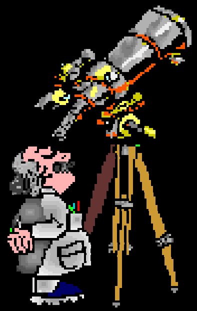


CHAPTER 1 Optical Telescope

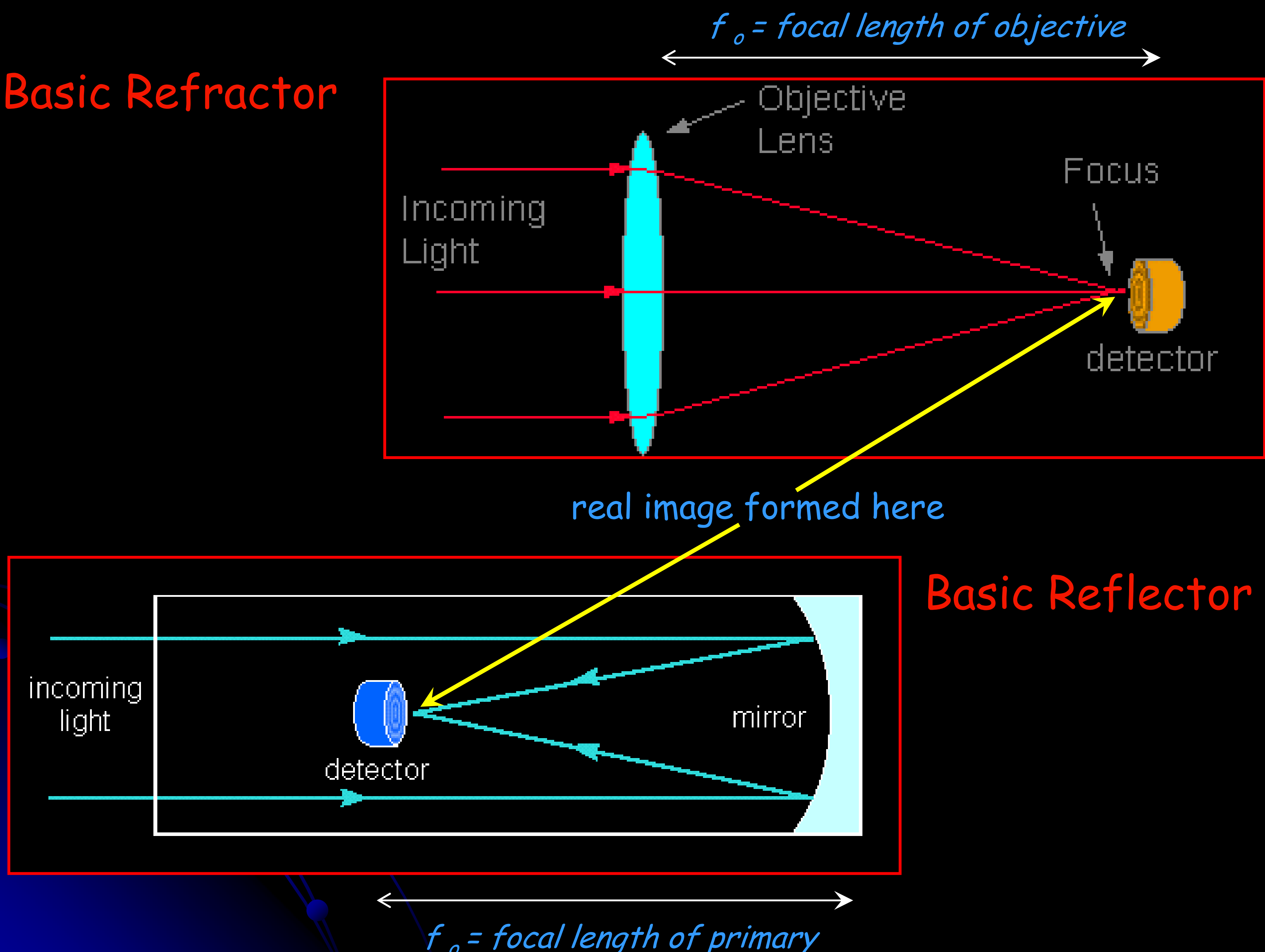
I. Reflective and Refractive Telescopes
II. Telescope Optics
III. Optical Aberrations
IV. Telescope Configuration
V. Telescope Mount
VI. Observatory and Observatory site

I. Reflective and Refractive Telescopes

- ✓ Telescopes serves three main functions: (1) they are light collectors. The simplest telescopes simply focus light rays to a small area.; (2) Resolve light so that finer details can be seen; (3) Magnification: making objects look bigger (closer)
- ✓ Two main types: refractive and reflective
- ✓ As we are observing objects at very large distances, light can be assumed to come from infinity and can be represented as parallel rays

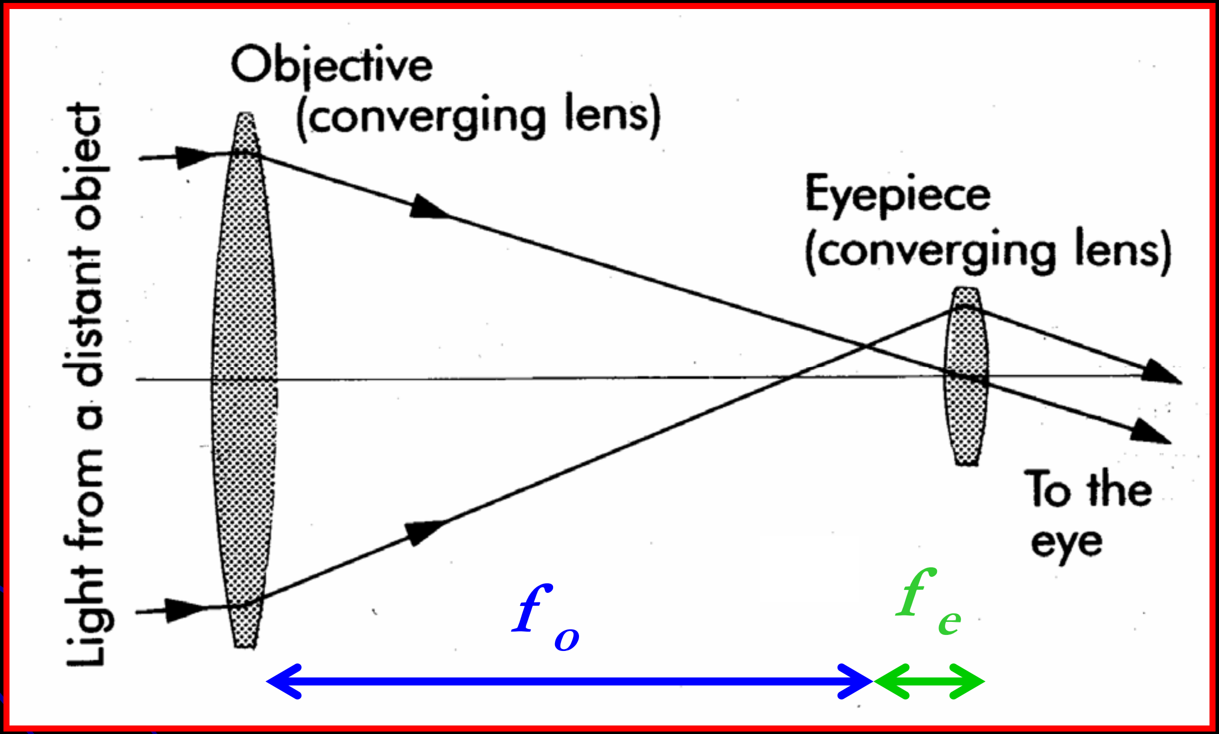
Basic Refractor

Basic Reflector



✓ For research telescopes or for astrophotography, we will place the analyzer (e.g. photometer, spectrometer) at the location of the focal plane

✓ For visual observations, we need an eyepiece to properly collect the light through the objective lens or the primary mirror into the eye

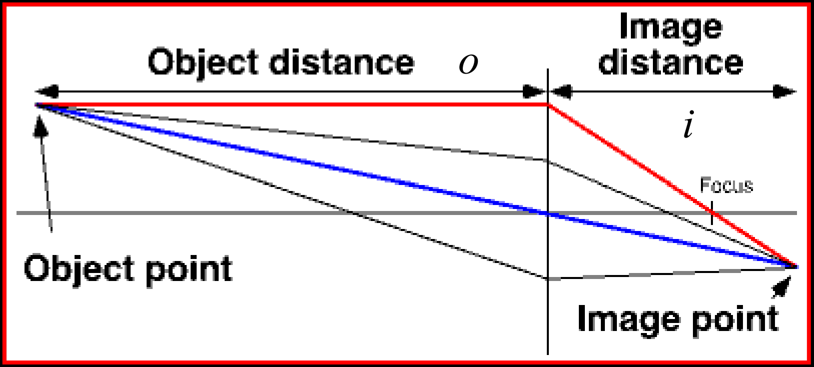


© C.R Kitchin: Telescope and Technique

Note: Focal point of objective and eyepiece coincide

Optics Review

✓ Lens Formula: $1/o + 1/i = 1/f$



where o = object distance from lens, i = images distance from lens, f = focal length of lens

✓ Linear magnification m: $m = -i/o$

where $m > 0$ if the image is erect,
$|m|>1$ if enlarged

Reference: *Optics* by Hecht and Zajac (Addison-Wesley)

II Telescope Optics

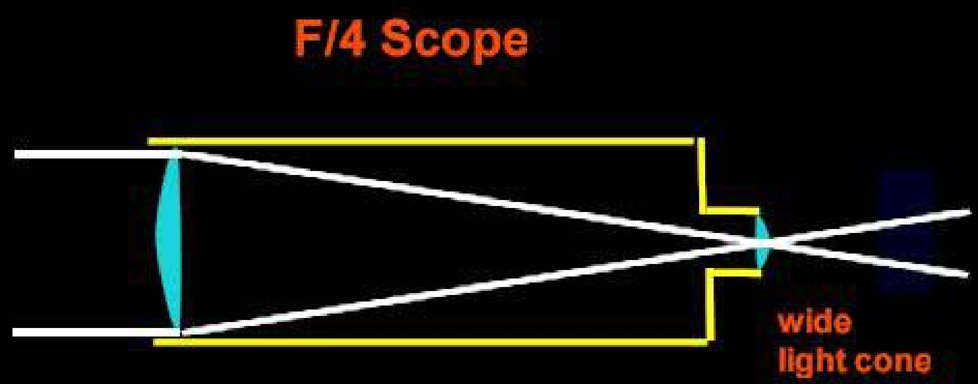
- One of the most important number that characterize a telescope is its focal ratio (or, f/ number)

$$focal\ ratio = \frac{Focal\ \ length\ \ of\ primary}{Aperture\ \ diameter\ \ of\ primary}$$

- E.g. Telescope's aperture diameter = 5 cm
  Focal length of primary = 25cm
  Focal ratio = 25cm/5cm = 5 (a f/5 telescope)

FAST telescope (or, fast scope, <~ 6)

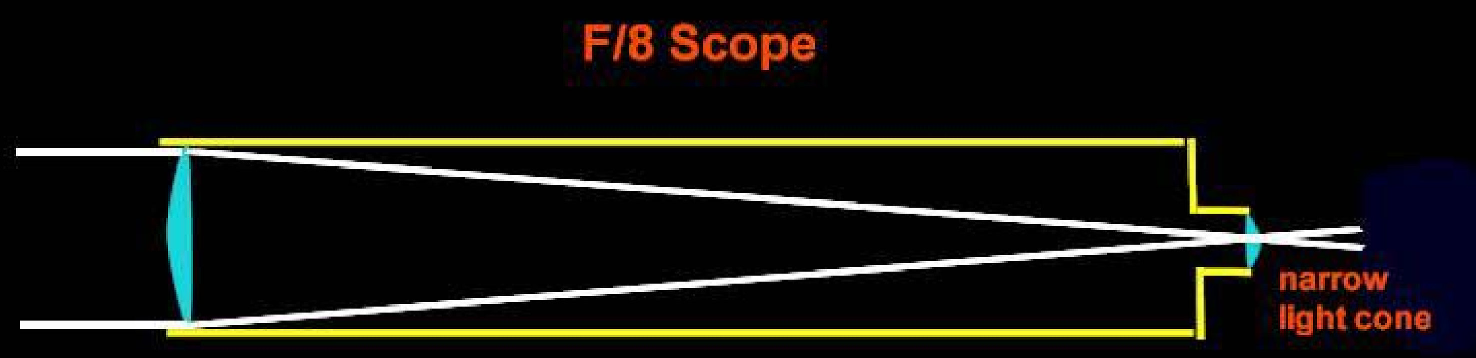
1. Small focal ratio (or, small f/ number)
2. So, short telescope for fixed aperture
3. Wide field of view (with same eyepiece)
4. Excel at low power (low magnification) views of deep sky objects, e.g. galaxies, nebula, or open clusters



Adapted from:
http://www.absolutebeginersastronomy.com/

SLOW telescope (or, slow scope, >~ 8)

1. Large focal number
2. Narrow field of field (with same eyepiece)
3. Good for high power (magnification), small field observing, e.g. planets, double stars
4. Most large research telescopes are slow, e.g. Hubble Space Telescope (f/24)

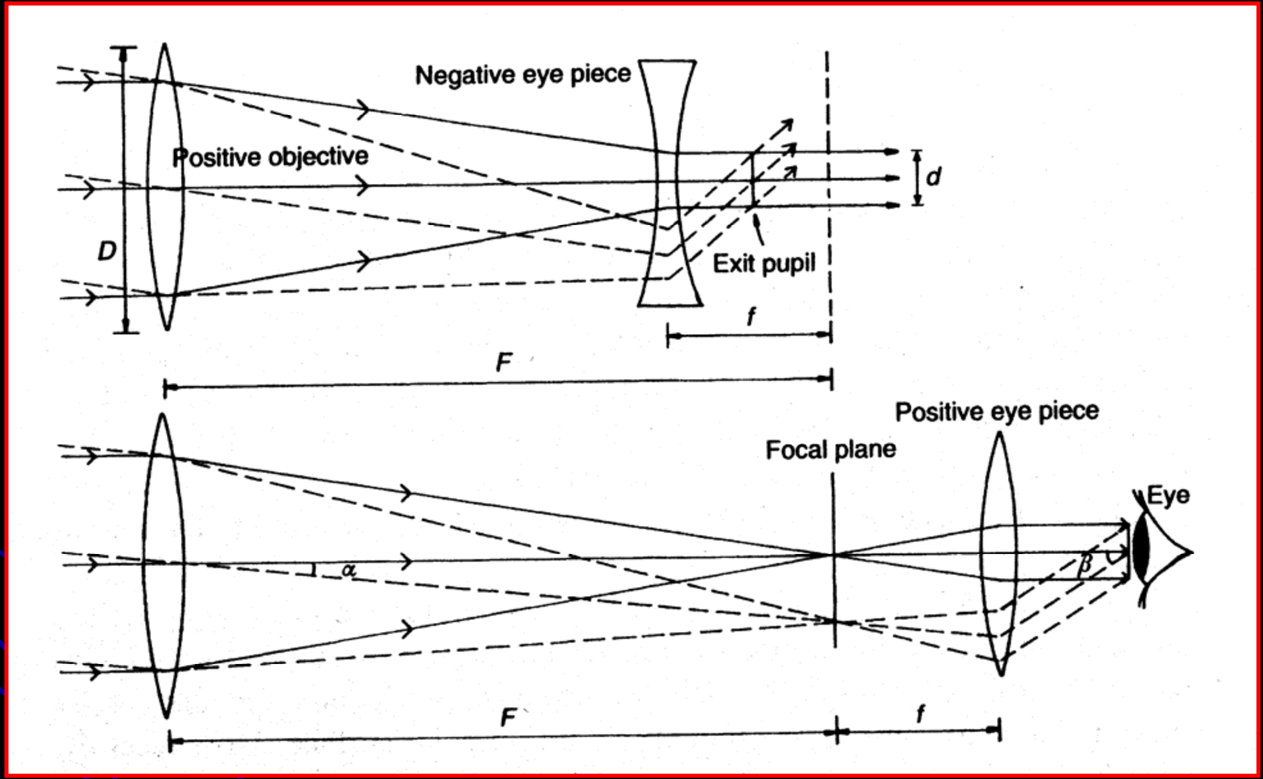


Adapted from:
http://www.absolutebeginersastronomy.com/

Magnification

$$f_o = F \text{ and } f = f_e$$

$$M = \frac{\beta}{\alpha} = \frac{f_o}{f_e}$$

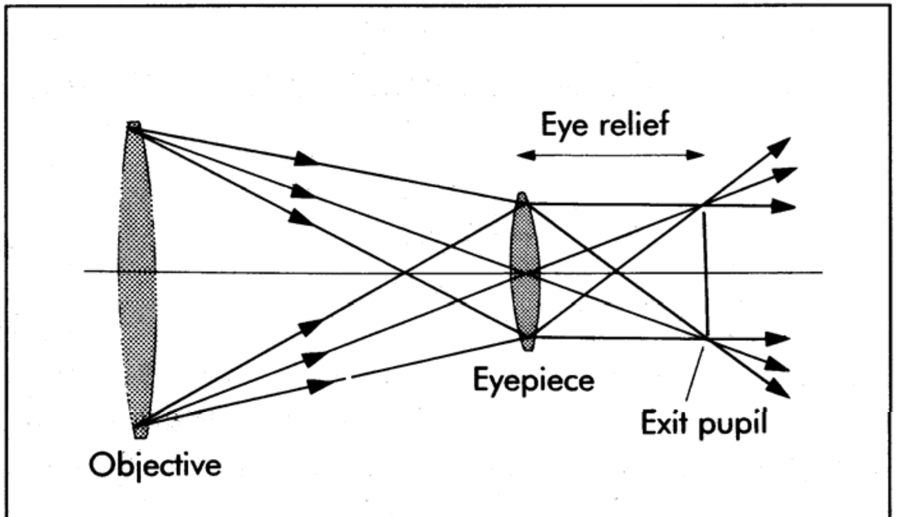


Adapted from: Observational Astrophysics by Robert C. Smith

Note: Negative sign in formula dropped

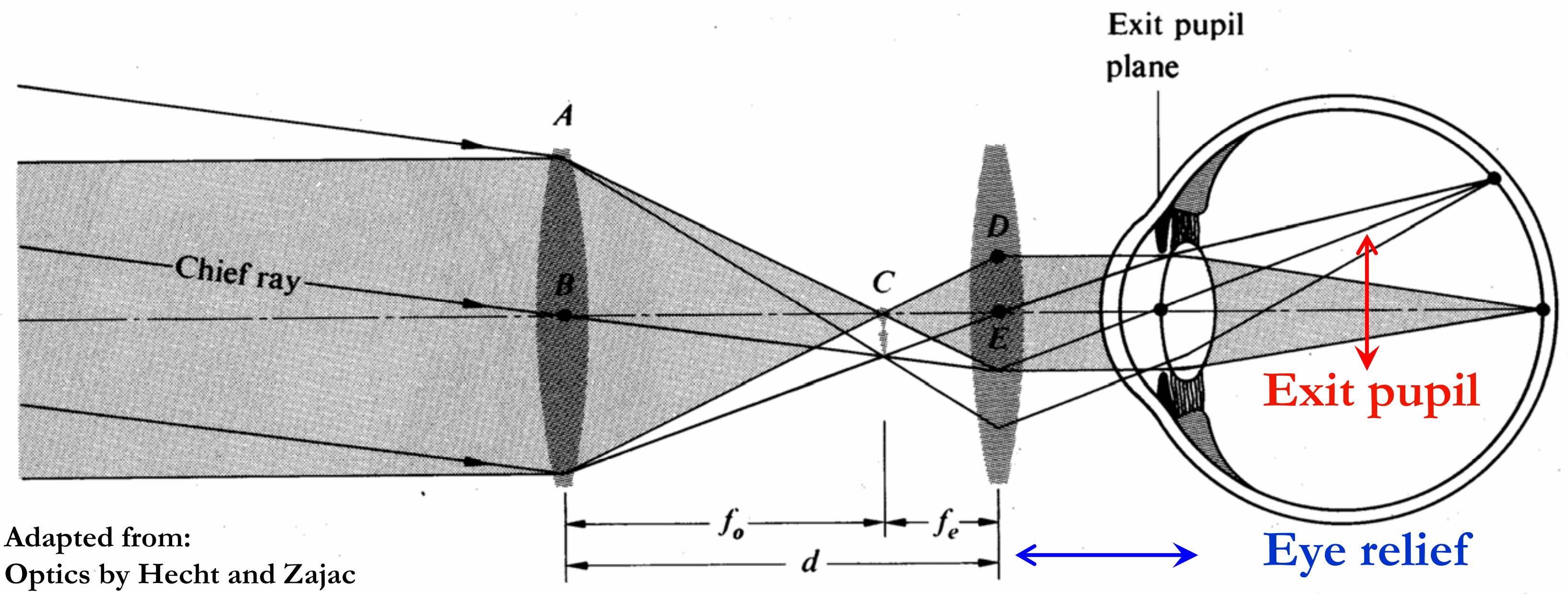
Exit pupil

- ✓ The size of image of objective lens as seen by the eyepiece is called the Exit Pupil
- ✓ All light passing through the objective must also pass through the exit pupil



Adapted from: Telescope and Technique by C.R Kitchin

- ✓ Eye Relief: distance between eyepiece and exit pupil



Adapted from:
Optics by Hecht and Zajac

✓ Suppose D = diameter of primary/objective

d = diameter of exit pupil

$$\boxed{\frac{d}{D} = \frac{i}{o} = \frac{f_e}{f_o + f_e} \approx \frac{f_e}{f_o} = \frac{1}{M}}$$

because usually $f_o >> f_e$,and we have

$$\boxed{\therefore d = \frac{D}{M}}$$

Practical Information:

Diameter of human pupil ~ 7 mm

Comfortable eye relief ~ 6 – 10 mm

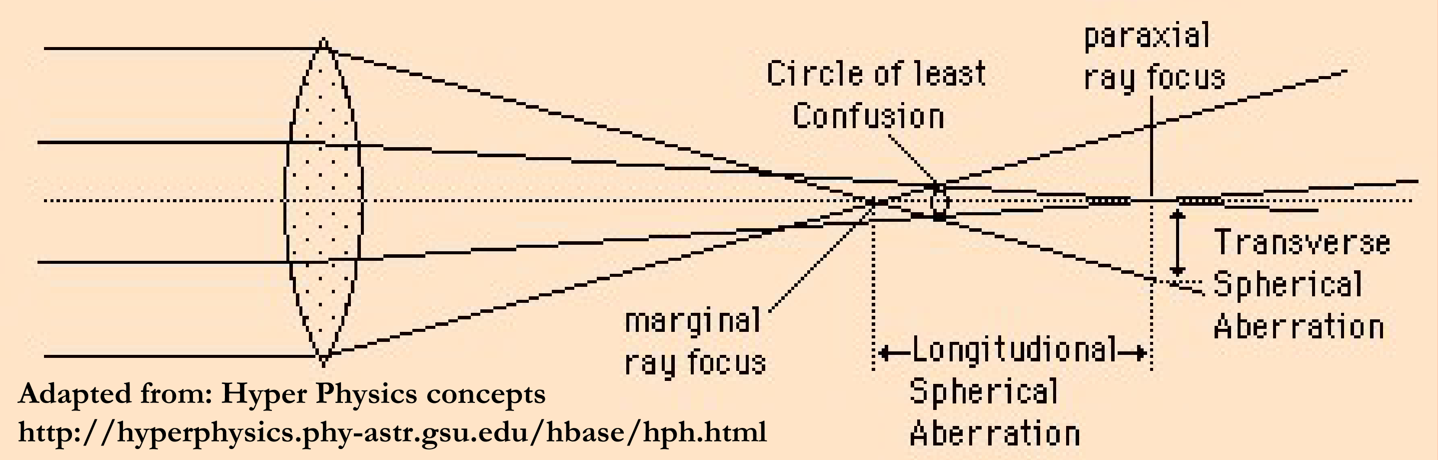
III Optical Aberrations

- ✓ Any deviation from perfection of an image not due to diffraction are known as aberrations

- ✓ There are six primary aberrations: Spherical aberration, Coma, Astigmatism, Distortion, Field Curvature, Chromatic aberration

- ✓ All, except the last one, affect both refractive and reflective telescopes. Chromatic aberration affects only refractive telescopes.

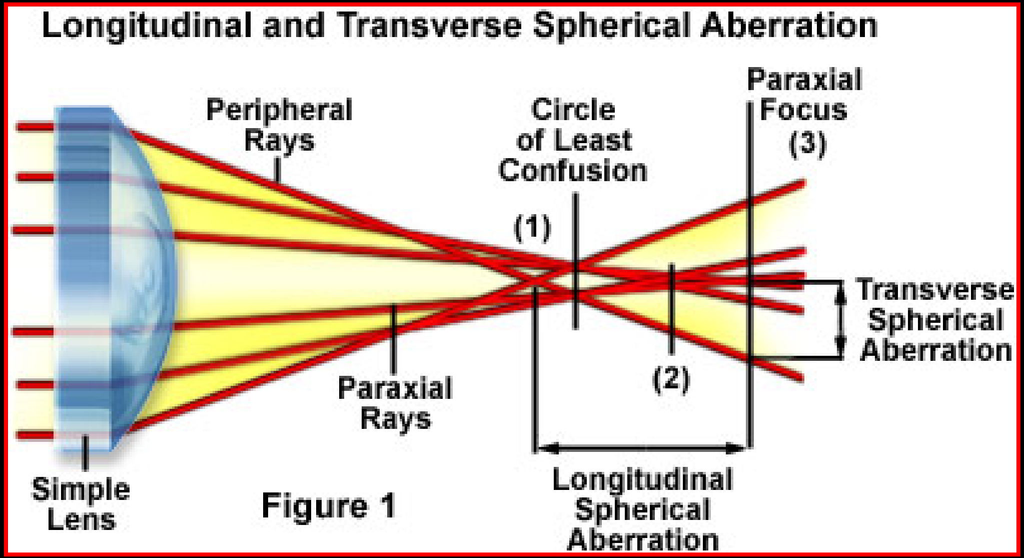
1. Spherical Aberration

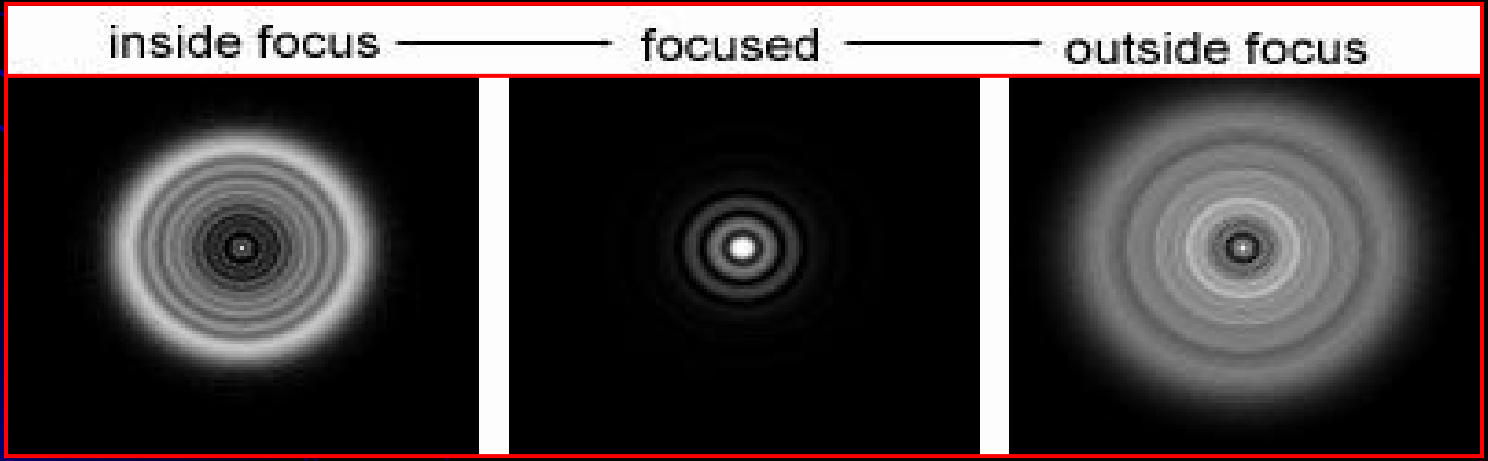


Adapted from: Hyper Physics concepts
http://hyperphysics.phy-astr.gsu.edu/hbase/hph.html

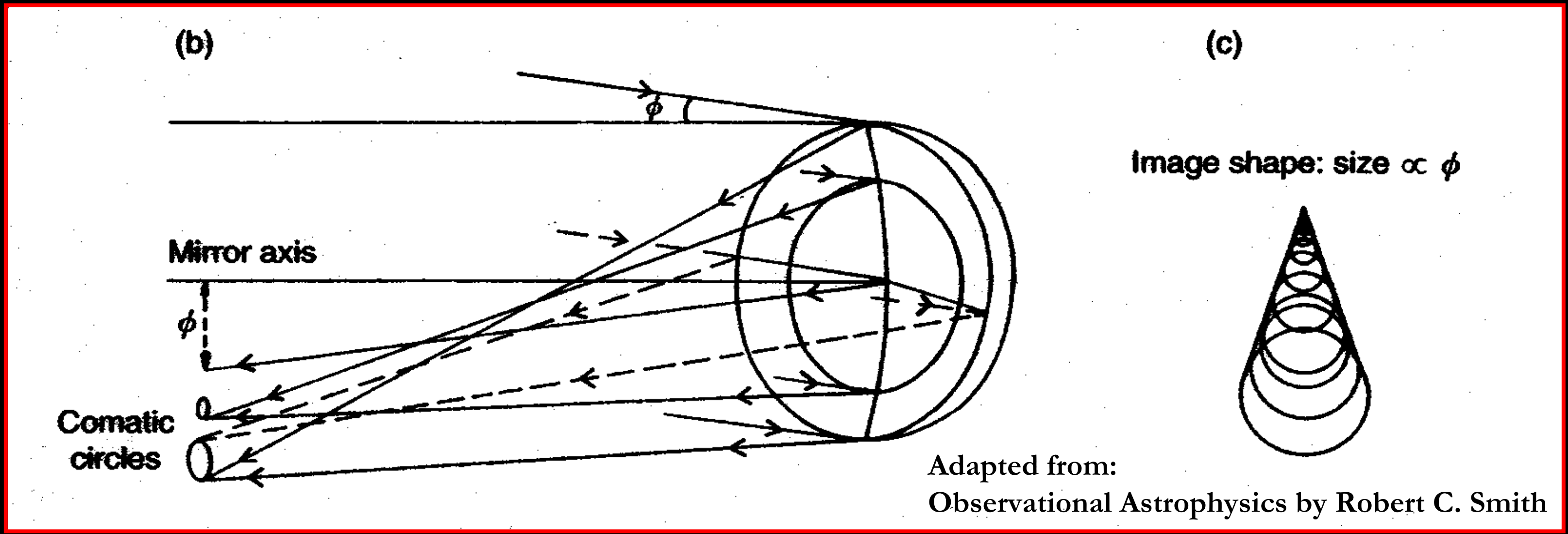
- ✓ For lenses and mirrors made with spherical surfaces, rays which are parallel to the optic axis but at different distances from the center fail to converge to the same point.
- ✓ Effect is usually a 1%, or larger, difference in focal length
- ✓ For mirrors, effect can be totally removed if the mirror is parabolic instead of spherical (However, it is difficult to grind parabolic shape!)

Demonstration of Spherical Aberration





2. Coma



✓ For light rays entering the lens at an angle (off-axis)

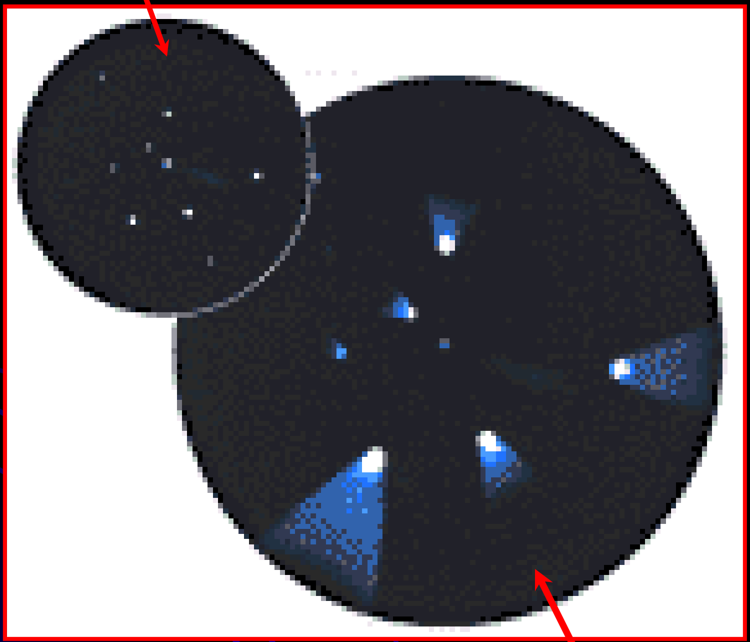
✓Coma is an effect where images of off-axis objects are displaced by increasing amount away from optical axis.

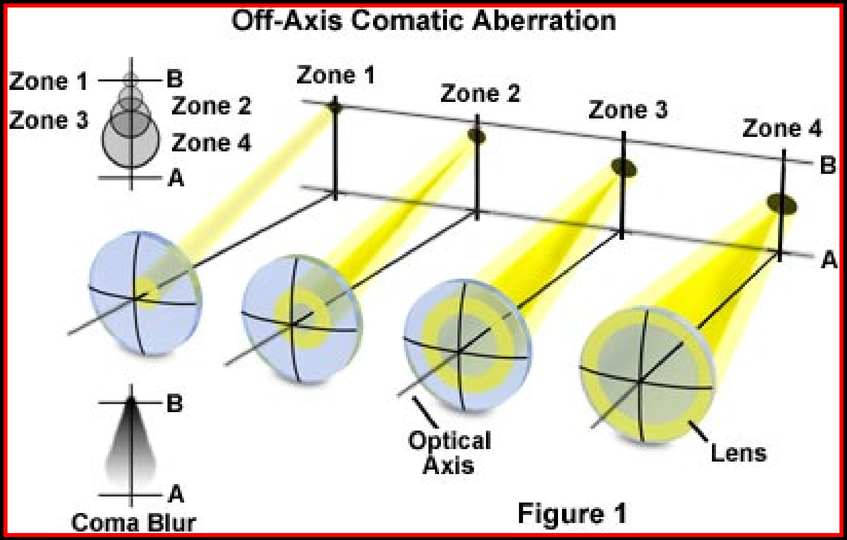
✓Create trailing "comet-like" blur directed away from axis.

✓May produce a sharp image in the center of the field, but become increasingly blurred toward the edges.

Demonstration of Coma Aberration

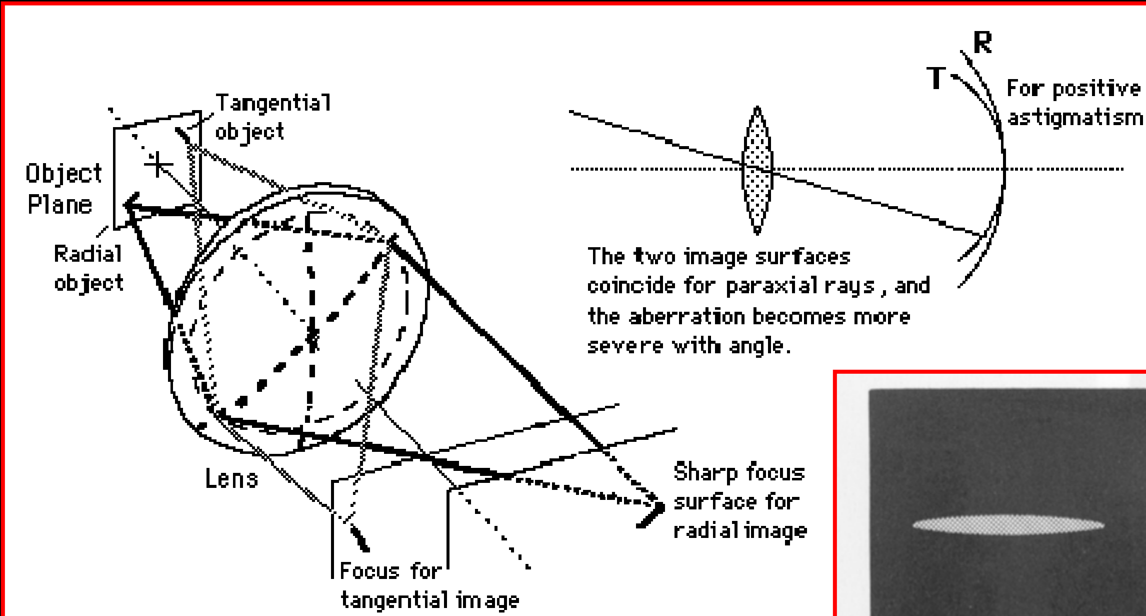
Circular stars





Comet-shaped stars

3. Astigmatism



Adapted from:
Telescope and Techniques by C. R. Kitchin

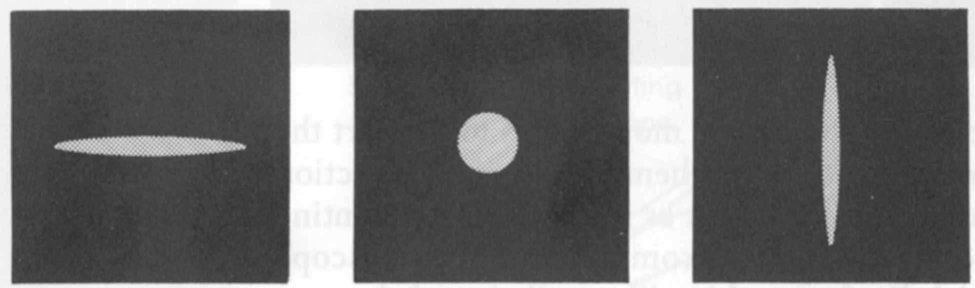


Image to one side of the position of the circle of least confusion

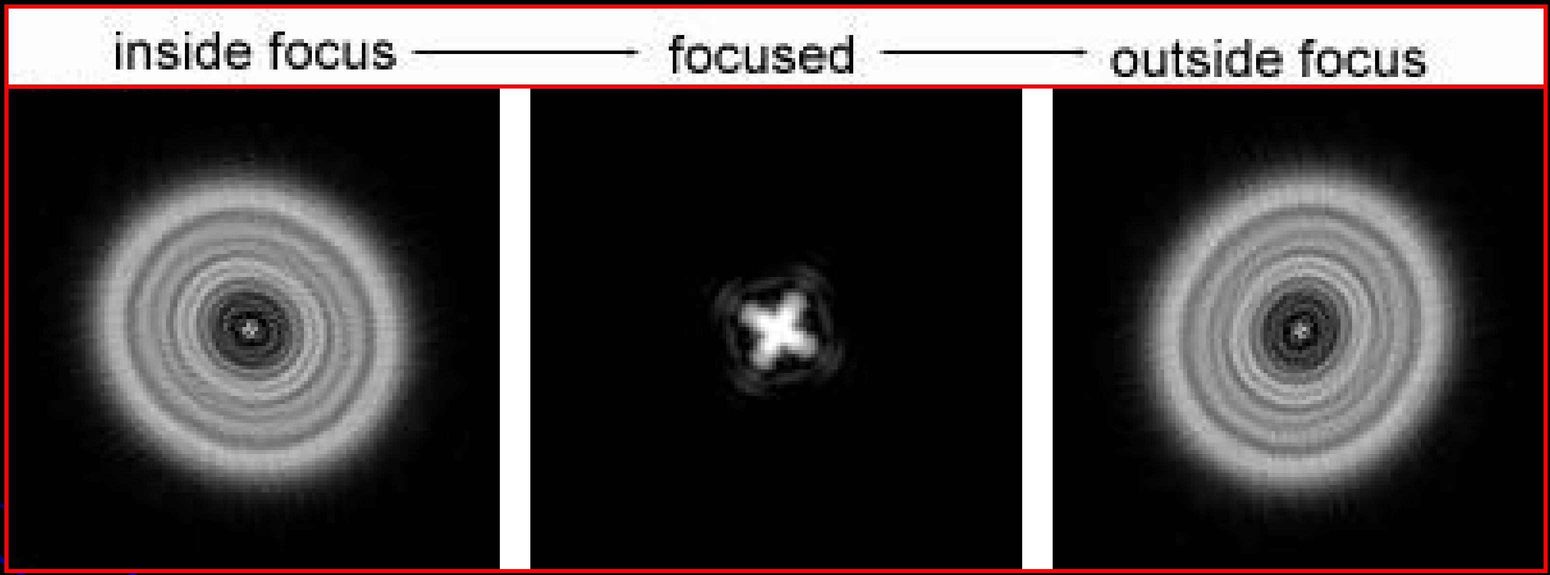
Circle of least confusion

Image to the other side of the position of the circle of least confusion

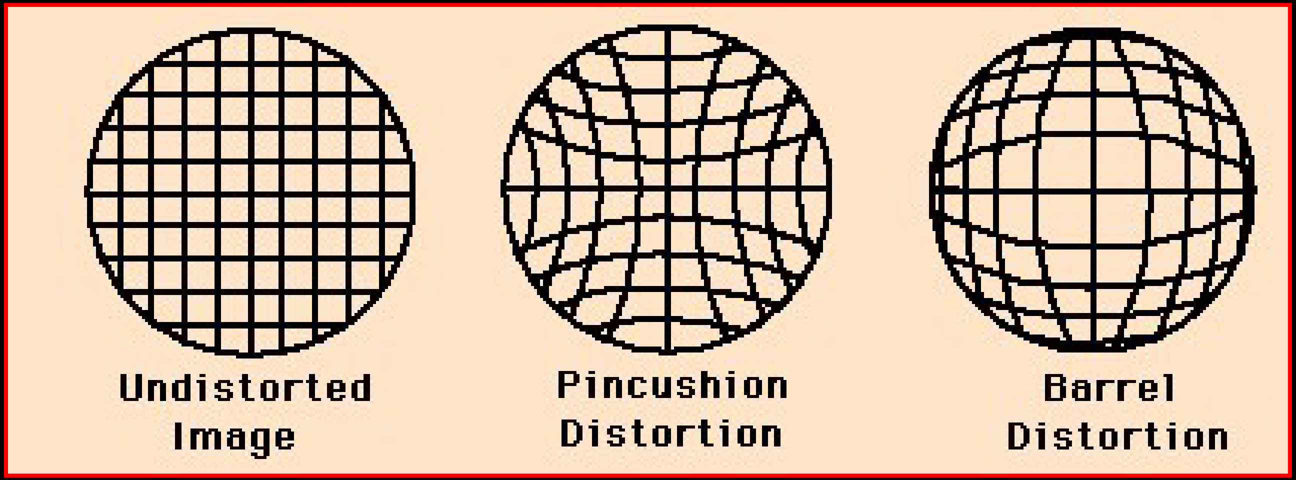
Adapted from:
Hyper Physics concepts
http://hyperphysics.phy-astr.gsu.edu/hbase/hph.html

- ✓ Different curvature in horizontal and vertical planes
- ✓ Only important for wide-field imaging

Demonstration of Astigmatism



4. Distortion



Adapted from: Hyper Physics concepts: http://hyperphysics.phy-astr.gsu.edu/hbase/hph.html

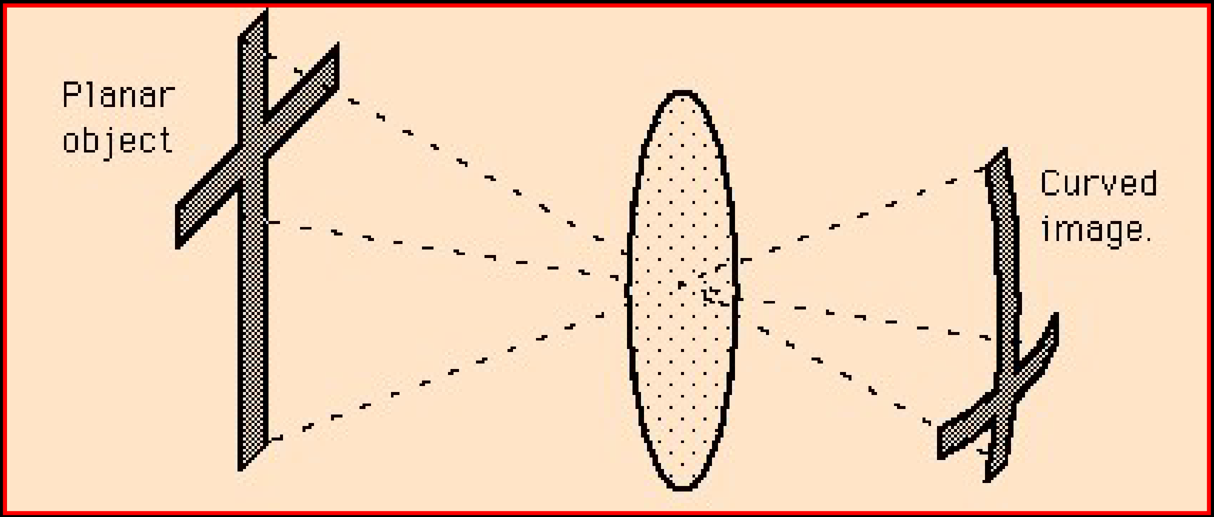
thick double convex lenses

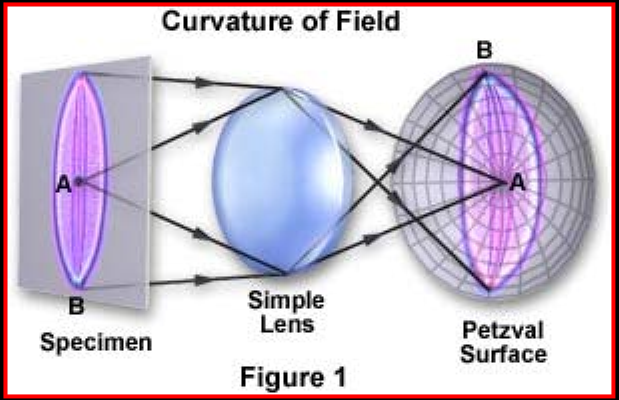
- ✓ Usually seen in thick double convex lenses

- ✓ Differential transverse magnification for different distances of image away from optical axis

- ✓ Explain why there is a practical limitation in the magnification achievable from a simple magnifier.

5. Field Curvature





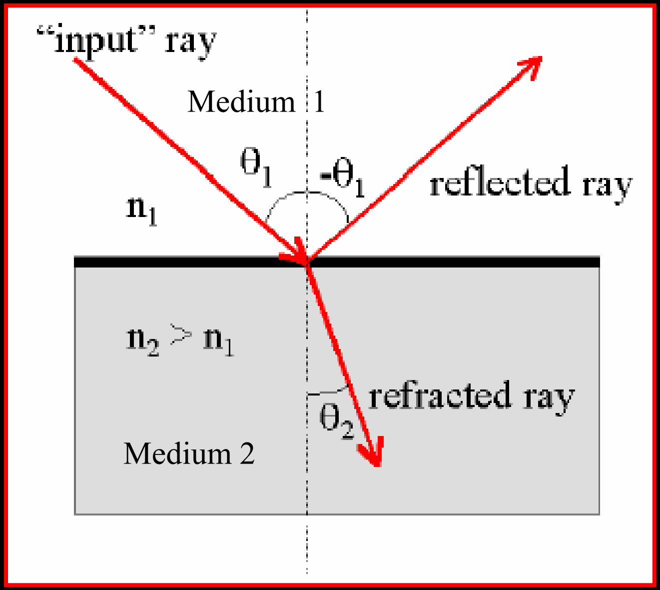
Adapted from: Hyper Physics concepts: http://hyperphysics.phy-astr.gsu.edu/hbase/hph.html

- ✓ The focal plane is not a plane, but a curved surface
- ✓ Flat detectors, e.g. CCD, will not be in focus over its entire region

6. Chromatic Aberration

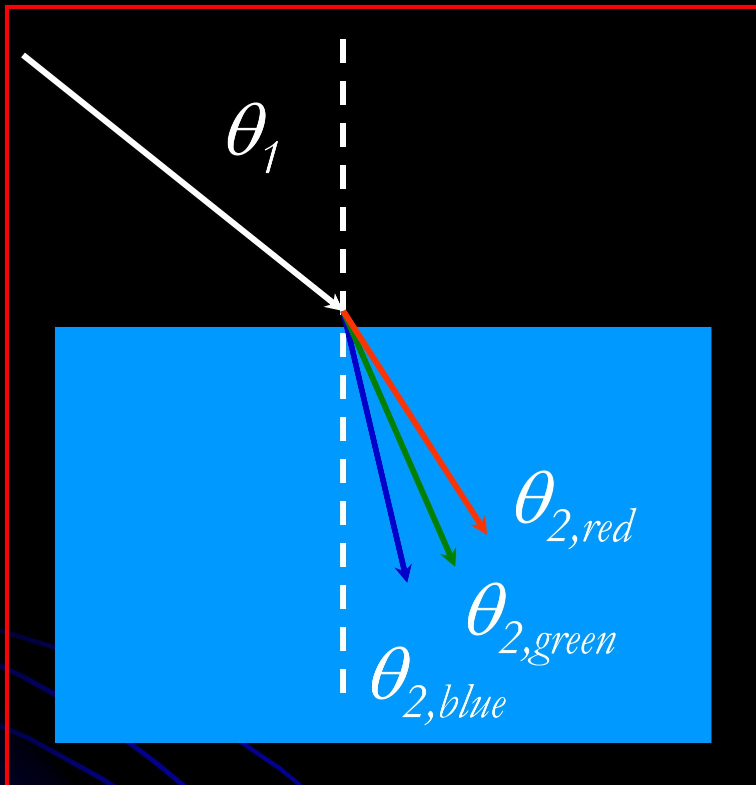
- First, recall the physics of refraction (Snell's Law):

$$\boxed{n_1 \sin\theta_1 = n_2 \sin\theta_2}$$

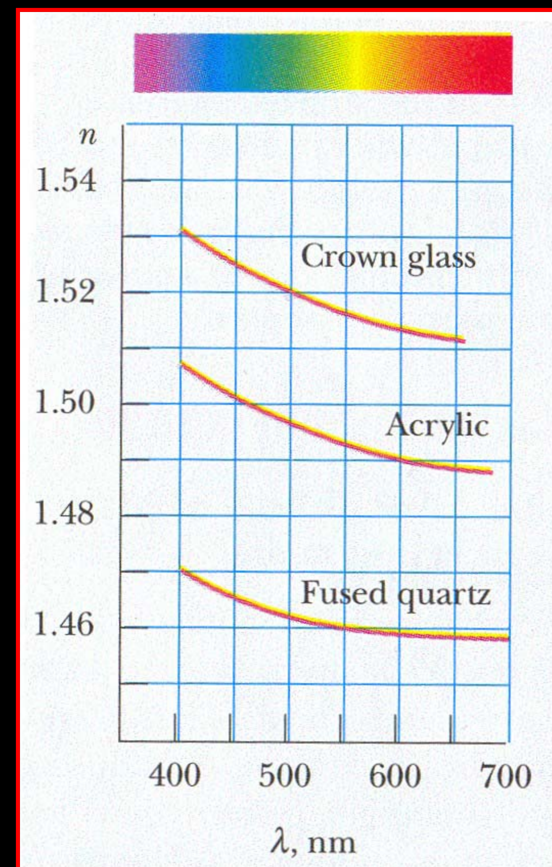


where n_1, n_2 are the index of refraction of the two media

✓ Index of refraction for most transparent materials are wavelength dependent, i.e. n is a function of λ



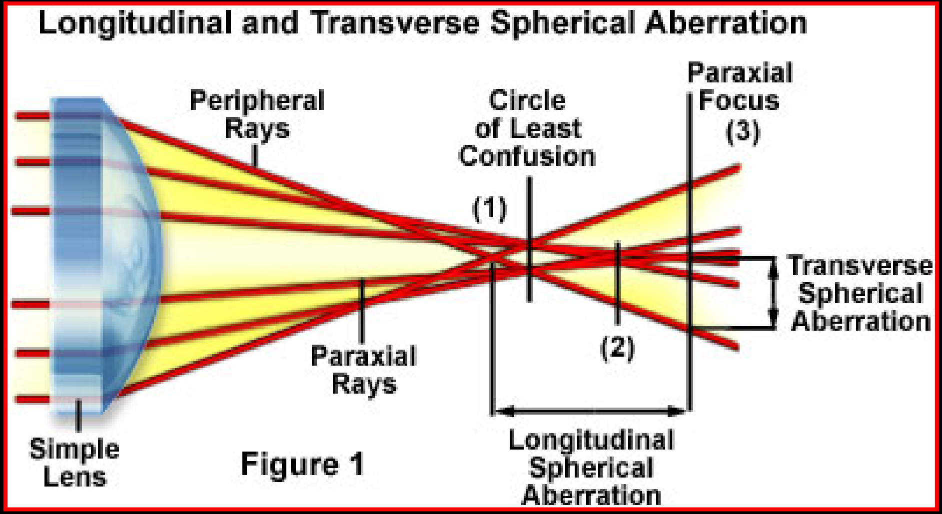
$$q_{2,blue} < q_{2,green} < q_{2,red} < q_1$$
$$n_{2,blue} > n_{2,green} > n_{2,red} > n_1$$

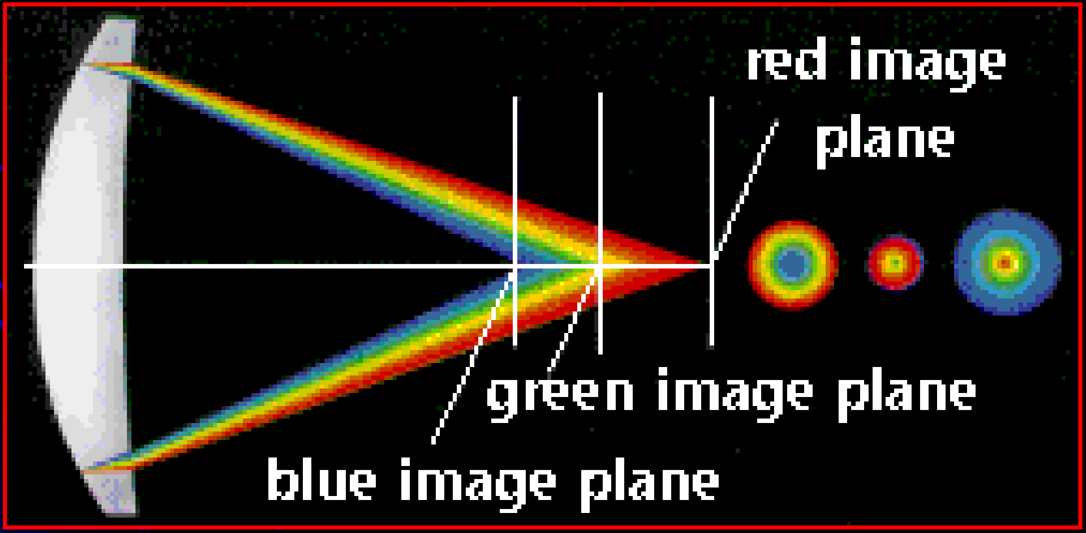


✓ Chromatic aberration is the visual effect of the wavelength dependent refraction

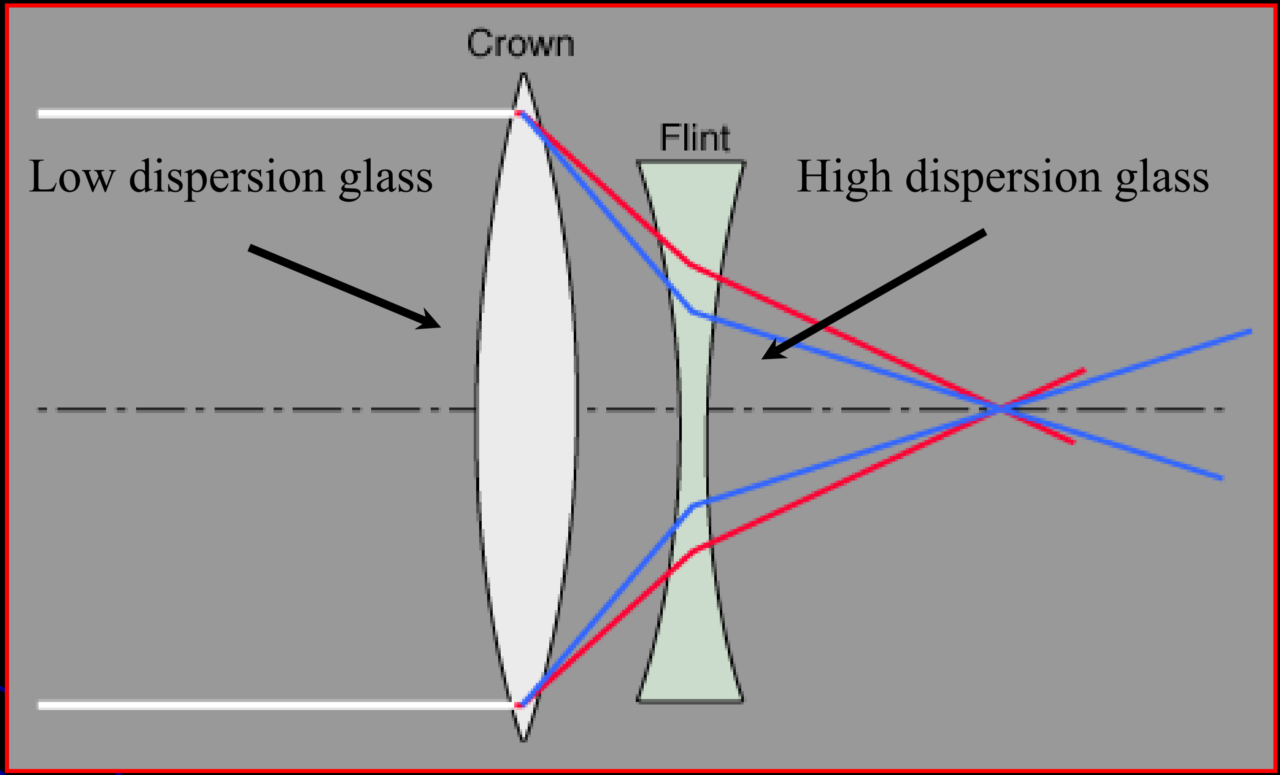
✓ BUT, light reflects all wavelengths of light identically

Demonstration of Cromatic Aberration





✓ Chromatic aberration greatly reduced (~10 times) by multiple lens system, e.g. achromatic doublet



✓ Usually, two lens have same curvature and are cemented together

✓ Note: Same focal length for two wavelengths so that they can be corrected simultaneously

Summary of aberrations

Spherical	Mono-chromatic (affects single wavelength light), on- and off-axis
Coma	Mono-chromatic, off-axis only
Astigmatism	Mono-chromatic, off-axis only
Distortion	Mono-chromatic, off-axis only
Field Curvature	Mono-chromatic, off-axis only
Chromatic	Hetero-chromatic (affect multiple wavelength light), on- and off- axis

Corrections: Most of the aberrations can be reduced (but never totally removed) by using multi-lens system.

Correcting Coma/Field-Curvature Type Aberrations With Deconvolution

- ✓ Here's a stack of several calibrated images of NGC 6992 (the Veil nebula):

References

http://www.princeton.edu/~rvdb/images/deconv/deconv.html
http://www.astrosurf.org/buil/us/iris/deconv/deconv.htm

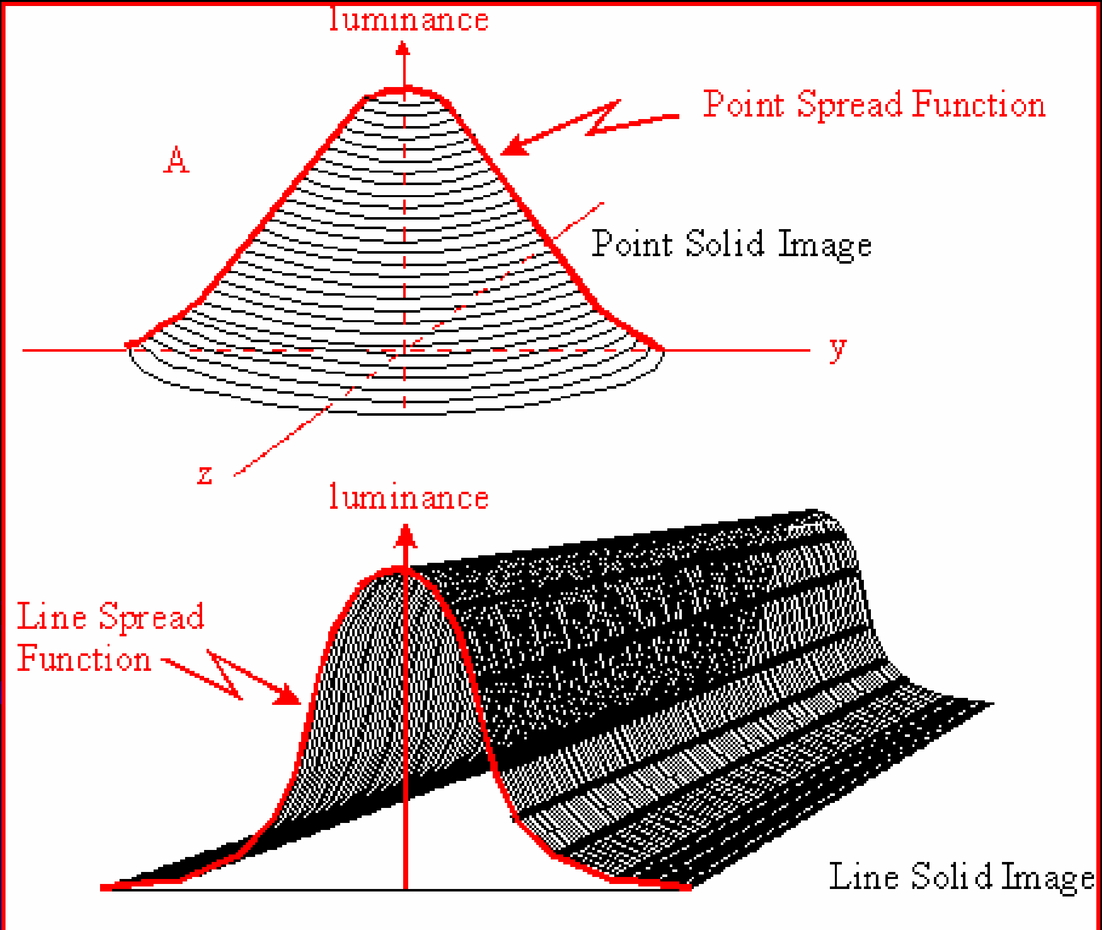
Correcting Coma/Field-Curvature Type Aberrations With Deconvolution

- ✓ The image appears soft because it is slightly out of focus (the temperature dropped significantly over the time frame during which the individual exposures were taken).

Correcting Coma/Field-Curvature Type Aberrations With Deconvolution

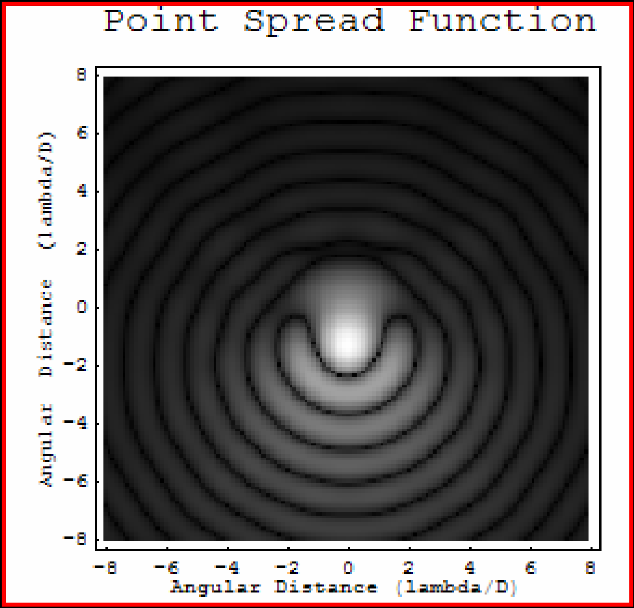
- ✓ With these values, the PSFs for 100 bright stars in the raw image are modeled as follows:

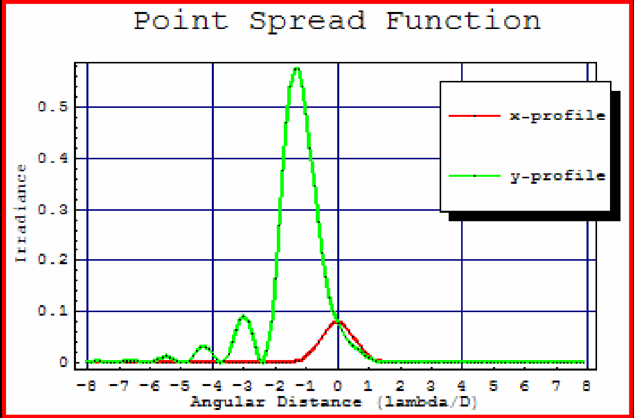
Point spread function - PSF



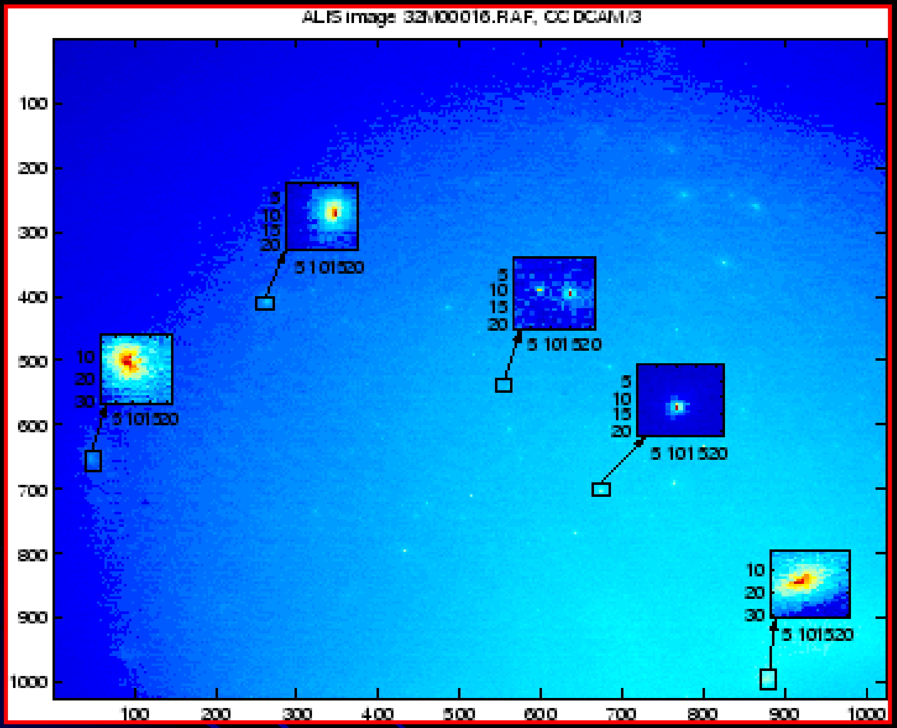
Sketches illustrating a point spread function (A) and a line spread funciton (B).

Adapted from Smith (1966)

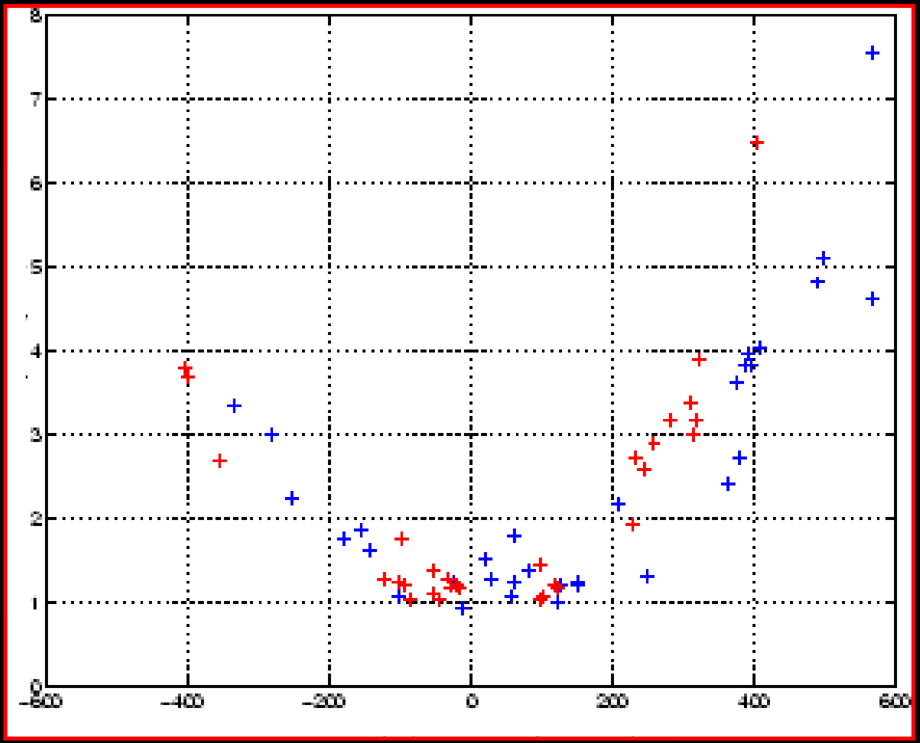




Point spread function - PSF



Typical ALIS background image with a few selected stars magnified, showing the variation of the PSF with image location.



Variation in widths of stars in ALIS images taken with an optics with 90 degrees field-of-view.

Correcting Coma/Field-Curvature Type Aberrations With Deconvolution

- ✓ Implemented the Richardson - Lucy deconvolution algorithm using this non constant model for the PSF. The resulting image after 10 iterations of the algorithm is shown here:

Correcting Coma/Field-Curvature Type Aberrations With Deconvolution

- ✓ More iterations gives even tighter stars but also begins to look over processed. Here's the result after 25 iterations:

Correcting Coma/Field-Curvature Type Aberrations With Deconvolution

- A better approach is to break the problem into two parts: (a) first, make the stars round, and then (b) make the image sharper. The "rounding" step can be done, for example, by doing 10 iterations with
- Then, the "sharpening" step can be accomplished by doing another 5 iterations with the suggested settings minor radius = 0.9,
- Here's the result:

IV. Telescope Configuration (Refractors)

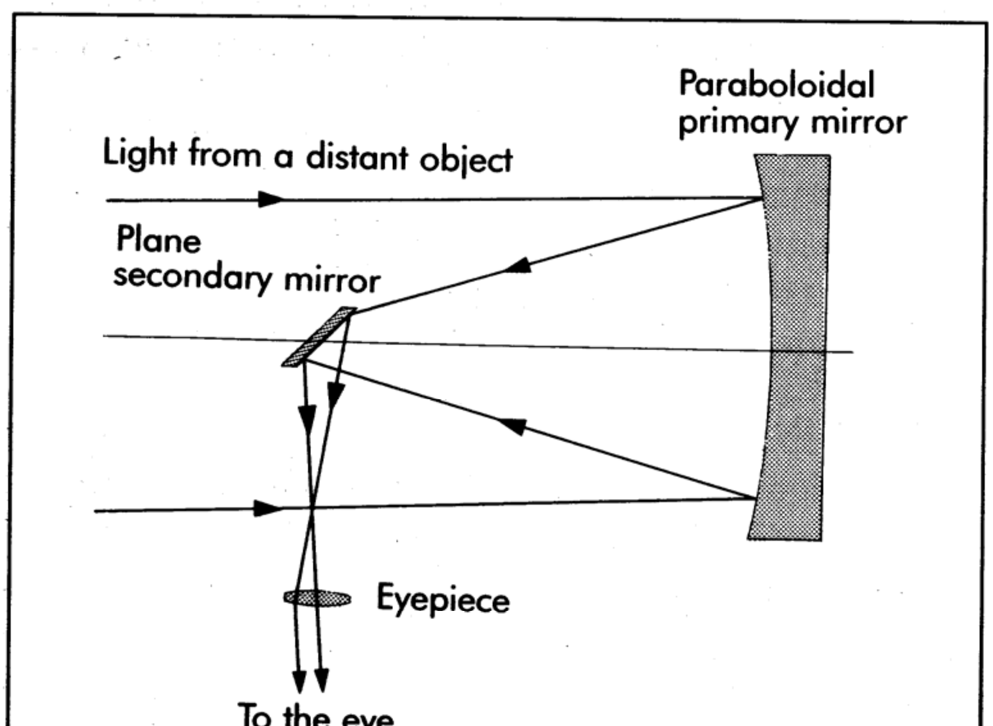
- ✓ Aberration overcome by having achromatic objective lens and multi-lens eyepiece
- ✓ Biggest refractor built: 1 m diameter (Yerkes)
- ✓ Limitations for building bigger refractors:
  1. Light absorption and chromatic aberration
  2. Objective lens has to be supported at the edges and they sag under their own weight (glass is a fluid!)
  3. To achieve large f/ number, telescope will be long and requires massive support and domes

IV. Telescope Configuration (Reflectors)

- ✓ The biggest optical telescopes (~10 m diameter, Keck) built in the world are reflectors
- ✓ Major advantages:

1. No chromatic aberration
2. No spherical aberration (parabolic mirrors)
3. Mirror can be supported at the back, no huge support structure needed
4. Improved technique on making big mirrors (Aluminium-on-glass, recoating needed)

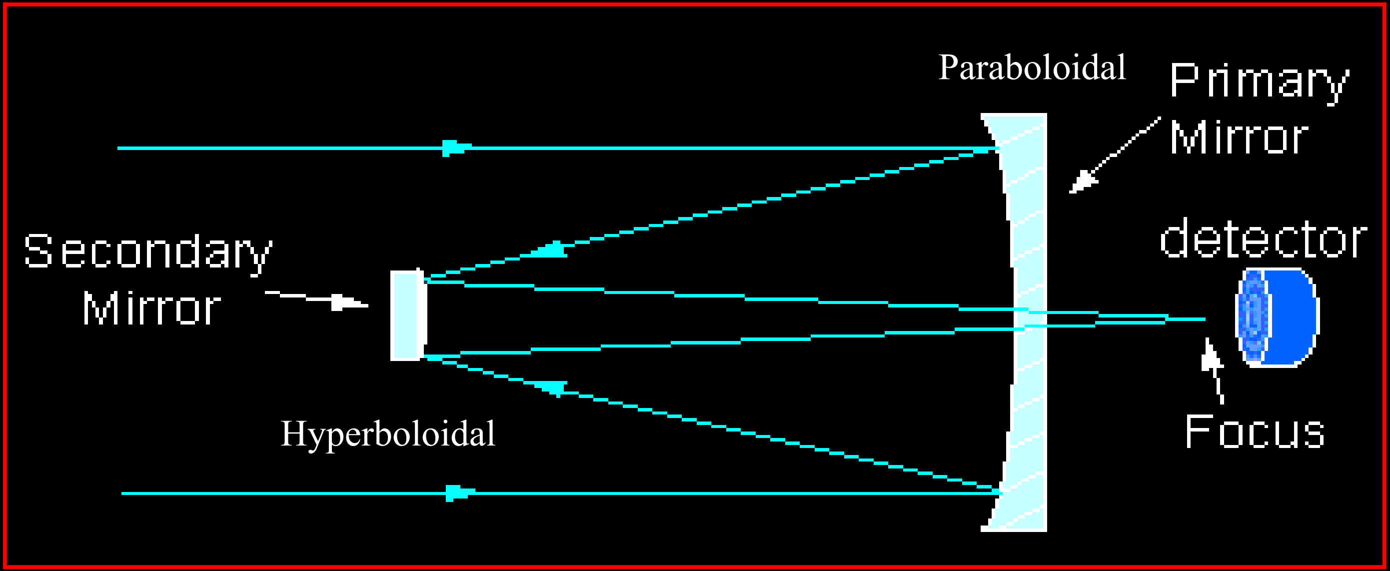
Newtonian



Adapted from: Telescope and Technique by C.R Kitchin

- ✓ The first working reflector (1668, 1 inch diameter)
- ✓ Eyepiece moved to the side of the telescope

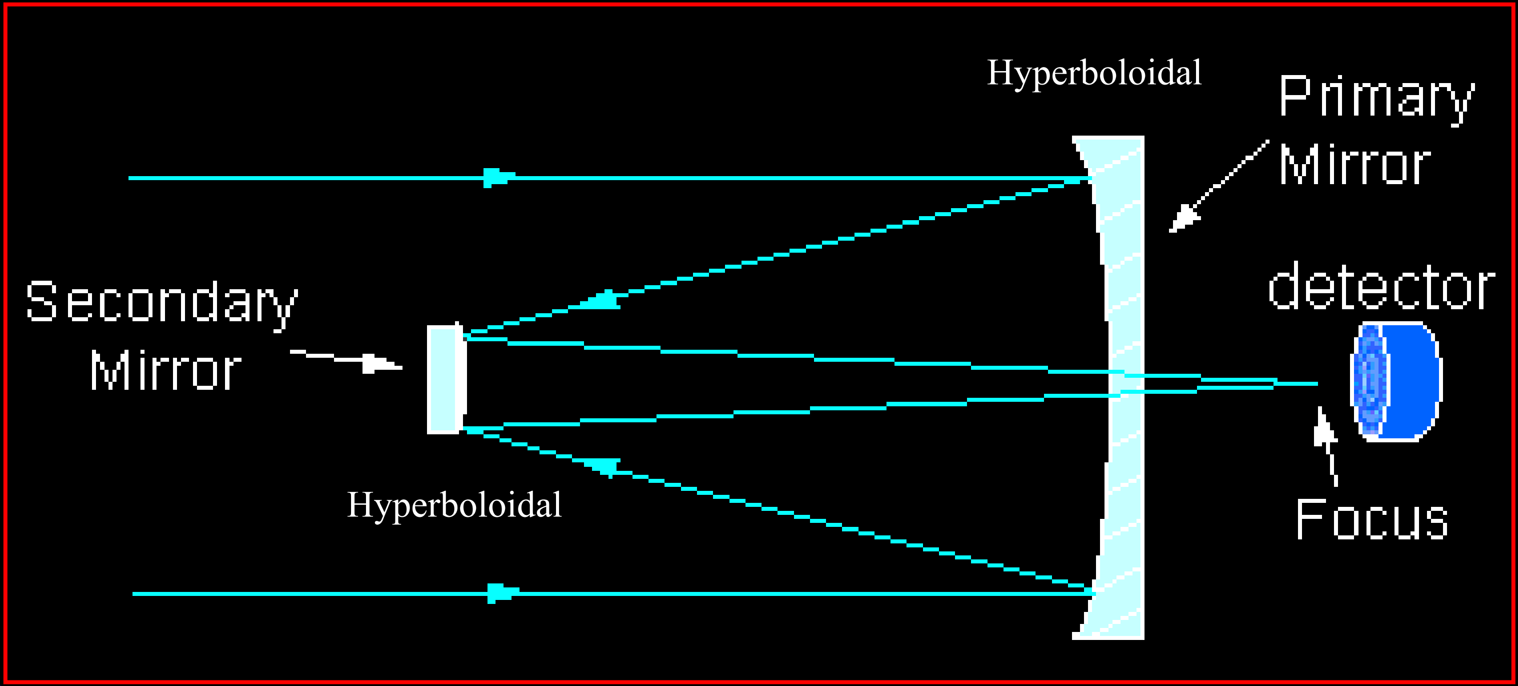
Cassegrain



Adapted from Tumbling Stone general dictionary http://spaceguard.ias.rm.cnr.it/tumblingstone/dict.htm

- ✓ Basic configuration for most large research telescopes (e.g. Hubble, Keck 10m, VLT 8.2m)
- ✓ Secondary mirror produces narrow cone of light
- ✓ Can have large focal length compared to the physical length of telescope (telephoto advantage)
- ✓ Small field of sharp focus (few arcminutes)

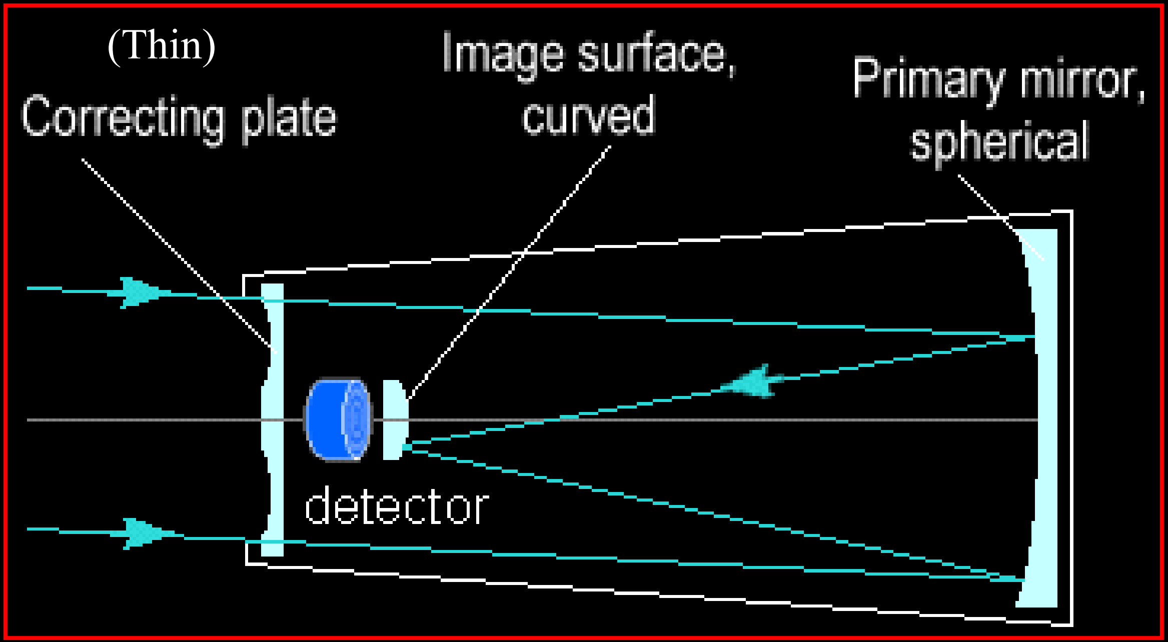
Ritchey-Chretien



Adapted from Tumbling Stone general dictionary http://spaceguard.ias.rm.cnr.it/tumblingstone/dict.htm

- ✓ Variation of the Cassegrain
- ✓ Remove coma aberration
- ✓ Good quality images over a larger field-of-view (10-20 arcminutes)

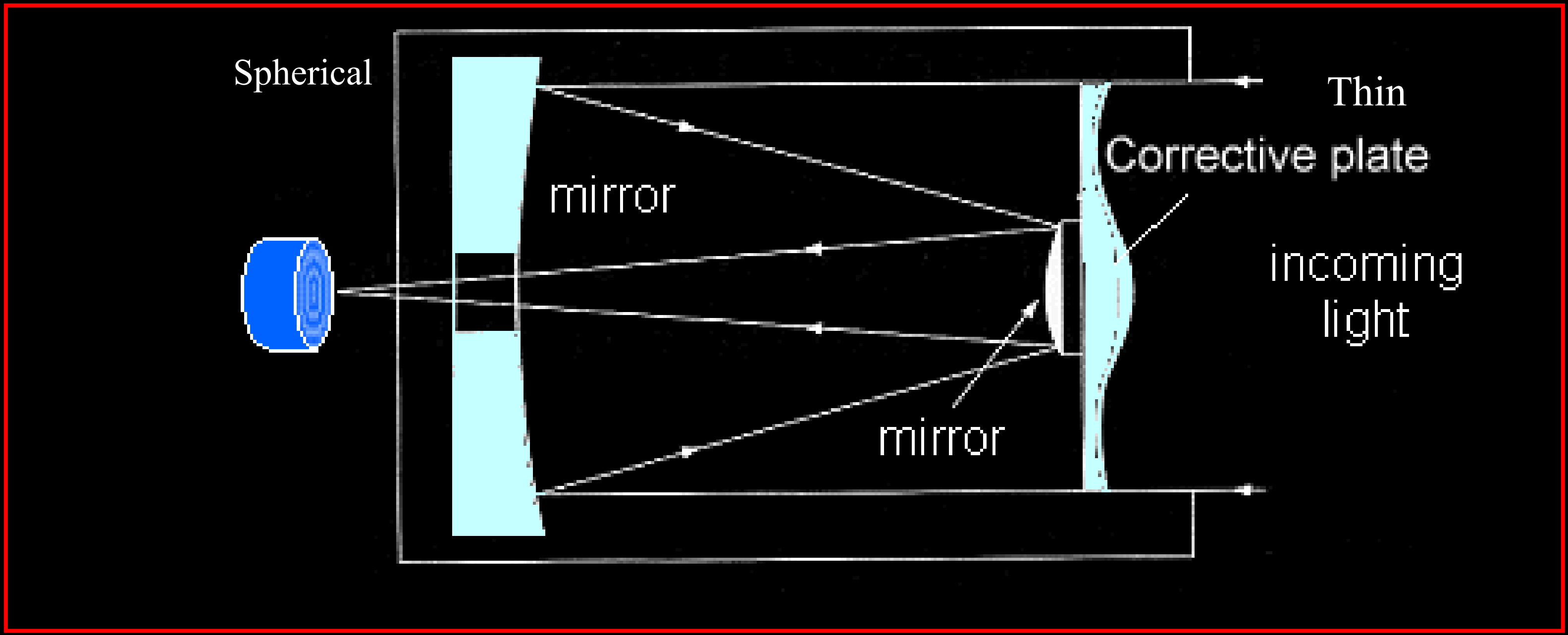
Combined Refractor and Reflector: Schmidt Camera



Adapted from Tumbling Stone general dictionary http://spaceguard.ias.rm.cnr.it/tumblingstone/dict.htm

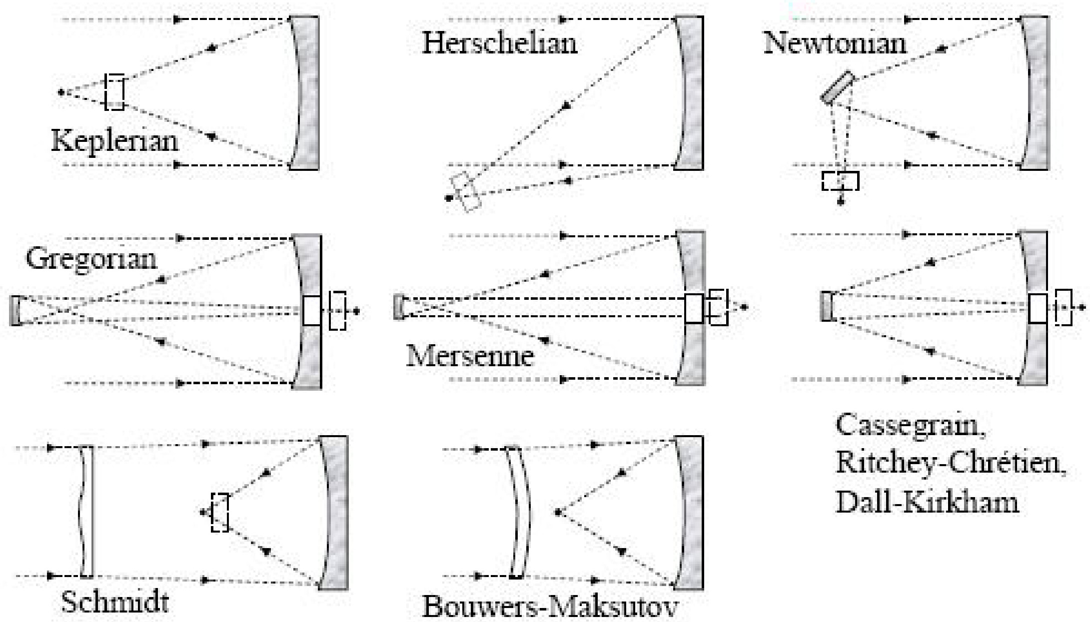
- ✓ Advantage: Wide field-of-view (6-10 degree), good for sky surveying work
- ✓ Two major ones: Palomar, Siding Spring (1.2m)
- ✓ Disadvantage: telephoto disadvantage (long telescope length versus focal length)

Schmidt-Cassegrain



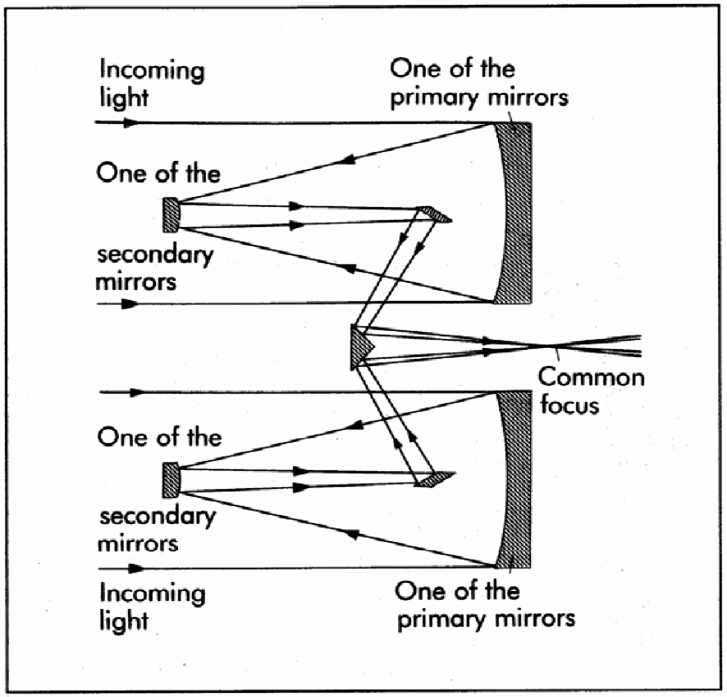
Adapted from Tumbling Stone general dictionary http://spaceguard.ias.rm.cnr.it/tumblingstone/dict.htm

- ✓ Compact design: compromise of large field-of-view and long focal length
- ✓ Popular design for small telescopes, especially for astro-photography



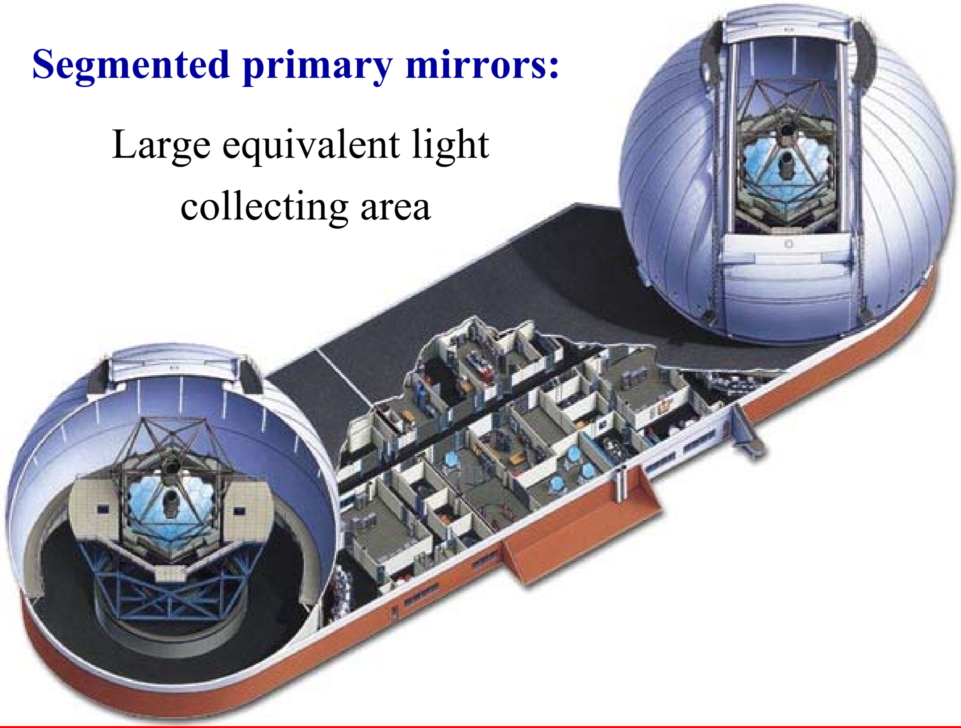
Type	Primary Optics	Secondary Optic
Keplerian	Sphere or parabola	None
Herschelian	Off-axis parabola	None
Newtonian	Parabola	Diagonal Flat
Gregorian	Parabola	Ellipse
Mersenne	Parabola	Parabola
Cassegrain	Parabola	Hyperbola
Ritchey-Chrétien	Modified parabola	Modified hyperbola
Dall-Kirkham	Ellipse	Sphere
Schmidt	Aspheric refractor	Sphere
Bouwers-Maksutov	Refractive meniscus	Sphere

New developments of optical telescopes



Segmented primary mirrors:

Large equivalent light collecting area



Adapted from:
Telescope and Technique by C.R Kitchin

36 mirror segment (1.8m) equivalent of a single 10m mirror

Very Large Telescope


Figure 2 - VLT Primary mirror blank in production (courtesy SCHOTT)

Primary mirror (8.2 m)

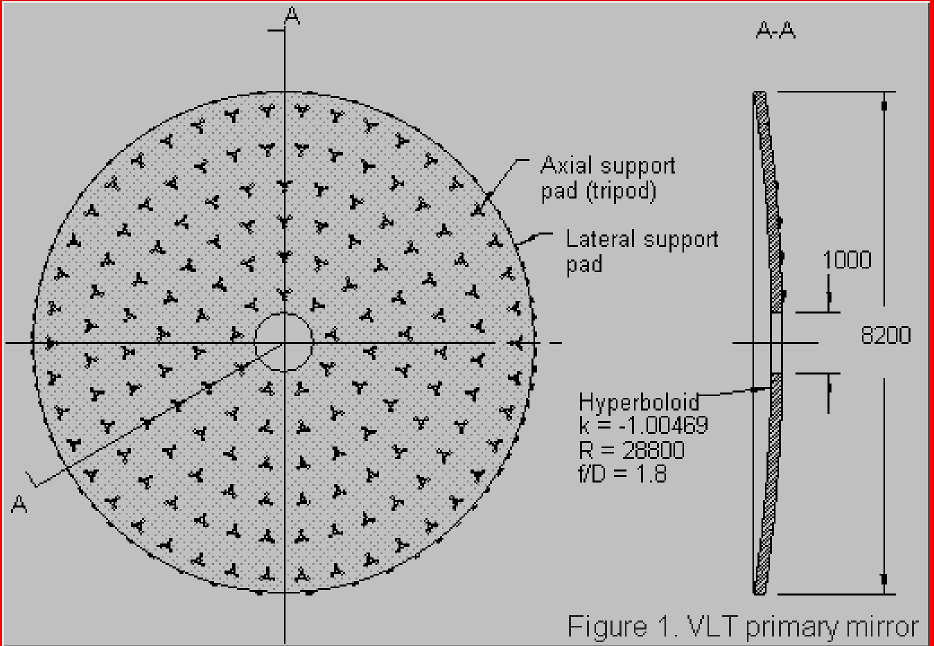


Figure 1. VLT primary mirror

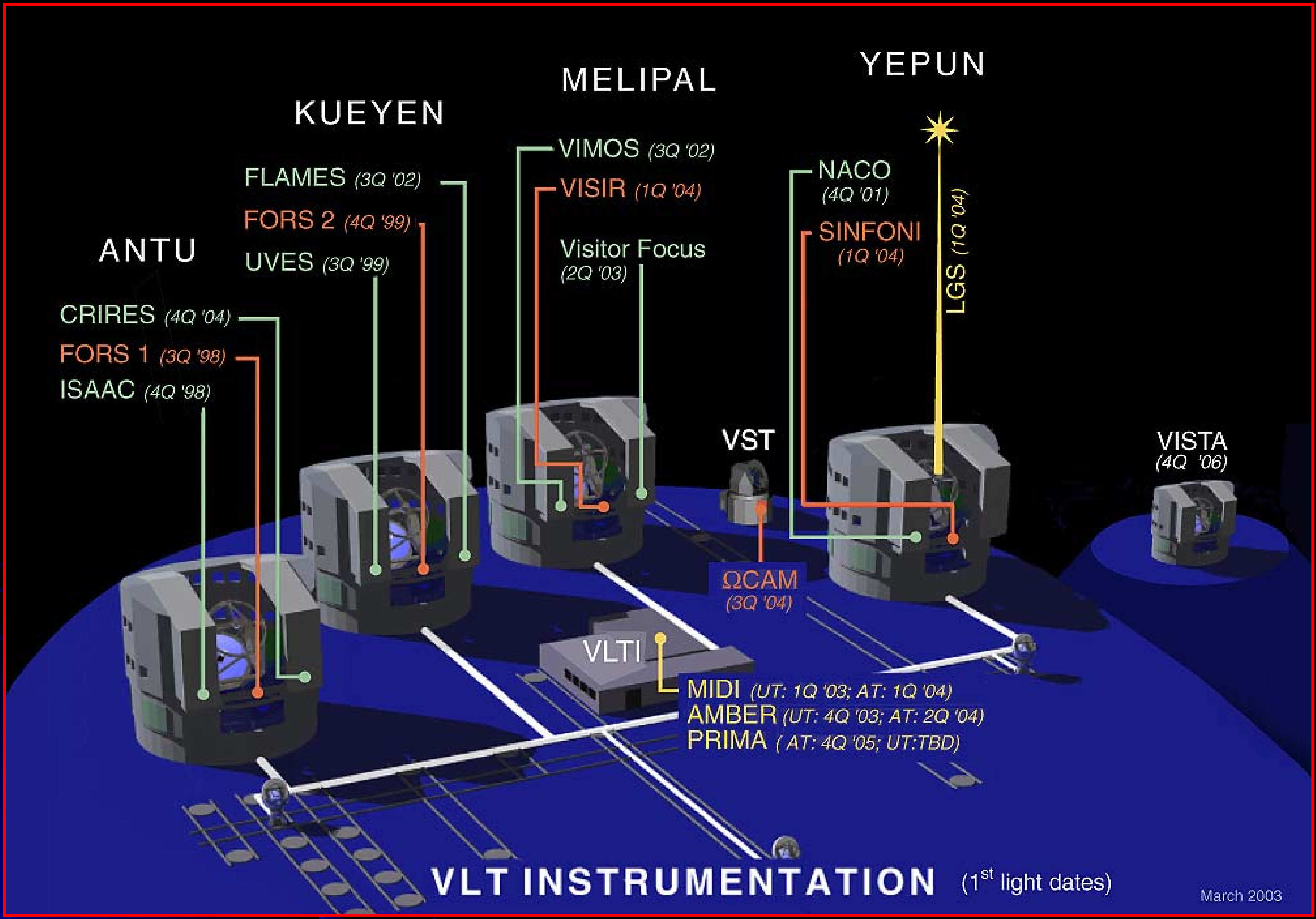
Adaptive Optics:

Telescope can correct for any deviation from its desired shape by active real-time mechanical control from behind the mirror

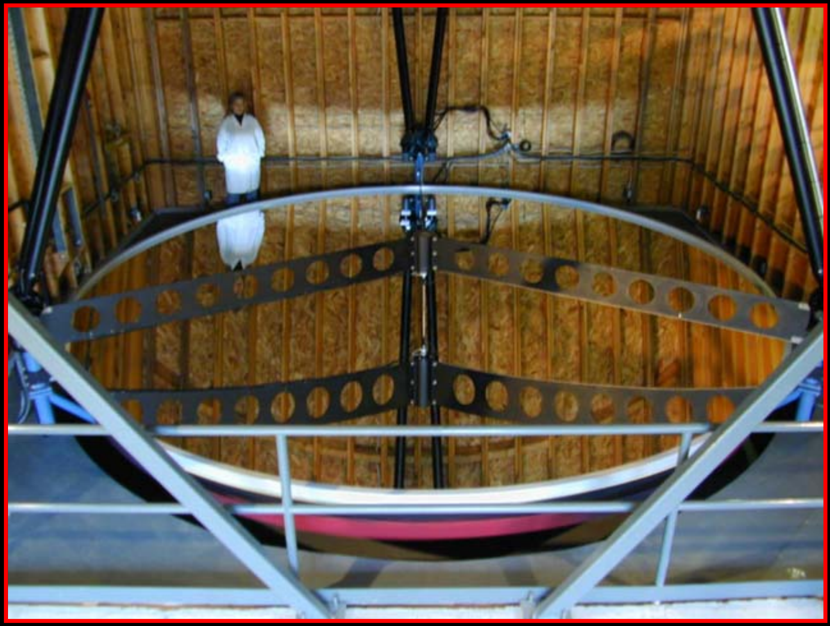
A total of 175 controlled actuators

VLT at Paranal

ESO PR Photo 43a/99 (8 December 1999)


YEPUN
MELIPAL
KUEYEN
ANTU
VIMOS (3Q '02)
VISIR (1Q '04)
Visitor Focus
(2Q '03)
FLAMES (3Q '02)
FORS 2 (4Q '99)
UVES (3Q '99)
NACO
(4Q '01)
SINFONI
(1Q '04)
LGS (1Q '04)
CRIRES (4Q '04)
FORS 1 (3Q '98)
ISAAC (4Q '98)
VST
VISTA
(4Q '06)
ΩCAM
(3Q '04)
VLTI
MIDI (UT: 1Q '03; AT: 1Q '04)
AMBER (UT: 4Q '03; AT: 2Q '04)
PRIMA (AT: 4Q '05; UT:TBD)
VLT INSTRUMENTATION (1st light dates)
March 2003

Large Zenith Telescope



Primary mirror (6 m)

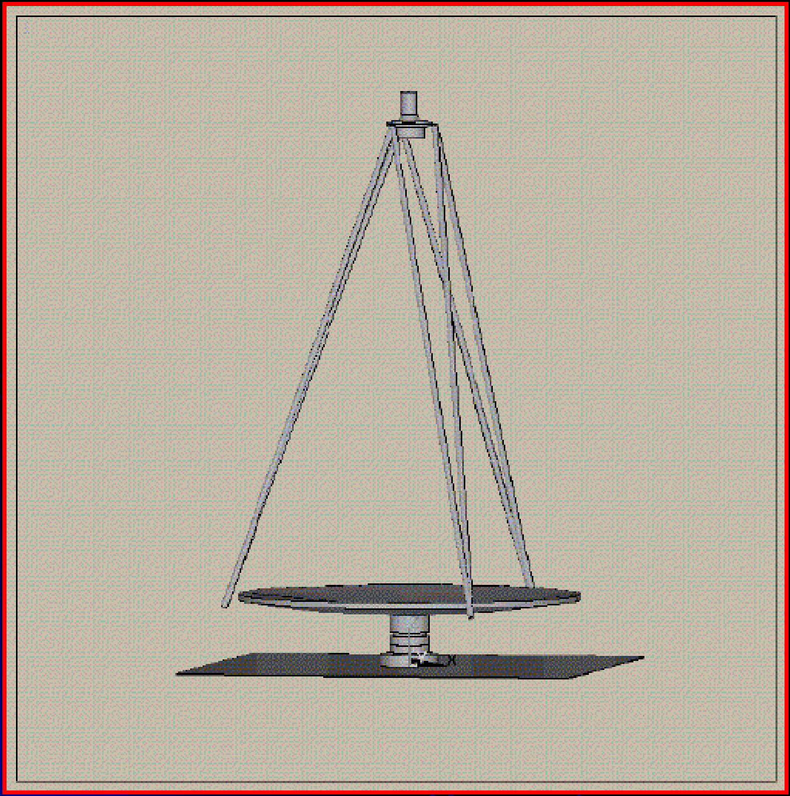
Liquid Mirror:

- ✓ Spin up liquid Mercury on parabolic surface
- ✓ Advantage: ~10 times cheaper than conventional mirror.
- ✓ Disadvantage: 1. Can only point straight up! (that explains the name); 2. Mercury is toxic

Rotate at period of ~8.5 second to get a thin (~2mm) layer of Mercury

The LZT is located at the Liquid Mirror Observatory in the UBC Malcolm Knapp Research Forest in Maple Ridge, British Columbia.

Design of the telescope



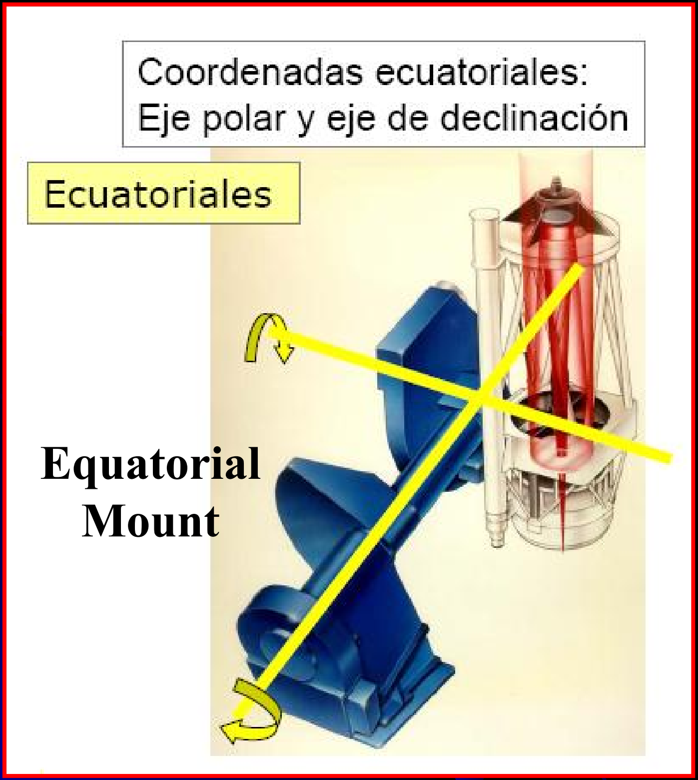
View of the primary mirror undergoing initial tests using water.

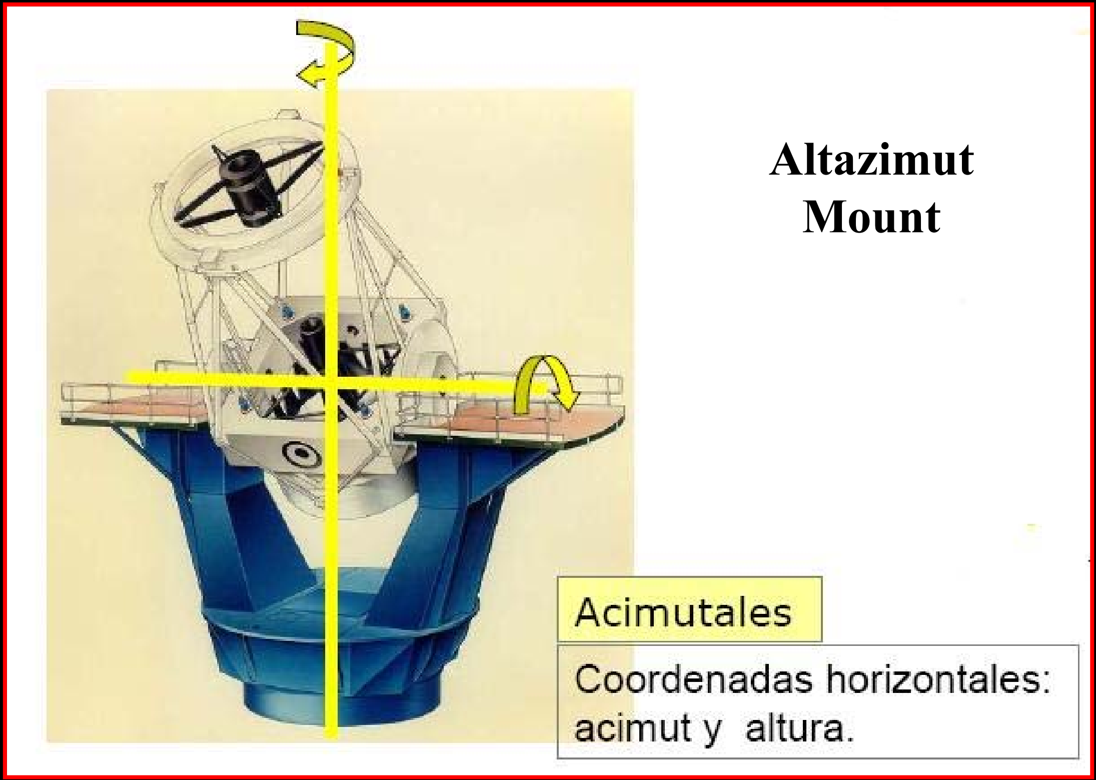
V. Telescope Mount

- ✓ Function: Support the optical components, point them to a required position, and track the object as it moves
- ✓ Two components: telescope tube, support for the tube (mounting)
- ✓ Actually, most research telescopes contain no tube (open frame)

Mounting

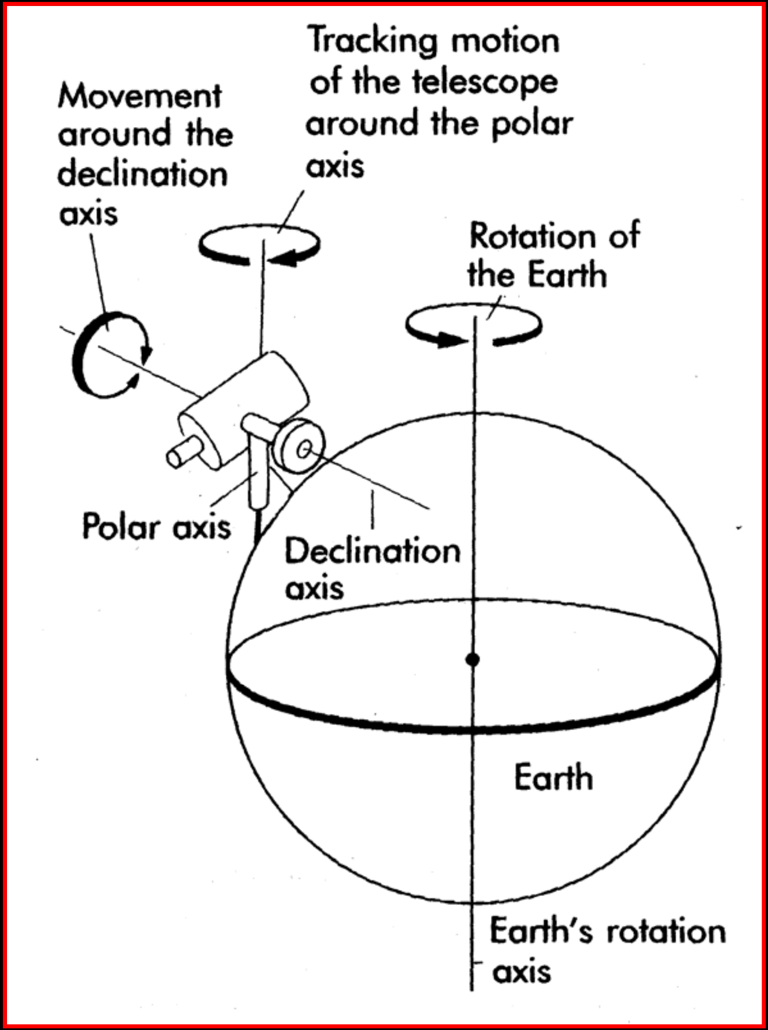
✓ A stable and rigid mounting is very important for observations
✓ Two main types: equatorial and alt-azimuth





Equatorial Mounting

- ✓ Two axes: Polar axis (parallel to Earth's rotation axis) and Declination axis (perpendicular to polar axis)
- ✓ Star tracking can be done with only one constant- speed motor rotating in opposite direction of earth's rotation along polar axis
- ✓ Disadvantage: expensive to build, asymmetry gravity effects

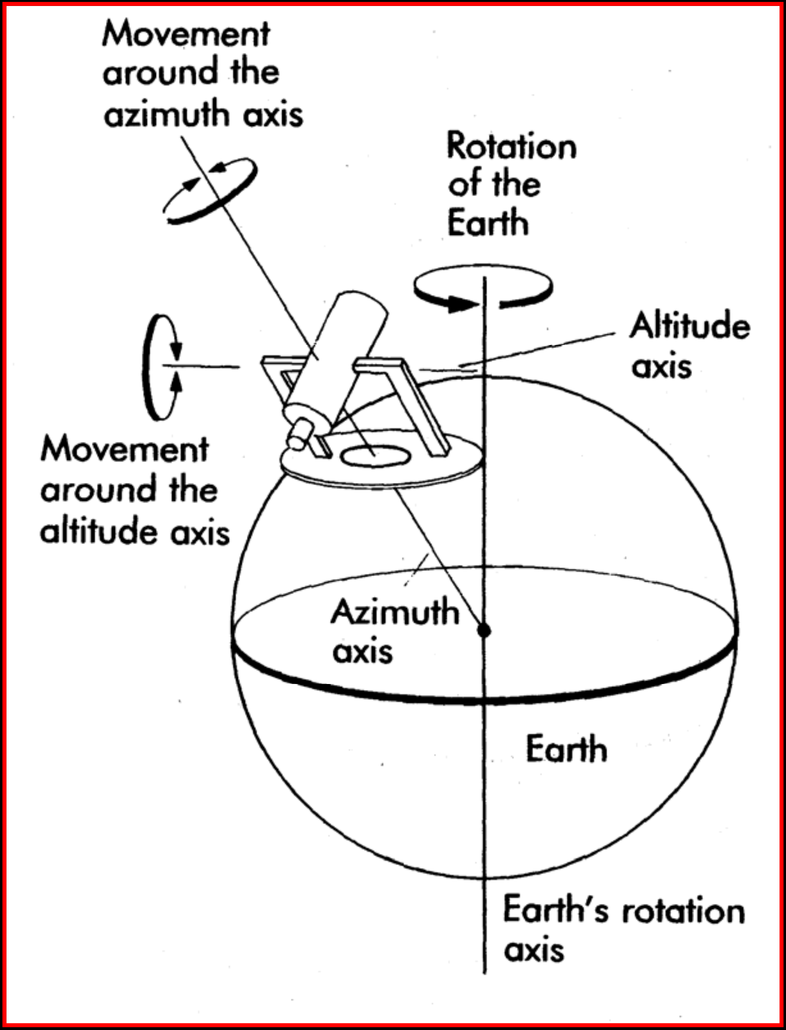


Adapted from: Telescope and Technique by C.R Kitchin

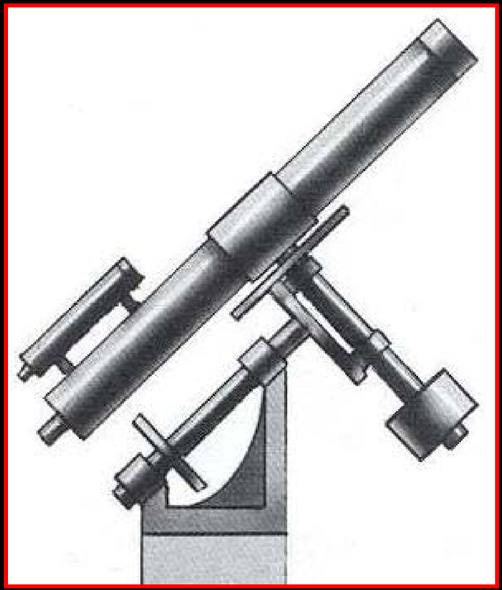
Alt-azimuth mounting

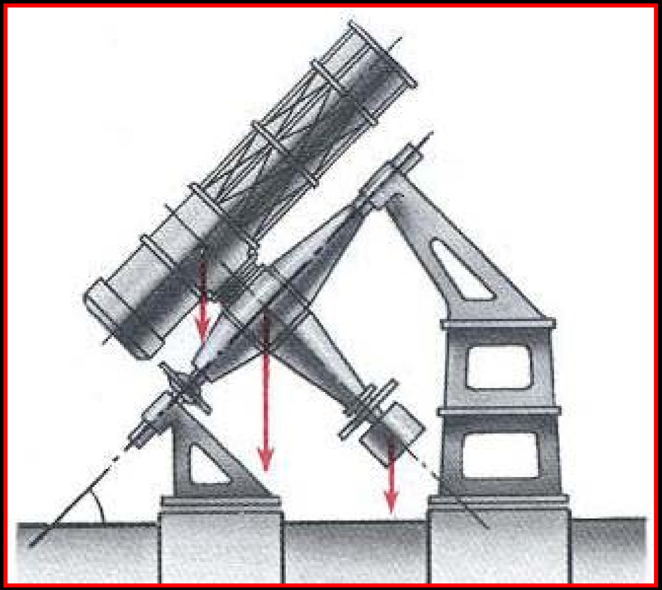
- ✓ Used by all big (>4m) telescopes recently built
- ✓ Symmetric gravity effects, cheaper to build
- ✓ Disadvantages:

1. To track objects in the sky, need two axes rotating at different speed;
2. Rotation of image during tracking need to be overcome (by rotating cameras!);
3. "Dead-zone" near zenith

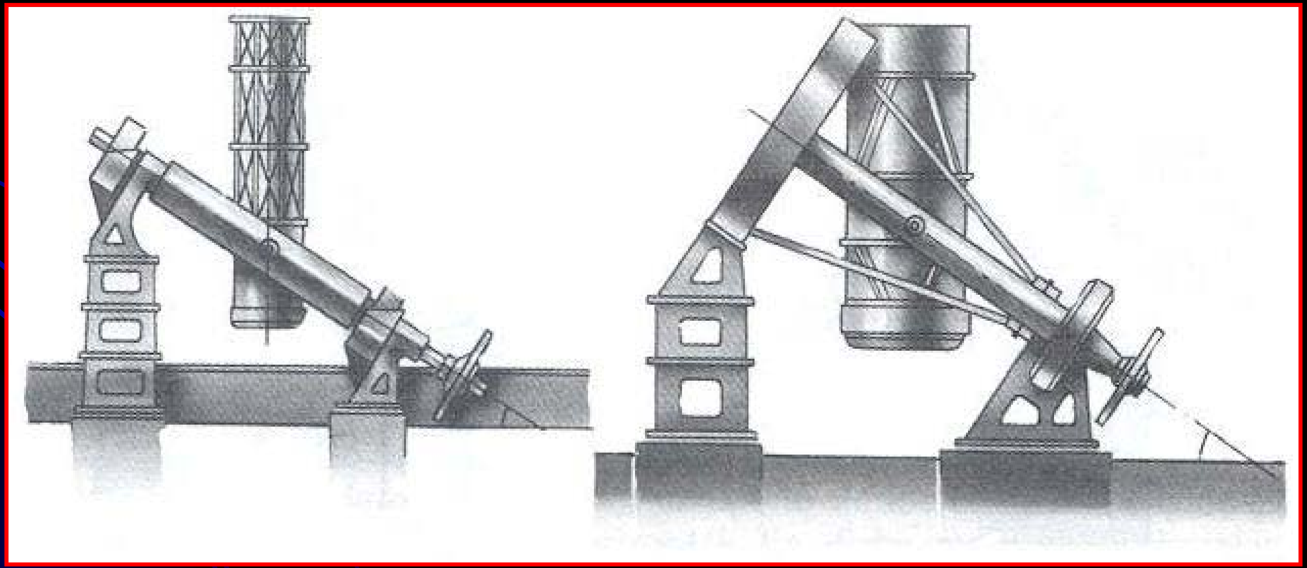


Adapted from: Telescope and Technique by C.R Kitchin


Montura tipo alemán


Montura tipo ingles


Montura tipo americano


Montura con el armazón

VI. Observatory and Observatory site

- All telescope can be benefited by placing in an observatory (sometimes known as "the dome")
- Classic design: a hemispherical roof with a open slot, rotating on a circular wall
- Choosing "good sites" means that majority of world's largest telescopes are located in a few places, e.g. Hawaii, Chile, Arizona, Canary Island, **Mexico (OAN-SPM)**
- Criteria: away from light pollution, "clean" atmosphere (low dust and water), height, accessibility, steady atmosphere, ……

This is what the Earth looks like at night

Finding map (for a place away from light pollution)