Properties of optical instruments

Visual optical systems
part 1: afocal systems (telescope type)

A basic optical description of the eye

Power: 60 diopters (at rest)

Equivalent to a single spherical surface, at 22.3mm from retina

Size of image on retina depends only on angle θ from the eye

Normal eye: accommodation from 25cm to infinity (4 diopters)

Myopic=near-sighted: from d<25cm to D finite
Hypermetropic=far-sighted: from d>25cm to D<0 (virtual obj)
Presbytic=shorter accommodation length (1/d-1/D<4diopters)

Angular resolution: about 1 or 2 minutes of arc

Lateral resolution=1'$(3.10^{-4}$rad)*25cm=75µm

Entrance pupil: from 1 to 4 mm, typ 2 mm in day vision

Field of view (diameter): 1° if eye fixed, 40 to 50° for mobile eye

Definition of a visual instrument

Image seen comfortably with a normal eye

$\Rightarrow$ Image at infinity

Two types of systems:

- Telescope type (afocal systems, either refractive or reflective): object at infinity
- Microscope type (includes magnifying glass, eyepiece): small object at a finite distance

Characteristics of visual instruments

	Telescope typ instr Object at infinity	***Microscope type instr Object at finite distance***
Size of image (magnification)	Angular magnification G	*Power P, magnifying power G*
Aperture	**Usually entrance pupil is primary lens or mirror** Exit pupil adapted to eye pupil	*Numerical aperture* *often entrance pupil is at infinity (telecentric stop)*
Resolution	Resolution of the eye Diffraction, aberrations	*Transverse resolution, to compare to the naked eye*
Field of view	Internal lenses act as field stop, field lens in eyepiece adapted to eye field of view	*similar*
Depth of field	Connected with resolution by also accommodation of the eye	*similar*

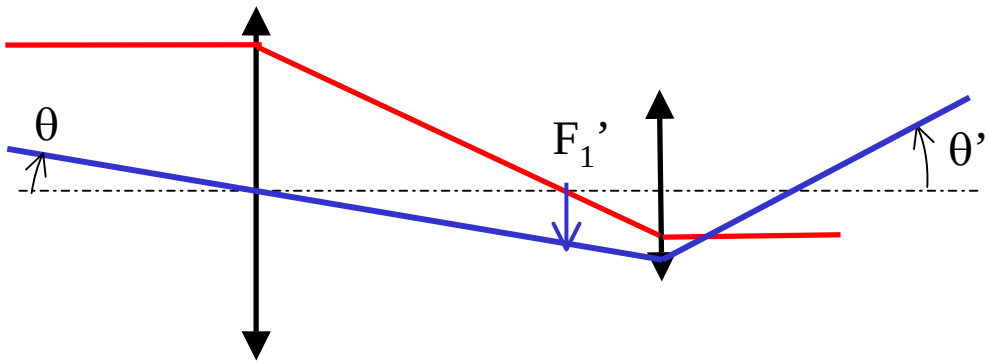
1 - Magnification for telescope type

Object and image at infinity (afocal systems)

Object with angular size θ, Image with angular size θ'

➔ Angular magnification

$$G=\left|\frac{\theta'}{\theta}\right|$$



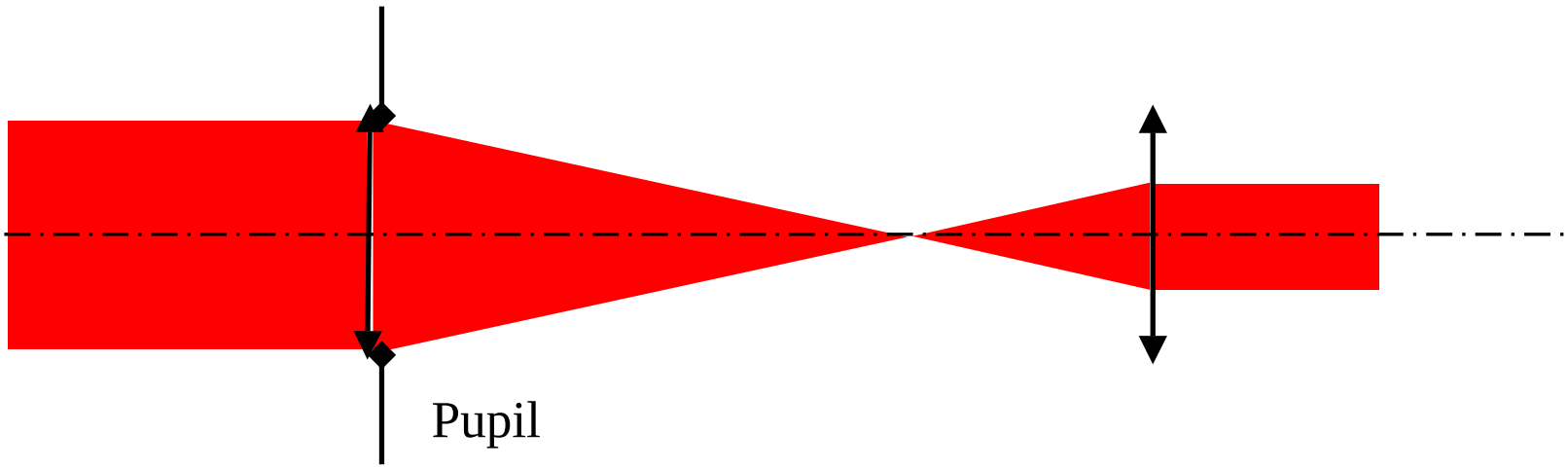
$$G=|g_\alpha|=\frac{1}{|g_y|}=\frac{f_1'}{f_2'}$$

Afocal system: $g_y=-\frac{f'_2}{f'_1}=cst$ $\quad g_x=g_y^2=cst$

2 - Aperture

Pupil (= aperture stop): diaphragm that limits the aperture of a bundle of rays passing through the instrument for an object on axis.

The pupil is defined **for a specific point** on axis (e.g. here at infinity)



Entrance pupil for telescope type

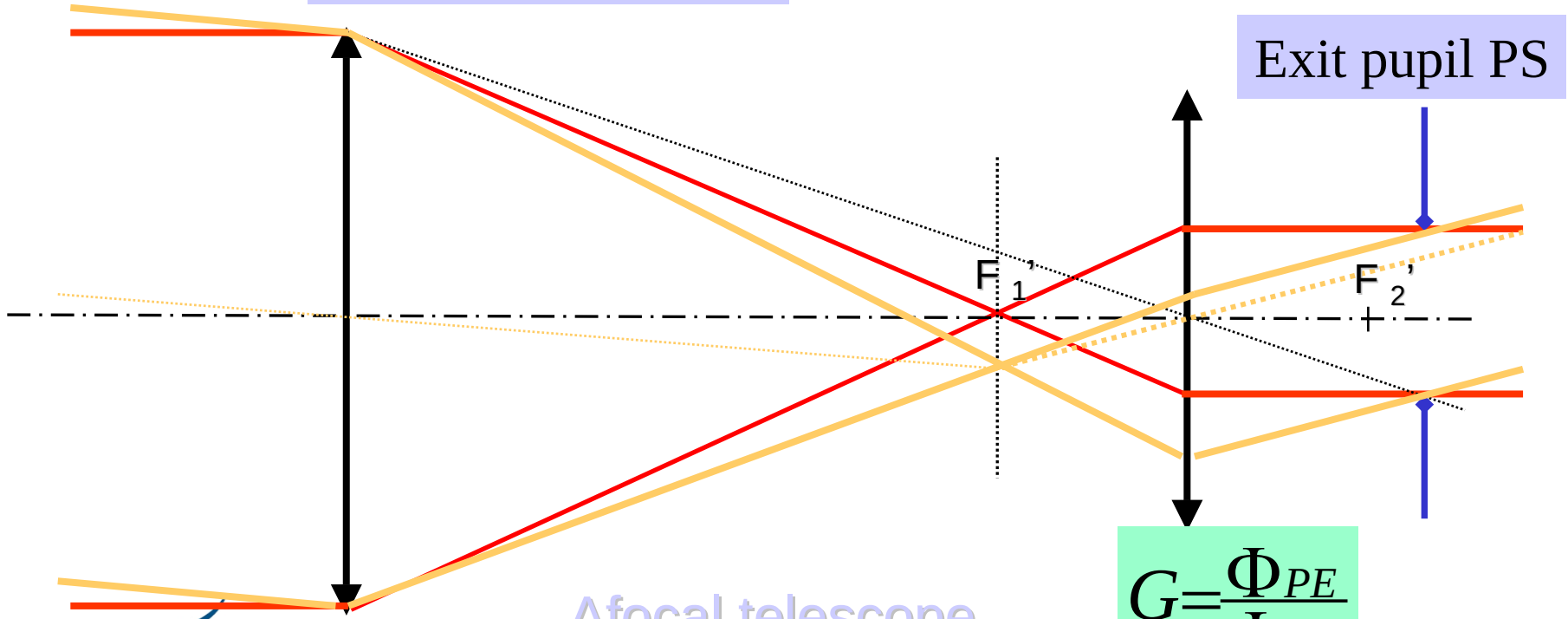
Usually limited by the objective lens diameter

Often written on the instrument such as: **10 x 40**, **4 x 20,…**

G

$Ø_{PE}$ (mm)

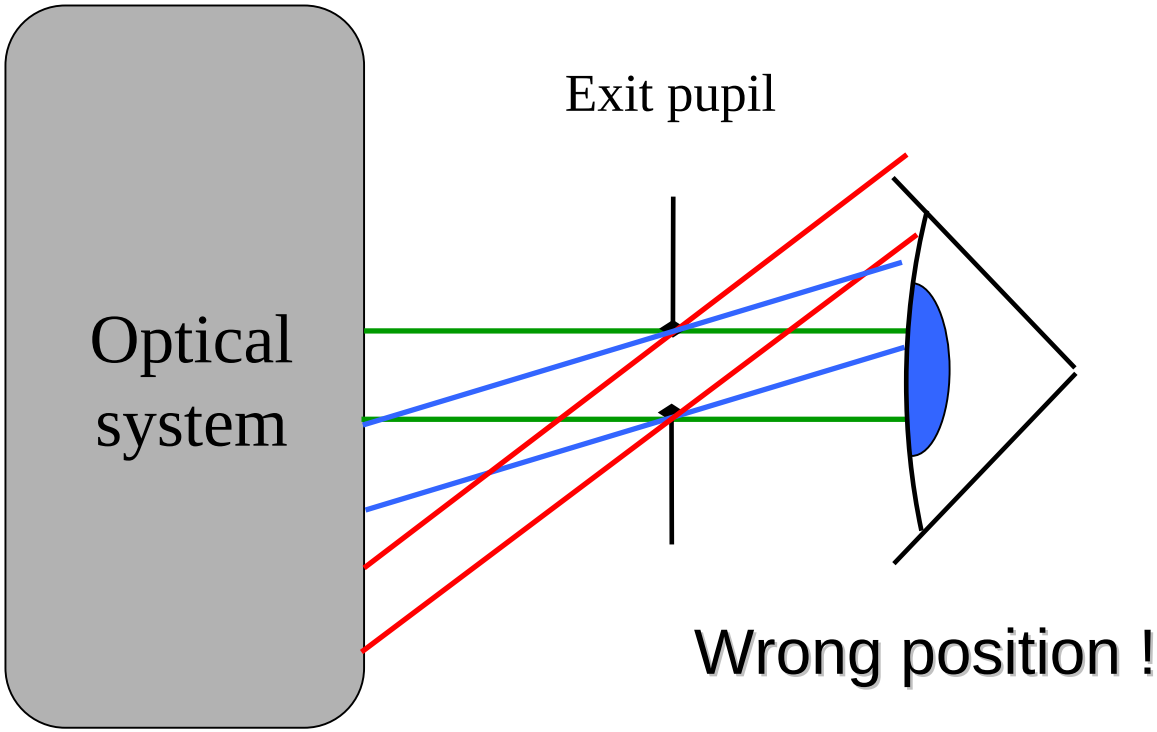
Pupil
= entrance pupil PE



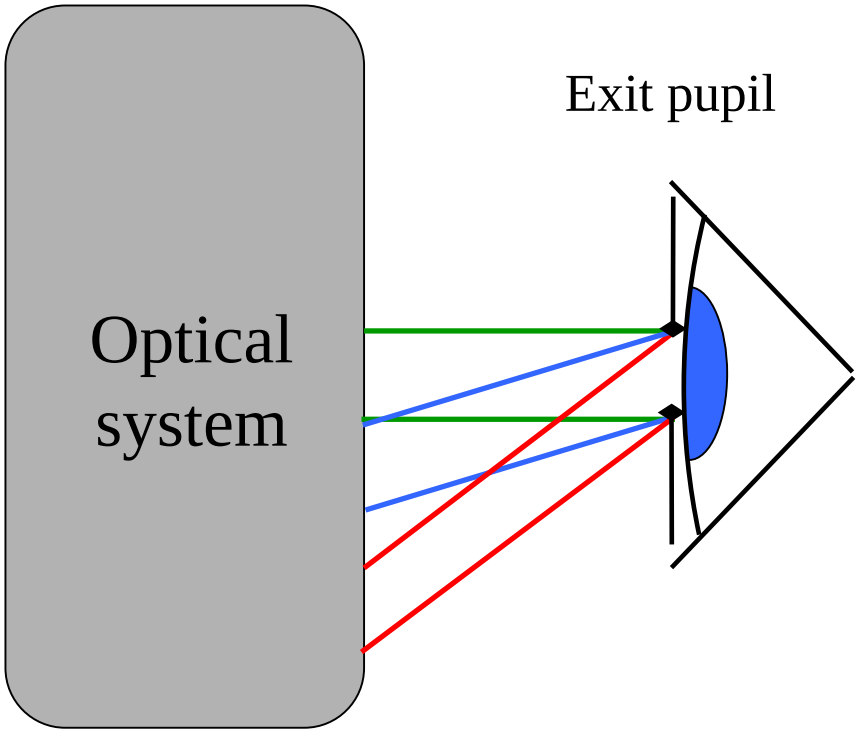
Afocal telescope

$$G = \frac{\Phi_{PE}}{\Phi_{PS}}$$

Position of the eye behind the instrument



Entrance pupil of the eye on the exit pupil of the instrument



3 - Resolution of a visual instrument

The angular resolution of a « standard » naked eye is:

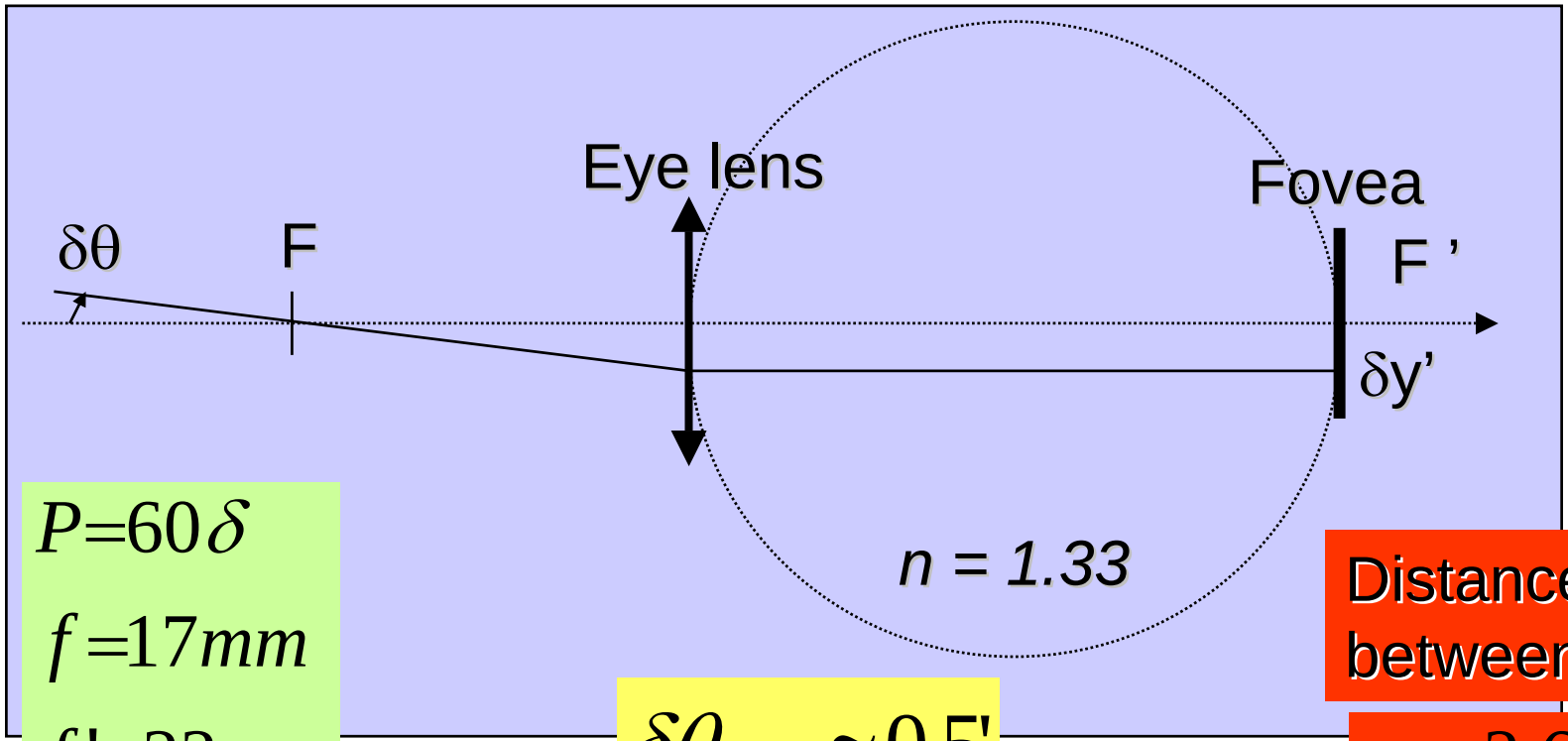
2’

Where does it come from?

How does that affect the resolution of a visual instrument?

Resolution limit of the eye due to the retina's receptors

Simplified EYE



$P = 60\delta$

$f = 17mm$

$f' = 22mm$

$\delta\theta_{1cone} \approx 0.5'$

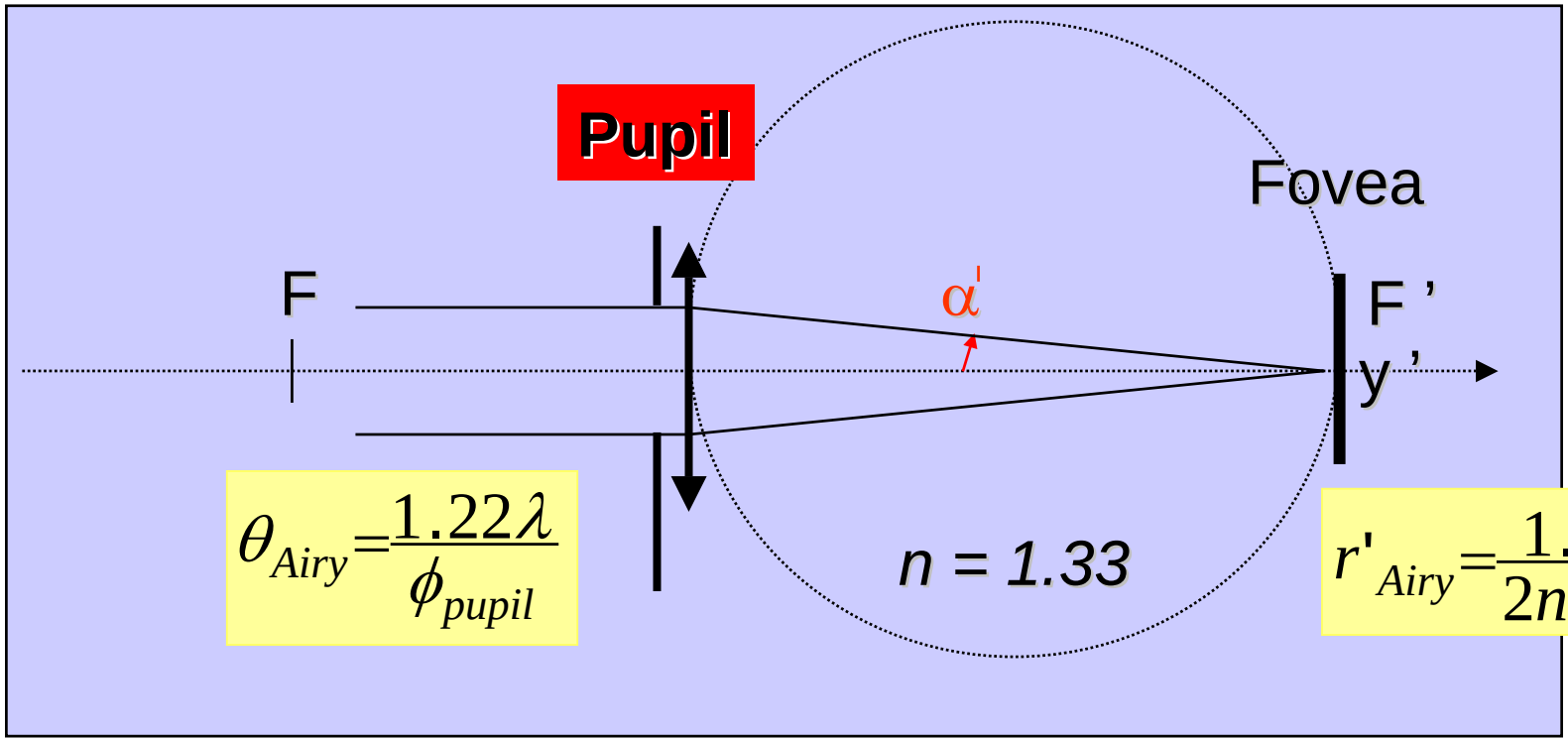
Distance between cones

$g \approx 2.6\mu m$

➡ The visual acuity of 2' corresponds to an image covering several cones

Resolution limit for the eye due to diffraction

Entrance pupil: from 1 to 4 mm, typ 2 mm in day vision



$\Phi_{pupil} = 1mm$ $\theta_{Airy} \approx 2'$ $r'_{Airy} \approx 10\mu m$

➡ The resolution of the eye will be limited by diffraction if we reduce its aperture to a pupil smaller than 1mm

Resolution of a visual instrument

• **if the exit pupil of the instrument is larger than 1 mm, the resolution of the instrument in its object space will be limited by the eye (visual acuity): $2'/G$**

• **if the exit pupil of the instrument is smaller than 1 mm, the resolution of the instrument will be limited by diffraction: $1.22\lambda/\text{Ø}_{PE}$**

For a given entrance pupil, the resolution limit decreases with G (i.e. gets better) until we reach a minimum at $1.22\lambda/\text{Ø}_{PE}$

Example : what is the resolution limit of this astronomical telescope ?

$$\Phi_{pupil}=60mm$$
$$G=35$$
$$\Phi_{PS}=\frac{\Phi_{pupil}}{G}\approx 1.7mm$$

Here the visual acuity limits the resolution: 2 ''/G=3.4''

$$G=70$$
$$\Phi_{PS}=\frac{\Phi_{pupil}}{G}\approx 0.85mm$$

With this eyepiece, the resolution is limited by diffraction (unless aberrations limit it first):

$1.22\lambda/\Phi_{pupil}=2''$

The FirstScope 60AZ Specifications:

- 60mm (2.4") Refractor
- 700mm Focal Length, f/12
- Slow Motion Control Rod for smooth vertical adjustments
- Sturdy Adjustable Aluminum Tripod with Accessory Tray
- Telescope Weight: 7 lb.

The FirstScope 60AZ Standard Accessories:

- 1-1/4" 20mm (35x), 10mm (70x) Eyepieces

4 - Depth of field

In addition to the depth of field due to the resolution:

- **Influence of the accommodation of the eye :**

  normal eye accommodates for 4 diopters

Final image at 250 mm rather than at infinity

$\Rightarrow$ Determine the position of the object corresponding to this location of the image (hyperfocal distance)

Can be improved if we reduce the accommodation with a graticule.

Example of a calculation of the hyperfocal distance due to accommodation

The FirstScope 60AZ Specifications:

- 60mm (2.4") Refractor
- 700mm Focal Length, f/12
- Slow Motion Control Rod for smooth vertical adjustments
- Sturdy Adjustable Aluminum Tripod with Accessory Tray
- Telescope Weight: 7 lb.

The FirstScope 60AZ Standard Accessories:

- 1-1/4" 20mm (35x), 10mm (70x) Eyepieces

$$\overline{F_{oc}'A'} = -250mm$$

$$\overline{F_{oc}'A'} = -f'^{2}_{oc} \Big/ F_{oc}A_i$$

$$\overline{F_{ob}A} = -f'^{2}_{ob} \Big/ F'_{ob}A_i$$

eyepiece : 20mm

$$\overline{F_{ob}A} = -300m$$

eyepiece : 10mm

$$\overline{F_{ob}A} = -1200m$$

INSTITUT d'OPTIQUE GRADUATE SCHOOL

Comparison with the hyperfocal distance limited by the resolution

Resolution in the object space: $\delta\theta$

The FirstScope 60AZ Specifications:

- 60mm (2.4") Refractor
- 700mm Focal Length, f/12
- Slow Motion Control Rod for smooth vertical adjustments
- Sturdy Adjustable Aluminum Tripod with Accessory Tray
- Telescope Weight: 7 lb.

Hyperfocal distance:
$D=Ø_{PE}/\delta\theta$

eyepiece : 20mm (G=35)
$\delta\theta=2'/G=3.2"$
D=3.5km

eyepiece : 10mm (G=70)
$\delta\theta=1.22\lambda/ Ø_{PE} =2"$
D≈6km

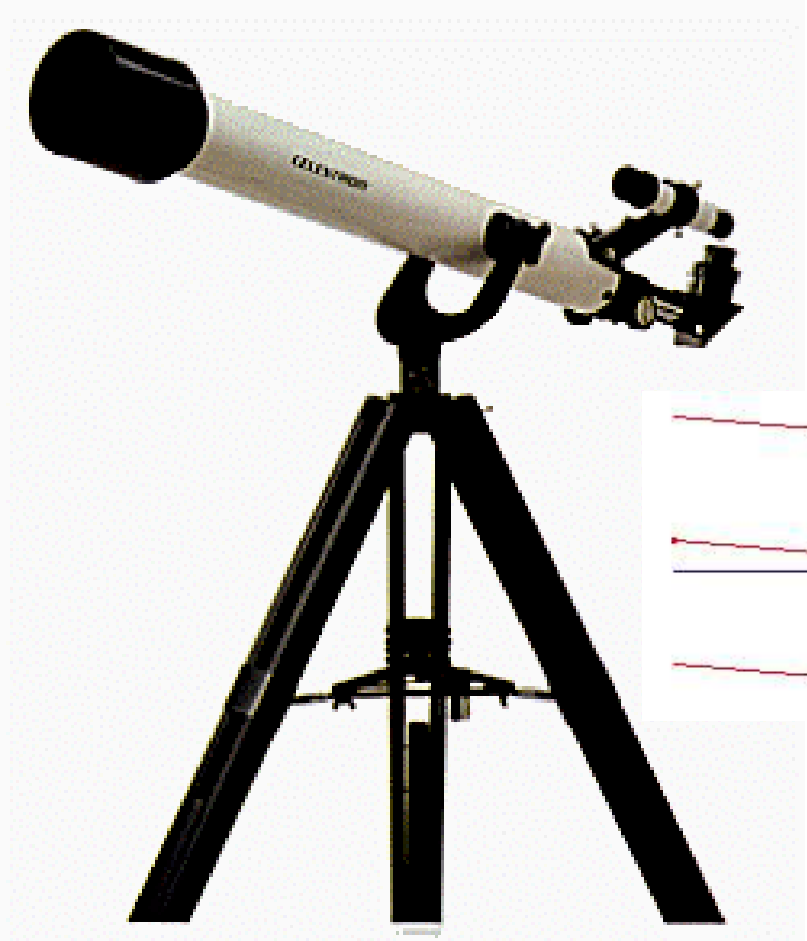
The FirstScope 60AZ Standard Accessories:

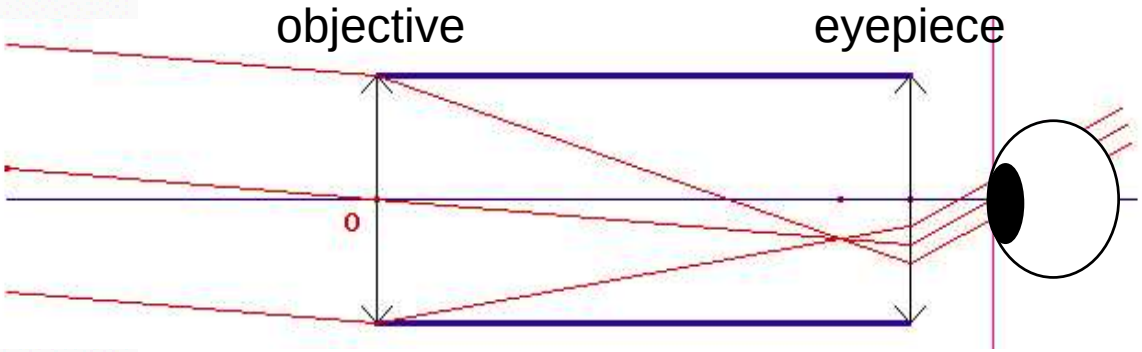
- 1

➡ The depth of field is due to the accommodation

5 – Orientation of the image

In a standard astronomical telescope:



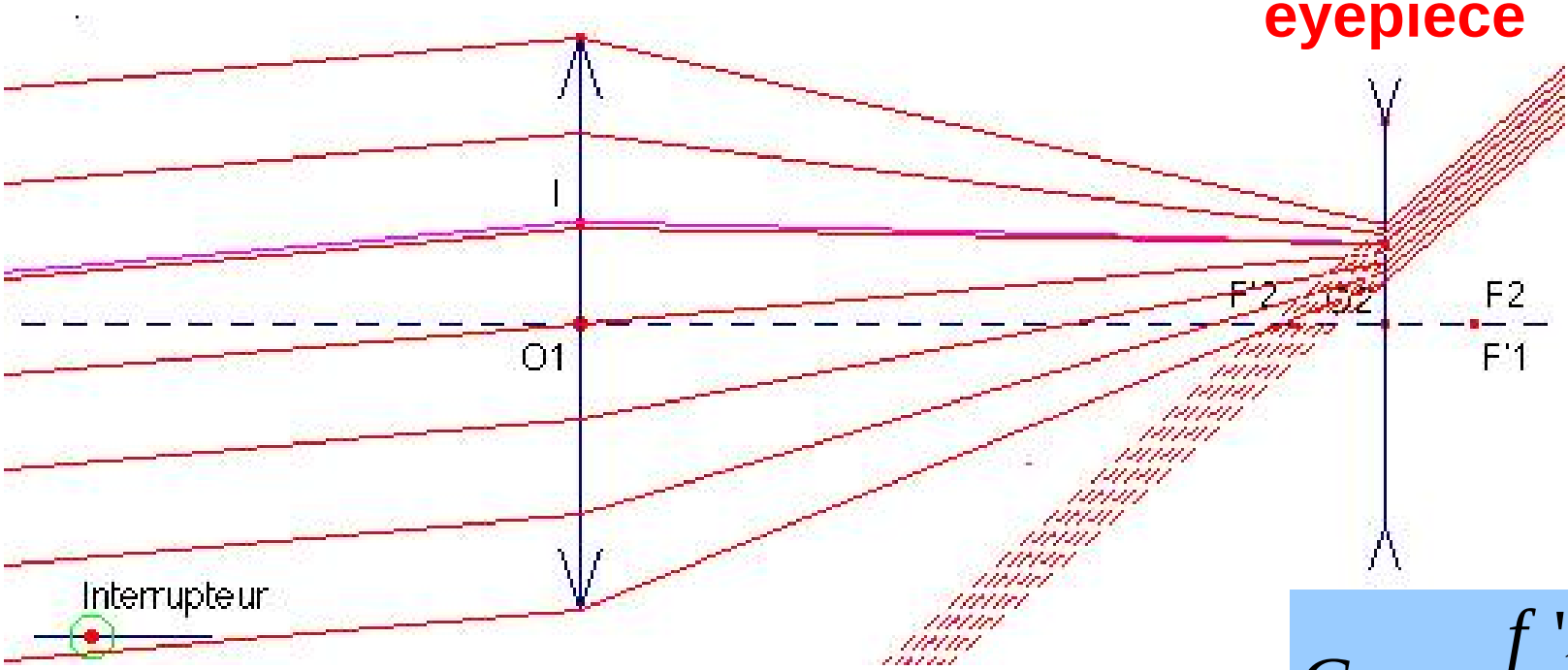


The image is inverted!

Different solutions to erect the image:

Galilean telescope

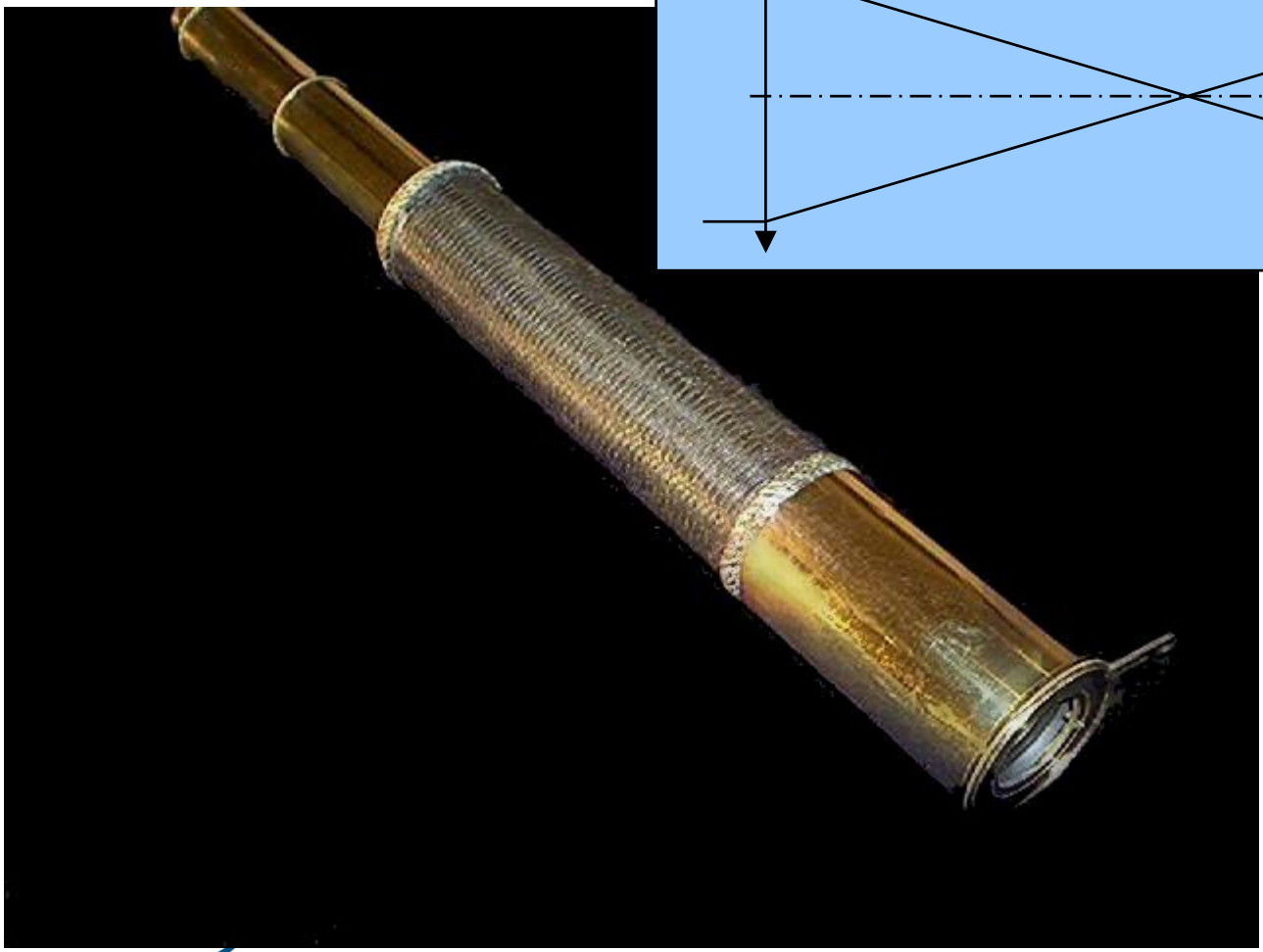
negative eyepiece

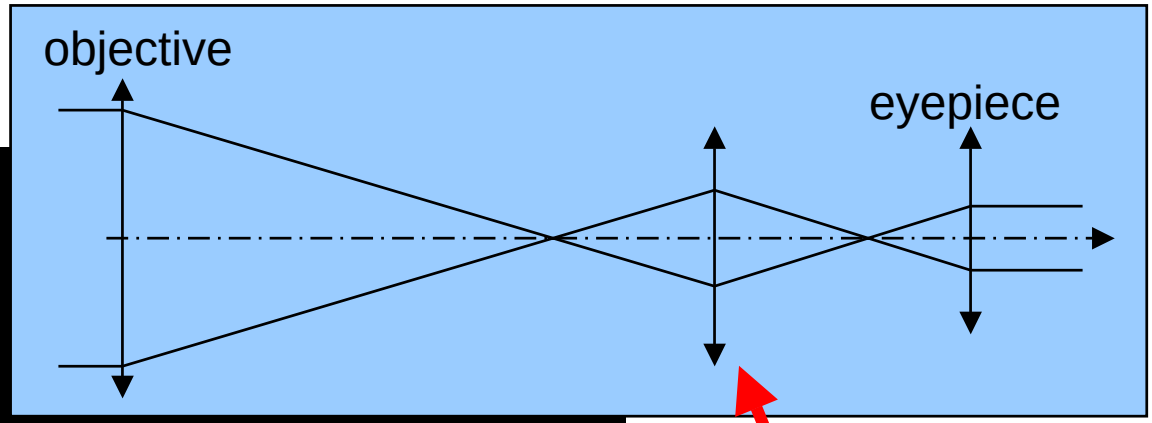


$$G = -\frac{f'_1}{f'_2} > 0$$

Erect image + Shorter system for a given magnification but virtual exit pupil

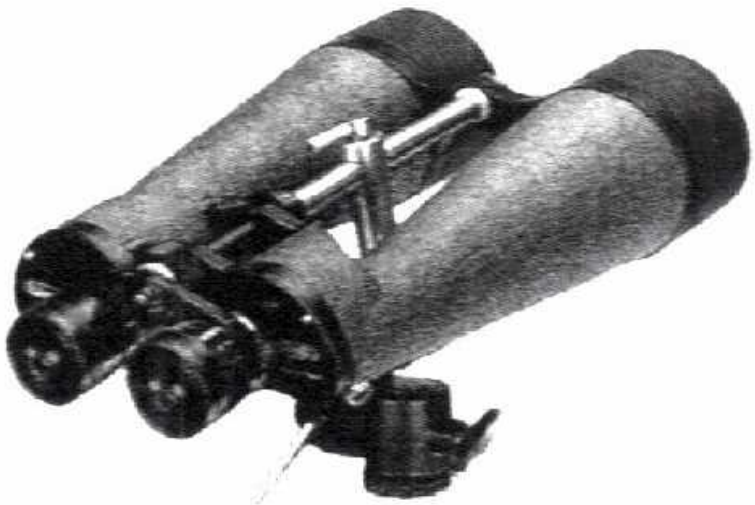
Lens erecting telescope

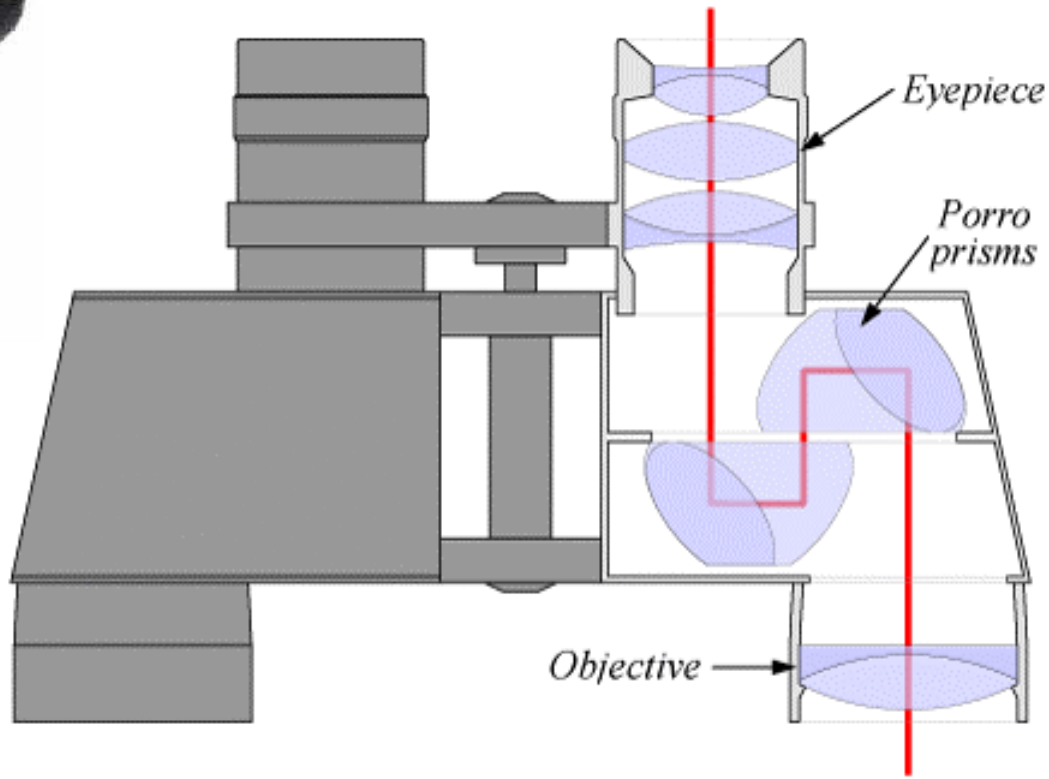




Erector lens

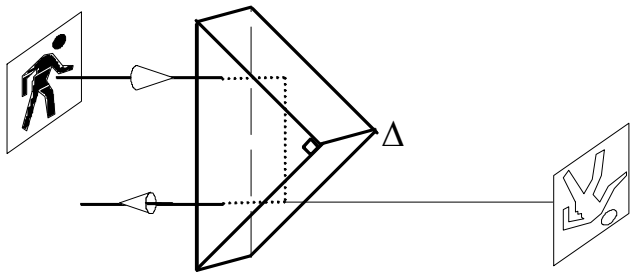
Binoculars



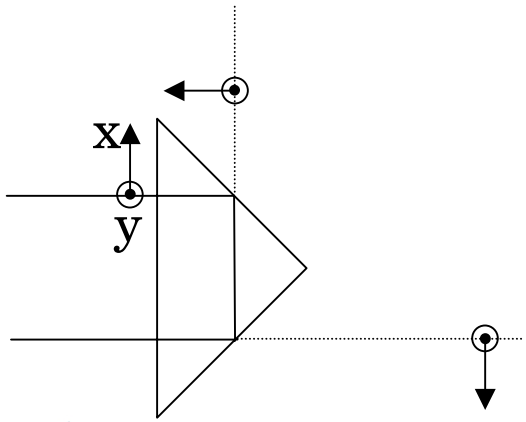


Similar design as astronomical telescope with Porro prisms to erect the image

Effect of one Porro prism on the orientation of the image



Porro prism: right angle prism, used with two total internal reflections. The image is rotated by 180° with respect to object.



The first Porro prism with Δ//y inverts the x axis, a second Porro prism with Δ//x , will invert the y axis.