Part A
Spherical aberration

Aim: To design a lens with minimum spherical aberration.

Take a parallel input on-axis ray bundle. A perfect lens will focus this bundle to an infinitesimal point. However, a real lens cannot do this. The light distribution near the focal point is as shown in fig1. Rays near the edge of the bundle will focus somewhere closer to the lens than rays closer to the axis (paraxial rays). The distance between the paraxial focal point and the edge ray focal point is known as longitudinal spherical aberration. When the edge rays intercept the paraxial focal plane, the interception points are also displaced from the paraxial point. This separation is known as transverse spherical aberration.

Fig1. Spherical Aberration
**Lens Entry:**

Model a plano-convex lens of radius of curvature $R_1 = 50$. Let the entrance beam radius be 10 mm and field angle be 20 degree. Assume the thickness of surface 1 to be 10 mm. Place the image surface at the point where axial ray height goes to zero. Let the lens material be BK7.

In the graphics window, click “report graphics ray analysis”. The longitudinal spherical aberrations for the 3 wavelengths will be displayed as shown in fig2. The wavelength specified by us is in green.

![Longitudinal Spherical Aberration](image)

**Fig2. Longitudinal Spherical Aberration**

**Spot diagram Analysis**

A spot diagram shows the images of the three points $FBY=1$, $FBY=0.7$, $FBY=0$ on the image plane, where $FBY$ is ratio of the height of the point in consideration to the maximum height of the object. Note that the maximum height of the object is determined by the field angle specified. Choosing the spot diagram analysis in the graphics window gives a diagram as shown in fig3.
Optimization:

We will optimize the design such that the lens has a focal length of 150 mm and has minimum spherical aberration. The operands are SA3 which refers to spherical aberration of the third order which is sufficient for all practical purposes and EFL which refers to effective focal length. Choose the curvatures of the two surfaces as variable and iterate. Now, the graphics ray analysis looks as shown in fig4.

Note that in order to compare the curves before and after optimization we need to make sure that the axes before and after optimization are of the same scale.
The spot diagram analysis after optimization is as shown in fig5:

Comparing these two analysis diagrams, we can see the effect of spherical aberration on the optical system. Remember that effective comparison can be carried out only when the scales are the same in both spot diagrams. To change the scale of the diagram right click on the diagram and choose “Re-calculate using new parameters” and then change the scale.

Part B
Comatic aberration

Aim: To design a lens with minimum comatic aberration.

Lens Entry:

Model a bi-convex lens of radius of curvature R1= 50, R2=-50. Let the entrance beam radius be 10 mm and field angle be 20 degree. Make surface 3 as the aperture stop. Assume the thickness of surface 1 to be 10 mm, surface 2 to be 10 mm and AST to be 30 mm.

Graphical analysis for reducing coma

Perform spot diagram analysis.
Hint: While optimizing, select the variables properly in order to get proper results.

**Ray fan analysis:** This analysis shows the effect of the optical system on a beam of rays. To see the effect of coma on the ray beam, we can use a 2-D or a 3-D ray fan analysis. Click the setup window icon in the graphics window and choose lens drawing toolbar. In this toolbar select the ray fan analysis icon.
Points to be noted:

- We chose the biconvex lens here to demonstrate the effect of coma because coma is minimum in convex-plano lens.
- Remember, while optimizing an aberration operand we are changing parameters of the optical system. So it is bound to make changes in the other operands. You can check it out by first optimizing the lens for spherical aberration and then for coma.
As an additional exercise you can try to optimize a particular lens system for minimum coma as well as spherical aberration and see how different parameters change as compared to the shown exercises.

Part C
Astigmatism

Aim: To design a lens with minimum astigmatism.

When an off-axis object is focused by a spherical lens, the natural asymmetry leads to astigmatism. The system appears to have two different focal lengths. As shown in fig10, the plane containing both optical axis and object point is called the tangential plane. Rays that lie in this plane are called tangential rays. Rays not in this plane are referred to as skew rays. The chief, or principal, ray goes from the object point through the center of the aperture of the lens system. The plane perpendicular to the tangential plane that contains the principal ray is called the sagittal or radial plane. The figure illustrates that tangential rays from the object come to a focus closer to the lens than do rays in the sagittal plane. When the image is evaluated at the tangential conjugate, we see a line in the sagittal direction. A line in the tangential direction is formed at the sagittal conjugate. Between these conjugates, the image is either an elliptical or a circular blur. Astigmatism is defined as the separation of these conjugates. The amount of astigmatism in a lens depends on lens shape only when there is an aperture in the system that is not in contact with the lens itself. (In all optical systems there is an aperture or stop, although in many cases it is simply the clear aperture of the lens element itself.) Astigmatism strongly depends on the conjugate ratio.

Fig10. Astigmatism
Lens Entry:

Model a bi-convex lens of radius of curvature $R_1=50$, $R_2=-50$. Let the entrance beam radius be 10 mm and field angle be 20 degree. Make surface 3 as the aperture stop. Assume the thickness of surface 1 to be 10 mm, surface 2 to be 10 mm and AST to be 30 mm.

Optimization:

Use AST3 as the aberration operand for astigmatism. Note that the effects of astigmatism are best viewed when there is no coma or spherical aberration. But, here we optimize only for astigmatism and show graphically the changes as a result of that. As an exercise you should try minimizing the coma and spherical aberration and then all the three operands. Shown below are the ray intercept curve analysis diagrams and spot diagrams before and after optimization.

![Ray Intercept curve](image)

Fig11. Ray Intercept curve (a) before optimization (b) after optimization

Hint: While optimizing, select the variables properly in order to get proper results.
Fig. 12. Spot diagram before optimization

Fig. 13. Spot diagram after optimization
Notice that after optimization, the difference between the X-spot size and the Y-spot size has decreased which is verified through the Skew Beam analysis.

**Skew Beam Analysis:**

This can be used to analyze the beam of rays in XZ and YZ planes separately. Click on ‘source’ in the main menu bar and choose Skew Gaussian beam. A new window will popup. Change the beam size to 5 in x and y direction at the object surface. Set the object point FBY=1.

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**Fig14. Skew Beam Analysis**

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Notice that the difference between the x spot size and y spot size has decreased after optimization.

Practice Exercise:

Design a lens with parameters: focal length = 100 mm, f/10 and FOV = ±17°. Assume the lens to be the aperture stop. Constrain the focal length to 100 mm and change the lens shape.

From the spreadsheet buffer, obtain the values of coma and spherical aberration and use a software such as Matlab or excel to plot* a graph of aberration vs. lens bending (ie the Coddington shape factor; CSF = (R2+R1)/(R2-R1).

*Note:
The x-axis must be the shape factor and the y-axis must be the aberration. However, CSF must be plotted for curvature of the first lens surface varying from (-0.04, -0.02, 0, 0.02, 0.04, 0.06). This is equivalent to R1 varying from -25mm, -50, ∞, +50, +25, 16.7 mm

(Hint: Use ‘Abr’ button in text window to obtain the values of different aberrations)

References:
Figures 1, 8, 9 and 10 are taken (with permission) from the OSLO manual.
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