# Assignment 9

## OPTI 502 Optical Design and Instrumentation I

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## Exercise 1

We use raytracing with the chief and marginal ray and the information given. Recall that the stop is placed at the primary mirror, so the chief ray must have 0 height at that location. Also, we put a **dummy surface** at the primary mirror to use it for vignetting, and working

| | | Object space | EP | | $M_1$ (stop) | | $M_2$ | | Dummy | | XP | | Image space |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $R$ | | | | $-500$ | | $-125$ | | $\infty$ | | | | |
| | $t$ | | | $z_{EP} =$ | | $-200$ | | 200 | | | | | |
| | $n$ | 1 | | 1 | | -1 | | 1 | | 1 | | 1 | |
| | $-\phi$ | | | | $-0.004$ | | 0.016 | | 0 | | 0 | | |
| | $t/n$ | | | $\tau_{EP} =$ | | 200 | | 200 | | $-247.619$ | | 297.625 | |
| | $y$ | | | | 0 | | 20 | | 104 | | 0 | | 123.743 |
| CR | $nu$ | | | 0.1 | | 0.1 | | 0.42 | | 0.42 | | 0.42 | |
| | $u$ | | | | | | | | | | | | |
| | $y$ | | $R_{EP} =$ | | 1 | | 0.2 | | 0.04 | | $R_{XP} = 0.2381$ | | 0 |
| MR | $nu$ | | | 0 | | $-0.004$ | | $-0.0008$ | | $-0.0008$ | | $-0.0008$ | |
| | $u$ | | | | | | | | | | | | |

Table 1: Raytrace, with CR=Chief ray, MR=Marginal ray.

From the marginal ray, we know that the effective focal length is:

$$f = -\frac{y_1}{\omega_k} = -\frac{1}{-0.0008} = 1250 \; mm.$$

The working distance is the sum of the distance from the dummy surface to the exit pupil and the distance from the exit pupil to the image location:

$$\text{WD} = -247.619 + 297.625 \approx 50 \; mm.$$

By looking the distance of the dumy to the exit pupil, we say that the exit pupil is located 247.619 $mm$ to the left of the primary mirror.

The potential chief ray must be scaled to reach the maximum image size required. We found that the potential CR has an image size of 123.743 $mm$ and the required is 8 $mm$, so we need to downscale it at the image location by a factor of

$$m_{CR} = \frac{y'_{\text{required}}}{\bar{y}'} = \frac{8}{123.743} = 0.0646.$$

In the same way, for the potential marginal ray, we need to upscale at the stop so that the F-number is satisfied:

$$f/\# = 4 = \frac{f}{D_{EP}} \longrightarrow D_{EP} = \frac{1250}{4} = 312.5\ mm.$$

and, remembering that the EP is at the same location that the stop:

$$m_{MR} = \frac{y_{\text{required at EP}}}{y_{\text{EP}}} = \frac{312.5/2}{1} = 156.25\ mm.$$

The object FOV is determine with the slope ray of the chief ray at the entrance pupil:

$$\text{FOV} = \pm\tan^{-1}(m_{CR}\cdot\bar{u}_{\text{EP}}) = \pm\tan^{-1}[(0.1)(0.0646)] = \pm 0.371^\circ.$$

The diameter of the exit pupil is therefore:

$$D_{XP} = 2m_{MR}y_{\text{XP}} = 2(156.25)(0.2381) = 74.397\ mm.$$

The diameter of the secondary mirror as well as the diameter of the hole must be obtained by setting the non-vignetting condition. At the secondary mirror, we have

$$a_S \geq |y_S| + |\bar{y}_S| = 1.292 + 31.25 = 32.542\ mm \longrightarrow D_S \geq 2a_S = 65.084\ mm.$$

In the same way, for the hole we have that

$$a_H \geq |y_H| + \bar{y}_H| = 6.718 + 6.25 = 12.968 \longrightarrow D_H \geq 2a_H = 25.937\ mm.$$

## Exercise 2

A relaxed eye means that the intermediate image must be at the front focal plane $f_{EP}$ of the eyepiece so that the rays output parallel. The magnifying power is:

$$MP = \frac{250\ mm}{f_{EP}} = 10 \longrightarrow f_{EP} = 25\ mm.$$

a) For a simple eyepiece, the $f_{EP}$ corresponds to the front focal length of the eyepiece: $f_{eye} = f_{EP}$. Because the stop is 200 $mm$ to the left of the intermediate image, which is 25 $mm$ to the left of the eyepiece, the total distance from this lens is:

$$z = -200 - f_{eye} = -200 - 25 = -225\ mm.$$

Using the thin-lens equation, we find the distance of the object and therefore the eye relief:

$$\frac{1}{ER} = \frac{1}{z} + \frac{1}{f_{eye}} \longrightarrow ER = \frac{1}{\frac{1}{-225} + \frac{1}{25}} = 28.125\ mm.$$

b) In the case of a compound eyepiece, the field lens is placed at one front focal length from the eye lens. This implies that only the rear principal plane and the ER change from the simple eyepiece discussed previously. It is shifted by the following amount:

$$d' = -\frac{\phi_F}{\phi_{EP}}t = -\frac{f_{eye}^2}{f_F} = -\frac{25^2}{40} = -15.625\ mm.$$

The eyerelief is then shifted by the same amount to the left:

$$ER = 28.125 - 15.625 = 12.5\ mm.$$

c) In the Ramsden eyepiece, we need to have the same eye relief of part b) knowing that the field lens is located 12 $mm$ to the right of the intermediate image plane. Recall also that we have to achieve the magnyfying power and the image location, so we have three conditions to meet.

$$f_{EP} = 25\ mm, \quad d' = -\frac{\phi_F}{\phi_{eye}} t, \quad f_{EP} = 12 + d = 25\ mm, \quad \frac{1}{z'} = \frac{1}{z} + \frac{1}{f_{EP}}.$$

First, the focal length $f_{EP}$ allows us to obtain the shift of the front principal plane:

$$f_{EP} = 12 + d = 25 \longrightarrow d = 13\ mm.$$

This shifting is equal to the ratio of powers, which enables us to solve for the power of the eye:

$$d = 13 = \frac{\phi_{eye}}{\phi_{EP}} t \longrightarrow \phi_{eye} t = \frac{d}{f_{EP}} = \frac{13}{25} = 0.52.$$

The distance of the stop to the front principal plane is:

$$z = -200 - 23 - d = -225\ mm.$$

Using the thin-lens equation:

$$\frac{1}{z'} = \frac{1}{z} + \frac{1}{f_{EP}} \longrightarrow z' = 28.215\ mm.$$

This distance is from the rear principal plane to the exit pupil so we can extract the shifrt $d'$:

$$ER - d' = 28.215 \longrightarrow d' = -15.625\ mm.$$

We can relate it to tits formula and get the term $\phi_F t$:

$$d' = -\frac{\phi_F}{\phi_{EP}} t \longrightarrow \phi_F t = -\frac{d'}{f_{EP}} = 0.625.$$

Using the overal power multiplied by $t$ allow us to get this distance,

$$\phi_{EP} t = \phi_F t + \phi_{eye} t - \phi_F \phi_{eye} t^2 = 0.625 + 0.52 - 0.625 \cdot 0.52 = 0.82.$$

Therefore,

$$t = \frac{0.82}{\phi_{EP}} = 0.82 f_{EP} \longrightarrow t = 20.5\ mm.$$

With this distance, we now have the focal length of the eye and the field lens:

$$\phi_{eye} = \frac{0.52}{20.5} = \frac{1}{f_{eye}} \longrightarrow f_{eye} = 39.42\ mm$$
$$\phi_F = \frac{0.625}{20.5} = \frac{1}{f_F} \longrightarrow f_F = 32.8\ mm.$$