Telescope Eyepieces

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Overview

- Motivation
- Simple astronomical telescope and Aberrations
- Introduction to eyepiece optics
- Practical measurement of:
  - Eye Relief
  - Field Of View
  - Focal Length
  - Principal Planes
- Other eyepiece properties
- Evolution of eyepiece designs

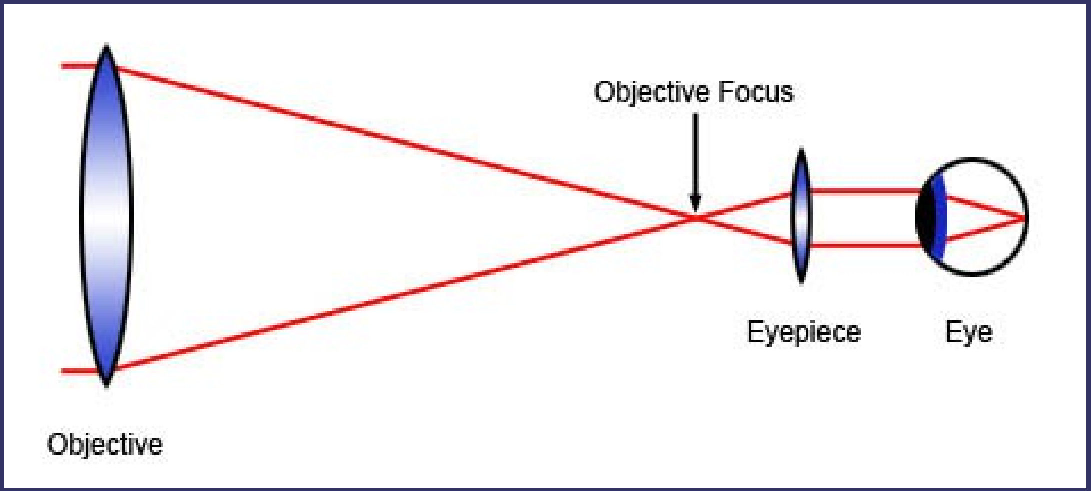
- Future workshops?

Tomline Refractor Eyepieces

Old Knurly

- What is its focal length?
- What is its field of view?
- What is its provenance?

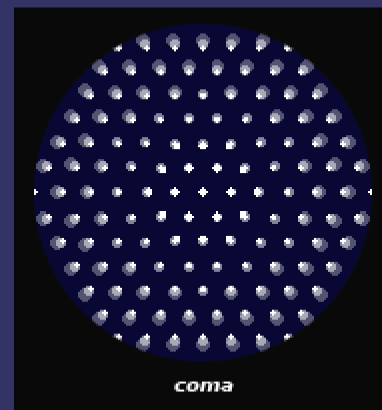
Introduction to optics

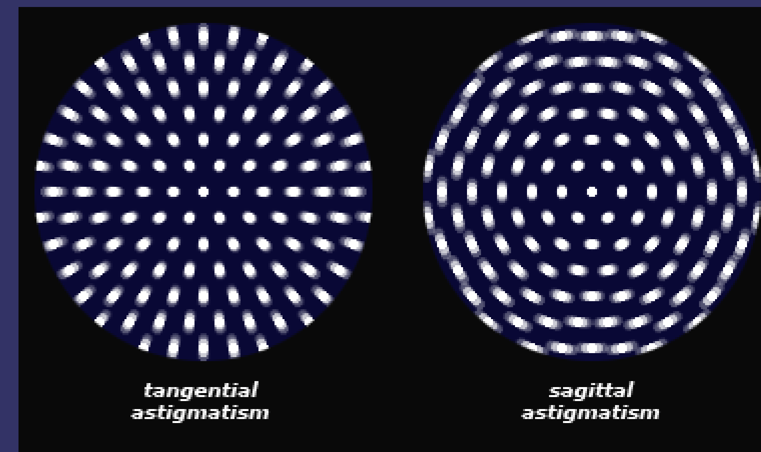


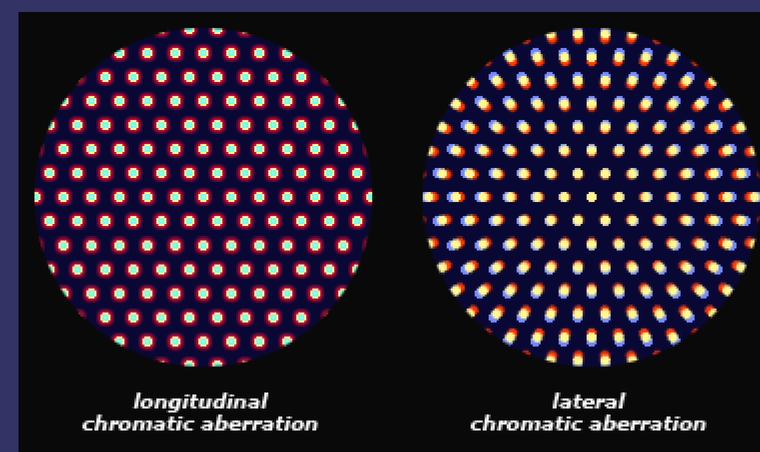
- Simple astronomical telescope (inverted image)
- Both lenses are converging
- Eye sees an image focussed at infinity (afocal)
- Magnification = Objective Focal Length / Eyepiece Focal Length
- Exit Pupil Diameter = Objective Diameter / Magnification
  (aka Ramsden Disc)
  = Eyepiece Focal Length / Telescope Focal Ratio

Aberrations

- Coma
- Astigmatism
- Defocus
- Distortion
- Spherical Aberration
- Chromatic Aberration
- Field Curvature

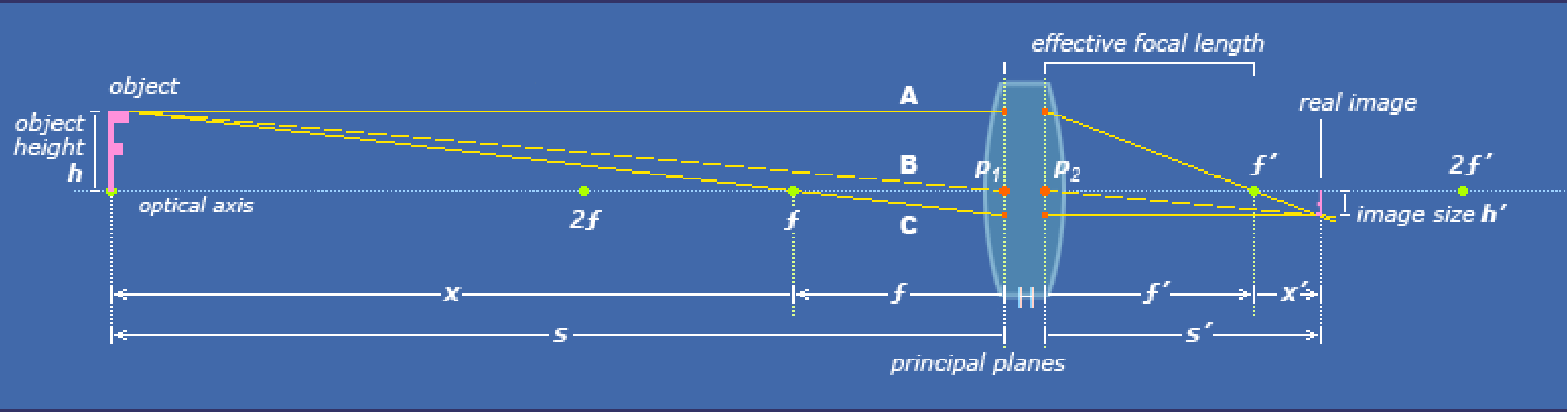






- All can be reduced by optical designs using multiple lens elements

Thick Lens Model

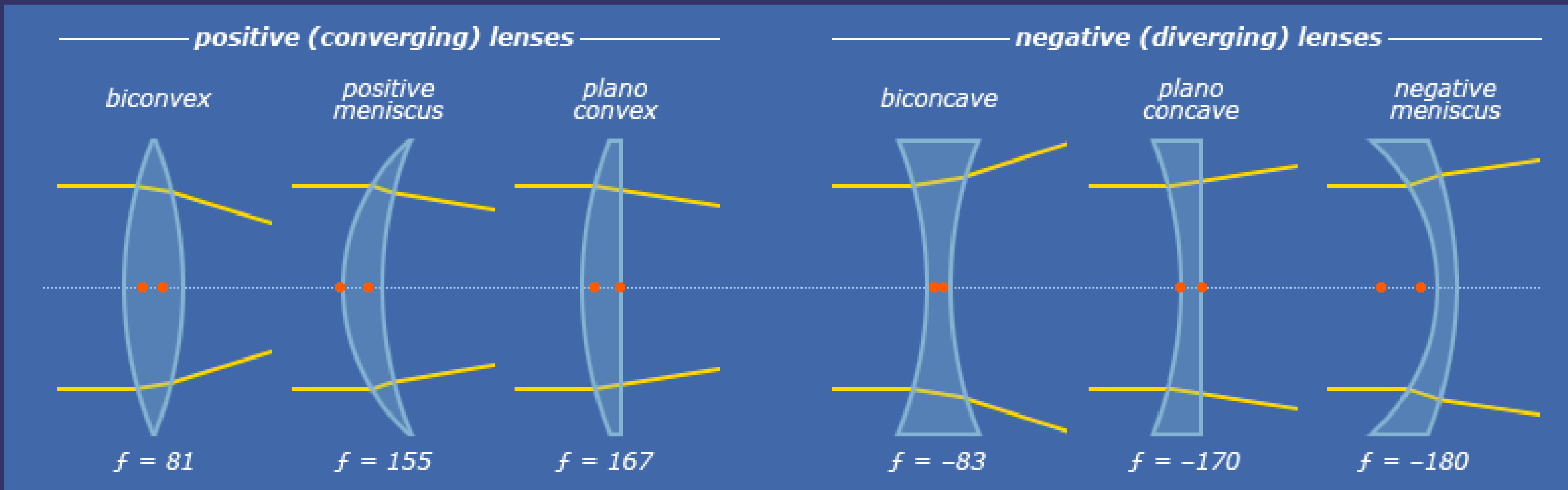


Thick Lens model identifies:

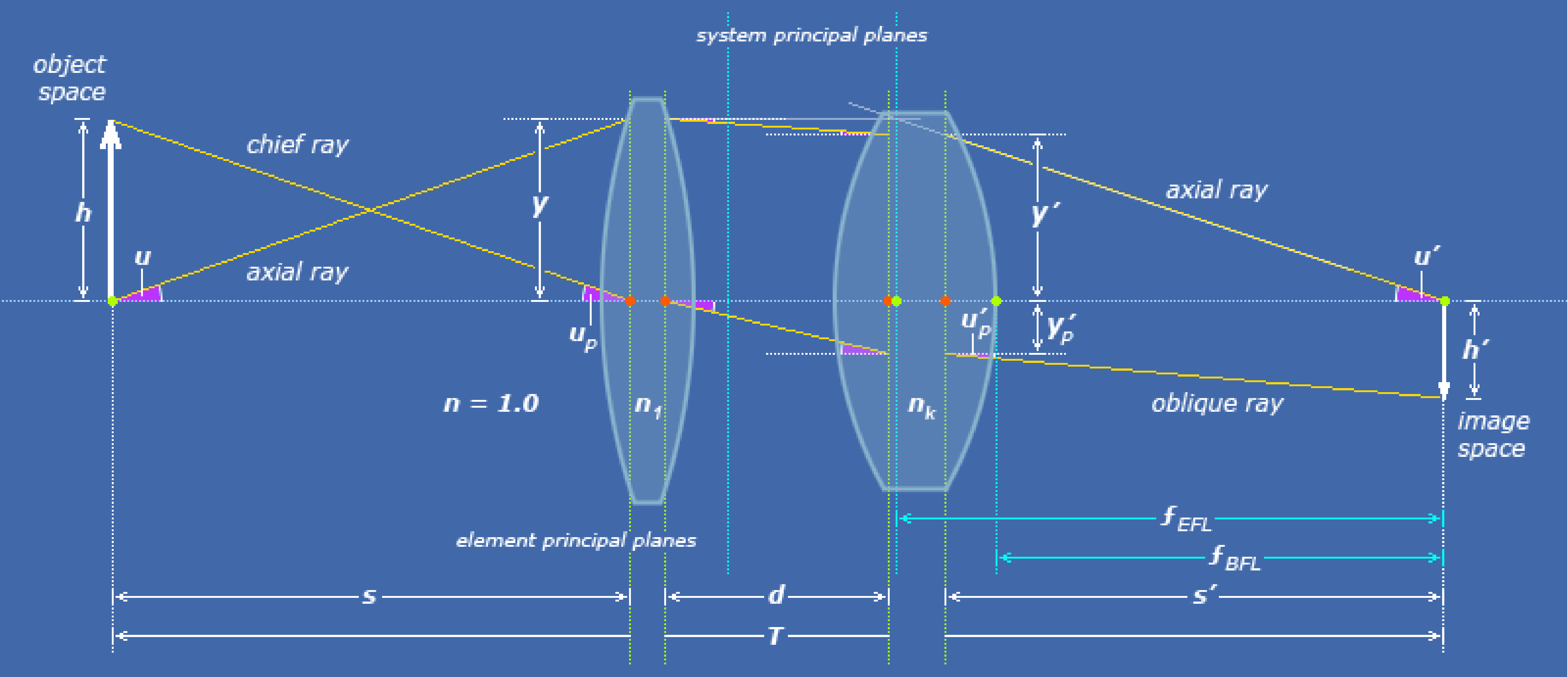
- Two Principal Points/Planes P1, P2 separated by Hiatus H
- (In air, Principal Points in same place as Nodal Points)
- Object side Focal Length f measured from P1
- Image side Focal Length f ' measured from P2

- Light path A enters parallel to axis and exits through focus f'
- Light path B enters and exits lens at same angle
- Light path C enters through focus f and exits parallel to axis

Principal Points for Various Lenses

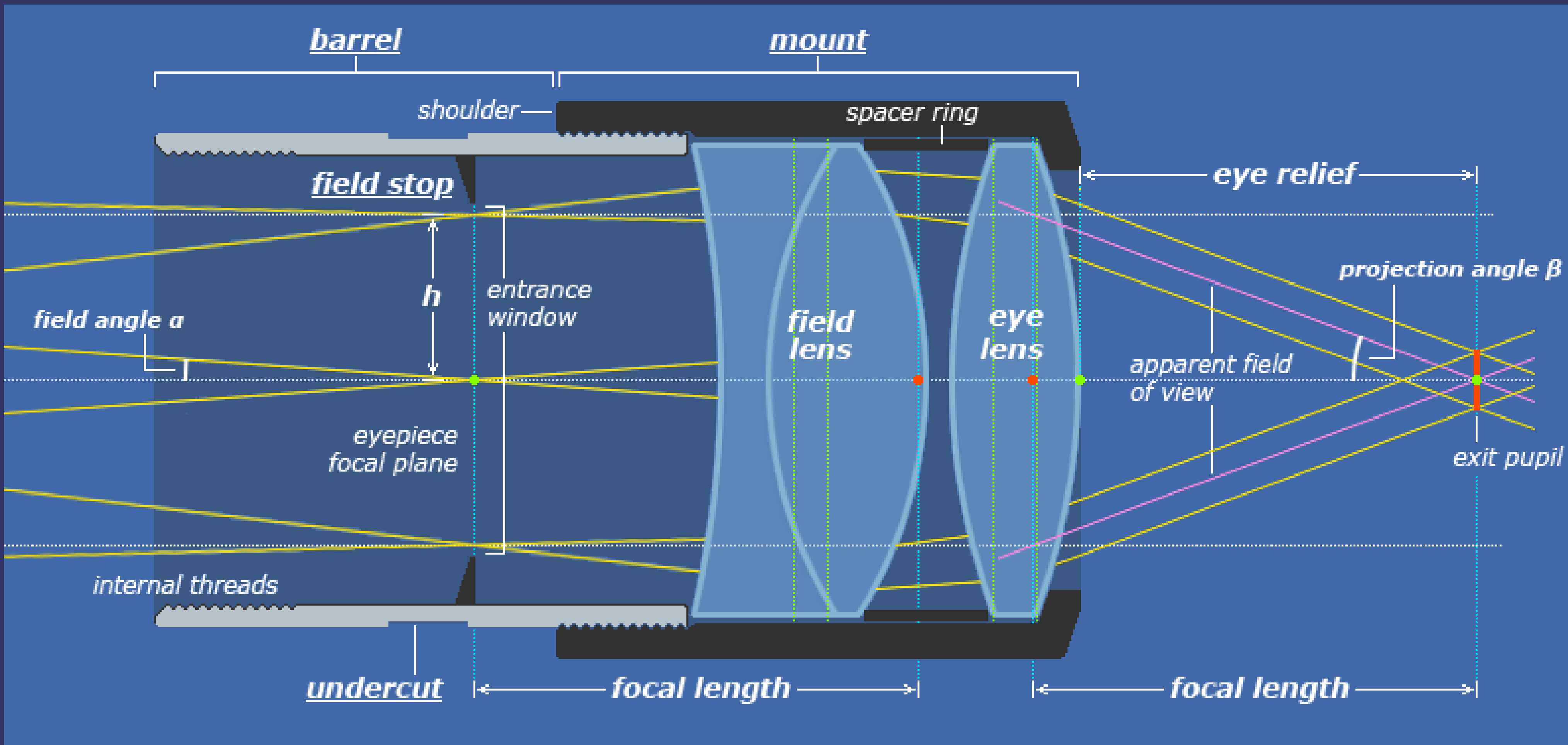


Multiple Lenses



- The combination of multiple lenses results in two NEW System Principal Plane positions
- Effective Focal Length f_{EFL} is measured with respect to the Second System Principal Plane

Example Eyepiece Design



- Key eyepiece parameters:

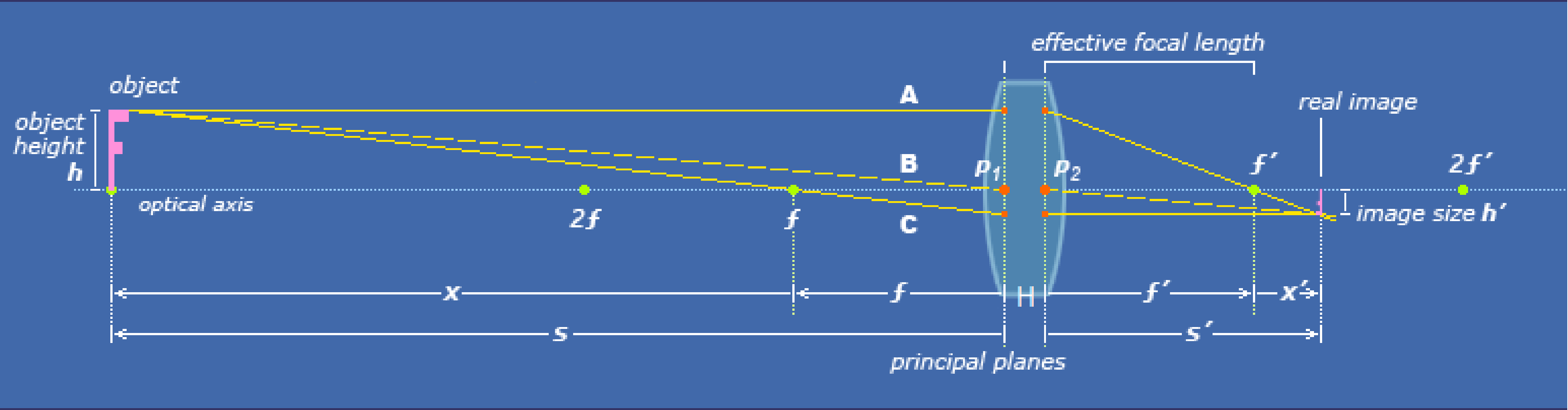
  Focal Length Eye Relief

  Apparent Field of View

Measuring an unknown eyepiece

- Eye Relief
  - Project distant object and measure distance to lens surface
- Apparent Field of View
  - Good estimate: Illuminate field (object) side and measure angle of emerging light cone
- Focal Length
  - Simple method of projecting distant object doesn't work since position of Principal Planes unknown. Use a geometric measure of magnification instead
- Principal Planes
  - Use 'Nodal Slide' to locate, to improve accuracy of Focal Length meausurement

Lens Equations



Newtonian (measure with respect to Focal points)

$$xx' = f^2 \qquad M = h'/h = -x'/f = -f/x$$

Gaussian (measure with respect to Principal points)

$$f/S' + f/S = 1 \qquad M = h'/h = S'/S$$

All above assumes lens is in air so f = f ' , and small (Paraxial) angles

Measuring Eye Relief

- In normal use, exit pupil is at focal point so:

  Find focal point by projecting a 'distant' object
  Measure distance from focal point to lens surface

- To get error from true focus (= x') to be <f/20 for example,

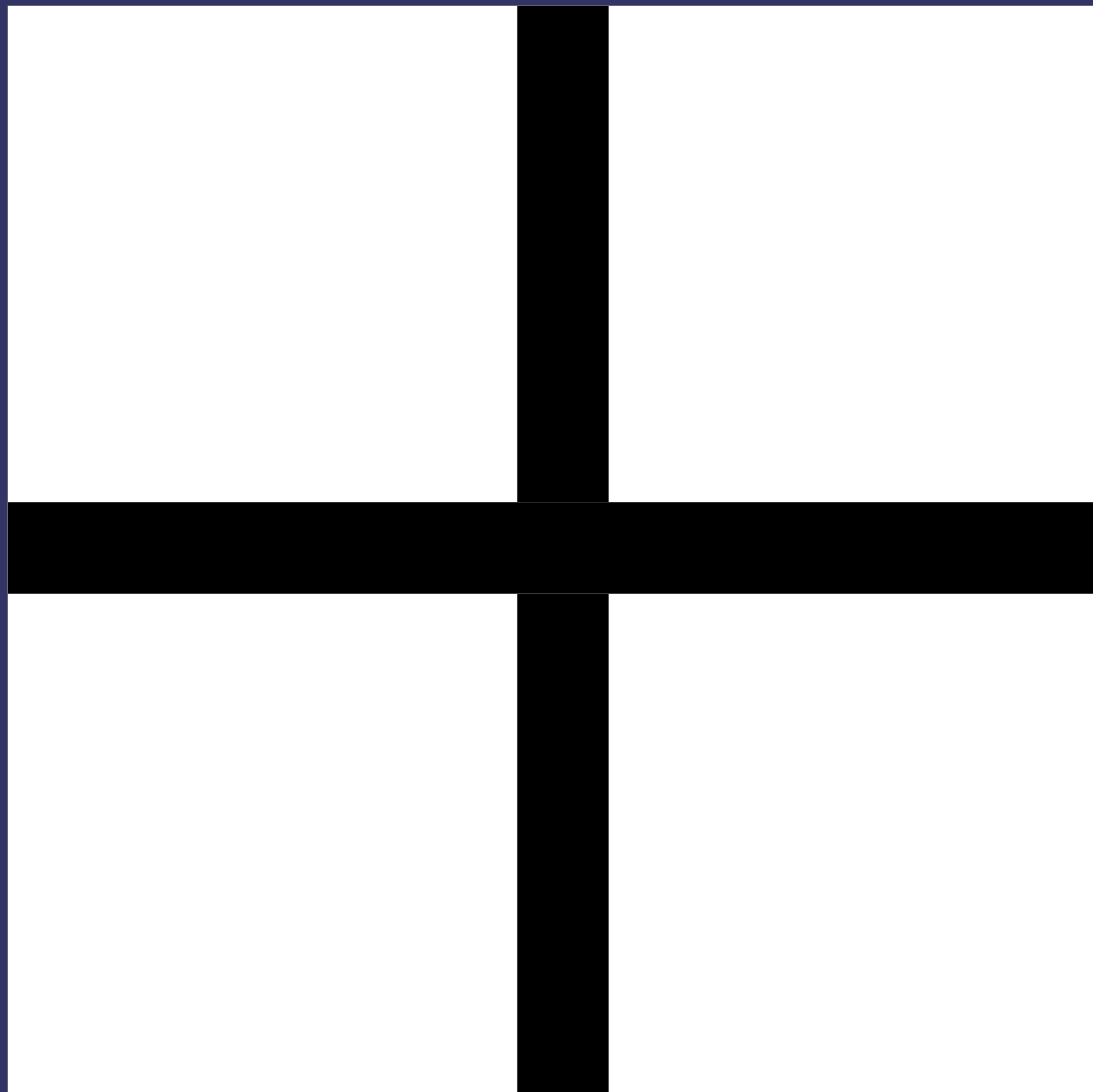
$$x' < f/20 \quad \text{and} \quad xx' = f^2 \quad \text{so} \quad x > 20f$$

- i.e 'distant' object must be >20(+1) times focal length from lens

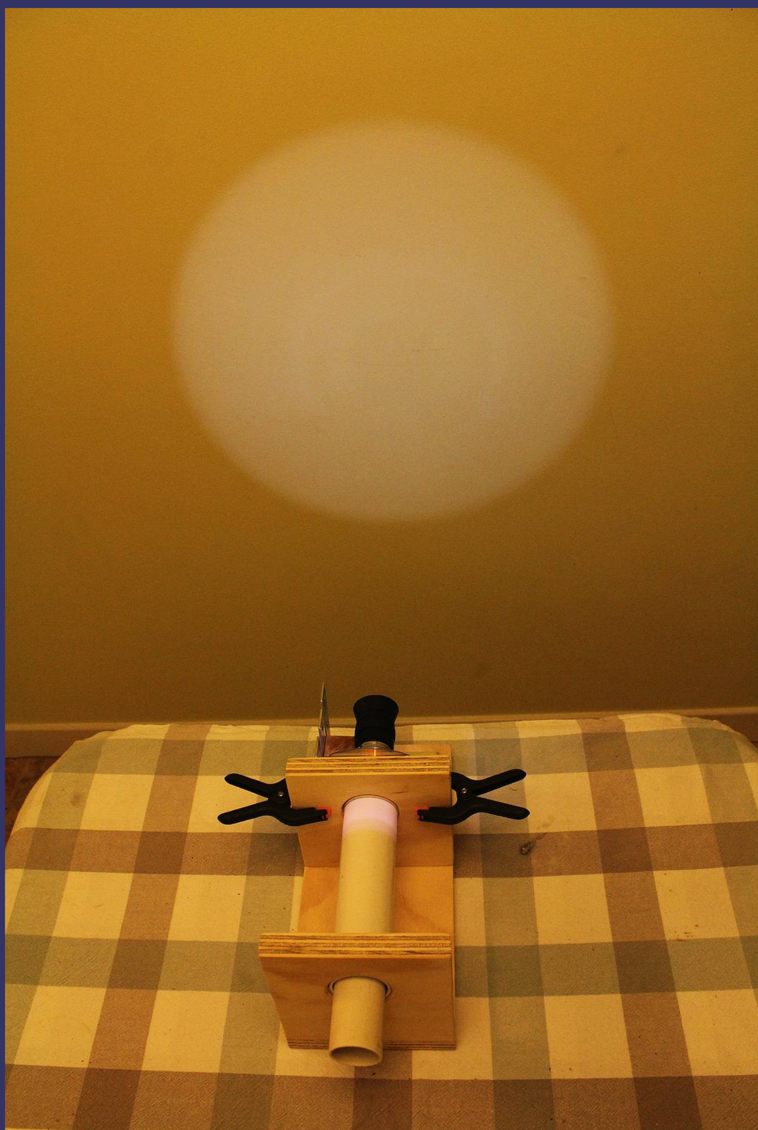
- Or use collimated light source (distance = infinity)

- Or measure x and calculate offset x' of exit pupil from focus

Test Object



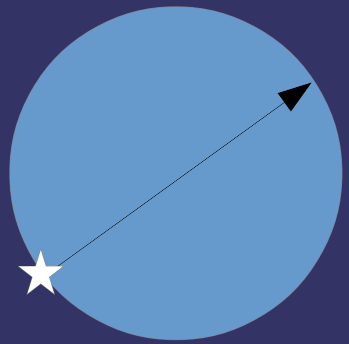
Measuring Apparent Field of View (1)



- Illuminate field end of eyepiece with a torch
- Measure distance p between exit pupil and screen
- Measure diameter d of projected circle
- AFOV = 2 arctan (d/2p)

Measuring Apparent Field of View (2)

Star Drift Method



Measure time T for a star of Declination Dec to drift across full field of view of telescope with chosen eyepiece

$$\text{Telescope FOV (TFOV)} = \frac{360 \times T \times \text{Cos(Dec)}}{86164}$$

(23h 56m in seconds)

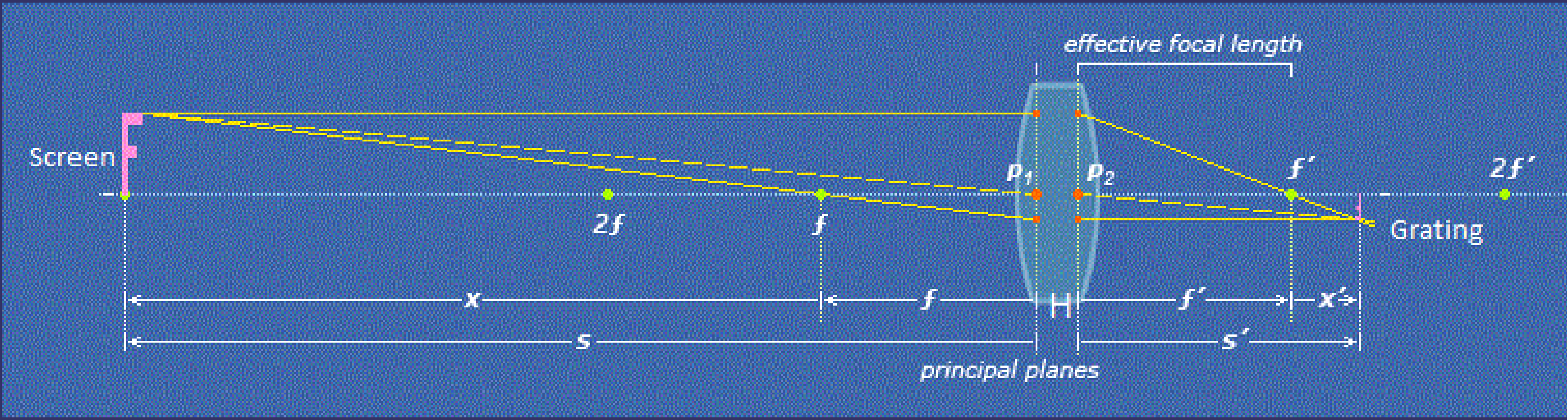
$$\text{Apparent FOV (AFOV)} = \frac{\text{TFOV} \times F}{f}$$

(Telesope Focal Length)
(Eyepiece Focal Length)

$$\text{So AFOV} = \frac{F \times T \times \text{Cos(Dec)}}{f \times 239.3}$$

Measuring Focal Length

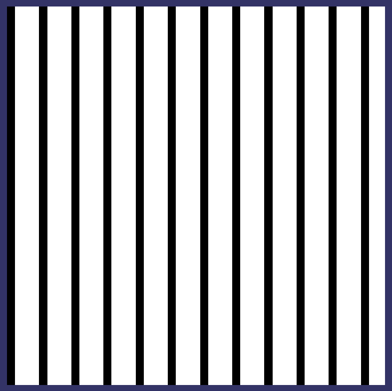
- Focal Length measured from Second Principal Plane – but its position is usually unknown.
- Solution - use Magnification of Object to Image which is less dependent on knowing Principal Plane positions:



- Method 1 – Project a grating onto a screen, at two distances
- Method 2 – Project a grating onto a screen, and estimate error due to Hiatus H

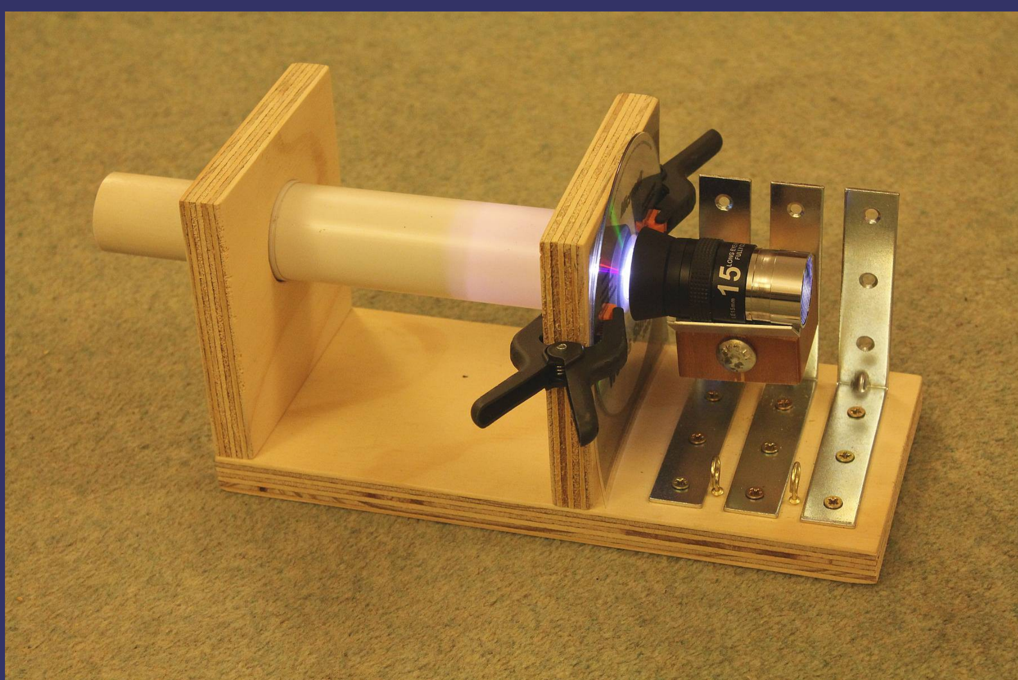
Making a Grating

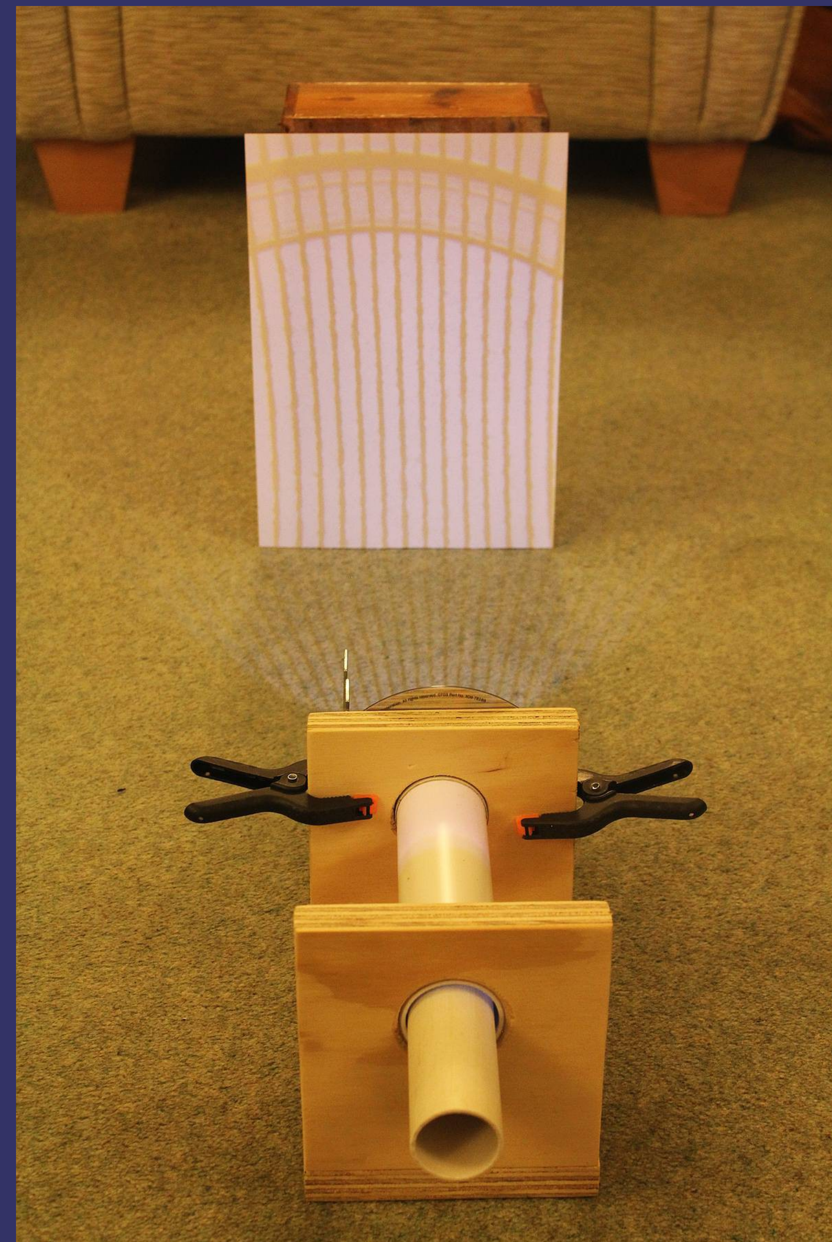
- My B/W Laser Printer has claimed resolution up to 1200 Dots/Inch (= Grating of 600 Lines/Inch)
- Print onto Laser Printer grade transparency film (NOT Acetate – it melts in the printer!)
- Program used to print: grating.exe (Pgrating.zip)
- Best usable quality obtained at 50 Lines/Inch (LPI) using black stripe width of ¼ of grating periodicity
- 50 LPI = 1.9685 Lines/mm (LPmm) (Or round to 1.97 LPmm with error <0.1%)



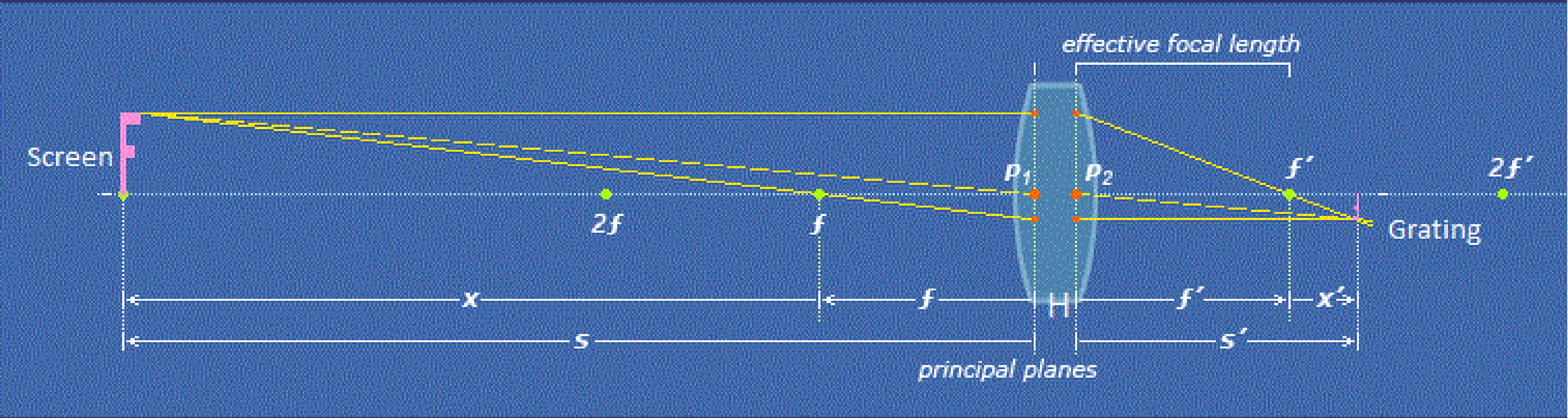
Projecting a Grating

- Printed 1.97 Lines Per mm (LPmm) grating held flat with an old CD
- LED torch in tube slides to optimise illumination
- Eyepiece and carrier adjusted to achieve best focus on screen





Focal Length - Method 1



- Project 1.97 LPmm Grating (right) onto a Screen (left) and measure:
  Distance D_1 (mm) from Screen to convenient point on <u>Eyepiece</u>
  Span W_1 (mm) of N_1 lines+spaces (→ projected image LPmm)
- Reduce Grating to Screen distance to roughly half
- Measure D_2,W_2 and N_2

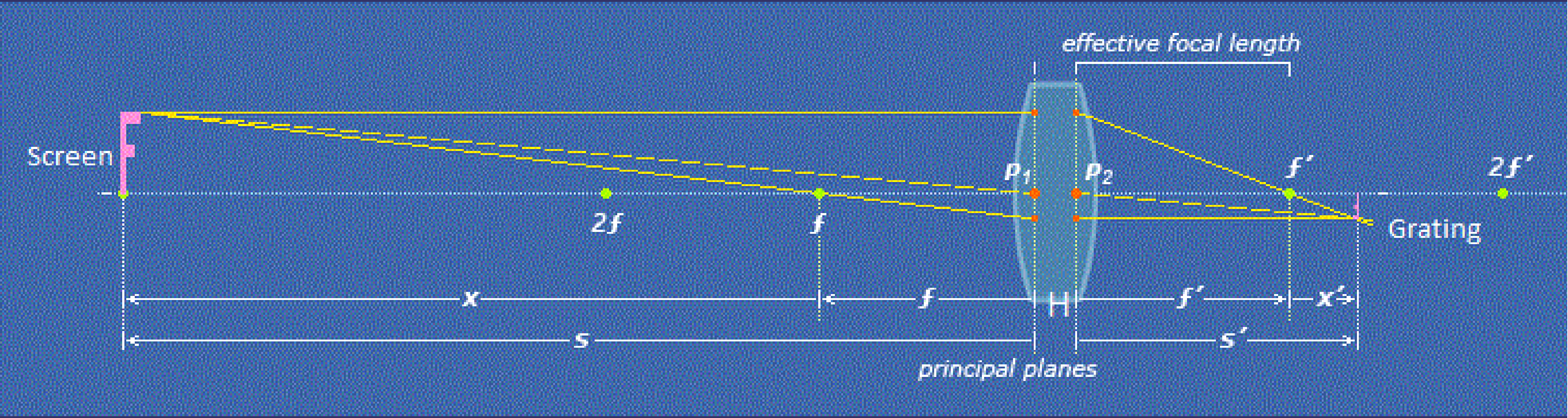
Calculate Magnifications: $M_1 = 1.97*W_1/N_1$ and $M_2 = 1.97*W_2/N_2$
But also, from lens equations, $M_1 = x_1/f$ and $M_2 = x_2/f$
So $M_1\text{-}M_2 = (x_1\text{-}x_2)/f$
Rearrange to calculate f : $f = (x_1\text{-}x_2)/(M_1\text{-}M_2) = (D_1\text{-}D_2)/(M_1\text{-}M_2)$

Critique of Method 1

- Good points:
  - Uses simple grating projection, and distance measurements
  - Requires no knowledge of Hiatus H to give theoretically exact result

- Bad points:
  - Requires 4 distance measurements
  - Differencing two sets of measurements amplifies any errors
  - Measuring distance from eyepiece can disturb the eyepiece

Focal Length - Method 2



- Project 1.97 LPmm Grating (right) onto a Screen (left) and measure:
  Distance L (mm) from Screen to Grating
  Span W (mm) of N lines+spaces (gives projected image LPmm)

L = x + f + H + f + x' but also from lens equations M = x/f = f/x'

so substituting for x and x' and rearranging, (L-H) = Mf + 2f + f/M

so f = (L-H) / (M+2+1/M) where M = 1.97*W/N

Approximations in Method 2

$f = (L-H) / (M+2+1/M)$ where $M = 1.97*W/N$

- But if projected lines are say >10mm apart then M>20 so effect of 1/M term compared to M is <0.25% and can reasonably be ignored

- If Hiatus H is << L can we ignore H as well?

- H measured typically from 5mm to 60mm (see next section) so for example:
  If projection distance L were 3m and H were 30mm the error in calculated f would be ~1%

Approximate Formula: $f = L/(M+2)$

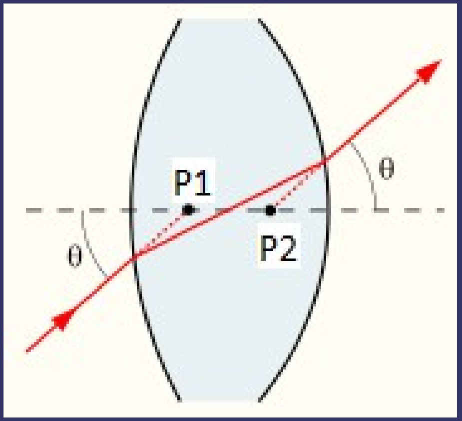
Critique of Method 2

- Good points:
  - Uses simple grating projection, and distance measurements
  - Requires only two distance measurements
  - Simplified formula can give approximate result with only small % error

- Bad points:
  - Requires knowledge of Hiatus H to give theoretically exact result

Locating the Principal Planes

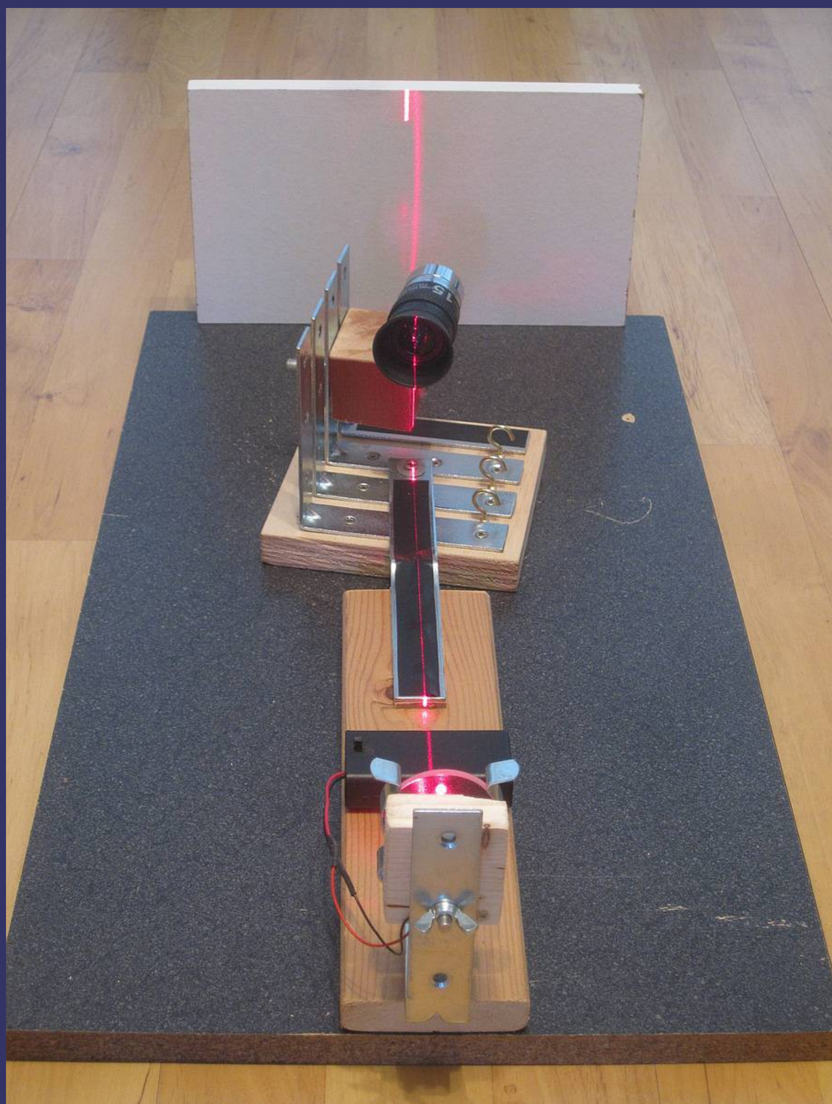
- Focal Length measurement is more accurate if we can also measure the Hiatus gap H
- A light ray through First Principal Point P1 entering at angle Ɵ exits at same angle Ɵ through P2
- Equivalent to rotating the lens about P1 by angle Ɵ



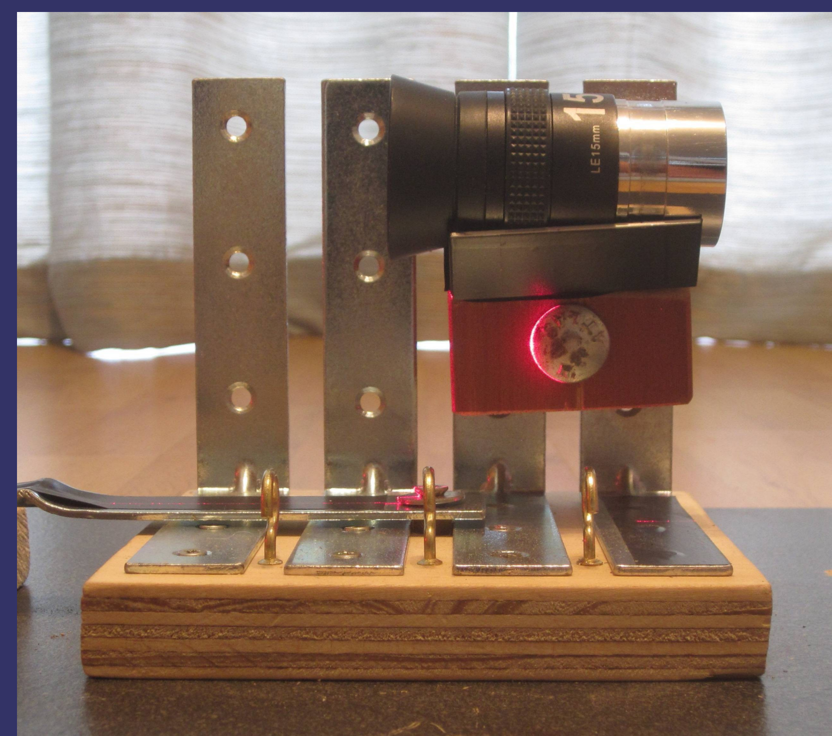
  - Use 'Nodal Slide' to rotate lens about arbitrary points on lens axis
  - Search for point where input angle and output angle are the same – this point identifies P1
    (Note – light ray is offset sideways as it crosses Hiatus)
  - Reverse lens and repeat to locate P2

(Nodal Slide usually used by projecting distant object onto screen at focus f, but impractical for small f)

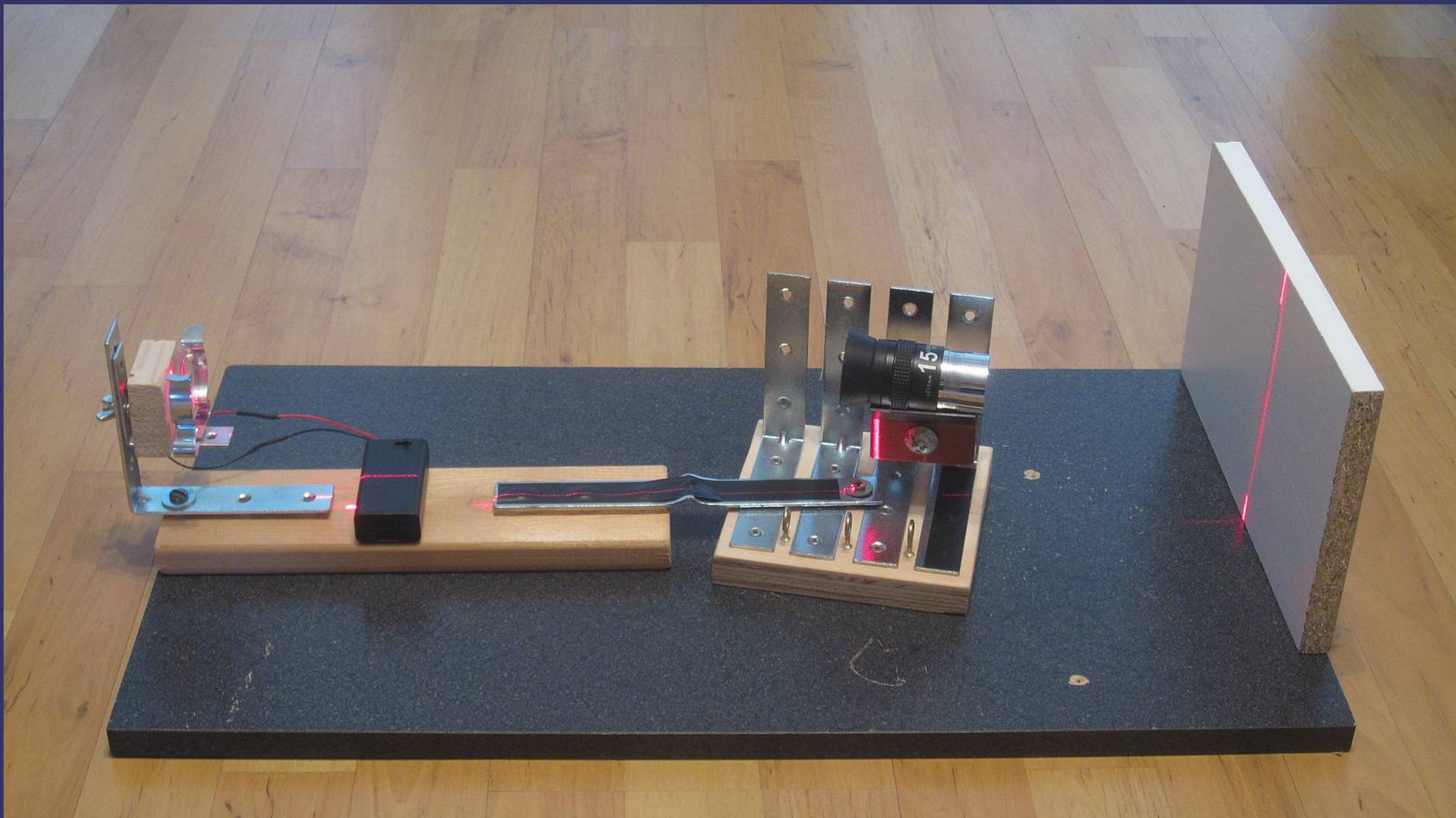
DIY Nodal Slide



- Eyepiece carrier rotates about central pivot point on base
- Laser projects line through pivot point, and can also rotate round pivot
- Eyepiece moved fore/aft on carrier, and carrier rotated - deflection of laser line observed



DIY Nodal Slide



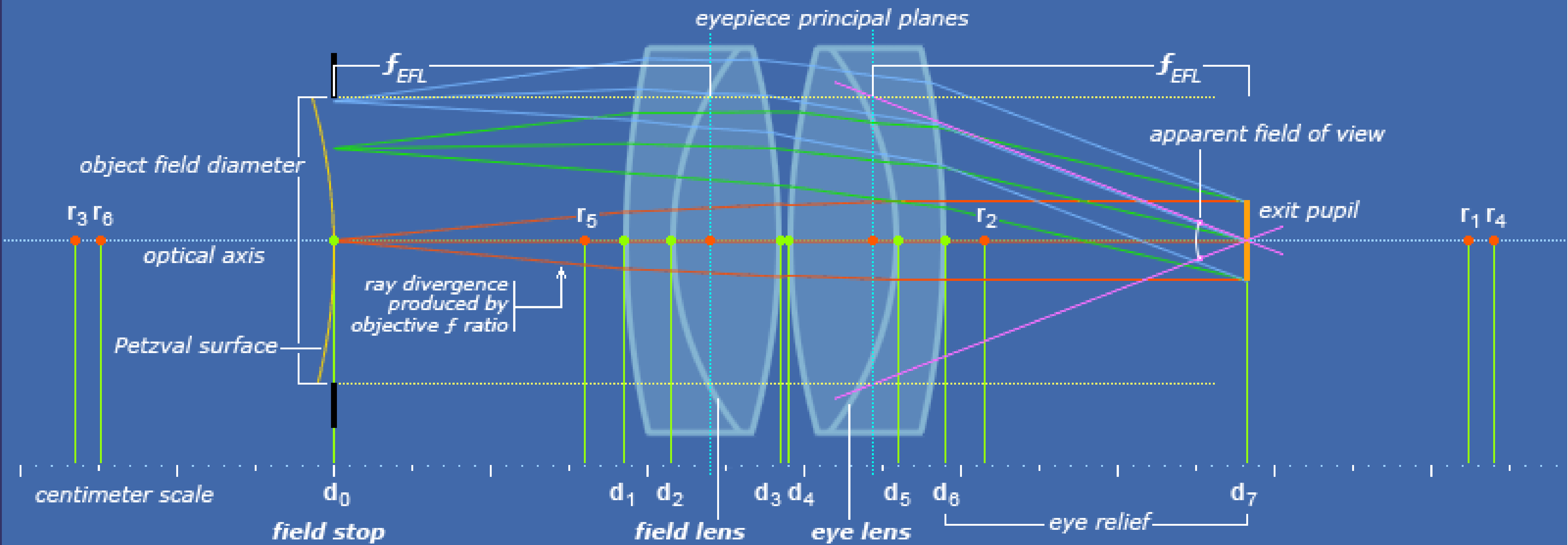
Results Summary

Measured →	Focal Length	Eye Relief from Lens Surface	Principal Plane Separation	Field Of View	Specified Field Of View
Units →	mm	mm	mm	degrees	degrees
Old Knurly	37.2	19	~20	76	
Old X80	48.1	12	29	33	
Old X??	51.0	15	12	39	
Old F=0.6” (=15mm)	13.4	2	17	33	
Old F=0.9” (=23mm)	21.6	4	36	48	
20mm Kellner	19.6	14	8	55	
10mm Kellner	10.4	7	6	58	
15mm high eye relief	14.7	18	17	51	50
5mm high eye relief	4.9	22	60	43	45

Other eyepiece considerations

- Parfocal or not?
  - Field Stop relationship with Shoulder
- Barrel size – 1.25” or 2” (or other)
  - 1.25” barrel limits AFOV to ~50deg at f~32mm
- Balance of Astigmatism/Field Distortion/Coma/Chromatic Aberration
  - Cancelling / Balancing requires more lens elements
- Ghosting / Loss of Contrast
  - Problems increase with more lens elements but controlled by multicoating
- Suitability for Telescope F ratio (= Focal Length / Diameter)
  - Smaller F ratio means wider entrance (field) angle means distortions generally increase – need complex design?
- Field Curvature (Petzval Radius)
  - Eye normally compensates but can match eyepiece to telescope, or use field flattener (or Barlow lens?)
- Exit pupil = Eyepiece Focal Length / Telescope Focal Ratio
  - Exit pupil >7,6,5...mm means light 'wasted'
- Weight and price!

Example Plössl Eyepiece Design



prescription data

	radius		distance	glass
field stop		d_0	0	
r_1	53.894	d_1	18.45	.
r_2	22.967	d_2	2.997	Schott N-SF1
r_3	–44.961	d_3	7.061	Schott N-SK14
r_4	44.961	d_4	0.508	.
r_5	–22.967	d_5	7.061	Schott N-SK14
r_6	–53.894	d_6	2.997	Schott N-SF1
eye relief		d_7	19.330	.

Object field diameter	18.2 mm
Exit pupil	5 mm
Effective Focal Length (f_{EFL})	24 mm
Eye relief	19.3 mm
Field of View	~42°
Petzval radius	–35 mm

Eyepiece Designs

Diagrams and notations courtesy of:

Bruce MacEvoy at Black Oak Observatory, California
and “The Evolution of Eyepiece Design” by Christopher Lord, UK

Eye Relief as fraction of
eyepiece focal length

Typical Apparent
Field Of View

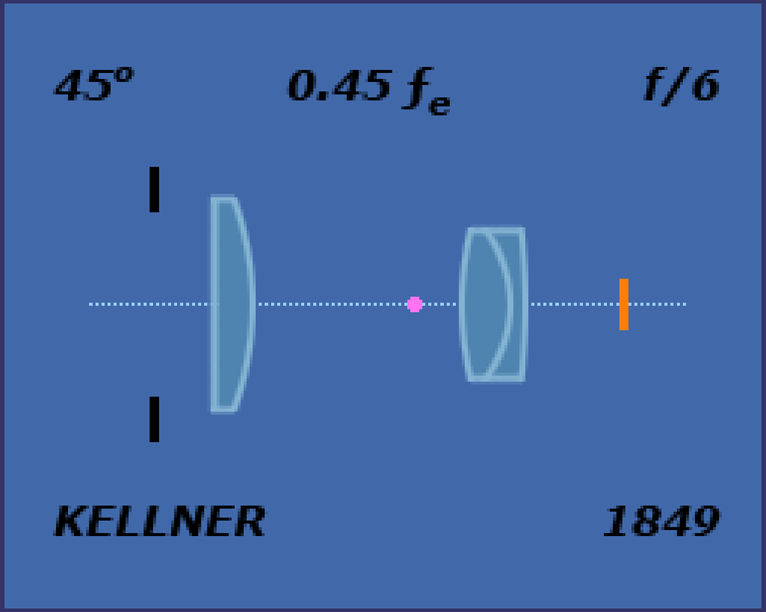
Minimum suitable
telescope
F number ?

Field Stop

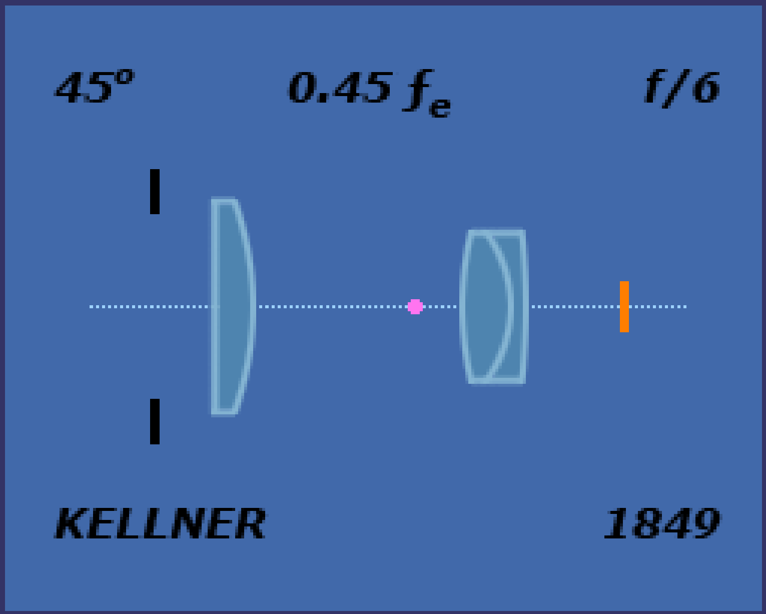
Exit Pupil

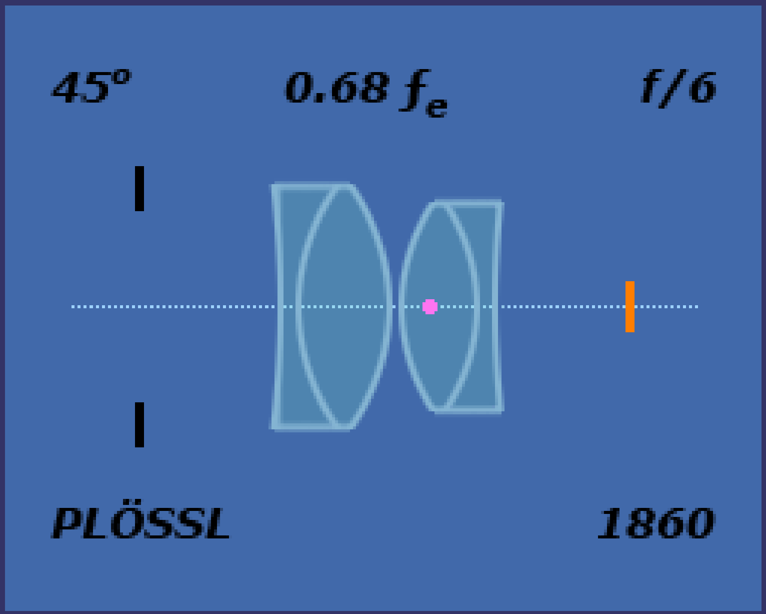
Designer / Type

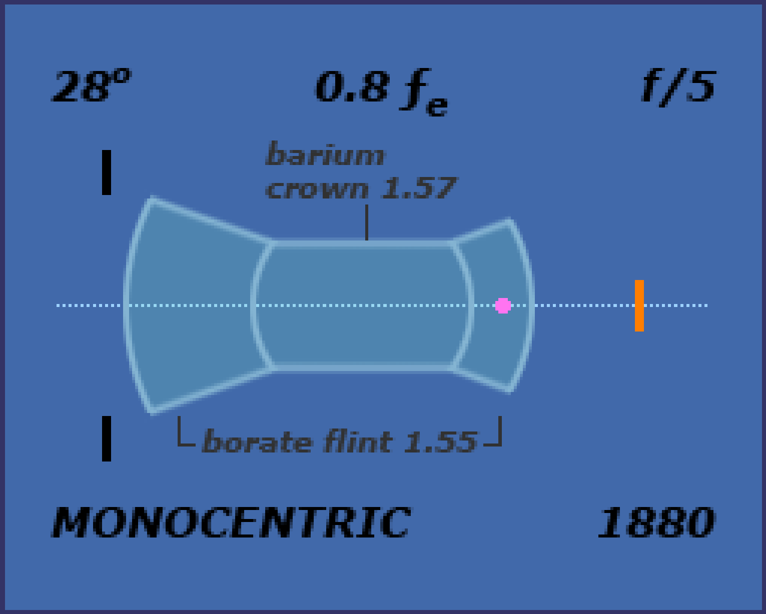
Year of design

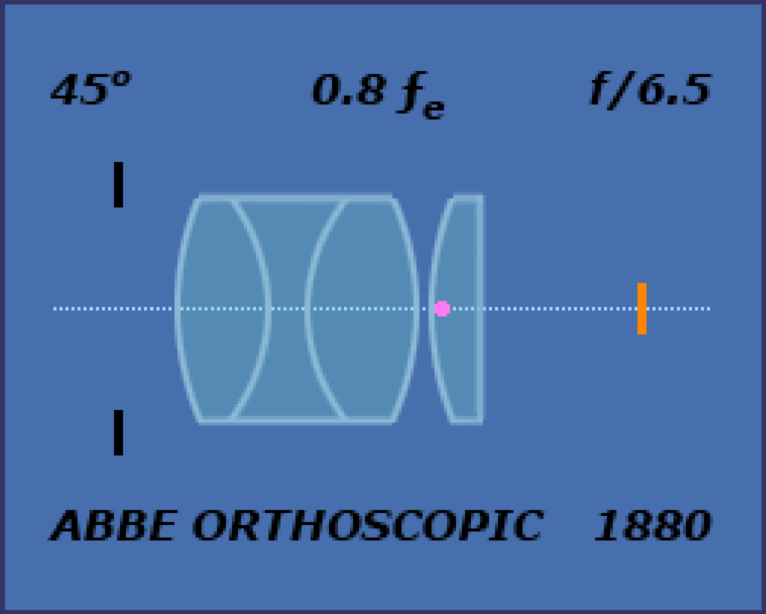


Eyepiece designs - 19th Century

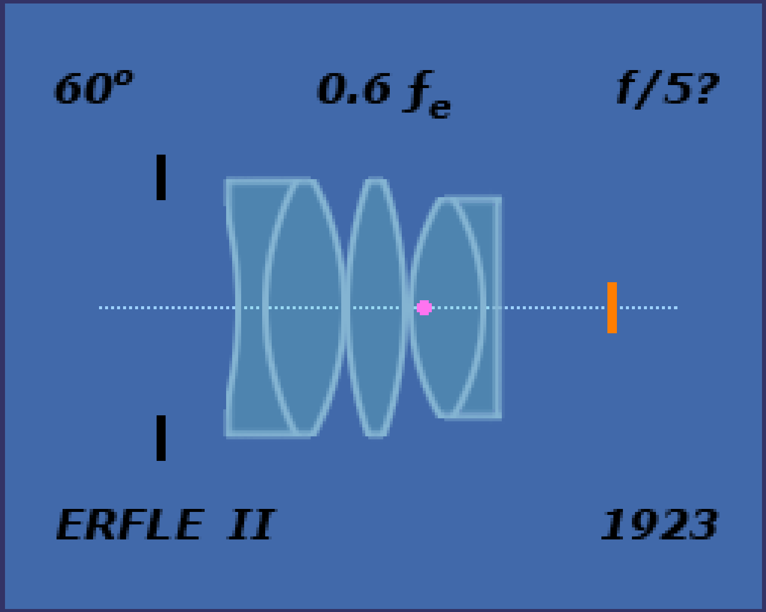


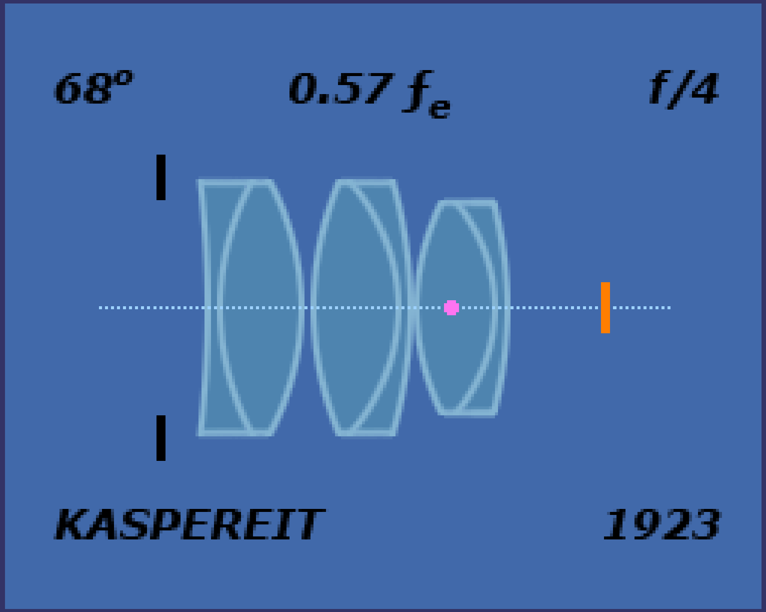


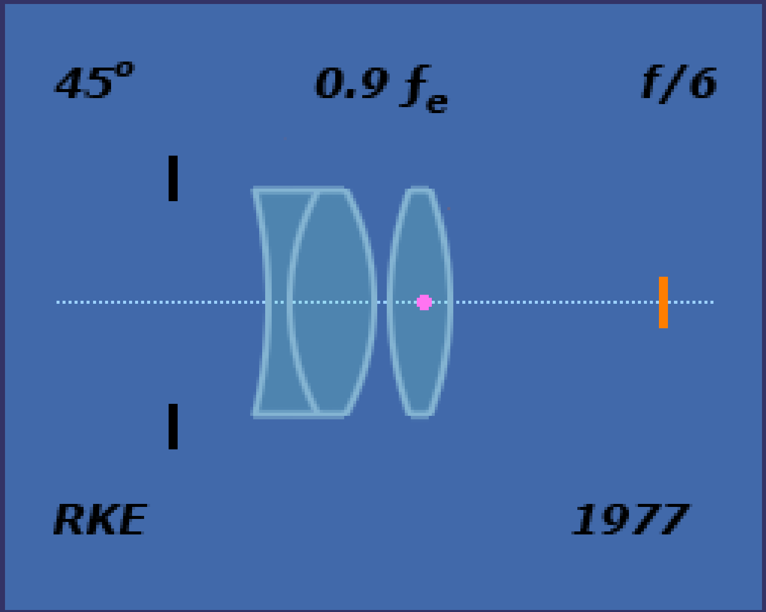


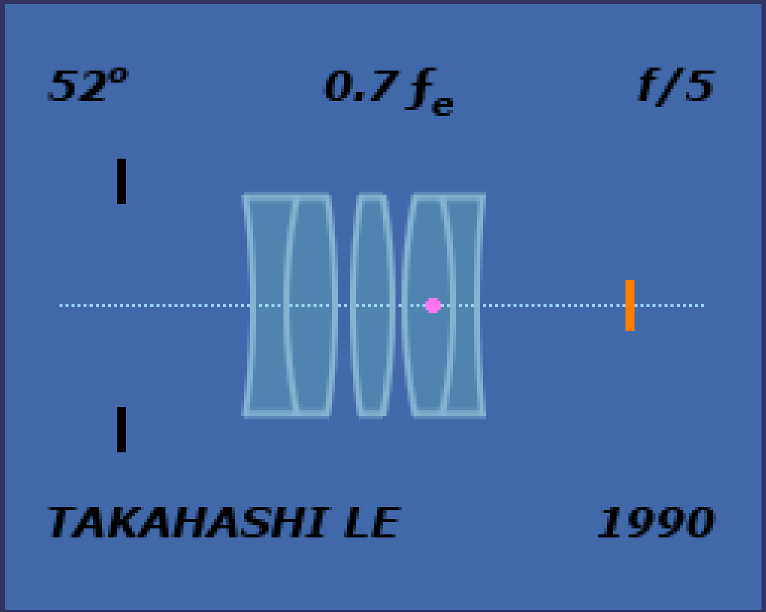


Eyepiece designs - 20th Century

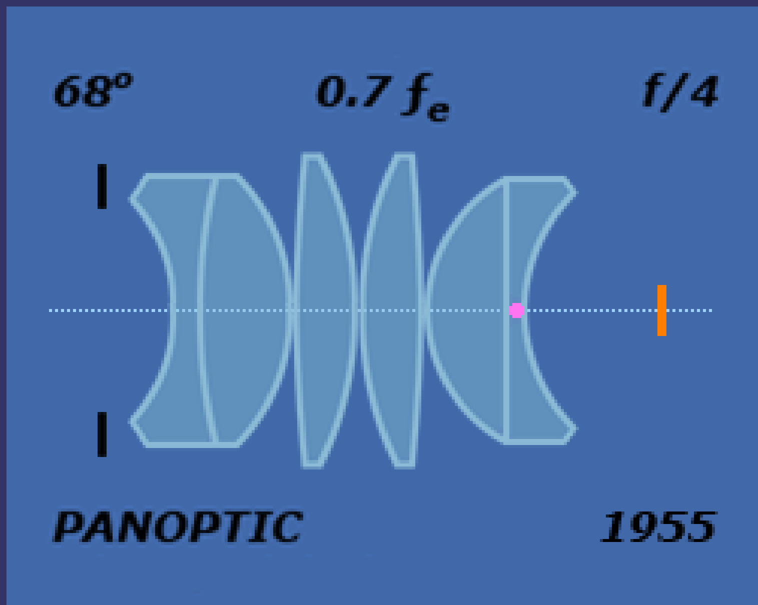


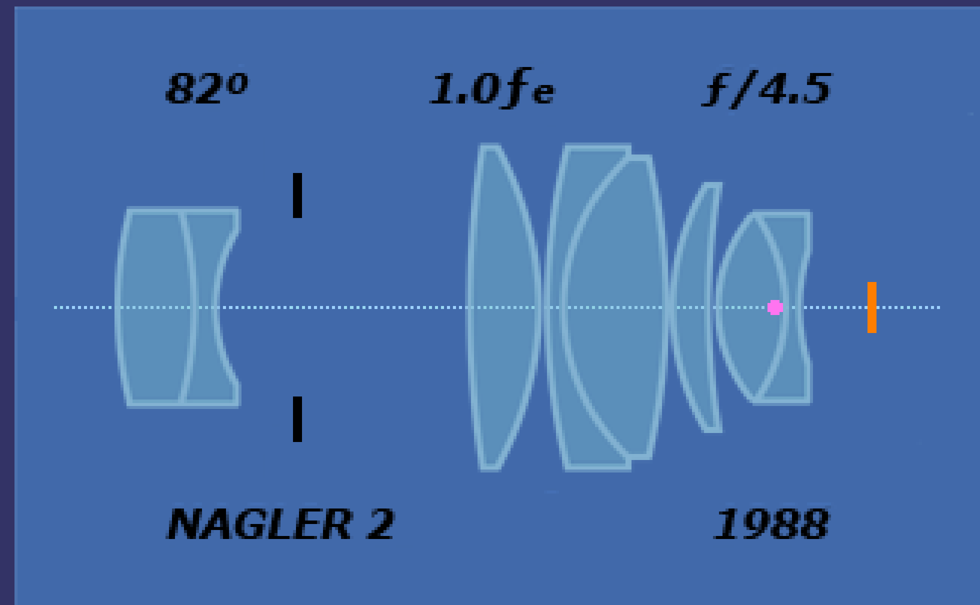


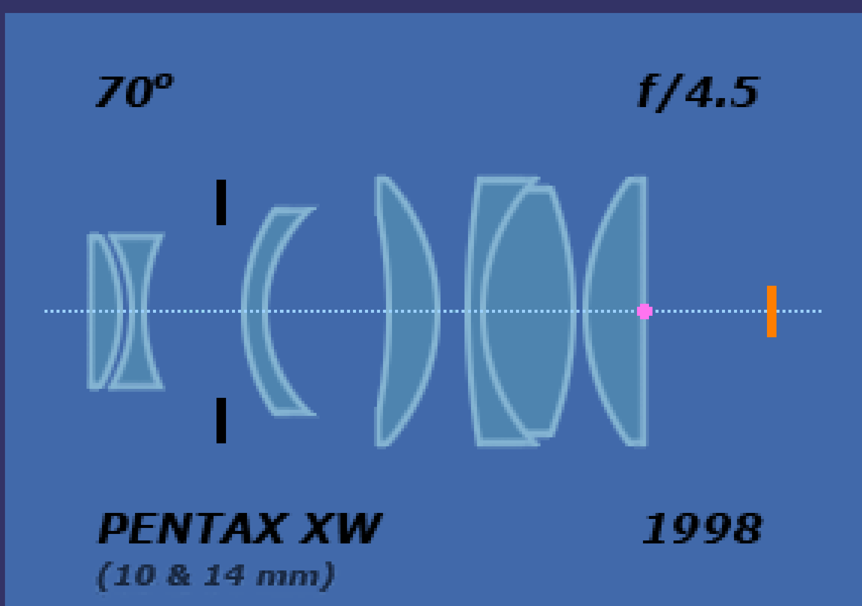


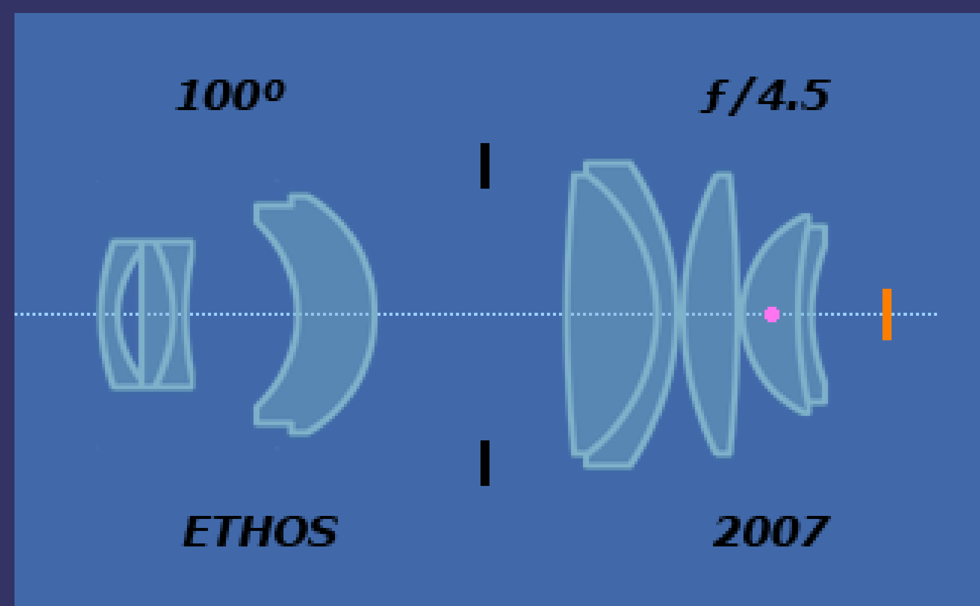


Eyepiece designs – Wide Angle









Summary

- Easy ways to measure eyepiece parameters:
  Eye relief – focus distant object onto paper
  AFOV – measure projected light cone, or use star drift
  Focal Length – project grating with torch then f ~ L/(M+2)
- More complex methods can yield more exact focal length if required
- Eyepiece designs increase in complexity to better control aberrations, or increase AFOV
- 'Classic' designs such as such as Plössl, Orthoscopic, Erfle still very good assuming quality manufacture
- More complex (costly) eyepieces more justified on low F ratio telescopes or to get a high AFOV

Future Workshops?

- Interaction of exit pupil size and eye pupil size
- Brightness of extended objects versus point sources – effect of magnification etc.
- Aberrations in more detail – how to measure and/or compare them
- History of eyepiece evolution
- Field Curvature – does it matter ?

Acknowledgements and Resources

- Most optics diagrams used with kind permission of Bruce MacEvoy at Black Oak Observatory, California, Astronomical Optics section at http://www.handprint.com/ASTRO/
- “The Evolution of Eyepiece Design” by Christopher Lord, Brayebrook Observatory UK at http://www.brayebrookobservatory.org/BrayObsWebSite/BRAYOBS%20PUBLICATIONS.html
- http://www.telescope-optics.net/
- http://www.jim-easterbrook.me.uk/astro/ep/method/