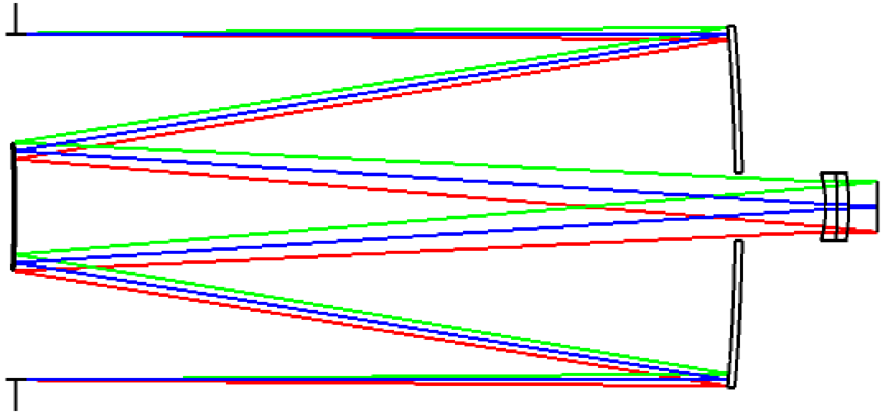
Lectures Notes on Optical Design using Zemax OpticStudio

Lecture 13

Telescopes



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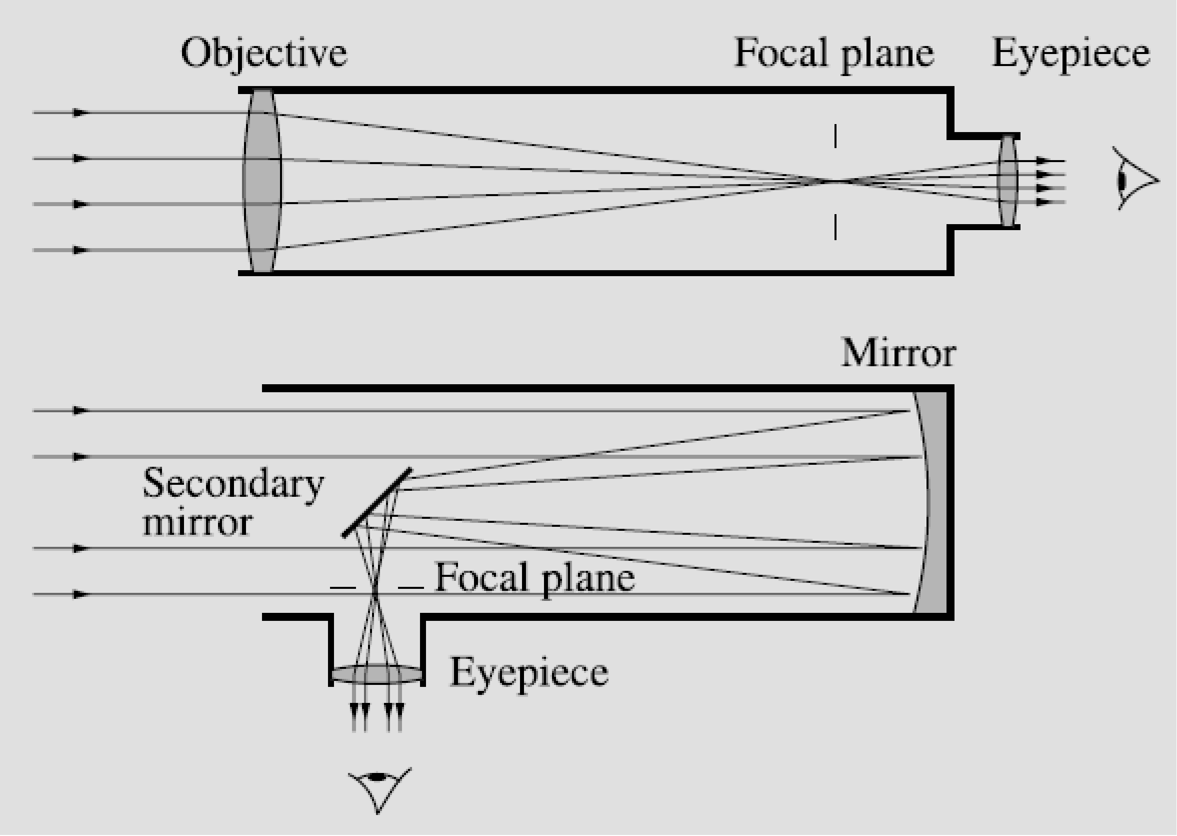
Telescope

- Telescopes are designed to aid in viewing distant objects, such as the planets in our Solar System.

- There are two different types:
  - **refracting telescopes**
    uses a combination of lenses
  - **reflecting telescopes**
    uses a mirrors and a lenses



Telescope

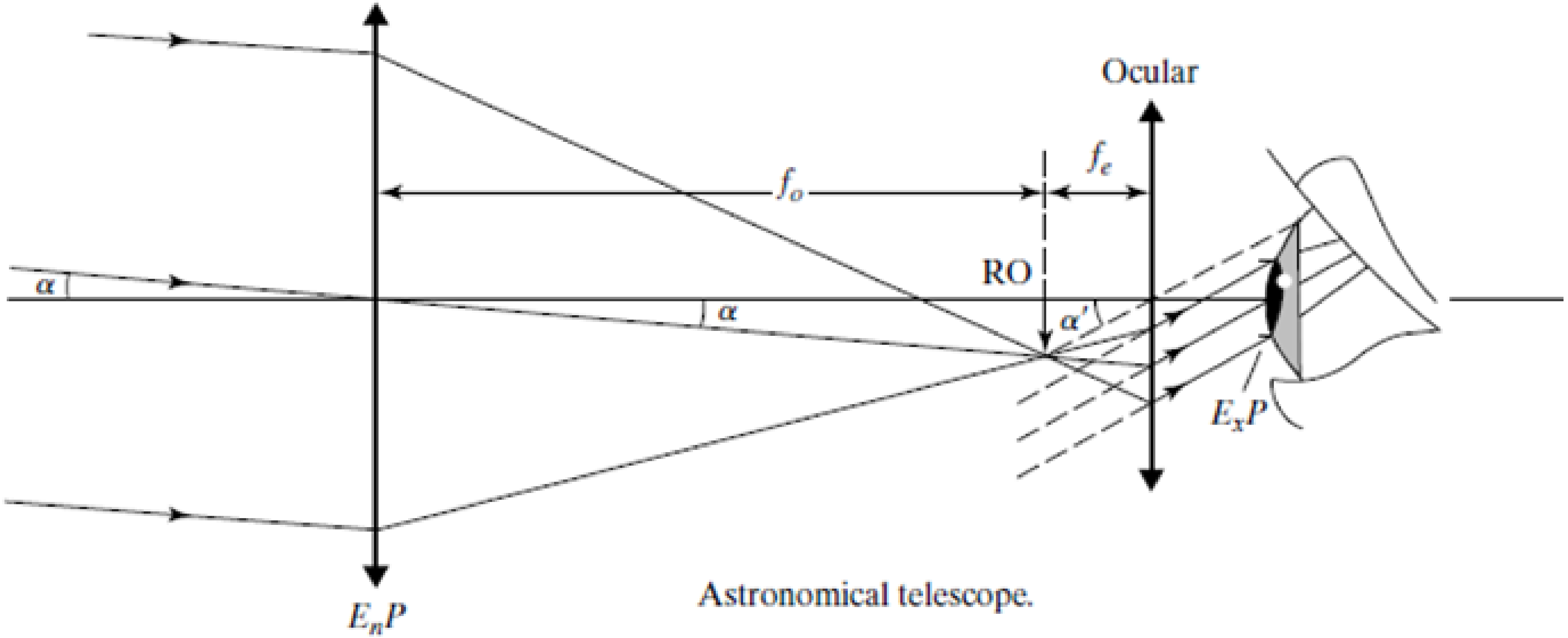
The telescope fulfils three major tasks in astronomical observations:

1. It collects light from a large area, making it possible to study very faint sources.
2. It improves resolution and increases the apparent angular diameter of the object.
3. It is used to measure the positions of objects.

Keplerian (Astronomical) Telescope

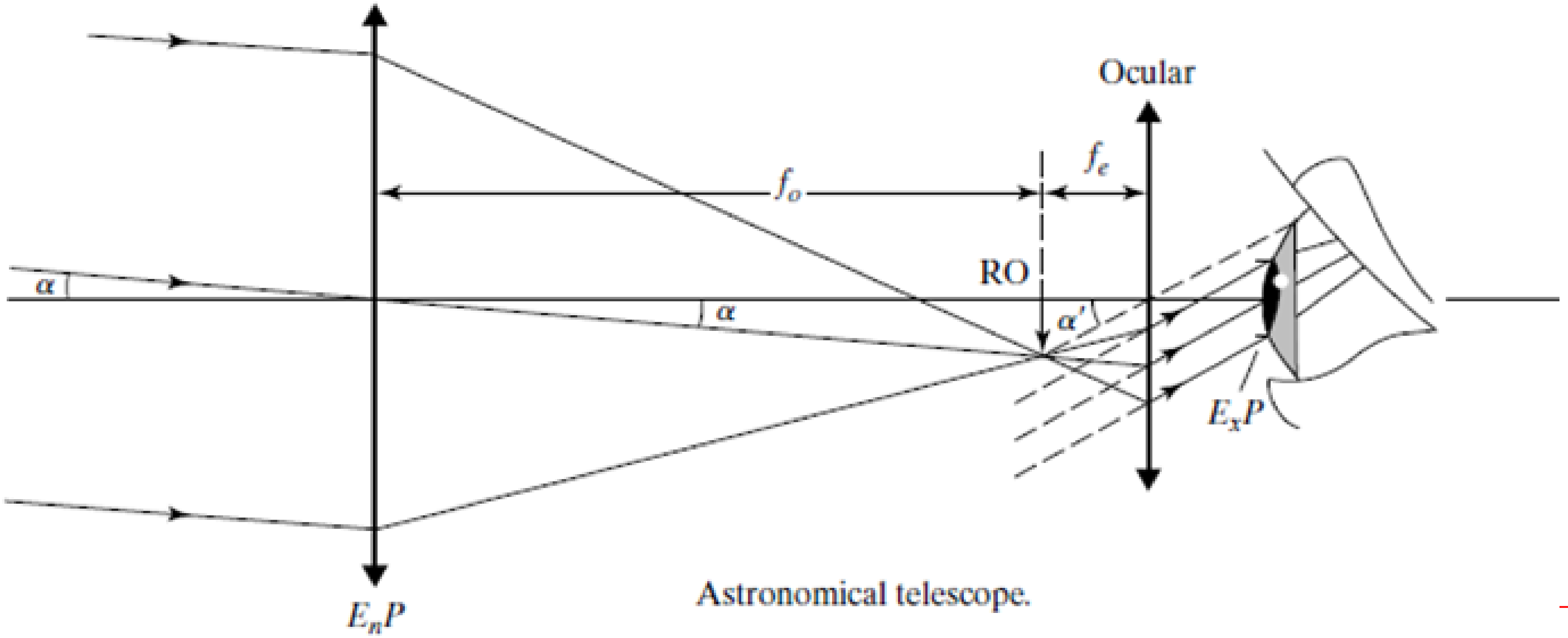
It has two lenses:

- the **objective** which collects the incoming light and forms an image in the focal plane
- the **eyepiece** (ocular) which is a small magnifying glass for looking at the image.



Astronomical telescope.

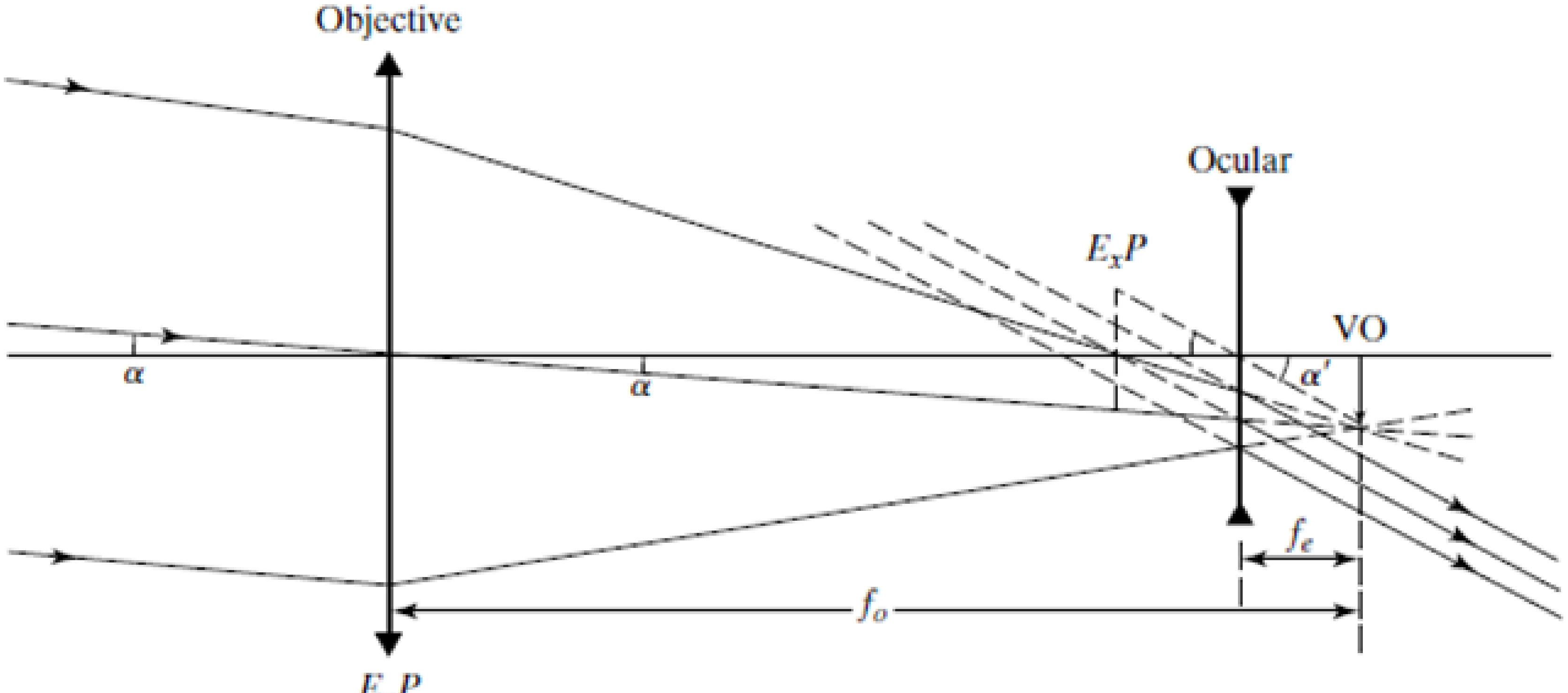
- The diameter of the objective, D_{EnP}, is called the *Aperture* or *Entrance Pupil (EnP)* of the telescope.
- *Exit Pupil (ExP)* of the telescope is the diameter of the output light rays. *ExP* of a telescope is usually selected as the size of human pupil (2 mm in daylight and 8 mm in dark). We desire: ExP diameter < (eyepiece diameter) [$D_{ExP} < D_e$]



Astronomical telescope.

Galilean Telescope

The Galilean or terrestrial telescope uses a positive objective and a negative eyepiece. It gives erect images and is shorter than the astronomical telescope with the same power.

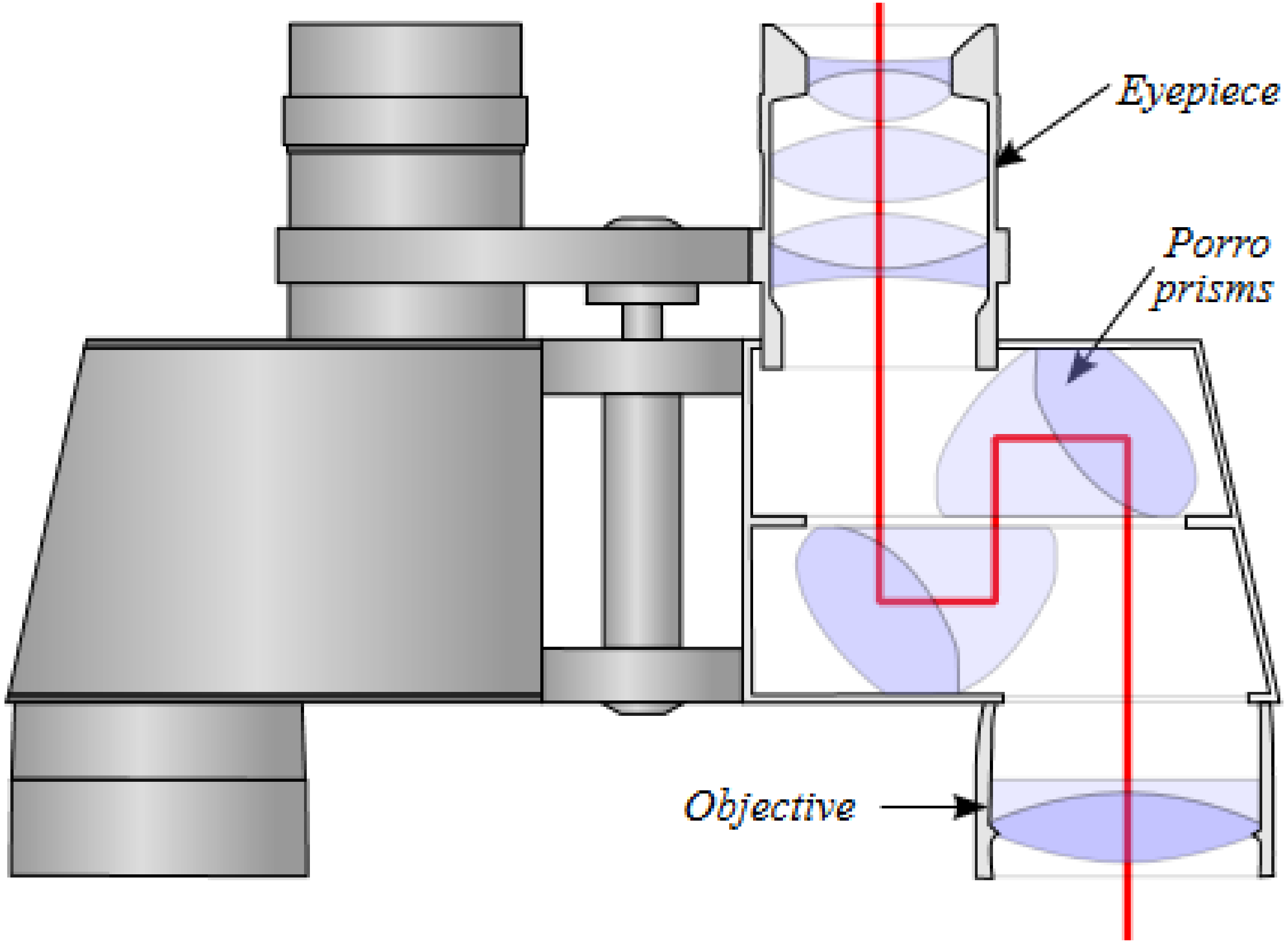


Galilean telescope.

Binoculars

- Binoculars afford more comfortable telescopic viewing, allowing both eyes to remain active.

- In addition, the use of Porro (or other) prisms to produce erect final images also permits the distance between objective lenses to be greater than the interpupillary distance, enhancing the stereoscopic binocular vision.


Eyepiece
Porro prisms
Objective

Design Equations (for Keplerian, Galilean and Binoculars)

Angular magnification of the telescope is defined as: $m = \alpha'/\alpha$

From basic geometry, the following equations can be derived:

Magnification: $m = -\frac{f_o}{f_e}$ and $|m| = \frac{D_{EnP}}{D_{ExP}}$

Distance between Lenses: $t = f_o + f_e$

Angular Field of View: $\theta_{FOV} = \frac{D_e}{t}$

Eye relief: $ER = r = \frac{(f_o+f_e)f_e}{f_o}$

The eye relief of an optical instrument (such as a telescope, a microscope, or binoculars) is the distance from the last surface of an eyepiece within which the user's eye can obtain the full viewing angle.Or more techically, eye relief is the distance of the exit pupil from the eyepiece.

Example: Basic Binocular Design

Consider the design of 6 x 30 for binoculars. (6x means that the angular magnification is 6 and the diameter of the objective lens is 30 mm). Its objective focal length 150 mm and eyepiece diameter 15 mm. Then,

Exit pupil diameter: $D_{ExP} = 30 / 6 = 5$ mm

Eyepiece focal length: $fe = -150/-6 = 25$ mm

FOV: $\theta_{FOV} = 15 / (150+25) = 0.086$ rad $(\sim 5^{o})$

Eye relief: $r = 29.7$ mm

Reflecting Telescope

We have seen that larger-aperture objective provide greater light gathering power and resolution.

Problems with refraction telescopes:

- large homogeneous lenses are difficult to produce without optical defects
- the weight of larger lens is difficult to support.
- chromatic aberrations have to be overcame

Solution:

Reflecting surfaces are used in place of lenses.

Reflecting Telescope

Nowadays the most common telescope type is the mirror telescope. As a light-collecting surface, it employs a mirror coated with a thin layer of aluminium.

The form of the mirror is usually *parabolic*. A parabolic mirror reflects all light rays entering the telescope parallel to the main axis into the same focal point.

The image formed at this point can be observed through an eyepiece or registered with a detector.

One of the advantages of reflectors is the absence of chromatic aberration, since all wavelengths are reflected to the same point.

Some Basic Reflecting Telescopes

1. Newtonian Telescope

- Uses two mirrors: parabolic and flat.
- Typical f-numbers: f/3 . . . f/10.
- Total length of telescope is in the order of focal length of mirror.

2. Cassegrain Telescope

- Uses two mirrors: parabolic and convex hyperbolic.
- Typical f-numbers: f/8 . . . f/15.
- Primary and secondary focal foints are the foci of the hyperbola.
- Total length of the telescope is much shorter than Newtonian for the same primary focal length.

3. Gregorian Telesscpope

- Uses two mirrors: parabolic and concave elliptical.
- The primary and secondary focal points of this telescope are the foci of the ellipse.

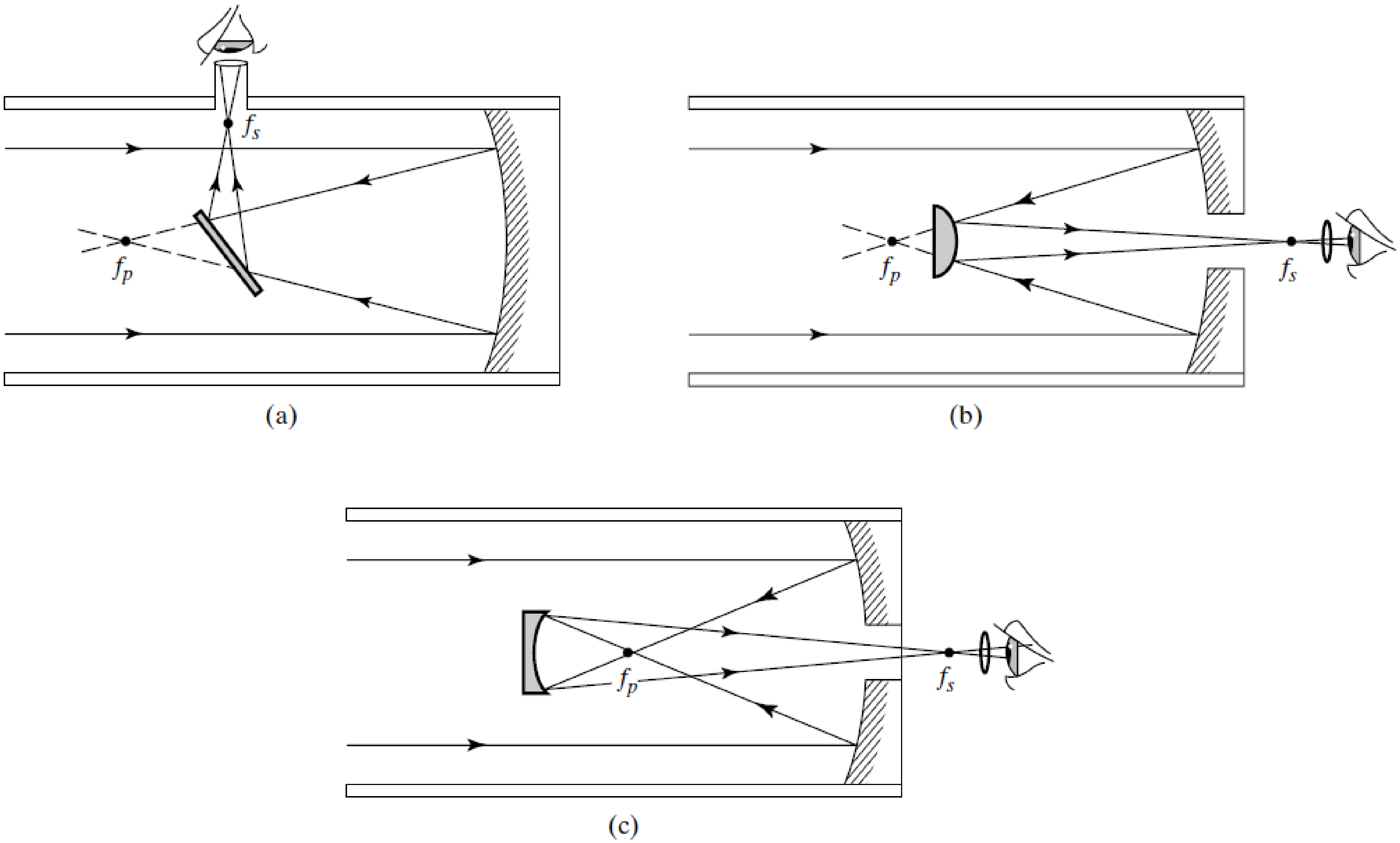


Figure 34 Basic designs for reflecting telescopes. (a) Newtonian telescope. (b) Cassegrain telescope. (c) Gregorian telescope.

Our Newtonian Telescope Project

http://www1.gantep.edu.tr/~bingul/hezarfen

- The largest *reflecting* telescopes in the world are at the Keck Observatory on Mauna Kea, Hawaii at an elevation of **4145 meters**.
- Two telescopes with **diameters of 10 m**, each containing 36 hexagonally shaped, computer-controlled mirrors that work together to form a large reflecting surface.

Example: Newtonian Telescope

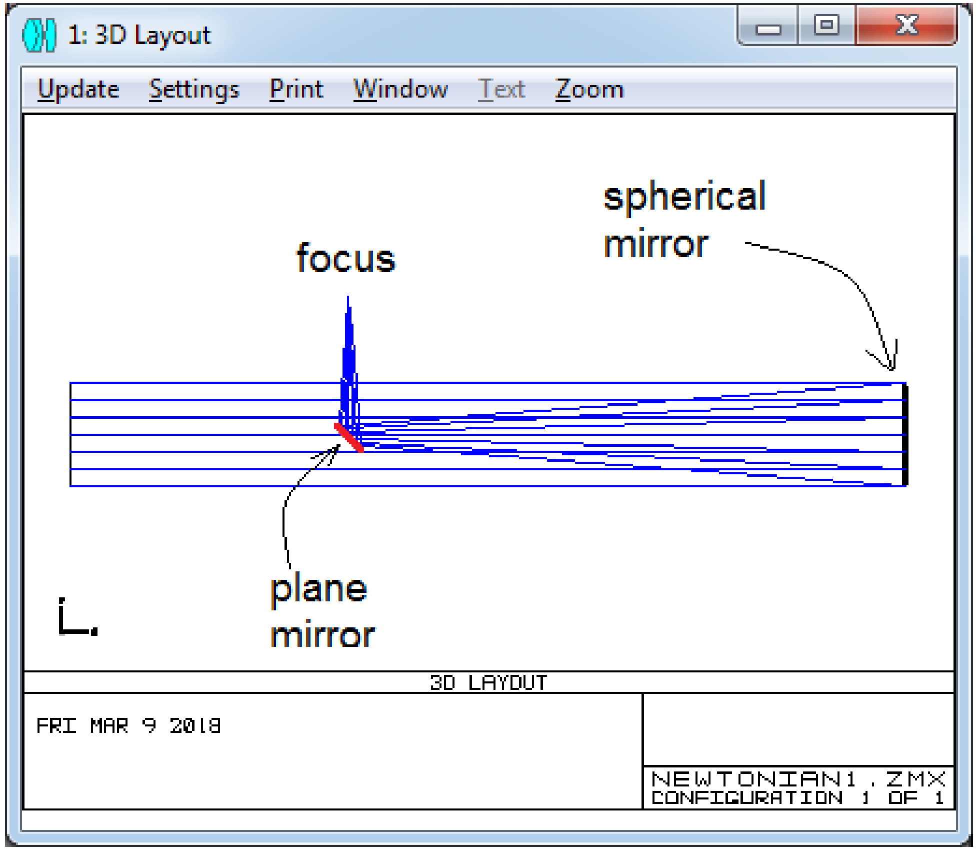
(a) In Zemax, fulll the simulation of the Newtonian Telescope; one concave mirror and one flat mirror. Let the entrance pupil 150 mm, radius of curvature of the mirror is |R| = 1.5 m and the distance between primary and secondary mirror is 0.6 m. Image plane is placed at a distance 0.2 m from the flat (secondary) mirror.

(b) What is the geometric radius of the spot diagram on the image plane?

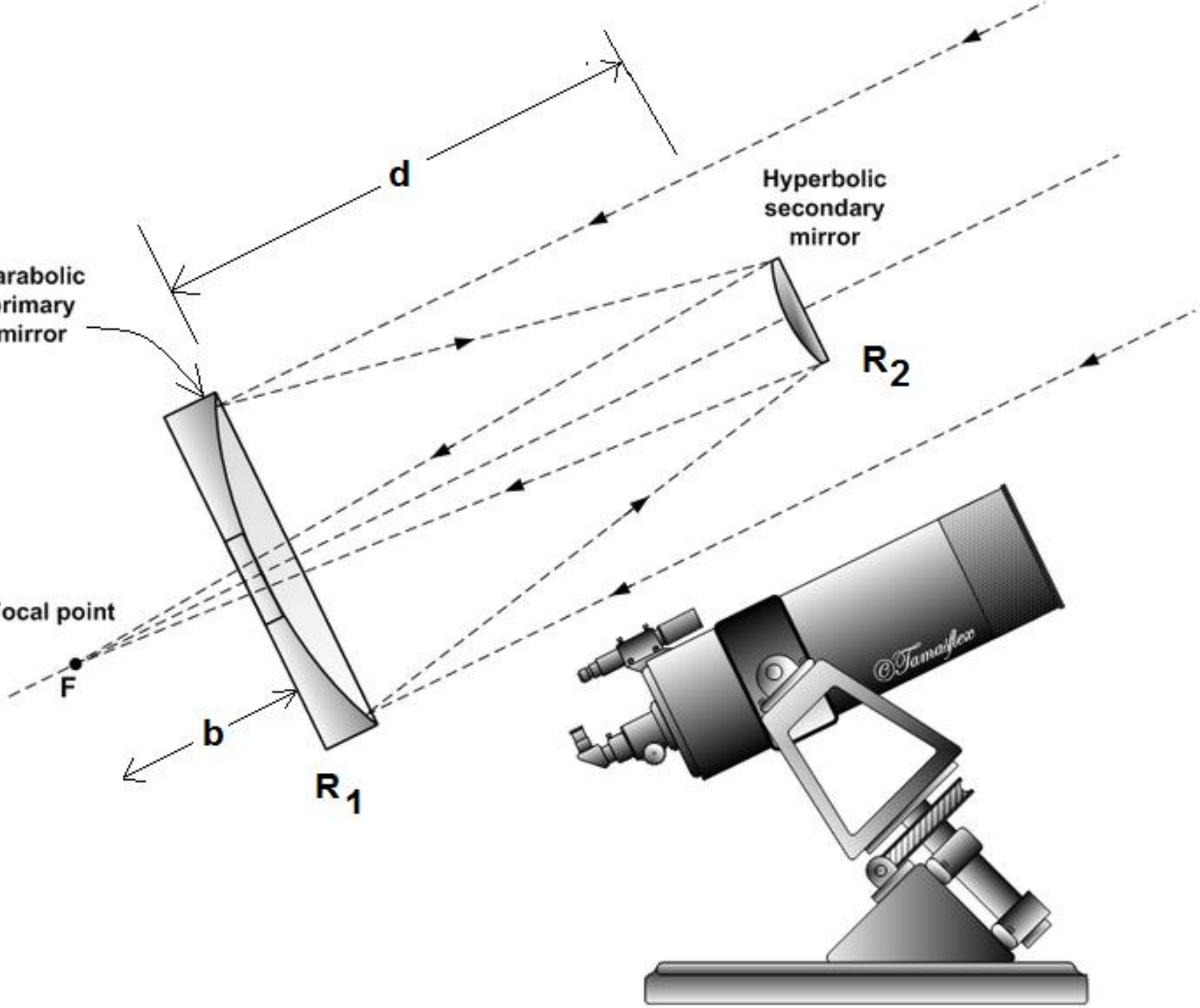
(c) What is the dimension of secondary mirror?

(d) Determine the location of image plane where we have a minimum spot size.

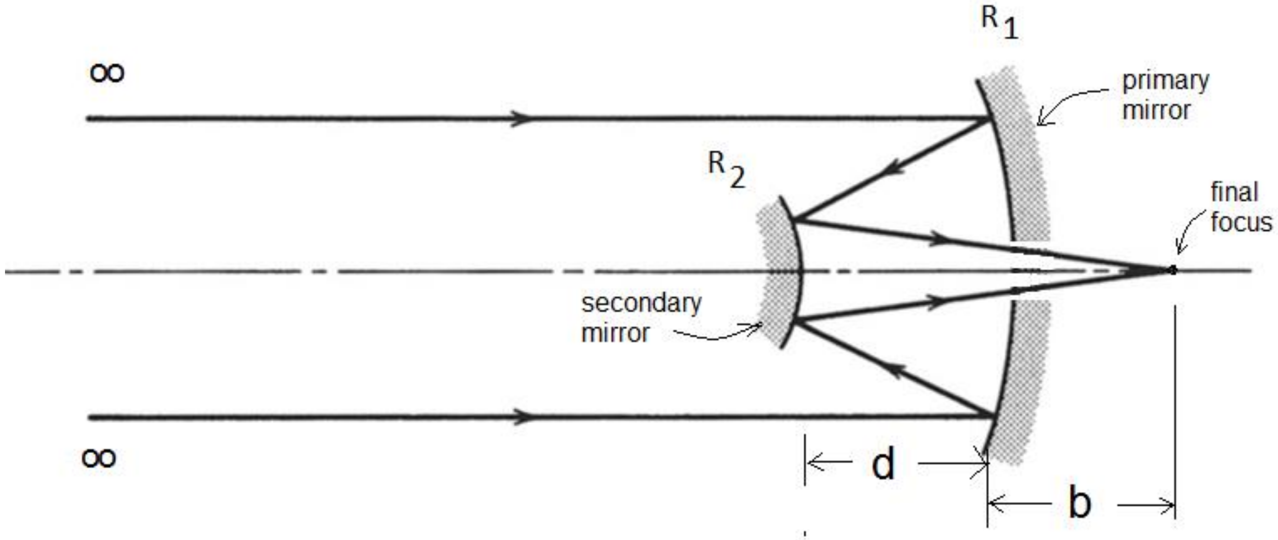
(e) What is magnification of the telesccope with an eyepiece having focal length of 20 mm?



Cassegrain Telescope



R_1 = radius of primary (first) mirror
R_2 = radius of secondary mirror
d = distance between mirrors
b = back focal distance (BFD)
f = focal length of the telecscope
$f_1 = R_1/2 < 0$ (focal length of Mirror 1)
$f_2 = R_2/2 < 0$ (focal length of Mirror 2)



For two spherical mirrors, we can obtain the following equations via paraxial ray tracing:

$$\frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{d}{f_1 f_2}$$

$$d + b = \left(1 - \frac{d}{f_1}\right) f$$

Example: Cassegrain Telescope

Implement a Cassegrain Telescope whose system parameters are:

System focal length f = 800 mm
Distance between mirrors d = 200 mm
Back focal distance (BFD) b = 50 mm
Primary mirror diameter D = 200 mm

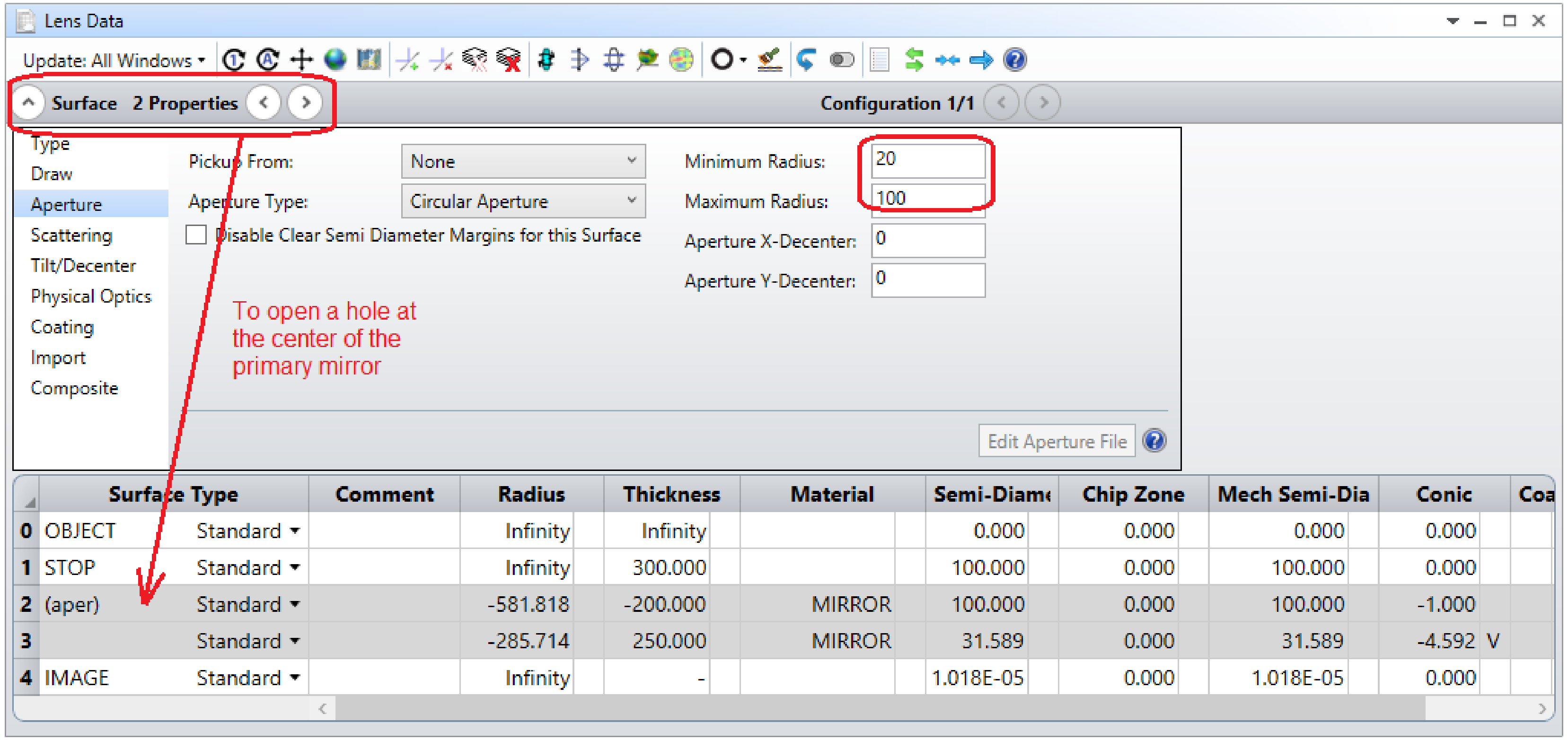
We have two equations:

$$\frac{1}{800} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{200}{f_1 f_2} \qquad 250 = 800(1 - \frac{200}{f_1})$$

Solving for focal lengths and radii of the mirrors:

$f_1 = +290.909$ mm => $|R_1| = 581.818$ mm
$f_2 = -142.857$ mm => $|R_2| = 285.714$ mm

Note that the total distance of telescope is b+d = 250 mm. Focal length is f = 800 mm.



Pickup From: None

Aperture Type: Circular Aperture

☐ Disable Clear Semi Diameter Margins for this Surface

Minimum Radius: 20

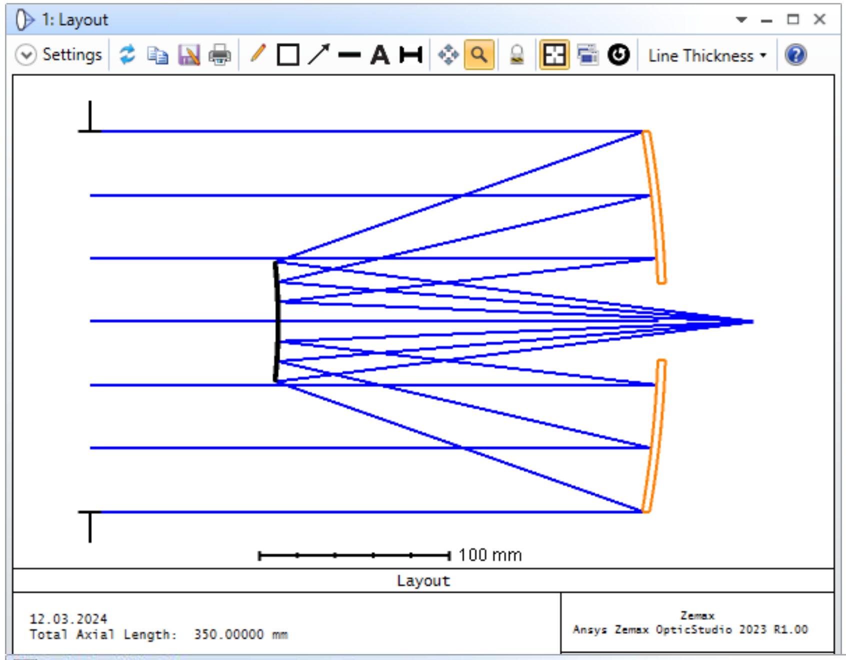
Maximum Radius: 100

Aperture X-Decenter: 0

Aperture Y-Decenter: 0

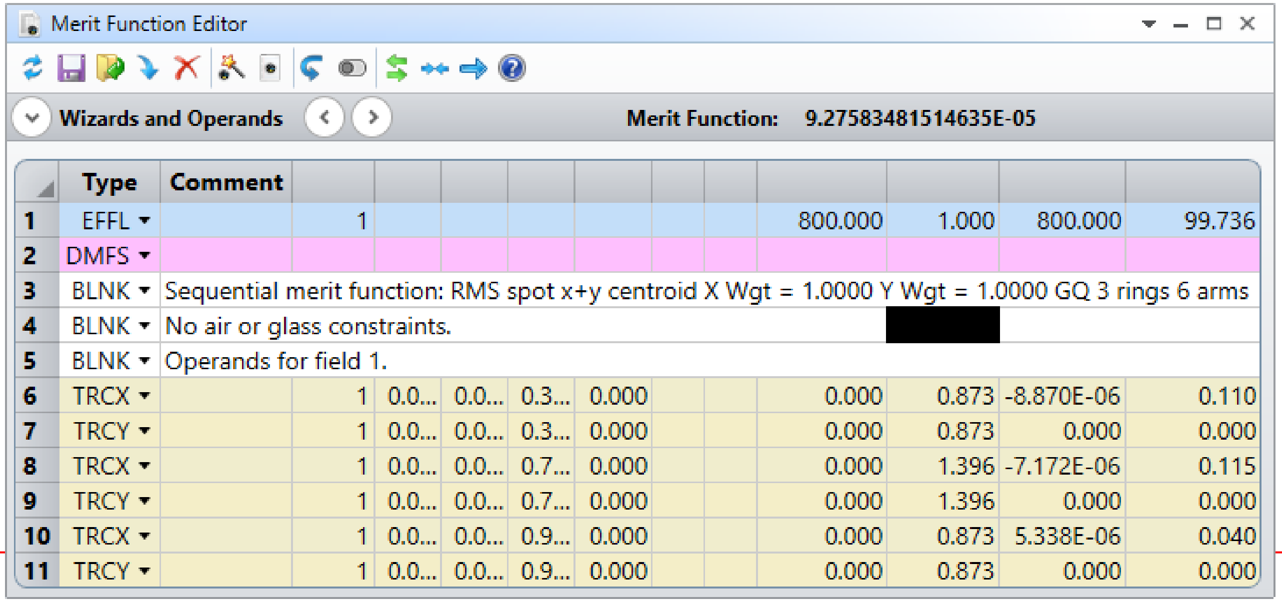
To open a hole at the center of the primary mirror

	Surface Type		Comment	Radius	Thickness	Material	Semi-Diame	Chip Zone	Mech Semi-Dia	Conic	Coa
0	OBJECT	Standard ▾		Infinity	Infinity		0.000	0.000	0.000	0.000	
1	STOP	Standard ▾		Infinity	300.000		100.000	0.000	100.000	0.000	
2	(aper)	Standard ▾		-581.818	-200.000	MIRROR	100.000	0.000	100.000	-1.000	
3		Standard ▾		-285.714	250.000	MIRROR	31.589	0.000	31.589	-4.592 V	
4	IMAGE	Standard ▾		Infinity	-		1.018E-05	0.000	1.018E-05	0.000	



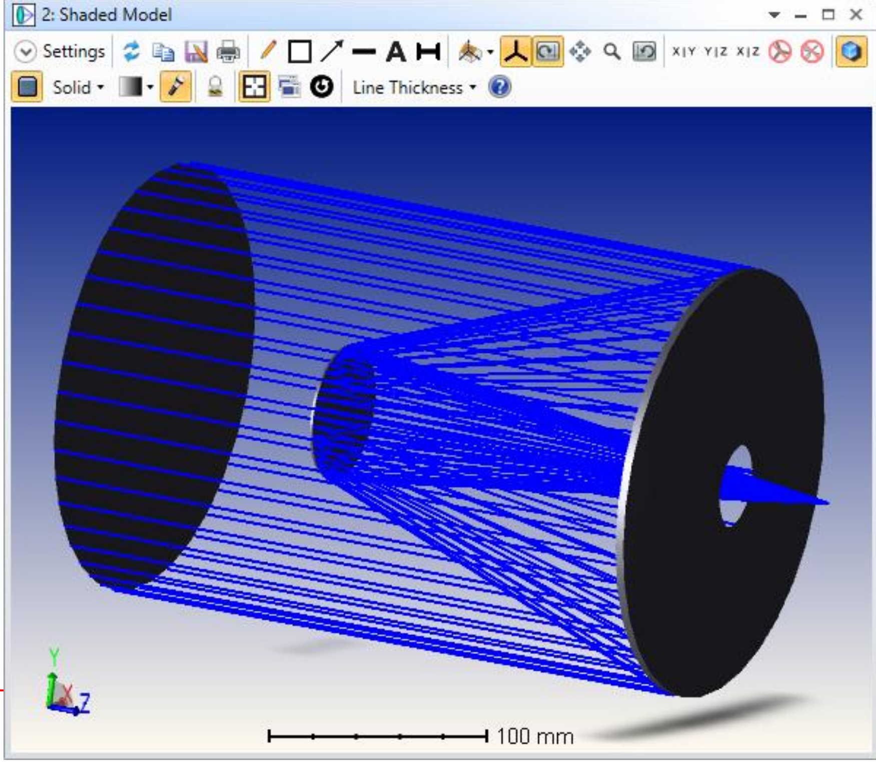
12.03.2024
Total Axial Length: 350.00000 mm

Zemax
Ansys Zemax OpticStudio 2023 R1.00



Merit Function: 9.27583481514635E-05

	Type	Comment											
1	EFFL ▾		1							800.000	1.000	800.000	99.736
2	DMFS ▾												
3	BLNK ▾	Sequential merit function: RMS spot x+y centroid X Wgt = 1.0000 Y Wgt = 1.0000 GQ 3 rings 6 arms											
4	BLNK ▾	No air or glass constraints.									[redacted]		
5	BLNK ▾	Operands for field 1.											
6	TRCX ▾		1	0.0...	0.0...	0.3...	0.000			0.000	0.873	-8.870E-06	0.110
7	TRCY ▾		1	0.0...	0.0...	0.3...	0.000			0.000	0.873	0.000	0.000
8	TRCX ▾		1	0.0...	0.0...	0.7...	0.000			0.000	1.396	-7.172E-06	0.115
9	TRCY ▾		1	0.0...	0.0...	0.7...	0.000			0.000	1.396	0.000	0.000
10	TRCX ▾		1	0.0...	0.0...	0.9...	0.000			0.000	0.873	5.338E-06	0.040
11	TRCY ▾		1	0.0...	0.0...	0.9...	0.000			0.000	0.873	0.000	0.000



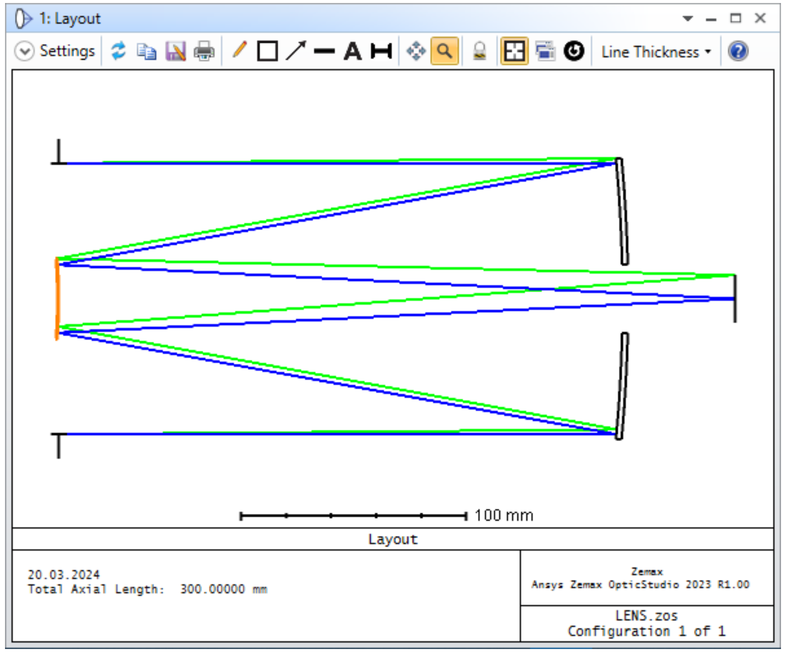
Cassegrain Design with Field Corrector Lenses

The typical Cassegrain design is known for its excellent on-axis optical performance but tends to perform poorly in off-axis applications.

For parabolic mirror, third order angular aberration is given by:

$$\mathrm{AA3} = 3a_1 y^2\theta/R^2 + 2a_2 y\theta^2/R + a_3\theta^3$$

E.g. Cassegrain design with f/10, D= 120 mm, and FOV = 1º.



20.03.2024
Total Axial Length: 300.00000 mm

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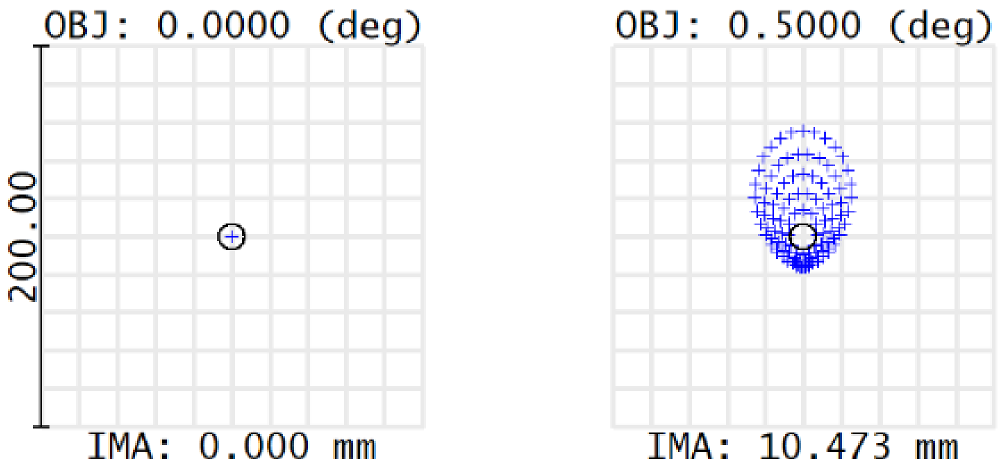
LENS.zos
Configuration 1 of 1



Cassegrain Design with Field Corrector Lenses

To improve off-axis performance usually a field corrector lens system is added to the mirror system before image sensor.

Note:
If we want to design Cassegrain Telescope
whose target (final) focal length F with
a corrector lens,

1. Design Cassegrain mirror system with focal length a bit grater or smaller than the target F. Namely, two-mirror focal length should be: $F' = F + \Delta F$ or $F' = F - \Delta F$
2. Add corrector lenses and optimize full system to reach target focal length, F.

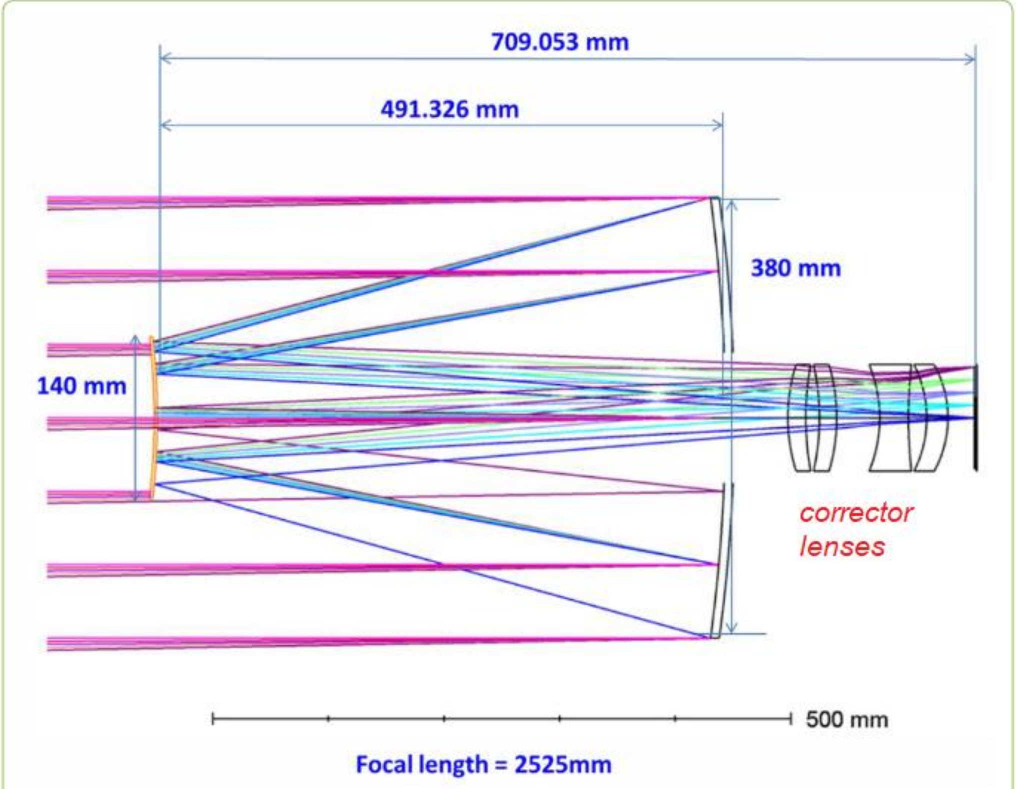


Figure 1: Optical design layout of the Micro-satellite telescope.

Int J Nano Rech 2019 V2:1, ISSN: 2581-6608

Example: Cassegrain Telescope with Corrector Design

Design a Cassegrain Telescope with corrector to satisfy the following specifications:

EFFL = 1000 mm

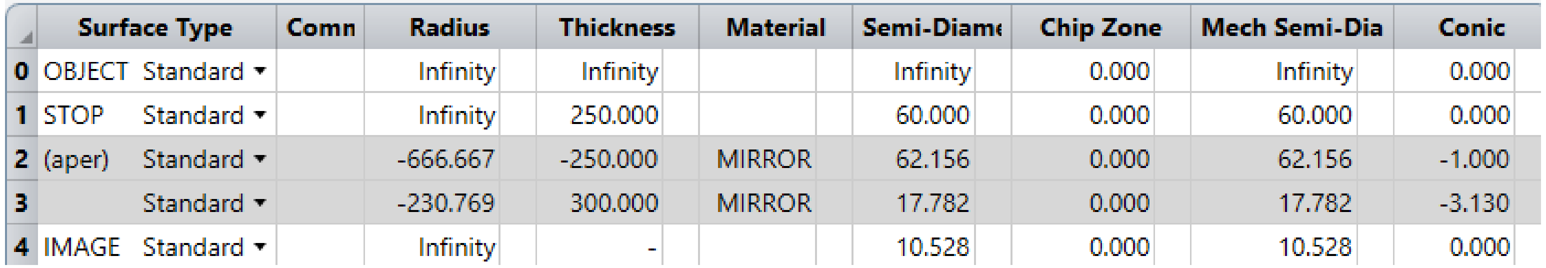
F/# = 10

WAVE = F, d, C (visible)

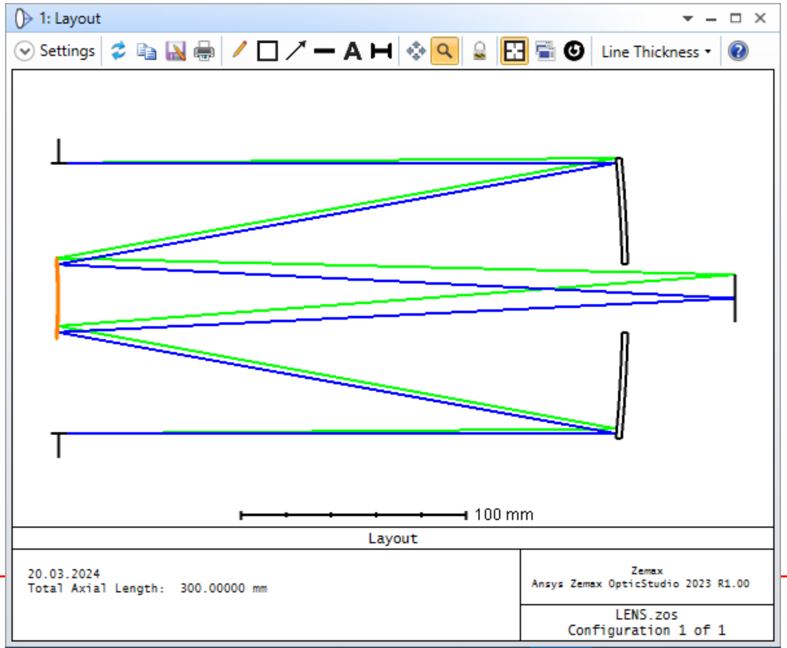
FOV = 1^{o}

TOTR < 300 mm

Step 1: Design Cassegrain mirrors such that system focal length is F' = 1200 mm as follows:

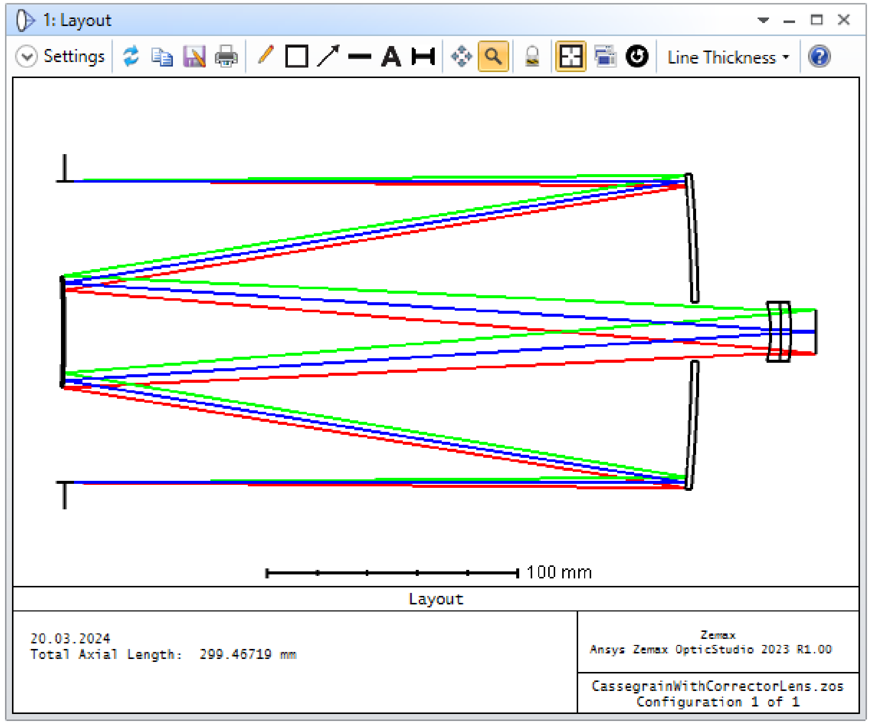


	Surface Type		Comn	Radius	Thickness	Material	Semi-Diame	Chip Zone	Mech Semi-Dia	Conic
0	OBJECT	Standard ▾		Infinity	Infinity		Infinity	0.000	Infinity	0.000
1	STOP	Standard ▾		Infinity	250.000		60.000	0.000	60.000	0.000
2	(aper)	Standard ▾		-666.667	-250.000	MIRROR	62.156	0.000	62.156	-1.000
3		Standard ▾		-230.769	300.000	MIRROR	17.782	0.000	17.782	-3.130
4	IMAGE	Standard ▾		Infinity	-		10.528	0.000	10.528	0.000



20.03.2024
Total Axial Length: 300.00000 mm

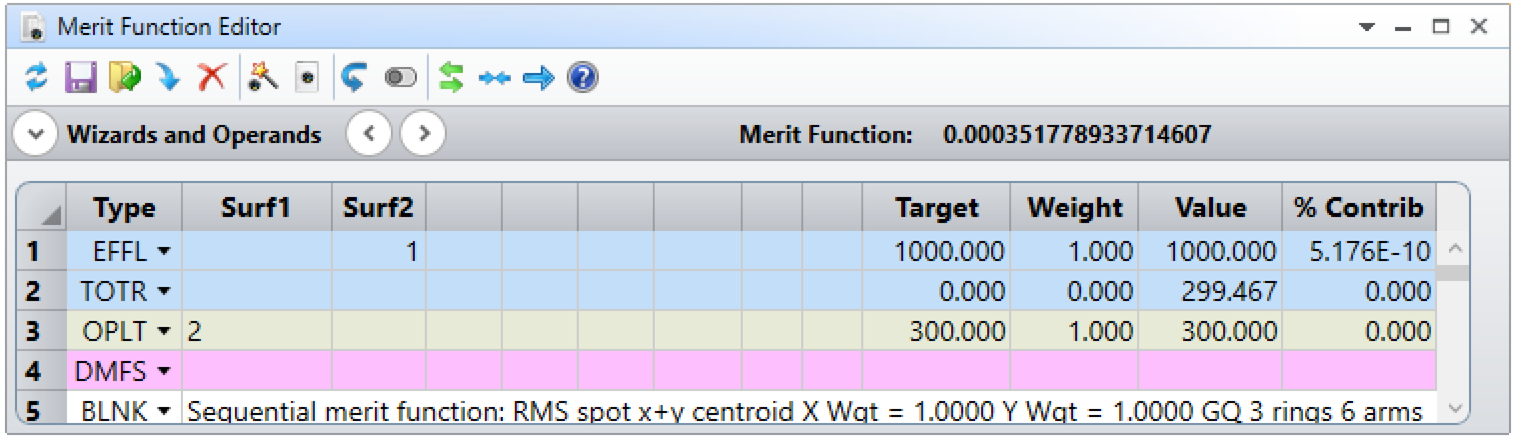
Step2: Add a doublet lens and optimize the system as follows. Notice F = 1000 mm.



20.03.2024
Total Axial Length: 299.46719 mm

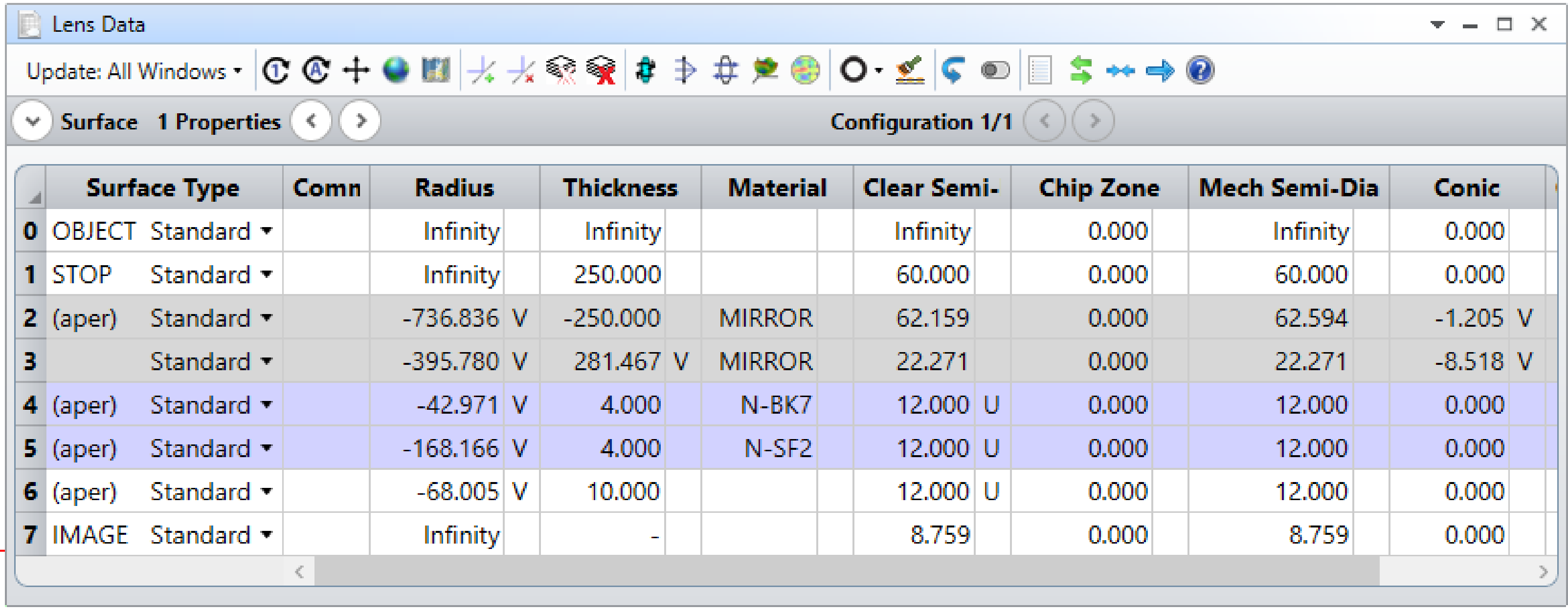
Zemax
Ansys Zemax OpticStudio 2023 R1.00

CassegrainWithCorrectorLens.zos
Configuration 1 of 1



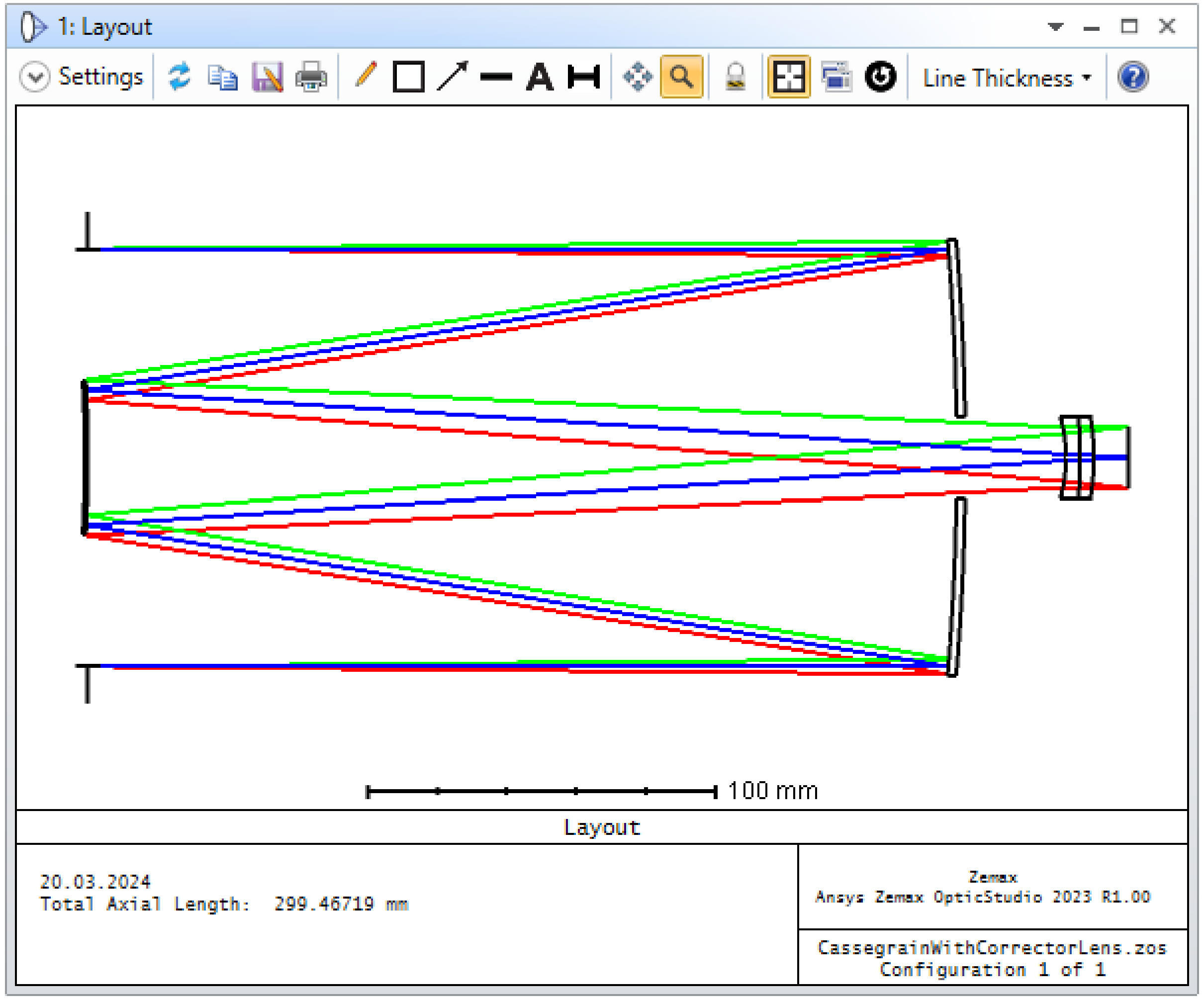
Merit Function: 0.000351778933714607

	Type	Surf1	Surf2							Target	Weight	Value	% Contrib
1	EFFL		1							1000.000	1.000	1000.000	5.176E-10
2	TOTR									0.000	0.000	299.467	0.000
3	OPLT	2								300.000	1.000	300.000	0.000
4	DMFS												
5	BLNK	Sequential merit function: RMS spot x+y centroid X Wgt = 1.0000 Y Wgt = 1.0000 GQ 3 rings 6 arms											



Configuration 1/1

	Surface Type		Comn	Radius	Thickness	Material	Clear Semi-	Chip Zone	Mech Semi-Dia	Conic
0	OBJECT	Standard		Infinity	Infinity		Infinity	0.000	Infinity	0.000
1	STOP	Standard		Infinity	250.000		60.000	0.000	60.000	0.000
2	(aper)	Standard		-736.836 V	-250.000	MIRROR	62.159	0.000	62.594	-1.205 V
3		Standard		-395.780 V	281.467 V	MIRROR	22.271	0.000	22.271	-8.518 V
4	(aper)	Standard		-42.971 V	4.000	N-BK7	12.000 U	0.000	12.000	0.000
5	(aper)	Standard		-168.166 V	4.000	N-SF2	12.000 U	0.000	12.000	0.000
6	(aper)	Standard		-68.005 V	10.000		12.000 U	0.000	12.000	0.000
7	IMAGE	Standard		Infinity	-		8.759	0.000	8.759	0.000



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20.03.2024
Total Axial Length:  299.46719 mm
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Zemax
Ansys Zemax OpticStudio 2023 R1.00
CassegrainWithCorrectorLens.zos
Configuration 1 of 1
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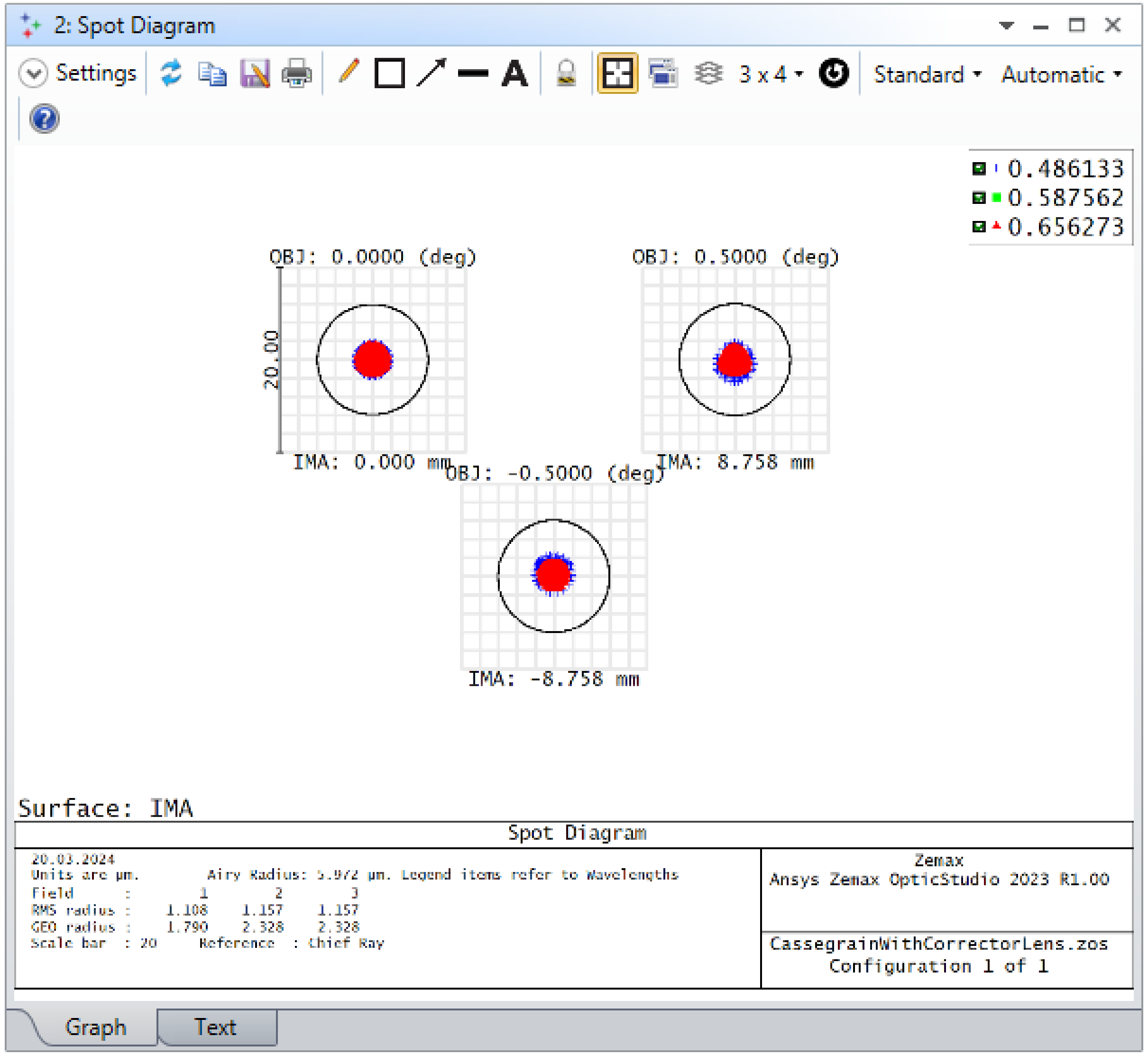

```
20.03.2024
Units are µm.          Airy Radius: 5.972 µm. Legend items refer to Wavelengths
Field       :        1        2        3
RMS radius  :    1.108    1.157    1.157
GEO radius  :    1.790    2.328    2.328
Scale bar   : 20     Reference   : Chief Ray
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Zemax
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CassegrainWithCorrectorLens.zos
Configuration 1 of 1
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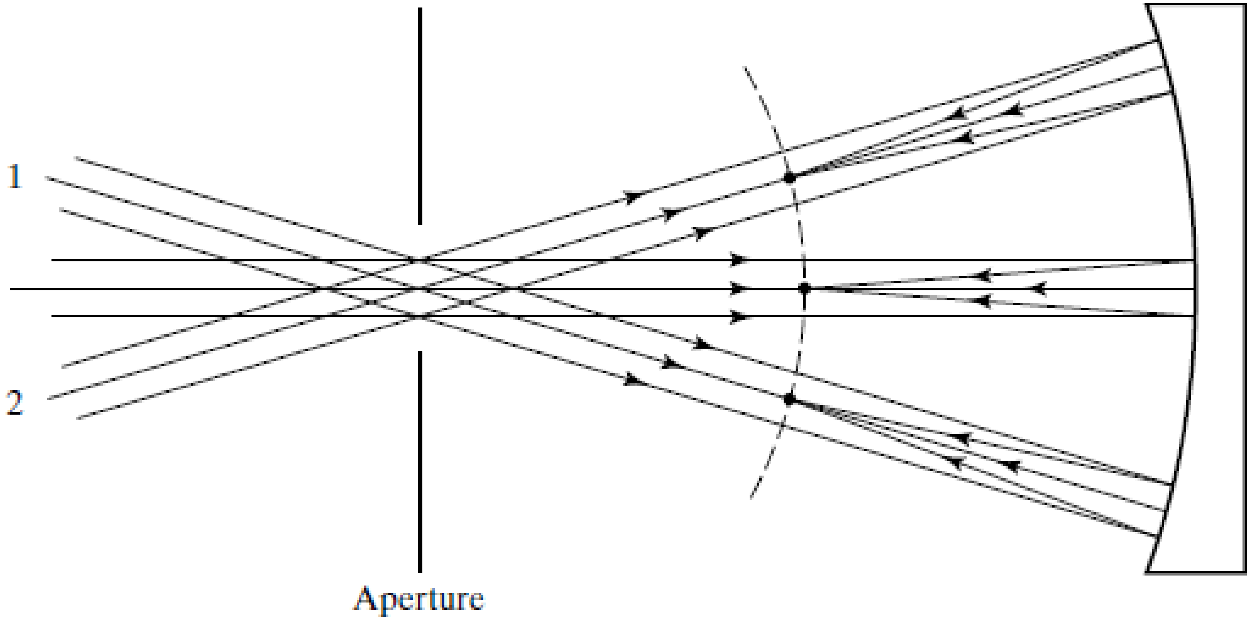
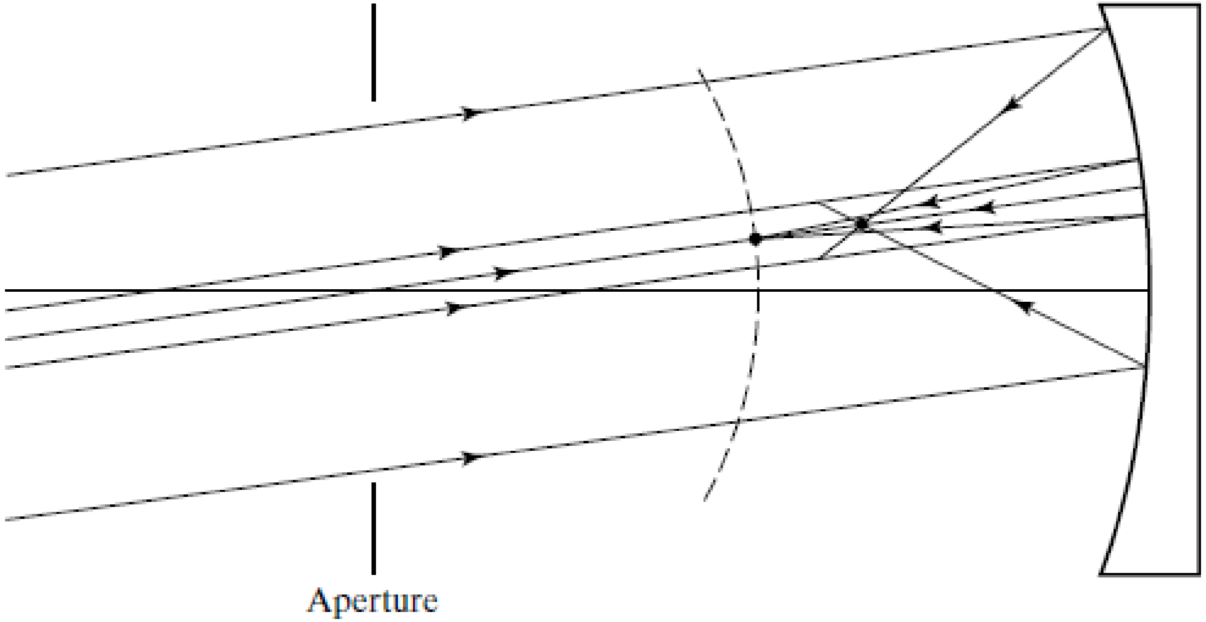
Catadioptric Telescopes

A catadioptric optical system is one where **refraction** and **reflection** are combined in an optical system, usually via lenses (dioptrics) and curved mirrors (catoptrics). Catadioptric combinations are used in focusing systems such as searchlights, headlamps, early lighthouse focusing systems, optical telescopes, microscopes, and telephoto lenses.

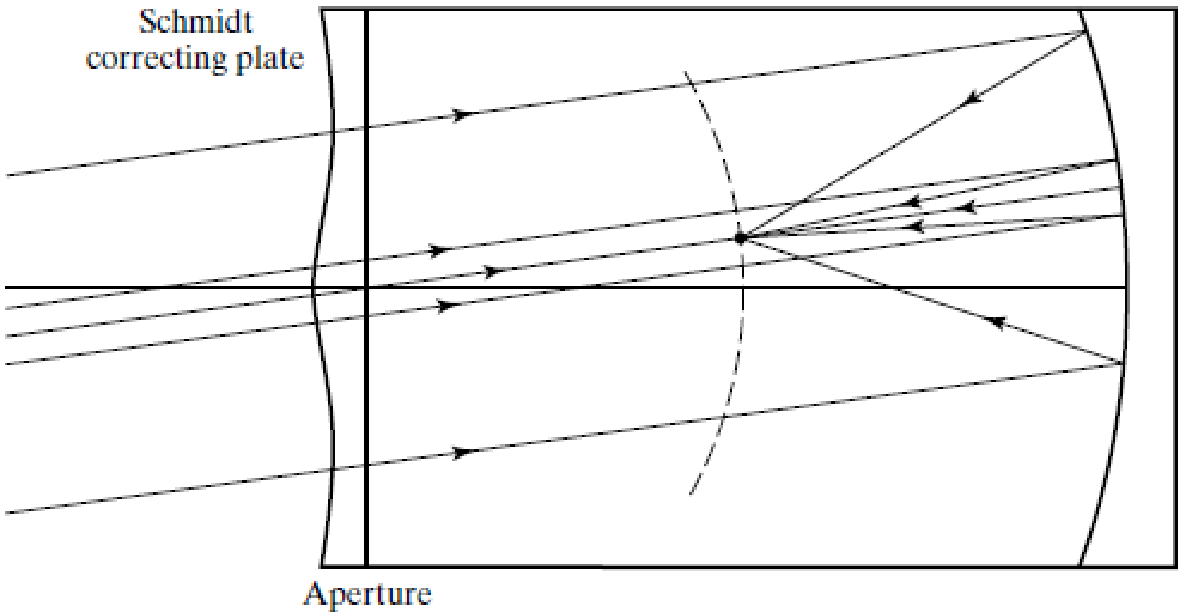
Perhaps the most celebrated catadioptric telescope is due to a design of Bernhardt Schmidt. He sought to remove the spherical aberration of a primary spherical mirror by using a thin refracting correcting plate at the aperture of the telescope.



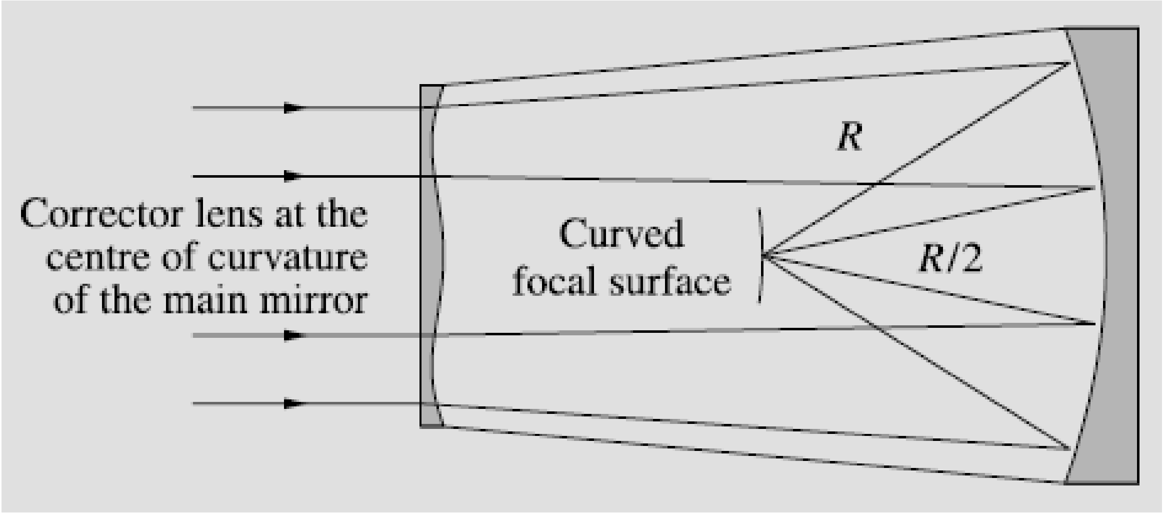
(a)



(b)



(c) The Schmidt optical system.

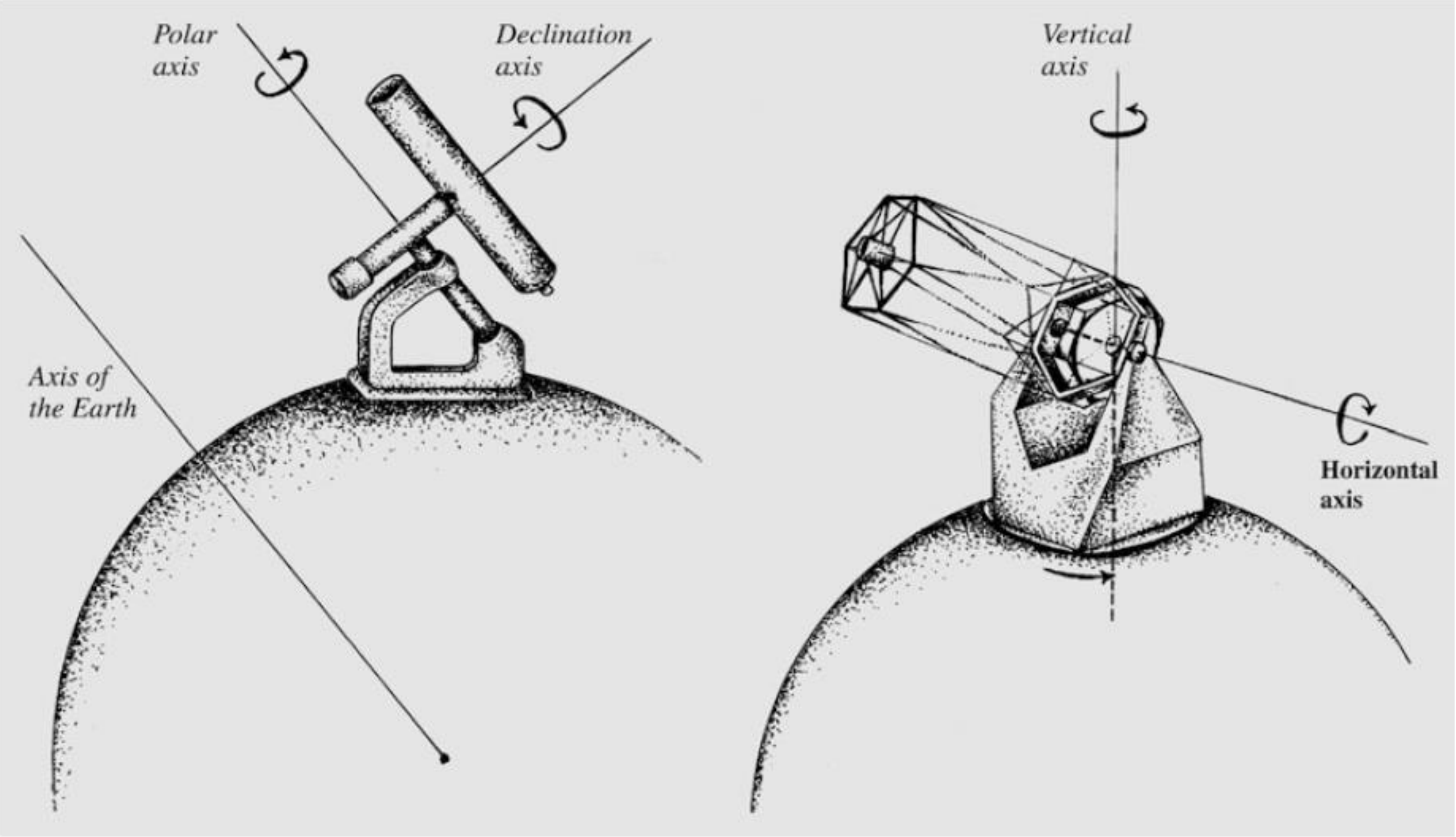


The principle of the Schmidt camera. A correcting glass at the centre of curvature of a concave spherical mirror deviates parallel rays of light and compensates for the spherical aberration of the spherical mirror. (In the figure, the form of the correcting glass and the change of direction of the light rays have been greatly exaggerated.) Since the correcting glass lies at the centre of curvature, the image is practically independent of the incoming angle of the light rays. Thus there is no coma or astigmatism, and the images of stars are points on a spherical surface at a distance of $R/2$, where R is the radius of curvature of the spherical mirror. In photography, the plate must be bent into the form of the focal surface, or the field rectified with a corrector lens

Mountings of Telescopes

A telescope has to be mounted on a steady support to prevent its shaking, and it must be smoothly rotated during observations. There are two principal types of mounting, equatorial and azimuthal

In the equatorial mounting, one of the axes is directed towards the celestial pole. It is called the polar axis or hour axis. The other one, the declination axis, is perpendicular to it. Since the hour axis is parallel to the axis of the Earth, the apparent rotation of the sky can be compensated for by turning the telescope around this axis at a constant rate. In the azimuthal mounting, one of the axes is vertical, the other one horizontal. This mounting is easier to construct than the equatorial mounting and is more stable for very large telescopes.



The equatorial mounting (*left*) and the azimuthal mounting (*right*)