PH 301

ENGINEERING OPTICS

Lecture_Optical Systems_24

Optical Instruments

An optical instrument is defined as a device used for observing, measuring, & recording optical data or information.

Most optical instruments are those intended to enhance visual capability.

Magnifying Glass

A magnifying glass or Loupe (French, imperfect gem) is the simplest of optical instruments intended for the enhancement of visual capability.

- **A magnifier is any positive lens with a focal length of less than 250 *mm*.**

- **A healthy human eye is capable of focusing from infinity, down to a minimum distance of about 250 *mm*.**

- **This same average eye is capable of resolving a repeating high-contrast target with equal width black & white lines when each line subtends an angle of 1 *arcmin* or more.**

- **Most often, when viewing an object it is our intent to distinguish as much detail on that object as possible. To that end we first bring the object as close as possible to the eye.**

- **When that closest distance is 250 mm, the smallest resolved element on the object – a detail that subtends an angle of 1 min**

$$\tan\theta = 0.0003$$

will have an actual size of

$$250\ \text{mm} \times 0.0003 = 0.075\ \text{mm}$$

- **If this resolved element is a part of a repeating pattern of equal thickness parallel black & white lines, then each cycle (1 black line + 1 white line) will have a thickness of 0.150 mm.**

- **Frequency of this finest resolvable pattern will then be**

$$1/0.150\ \text{mm} = 6.67\ \text{cycles/mm}$$

- **Approximate magnification *M* provided by lens is calculated by dividing its focal length into 250. A 50 mm lens will provide a magnification of**

$$M = 250/50 = 5X$$

- **This formula applies to the case where object is placed at the focal plane of magnifier lens & virtual image being viewed appears at infinity.**

- **A reasonable maximum limit for magnification by a simple magnifier would be about 20 to 25X.**

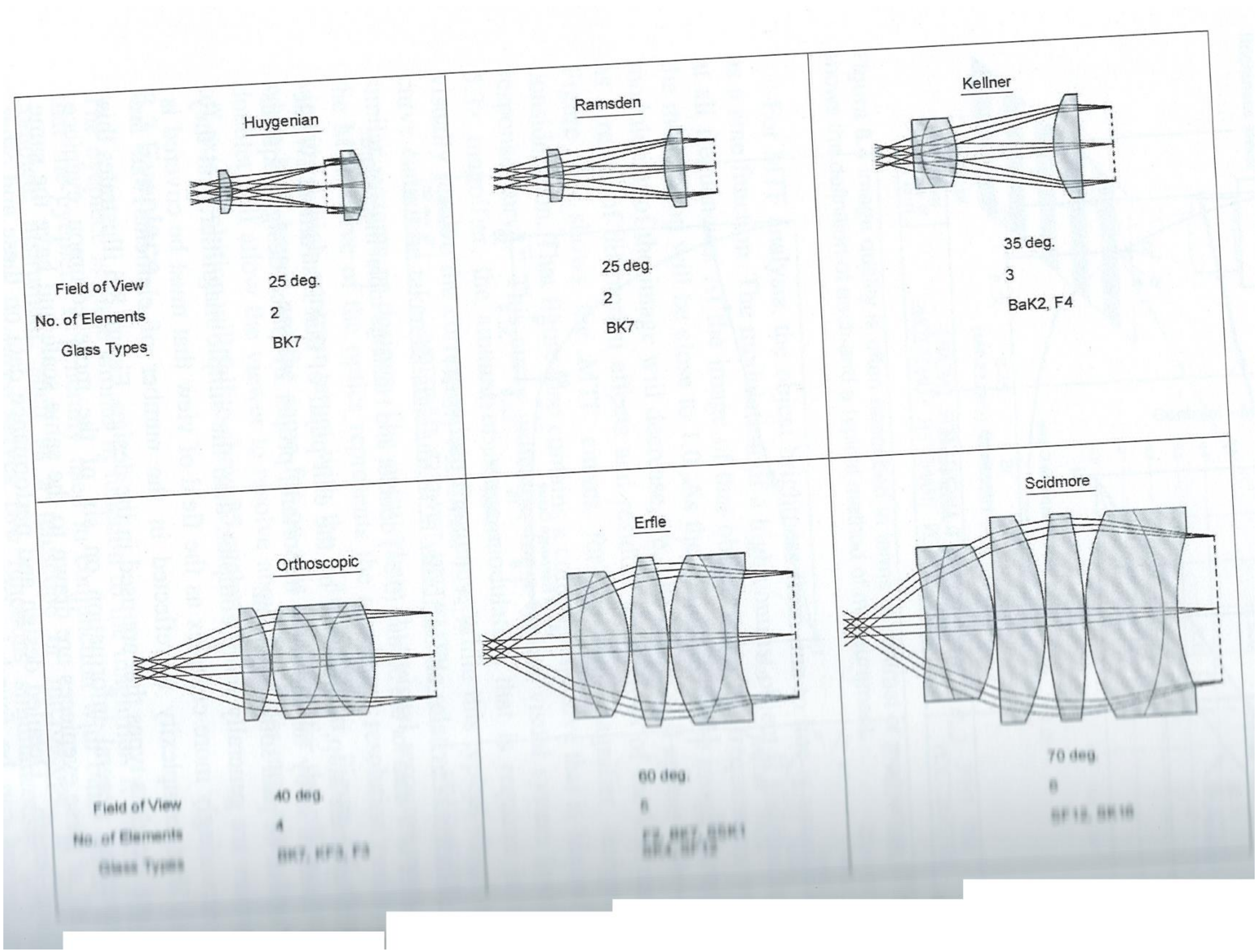
Eyepiece

Eyepiece is quite similar in function to the magnifier. It differs primarily in that the eyepiece is generally used in conjunction with other optics to form a complete instrument, such as a telescope or microscope.

- **Eyepiece serves two functions simultaneously:**
  - Projects final image to the viewer's eye, &
  - Forms an image of the system aperture stop, which will be exit pupil of that instrument.

- **Eyepieces become increasingly complex as the field of view to be covered is increased.**

- **Complexity is reflected in no. of elements that are required & glass types that are used in design.**



Family of common eyepiece designs, showing the increase in complexity as a function of the field of view that must be covered.

- **In most applications, eyepiece must be made axially adjustable to permit focus to accommodate for differences in the eyesight of viewers. A normal adjustment range from + 3 to - 4D will satisfy most requirements.**

- **Amount of eyepiece travel (in mm) can be calculated as,**

$$\textbf{Axial travel per diopter} = EFL^2/1000$$

- **For a 28-mm EFL eyepiece, each diopter of adjustment will require:**

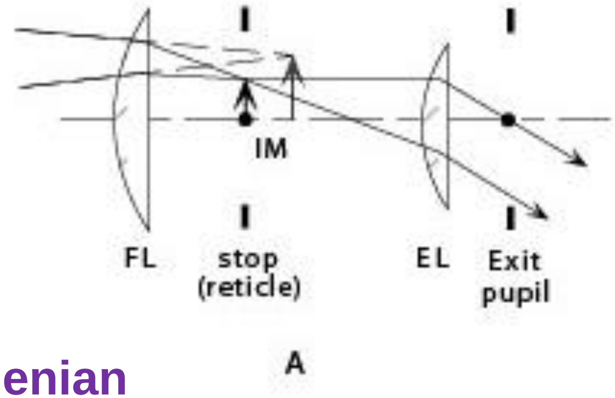
$$\textbf{Axial travel per diopter} = 28^2/1000 = 0.784 \text{ mm/D}$$

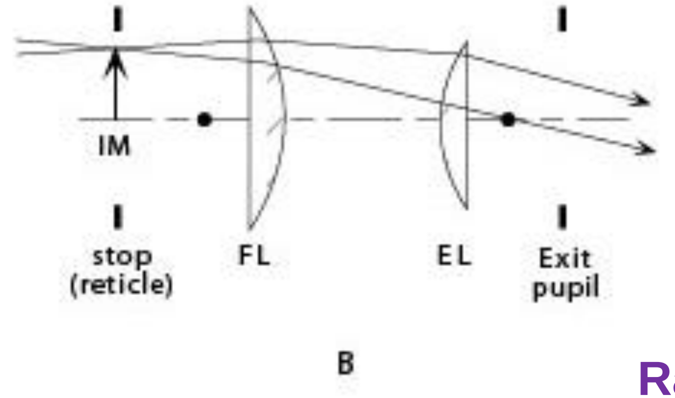
- **Moving eyepiece closer to image being viewed will result in a diverging output beam, which corresponds to a negative diopter setting.**

- **To achieve + 3 to - 4 D focus image, 28 mm eyepiece will have to be moved from - 3.2 to + 2.4 mm relative to infinity or zero-diopter setting.**

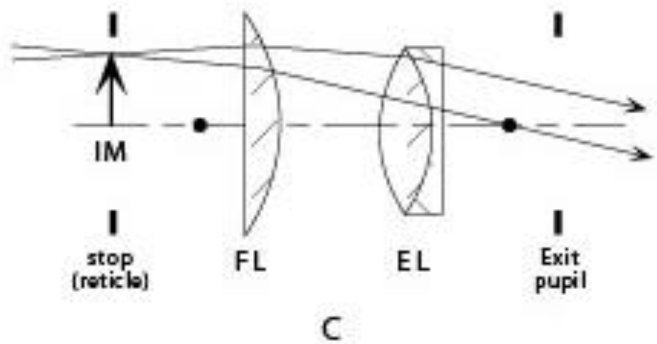
Microscope Eyepiece or Ocular

Huygenian





Ramsden



Kellner

Simple eyepieces are constructed of two Plano-convex lenses (A,B). More corrected lenses consist of three or more lenses, with at least one as an achromatic doublet (C). All eyepieces also have an internal aperture, that is used to reduce aberrations but that limits field of view.

Earliest eyepiece is Huygenian eyepiece. It has aperture (or diaphragm) placed between two lenses.

Ramsden eyepiece has aperture placed before first lens (B). Both eyepiece designs suffer from chromatic aberration. Ramsden yields a better image.

Kellner eyepiece, a variation of Ramsden, replaces Eye Lens with an achromatic doublet. It has good chromatic correction, & is reasonably inexpensive. Modern eyepieces are a variation of Kellner design. With increased use of achromatic doublets & triplets. Chromatic aberration is eliminated & field flattened.

Power (P, magnification of an eyepiece is defined as D/focal length; where *D* = the closest distance of distinct vision, or 250 mm.

Magnification of a compound microscope = $P_{obj} \times P_{eye}$

Eyepieces are usually 6.3X, 8X, 10X, 12X, 16X, 20X.

As magnification of eyepiece increases, the field of view decreases.

Microscope

- **A reasonable maximum limit for magnification by a simple magnifier would be about 20 to 25X.**

- **When a higher magnification is required, a compound magnifier is used, which is commonly referred to as a *microscope*.**

- **It consists of two lens assemblies: objective lens & eyepiece.**

- **Objective lens will form a magnified image of object, while eyepiece will be used to view that magnified image, thus providing additional magnification.**

- **Most often a microscope is designed by selecting a wide variety of commercially available components. While custom microscope design is an active & challenging area of optical design.**

Compound microscope

Total microscope magnification = (10X) × (4X) = 40X

$f/\# = 1/(2NA) = 1/(2 \times 0.12) = 1/0.24 = f/4.17$

- **At field stop this *f*/# will be increased by magnification factor, making it 4 × 4.17 = *f*/16.67.**

- **Since we are using a 10× (25 mm EFL) eyepiece, we can calculate the exit pupil diameter to be 25/16.67 = 1.5 mm.**

- **Microscope's field of view: 16 mm diameter field stop will limit actual filed of view to 16/4 = 4.0 mm diameter at object surface.**

- **When viewing 16 mm diameter field stop through 25 mm EFL eyepiece, it will have an apparent angular half field of view whose tangent is 8/25 = 0.32.**

- **We can see that 4.0 mm diameter object, which would subtend a half-field angle with a tangent of 2/250 = 0.008 when viewed at a distance of 250 mm with naked eye, will now subtend a half angle whose tangent is 0.32 when viewed through microscope.**

- **New apparent object size is magnified by a factor of 0.32/0.008 = 40X.**

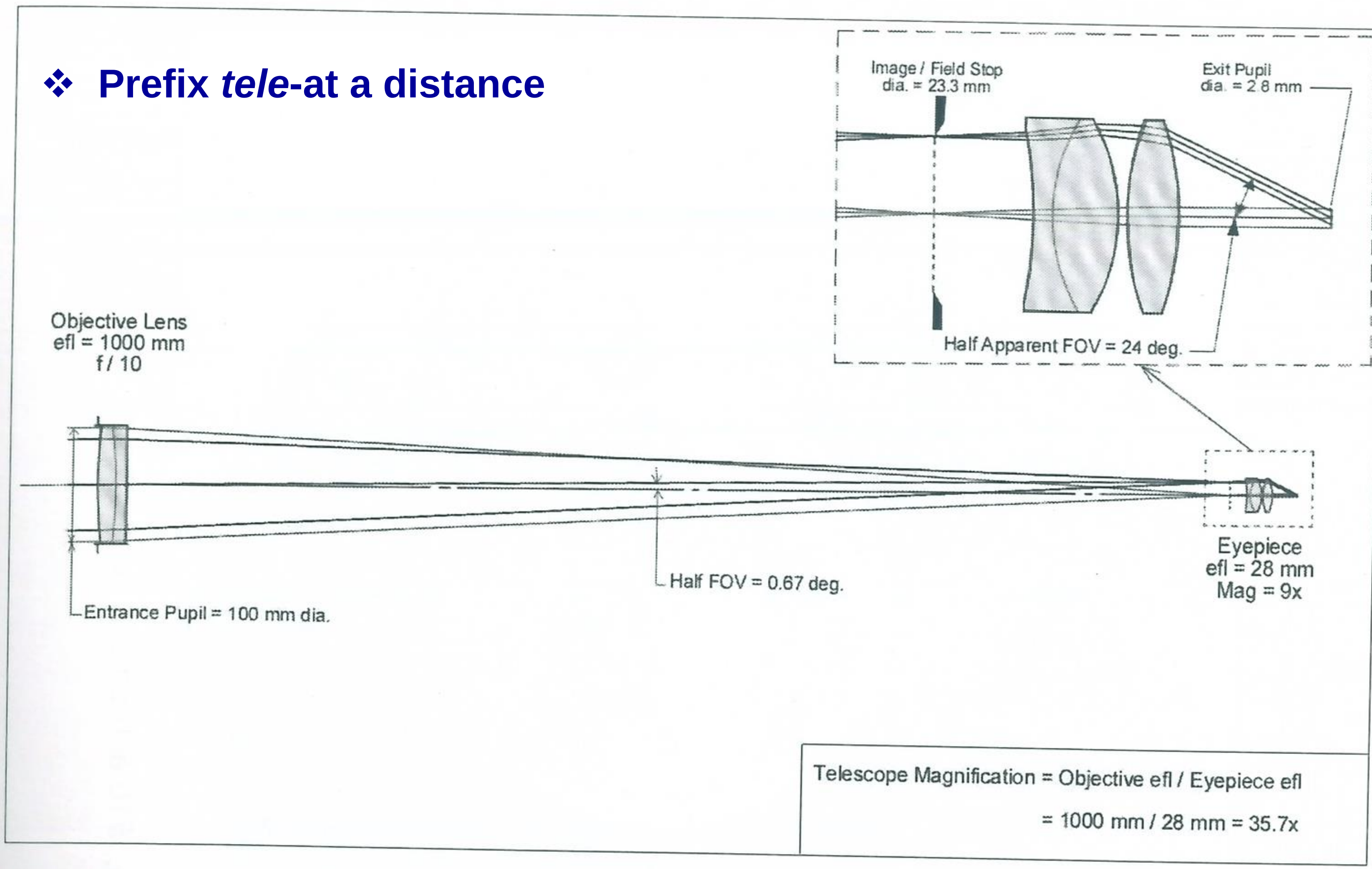
Compound Microscope

Eyepiece (ocular)
Eyepiece
Tube
Head
Arm
Nosepiece (turret)
Objective Lenses
Stage Clips
Aperture
Coarse Focus Knob
Stage
Fine Focus Knob
Condenser
Iris Diaphragm
Illuminator
Base

Telescope

Telescope

- Prefix *tele*-at a distance



Basic optical parameters of an astronomical telescope made up of a 1000 *mm f/*10 objective lens, & a 28 *mm* eyepiece.

Telescope

- Telescope is used to view large objects that are at great distances from us when it is not practical to reduce the distance to the object.

Dimensional parameters:

- A practical limit on the size of an objective lens, based largely on cost, would be about 100 mm diameter, with a speed of *f*/10, making focal length 1000 mm.

- Telescope magnification is calculated by dividing the eyepiece focal length (1000 mm) into the objective focal length (28 mm).

$$M = 1000\ \text{mm}/28\ \text{mm} = 35.7\text{X}$$

- Angular field of view that will be seen is limited by the diameter of field stop in eyepiece, (supplier data, 23.3 mm). Resulting field of view for objective lens will be:

$$\tan^{-1}\left(\frac{23.3}{1000}\right) = \tan^{-1}(0.0233) = 1.34\,\text{deg}$$

Telescope

- **Exit pupil diameter: It will be equal to the objective lens diameter divided by telescope magnification,**

100 mm/35.7X = 2.8 mm

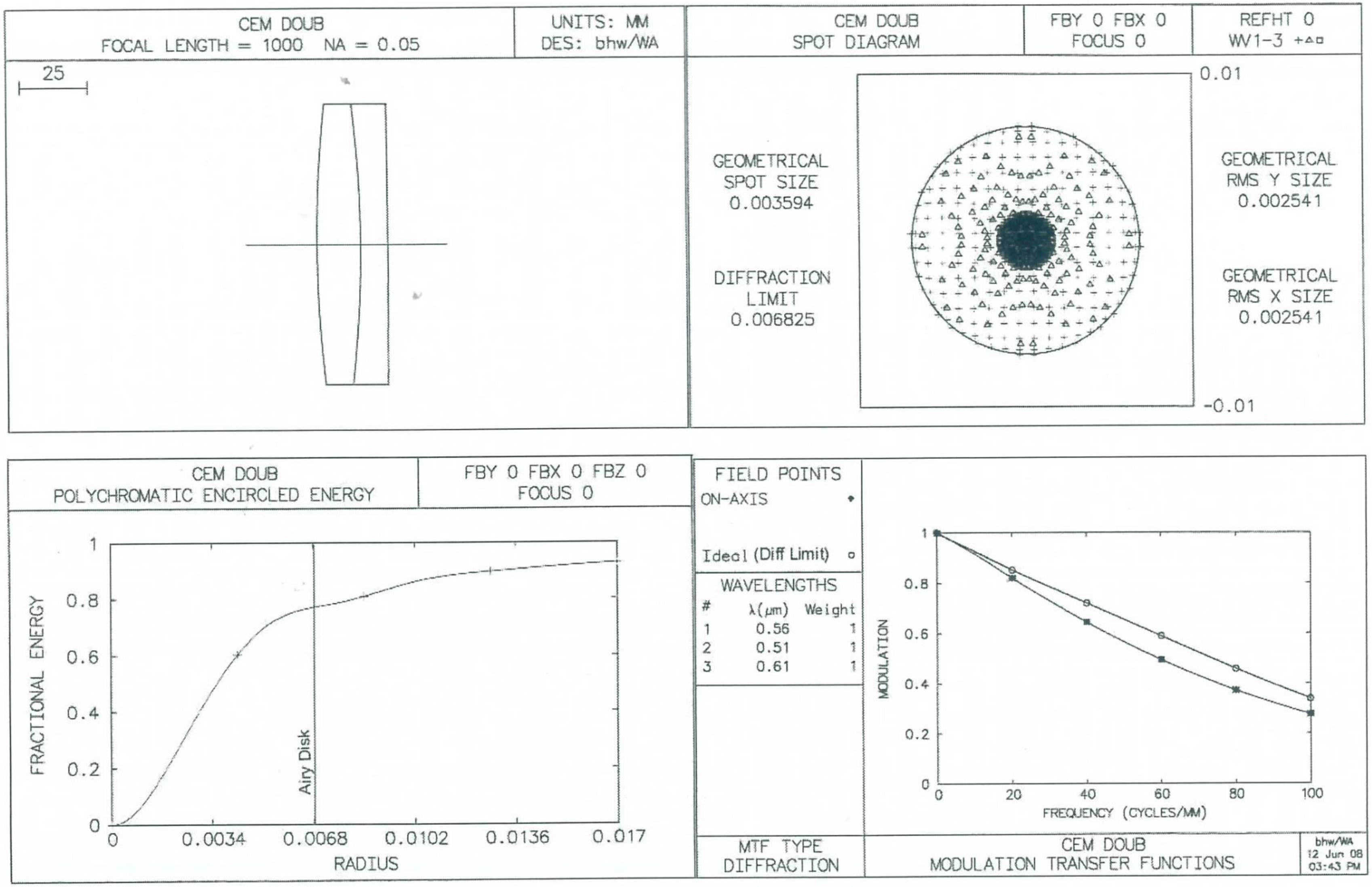
Optical performance:

- **For an astronomical telescope objective lens it is reasonable to strive for near-diffraction-limited performance. To determine the radius of diffraction-limited blur spot (Airy disk):**

$$Airy\ disk\ radius\ R = 1.22 \times \lambda \times f/\#$$

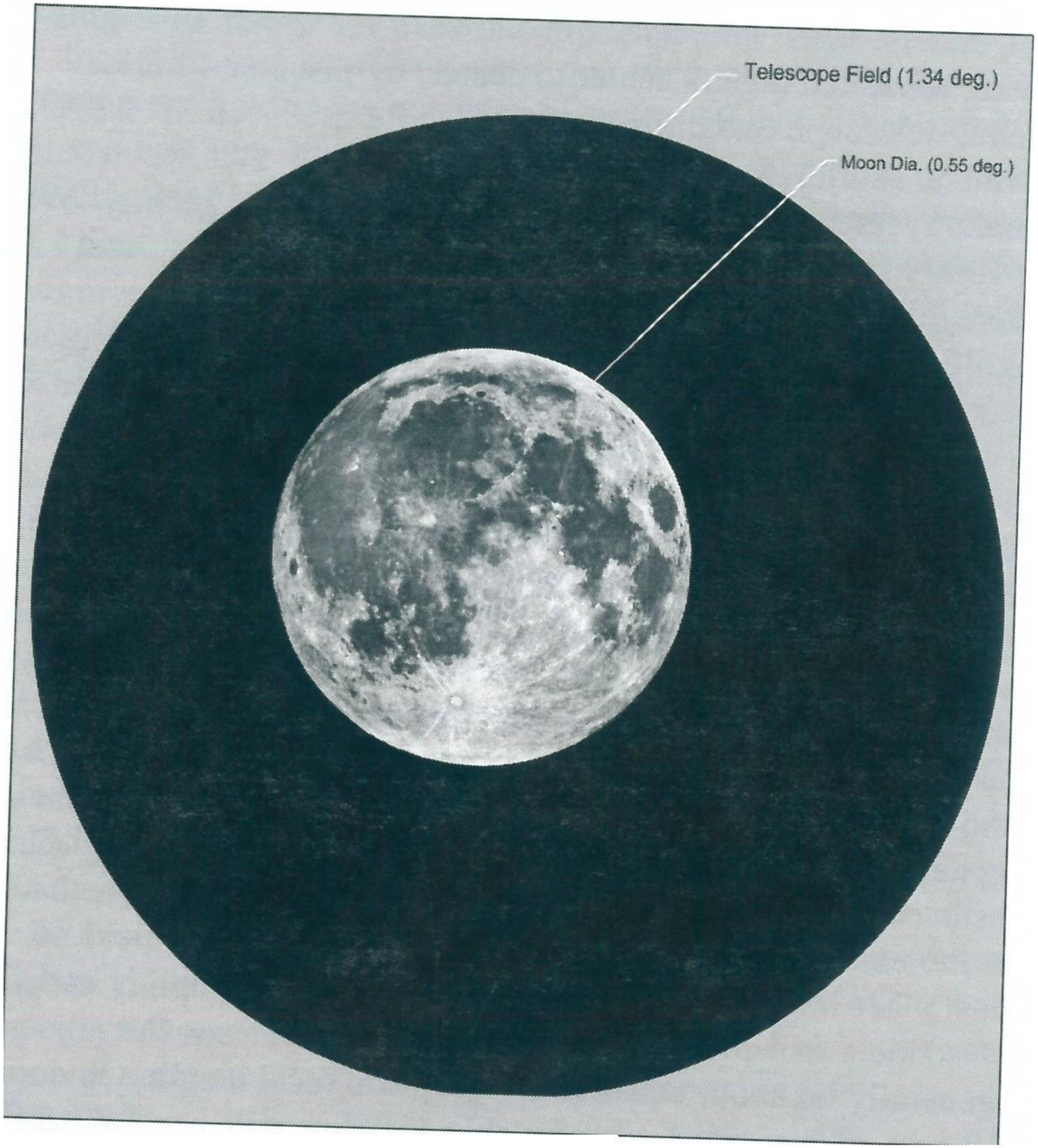
- **For this objective lens,** $R = 1.22 \times 0.00056 \times 10 = 0.0068\,mm$

- **Image formed by objective lens will be viewed using 28 mm EFL (9X) eyepiece.**



Lens picture & on-axis performance data for a 1000 *mm*, *f*/10 achromatic cemented doublet.

Observing the moon



Field of view as seen through a telescope with a 1.34 deg field of view.

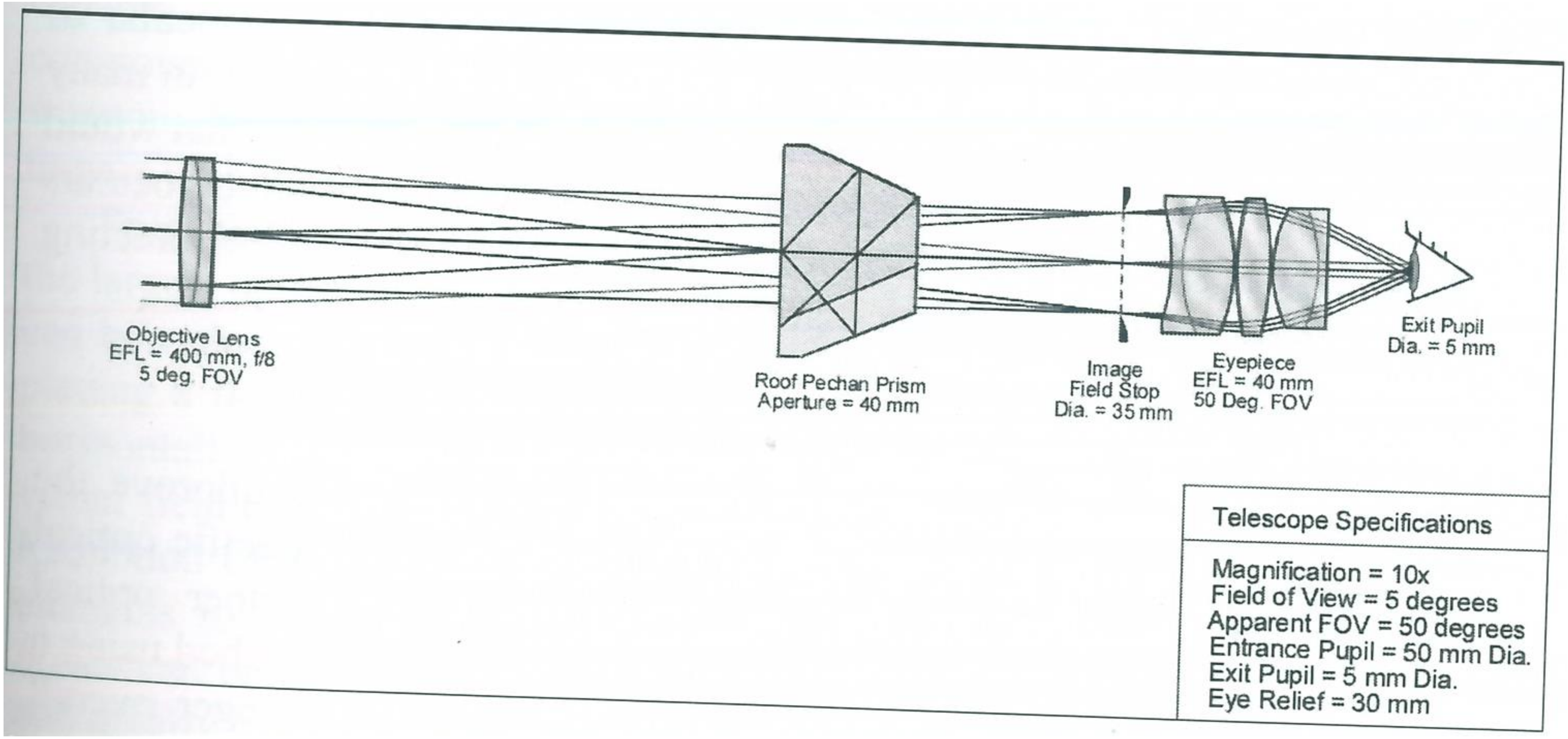
- Looking through eyepiece, moon’s disk will subtend an angle of about 20 deg to eye.
- Without telescope, moon subtends an angle of 0.55 deg to naked eye.
- Based on visual resolution limit of 1 *arcmin* per element, we can conclude that, with naked eye, we will resolve 0.55 deg × 60 = 33 elements across moon’s diameter (2160 miles).
- Thus, we can conclude that the smallest element on the moon’s surface that we can resolve with our naked eye will be 2160 miles/33 = 65 miles.
- With the help of our new telescope, that number will be reduced to just under 2 miles.

- Certainly naked eye can see a dark crater on the bright moon’s surface (high contrast), even if that crater is less than 65 miles in diameter.

- But, if there are two 50 mile diameter craters that are separated by 50 miles (center to centre), naked eye will not be able to determine that there are indeed two separate craters, i.e., they will not be resolved.

- However, if we look at these two craters with our new telescope, we will clearly resolve two separate & distinct craters.

- Additional telescope magnification will be introduced if we choose an eyepiece with a shorter focal length.



Basic optical parameters of a 10× compact terrestrial telescope, consisting of a 400 mm, *f*/8 objective lens, a roof Pechan derotation prism, & a 40 mm EFL eyepiece.

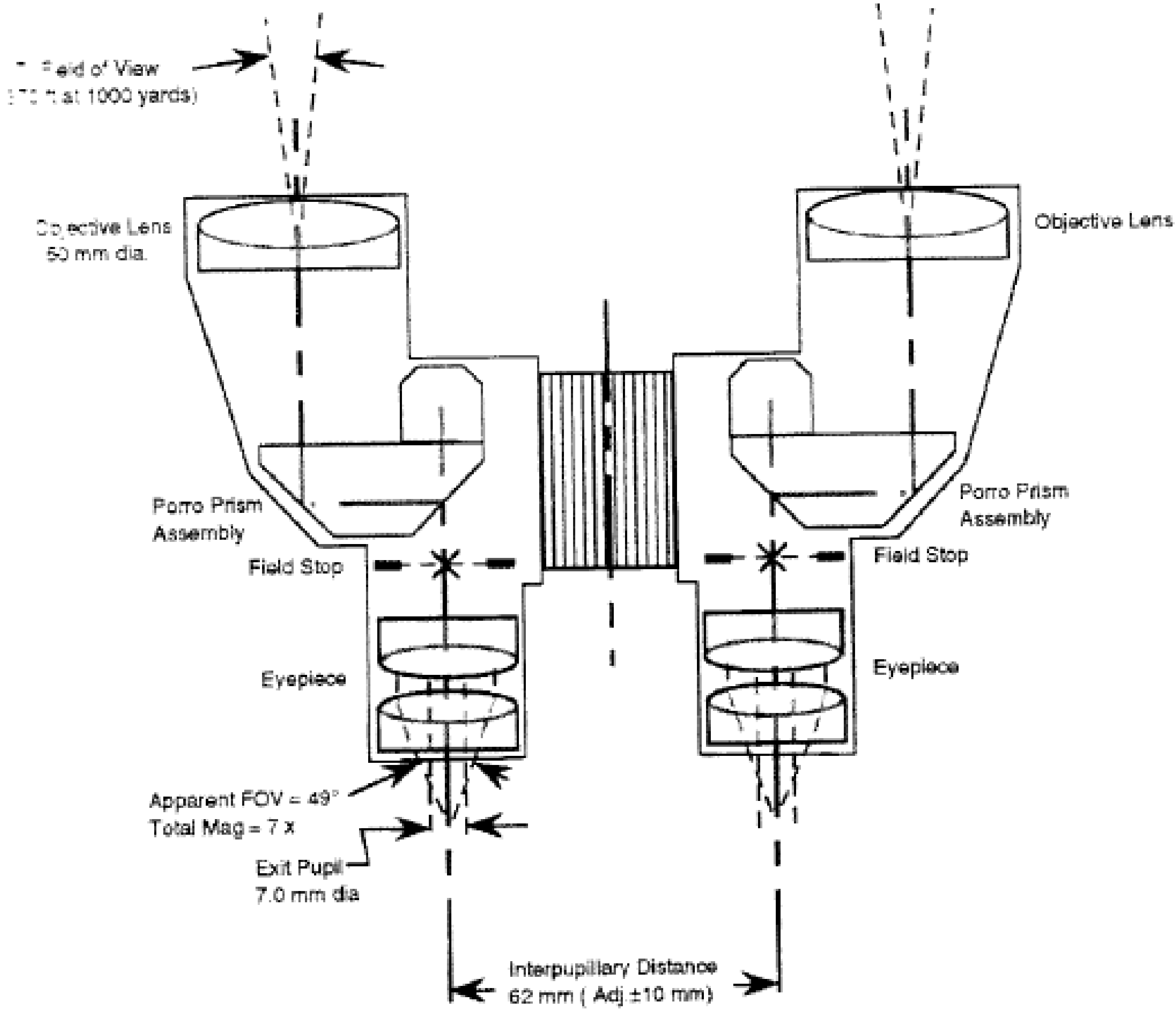
- ❖ **Ideal configuration for viewing & recording celestial objects today involves replacing the eyepiece with a modern digital camera designed specifically for astrophotography.**

- ❖ **Such a camera can be connected directly to a laptop computer where objects imaged by objective lens can be viewed on computer screen & then captured & stored for later examination & fine tuning.**

- ❖ **Application: viewing sporting event from a distance of some 400 ft.**

Binoculars

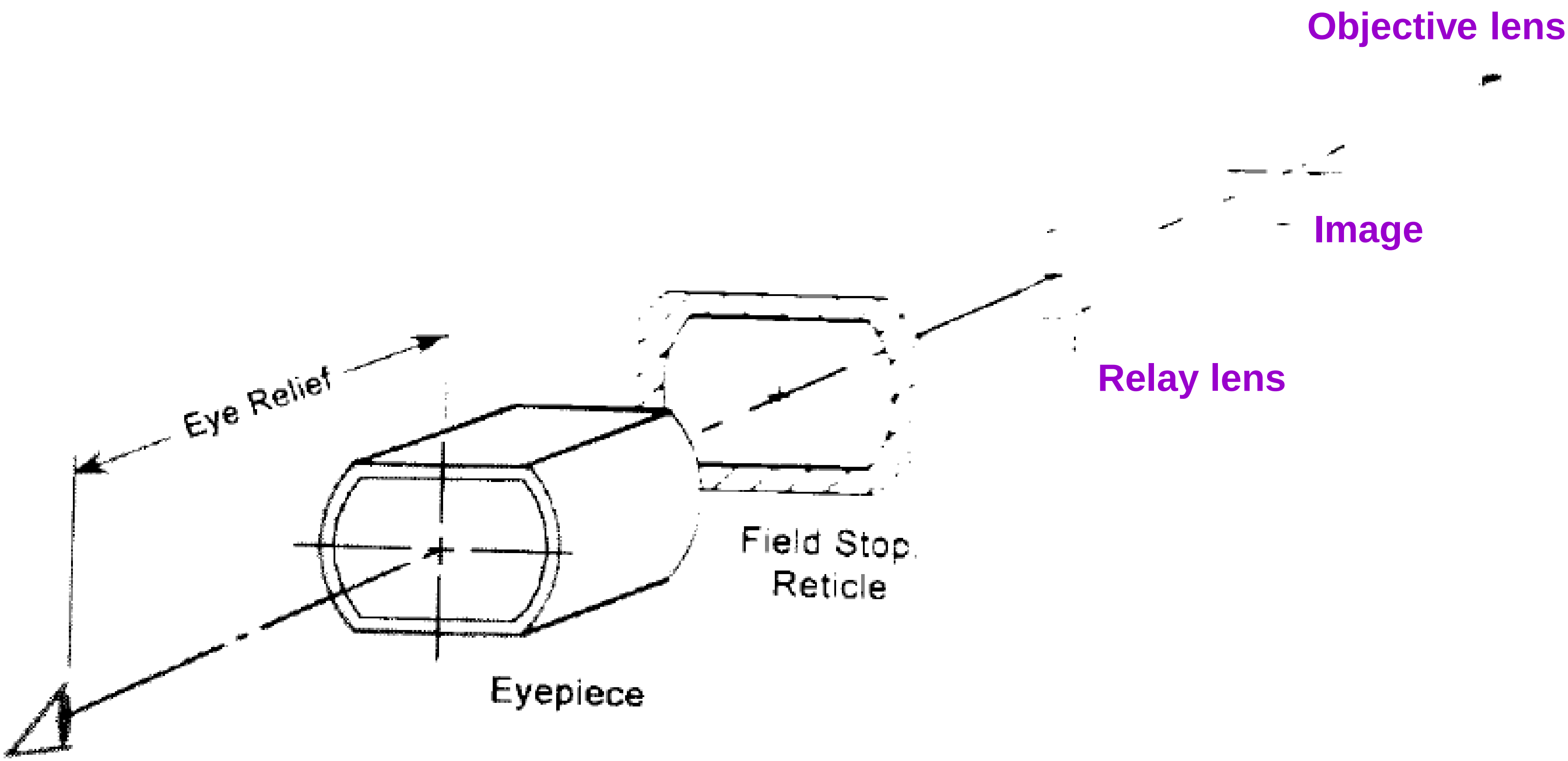
- A pair of binoculars is made up of two identical terrestrial telescopes, linked together such that their optical axes are parallel.
- Distance between two exit pupils is made to be adjustable to accommodate individual differences in eye separation (interpupillary distance, or IPD).
- Average value of IPD is about 64 *mm*, with an adjustment of +/-10 *mm* adequate to satisfy most requirements.
- It is critical that two optical axes be parallel as they enter viewer's eyes. A maximum misalignment tolerance of one arcminute will be accommodated by most users with little difficulty.
- Dual optical paths result in more natural, relaxed viewing, with an enhanced stereo effect relative to that provided by a single telescope, i.e., a monocular.



Optical layout of a pair of 7 × 50 Porro prism binoculars

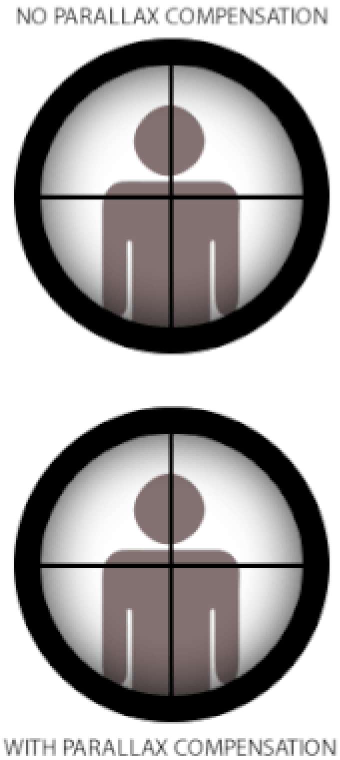
Riflescope

Riflescope is a low-power telescope designed specifically to improve the sighting accuracy of a rifle or similar weapon.



Optical system of the riflescope contains a relay lens to correct image orientation, & it requires greater-than-usual eye relief.

Parallax problems result from the image from the objective not being coplanar with the reticle.



If image is not coplanar with reticle (i.e. focal plane of objective image is either in front of or behind reticle), then putting eye at different points behind eyepiece causes reticle to appear to be at different points on the target.

This optical effect causes parallax-induced aiming errors that can make a telescopic sight user miss a small target at a distance for which the telescopic sight was not parallax-adjusted. This is known as *parallax shift* where the reticle seems to "float" around over the target whenever there are small movements of the user's head & eyes.