Laboratory experiment — aberrations

Obligatory laboratory experiment on course in Optical design, SK2330/SK3330, KTH.

Date

Name

Pass

Objective

This laboratory experiment is intended to demonstrate the most relevant aberrations, namely first-order chromatic aberrations (longitudinal chromatic aberration and lateral chromatic aberration) and third-order monochromatic aberrations (namely spherical aberration, coma, astigmatism, field curvature, and distortion). You will see the aberrated images of a point source, and investigate how they change with field angle and aperture size.

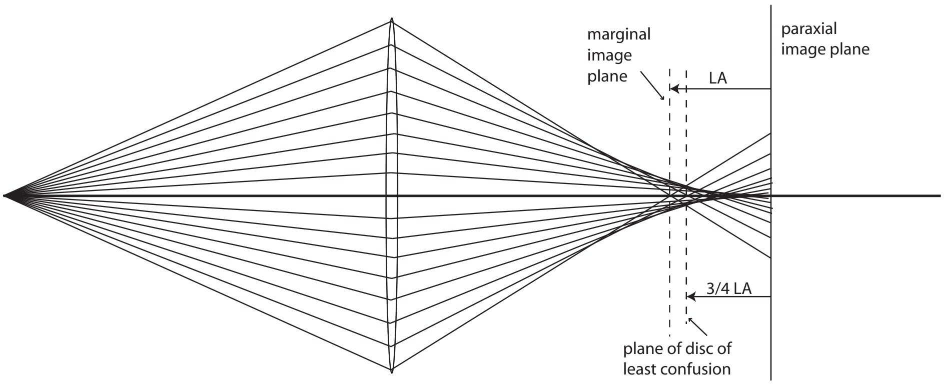
Equipment

Light source with light guide
Positive lenses of different focal lengths
Iris diaphragms (mounted on lenses)
Metal apertures an pinholes
Mounts
Color filters
Reticle, screen, scotch tape

The scotch tape is a good way of making an aperture diffuse, by just placing a bit of tape over it. Remember, throughout this lab, that when an aperture (or pinhole) is used as an object, it should be diffusing. (Every object point should send out light in every direction.) When used as an aperture stop, it should *not* be diffusing. (A stop should be a clear opening that doesn't change the direction of the rays.)

Spherical aberration

Spherical aberration is the only on-axis monochromatic aberration. Marginal rays are refracted more than paraxial rays, which causes a blur at the paraxial focal plane. This blur can be decreased by a factor of 4, if the system in defocused in the right way, as indicated in the figure below. By defocusing $3/4$ of the longitudinal aberration, the blur goes down to $1/4$.



Use the smallest single pinhole, and image it strongly demagnified (roughly, using a magnification of $-1/7$) onto a screen. Use a lens of focal length $50\,\mathrm{mm}$ with a pre-mounted iris diaphragm. Turn the lens the right way around, i.e., with the curved side facing the flattest field. Filter the light with a bright red filter, to avoid the disturbance of chromatic aberrations. Close down the aperture, and find the paraxial focus. Open up the aperture. By looking at the result, you can figure out whether the system is properly aligned . (How?) If not, align it as well as possible. **Draw figures in the table below, showing the shape of the focus at different screen positions.**

Before marginal image plane	At marginal image plane	At disc of least confusion	Between dlc and paraxial image	At paraxial image plane
Position	Position	Position	Position	Position

Describe the effects of closing down the aperture, regarding both the spot size and the position of the best focus.

Turn the lens around, so that the flat side faces the flattest field. How does this affect the spherical aberration?

Set the aperture diameter to $30\,\mathrm{mm}$ and **estimate the spot sizes for the lens turned both the wrong way and the right way. Compare to the theoretical values for thin, plano-convex lenses.**

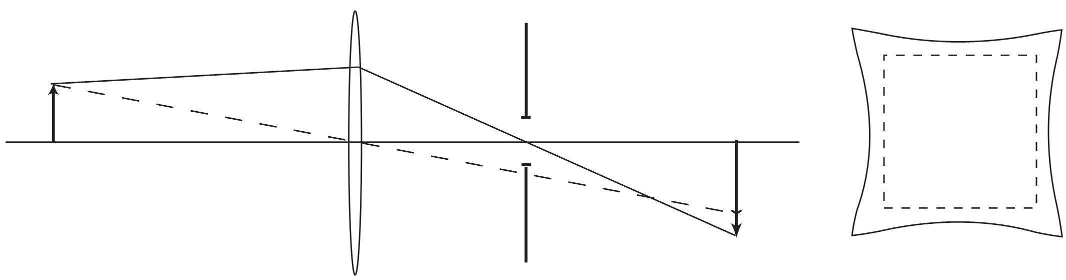
Lens	Orientation	Spot size, best focus [mm]	Predicted spot size [mm]
50 mm, plano-convex	Wrong way		
50 mm, plano-convex	Right way		

Finally, close the aperture down so that no spherical aberration is seen. **Sketch the image at different image planes around the paraxial image plane, in the table below. Note the difference in symmetry compared to the aberrated case.** Has the depth of focus increased or decreased? Why?

Much bef. focus	Before focus	At focus	After focus	Much after focus

Distortion

Distortion is a field aberration where the magnification varies with field angle. Below is a set-up for pincushion distortion.

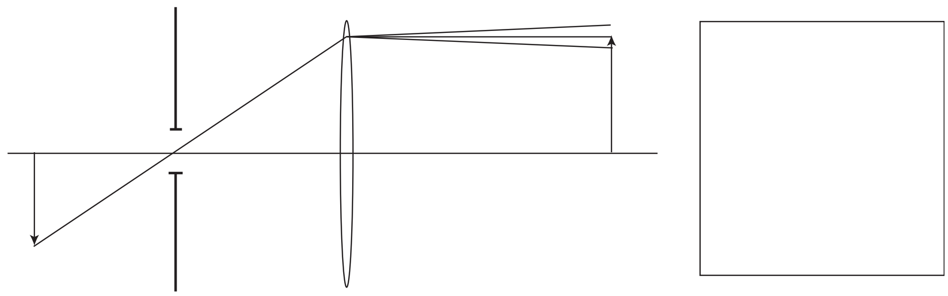


Build a set-up to view pincushion distortion. The object is a piece of an OH sheet with millimeter markings, and you can use the largest of the metal pinholes as aperture. Remember, the object must be diffusing but the aperture must not! Use a lens of focal length $50\,\mathrm{mm}$. **Study the effect of moving the aperture and write down your findings.**

A set-up for barrel distortion is trickier, both because of light economy and because there is no room for the holders between object and lens. Give it a try if you want to!

Lateral chromatic aberration

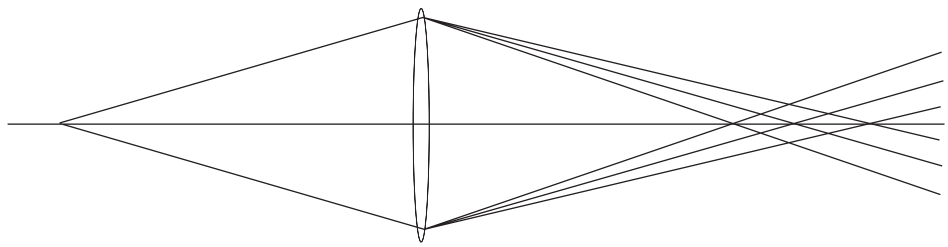
Lateral chromatic aberration can be seen as a pure prism effect, connected with the dispersion of the principal ray. Consequently, it happens only if the stop is not at the lens. The result is that magnification varies with color, as shown in the figure below. **Mark the three rays by their appropriate colors.**



Use a large-aperture 200 mm lens (without iris diaphragm) to image a pinhole (use the one with multiple holes, as those are the smallest) onto the screen. Use another aperture, either the largest metal aperture or one made of paper, to force the rays to pass close to the edge of the lens. Adjust your set-up until you can observe lateral chromatic aberration. **Draw a figure of the image in the box above!**

Longitudinal chromatic aberration

Refractive index, and consequently focal length and image distance, will vary with wavelength due to dispersion of the marginal ray. An example is shown below. Mark the three rays by their appropriate colors.



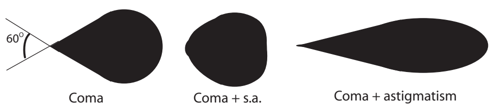
Use a lens of focal length 200 mm, with an iris diaphragm mounted on it. Image a pinhole (use the one with multiple holes, as those are the smallest) onto the screen. Use the largest magnification you can fit onto the optical rail, i.e., make the image as big as possible to see the chromatic effects more clearly. Use colored pencils and **draw pictures of the five different image positions in the table below**.

Defocus, before image	Blue focus	Yellow/green focus	Red focus	Defocus, after image
Position	Position	Position	Position	Position

Now you will measure the dispersion, or the Abbe number. Change the magnification to -1 to simplify the calculations. (Hint: what object and image distances are required for $M = -1$?) Find the positions of the red, green and blue images using the three darker color filters, and use this to **determine $\Delta f/f = 1/V$. Compare this to the theoretical value**. The lens is made from BK7 (517642). If measured and theoretical values don't agree, suggest possible reasons.

Coma

Coma is a point aberration, where the image of a point source resembles a comet. It can be seen as the result of a magnification that varies with image height, combined with a defocus that varies with pupil size. If there is much spherical aberration the comet shape will be less marked, and if there is much astigmatism it will be prolonged. Due to its asymmetric shape, coma is avoided as far as possible in imaging systems.



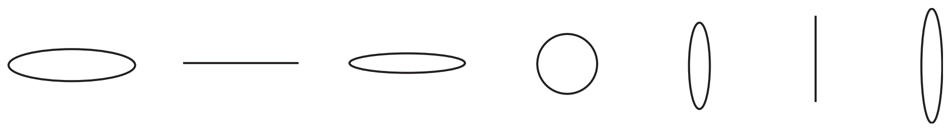
Use the set-up prepared for longitudinal chromatic aberration, and insert a bright red color filter. Find the paraxial image (How?) and check that the system is properly aligned. Then tilt the lens slightly, while watching the image. Coma should be present.

Investigate how changing the aperture diameter and the field angle affects the spot size and shape. You will also observe astigmatism. **Will the coma dominate over astigmatism for large field angles, or for small? For large apertures, or for small?** Remember the spot size for coma is proportional to the square of the aperture diameter, and linearly proportional to the field angle, while astigmatism is linearly proportional to the aperture diameter and proportional to the square of the field angle.

Astigmatism and field curvature

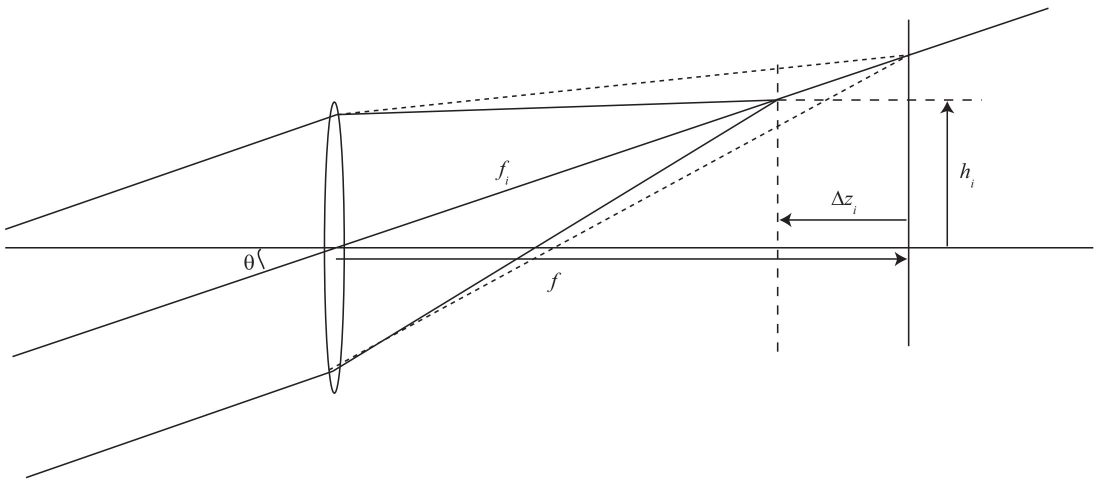
Field curvature is a field aberration, resulting in a curved image surface. It has the same image plane for both tangential and sagittal ray fans. This is not the case for astigmatism, where the image planes are separated. In the case of zero field curvature, the sagittal image plane coincides with the paraxial image plane. **Write down the definitions of the meridional (tangential) and sagittal planes.**

With astigmatism present, an image sequence at different planes could look as below:



Use a lens of focal length 200 mm to collimate the light from the object, then image it using the 200 mm lens with attached iris diaphragm. Turn the lenses so that the flat surfaces face the object and image (to minimize s.a. and coma). Tilt the second lens so that you observe astigmatism. Adjust the aperture and field angle so that astigmatism dominates over coma. **Identify the optical axis, and the sagittal and tangential planes in your set-up. Draw images of the focus at different distances from the lens, corresponding to those given above.**

Investigate how the size and position of the image lines varies with aperture size and field angle. Write down your conclusions.



Finally, we try to find and plot the tangential and sagittal focal planes. Start at the paraxial image plane and measure the focal length f. Then use a field angle θ of 10°, 20°, and 30°.

For each angle, measure the focal lengths f_s and f_t of the sagittal and tangential line foci as shown in the figure above. Use those to calculate the image plane deviations Δz_s and Δz_t and the corresponding image heights h_s and h_t as

$$\Delta z_i = f_i \cos\theta - f \tag{1}$$
$$h_i = (f + \Delta z)\tan\theta \tag{2}$$

where $i = s, t$. **Plot those in the figure below**, using suitable scales, for both tangential and sagittal planes. The difference between the flat paraxial image plane and the curved sagittal plane is due to field curvature, while the difference between sagittal and tangential image planes is due to astigmatism.