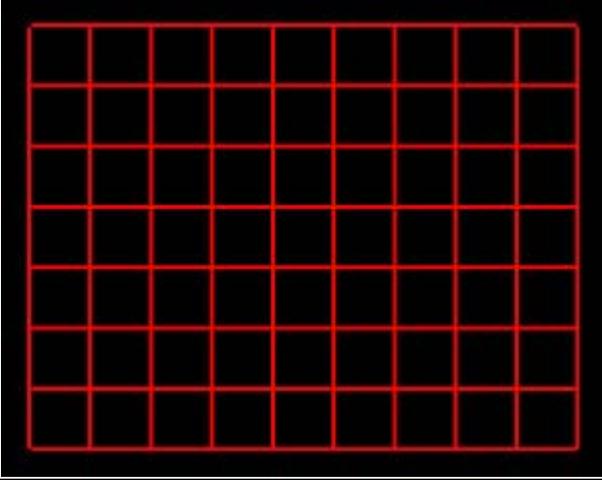
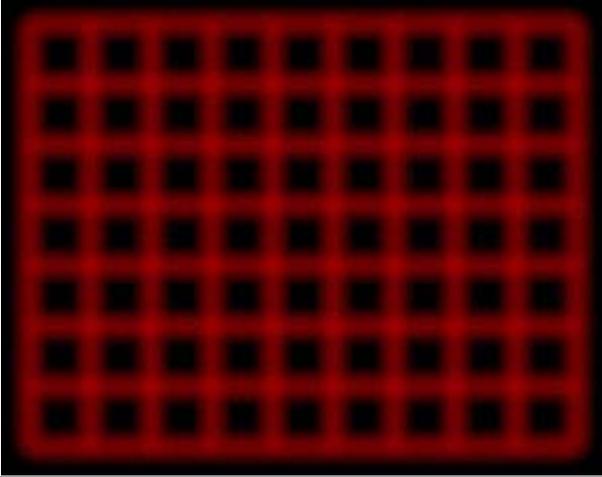
In the picture, light emitted from a grid of horizontal and vertical lines is focused by a convex spherical lens. Light from every point on the grid is focused to a corresponding point at the *focal plane*. If the grid is placed at twice the focal length of the lens behind the lens, the sharp, focused image of grid will appear at the same distance in front of the lens.

(Note: With this geometry, the grid image will also appear to be the same size as the original object grid. For the purposes of this discussion, we will ignore differences in size or magnification when looking at focused images, since those issues are orthogonal to an understanding of astigmatism.)

If we were to place a white card or screen at the locations indicated in the diagram, we could observe the light from the lens as it appears at other distances as well as at the focus. Here's a closeup of the above diagram that shows, conceptually if not literally, what happens.



At locations in front of or behind the focal plane, the light from each point in the object grid shines on an area that's bigger than just a single point: the light has either not completely converged yet, or it is already diverging again after focusing. We call such a pattern that we see on the card or screen "blur."

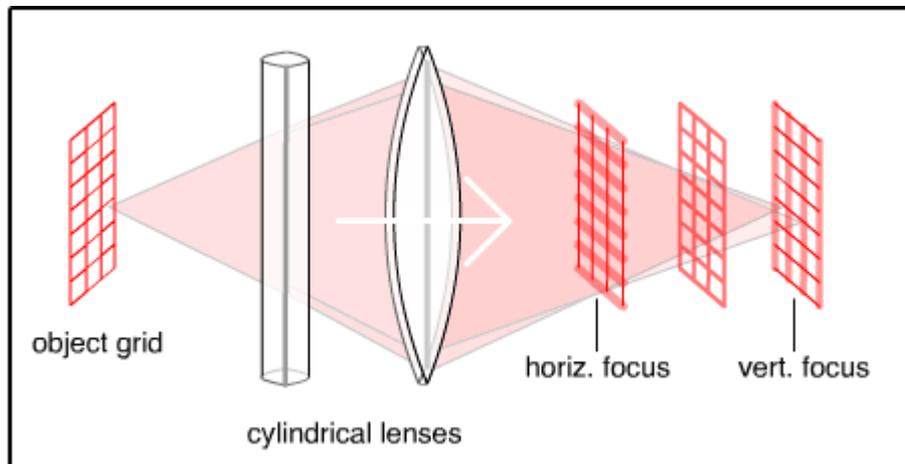
Location	Image
<p>A blurred image appears between the lens and the focal plane. (This image and all others on this page are simulated, not actual, optical effects.) The image is relatively dark because the energy that would have been focused down to a grid is instead spread out over a larger area.</p>	
<p>The sharp image of the grid is projected at the focal plane.</p>	
<p>The blurred image is also projected beyond the focal plane. (Remember, we are only simulating the focus of the image, not its relative size. If we took the lenses magnification into account, this image would be larger than the focal plane image.)</p>	

Crossed cylindrical lenses with astigmatism

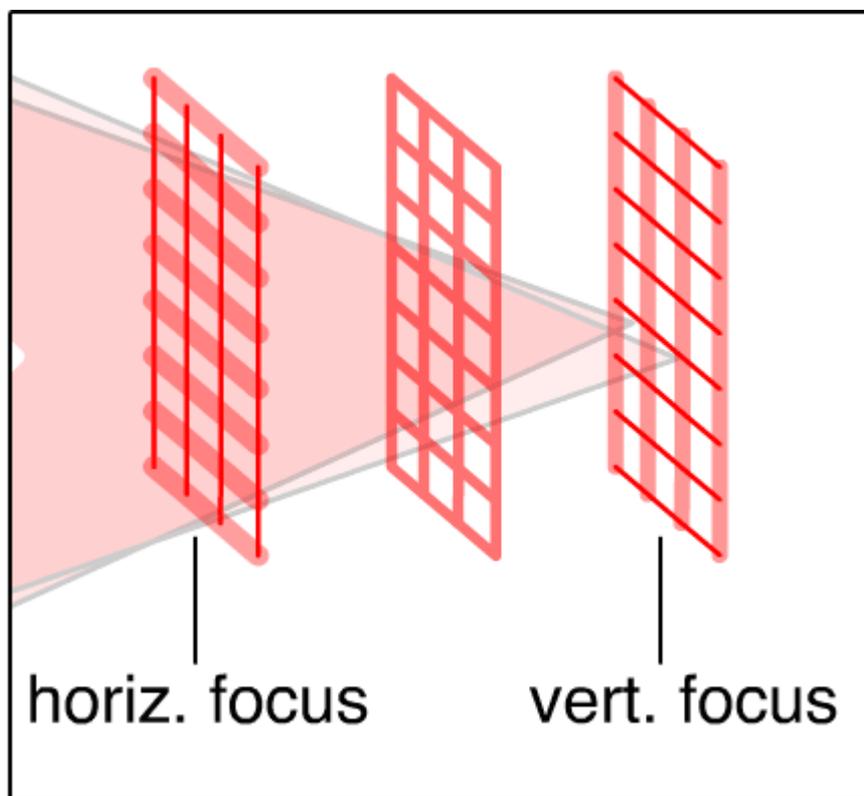
Unlike a radially symmetric lens like a magnifying glass, a cylindrical lens bends light (i.e., has optical power) in only one axis. A glass rod or a cylindrical glass of water act as approximations to ideal cylindrical lenses. Since a cylindrical lens only has the ability to reconverge light from an object to its focus in one direction, the light in the other direction isn't focused: it's blurred just as if no lens was there. With a source object like a grid (assuming that one of the axes of the grid is aligned with the orientation of the cylindrical lens), only one orientation of lines, vertical or

horizontal, will be focused by such a lens.

If we use two crossed cylindrical lenses (i.e., one oriented orthogonally to the other, in our example horizontally and vertically), we can focus light of both orientations to *some* location, but the locations where, say, vertical lines are focused will be, in general, different from the location where horizontal lines are focused. Exactly where the lenses focus light depends on their relative position and their individual optical power. The following diagram shows this optical geometry.

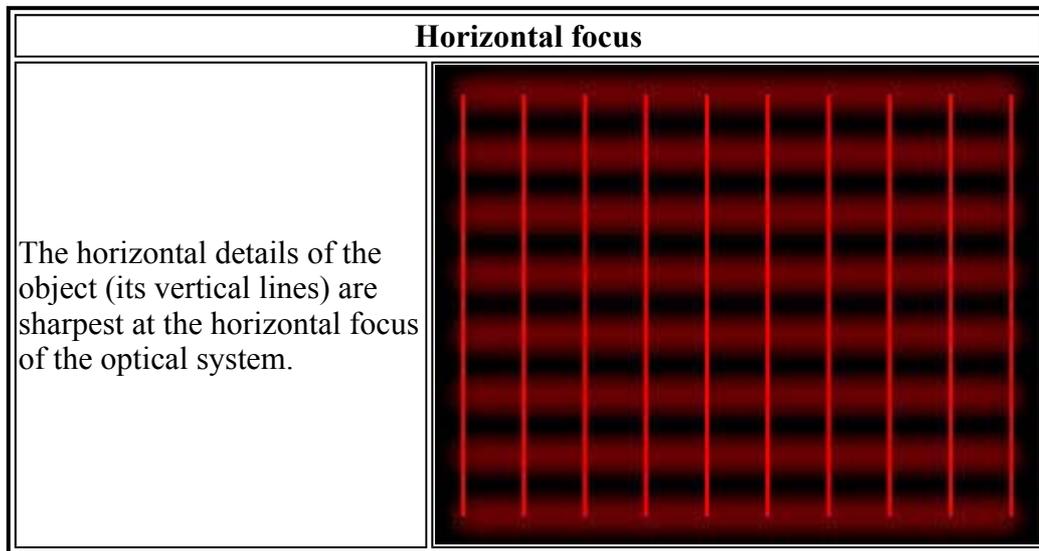


The lens closest to the object is a cylindrical lens shaped approximately like a vertical tube. This lens bends light only in the horizontal direction (into or out of the plane of this diagram); vertically, the light from each point in the object grid continues to expand. The second cylindrical lens is oriented so that it bends light in the vertical axis only. Since the lenses are offset and have different power, the horizontal and vertical foci fall at different planes in space. Here is a conceptual closeup of the area around the focuses:



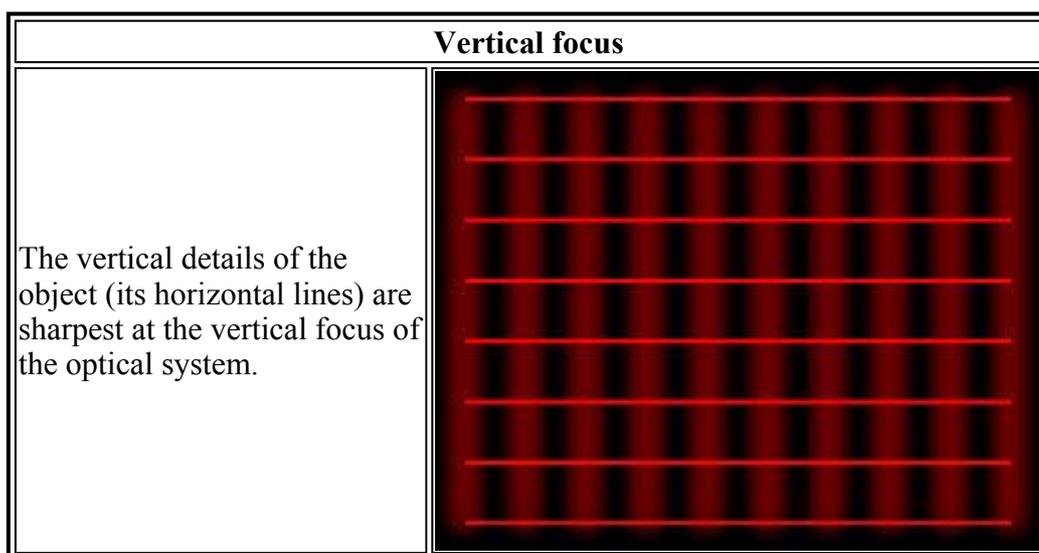
Horizontal focus

At the focus of the first, vertical cylindrical lens, the vertical lines of the grid appear sharp. Since the horizontal lines have not yet fully converged at that depth, they appear blurred. Vertical lines represent the horizontal detail of the object. The location where this *horizontal detail* is focused is called the *horizontal focus* of the optical system. In three-dimensional imaging systems like display holograms, horizontal detail (vertical lines) provides the human brain with information that its stereoscopic image analysis mechanisms can use to extract depth. For this reason, we sometimes refer to the horizontal focus as the *parallax focus*.



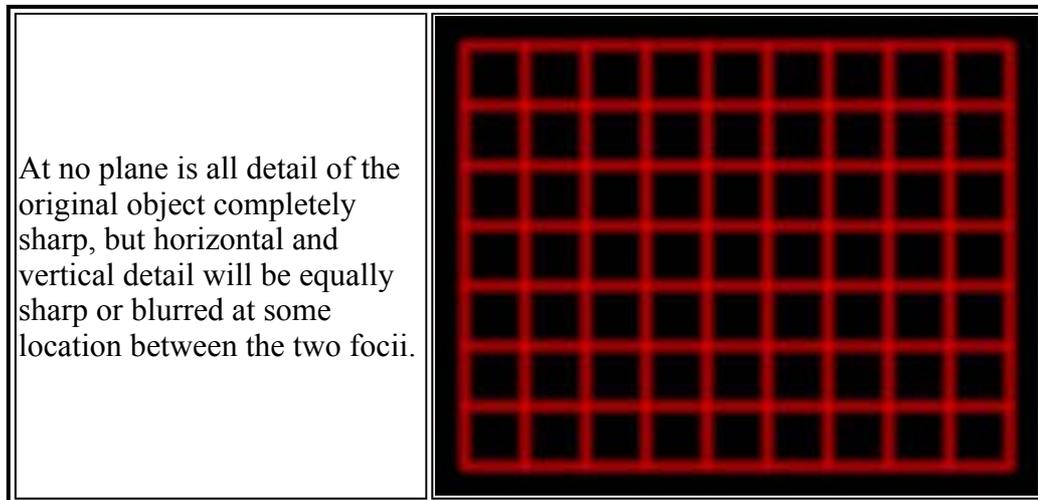
Vertical focus

Similarly, the *vertical focus* is the location where vertical detail (horizontal lines) appear sharp. At the vertical focus plane, rays of light that converged at the horizontal focus is already diverging and appears blurry. In off-axis white light holography, the vertical focus is important for determining where different color images are focused. Because holograms are typically illuminated from above or below, chromatic dispersion (color blur) due to diffraction occurs mainly in the vertical direction. Horizontal lines are most vulnerable to this color blur because each wavelength is focused to a different vertical focus. For this reason, holographers sometimes call the vertical focus the *color focus*.



Plane of sharpest focus

The sharpness of object details varies continuously throughout space in the astigmatic optical system as well as the spherical one. Since the horizontal and vertical foci are at two different locations, there is no position in space where all of the vertical and all of the horizontal detail are completely sharp. However, at some location in between the horizontal and vertical focal planes, the extent of the horizontal and vertical blurs will be the same. The location is sometimes known as the plane of sharpest focus.



Implications for 3D objects

The grid object was chosen for the examples above because it has strong and recognizable horizontal and vertical detail and because it was two dimensional. In holography, we are generally interested in creating images of three-, not two-dimensional objects. Lenses (and their holographic equivalents) continue to work the same way for three-dimensional objects: Horizontal and vertical lines for the three-dimensional object are both focused into the space beyond the lens. In the astigmatic case, however, the vertical and horizontal lines are longitudinally displaced from each other by some distance proportional to the optical system's astigmatism.

Nothing, however, prevents the horizontal detail of one part of the object from overlapping the vertical detail from another part. Astigmatism just says that the horizontal and vertical detail from the *same* part of the object won't fall at the same plane. This overlap of different focii of different parts of the object can sometimes make visual analysis of a projected astigmatic image difficult or confusing.

Why does astigmatism happen in holography?

This question is difficult to answer in an intuitive and non-analytic fashion. Let's start by qualifying our answer by considering inline holograms and off-axis holograms independently.

Inline holograms

Inline holograms, where the reference, object, and illumination sources lie on a line that is perpendicular to the holographic plate, do not generally suffer from essentially any astigmatism. There is no asymmetry between the horizontal and vertical axes of the hologram. If we cannot visually distinguish between the optical setup seen from its side or seen from the top, there's no way for the hologram to know the difference. The pattern formed, a circular zone plate, doesn't have any preferred rotational orientation. What's more, any change in the illumination distance will change horizontal and vertical ray directions the same. Even a wavelength change will only pull the a focused point in or out a little, keeping it symmetric with the center of the Gabor zone plate pattern.

In short, there's just no way to distinguish horizontal from vertical.

(As an aside, inline holograms *may* suffer from aberrations such as spherical aberration. The distortion just happens to be symmetric like the zone plate pattern.)

Off-axis holograms

Off-axis holograms are vulnerable to astigmatism, but usually only when a change happens between exposure and illumination. If the hologram is illuminated from the same position as the reference source, the wavelength of illumination matches exposure, and the plate and emulsion aren't strangely affected, the $m=1$ order image will appear at the object location both horizontally and vertically (no astigmatism). Astigmatism can occur if any of these parameters change.

Here's a basic idea of *why* astigmatism happens in off-axis holography. The large angular offset of the reference and object sources produces a high spatial frequency in the vertical direction on the plate, but a much smaller one across it horizontally: moreover, the basic pattern of spatial frequencies is symmetric side to side (since the object is usually centered horizontally with respect to the plate) but asymmetric vertically (the top of the plate may be at a different angle to the reference or illumination source than the bottom of the plate).

Even worse, changes between exposure illumination are generally more significant in the vertical than in the horizontal direction. To compensate for a change in wavelength, for example, we might change the angle of reference of illumination. That change doesn't alter the horizontal component of the ray directions of light hitting the plate very much, but the vertical component of all the rays are changed. Wavelength changes also result in asymmetric changes in focus: while it is possible to minimize astigmatism for one wavelength in off-axis holography, it is impossible to eliminate it for all wavelengths. The best as can do is predict astigmatism's effects and design our optical setups to minimize its detrimental consequences.

Notes

- Images are simulated, not captured optically. The intensities are not literal to what you'd see, but they do convey the basic idea of blur and focus.
- Magnification of images based on distance from the lens and the intensity changes that accompany it is ignored in the diagrams and images.
- The regions of the schematic diagrams showing the light passing from the object grid through the lens and focusing down as well as the out-of-focus images in the diagrams are schematic, not literal. In particular, the blur at the out-of-focus planes shown in the drawings would be much more severe than diagrams indicate.

*Please refer back to the CMS Readings Section