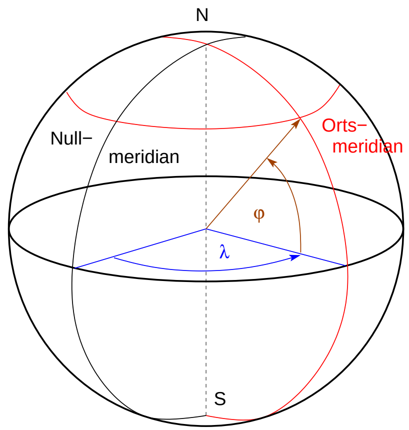
Observations

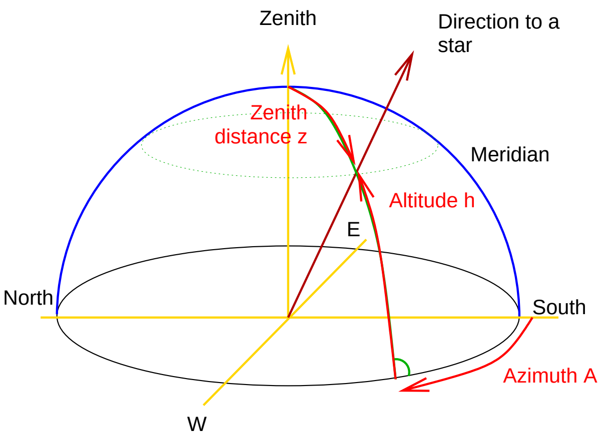
Positions on Earth



λ: geographic longitude (deg),
φ: geographic latitude (deg)

$\lambda = 0^\circ$ defined by position of a meridian circle in Greenwich (London)

Horizon System



Position on sky:

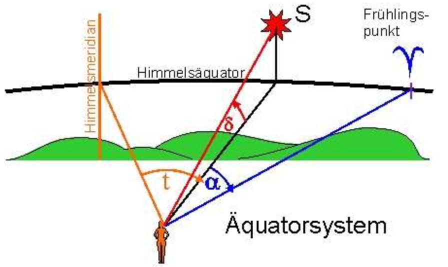
- Define position by giving direction to star.
- Azimuth A: angle in horizontal S-W-N-E
- Altitude h: angle from horizon towards zenith
- Zenith distance z: $z = 90^\circ - h$

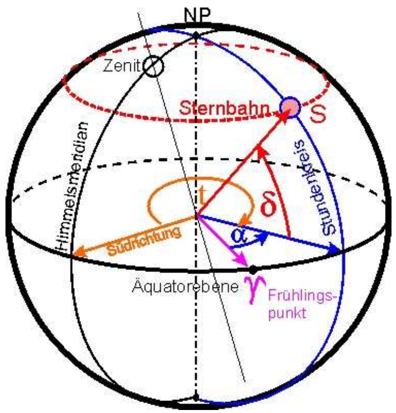
after Giese

http://joeorman.shutterace.com/Trails/Trails_021227_5.html

Earth rotates: A, h do not define position of stars at any time

Equatorial System, fixed

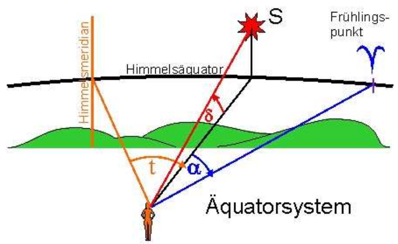




t = hour angle (h,m,s), changes constantly with time

δ = declination (deg), constant with time

Equatorial System, co-moving

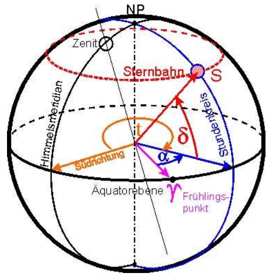


correct for earth rotation

$\Longrightarrow$ use vernal equinox as a co-rotating zero point on the sky

α = Right ascension (h,m,s) measured from vernal equinox

δ = declination



Θ siderial time = hour angle of the vernal equinox

transformation from fixed to co-moving equatorial system:

$$\boxed{\Theta = t + \alpha}$$

Equatorial System, co-moving

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

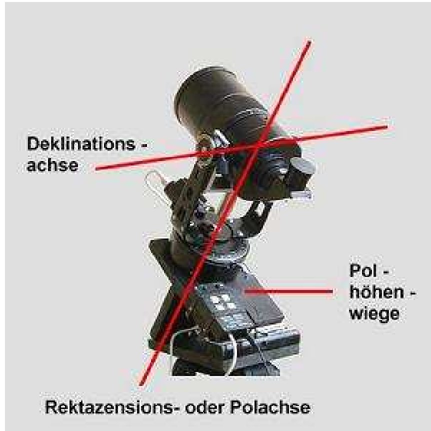
Angular speed of Sun: 360° degrees in 365.25 days, i.e., $0.9856^\circ\,\mathrm{d}^{-1}$.

$\Longrightarrow$ During 365.25 days the Earth rotates 366.25 times

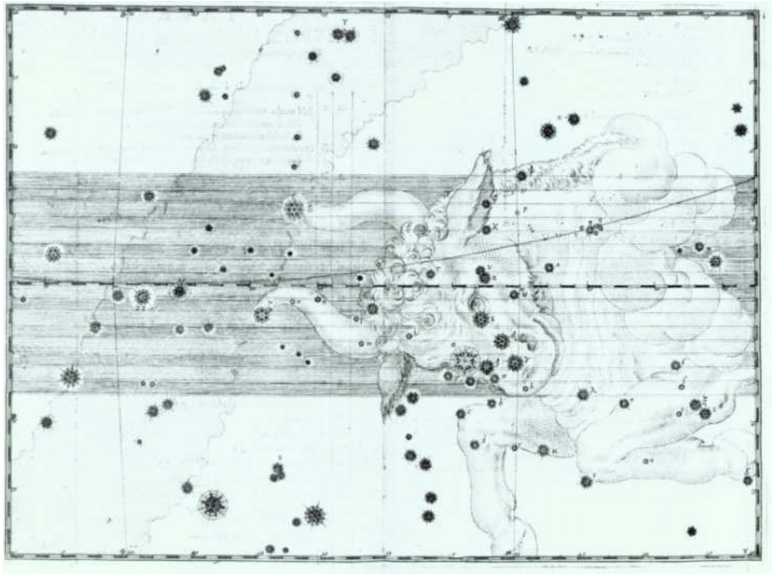
$\Longrightarrow$ Earth's rotation takes $24\,\mathrm{h} \times 365.25/366.25 = 23\,\mathrm{h}\ 56$ minutes.

Telescope Mountings

azimuthal mounting: horizontal axis and vertical axis



equatorial mounting: declination axis and polar axis

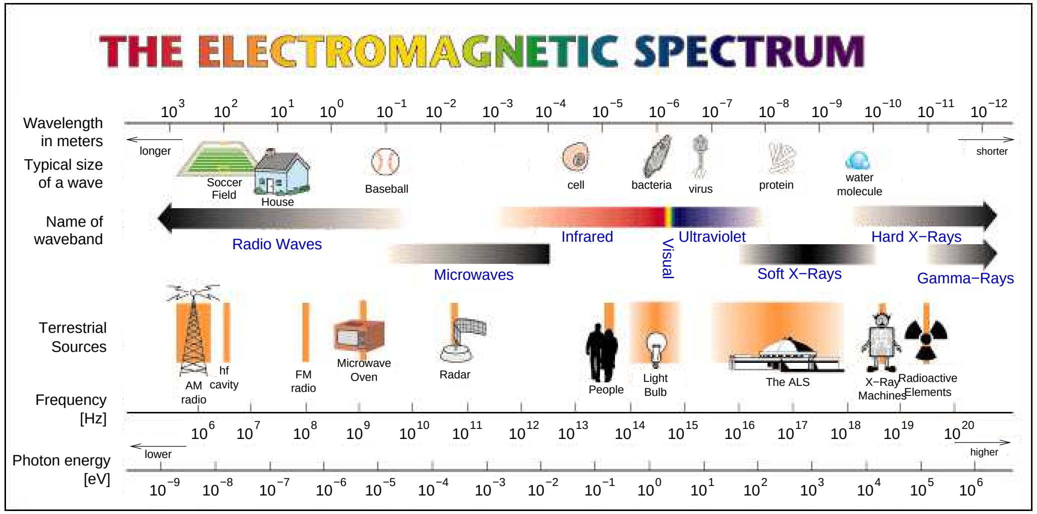


Bayer's Uranometria (1603; University of Illinois collections)

Because of precession and nutation: need to state epoch of coordinate!

Aldebaran = α Tau: $\alpha_{\mathrm{J2000.0}} = 04^{\mathrm{h}}35^{\mathrm{m}}55.2387^{\mathrm{s}}$, $\delta_{\mathrm{J2000.0}} = +16^\circ 30' 33.485''$

corresponding to $\alpha_{\mathrm{B1950.0}} = 04^{\mathrm{h}}33^{\mathrm{m}}02.9^{\mathrm{s}}$, $\delta_{\mathrm{B1950.0}} = +16^\circ 24' 37.6''$



Electromagnetic Spectrum

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:

$$\lambda\nu = c \qquad E = h\nu \qquad T = E/k \tag{2.1}$$

where

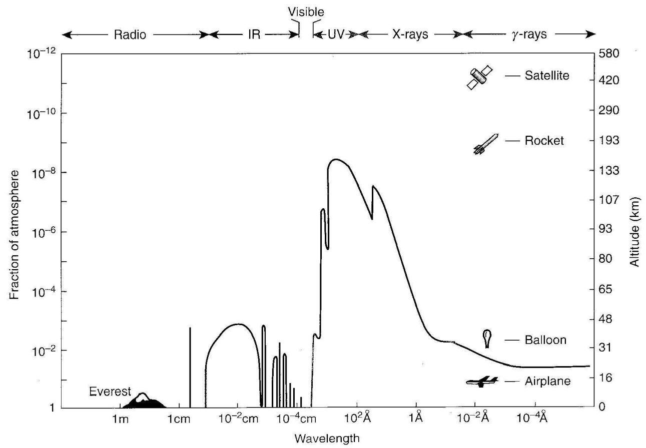
$$c = 299792458\,\mathrm{m\,s^{-1}} \tag{2.2}$$

$$h = 6.6260693(11) \times 10^{-34}\,\mathrm{J\,s} \tag{2.3}$$

$$k = 1.3806505(24) \times 10^{-23}\,\mathrm{J\,K^{-1}} \tag{2.4}$$

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 very 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...

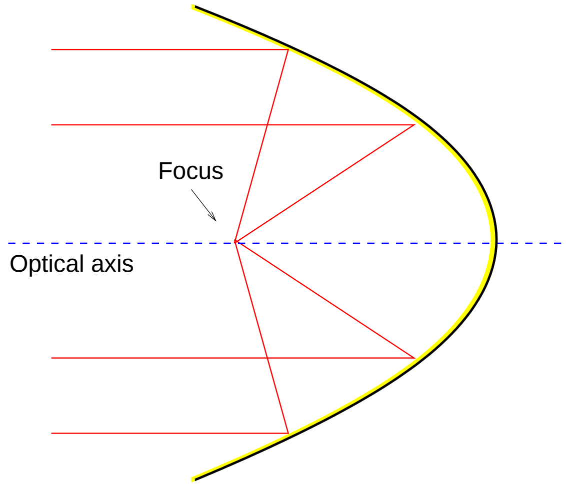
1. to make images
   $\Longrightarrow$ Imaging (with Charge Coupled Devices [CCDs], formerly also with film)
2. to measure spectra
   $\Longrightarrow$ Spectrographs
3. to measure stellar brightness
   $\Longrightarrow$ Photometers (often CCDs, but there are also dedicated photometers for msec-resolution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

Types of Telescopes

To collect light, we have two possibilities:

1. Lenses: Refractors
   Disadvantage: lens cannot be supported from the back
   $\Longrightarrow$ limits max. diameter to $\lesssim 1\,\mathrm{m}$
   largest refractor at Yerkes Observatory (University of Chicago): $d = 1.02\,\mathrm{m}$
   $\Longrightarrow$ not of interest for science
2. Mirrors: Reflectors
   Mirrors can be supported, instrument of choice for today, with diameters up to 11 m

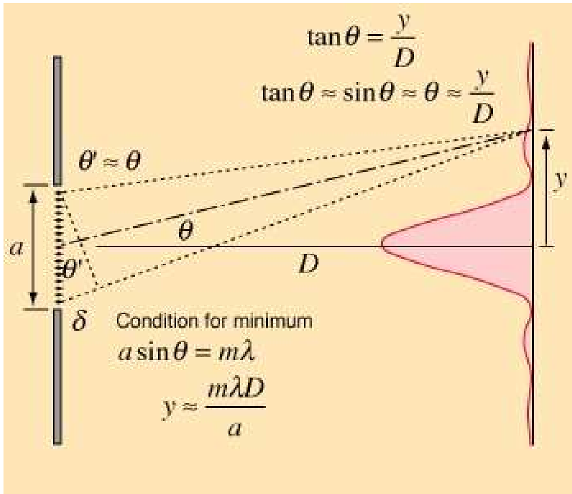
Types of Telescopes



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).

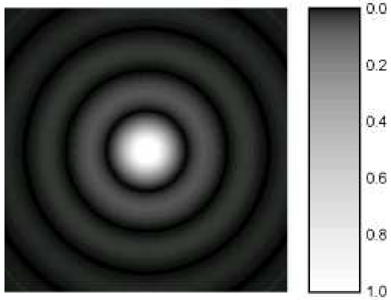
Resolution



GSU

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

Resolution



Diffraction pattern on telescope aperture: Airy pattern
For a circular aperture with radius r:

$$I(\theta) \propto \pi^2 r^4 \left[\sum_{n=0}^{\infty} (-1)^n \frac{1}{n+1} \left(\frac{m^n}{n!}\right)^2\right]^2 \propto \frac{\pi^2 r^4}{m^2} (J_1(2m))^2 \tag{2.5}$$

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

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

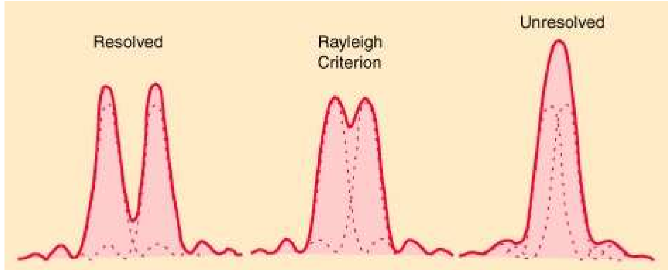
$$\sin\theta = \frac{1.916\lambda}{\pi r}, \frac{3.508\lambda}{\pi r}, \frac{5.087\lambda}{\pi r}, \dots \tag{2.6}$$

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

$$\theta = \frac{1.220\lambda}{d}, \dots \tag{2.7}$$

where d: diameter.

Resolution



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

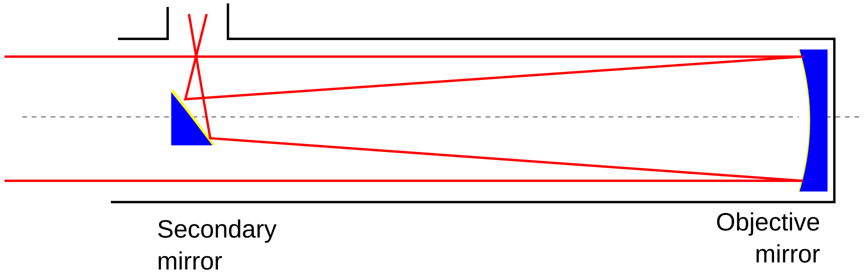
Rayleigh criterion for resolution: maximum of diffraction pattern of one source must fall into minimum of diffraction pattern of other source.

Therefore the diffraction limited resolution is

$$\alpha = \frac{1.220\lambda}{d} = \frac{12''}{D/1\,\mathrm{cm}} \quad \text{for optical light} \tag{2.8}$$

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$\times$ smaller are achievable.

Newtonian Telescope

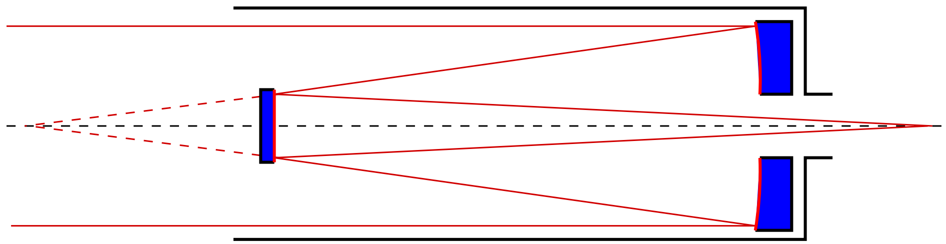


Newtonian telescope: reflector with parabolic mirror.

Common in cheaper telescopes.

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

Cassegrain Telescope



Cassegrain telescope, after Wikipedia

Cassegrain telescope: reflector with “folded optical path”

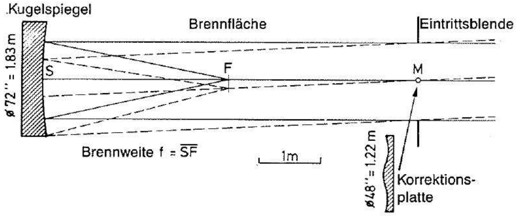
(M1: paraboloid, M2: hyperboloid)

$\Longrightarrow$ Much shorter than Newtonian

$\Longrightarrow$ Telescope of choice for modern instruments

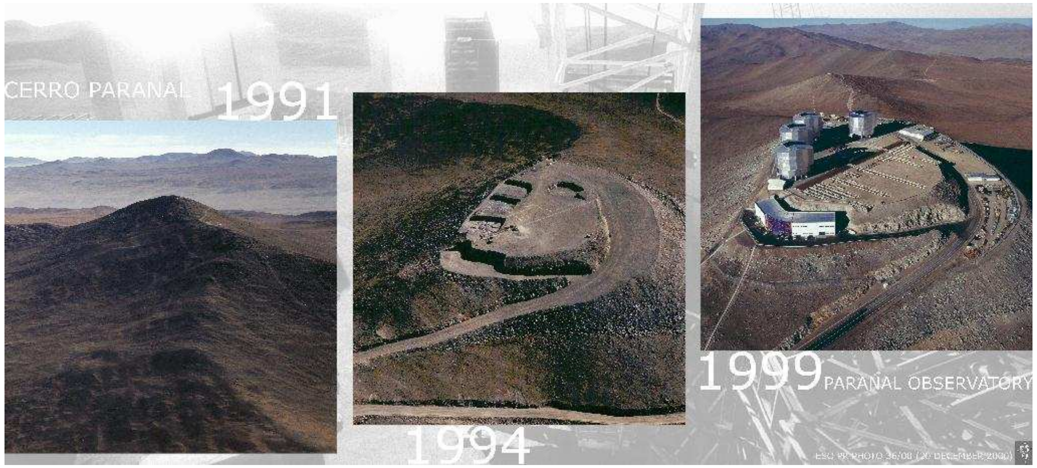
Schmidt Telescope

2m Schmidt telescope at the Landessternwarte Thüringen in Tautenburg near Jena:
largest Schmidt telescope in the world.



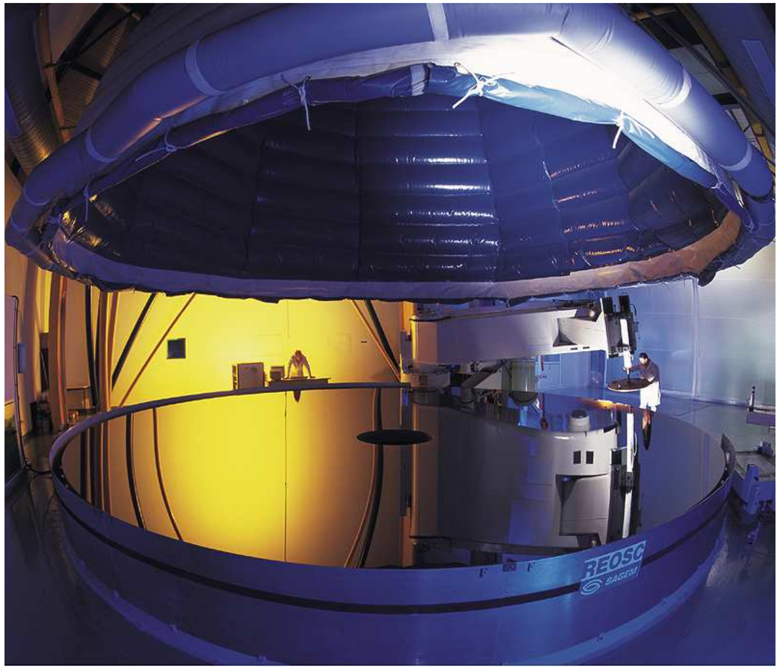
Uses spherical mirror for larger field view, correction plate used to correct for spherical aberration.

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

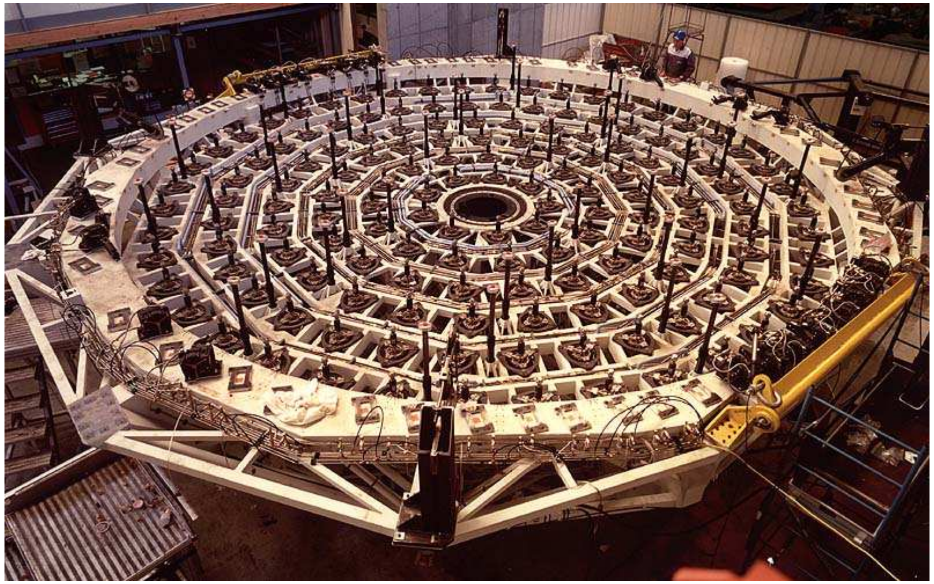


Example: Building of the European Southern Observatory's Very Large Telescope

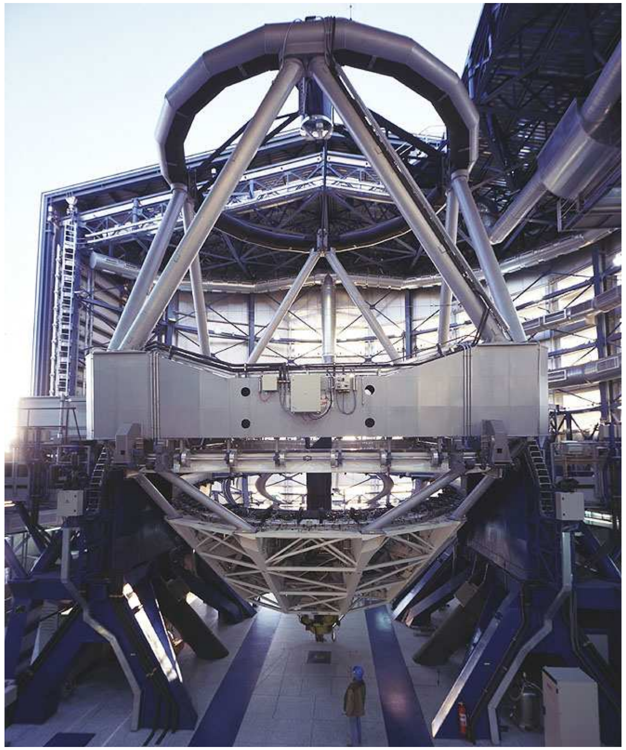
ESO



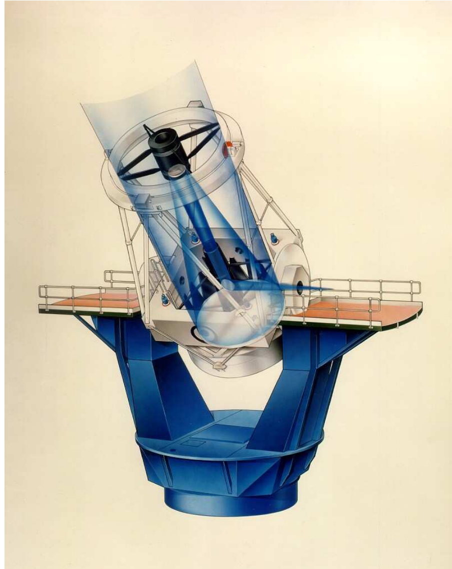
The Polished Fourth VLT 8.2-m Mirror at REOSC
Photo: SAGEM
ESO PR Photo 44/99 (14 December 1999)
European Southern Observatory



Mirror cell supporting the mirror, actuators keep mirror in shape
("active optics", correcting all possible deformations of the mirror).



Building the VLT



Nasmyth Focus:
light reflected through axis

- ideal for modern azimutal mountings

  e.g., European Southern Observatory's Very Large Telescope
- two stationary platforms
- can host large instruments
- very stable

William Herschel Telescope, La Palma

VLT at Paranal

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

Adaptive Optics

From Eq. 2.8, the resolution of a telescope of diameter d is

$$\alpha = \frac{1.220\lambda}{d} = \frac{12''}{D/1\,\mathrm{cm}} \tag{2.8}$$

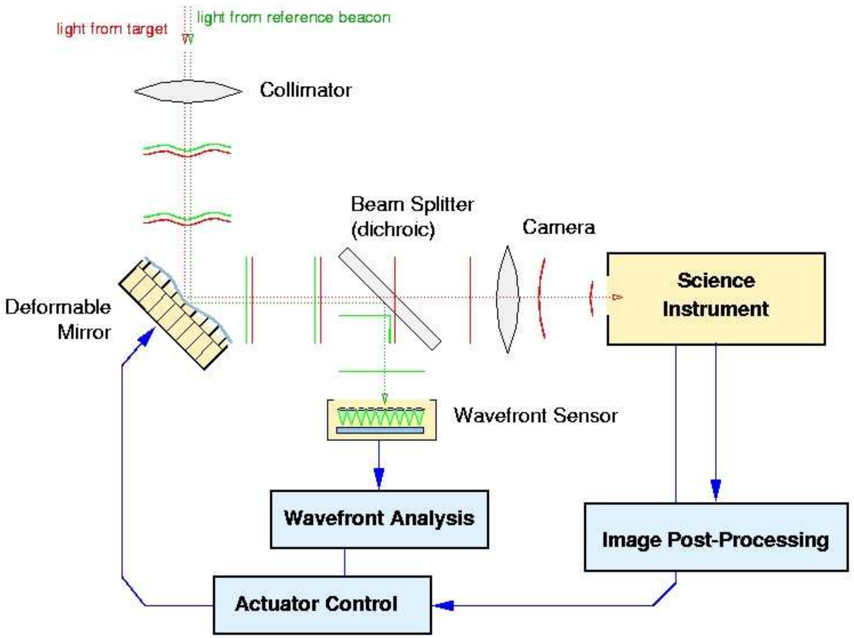
Problem: astronomical seeing

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

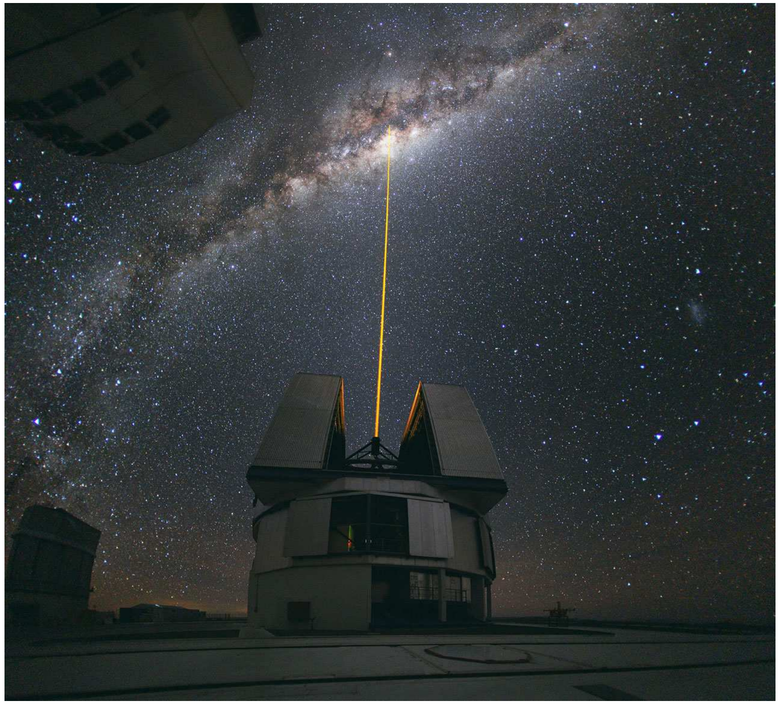
$\Longrightarrow$ Increasing telescope diameter to $\gtrsim$40 cm does *not* result in increase in resolution!

Solution to seeing problem: adaptive optics

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



Scheme of an adaptive optics system (Lick observatory)



5W laser at the VLT.

Adaptive Optics

Gemini North/AURA

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

Adaptive Optics

Gemini North/AURA

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

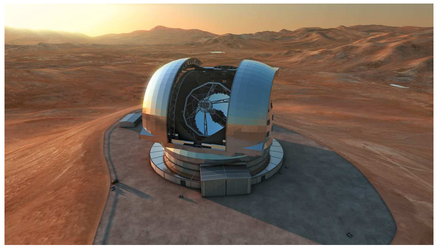
. . . and corrected with adaptive optics

$\Longrightarrow$ Resolution: diffraction limited!

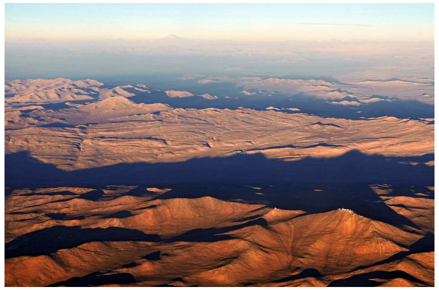
$$\theta = 1.22'' \cdot \lambda/d \sim 70\,\text{mas} \qquad (2.9)$$

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

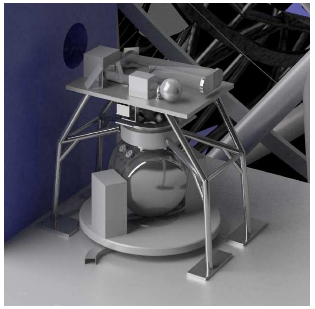
Building the E-ELT



39m E-ELT, $\sim$800 mirror segments



Cerro Amazones, Atacama



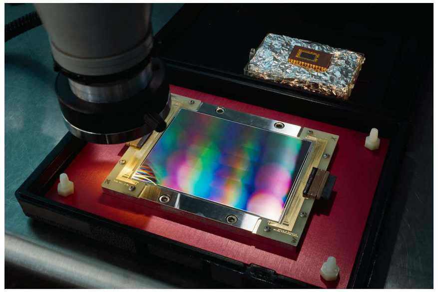
first light instrument ($\sim$2024):

MICADO

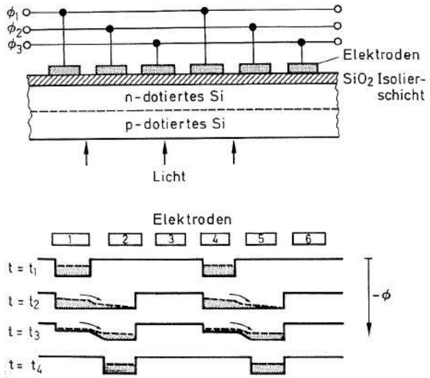
Imager & Spectrograph

$\Longrightarrow$ Innsbruck contribution

CCDs



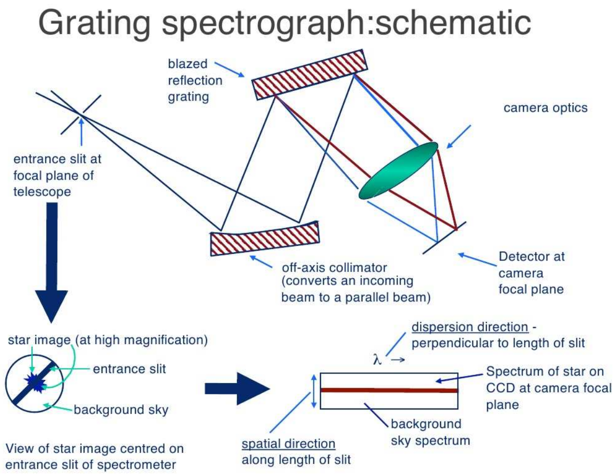
- basics of operation:



- linear detector
  (photographic plate: nonlinear)
- high quantum efficiency: up to ∼90%
  (photographic plate: ∼2%)

imaging of large fields of view: CCD arrays

Spectrographs



Dispersion

- grating equation:

$$a(\sin\phi - \sin\phi_0) = n\lambda \quad (2.10)$$

a: grating constant; ϕ_0: incident angle; ϕ: emergent angle; n: spectral order

- angular dispersion:

$$\frac{d\phi}{d\lambda} = \frac{n}{a\cos\phi} \quad (2.11)$$

- linear dispersion:

$$\frac{dx}{d\lambda} = f \cdot \frac{d\phi}{d\lambda} \quad (2.12)$$

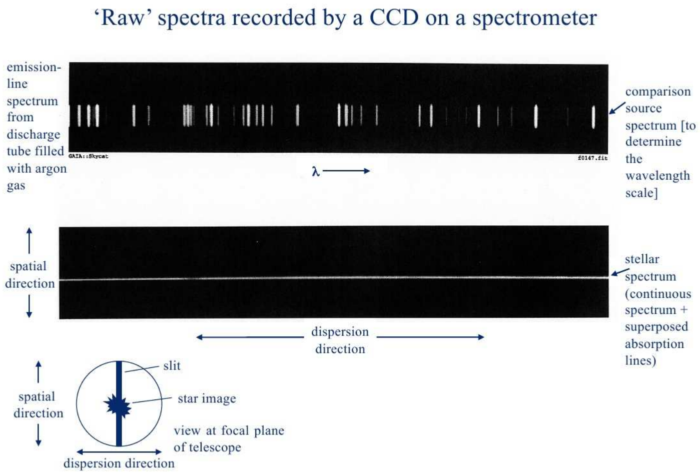
f: focal length of camera

Spectral resolving power:

$$R = \frac{\lambda}{\Delta\lambda} = nN \quad (2.13)$$

N: number of grating rules

Spectrographs



$R < 1000$: low; $R = 1000 \ldots 10000$: intermediate; $R > 10000$: high resolution