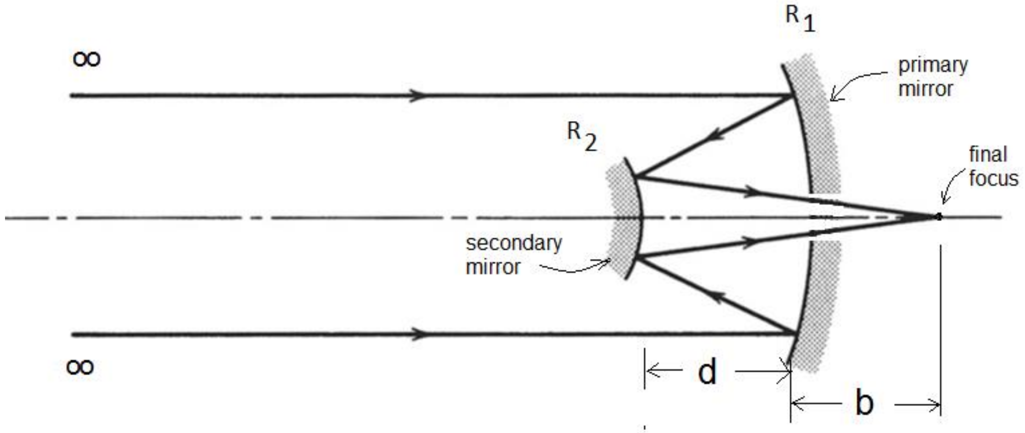
Lectures Notes on Optical Design using Zemax OpticStudio

Lecture 7

Some Optical Instruments



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Content

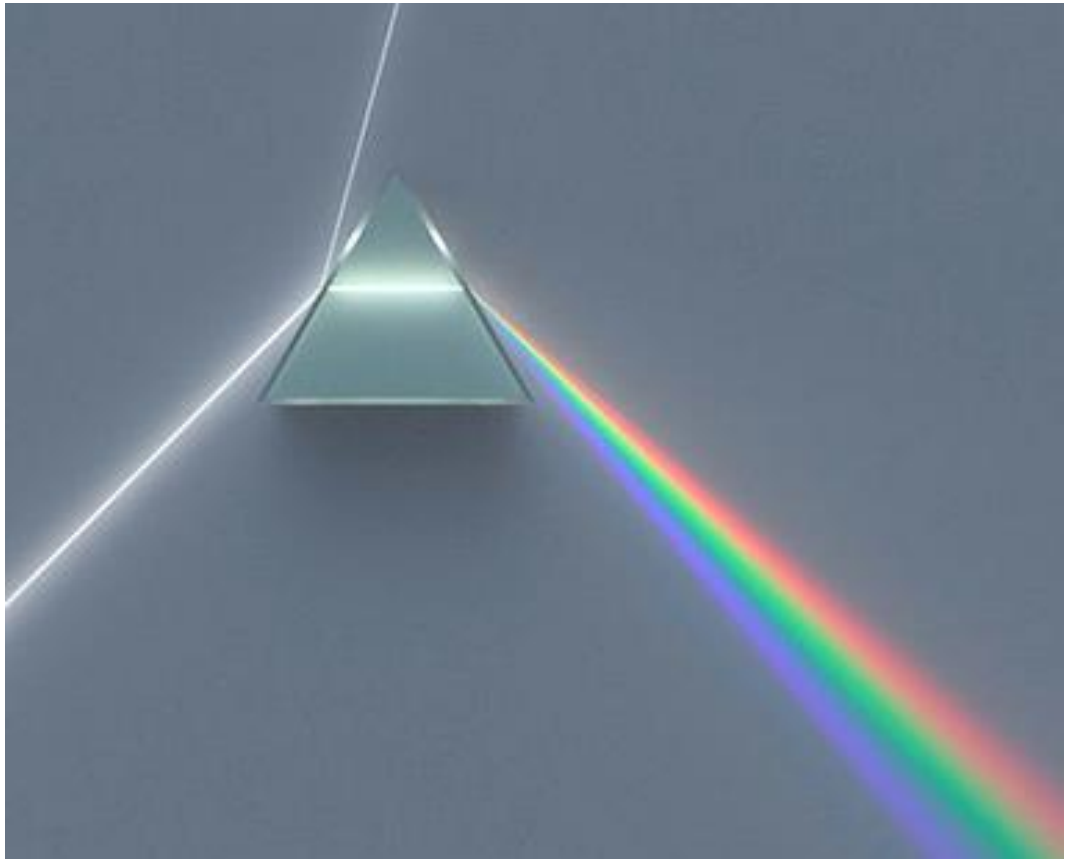
In this chapter we’ll briefly investigate some optical componets and designs

- Prisms and Beam splitters
- Optical Slab
- Diffraction Grating
- Eye
- Beam Expanders
- Telescopes

Prisms and Beam Splitters

Prism

Transparent medium between two planes is called a prism



Prism

Deflecting Prisms

Wedge prism
Anamorphic Prism Pairs

Polarizing Prisms

Nicol prism
Wollaston prism
Nomarski prism
Rochon prism
Senarmont prism
Glan–Foucault prism
Glan–Taylor prism
Glan–Thompson prism

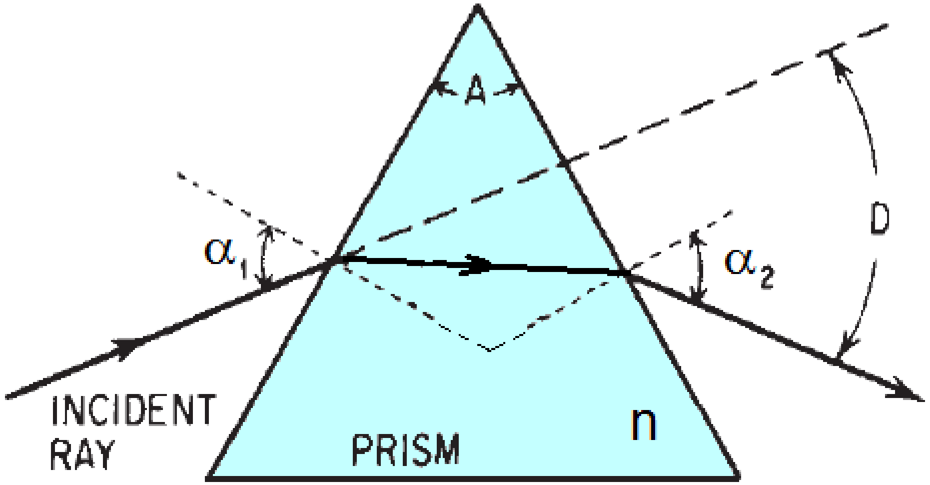
Reflective prisms

Dove prism
Porro prism
Porro–Abbe prism
Amici roof prism
Pentaprism
Abbe–Koenig prism
Schmidt–Pechan prism
Bauernfeind prism
Retroreflector prism

Dispersive Prisms

Triangular prism
Abbe prism
Pellin–Broca prism
Roof prism
Compound prism

Triangular Prisms



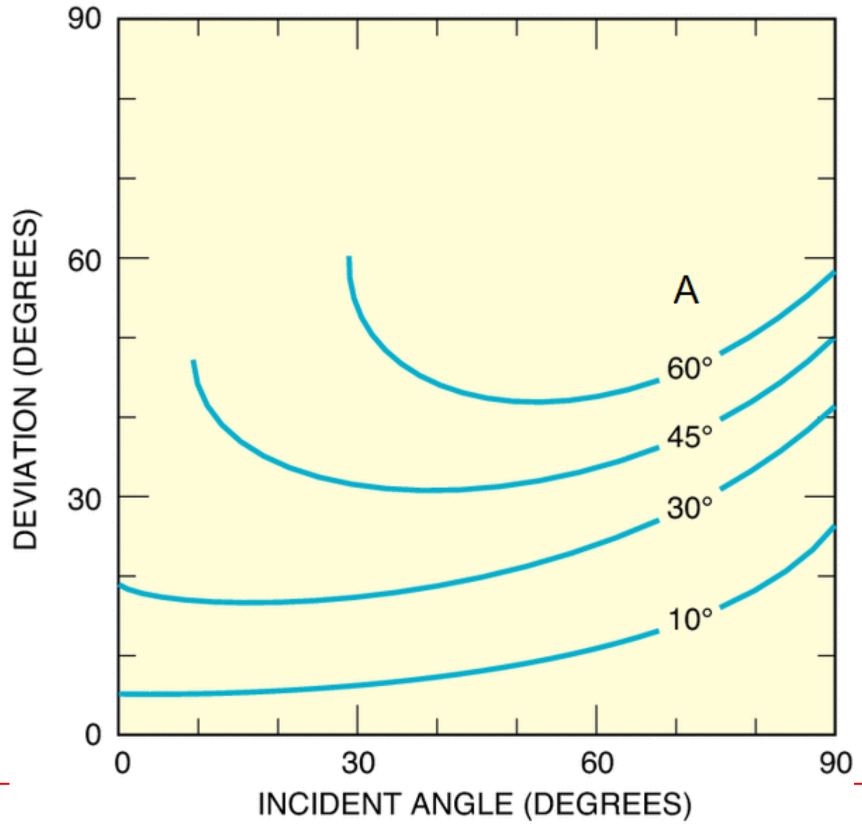
In a typical dispersing prism:
n = refractive index
α_1= angle of incidence
α_2 = outgoing angle
A = apex angle
D = angle of deviation

From basic geometry, we can show that

$$D = \alpha_1 + \alpha_2 - A$$

By applying Snell's law at both surfaces, we have

$$\alpha_2 = \sin^{-1}[\sqrt{n^2 - \sin^2 \alpha_1} \sin A - \cos A \sin \alpha_1]$$



Minimum deviation occurs when $\alpha_1 = \alpha_2$.

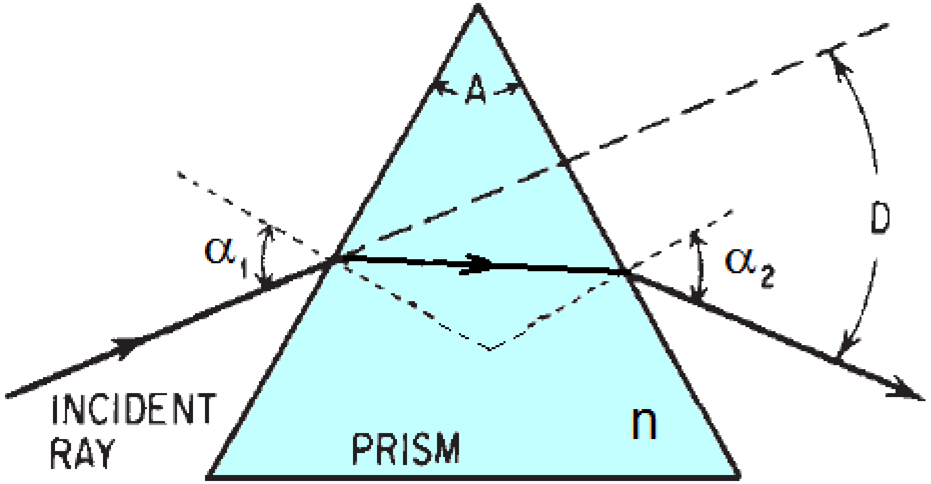
$$D_{\min} = 2\alpha_1 - A$$

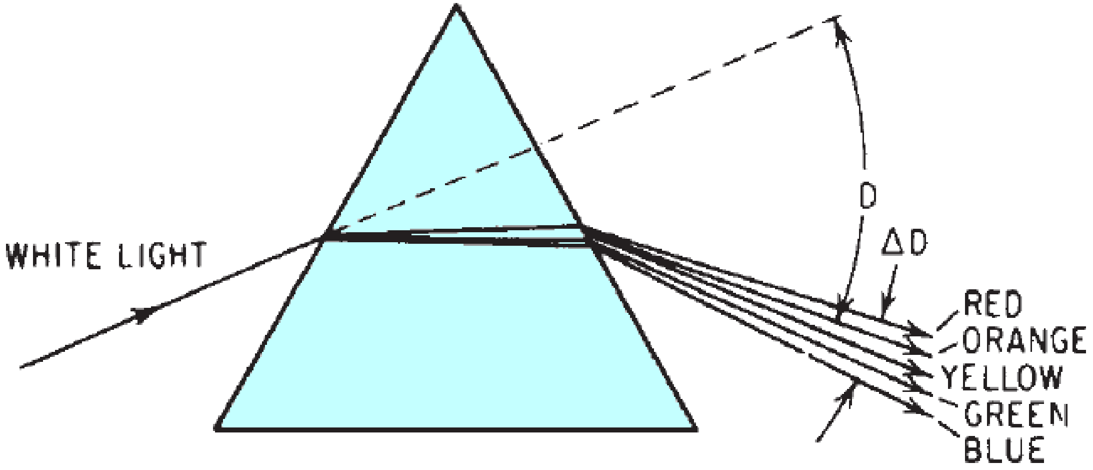
and index of refraction is given by:

$$n = \frac{\sin[(A + D_{\min})/2]}{\sin[A/2]}$$

Note that for a thin prism (i.e. *A* is small), deviation angle is

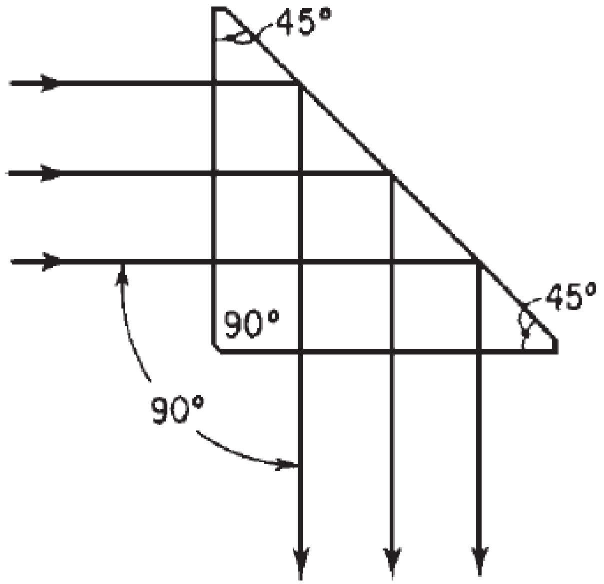
$$D \approx (n-1)A$$



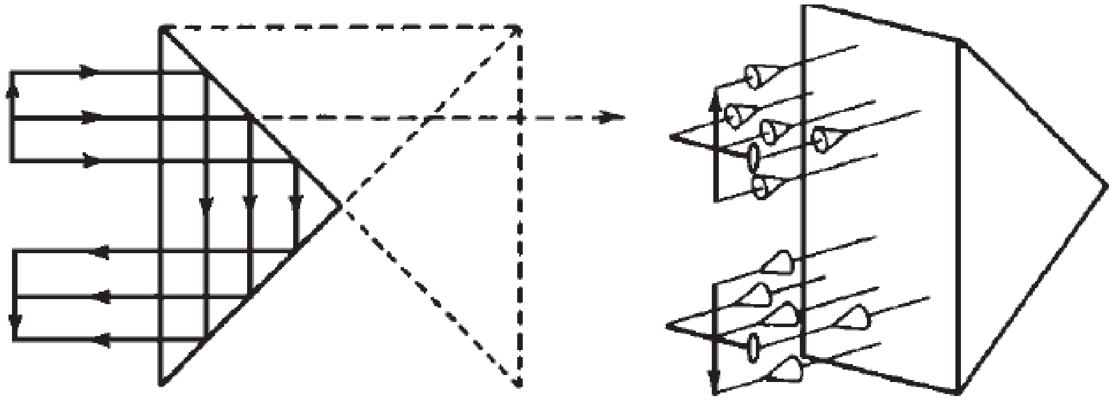


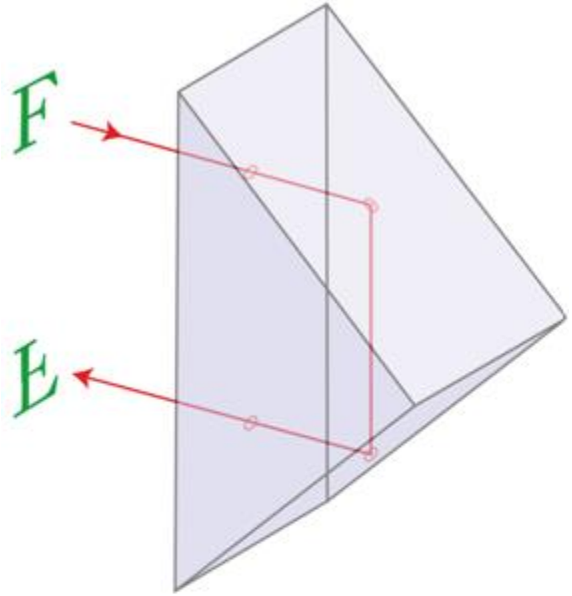
The dispersion of white light into its component wavelengths by a refracting prism (highly exaggerated).

Right-Angle Prism

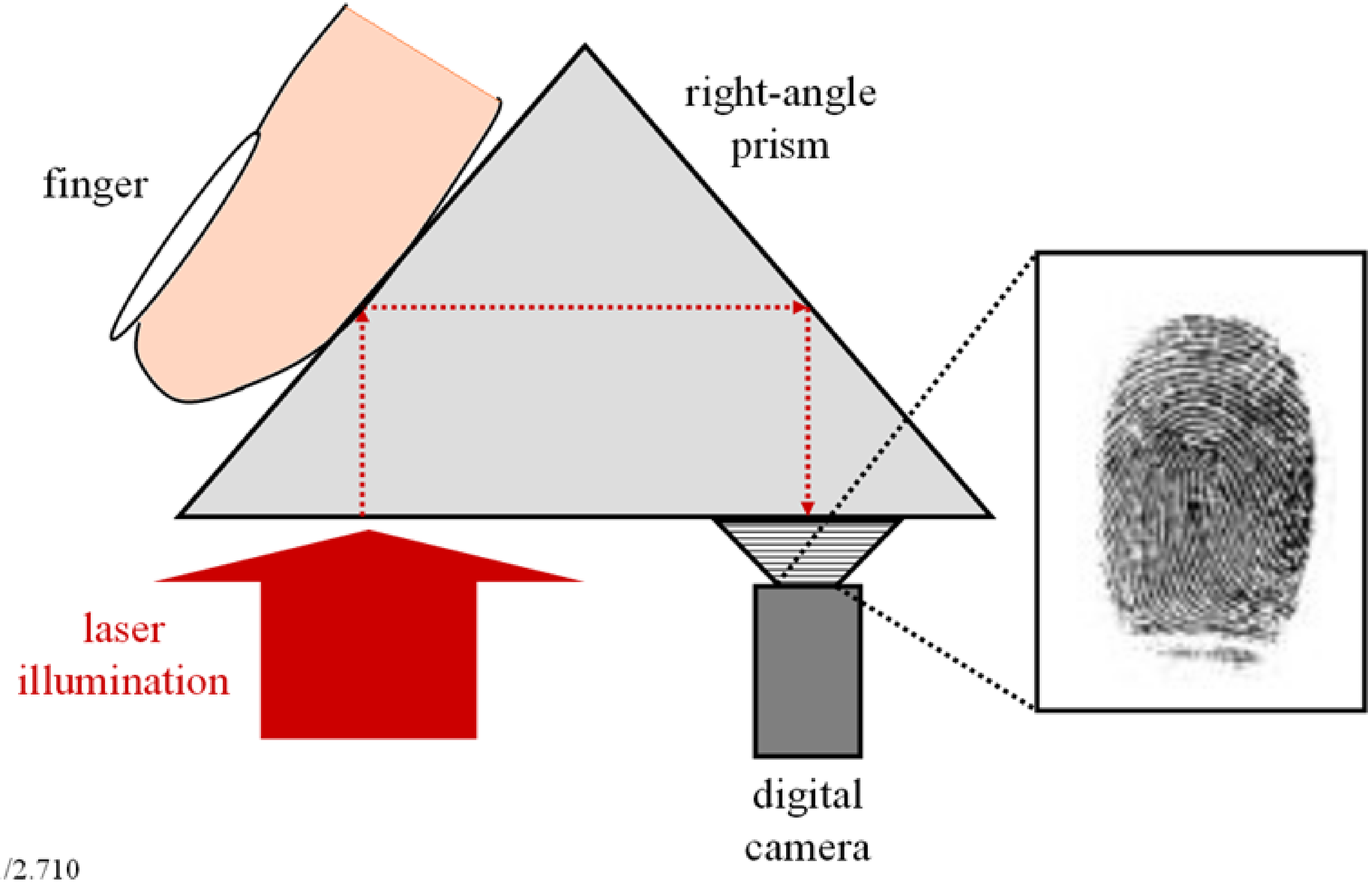


Modern Optical Engineering, W.J. Smith





Fingerprint sensors



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Fabrication Errors

Due to manufacturing tolerances, the prism angles can be produced with certain errors.

Assume that the upper angle is 45 + ε degrees.

Final outgoing ray will deviate at angle 3ε w.r.t normal.

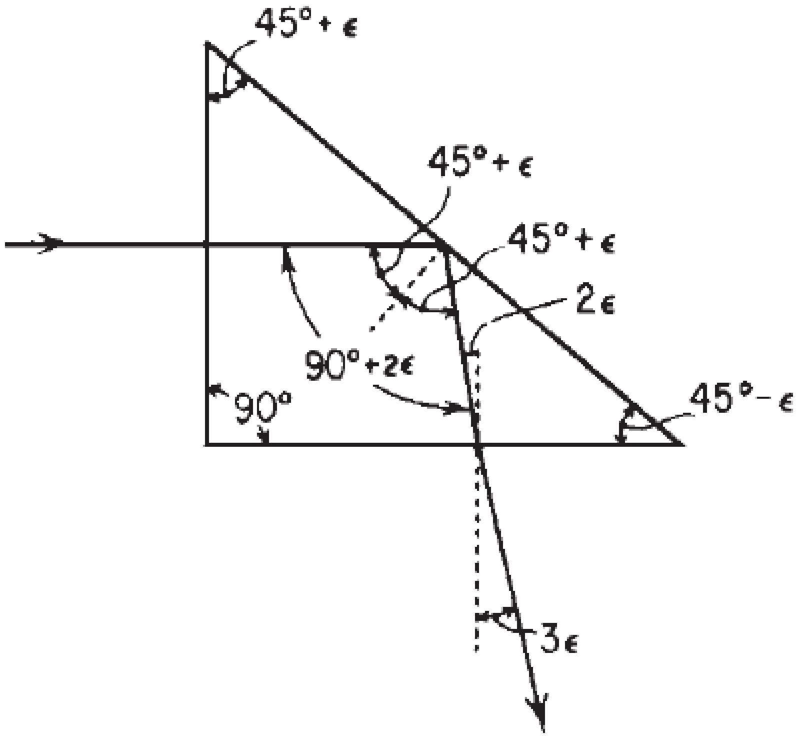

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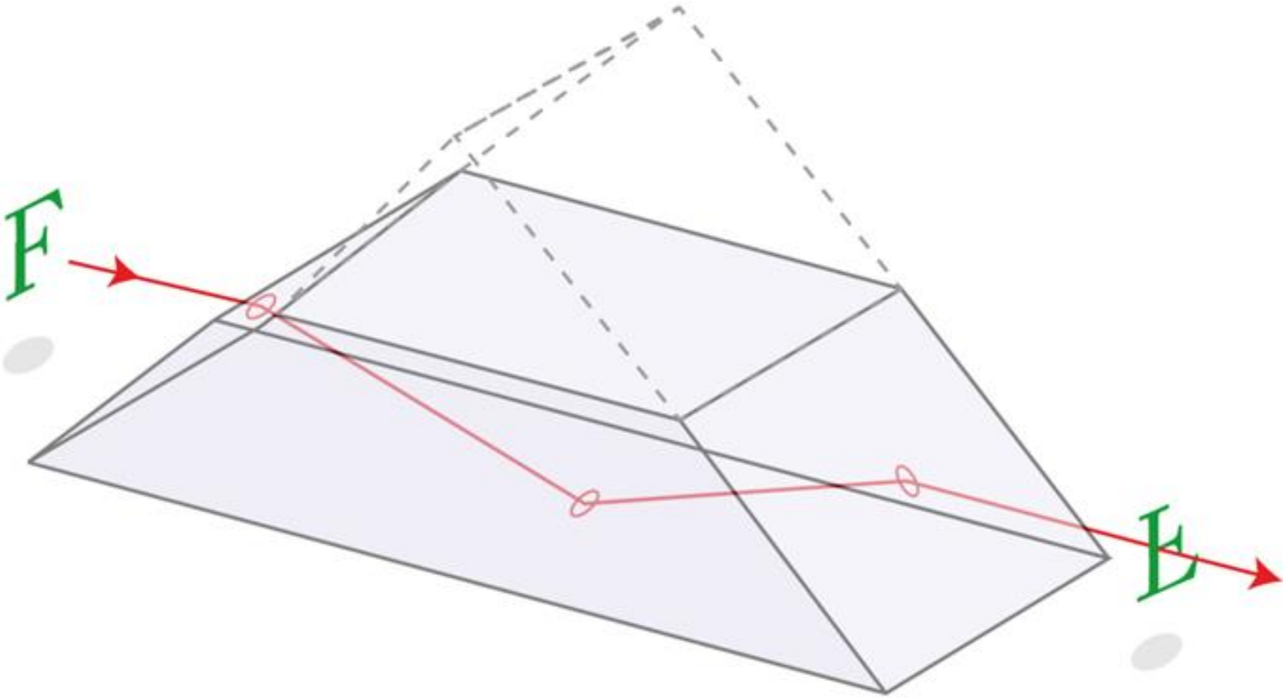
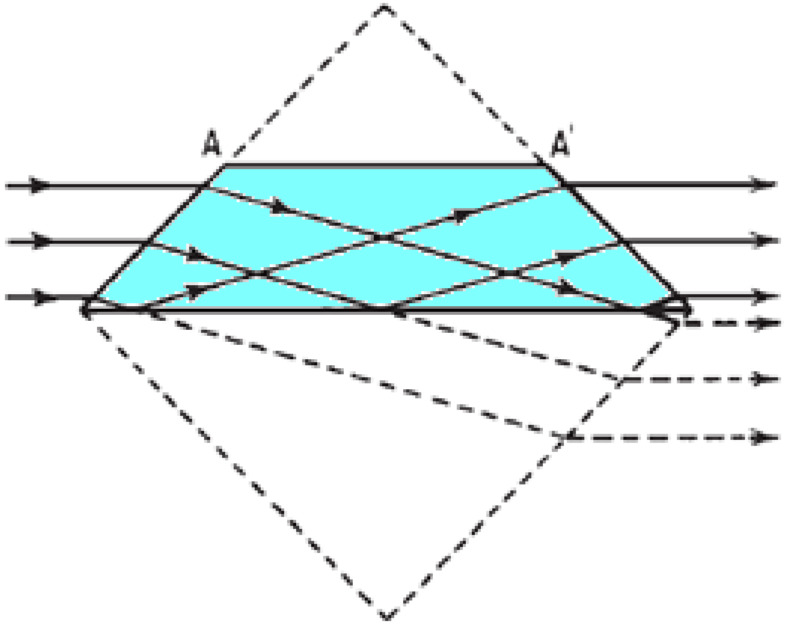
Figure 4.40 The passage of a ray through a right-angle prism whose hypotenuse face is tilted from its proper position by a small angle ϵ. After reflection, the ray is deviated by 2ϵ; this is increased to 3ϵ (or $2n\epsilon$) by refraction at the exit face.

Dove Prism

Dove prism is used to invert an image.

Dove prisms are shaped from a truncated right-angle prism.





Dove Prism as Beam Rotator

When a Dove Prism is rotated along its longitudinal axis, the transmitted image rotates at twice the rate of the prism.This property is used in astronomy and pattern recognition.

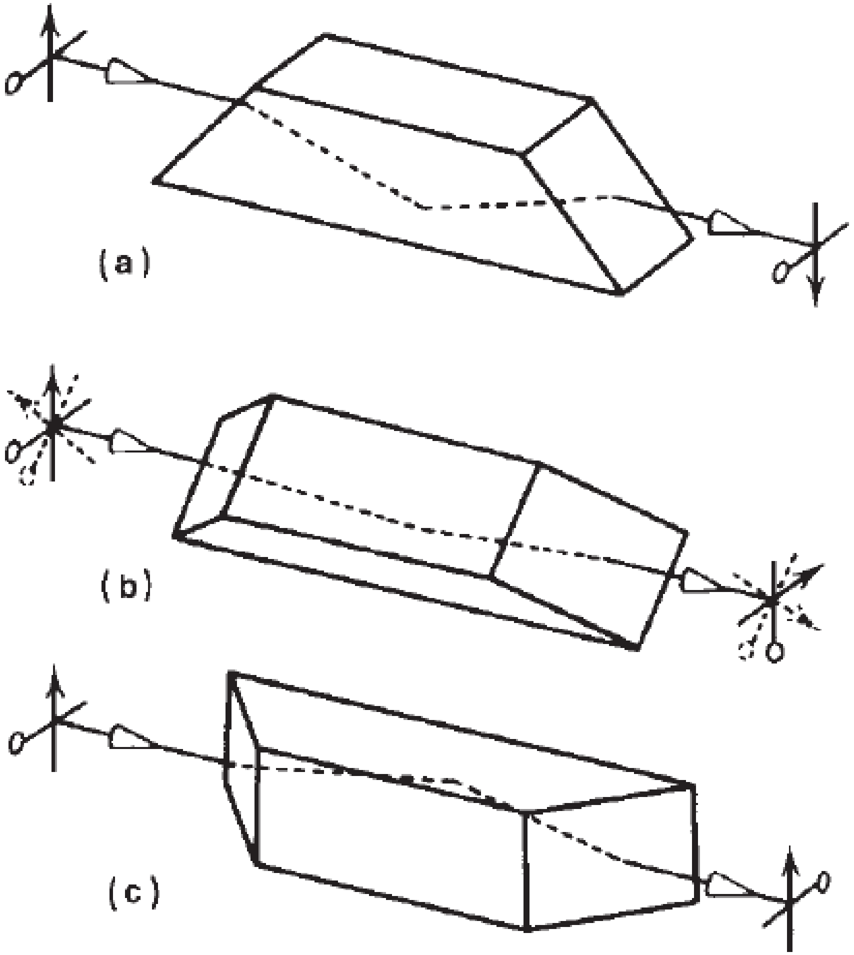


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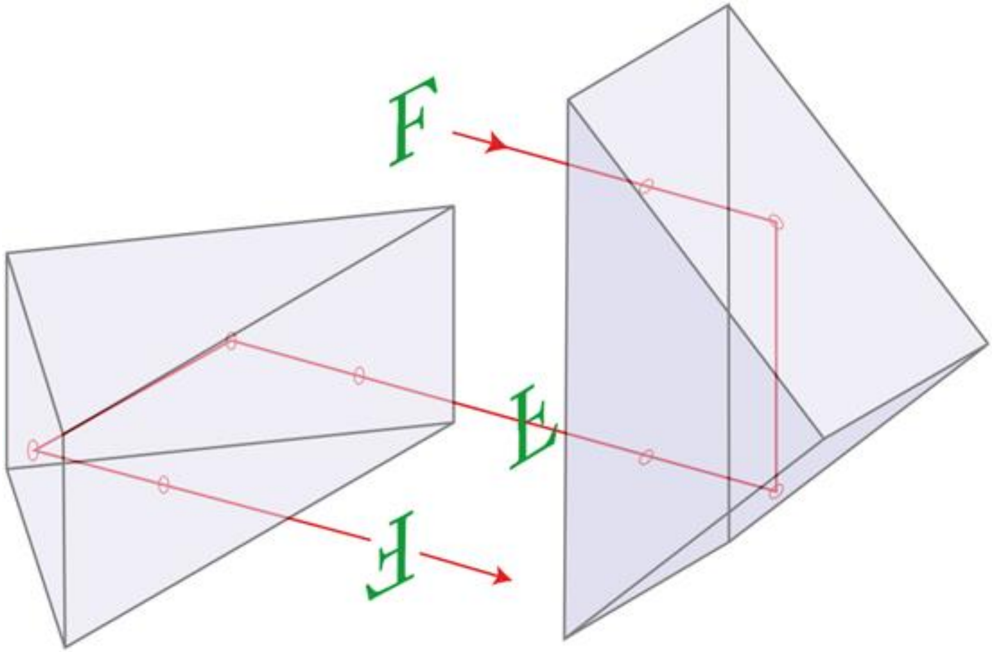
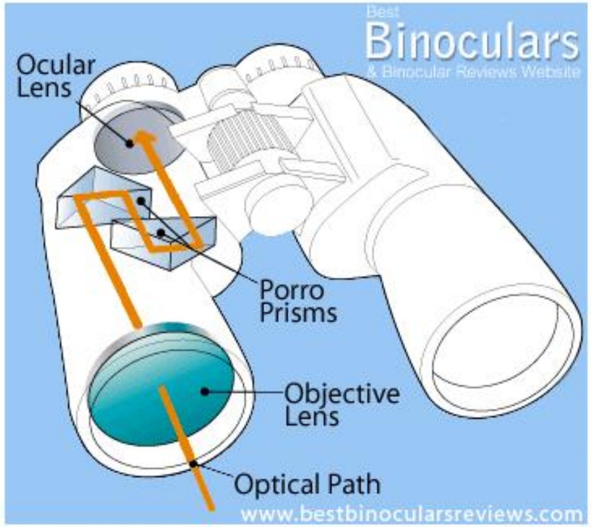
Figure 4.20 The orientation of an image by a Dove prism. (a) Original position. (b) Prism rotated 45°; image is rotated 90° (c) Prism rotated 90°; image is rotated 180°. Note that the dotted arrow and crossbar in (b) is oriented so that the dotted arrow is in the plane of incidence to simplify the analysis of the image orientation.

Porro Prism

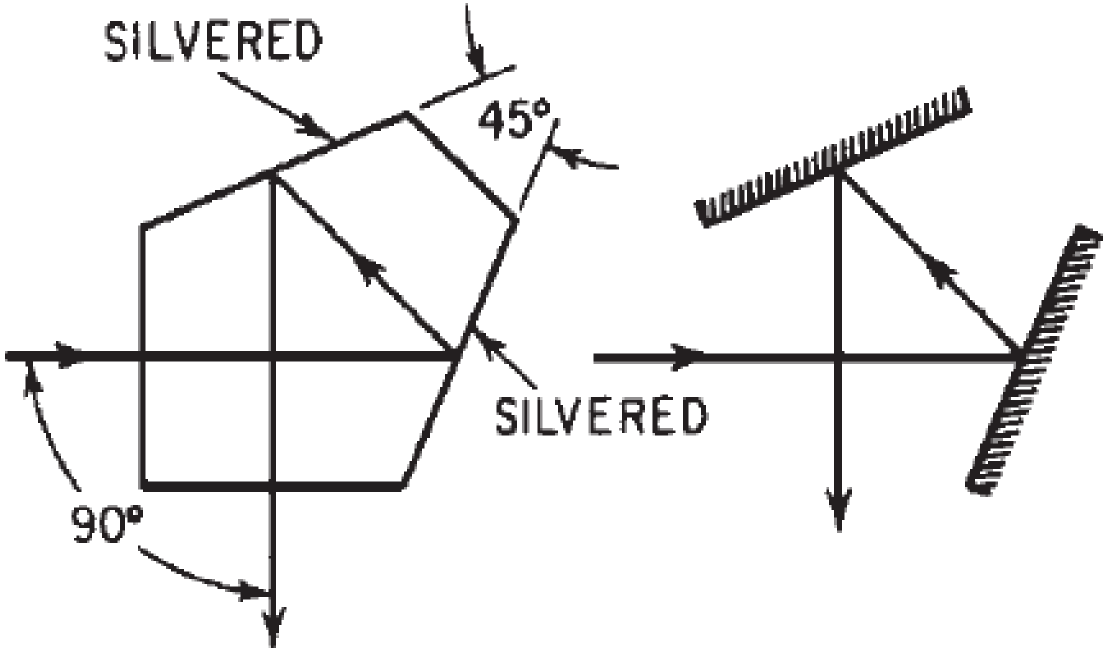
- Porro prism is used to alter the orientation of an image.
- Porro prism systems are used in small optical telescopes and in binoculars to re-orient an inverted.



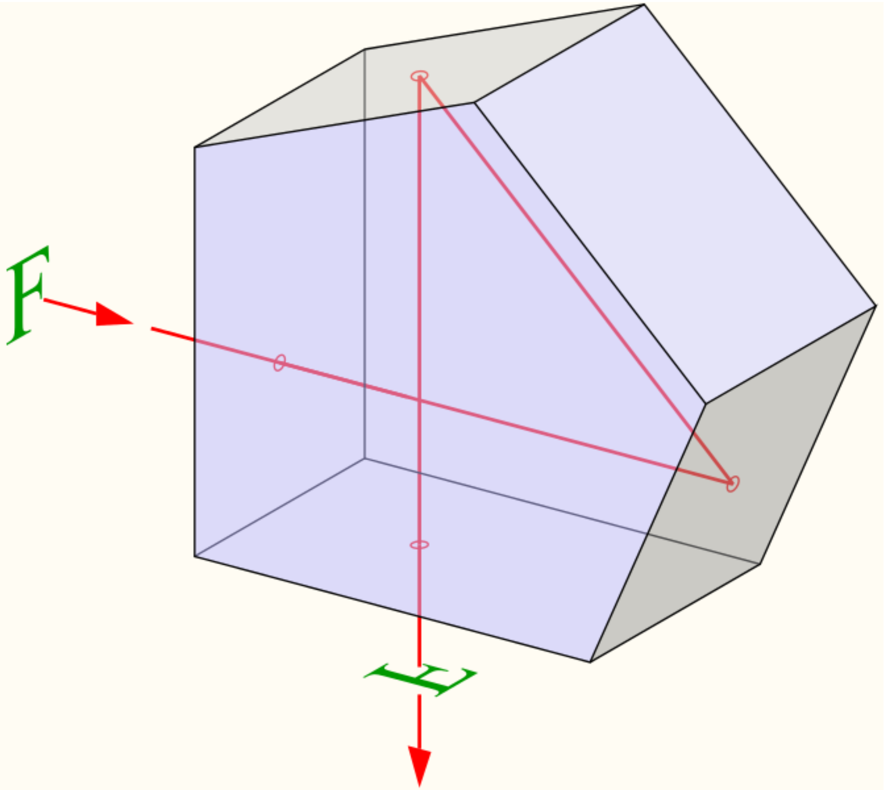


Penta Prism

- Neither invert nor reverse the image.
- The function is to deviate the line of sight by 90º.
- Commonly used in the viewfinder of single-lens reflex cameras.

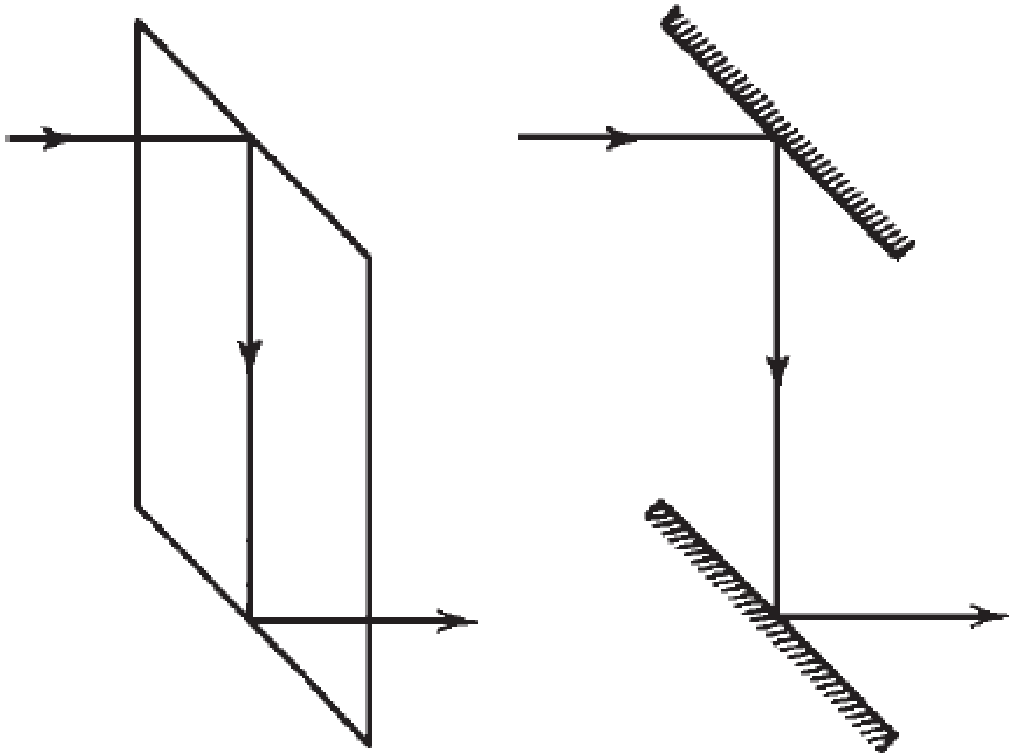


Penta prism and its mirror equivalent



Rhomboid Prism

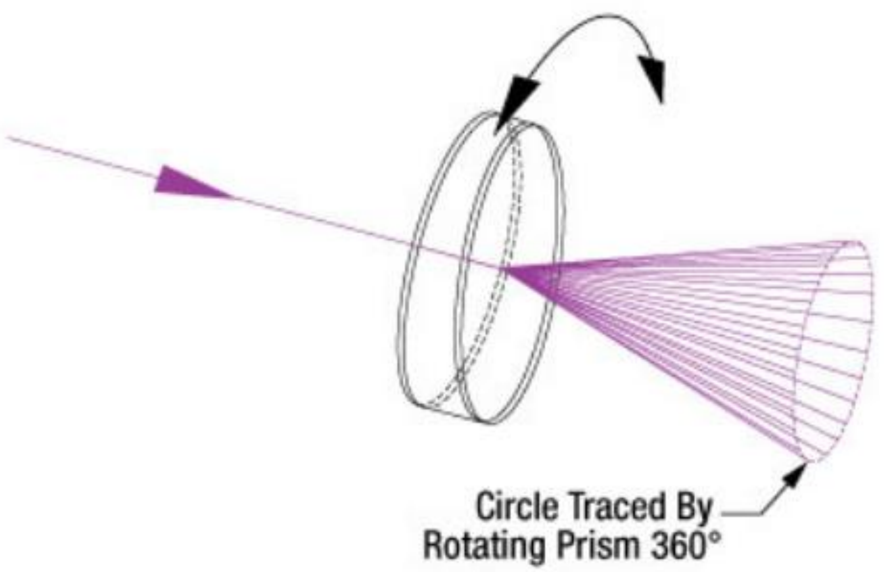
The rhomboid prism displaces the ray without affecting the orientation of the image or deviating the line of sight.



Rhomboid prism and its mirror equivalent

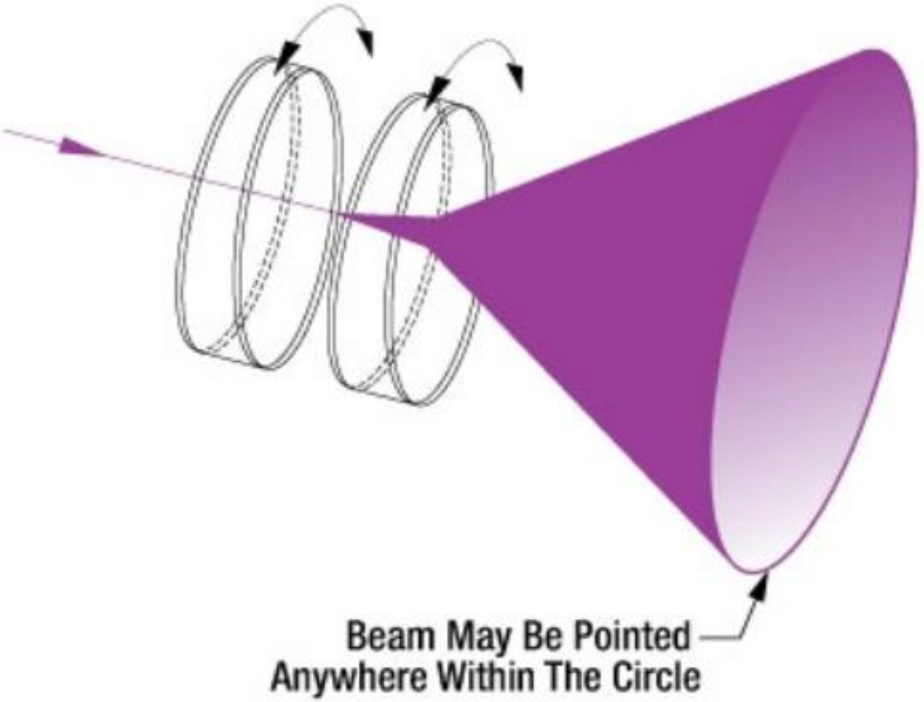
Wedge Prisms

- are ideal for laser beam steering applications.
- deflect a beam normal to the prism's perpendicular surface through an angular deviation ranging from 2^{o} to 10^{o}.



Click to Enlarge

The drawing above depicts a single wedge prism and an incident beam of light. The incident light is refracted at the specified deviation angle. As the wedge is rotated, the deviated beam traces out a circle defined by an angle equal to two times the specified deviation angle.



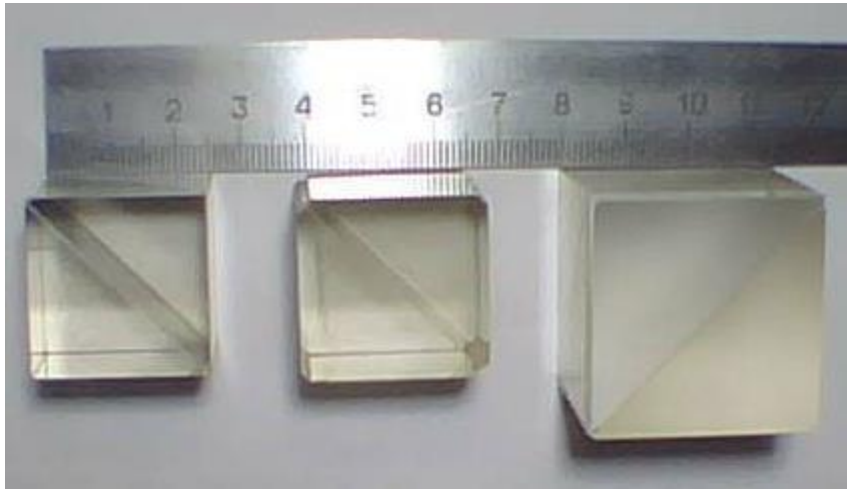
Click to Enlarge

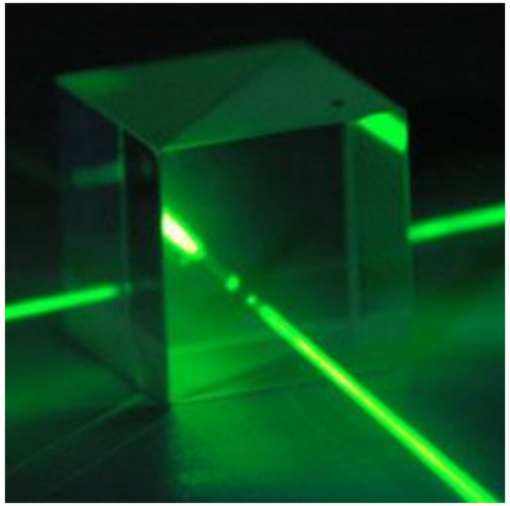
The drawing above depicts two wedge prisms and an incident beam of light. Since each individual prism can trace out a circle of two times the deviation angle, the total deviation by two prisms will be four times the deviation angle. By controlling the angle of each prism independently, the beam can be positioned at any point within the circle.

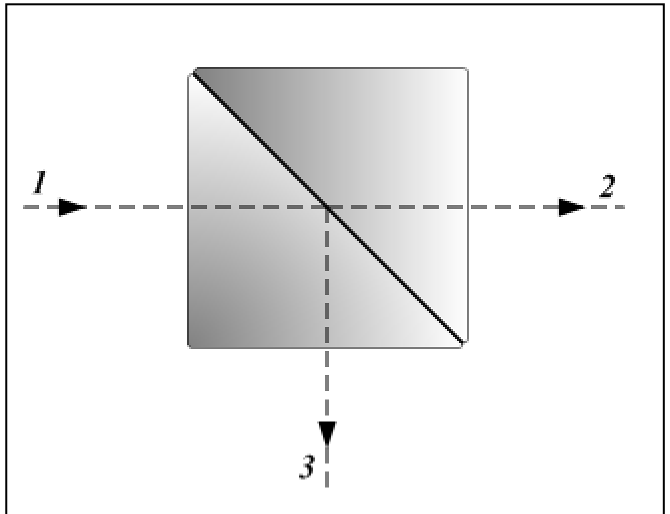
Beam-Spliters

A beamsplitter cube

- is composed of two right-angle prisms cemented together (The hypotenuse of one prism is coated with a semi-reflecting coating before cementing)
- is used for separating one beam into two
- is used for combining two beams (or images) into one
- is the crucial part of most interferometers







Beam splitter cube:

1 - Incident light

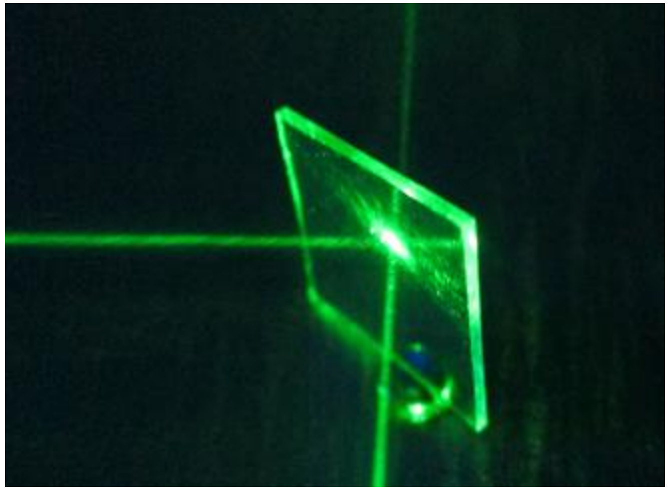
2 - 50% Transmitted light

3 - 50% Reflected light

Beam-Spliters

A beamsplitter mirror

Another design is the use of a half-silvered mirror. This is composed of an optical substrate, which is often a sheet of glass or plastic, with a partially transparent thin coating of metal (such as Al).



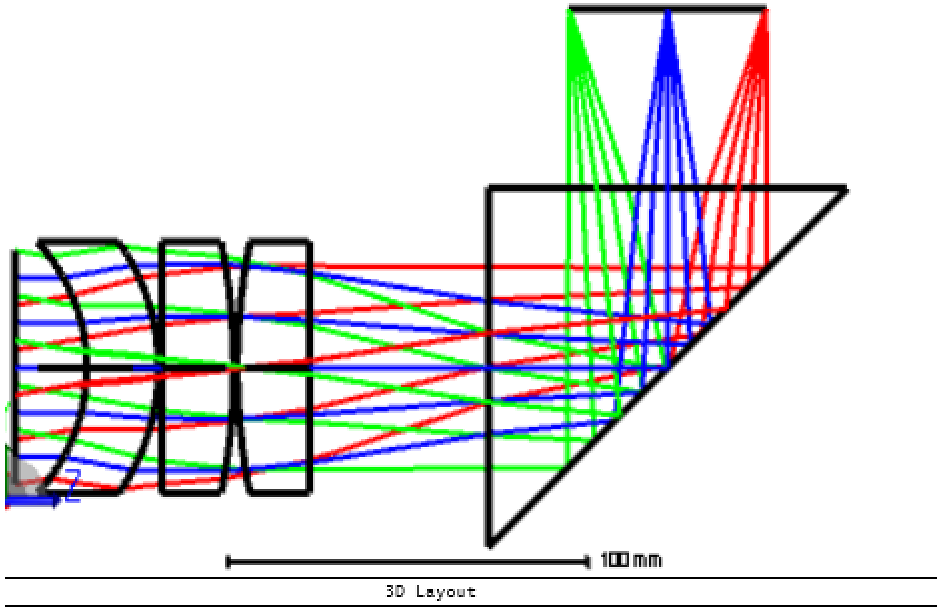
Example: Prisms and Beam Spitterts in Zemax

Look at the Zemax sample folder:

...\Zemax\Samples\Sequential\Tilted systems & prisms

E.g. investigate the following samples:

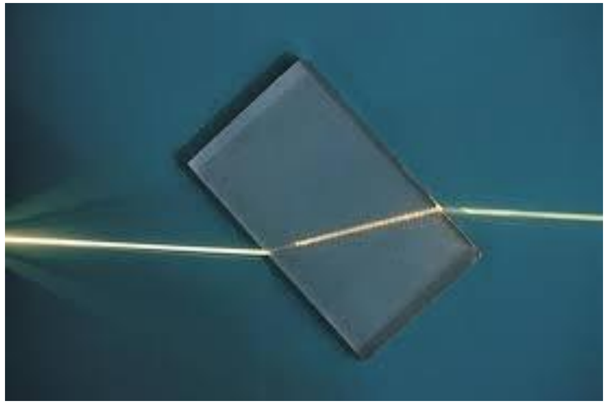
- Prism using total internal reflection.zmx
- Beamsplitter cube.zmx

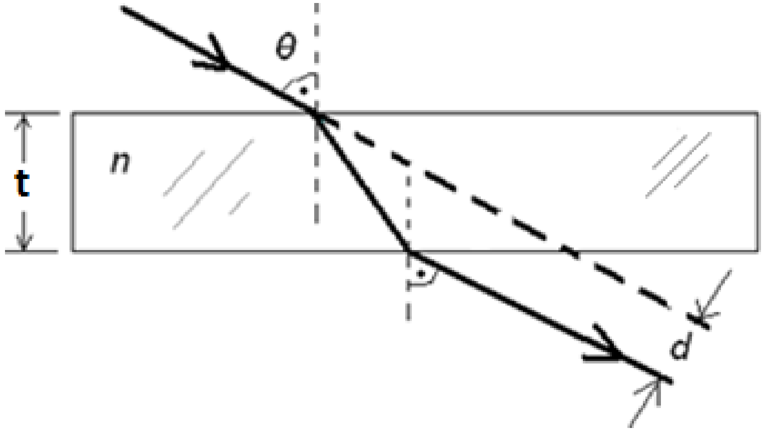


Optical Slab

Optical Slab

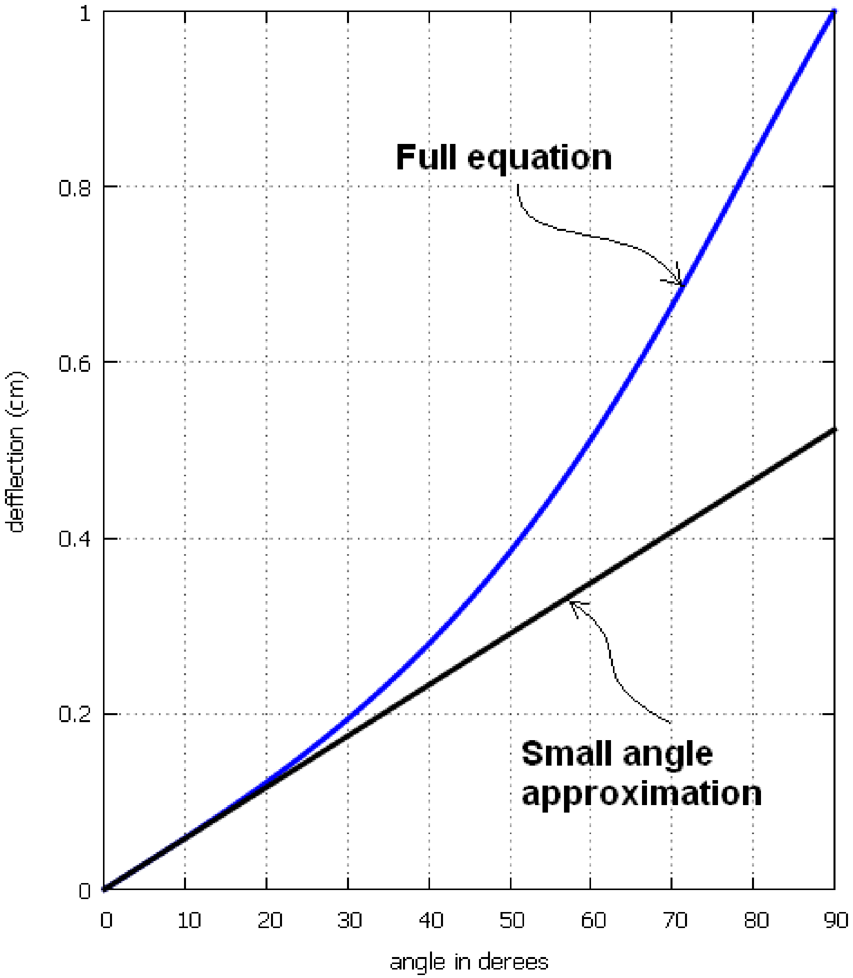
It is a flat piece of glass can be used to displace a light ray laterally without changing its direction.



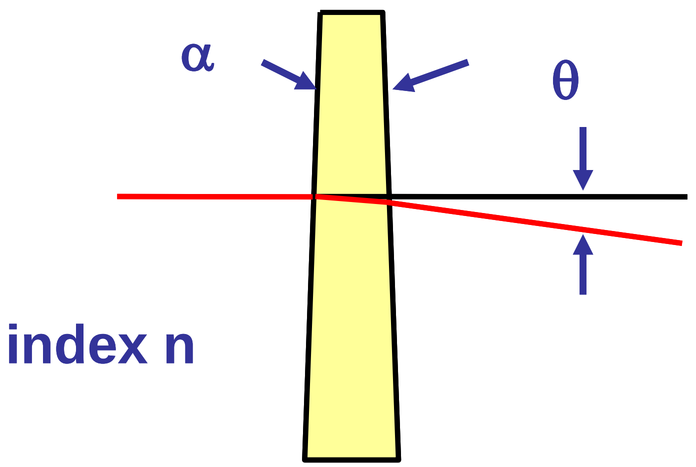


$$d = t\sin(\theta)\left(1 - \frac{\cos(\theta)}{\sqrt{n^2 - \sin^2(\theta)}}\right)$$

Note that if θ is small then: $$d \approx \frac{(n-1)\,t\,\theta}{n}$$

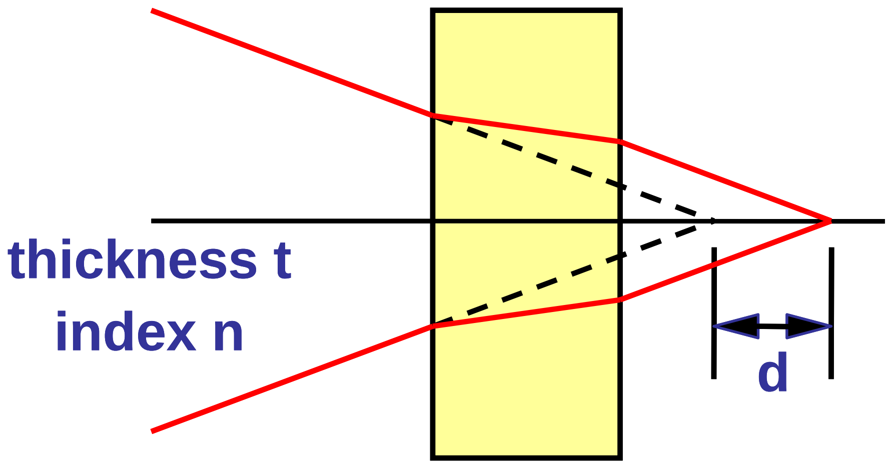


Optical Slab (for small angles)

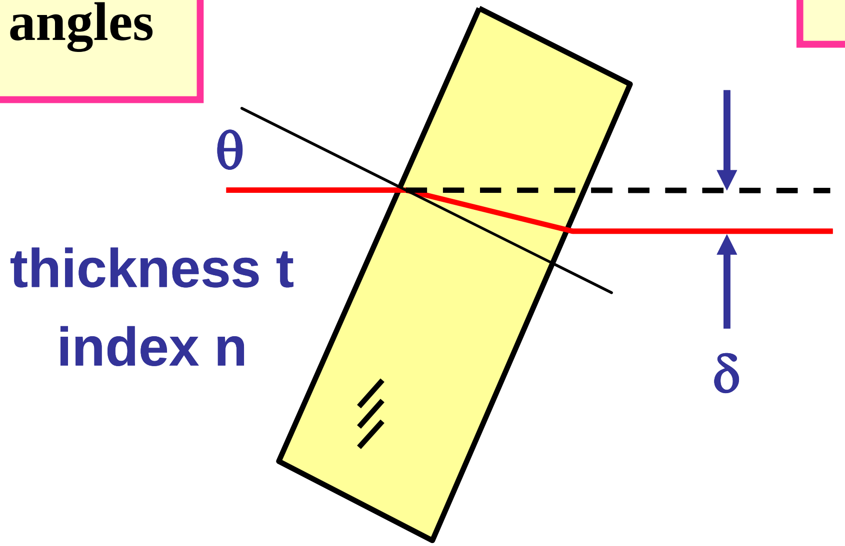


$\theta = (n - 1)\,\alpha$

for small angles



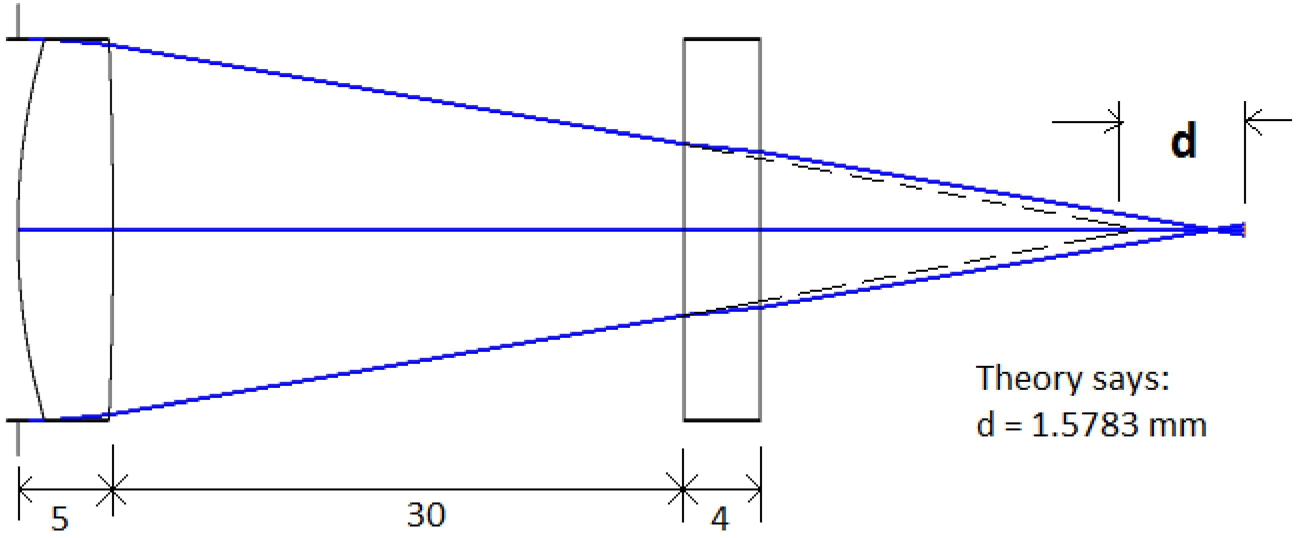
$$d = \frac{(n-1)\,t}{n}$$



$$\delta = \frac{(n-1)\,t\,\theta}{n}$$

Example: Shifting Total Length via Slab

In this example, we will see how to shift total length of an optical system.



- $*$ ENPD = 20 mm
- $*$ λ = 550 nm.
- $*$ Object is at infinity
- $*$ Image plane is placed at **paraxial focus**
- $*$ N-BK7 lens: R_1 = 36 mm, R_2 = -240 mm, ct = 5 mm
- $*$ N-SF2 Slab: t = 4 mm

ENPD: Entrance Pupil Diameter

EFFL: Effective Focal Length

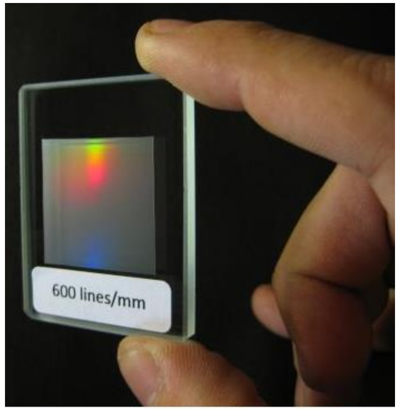
TOTR: Total Track Length

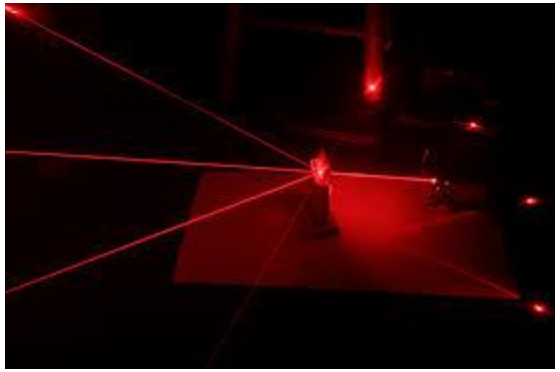
Determine EFFL and TOTR of the system with and without optical slab.

Diffraction Grating

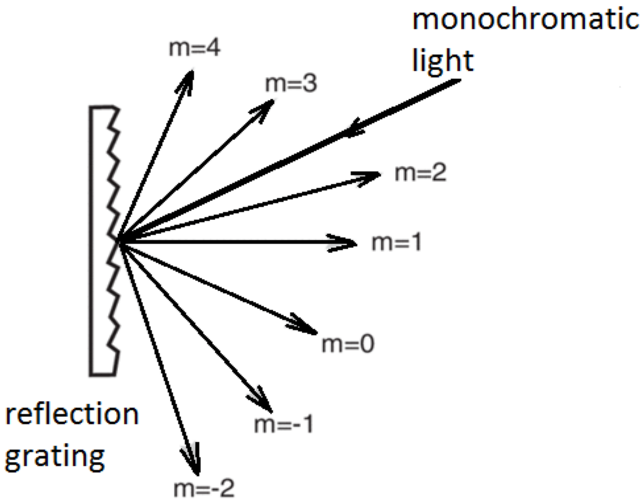
Diffraction Grating

A large number of equally spaced parallel slits is called a diffraction grating. Gratings containing 1,000 lines (or slits) per millimeter are common, and are very useful for precise measurements of wavelengths.





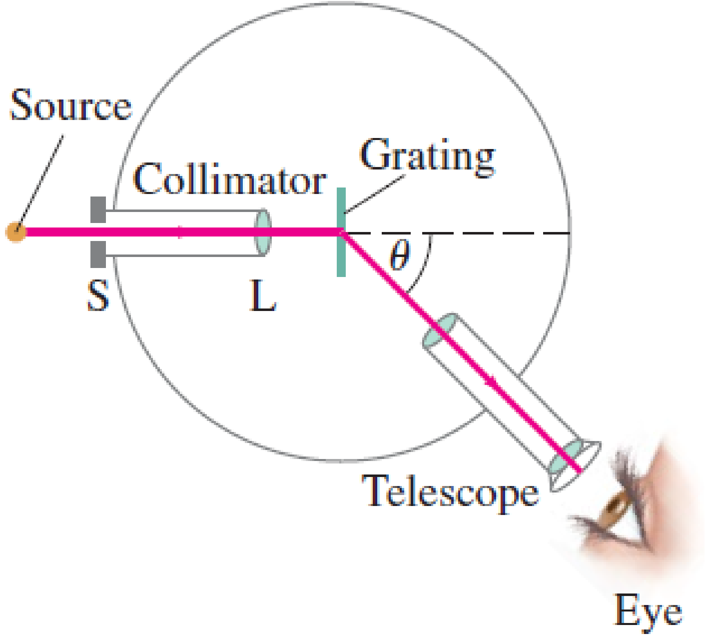
Transmission Grating



The reflection grating

A CD illuminated with white light is a reflection diffraction grating

Diffraction Grating



The diraction grating for peak angular position of bright fringes equation is:

$$d \sin(\theta) = m\lambda$$

m = an integer to represent the order of the diffraction.

λ = wavelength of the incident light

d = slit with

If N is the number of rulings per unit length (e.g. lines/mm) then d = 1 / N.

For example, if we have a grating with N = 600 lines/mm then d = 1/600 mm.

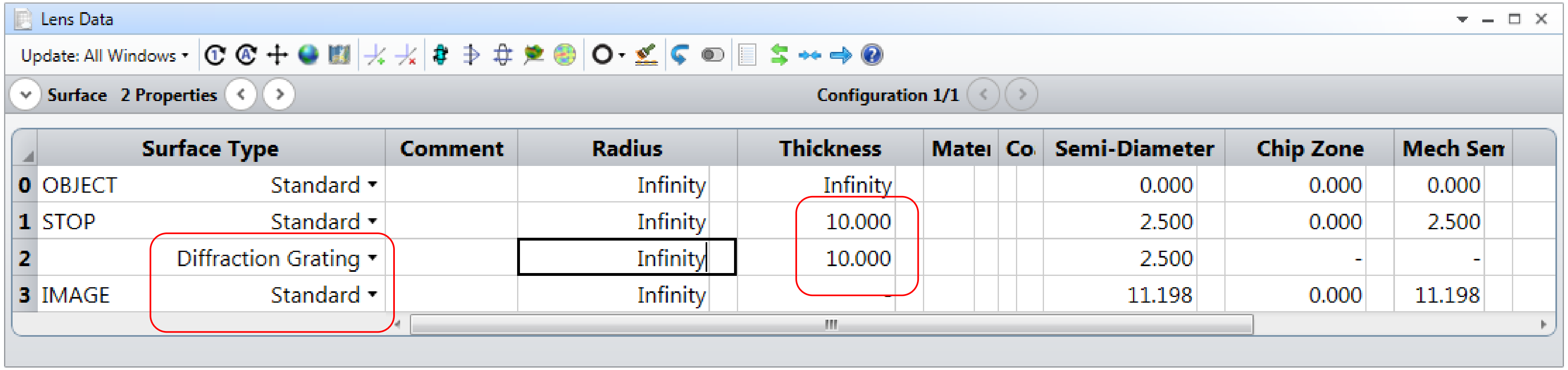
This equation is used in spectrometers which is a device to measure wavelengths accurately using a diffraction grating to separate different wavelengths of light.

Example: Diffraction Grating in Zemax

A simple diffraction grating can be added in Zemax as follows.

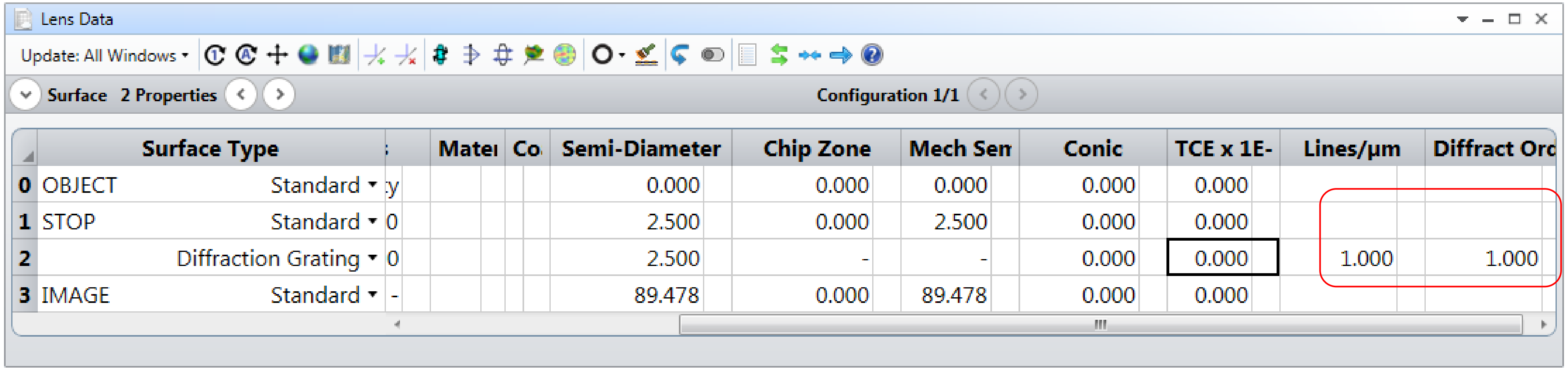
First insert a surface in LDE.

Then, change the surface type as **Diffaction Grating**

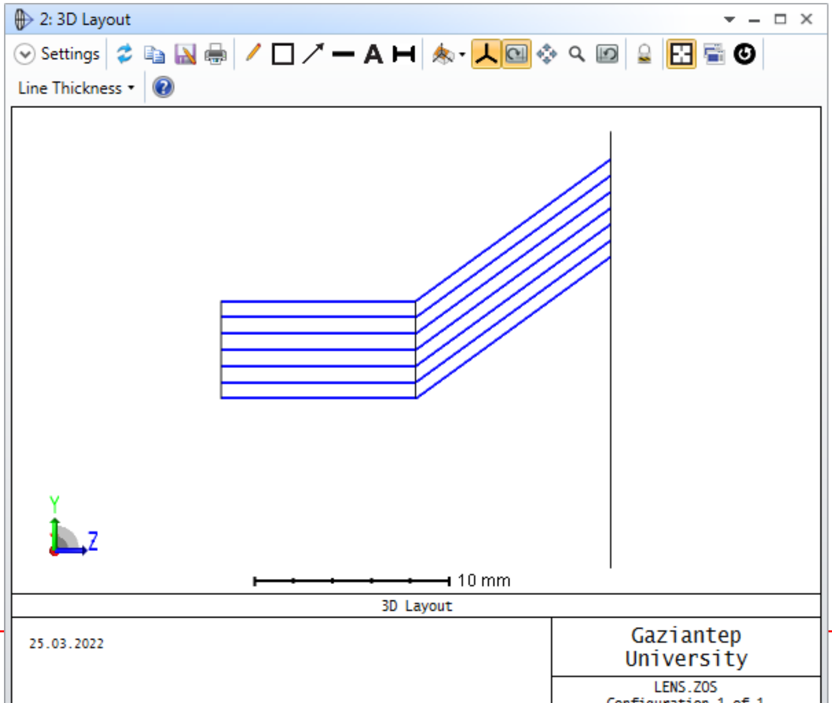


	Surface Type		Comment	Radius	Thickness	Mater	Co	Semi-Diameter	Chip Zone	Mech Sem
0	OBJECT	Standard		Infinity	Infinity			0.000	0.000	0.000
1	STOP	Standard		Infinity	10.000			2.500	0.000	2.500
2		Diffraction Grating		Infinity	10.000			2.500	-	-
3	IMAGE	Standard		Infinity	-			11.198	0.000	11.198

Let N = 1000 lines/mm = 1 line / µm, m = 1 (diffraction order), λ = F,d, C (visible), ENPD = 5 mm



	Surface Type		:	Mate	Co	Semi-Diameter	Chip Zone	Mech Sem	Conic	TCE x 1E-	Lines/µm	Diffract Ord
0	OBJECT	Standard	y			0.000	0.000	0.000	0.000	0.000		
1	STOP	Standard	0			2.500	0.000	2.500	0.000	0.000		
2		Diffraction Grating	0			2.500	-	-	0.000	0.000	1.000	1.000
3	IMAGE	Standard	-			89.478	0.000	89.478	0.000	0.000		



3D Layout

25.03.2022

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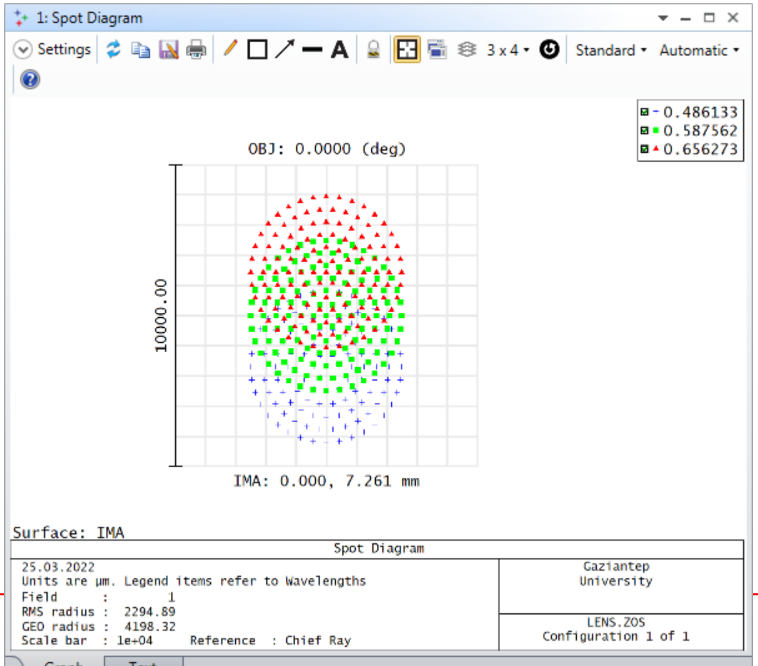
LENS.ZOS



Surface: IMA

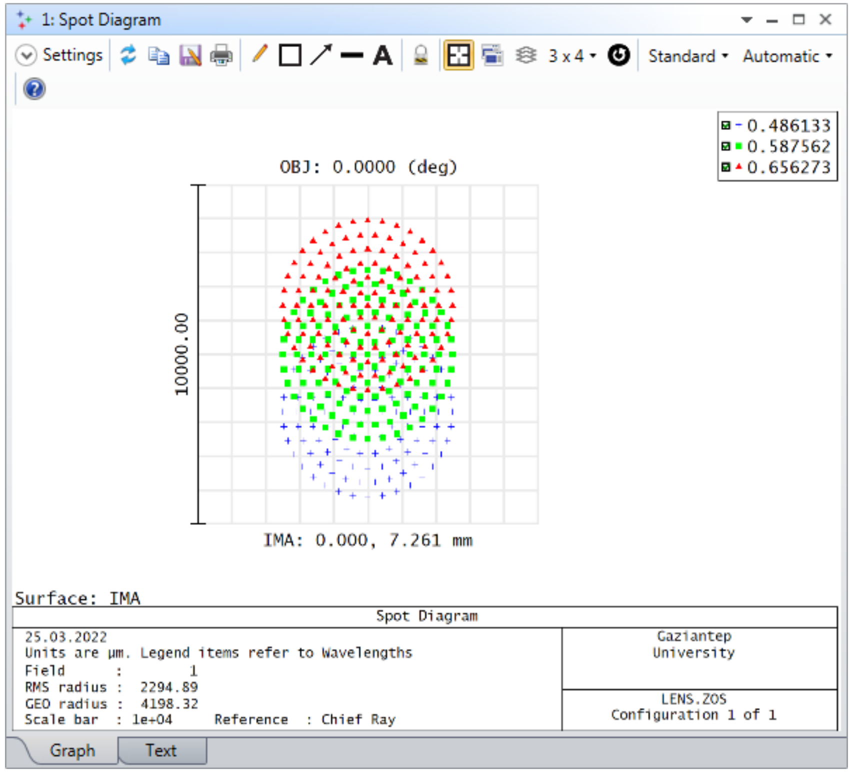
Spot Diagram

25.03.2022
Units are µm. Legend items refer to Wavelengths
Field : 1
RMS radius : 2294.89
GEO radius : 4198.32
Scale bar : 1e+04 Reference : Chief Ray

Gaziantep University

LENS.ZOS
Configuration 1 of 1

Spot diagram



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Surface: IMA
                         Spot Diagram
25.03.2022                                              Gaziantep
Units are µm. Legend items refer to Wavelengths         University
Field       :        1
RMS radius  :  2294.89
GEO radius  :  4198.32                                   LENS.ZOS
Scale bar   : 1e+04     Reference  : Chief Ray    Configuration 1 of 1
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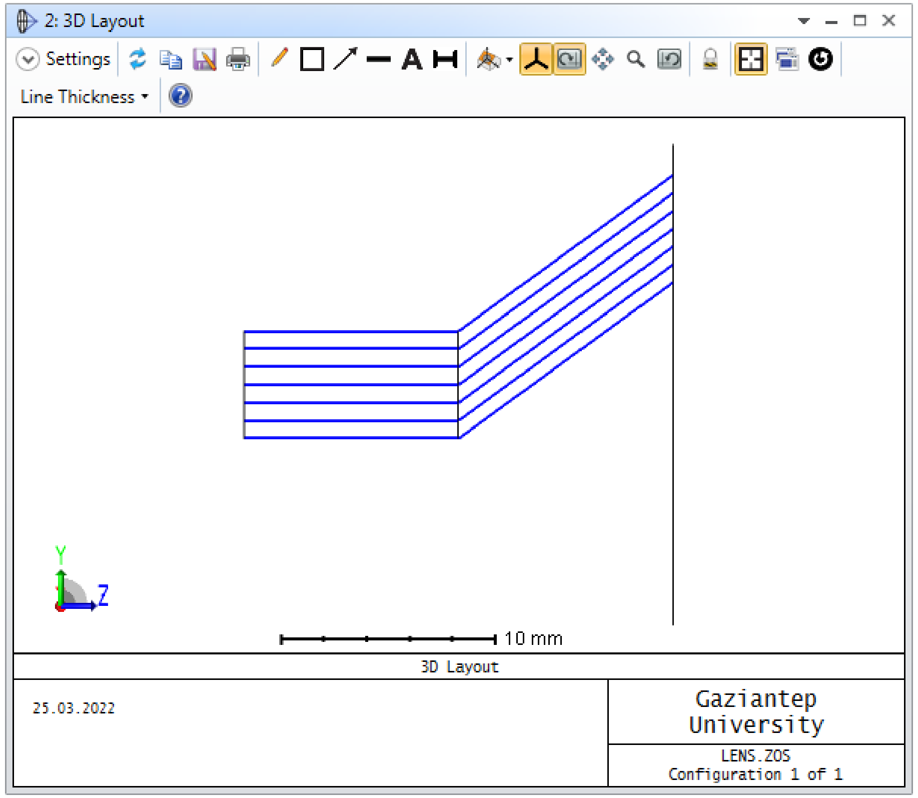
3D Layout



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                         3D Layout
25.03.2022                                              Gaziantep
                                                        University
                                                         LENS.ZOS
                                                  Configuration 1 of 1
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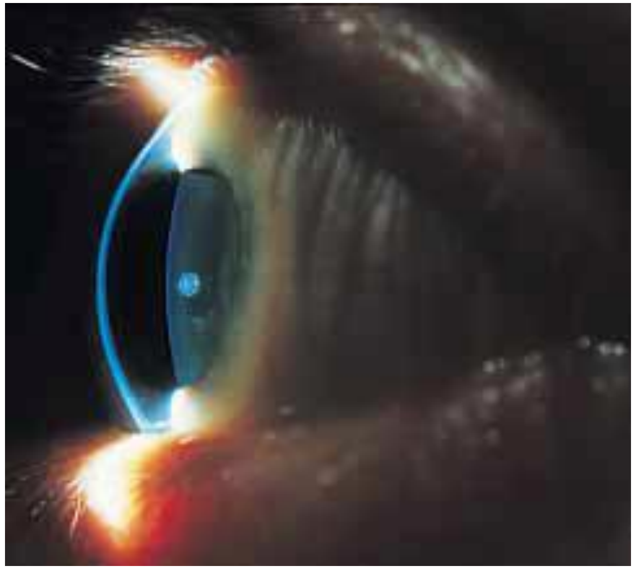
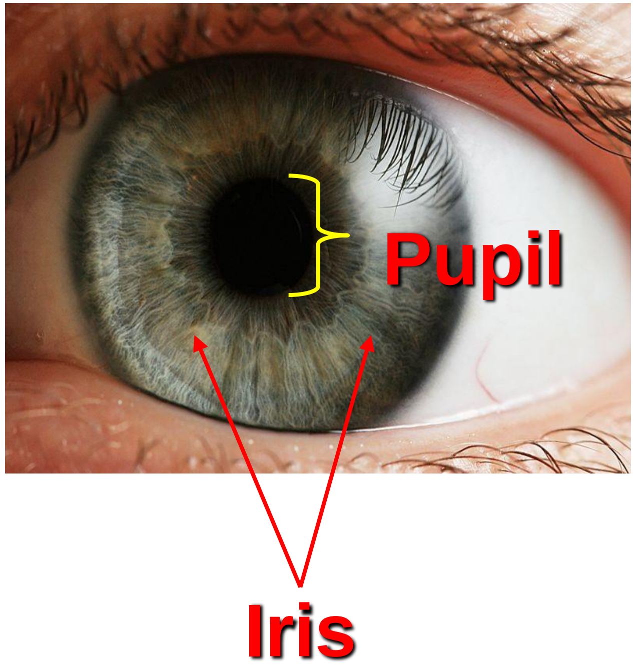
Eye

Eye (Perfect Light Detector)

- The majority of optical systems utilize the eye as the final element of the system
- A normal eye focuses light and produces a sharp image better than a camera.
- Eye forms images of a continuum of objects, at distances of a 25 cm to infinity.





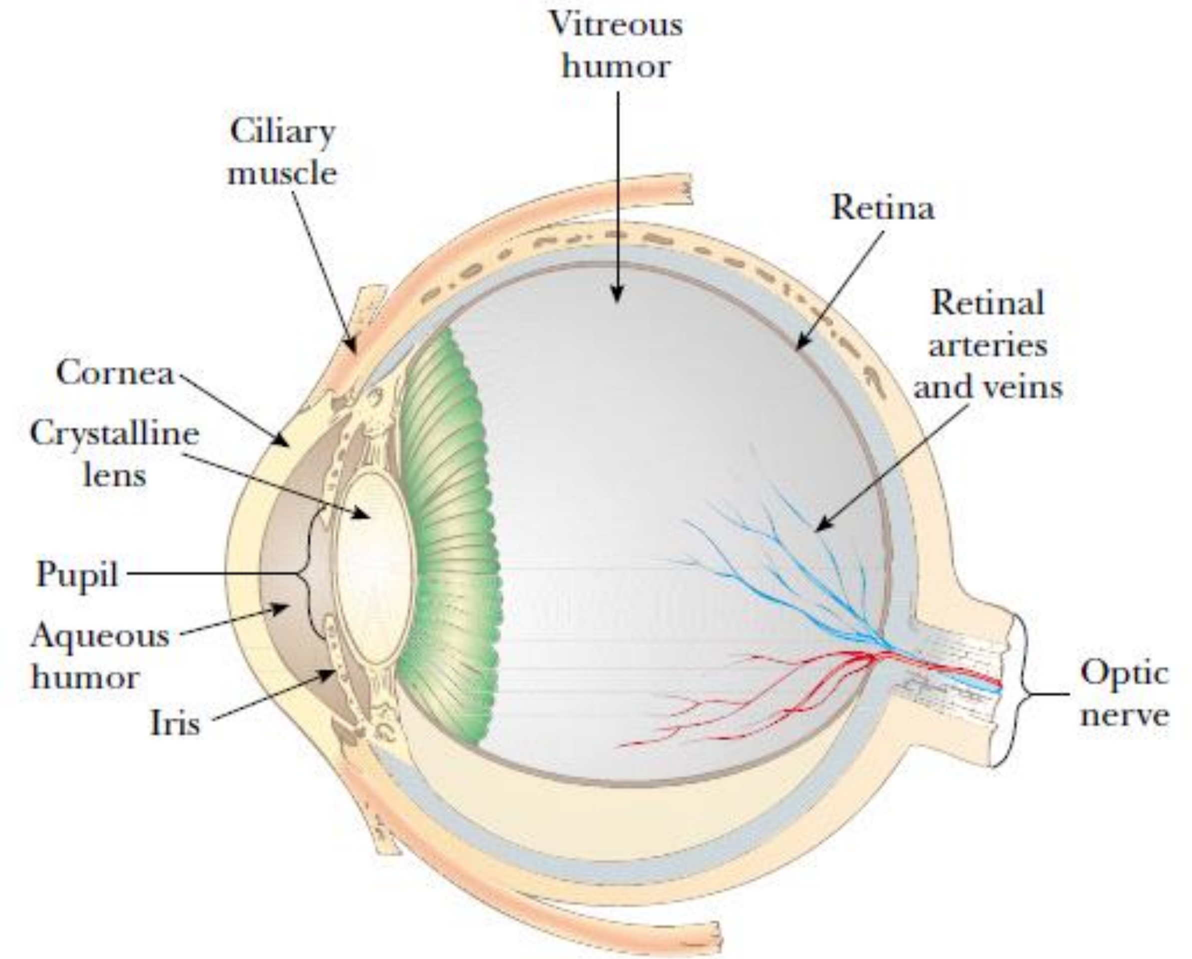
Biological Structure of Eye

1. Light entering the eye passes through a transparent structure called the cornea.

2. Pupils are opening in the iris.

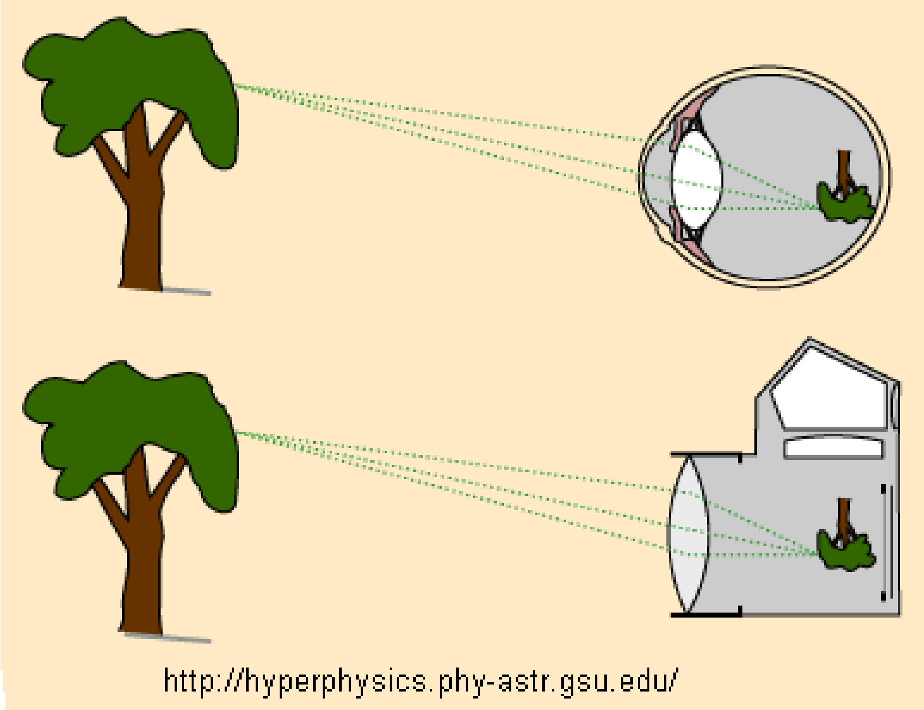
3. Crystalline lens focuses light onto the back surface of the eye, the retina which consists of millions of sensitive receptors called *rods* and *cones*.

4. The receptors send light impulses via the optic nerve to the brain, where an image is perceived.



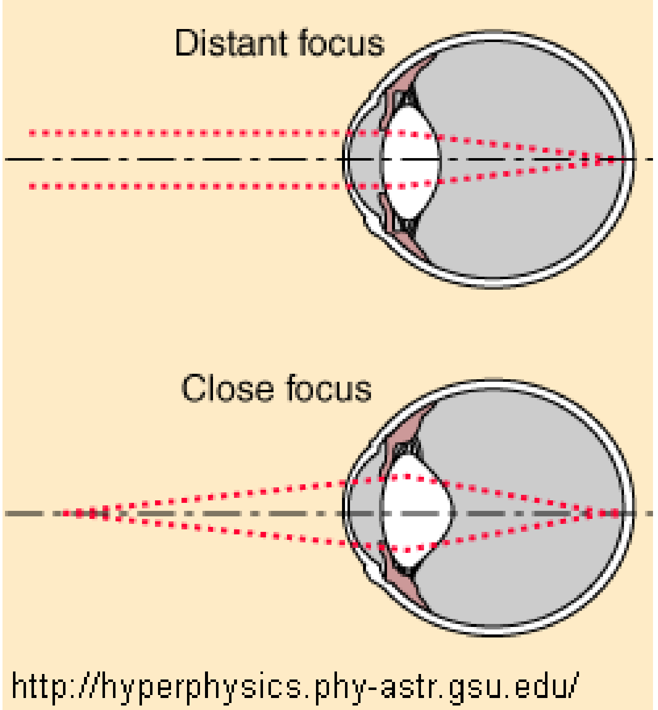
Eye and Camera

Image formation

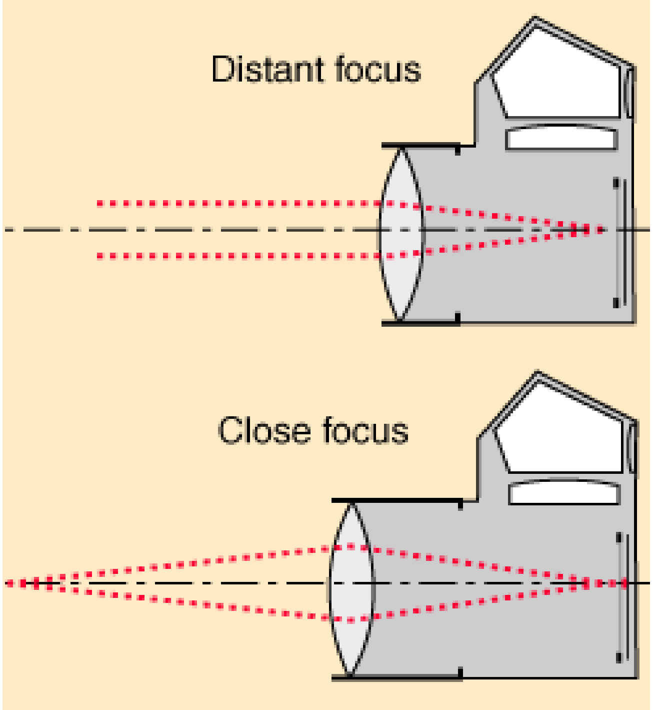


http://hyperphysics.phy-astr.gsu.edu/

Accommodation in Eye and Camera

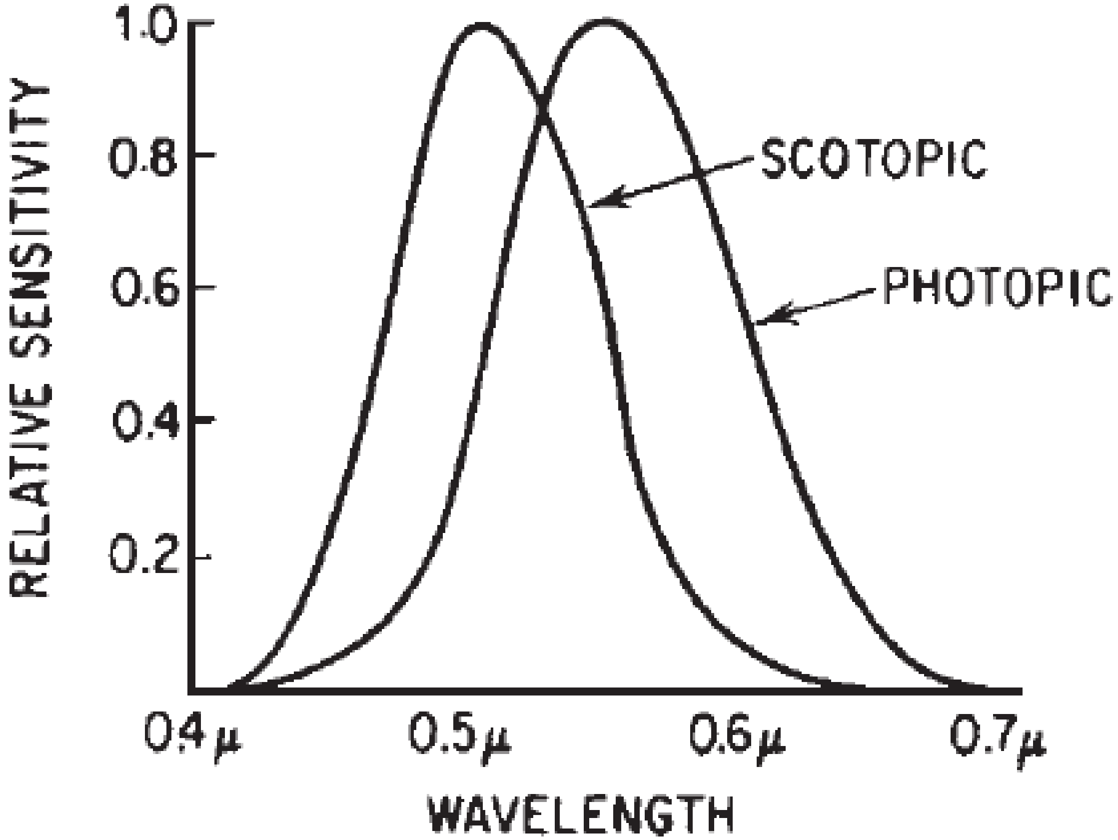


http://hyperphysics.phy-astr.gsu.edu/



Spectral Response of Eye

The human eye is not equally sensitive to all wavelengths of visible light.



The relative sensitivity of the eye to different wavelengths for normal levels of illumination (photopic vision) and under conditions of dark adaptation (scotopic vision).

Optical Represeantation of Eye

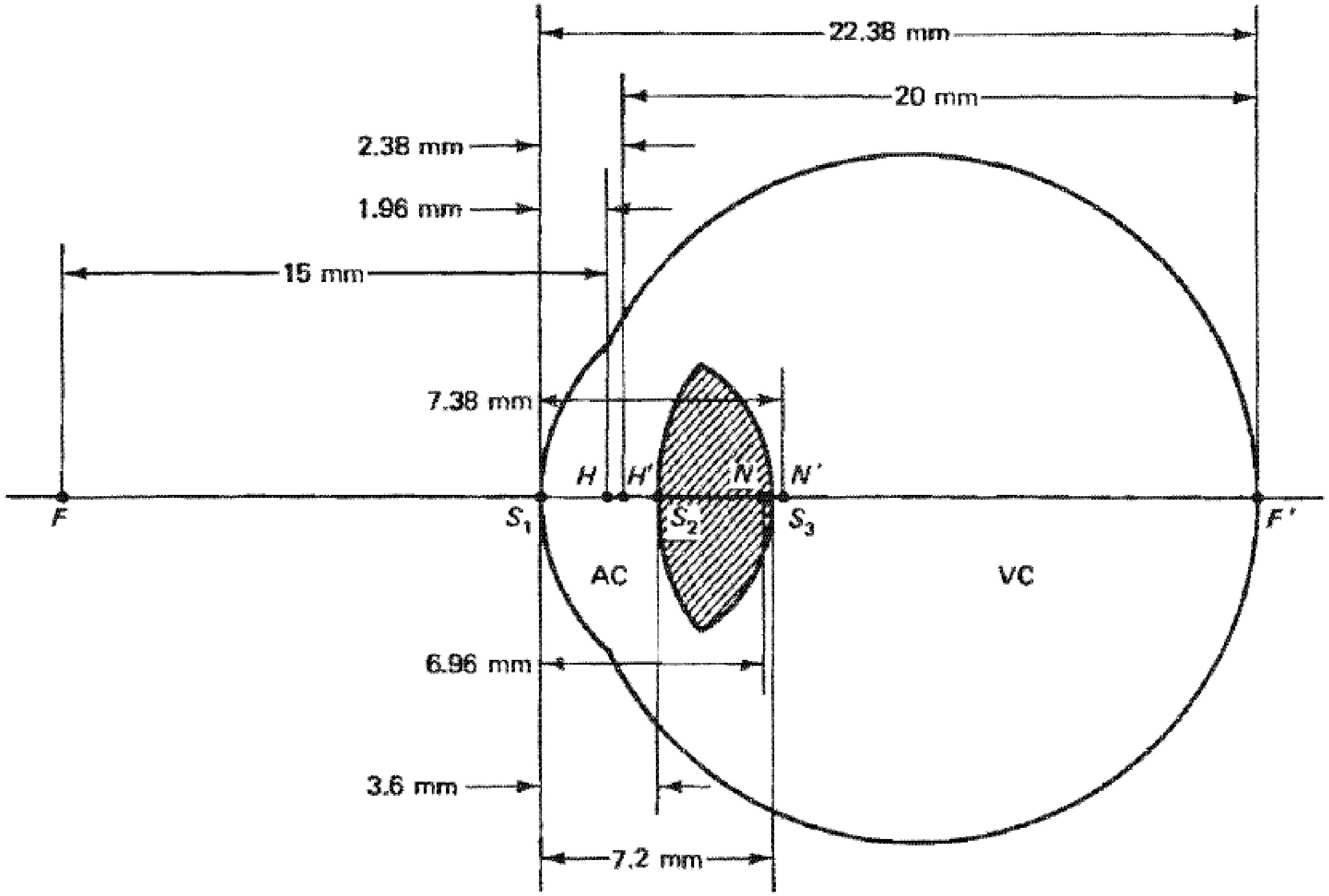
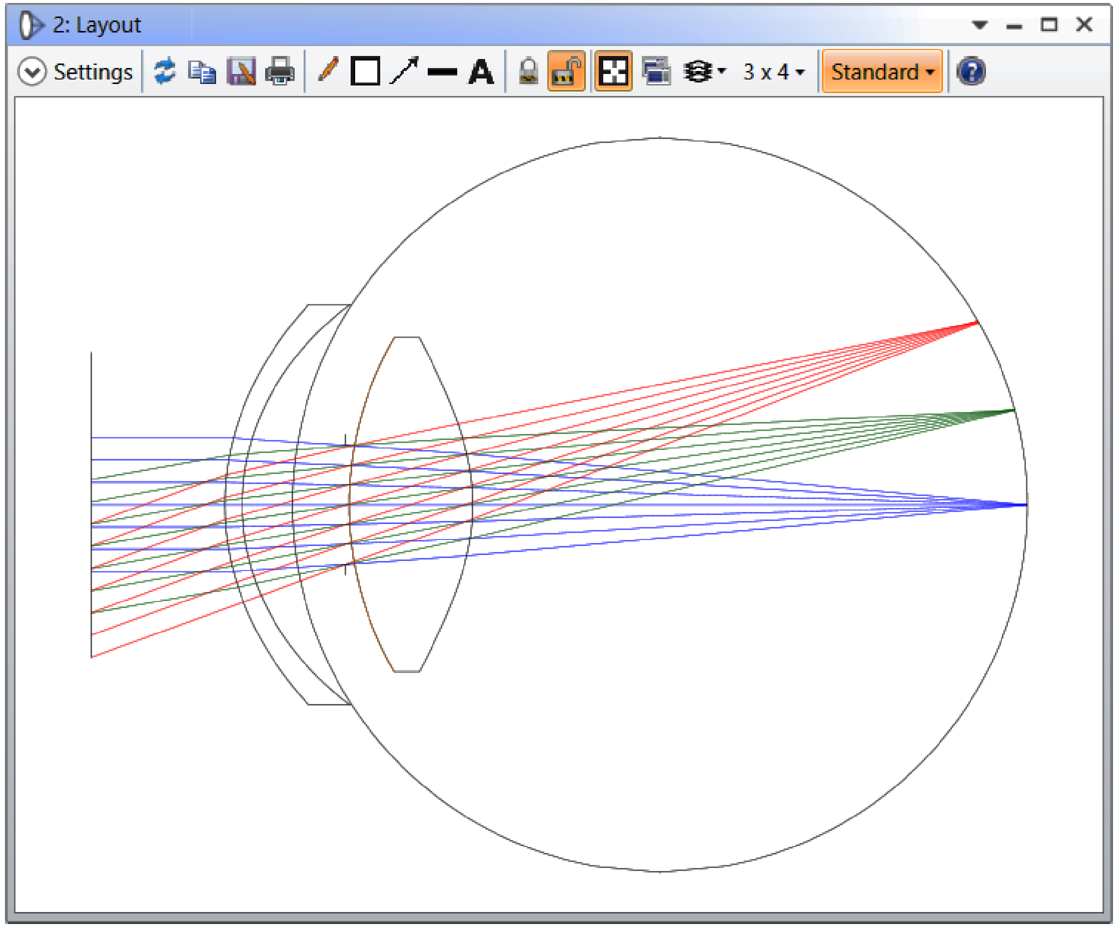


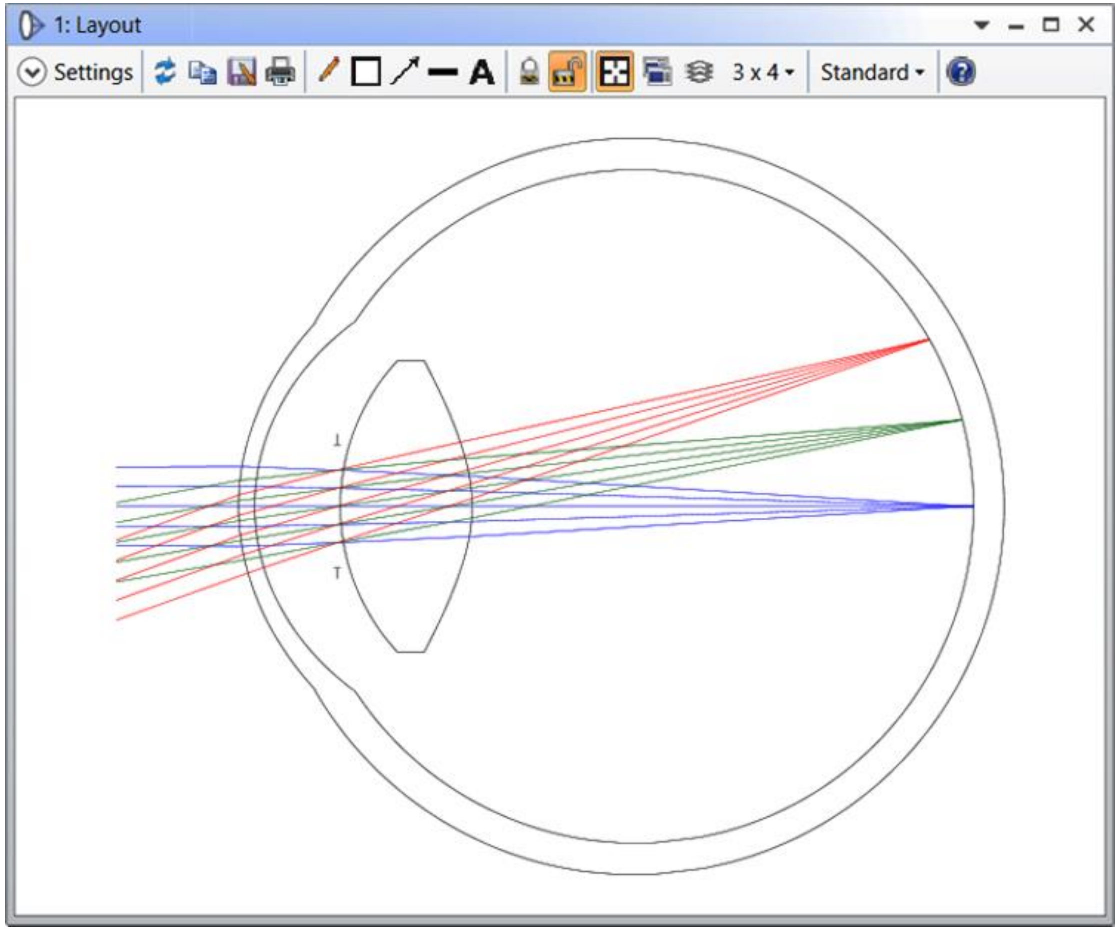
Figure 7-2 Representation of H. V. Helmholtz's schematic eye 1, as modified by L. Laurance. For definition of symbols, refer to Table 7-1. (Adapted with permission from Mathew Alpern, "The Eyes and Vision," Section 12 in *Handbook of Optics*, New York: McGraw-Hill, 1978.)

Eye Model in Zemax OpticStudio

Read the article:

https://support.zemax.com/hc/en-us/articles/1500005575082-OpticStudio-models-of-the-human-eye

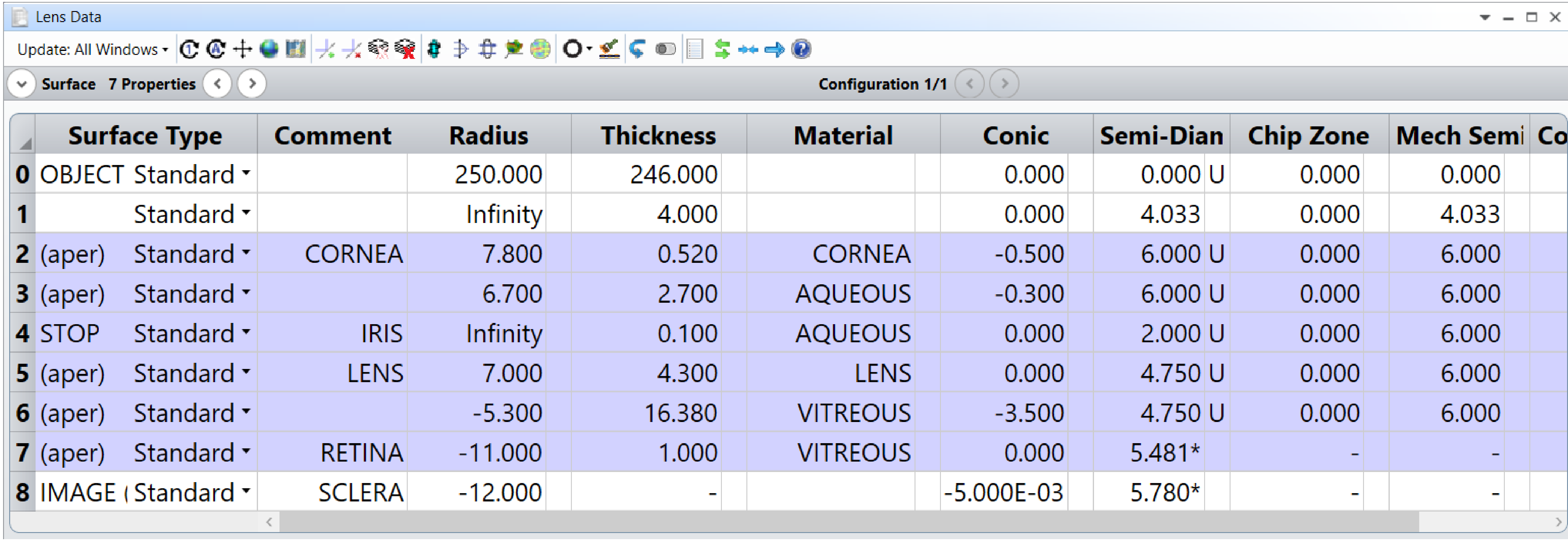




Eye Model in Zemax OpticStudio

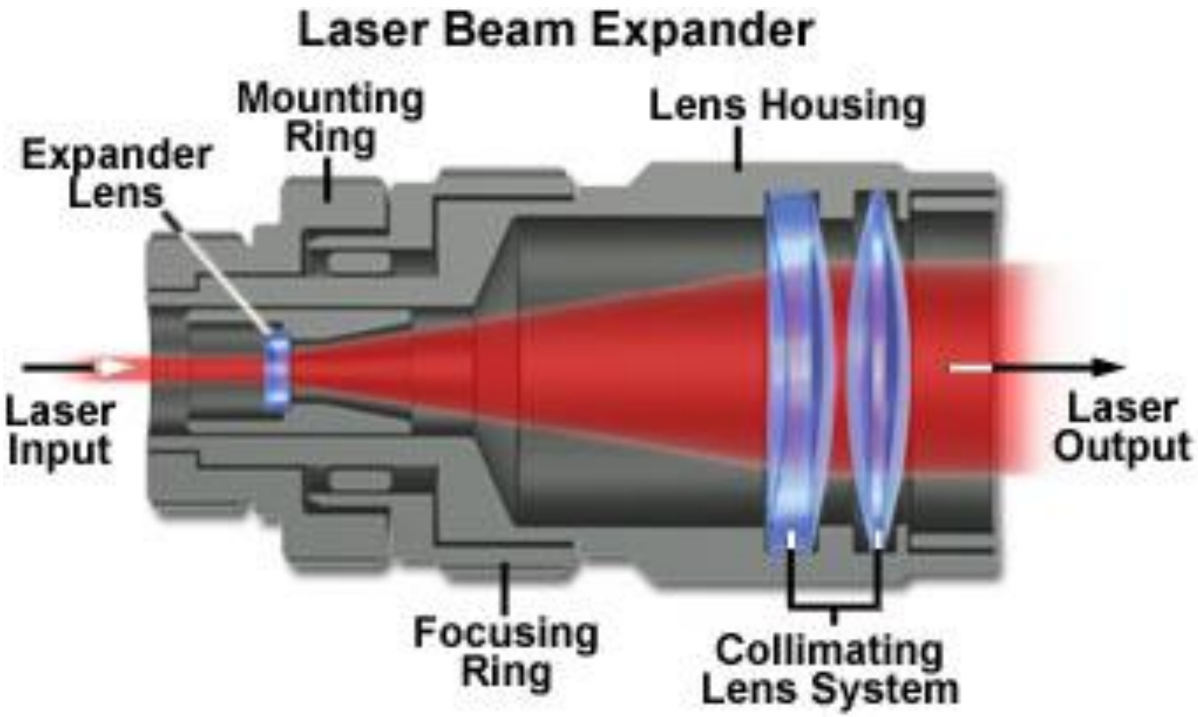
Read the article:

https://support.zemax.com/hc/en-us/articles/1500005575082-OpticStudio-models-of-the-human-eye



	Surface Type	Comment	Radius	Thickness	Material	Conic	Semi-Dian	Chip Zone	Mech Semi	Co
0	OBJECT Standard		250.000	246.000		0.000	0.000 U	0.000	0.000	
1	Standard		Infinity	4.000		0.000	4.033	0.000	4.033	
2	(aper) Standard	CORNEA	7.800	0.520	CORNEA	-0.500	6.000 U	0.000	6.000	
3	(aper) Standard		6.700	2.700	AQUEOUS	-0.300	6.000 U	0.000	6.000	
4	STOP Standard	IRIS	Infinity	0.100	AQUEOUS	0.000	2.000 U	0.000	6.000	
5	(aper) Standard	LENS	7.000	4.300	LENS	0.000	4.750 U	0.000	6.000	
6	(aper) Standard		-5.300	16.380	VITREOUS	-3.500	4.750 U	0.000	6.000	
7	(aper) Standard	RETINA	-11.000	1.000	VITREOUS	0.000	5.481*	-	-	
8	IMAGE (Standard	SCLERA	-12.000	-		-5.000E-03	5.780*	-	-	

Beam Expanders



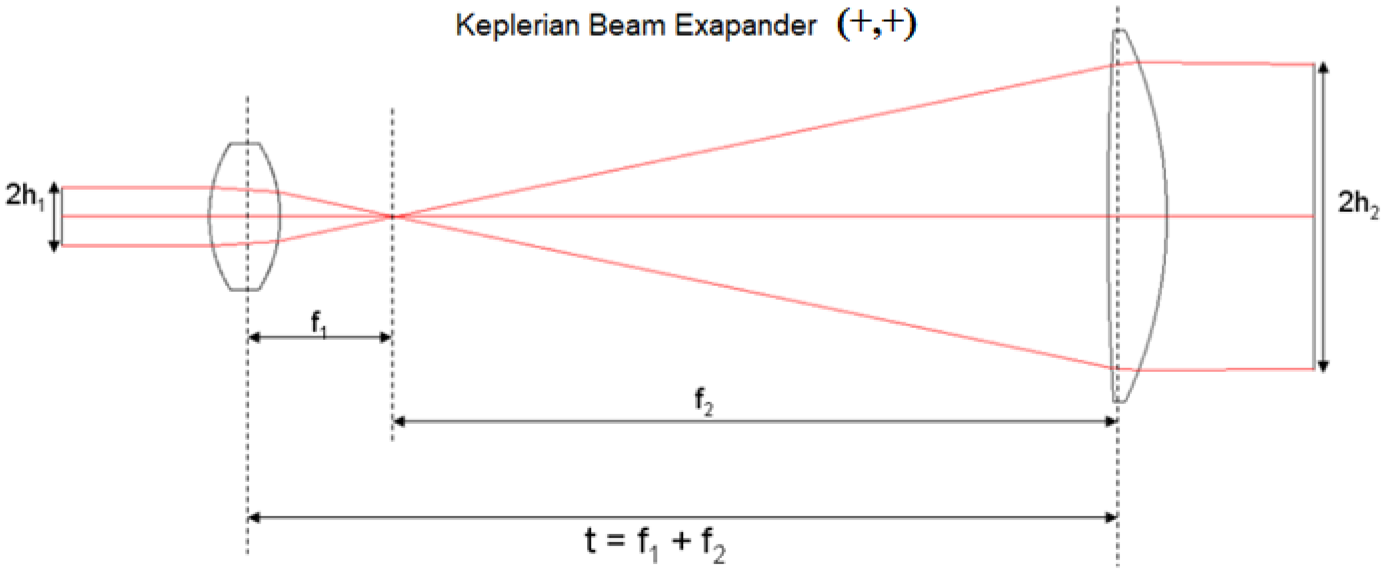
Beam Expander

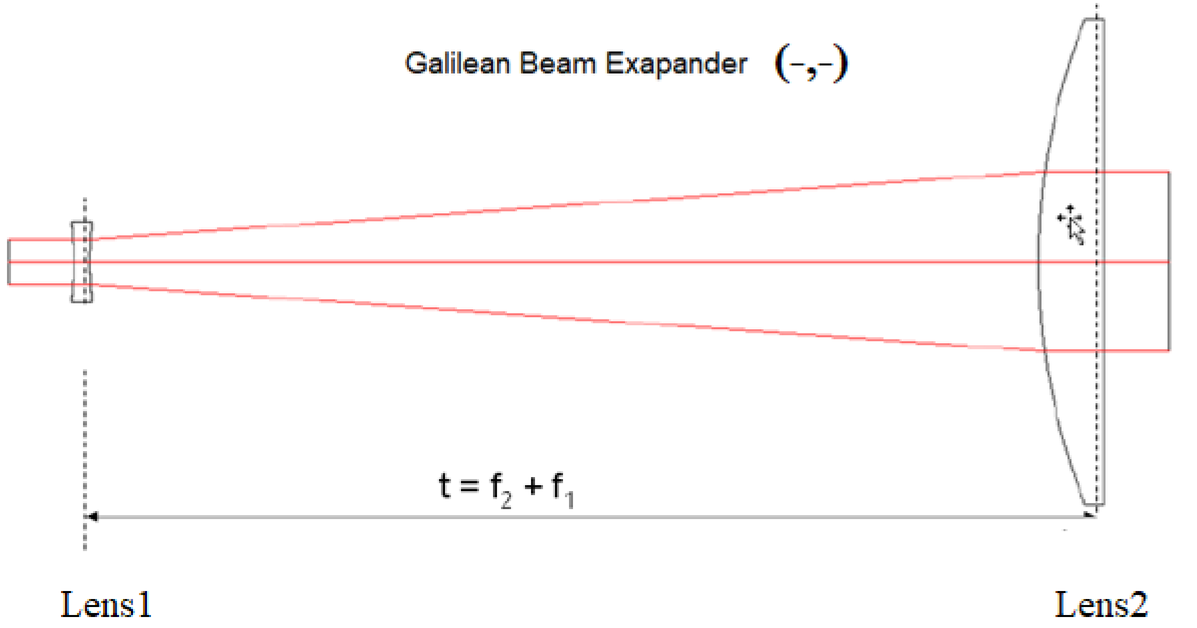
Beam exapanders are frequently used in optics lab.They are preferred in afocal apllications such as interferometer, laser scanner and collimator.

At basic level we use two lenses (PP and NP) with design parameters:

$$m = -\frac{f_2}{f_1} = \frac{h_2}{h_1} \qquad t = f_1 + f_2$$

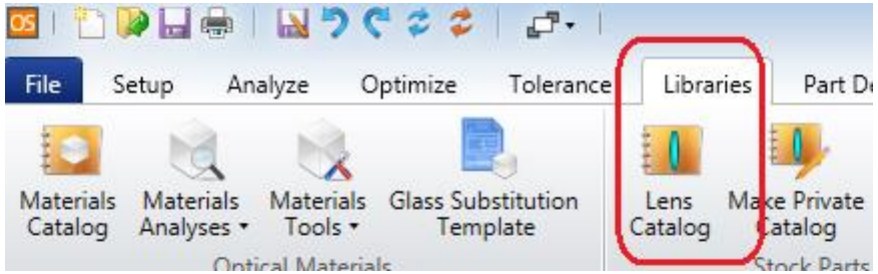
People usually select off-the-shelf (stock) optical components to design beam expanders, since they are easy and cheaper to construct.

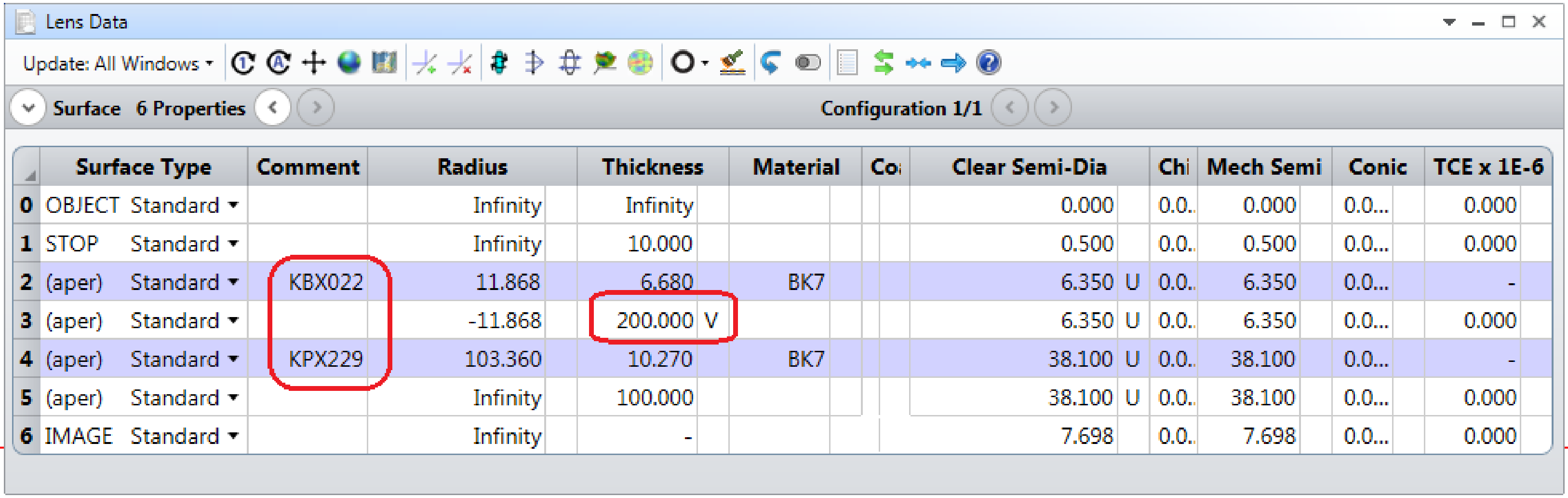




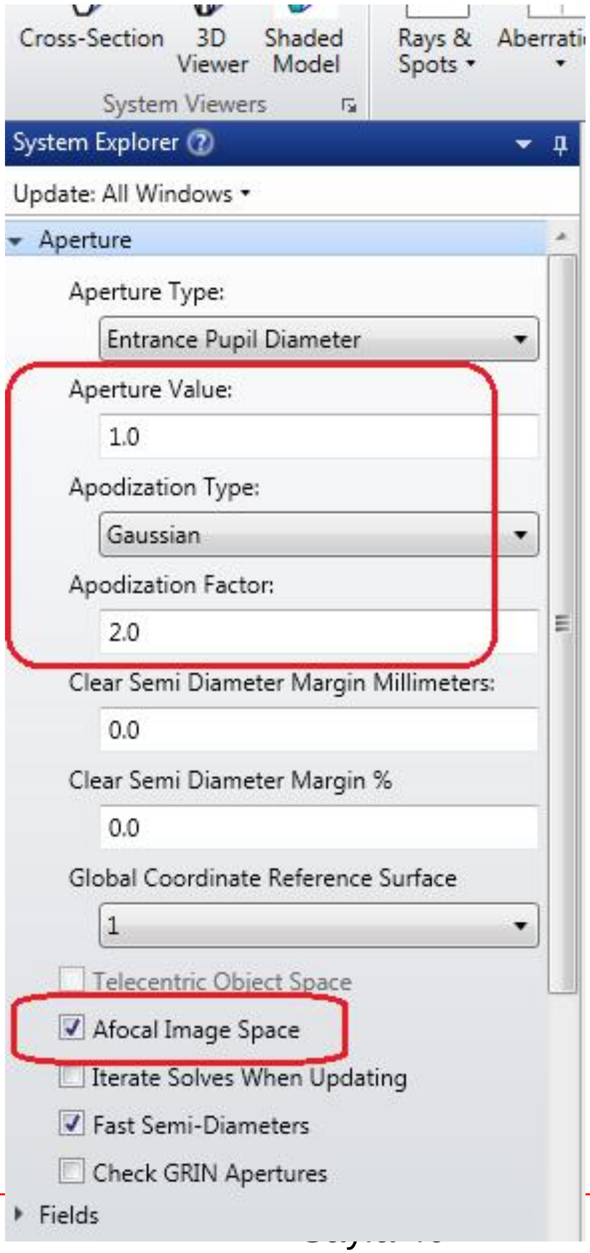
Example: Designing Beam Expander via Lens Catalog

- In this example, we'll design a beam expander using Newport's lenses KBX022 (f=+12.66mm) ve KPX229 (f=+199.3mm) which are available in **Zemax Lens Catalog**, hence the magnification is *m* = 16x.
- We need to optimize only the distance between lenses (*t* = ?).
- Insert these lenses to LDE.
- Design parameters:
  Wavelength = 632.8 nm (HeNe)
  Gaussian beam
  ENPD = 1 mm
  Apodization factor = 2





	Surface Type		Comment	Radius	Thickness		Material	Co	Clear Semi-Dia		Chi	Mech Semi	Conic	TCE x 1E-6
0	OBJECT	Standard ▾		Infinity	Infinity				0.000		0.0..	0.000	0.0...	0.000
1	STOP	Standard ▾		Infinity	10.000				0.500		0.0..	0.500	0.0...	0.000
2	(aper)	Standard ▾	KBX022	11.868	6.680		BK7		6.350	U	0.0..	6.350	0.0...	-
3	(aper)	Standard ▾		-11.868	200.000	V			6.350	U	0.0..	6.350	0.0...	0.000
4	(aper)	Standard ▾	KPX229	103.360	10.270		BK7		38.100	U	0.0..	38.100	0.0...	-
5	(aper)	Standard ▾		Infinity	100.000				38.100	U	0.0..	38.100	0.0...	0.000
6	IMAGE	Standard ▾		Infinity	-				7.698		0.0..	7.698	0.0...	0.000



Aperture Type: Entrance Pupil Diameter

Aperture Value: 1.0

Apodization Type: Gaussian

Apodization Factor: 2.0

Clear Semi Diameter Margin Millimeters: 0.0

Clear Semi Diameter Margin % 0.0

Global Coordinate Reference Surface 1

☐ Telecentric Object Space

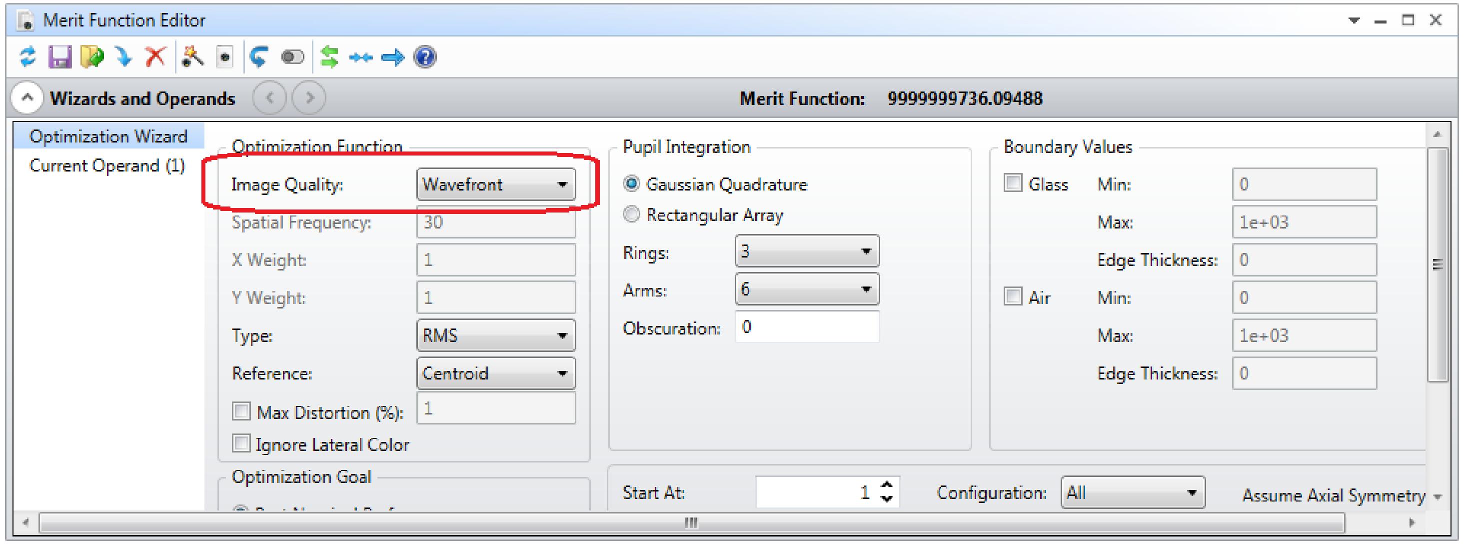
☑ Afocal Image Space

☐ Iterate Solves When Updating

☑ Fast Semi-Diameters

☐ Check GRIN Apertures

- Setup MFE as given below and click on **Apply** button.
- After optimization, it is clear that the distance betwwen lenses must be *t* = 209.563 mm.



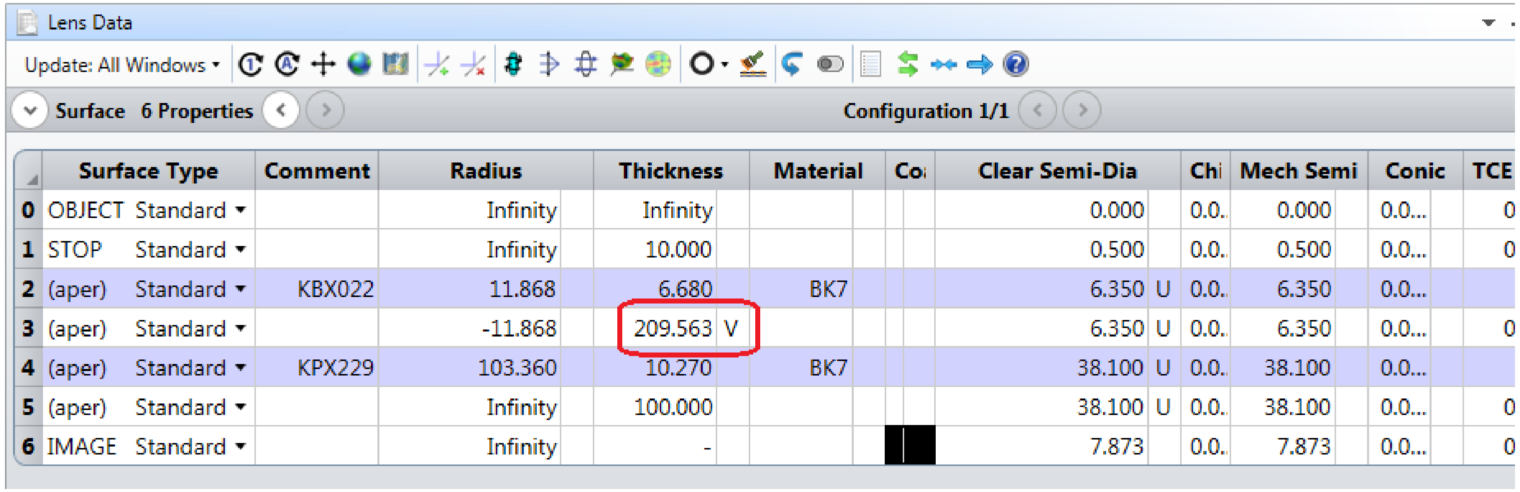
Merit Function: 9999999736.09488

Image Quality: Wavefront
Spatial Frequency: 30
X Weight: 1
Y Weight: 1
Type: RMS
Reference: Centroid
☐ Max Distortion (%): 1
☐ Ignore Lateral Color

● Gaussian Quadrature
○ Rectangular Array
Rings: 3
Arms: 6
Obscuration: 0

☐ Glass Min: 0
Max: 1e+03
Edge Thickness: 0
☐ Air Min: 0
Max: 1e+03
Edge Thickness: 0

Start At: 1
Configuration: All
Assume Axial Symmetry

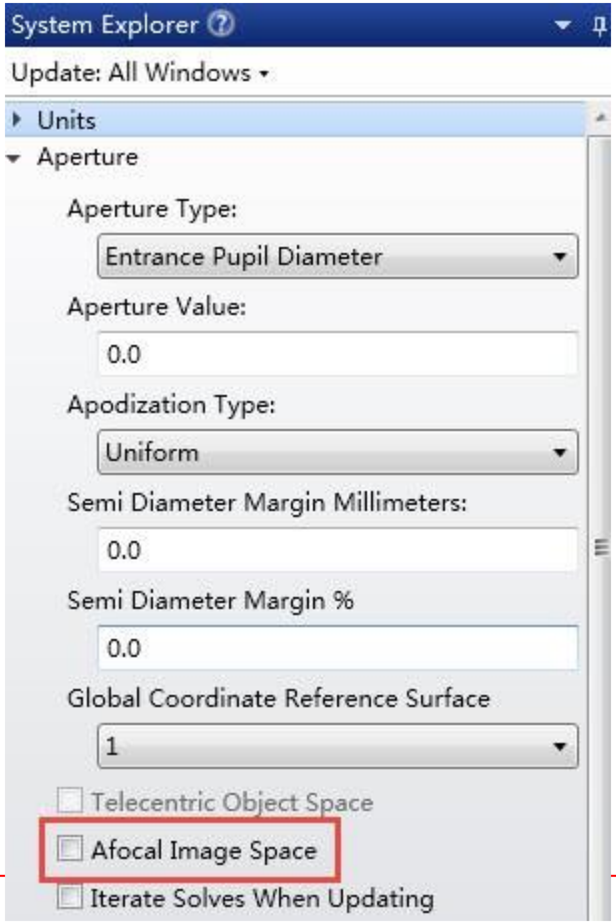


	Surface Type		Comment	Radius	Thickness		Material	Co	Clear Semi-Dia		Chi	Mech Semi	Conic	TCE
0	OBJECT	Standard		Infinity	Infinity				0.000		0.0..	0.000	0.0...	0
1	STOP	Standard		Infinity	10.000				0.500		0.0..	0.500	0.0...	0
2	(aper)	Standard	KBX022	11.868	6.680		BK7		6.350	U	0.0..	6.350	0.0...	
3	(aper)	Standard		-11.868	209.563	V			6.350	U	0.0..	6.350	0.0...	0
4	(aper)	Standard	KPX229	103.360	10.270		BK7		38.100	U	0.0..	38.100	0.0...	
5	(aper)	Standard		Infinity	100.000				38.100	U	0.0..	38.100	0.0...	0
6	IMAGE	Standard		Infinity	-				7.873		0.0..	7.873	0.0...	0

Example: Designing Beam Expander without Lens Catalog

Beam expanders are afocal systems. Afocal systems don’t have an effective focal length and thus provide no net convergence or divergence of the incident light beam.

To enable Afocal Image Space in Zemax, navigate to the System Explorer...Units and check the setting.



System Explorer

Update: All Windows

Units

Aperture

Aperture Type:
Entrance Pupil Diameter

Aperture Value:
0.0

Apodization Type:
Uniform

Semi Diameter Margin Millimeters:
0.0

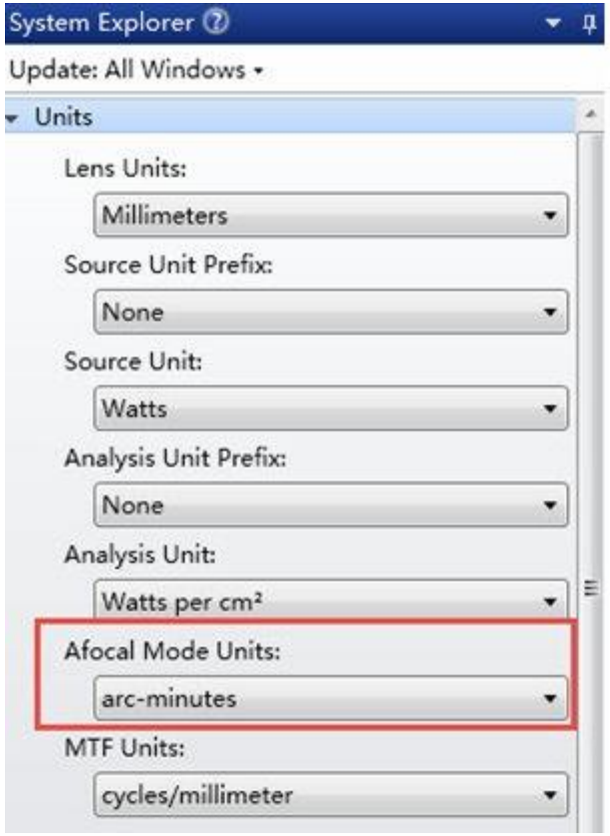
Semi Diameter Margin %
0.0

Global Coordinate Reference Surface
1

☐ Telecentric Object Space

☐ Afocal Image Space

☐ Iterate Solves When Updating



System Explorer

Update: All Windows

Units

Lens Units:
Millimeters

Source Unit Prefix:
None

Source Unit:
Watts

Analysis Unit Prefix:
None

Analysis Unit:
Watts per cm²

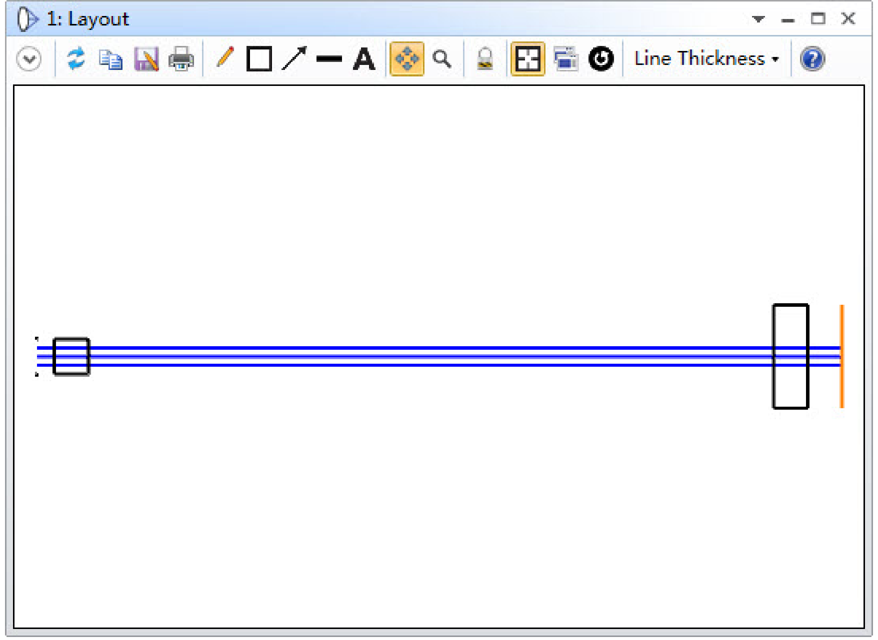
Afocal Mode Units:
arc-minutes

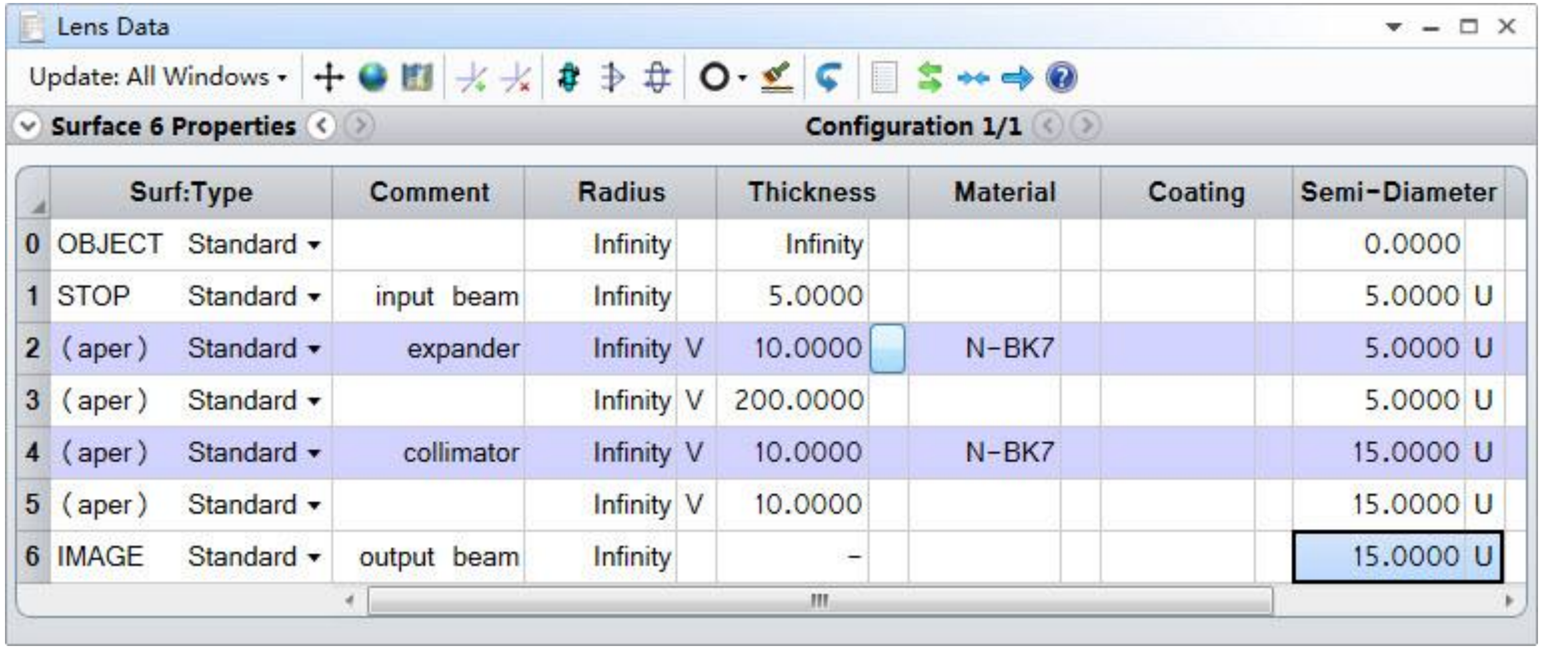
MTF Units:
cycles/millimeter

This is intended to be a 5x beam expander, working at the red He-Ne line, and to have minimum RMS wavefront error.

In the starting design there is no power in the optics and therefore no beam expansion.

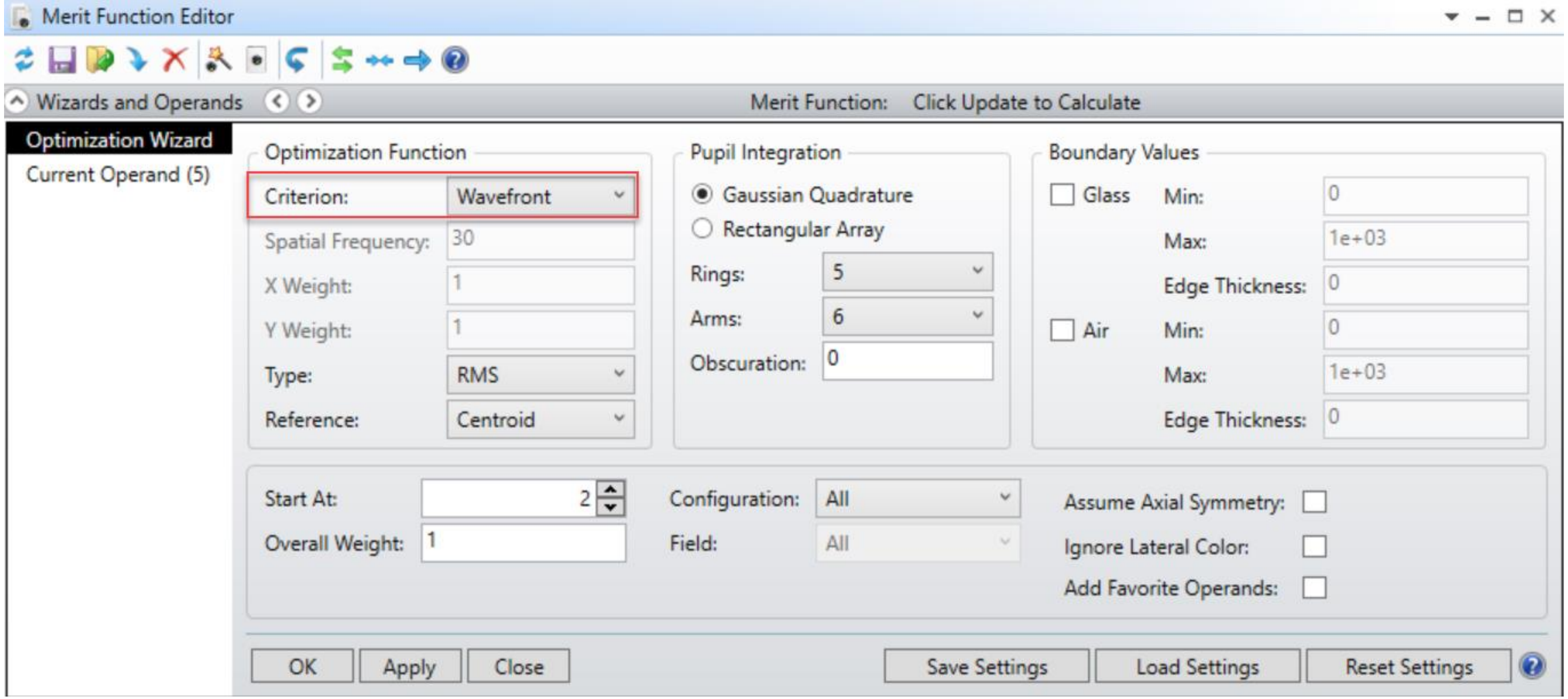
Let EnP = 5 mm





	Surf:Type		Comment	Radius		Thickness	Material	Coating	Semi-Diameter	
0	OBJECT	Standard		Infinity		Infinity			0.0000	
1	STOP	Standard	input beam	Infinity		5.0000			5.0000	U
2	(aper)	Standard	expander	Infinity	V	10.0000	N-BK7		5.0000	U
3	(aper)	Standard		Infinity	V	200.0000			5.0000	U
4	(aper)	Standard	collimator	Infinity	V	10.0000	N-BK7		15.0000	U
5	(aper)	Standard		Infinity	V	10.0000			15.0000	U
6	IMAGE	Standard	output beam	Infinity		-			15.0000	U

Then open the Merit Function via Optimize...Merit Function Editor and select Optimization Wizard from the settings.



Merit Function: Click Update to Calculate

Optimization Function

Criterion: Wavefront

Spatial Frequency: 30

X Weight: 1

Y Weight: 1

Type: RMS

Reference: Centroid

Pupil Integration

● Gaussian Quadrature

○ Rectangular Array

Rings: 5

Arms: 6

Obscuration: 0

Boundary Values

☐ Glass Min: 0

Max: 1e+03

Edge Thickness: 0

☐ Air Min: 0

Max: 1e+03

Edge Thickness: 0

Start At: 2

Overall Weight: 1

Configuration: All

Field: All

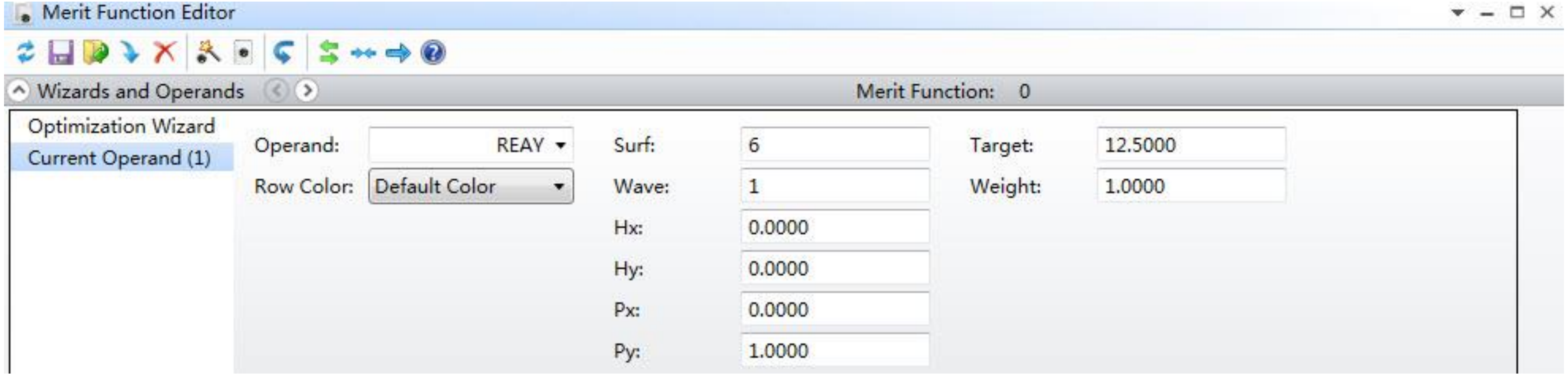
Assume Axial Symmetry: ☐

Ignore Lateral Color: ☐

Add Favorite Operands: ☐

Note that we can build a default Merit Function to minimize wavefront error, spot radius (and X, Y individually) or angular error as a radius or as x and y separately. In this case, we will choose Wavefront, and use 5 rings in the Gaussian Quadrature algorithm because we want a well-corrected system.

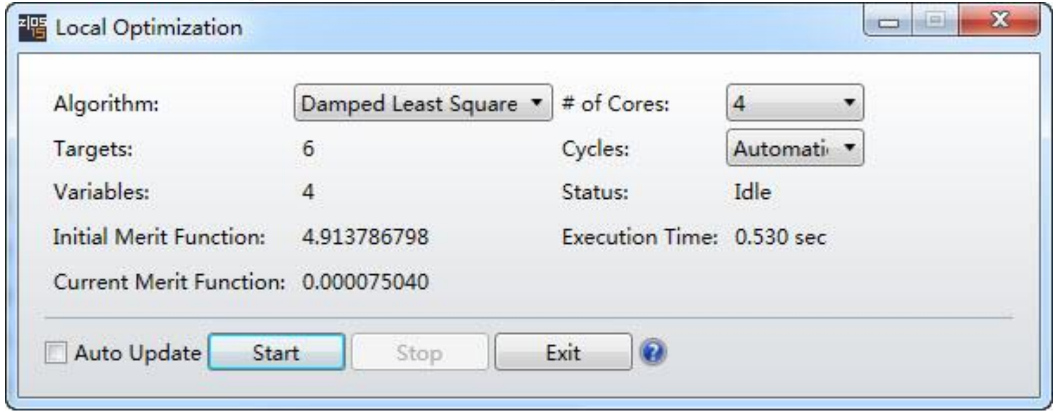
The only extra information OpticStudio needs is the size of the output beam.
The input beam is 5 mm, and the magnification is 5x, so the output beam should have a diameter of 25 mm. Insert a new operand before the DMFS statement in the merit function, and enter the REAY operand as follows:



Merit Function: 0

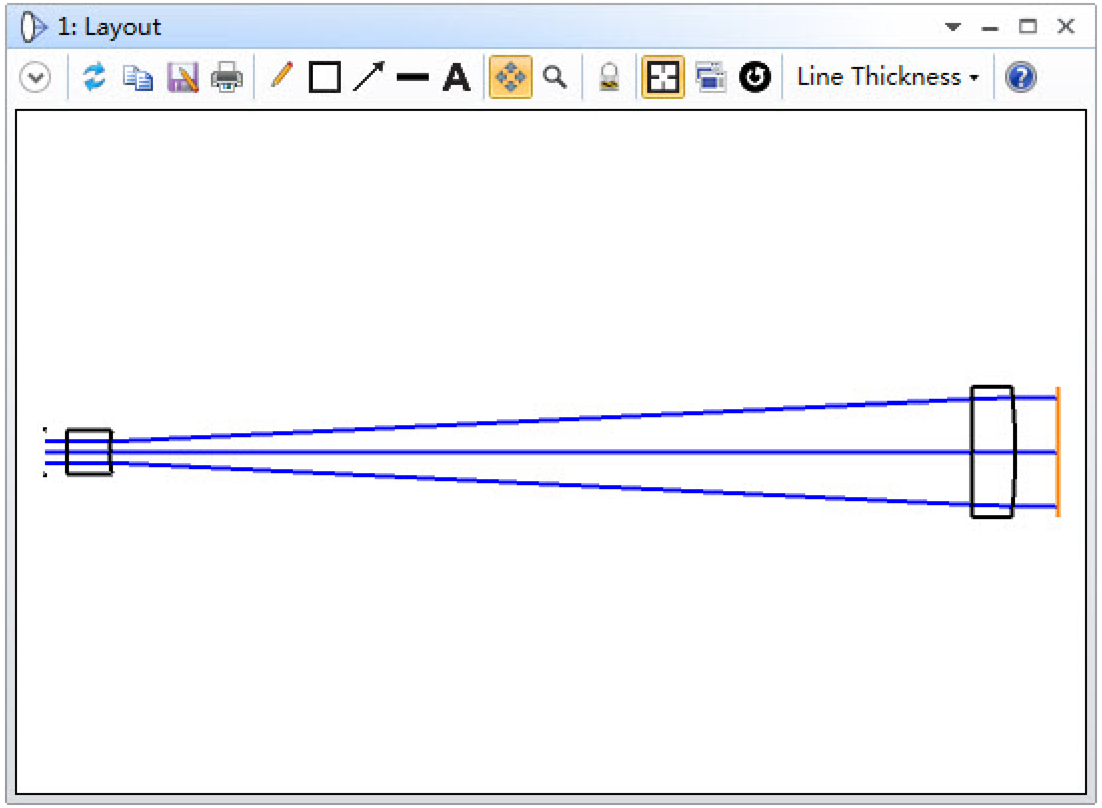
Operand: REAY
Row Color: Default Color
Surf: 6
Wave: 1
Hx: 0.0000
Hy: 0.0000
Px: 0.0000
Py: 1.0000
Target: 12.5000
Weight: 1.0000

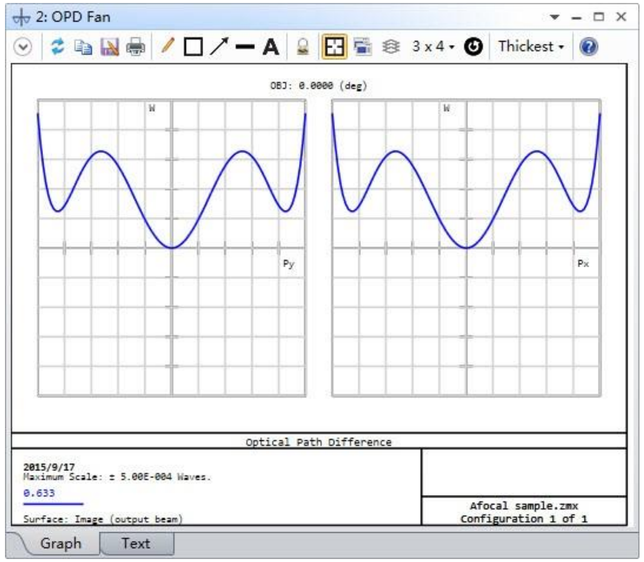
This requires the real ray y-coordinate on surface 6 (the image surface) to have a height of 12.5 mm. Then click Optimize...Optimize! and press the Start button.



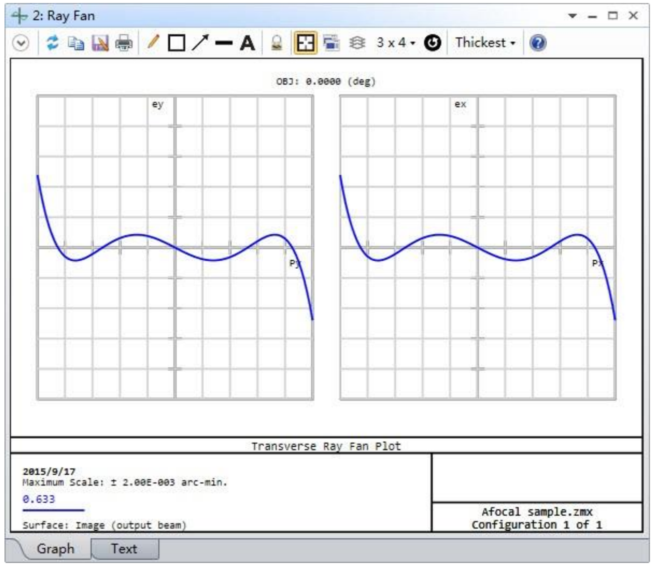
Algorithm: Damped Least Square
Targets: 6
Variables: 4
Initial Merit Function: 4.913786798
Current Merit Function: 0.000075040
# of Cores: 4
Cycles: Automati
Status: Idle
Execution Time: 0.530 sec

OpticStudio quickly optimizes the afocal system.

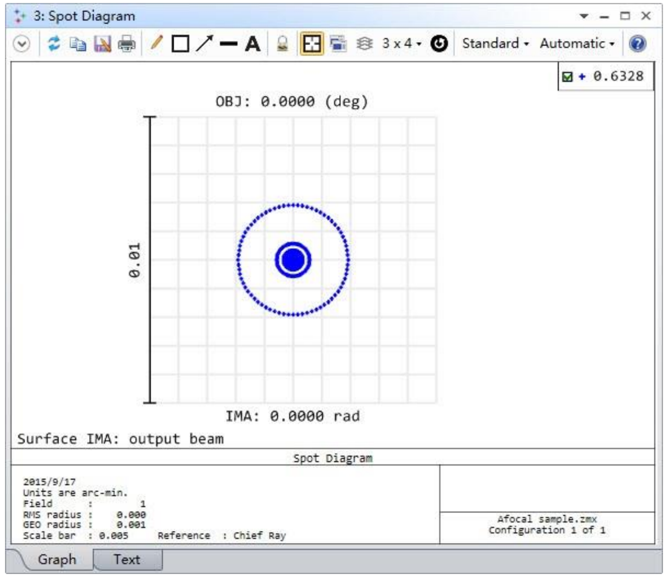




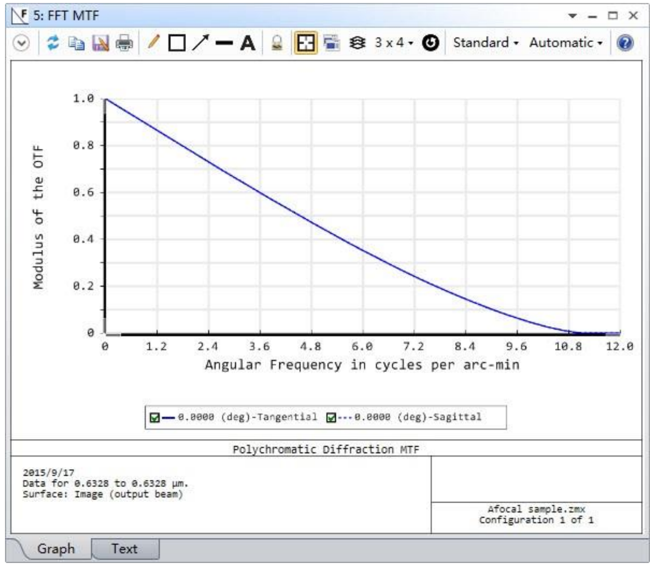
```
Optical Path Difference
2015/9/17
Maximum Scale: ± 5.00E-004 Waves.
0.633
Surface: Image (output beam)
Afocal sample.zmx
Configuration 1 of 1
```



```
Transverse Ray Fan Plot
2015/9/17
Maximum Scale: ± 2.00E-003 arc-min.
0.633
Surface: Image (output beam)
Afocal sample.zmx
Configuration 1 of 1
```



```
Surface IMA: output beam
Spot Diagram
2015/9/17
Units are arc-min.
Field       :        1
RMS radius  :    0.000
GEO radius  :    0.001
Scale bar   : 0.005      Reference   : Chief Ray
Afocal sample.zmx
Configuration 1 of 1
```



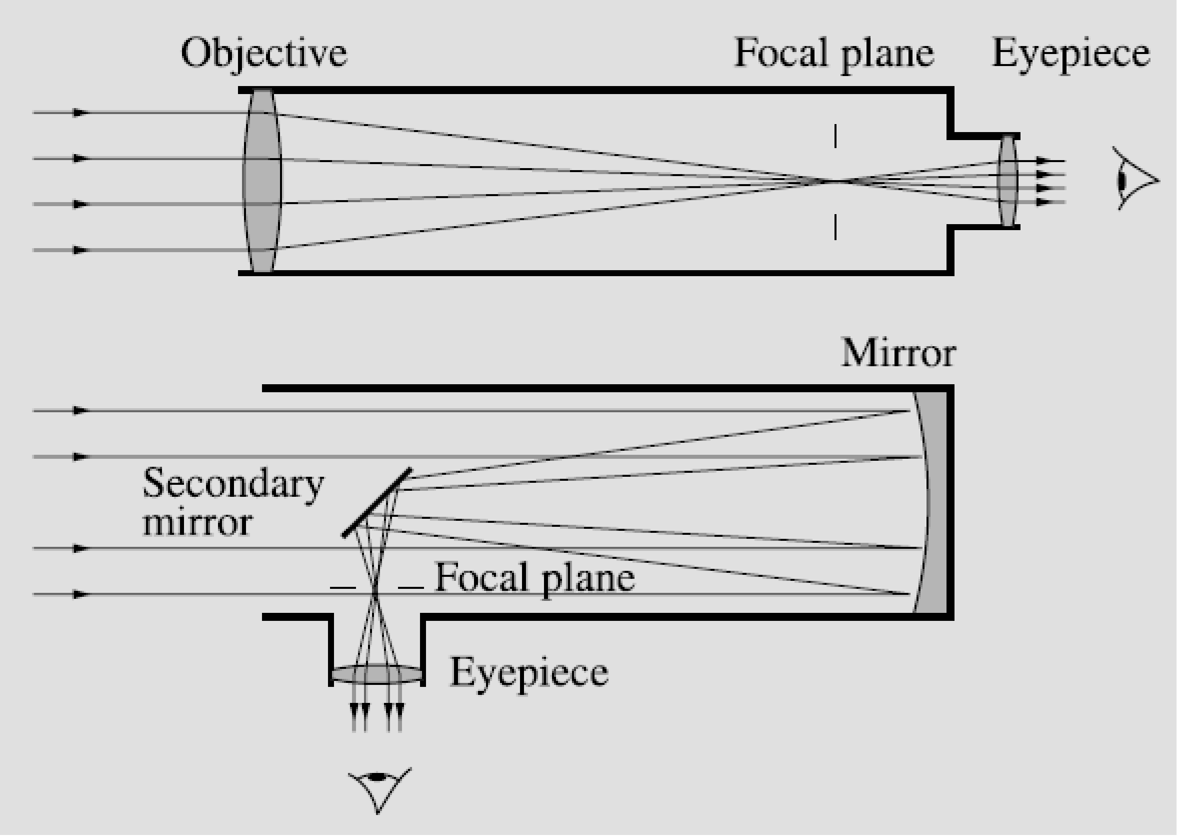
```
Polychromatic Diffraction MTF
2015/9/17
Data for 0.6328 to 0.6328 µm.
Surface: Image (output beam)
Afocal sample.zmx
Configuration 1 of 1
```

Telescopes

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

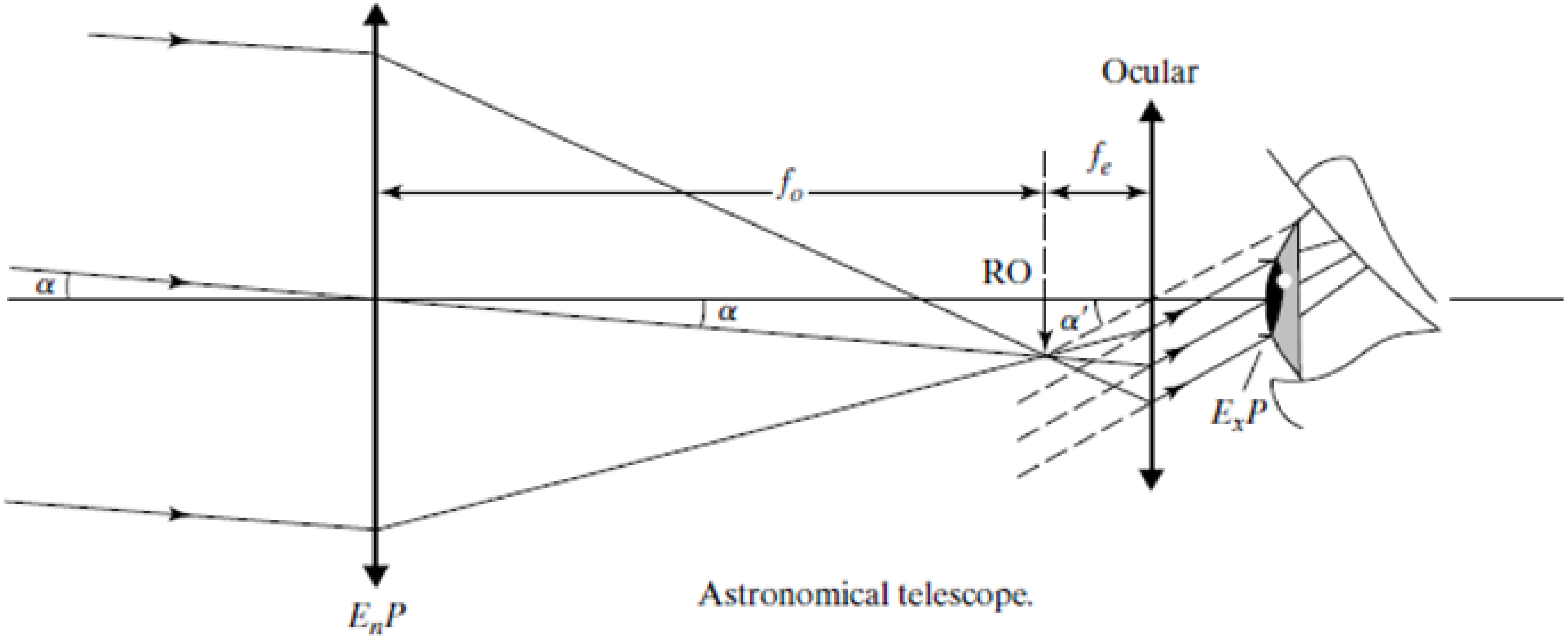
The telescope fulfils three major tasks in astronomical observations:

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

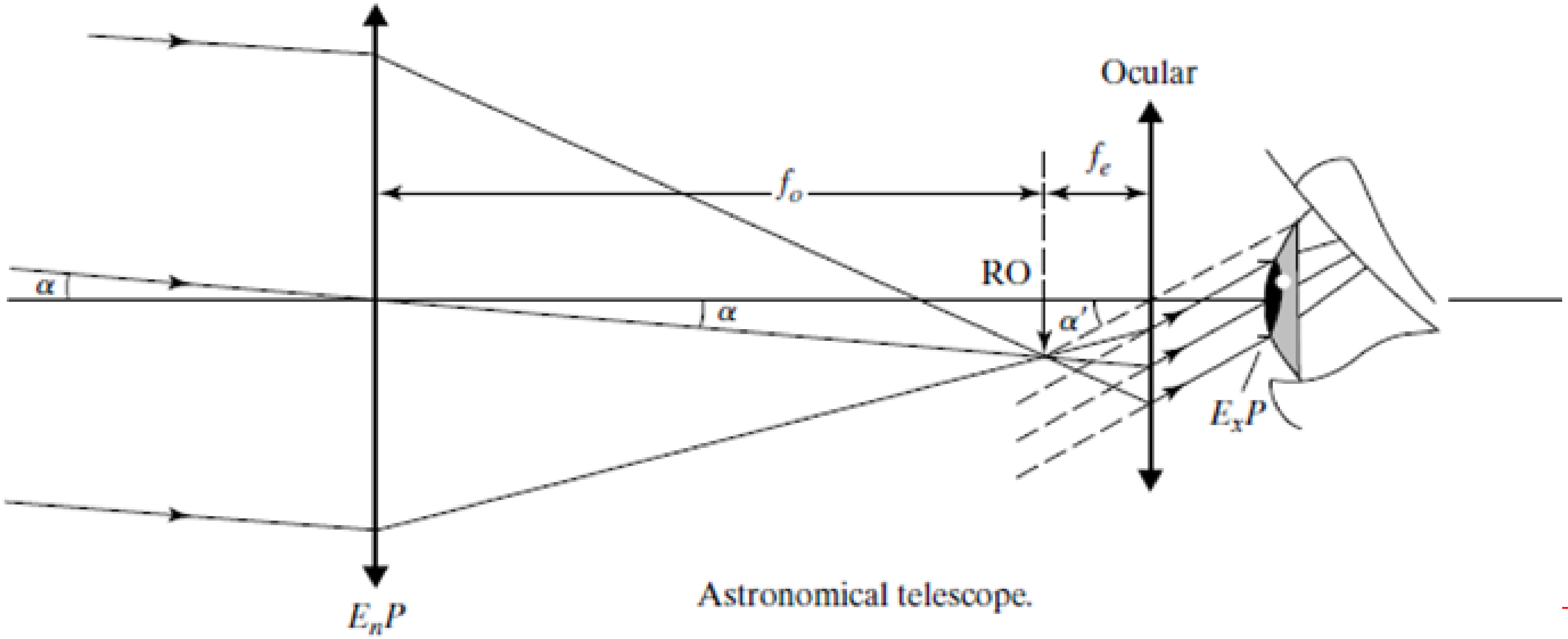
It has two lenses:

- 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.

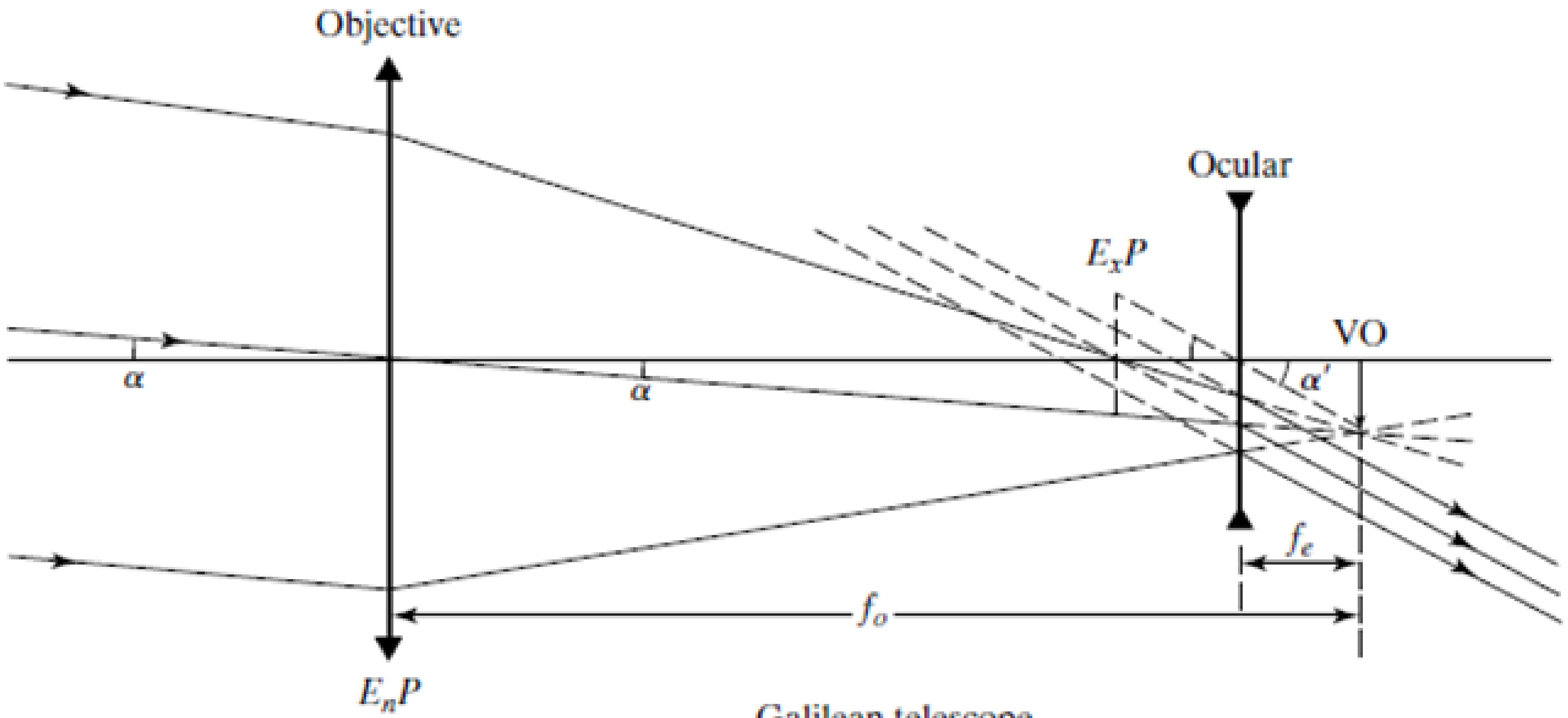
- The diameter of the objective, D_{EnP}, is called the *Aperture* or *Entrance Pupil (EnP)* of the telescope.
- *Exit Pupil (ExP)* of the telescope is the diameter of the output light rays. *ExP* of a telescope is usually selected as the sizeof human pupil (2 mm in daylight and 8 mm in dark). We desire: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

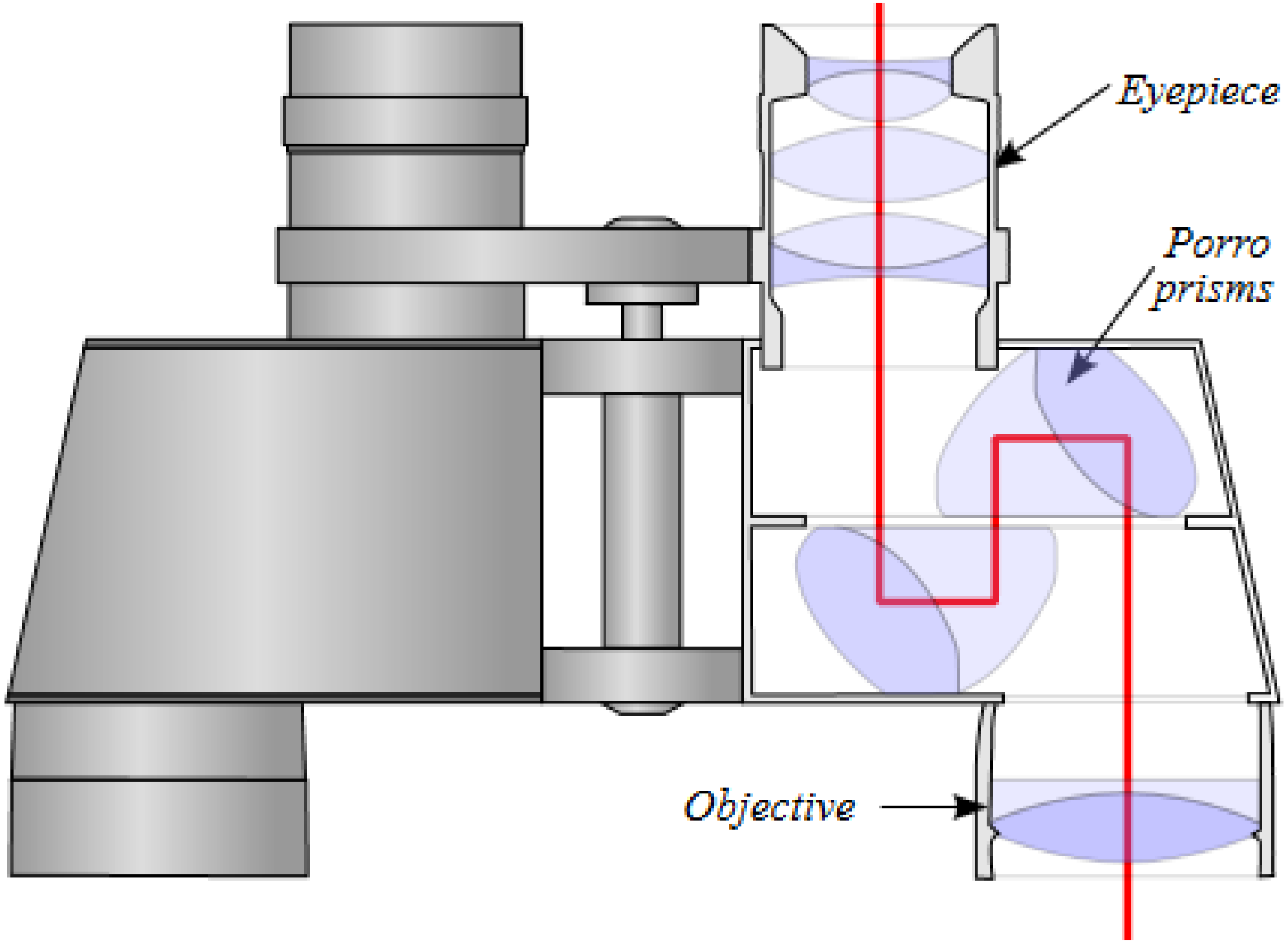


Galilean telescope.

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

Reflection 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.

Reflection 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.

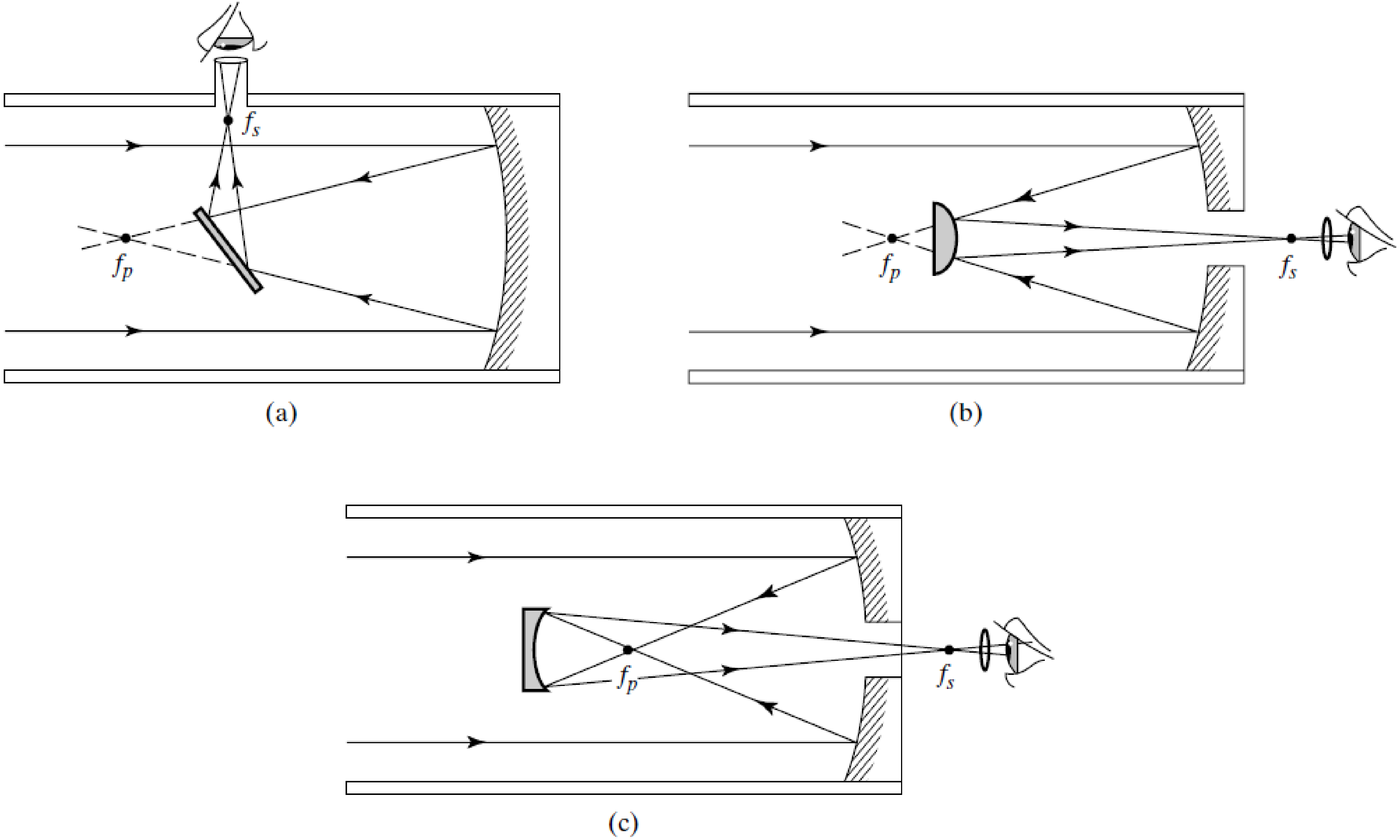


Figure 34 Basic designs for reflecting telescopes. (a) Newtonian telescope. (b) Cassegrain telescope. (c) Gregorian telescope.

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

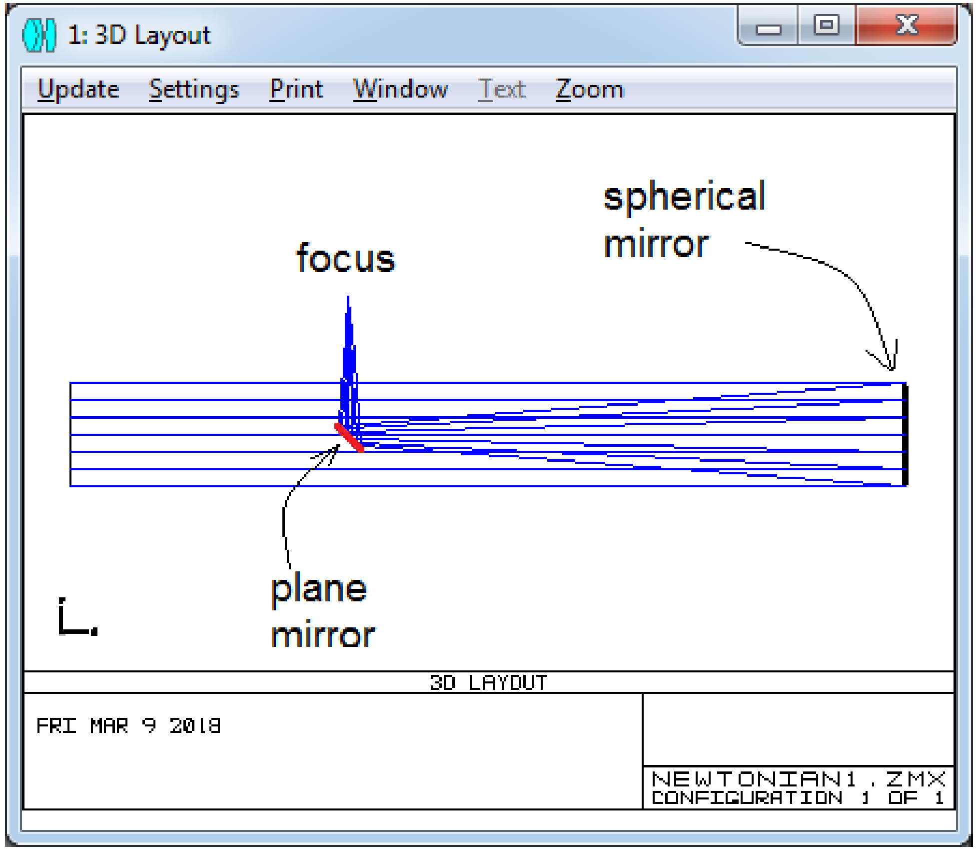
(a) In Zemax, fulll the simulation of the Newtonian Telescope; one concave mirror and one flat mirror. Let the entrance pupil 150 mm, radius of curvature of the mirror is |R| = 1.5 m and the distance between primary and secondary mirror is 0.6 m. Image plane is placed at a distance 0.2 m from the flat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

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

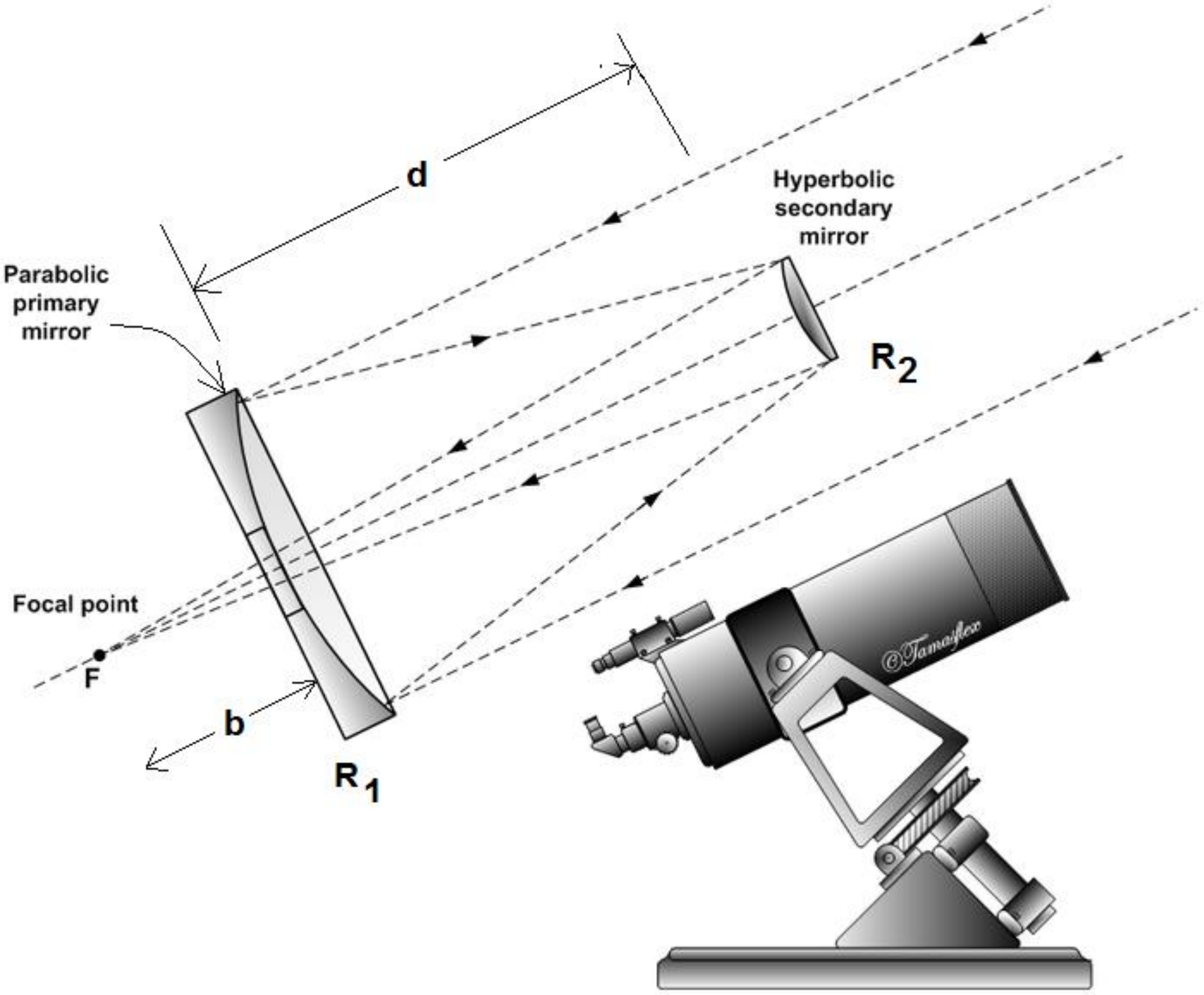
(c) What is the dimension of secondary mirror?

(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

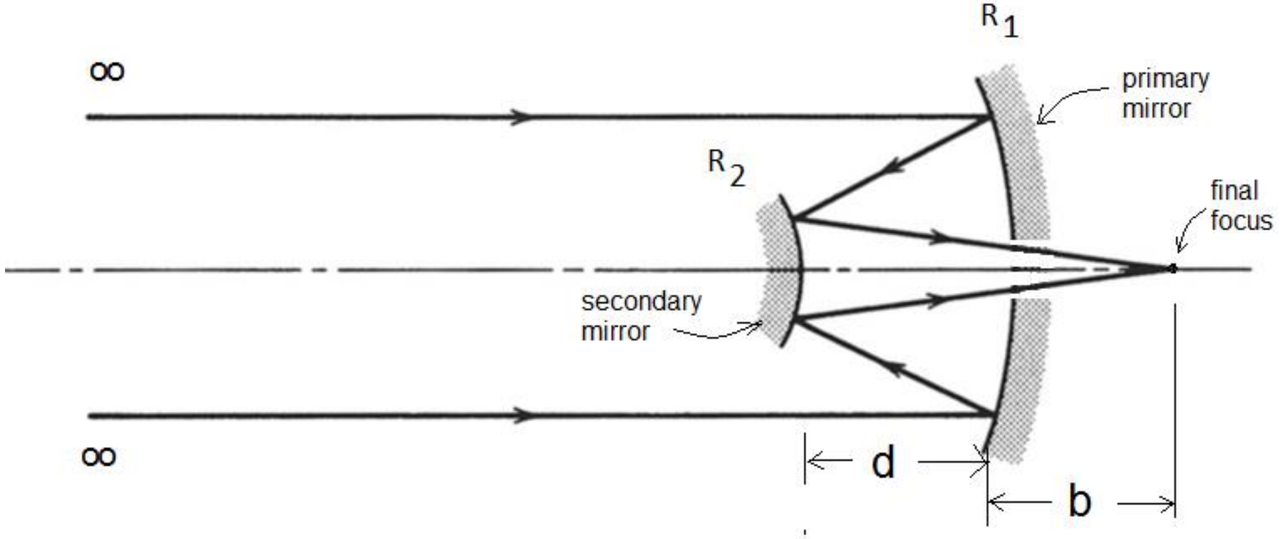
d = distance between mirrors

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:

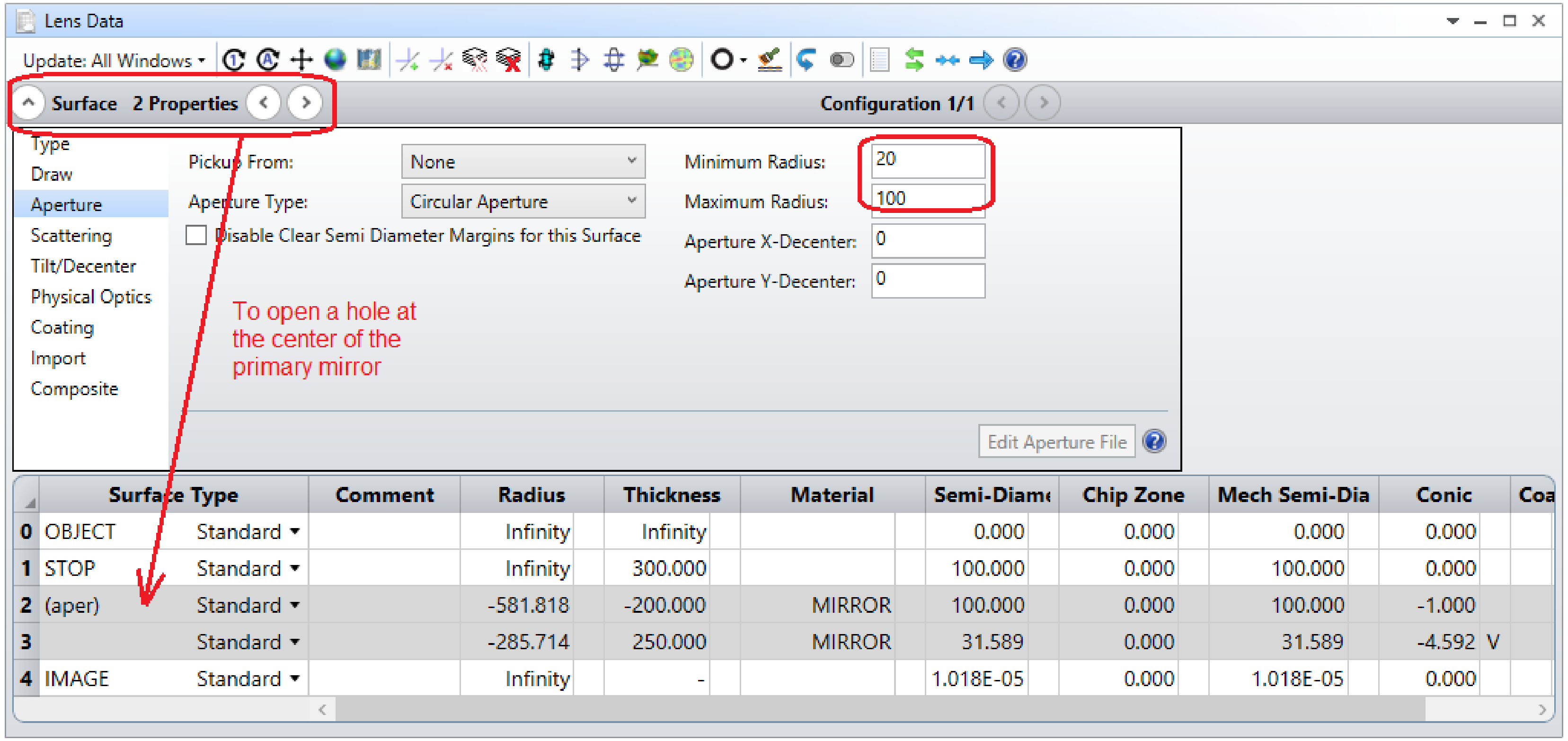
$$\frac{1}{800} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{200}{f_1 f_2} \qquad 250 = 800\left(1 - \frac{200}{f_1}\right)$$

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

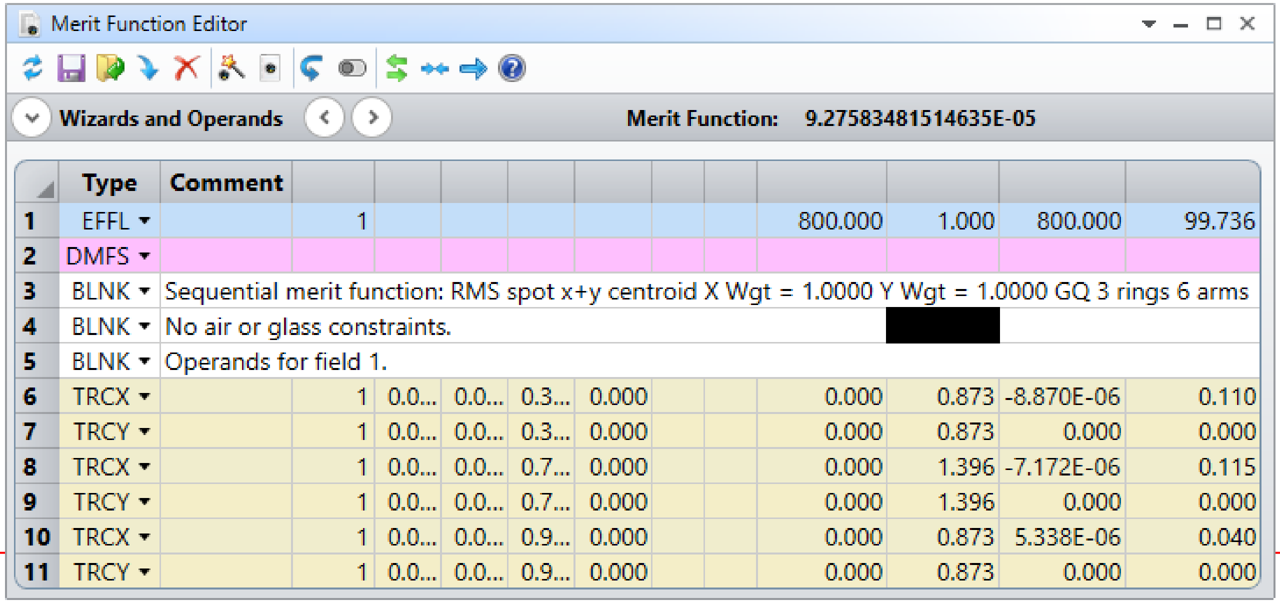
Maximum Radius: 100

Aperture X-Decenter: 0

Aperture Y-Decenter: 0

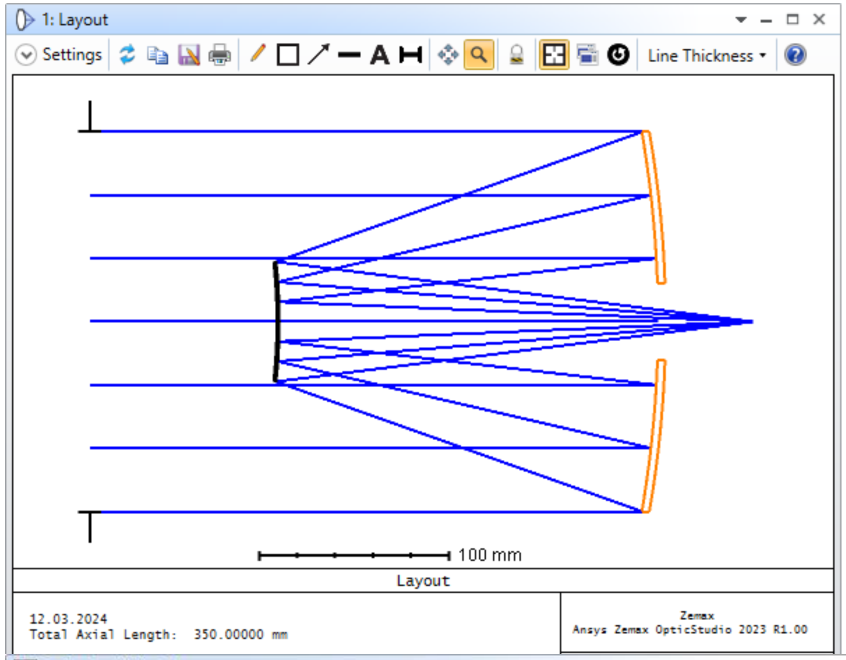
To open a hole at the center of the primary mirror

	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	



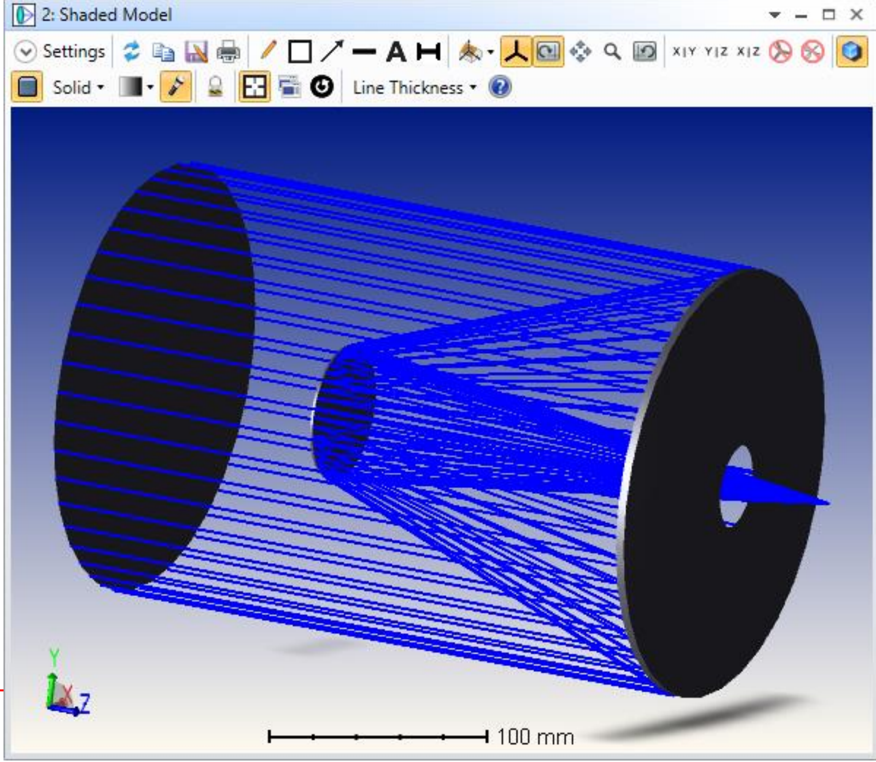
Merit Function: 9.27583481514635E-05

	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



12.03.2024
Total Axial Length: 350.00000 mm

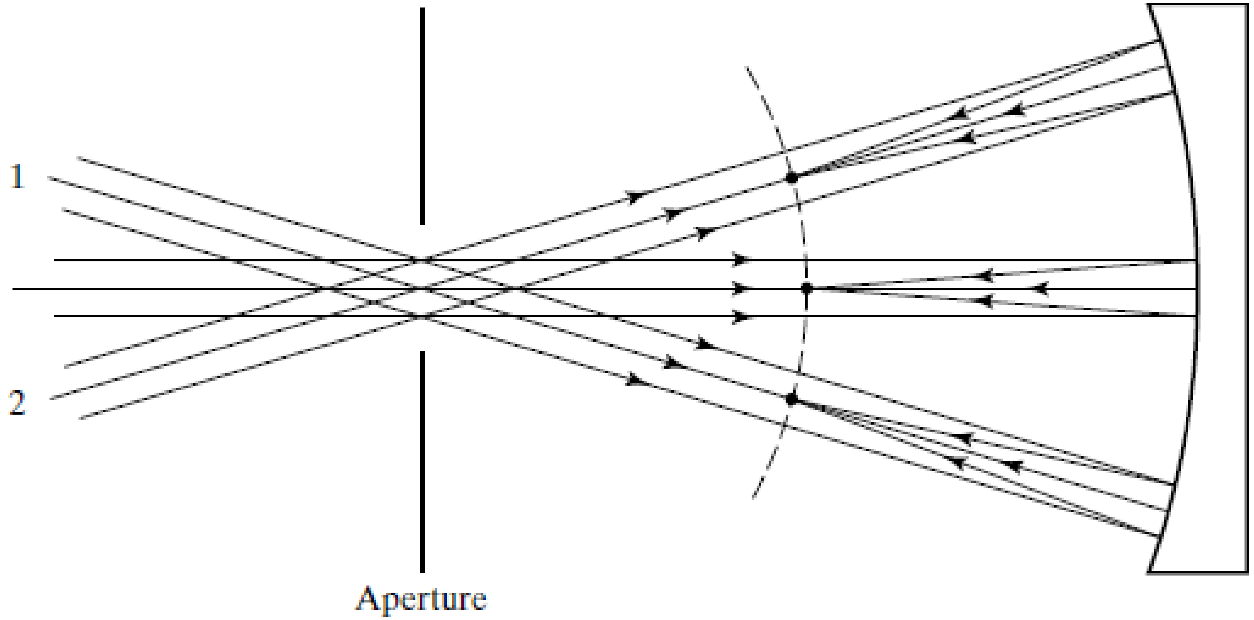
Zemax
Ansys Zemax OpticStudio 2023 R1.00



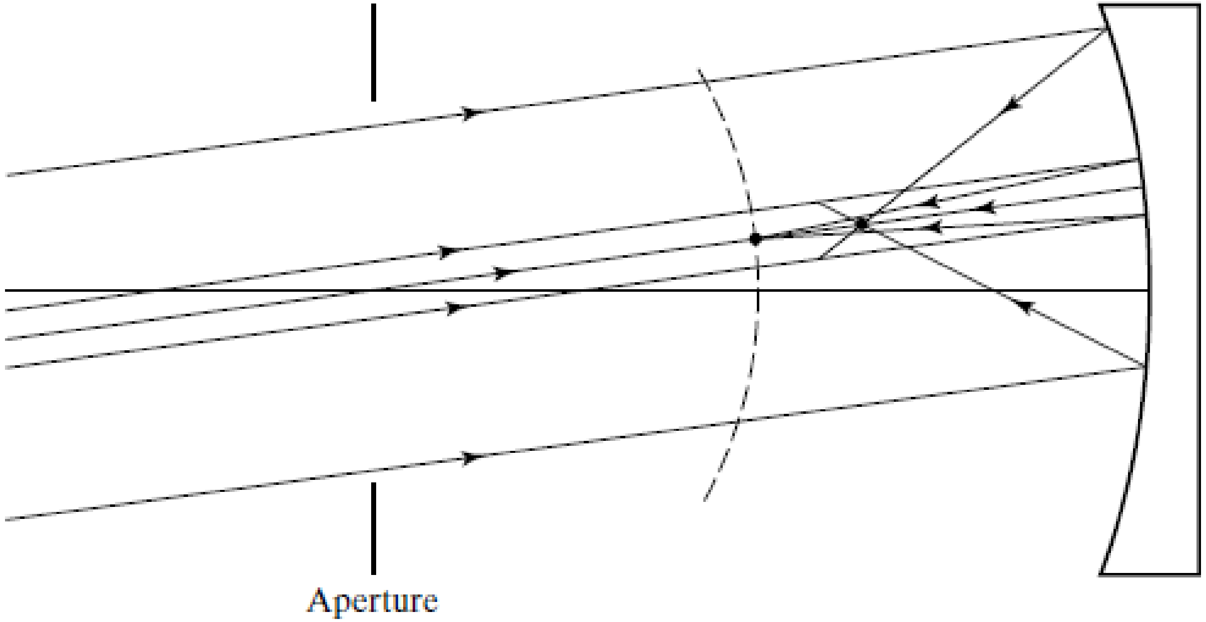
Catadioptric Telescopes

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.

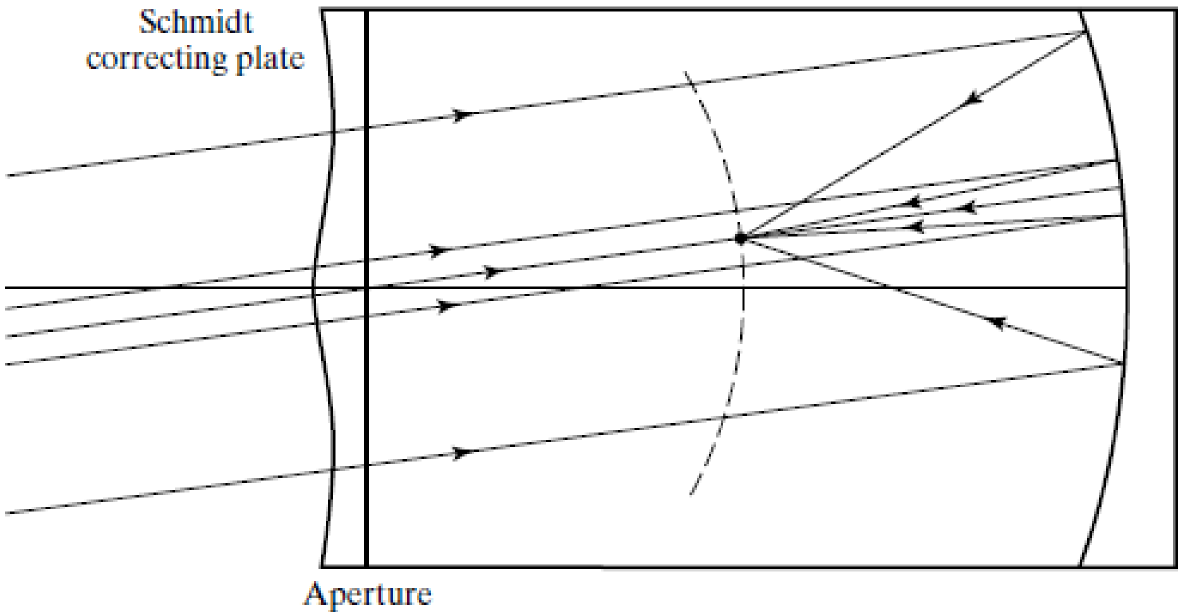
Perhaps the most celebrated catadioptric telescope is due to a design of Bernhardt Schmidt. He sought to remove the spherical aberration of a primary spherical mirror by using a thin refracting correcting plate at the aperture of the telescope.



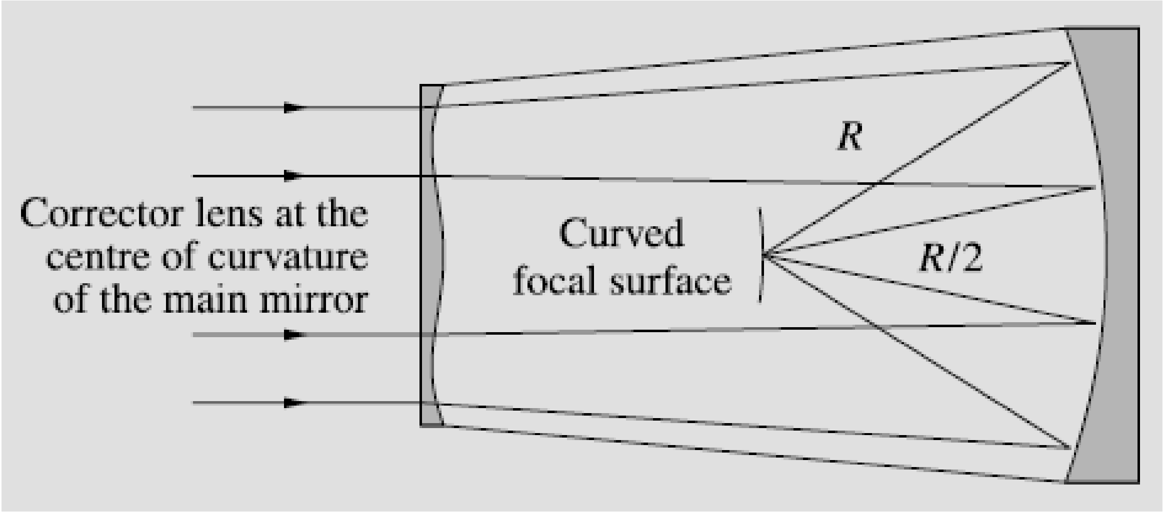
(a)



(b)



(c) The Schmidt optical system.

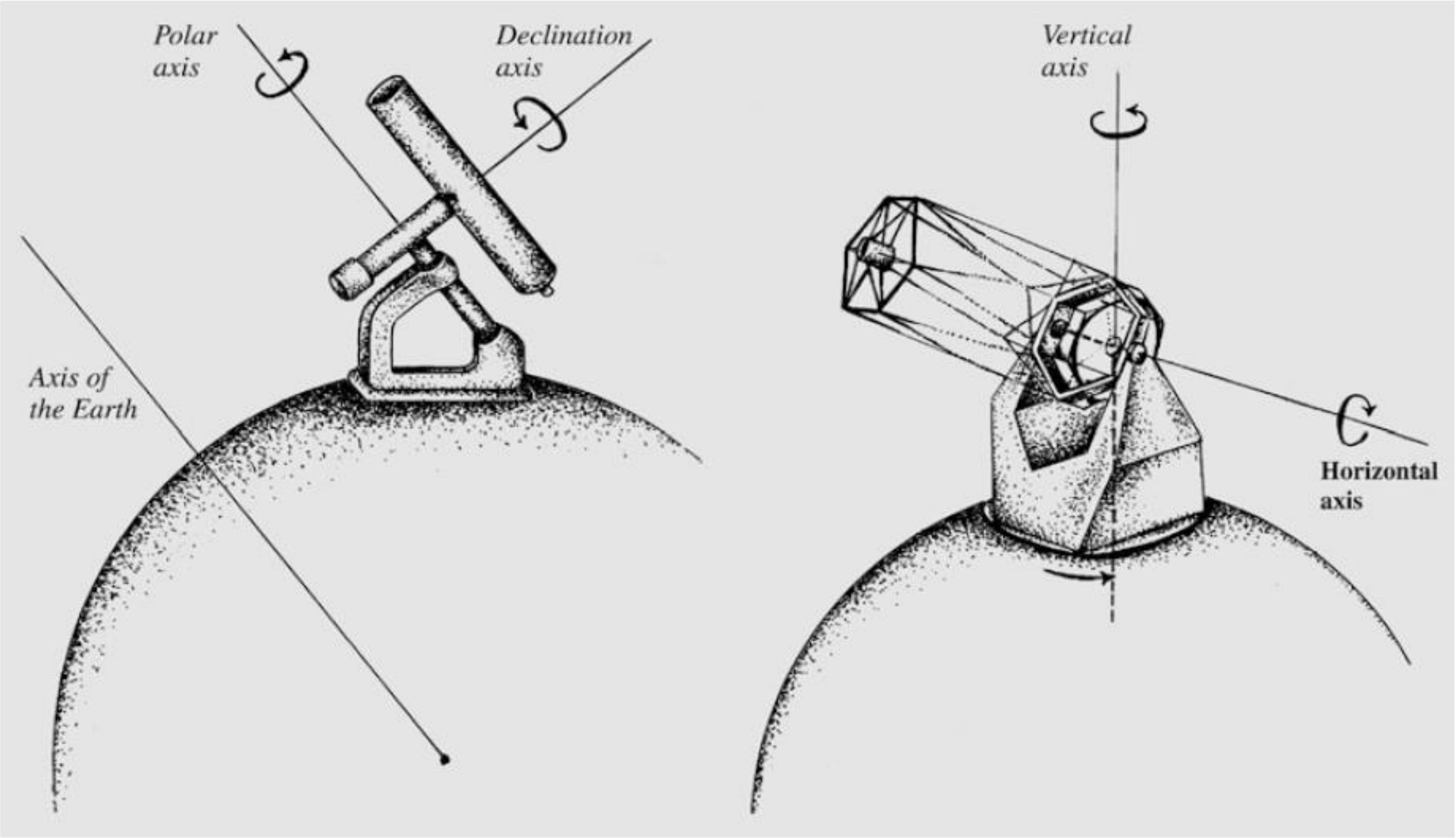


The principle of the Schmidt camera. A correcting glass at the centre of curvature of a concave spherical mirror deviates parallel rays of light and compensates for the spherical aberration of the spherical mirror. (In the figure, the form of the correcting glass and the change of direction of the light 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*)