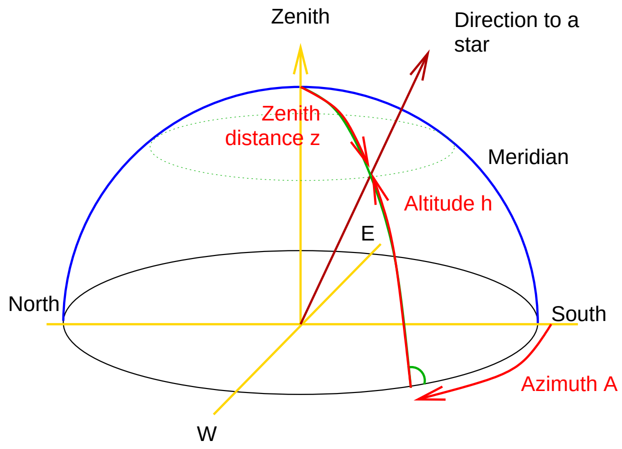
Coordinates and Measurement Methods

Introduction

We now move away from solar system $\Longrightarrow$ before we can continue with science, we need to understand

- where astronomical objects are $\Longrightarrow$ coordinate systems
- how astronomical measurements are made $\Longrightarrow$ telescopes

Horizon System, V

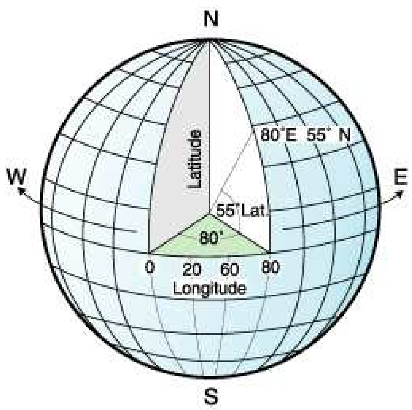


after Giese

Position on sky:

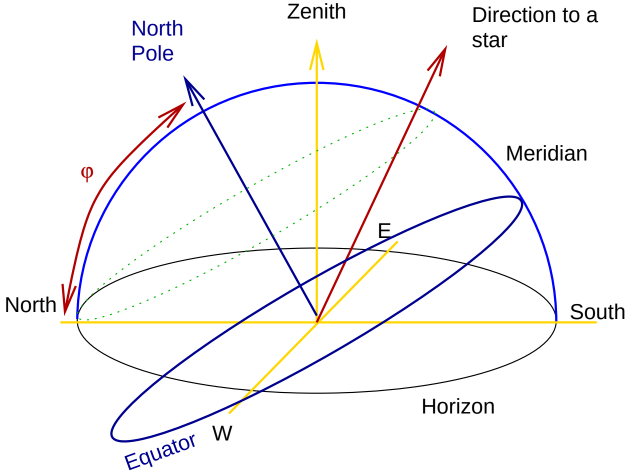
- Define position by giving direction to star.
- Azimuth A: angle in horizontal S-W-N-E
- Altitude h: angle from horizon towards zenith
- Zenith distance z: $z = 90^\circ - h$

Equatorial System, I



Problem: Earth rotates
$\Longrightarrow$ A and h change with time
$\Longrightarrow$ need coordinates "fixed" on celestial sphere, similar to geographic latitude, φ, and longitude, λ, on Earth.

Equatorial System, III



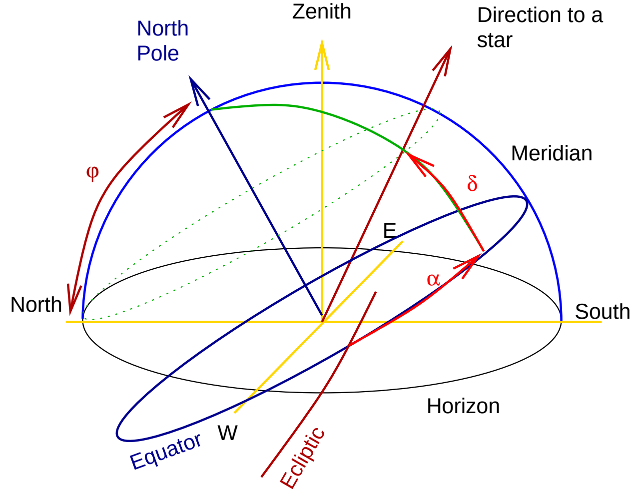
Let's look at our star again.

Rotation of Earth: Stars move over sky around celestial north pole.

North pole has altitude φ above horizon.

after Giese

Equatorial System, VIII

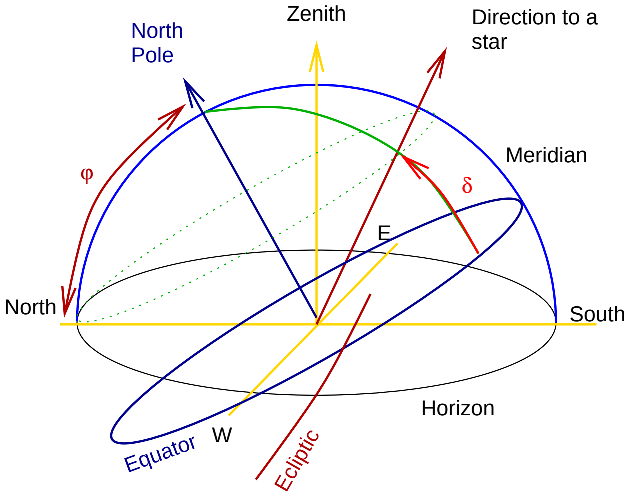


Define coordinates with respect to celestial equator

- Declination δ: angle from equator to star, measured in degrees (equivalent to latitude)
- Right ascension α: angle from vernal equinox to star, measured in easterly direction.

after Giese

Equatorial System, VII



Define coordinates with respect to celestial equator

- Declination δ: angle from equator to star, measured in degrees (equivalent to latitude)

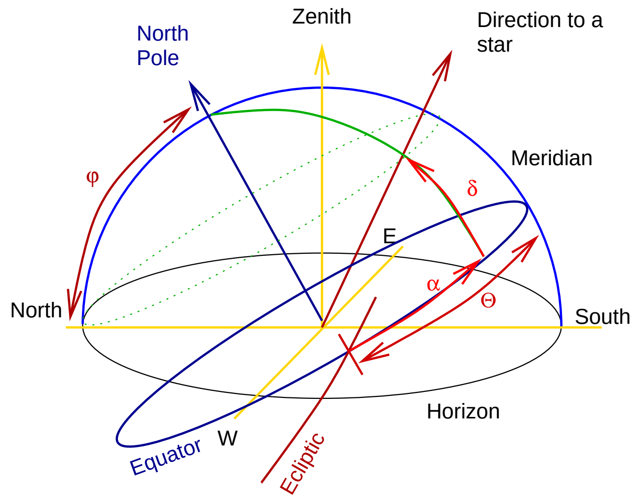
Equivalent to longitude more difficult: need a "Greenwich meridian".

$\Longrightarrow$ Defined by crossing of ecliptic (apparent path of Sun on sky) with equator: "ascending node", "vernal equinox" (Frühlingspunkt)

(location of Sun on 21 March)

after Giese

Siderial Time, I



Define siderial time: 24 h correspond one rotation of the celestial sphere.

0 h siderial time = time when vernal equinox passes through meridian.

$\Longrightarrow$ Local siderial time: Right ascension of stars passing through meridian.

Right Ascension is measured in hours, minutes, and seconds

1 h corresponds to 15°.
α increases towards East.

Siderial Time, II

Note: Siderial time $\neq$ common time

Common time: 24 h between culminations of the Sun (i.e., passes of Sun through meridian).

BUT

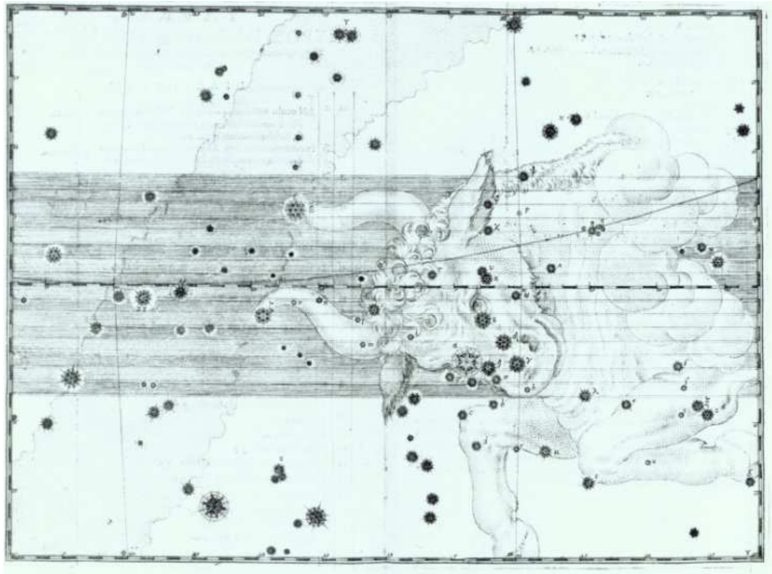
Sun moves on sky towards east

$\Longrightarrow$ one "solar day" takes slightly longer than one rotation of the Earth

Angular speed of Sun: 360° degrees in 365.25 days, i.e., $0.9856^\circ\,\mathrm{d}^{-1}$.

$\Longrightarrow$ During 365.25 days the Earth rotates 364.25 times

$\Longrightarrow$ Earth's rotation takes 24 h $\times 364.25/365.25$ = 23 h 56 minutes.



Bayer's Uranometria (1603; University of Illinois collections)

Aldebaran = α Tau: $\alpha_{\mathrm{J2000.0}} = 04^{\mathrm{h}}35^{\mathrm{m}}55.2387^{\mathrm{s}}$, $\delta_{\mathrm{J2000.0}} = +16^\circ30'33.485''$

corresponding to $\alpha_{\mathrm{B1950.0}} = 04^{\mathrm{h}}33^{\mathrm{m}}02.9^{\mathrm{s}}$, $\delta_{\mathrm{B1950.0}} = +16^\circ24'37.6''$

Precession and Nutation

There is one last problem, however:

Earth is $\sim$ rotational ellipsoid, orbits of Sun and Moon are *not* in plane of equator

(Earth's axis has tilt of $\sim$23.5°, moon's orbit tilted by 7° against ecliptic)

$\Longrightarrow$ Sun and Moon excert torques onto Earth

Earth's rotational axis is not stable in space.

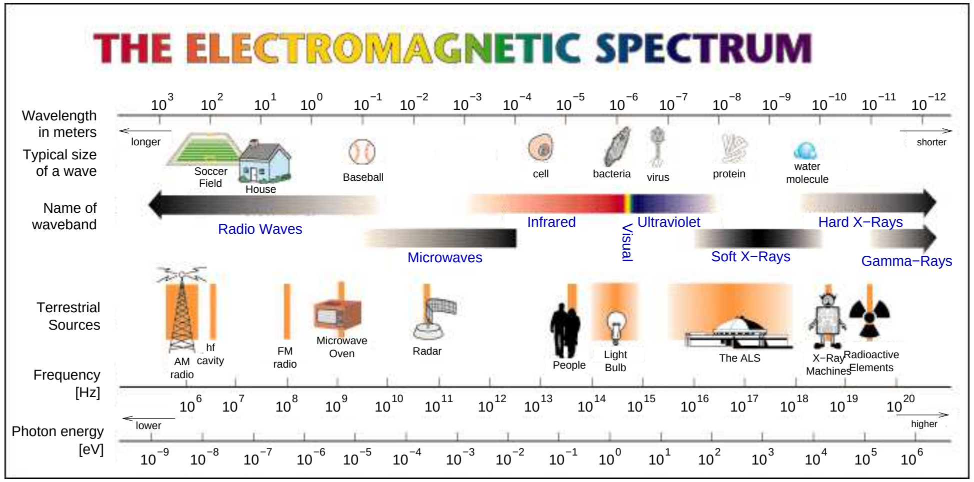
Two major effects:

lunisolar precession: Earth's axis rotates around pole of ecliptic once every 25800 years ($\sim$50$''$ per year).

Already discovered by Hipparcus in $\sim$200 BC!

nutation: "Wobble" with $\sim$18 year periodicity caused by short-term perturbations caused by Moon and Sun.

$\Longrightarrow$ Need to state **epoch** for coordinates. Typically use 1950.0 or 2000.0.



Electromagnetic Spectrum, II

As we all know, light can be characterized by

Wavelength: λ, measured in m, mm, cm, nm, Å.

Frequency: ν, measured in Hz, MHz.

Energy: E, measured in J, erg, Rydbergs, eV, keV, MeV, GeV.

Temperature: T, measured in K.

These quantities are related:

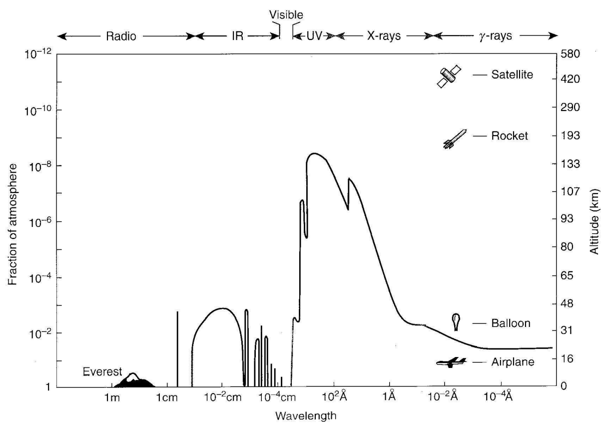
$$\lambda\nu = c \qquad E = h\nu \qquad T = E/k \tag{8.1}$$

where

$$c = 299792458\,\mathrm{m\,s^{-1}} \tag{8.2}$$
$$h = 6.6260693(11) \times 10^{-34}\,\mathrm{J\,s} \tag{8.3}$$
$$k = 1.3806505(24) \times 10^{-23}\,\mathrm{J\,K^{-1}} \tag{8.4}$$

Constants are 2002 CODATA values, `http://physics.nist.gov/cuu/Constants/index.html`
uncertainty is 1σ in units of last digit shown.

Earth's Atmosphere



Charles & Seward, Fig. 1.12

Earth's atmosphere is opaque for all types of EM radiation except for optical light and radio.

$\Longrightarrow$ Astronomy is today multi-wavelength astronomy, although optical studies are still the most important

$\Longrightarrow$ For time reasons only optical telescopes will be discussed.

Introduction

Scientific purposes of a telescope:

1. Collect light, lots of light, to show faint objects (“Light bucket”)
2. Resolve small features

Instrumentation used. . .

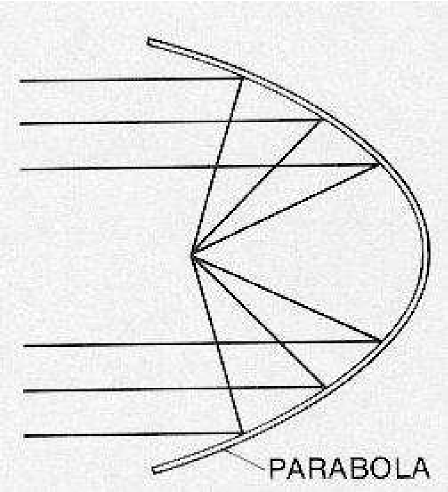
1. to make images
   $\Longrightarrow$ Imaging (with Charge Coupled Devices [CCDs], formerly also with film)
2. to measure spectra
   $\Longrightarrow$ Spectrographs
3. to measure stellar brightness
   $\Longrightarrow$ Photometers (often CCDs, but there are also dedicated photometers for msec-resolution photometry)

Reflectors, I

To collect light, we have two possibilities:

1. Lenses: Refractors
   Disadvantage: lens cannot be supported from the back $\Longrightarrow$ limits max. diameter to $\lesssim 2\,\mathrm{m}$
   $\Longrightarrow$ not of interest for science anymore.
2. Mirrors: Reflectors
   Mirrors can be supported, instrument of choice for today, with diameters up to 11 m

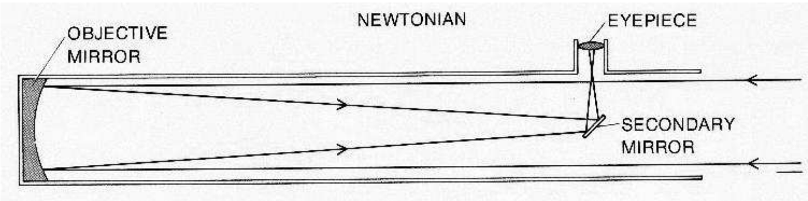
Reflectors, II



To form image: focus light with a parabolic mirror

Spherical mirrors show spherical aberration $\Longrightarrow$ *not* suited for astronomical telescopes, at least not without correction.

Newtonian Telescope

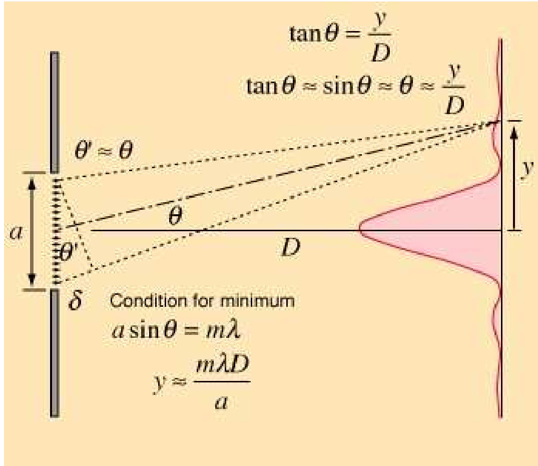


Newtonian telescope: reflector with parabolic mirror.

Common in cheaper telescopes.

Disadvantage: large size ($\sim$ focal length)

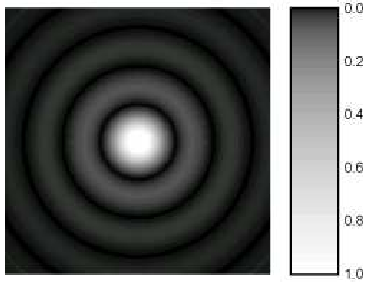
Resolution, I



GSU

Wave nature of light results in interference pattern caused by diffraction on optical elements in telescope (mainly aperture).

Resolution, II



Diffraction pattern on telescope aperture: Airy pattern

For a circular aperture with radius r:

$$I(\theta) \propto \pi^2 r^4 \left[\sum_{n=0}^{\infty} (-1)^n \frac{1}{n+1} \left(\frac{m^n}{n!} \right)^2 \right]^2 \qquad (8.5)$$

$$\propto \frac{\pi^2 r^4}{m^2} \left(J_1(2m)\right)^2$$

where $m = \pi(r/\lambda)\sin\theta$ and where $J_1(x)$ s the Bessel function of the first kind of order unity.

$I(\theta)$ has minima for $m = 1.916, 3.508, 5.087, \dots$, or

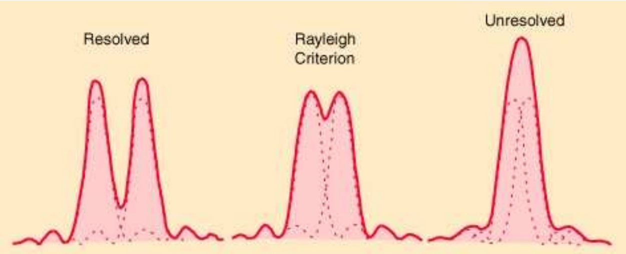
$$\sin\theta = \frac{1.916\lambda}{\pi r}, \frac{3.508\lambda}{\pi r}, \frac{5.087\lambda}{\pi r}, \dots \qquad (8.6)$$

or for θ small ($\sin\theta \sim \theta$) minima are found at:

$$\theta = \frac{1.220\lambda}{d}, \dots \qquad (8.7)$$

where d: diameter.

Resolution, III



Resolution of telescope: ability to separate two (point-like) light sources

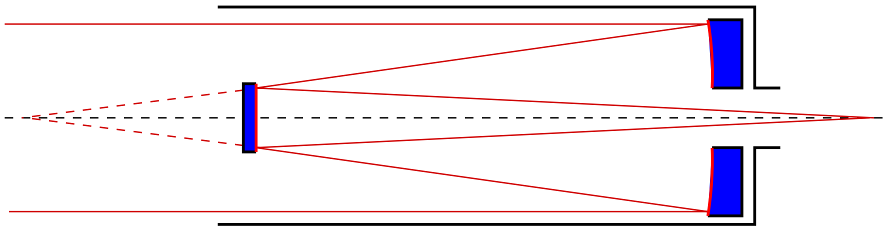
Rayleigh criterion for resolution: maximum of diffraction pattern of one source must fall into minimum of diffraction pattern of other source.

Therefore the diffraction limited resolution is

$$\alpha = \frac{1.220\lambda}{d} = \frac{12''}{D/1\,\mathrm{cm}} \quad \text{for optical light} \tag{8.8}$$

Note: Rayleigh criterion is a criterion, not a law. Detailed object separability depends on ratio of intensities of two objects, in practice resolutions up to 3× smaller are acheivable.

Cassegrain Telescope



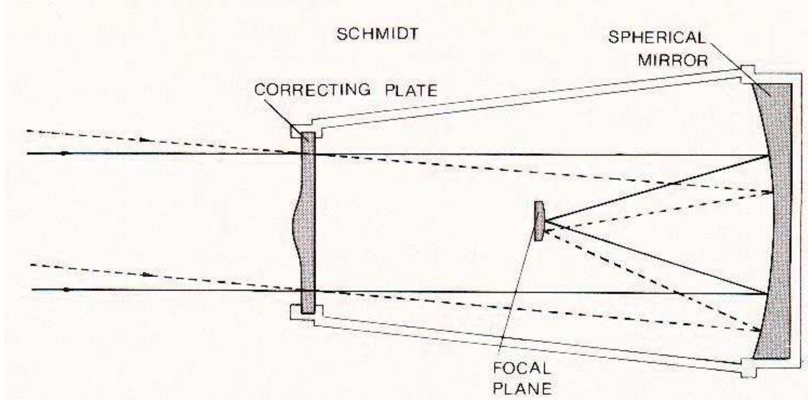
Cassegrain telescope, after Wikipedia

Cassegrain telescope: reflector with “folded optical path”

⟹ Much shorter than Newtonian

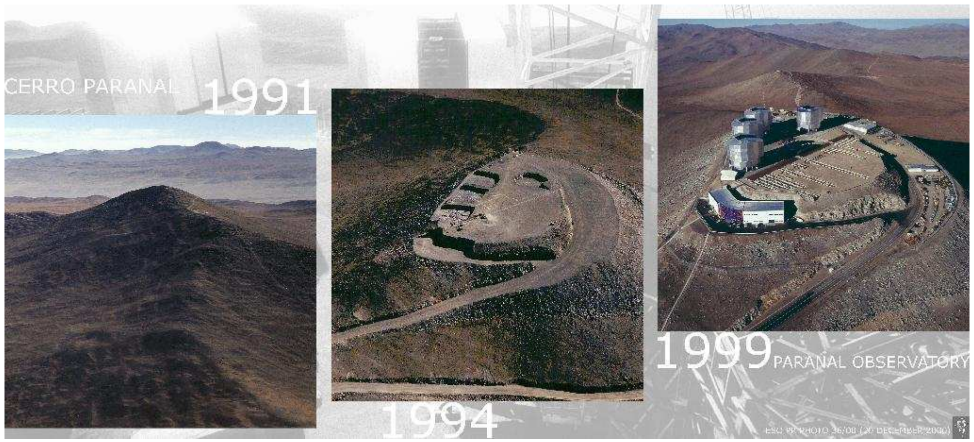
⟹ Telescope of choice for modern instruments

Schmidt Telescope

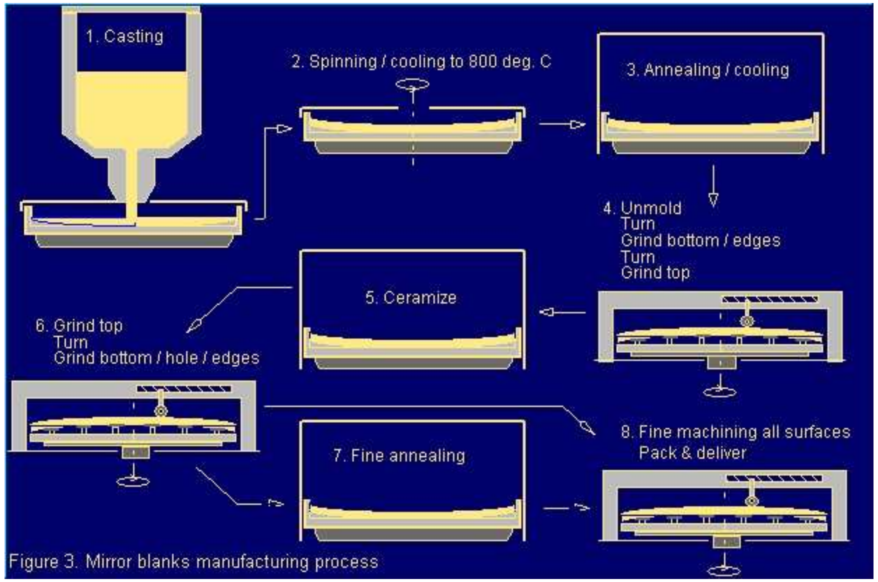


Schmidt telescope: Uses spherical mirror for larger field view, correction plate used to correct for spherical aberration.

Many amateur telescopes are combination of Schmidt telescope and Cassegrain telescope ⟹ Schmidt-Cassegrain telescopes.



Example: Building of the European Southern Observatory’s Very Large Telescope



ESO

Active Optics, I

From Eq. (8.8), the resolution of a telescope of diameter d is

$$\alpha = \frac{1.220\lambda}{d} = \frac{12''}{D/1\,\text{cm}} \tag{8.8}$$

Problem: astronomical seeing

$\Longrightarrow$ turbulence in atmosphere smears pictures of stars to disks with $\theta \gtrsim 0.3''$

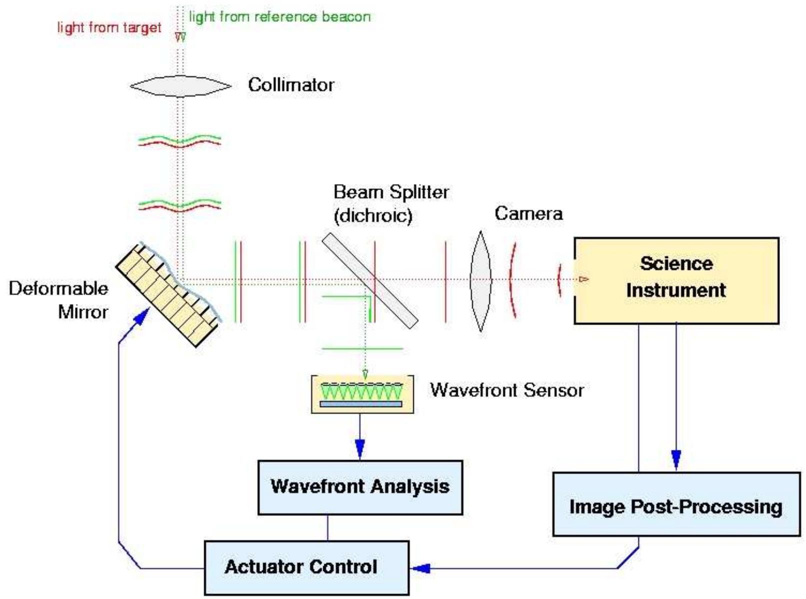
$\Longrightarrow$ Increasing telescope diameter to $\gtrsim$40 cm does *not* result in increase in resolution!

Solution to seeing problem: adaptive optics

...which only works in the IR so far, need to go to space for optical and UV

VLT at Paranal

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



Scheme of an adaptive optics system (Lick observatory)

Active Optics, V

Picture of the galactic centre in the IR taken with the Gemini North

Gemini North/AURA

Active Optics, VI

Picture of the galactic centre in the IR taken with the Gemini North

. . . and corrected with adaptive optics

$\Longrightarrow$ Resolution: diffraction limited!

$$\theta = 1.22\,\text{rad} \cdot \lambda/d \sim 70\,\text{mas} \quad (8.9)$$

(for $d = 8\,\text{m}$, $\lambda = 2.2\,\mu\text{m}$)

Gemini North/AURA