Ray Optics
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(9h-12h)

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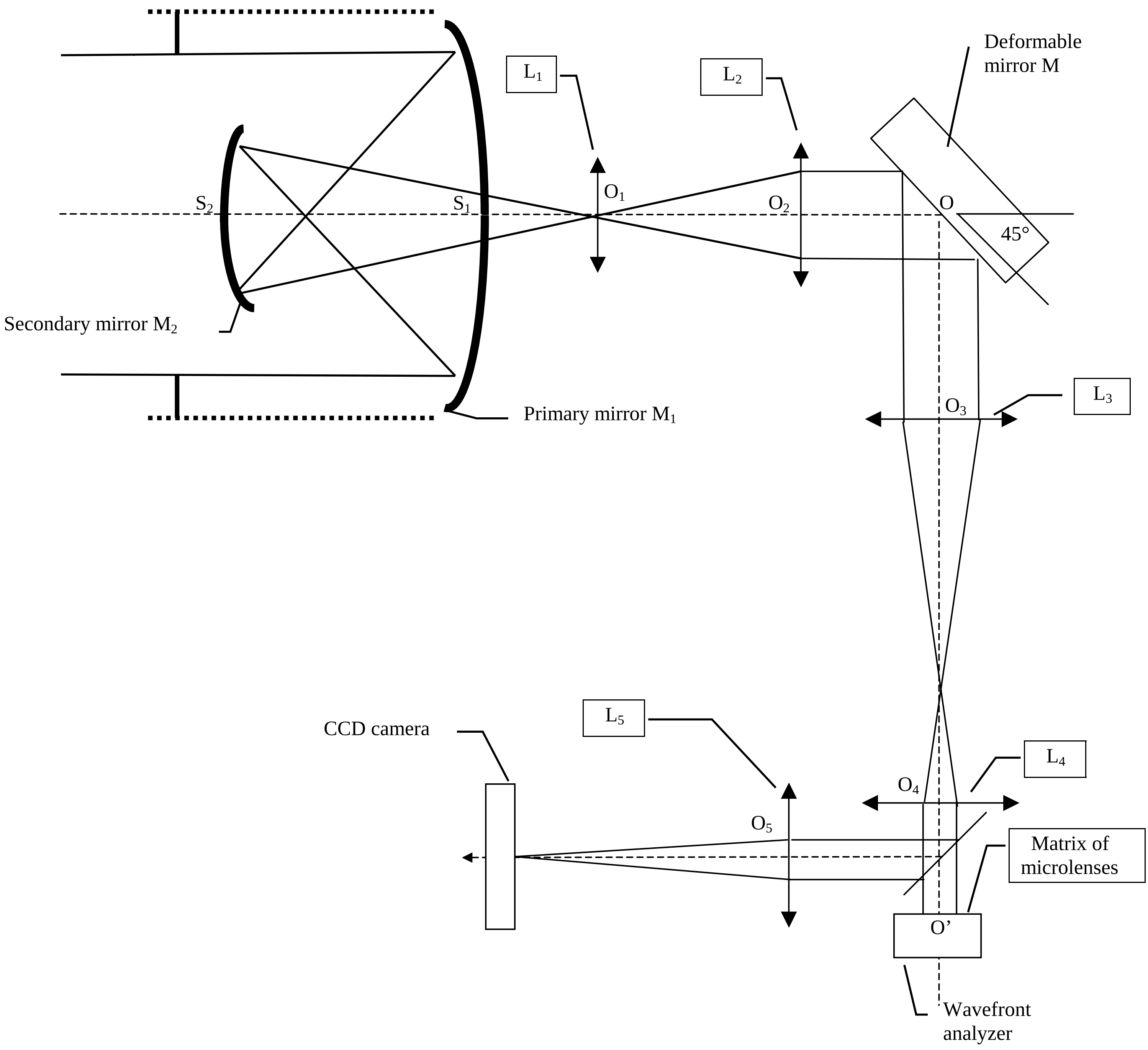
duration: 3h

Documents and calculator authorized

RAY OPTICS EXAM

<u>Simplified study of a telescope equipped with an adaptive optics system</u>

General structure of the optical system (the drawing is not to scale)



The resolution of optical telescopes is reduced due to atmospheric turbulence. Adaptive optics is a solution to this problem, by compensating in real time the wavefront deformations due to this turbulence. The general principle consists in measuring the defects of the wavefront disturbed by atmospheric turbulence and compensate for these in real time using a deformable mirror.

The optical setup that you will study consists of several parts :

- A small telescope in the Gregorian configuration consisting of mirrors M1 and M2
- A converging field lens L_1 with focal length **f'_1=100 mm** and a converging lens L_2 with focal length **f'_2 =150 mm.** As shown in the figure, L_1 is located in the image plane of the telescope and in the first focal plane of L_2.
- A deformable mirror used at an incidence angle of **45°**. Its shape is plane at rest, and can be modified electrically to compensate for the disturbance of the wavefront.
- An afocal system consisting of two converging lenses L_3 and L_4 with focal lengths **f'_3** (to be determined) **and f'_4= 50 mm**.
- A matrix of 10x10 microlenses with a square overall size of **6 mm by 6 mm** and a detector to analyze the wavefront

The final image can be observed on a CCD camera placed in the focal plane of a converging lens L_5 with focal length **f'_5=120 mm**.

The system is designed for the near-infrared, so calculations will be done for λ=1µm.

We will study independently the different part of the system and then put them together to study the final image. Parts A, B, C and D of the problem can be solved almost independently.

A. Study of the telescope :

The Gregorian telescope has **a focal length of *500 mm*** (absolute value). The radius of curvature of the primary concave mirror M_1 is ***R_1 = 200 mm***. The radius of curvature of the secondary mirror M_2, also concave, is ***R_2 = 50 mm.*** M_2 makes the image of the focal point F_1 of the primary mirror on the second focal point F' of the whole telescope.

The entrance pupil with diameter ***100 mm*** is located at the center of curvature of the primary mirror M_1.

Resolution of the telescope

1. Calculate the f-number of the telescope and its numerical aperture α' in the image space.
2. Calculate the resolution of the telescope in the object space in seconds of arc if we assume that it is limited by diffraction. The wavelength under consideration is ***λ=1µm.***
3. If we use a CCD matrix with ***20*20 µm*** square pixels in the image plane of this telescope, what will the angular resolution be ? What must be the precision of positioning of the CCD detector along the axis so that it does not affect this resolution?

Relative positions of all the elements

4. What is the sign of the focal length of the telescope? Determine the distance between the two mirrors, the transverse magnification of the image through the secondary mirror, and the distance of the final image in F' with respect to the vertex S_1 of the primary mirror.
5. Make a drawing of the telescope with scale 1 both along the axis and in the transverse direction. Represent on this drawing the entrance pupil which is located at the center of curvature C_1 of the primary mirror.
6. Calculate the position and diameter of the exit pupil of the telescope. Represent it on the previous drawing. Calculate the distance between the exit pupil and the final image in F',

and check that your results are coherent with the numerical aperture α’ in the image space that you calculated in question 1.

7. Trace on the previous drawing the path through the whole telescope of a bundle of rays from an object at infinity on axis passing on both edges of the entrance pupil. Represent the exit pupil.

Study of the field of view of the telescope :

We want in the image plane of the telescope a bright field of view $2y'_{BF}$ equal to ***10mm in diameter.***

8. Calculate the corresponding bright field diameter $2\theta_{BF}$ in the object space and $2y_{BF}$ in the intermediate space.
9. Trace on the previous drawing the path of a bundle of rays coming from one edge of the bright field and passing on both edges of the entrance pupil.
10. Determine both graphically and by calculation the minimum diameter of the hole at the center of M1, the minimum diameters of mirror M_2 and of mirror M_1 so that they do not limit the field.

B. Lenses L1 and L2

The combination of lenses L_1 and L_2 makes a parallel beam on the deformable mirror M. The positions and focal lengths of those two lenses are given in the introductory paragraph.

11. From the aperture α’ in the image space that you calculated in question 1, show that the size of the parallel beam hitting the deformable mirror has a diameter of 30mm.
12. Determine the focal length and the positions of the cardinal points (focal points and principal points) of the combination of L_1 and L_2.
13. We want to image through L_1 and L_2 the center of the exit pupil of the telescope with the center O of the deformable mirror. Calculate the distance between lens L_2 and the center of the mirror O.
14. Represent on a drawing with scale ½ along the axis and 1 in the transverse direction the part of the system including the exit pupil of the telescope, the lenses L_1 and L_2 and the exit pupil after L_2 centered in O. Draw the rays corresponding to the object on axis and the maximum aperture.
15. Reminding that the bright field in the image plane of the telescope has a diameter of 10mm, determine the diameter $2\theta'_{BF}$ of the bright field in the image space of lens L_2.
16. Calculate the minimum diameters of L_1 and L_2 so that they do not limit the bright field.

C. Deformable mirror M

17. Make a drawing with scale 1 of the parallel beam before and after reflection on the mirror M at 45°, for the object on axis and for objects on both edges of the bright field calculated in question 16.
18. What must be the size of the mirror so that it does not limit the beam?

D. Study of the afocal system

The main role of the afocal system L_3+L_4 is to image the pupil which is located on the deformable mirror on the matrix of microlenses. The matrix of microlenses is a square of 6 mm by 6 mm**,** so the whole beam can be analysed if it has **a diameter of 6mm**.

19. What must be the transverse magnification of this afocal system so that it images the pupil of 30mm on a pupil with diameter 6mm? What does that imply on the focal lengths of the two lenses L_3 and L_4? Calculate the focal length $\mathbf{f'_3}$ of L_3 so that this condition is fulfilled, knowing that we chose a focal length $\mathbf{f'_4 = 50\ mm}$ for lens L_4.

20. Suppose we place the center O of the deformable mirror at the first focal point of L_3: what will be the position of the matrix of microlenses with respect to the lens L_4? What will then be the total distance from the mirror to the microlenses?
21. We want to reduce that distance by reducing the distance between the deformable mirror and the first lens L3. If that distance OO_3 is equal to 90mm, what will then be the distance between L_4 and the matrix of microlenses? Make a drawing with scale 1/5 along the axis and 1 in the transverse direction of the afocal system showing the position of the entrance pupil of this afocal system (in O with diameter 30mm) and of the corresponding exit pupil.
22. We have calculated in question 16 the bright field $2\theta'_{BF}$ in the object space of the afocal system. Calculate the corresponding bright field $2\theta''_{BF}$ in the image space of L_4. What must be the size of lenses L_3 and L_4 so that they do not limit this bright field? Trace the corresponding rays on the previous drawing.

E. <u>Study of the final imaging on the CCD camera</u>

We know consider the whole imaging from the object at infinity in the object space of the telescope to the final image formed by lens L_5 on a CCD camera. This last lens L_5 has a focal length of 120mm.

23. Calculate the focal length of the whole system (from the telescope to the CCD camera).
24. Calculate the final size of the bright field in the plane of the CCD.
25. Is the resolution of the whole system limited by diffraction or by the 20*20µm size of the pixels? What must be the precision of positioning of the CCD detector along the axis so that it does not affect this resolution?