Vision Science 203B LABORATORY 7
OPTICS

OPTICAL ABERRATIONS

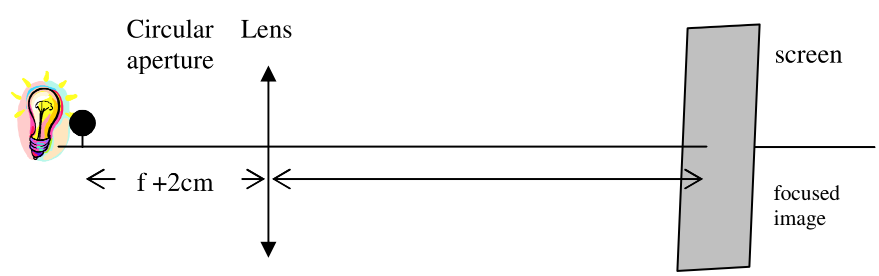
Purpose: The purpose of this session is to familiarize students with optical aberrations and distortions that affect the quality of the image seen through an optical system. In first semester labs, you used lenses to bring images into sharp focus, and measured paraxial distances and dioptric powers. In those labs you assumed a perfect optical system where all rays incident on the lens were focused in a single image plane. In reality, most optical systems suffer from aberrations and distortions that degrade the image quality. For example, it may be that central and peripheral rays are not focused in the same image plane, or that different wavelengths of light are brought to focus at different distances. In this lab you will observe several common optical phenomena including spherical aberration, chromatic aberration, radial astigmatism and distortion.

SECTION 1 - SPHERICAL ABERRATION

In a perfect system, all rays originating in a given object plane will pass through the lens and be brought to a focus in the same plane in image space, creating a sharp image. If a circular bundle of light is passed through a lens it can be focused on a screen as a circle. If some of the rays are blocked, theoretically the final image shouldn't change in shape or location but will become dimmer. You will find in this procedure that the peripheral rays of a lens are subject to spherical aberration. If the central part of the lens is blocked, the image will not only change in brightness but also in distance of best focus. For the next two procedures, record your results in the table at the end of this section.

Procedure 1.1
Plano side of lens towards object

1. Set up a light box with a circular aperture (it should slide right in the front). Adjust the aperture to be about 10 mm in diameter.
2. Tape a piece of transparency grid over the aperture to aid in focusing.
3. Set up a plano-convex lens, with the plano side facing the light box, at a distance about 2 cm longer than the focal length away from the circular aperture. Record the distance, u (from the aperture to the middle of the lens holder)
4. Set up a screen and find the position that gives the best overall focused image of the grid. Record the distance from the lens as $v_{overall}$.
5. Cut out a cardboard disk to occlude the central region of the lens so that the rays passing through the lens are confined to a peripheral annulus. Move the screen until the image of the grid is in best focus. Measure the image distance ($v_{peripheral}$).



6. Remove the disk. Now place a 35 mm aperture over the central region to exclude rays through the peripheral parts of the lens. Reposition the screen so the grid is again in sharp focus on the screen. Measure the image distance ($v_{central}$) in this situation.
7. Are the 3 positions of best focus different? If so why?
8. Which part of the lens best matches the image distance expected from the lens makers formula? (V=U+P)

Procedure 1.2

Plano side of lens towards image

1. Repeat steps 1-7 above with the plano side of the lens towards the image.
2. Are the 3 positions of best focus different? If so, was the spherical aberration greater or less with the plano side towards the image? Why?

	$v_{peripheral}$	$v_{central}$	$v_{overall}$
Plano side towards object			
Plano side towards image			

SECTION 2 - CHROMATIC ABERRATION

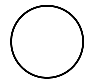
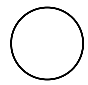
Chromatic aberration occurs because the index of refraction in a medium varies with wavelength. The angle of refraction varies with index of refraction and the result is that the shorter wavelengths come to a focus closer than the longer wavelengths. Consequently, for white light, there is no fixed place along the optical axis where there is a single, clear, focused image.

It may help you to understand chromatic aberration to think of a small section of a lens as behaving like a prism with its base towards the center of the lens. It bends the ray of light that enters towards the focal point and disperses the light's color spectrum. If lens is covered so that only a small spot of light gets through at the top, the light will bend towards the focus and disperse into a spectrum with blue refracted more than red. In this section you will see how the image formed by an optical system is affected by chromatic aberration.

Procedure 2.1

Chromatic aberration around the edges of a circular aperture

1. Rotate the same lens so that the plano side is again facing the object (light box and aperture).
2. Keep the circular aperture near the light box as in section 1. Remove the grid and the screen and tape a piece of paper to the inside of the circular aperture (make sure you remove it after so that you don't start a fire)..
3. Place the lens one focal length away from the circular aperture ($u = f$, therefore $v=\infty$).
4. Position your eye close to the lens and look at the image of the circular aperture. First, look through the center of the lens. Now move your head laterally so that you are looking through a peripheral region of the lens on the right side and then on the left. Notice the change in color along the edges of the image. Sketch a ray diagram that explains this appearance (label the colors).
5. Repeat steps 2 - 4 with the plano side of the lens facing away from the object. Is there any difference?

	Left	Center	Right
Plano towards object			
Plano towards image			

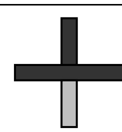
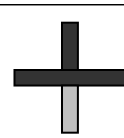
Procedure 2.2
Longitudinal chromatic aberration

1. Remove the circular aperture from the light source. Replace it with the cross aperture, to which pieces of red and blue transparency film are taped so that three spokes of the cross are red.
2. Place the lens f + 2 cm away from the cross aperture, with plano side towards the object.
3. Position the screen at the distance for which the red part of the cross is in best focus (v_{red}).
4. Reposition the screen to find the distance at which the blue part of the cross is in best focus (v_{blue}).

V_{red}	V_{blue}

Procedure 2.3
Lateral chromatic aberration

1. With the same cross aperture in place, move the lens 1f away from the cross; remove the screen.
2. Look at the cross through the +10D lens. Move your head from left to right and observe the half-red, half-blue vertical line image. As you move your head what happens? Explain below, with pictures.
3. Repeat step 2 with the plano side of the lens facing away from the object. Any difference?

	Left	Center	Right
Plano towards object			
Plano towards image			

Procedure 2.4

Chromatic aberration of the eye

Remove the lens and look directly at the back-illuminated cross with the red and blue sections of the vertical limb. Hold a 1 mm pinhole close to your eye and move it from one edge of your pupil to the other. Observe the relative alignment of the red and blue vertical lines. Why do you think this happens?

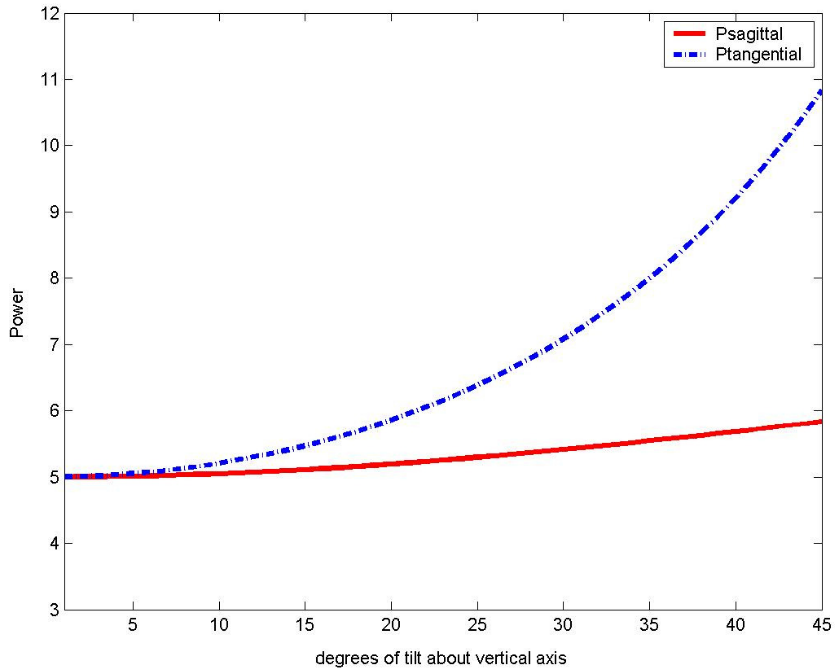
SECTION 3 - RADIAL ASTIGMATISM

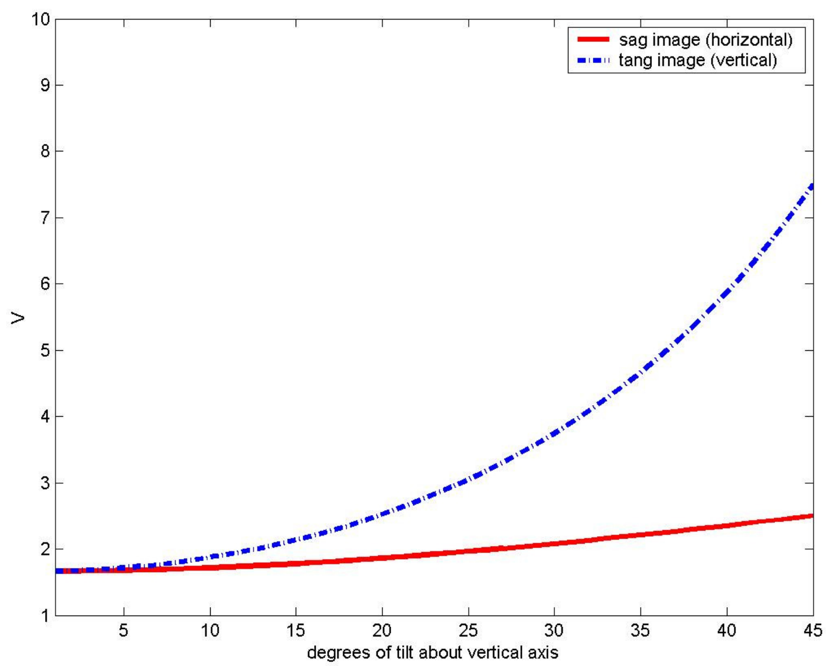
Radial astigmatism occurs because the symmetry of the exiting wavefronts for an off-axis object becomes toric. Radial astigmatism is analyzed in terms of the tangential and sagittal planes. The tangential plane is that which contains the optical axis and the chief ray. The sagittal plane is that which contains the chief ray and is orthogonal to the tangential surface. One result of radial astigmatism is that there is an apparent differential increase in the magnitude of the refracting powers in the tangential and sagittal meridians.

Procedure

1. Remove the red/blue transparency sheets from the cross-aperture. Leave the cross aperture in front of the light source.
2. Set the object distance to f+2cm. Use a 20 mm aperture to isolate the paraxial region of the lens. Move the screen back and forth until you locate a clear image of the horizontal limb. Find and record the image location.
3. Locate the image of the vertical limb. If the lens is mounted squarely on the optical bench (yaw = 0°) then the horizontal and vertical image locations should be the same.
4. Now turn the lens (yaw) so that the plane of the lens is 15° with respect to the optical bench axis
5. For this system, which are the sagittal and the tangential planes?
6. Position the screen so that the horizontal line is in best focus. Measure the distance to the center of the lens in centimeters, convert to diopters and record in the table below.
7. Position the screen so that the vertical line is in best focus. Measure the distance to the center of the lens in centimeters, convert to diopters and record in the table below.
8. Compute the radial astigmatism in diopters and record in the table below.
9. Repeat steps 3 - 8 with the lens rotated 30° and 45°.
10. Read off the expected powers from the graphs on the following page and plot your results against the calculated results on the same graphs.

	Tangential component		**Sagittal component**		**Radial astigmatism (D)**
	v	**P**	**v**	**P**	
0°					
15°					
30°					
45°					


Psagittal
Ptangential
Power
degrees of tilt about vertical axis
3
4
5
6
7
8
9
10
11
12
5
10
15
20
25
30
35
40
45


sag image (horizontal)
tang image (vertical)
V
degrees of tilt about vertical axis
1
2
3
4
5
6
7
8
9
10
5
10
15
20
25
30
35
40
45

SECTION 4 - COMA

Coma is like spherical aberration, only for off-axis objects. Coma is caused by over- or under-refraction of the rays through the peripheral parts of the lens and has an asymmetrical effect for rays from off-axis objects. Coma is very tricky and very messy. For a good explanation as to what is happening to an image, look at Figure 20.21 on page 455 of Keating, 2nd edition. There is positive and negative coma. Coma and spherical aberration both involve the image wavefront becoming aspheric so the ideal image is not obtained.

Procedure

1. Set up the light box with a small circular aperture in it.
2. Set up the 10D lens about f +2 cm away and with its plano surface towards the light source. Place the screen at the appropriate distance to image the light source.
3. Turn the lens clockwise slowly to about 45° and observe what happens to the image. Sketch the final image below.
4. Bring the lens back to its start position. Now turn the lens 45° in the opposite direction and observe the image. Sketch the final image below.
5. Now turn the lens so that its plano surface faces the image, and repeat steps 3 and 4.

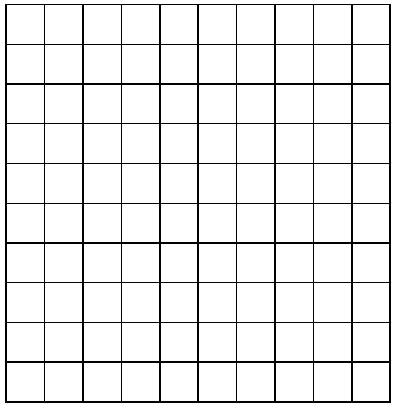
	45° clockwise	45° counter-clockwise
Plano towards object		
Plano towards image		

SECTION 5 - BARREL AND PINCUSHION DISTORTION

In pincushion distortion there is a progressive increase in magnification when the image is further from the axis. In barrel distortion, there is a progressive decrease in magnification when the image is further from the axis.

Procedure

1. Hold a plus lens right on top of the grid target on the next page, plano side down. Pick the lens up slightly from the paper and view the image of the grid. Draw this image on the next page under the column 'Near'.
2. Move the lens farther away and notice if the image changes at all. Sketch this new image under 'Far.'
3. Repeat steps 1 - 2 with the plano side up.
4. Repeat steps 1 - 2 with a minus lens.
5. Label your sketches as either barrel or pincushion distortion.



Questions:

- What is the effect of plano down versus plano up for the plus lens?
- What is the effect of near versus far for the plus lens?
- What is the effect of near versus far for the minus lens?

	Near	**Far**
Plus lens Plano down		
Plus lens Plano up		
Minus lens		