LOFAR

Low Band Antenna

High Band Antenna

LOFAR (Low Frequency Array): next generation interferometer, currently being built in the Netherlands with international partners, with antennas sensitive 30–80 MHz and 120–240 MHz

A beautiful overview by Rob Fender of LOFAR, its technology, and its science goals is at

`http://www.physics.ox.ac.uk/MCCT-SKADS/presentations/MCCT_Oxford_Rob_Fender.pdf`

. . . so no own slides are necessary here

SKA

SKA (Square Kilometre Array): Planned 1 km^2 radio array following up on LOFAR as next generation array

More information at `http://www.skatelescope.org`.

Again, a beautiful overview of status of SKA is available, see `http://www.hs.uni-hamburg.de/DE/Ins/Lofar/lofar_workshop/talks/`

. . . so again no own slides are necessary here

Burke, B. F., & Graham-Smith, F., 2002, An Introduction to Radio Astronomy: Second Edition

Cohen, M. H., Cannon, W., Purcell, G. H., Shaffer, D. B., Broderick, J. J., Kellermann, K. I., & Jauncey, D. L., 1971, ApJ, 170, 207

Cohen, M. H., Lister, M. L., Homan, D. C., Kadler, M., Kellermann, K. I., Kovalev, Y. Y., & Vermeulen, R. C., 2007, ApJ, 658, 232

Combes, F., 1991, ARA&A, 29, 195

Ewen, H. I., & Purcell, E. M., 1951, Nature, 168, 356

Gasiewski, A. J., & Klein, M., 2000, Journal of Geophysical Research-Atmospheres, 13, 17481

Högbom, J. A., 1974, A&AS, 15, 417

Kadler, M., Ros, E., Lobanov, A. P., Falcke, H., & Zensus, J. A., 2004, A&AS, 426, 481

Kadler, M., et al., 2008, ApJ, 680, 867

Kalberla, P. M. W., Burton, W. B., Hartmann, D., Arnal, E. M., Bajaja, E., Morras, R., & Pöppel, W. G. L., 2005, A&AS, 440, 775

Kameno, S., Sawada-Satoh, S., Inoue, M., Shen, Z.-Q., & Wajima, K., 2001, PASJ, 53, 169

Kellermann, K. I., et al., 2004, ApJ, 609, 539

Kovalev, Y. Y., et al., 2005, AJ, 130, 2473

Laing, R. A., & Bridle, A. H., 1987, MNRAS, 228, 557

Lister, M. L., et al., 2009, AJ, 137, 3718

Nilsson, K., Pursimo, T., Sillanpää, A., Takalo, L. O., & Lindfors, E., 2008, A&A, 487, L29

Reber, G., 1940, ApJ, 91, 621

Reber, G., 1944, ApJ, 100, 279

Ryle, M., 1962, Nature, 194, 517

Ryle, M., Elsmore, B., & Neville, A. C., 1965, Nature, 205, 1259

Shu, F. H., 1991, The Physics of Astrophysics, Vol. I. Radiation, (Mill Valley, CA: University Science Books)

Walker, R. C., 1989, in Techniques and Applications of Very Long Baseline Interferometry, 163

Weigert, A., & Wendker, H. J., 1989, Astronomie und Astrophysik - ein Grundkurs., (Weinheim: VCH Verlagsgesellschaft)

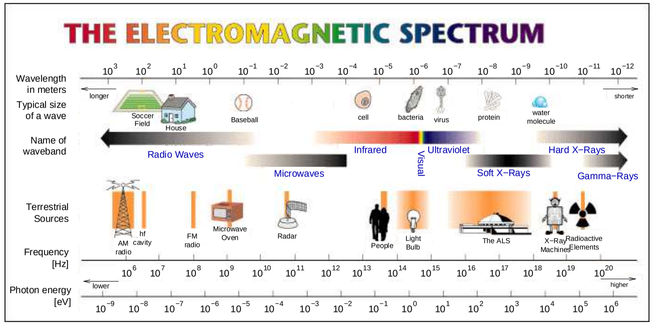
Whitney, A. R., et al., 1971, Science, 173, 225

Yang, J., Gurvits, L. I., Lobanov, A. P., Frey, S., & Hong, X.-Y., 2008, A&AS, 489, 517

Zensus, J. A., 1997, ARA&A, 35, 607

Optical Astronomy

Introduction



Optical astronomy: Astronomy mainly of the thermal universe. Since technology and physics in IR, optical, and UV are very similar $\Longrightarrow$ will deal with all three bands together

1. Telescopes
2. Detectors: Charge Coupled Devices (CCDs), IR Detectors

Introduction

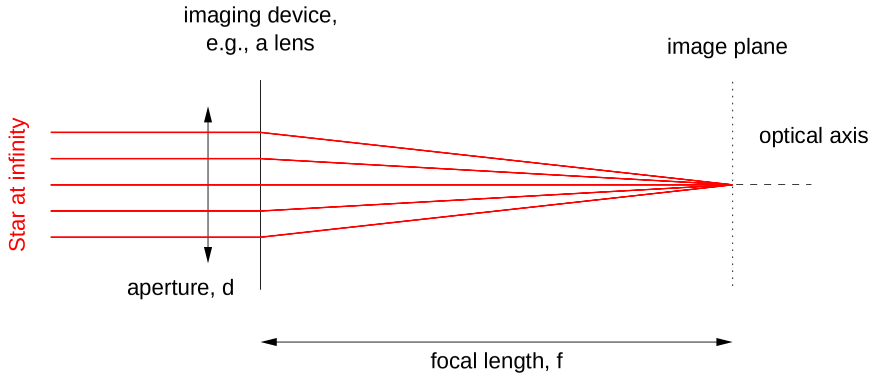
Scientific purposes of a telescope:

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 (normally also CCDs)

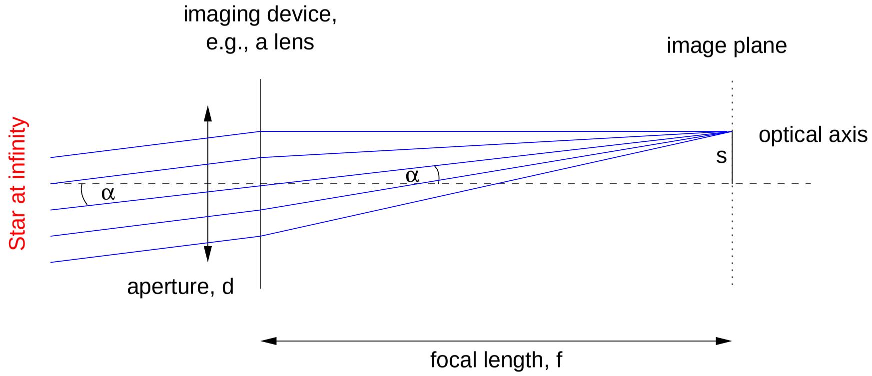
Image Formation, I



Characterize imaging system by:

- aperture, $d \Longrightarrow$ collecting area
- focal length, $f \Longrightarrow$ imaging capabilities

Image Formation, II



Simple geometry gives displacement for off-axis source:

$$s = f\tan\alpha \sim f\alpha \tag{6.1}$$

α in rad!

Image Formation, III

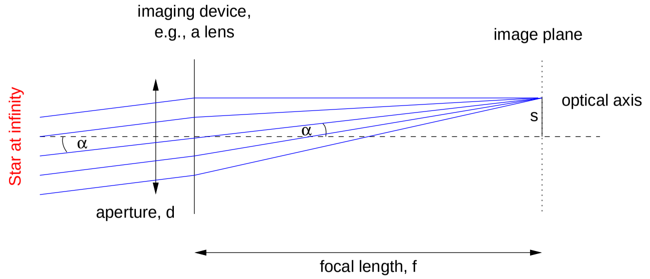


Plate scale: angle imaged onto unit length in focal plane:

$$P = \frac{\alpha}{s} = \frac{1}{f} \tag{6.2}$$

$\Longrightarrow$ large plate scale: s is small

P is typically not given in m^{-1}, but in “arcsec per mm”, $''$/mm.

older telescopes had comparably large detectors (photo plates, up to 30 × 30 cm^2)

$\Longrightarrow$ large f to get small P!

e.g., Lick 3 m telescope: $f = 15.2$ m, or 14$''$/mm,

Remeis 60 cm telescope: $f = 10$ m,...

Problem since *today's detectors are small* $\Longrightarrow$ focal reducers are needed

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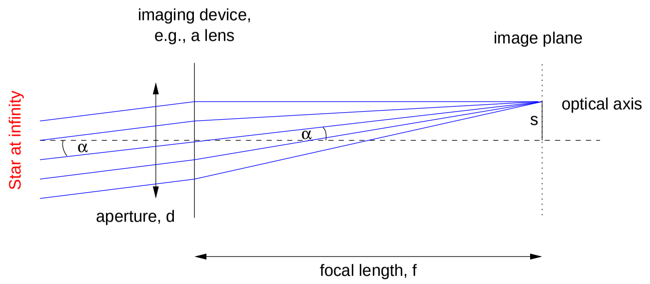
Image Formation, IV



For point sources in an ideal telescope: deposited energy only depends on diameter: $E_{\text{dep}} \propto d^2$

(this ignores refraction, see below!)

For source with finite angular size α, photons get deposited into circle of size s^2

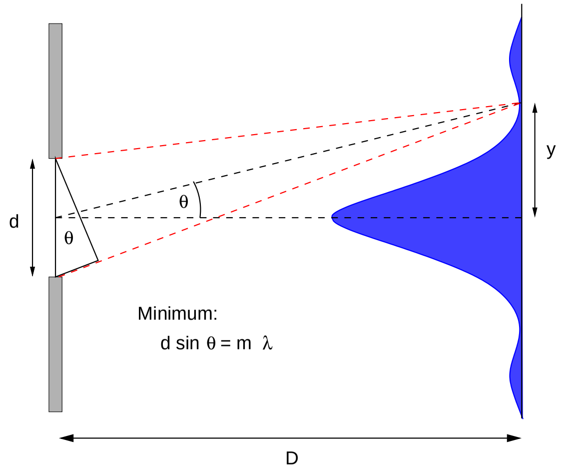
$\Longrightarrow$ energy collected on one picture element:

$$E \propto \left(\frac{d}{s}\right)^2 = \left(\frac{d}{f}\right)^2 = \frac{1}{\mathcal{R}^2} \quad \text{where the focal ratio} \quad \mathcal{R} = \frac{f}{d} \tag{6.3}$$

(German: “Blende”)

Typcally write as $f/\mathcal{R}$, i.e., $f/6$ means that the focal length is 6 × d.

Image Formation, V



after GSU

Wave nature of light results in interference pattern caused by diffraction on optical elements in telescope (mainly aperture): Intensity minimum for

$$d\sin\theta_m = m\lambda \tag{6.4}$$

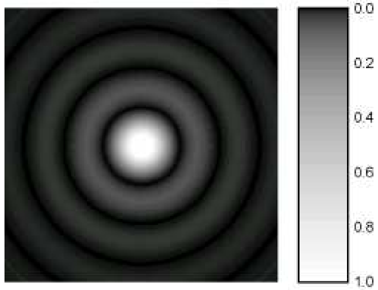
but

$$\sin\theta_m \sim \tan\theta_m = y/D \tag{6.5}$$

$\Longrightarrow$ intensity minima at

$$y_m = D\sin\theta_m = mD\frac{\lambda}{d} \tag{6.6}$$

Image Formation, VI



Precise theory of diffraction gives pattern on telescope aperture: Airy pattern

derivation: diffraction pattern = Fourier transform of aperture

For a circular aperture with radius r:

$$I(\theta) \propto \pi^2 r^4 \left[\sum_{n=0}^{\infty} (-1)^n \frac{1}{n+1} \left(\frac{m^n}{n!} \right)^2 \right]^2 \propto \frac{\pi^2 r^4}{m^2} \left(J_1(2m) \right)^2 \tag{6.7}$$

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,. . . , or

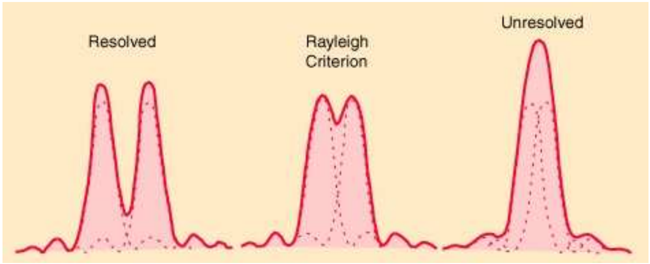
$$\sin\theta = \frac{1.916\lambda}{\pi r}, \frac{3.508\lambda}{\pi r}, \frac{5.087\lambda}{\pi r}, \dots \tag{6.8}$$

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

$$\theta = \frac{1.220\lambda}{d}, \dots \tag{6.9}$$

where d: diameter.

Image Formation, VII



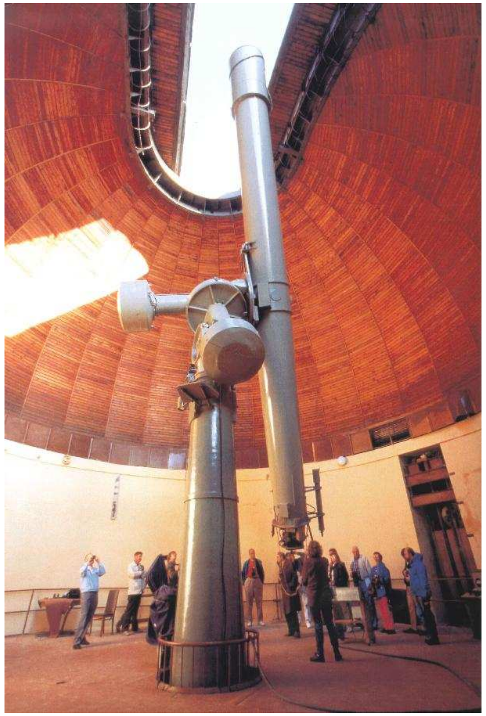
Resolution of telescope: ability to separate two (point-like) light sources

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

$$\alpha = \frac{1.220\lambda}{d} = \frac{12''}{D/1\,\mathrm{cm}} \quad \text{for optical light} \tag{6.10}$$

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.



Until 19th century: mainly telescopes with lenses (refractors)

Pulkovo Refractor (60 cm)
©R.E. Rossmeyer

Types of Telescopes, II

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 m

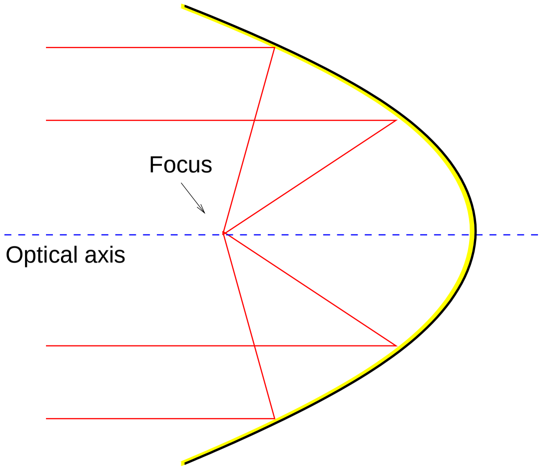
   largest refractor at Yerkes Observatory (University of Chicago): $d =$ 1.02 m

   $\Longrightarrow$ not of interest for science anymore

2. Mirrors: Reflectors

   Mirrors can be supported, instrument of choice for today, with diameters up to 11 m

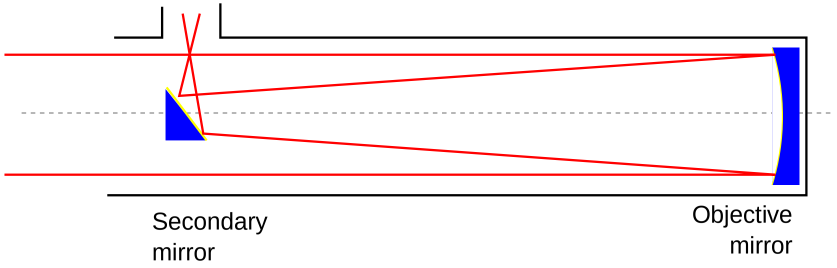
Types of Telescopes, III



To form image: focus light with a parabolic mirror

Spherical mirrors show spherical aberration ⟹ *not* suited for astronomical telescopes (at least not without correction).

Newtonian Telescope

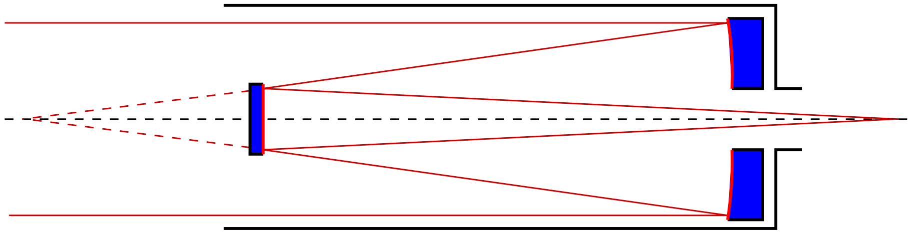


Newtonian telescope: reflector with parabolic mirror.

Common in cheaper telescopes.

Disadvantage: large size (∼ focal length)

Cassegrain Telescope



Cassegrain telescope, after Wikipedia

Cassegrain telescope: reflector with “folded optical path”

(M1: paraboloid, M2: hyperboloid)

⟹ Much shorter than Newtonian

⟹ Telescope of choice for modern instruments

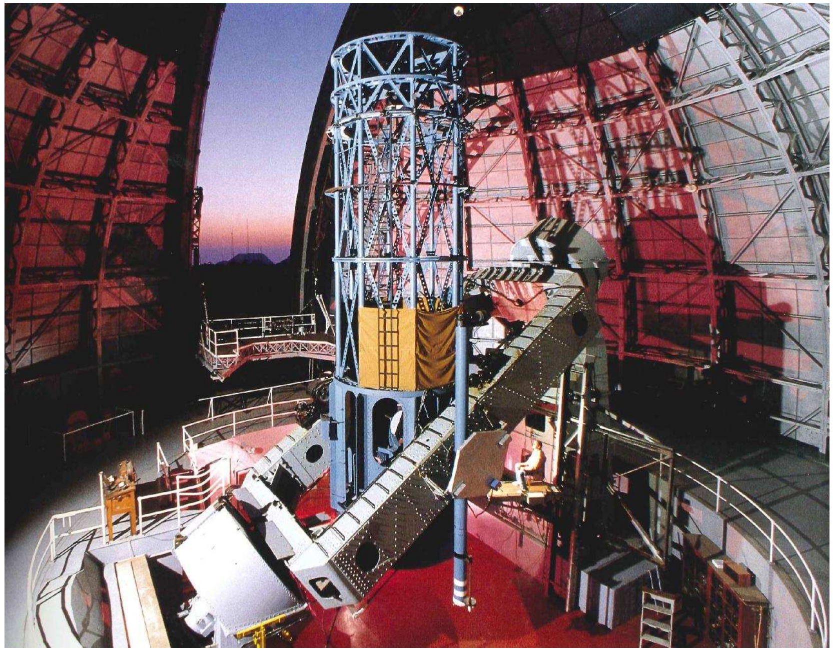
Schmidt Telescope

Bernhard Schmidt (Hamburg)
`http://www.sky-win.de/`

2 m Schmidt telescope at the Landesternwarte 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.



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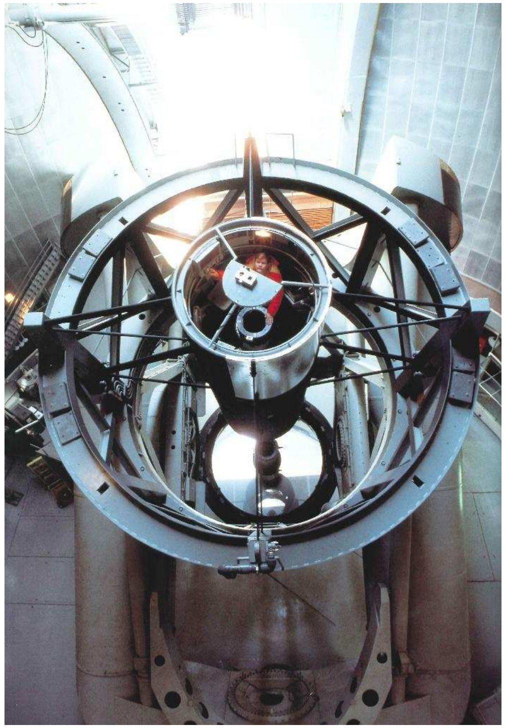
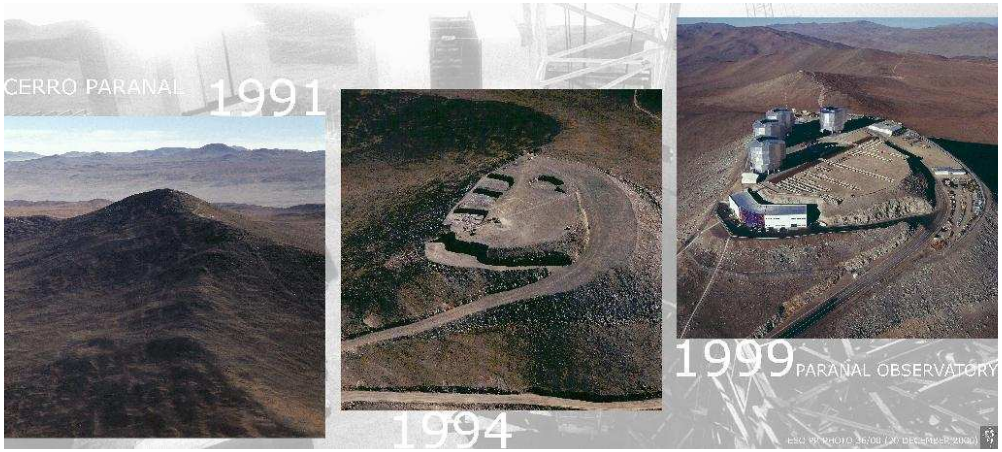
George E. Hale: Mt. Wilson 100′ (1st light 2 November 1917): First large reflector

© J. Wilms



Mt. Palomar Observatory (near San Diego)
5 m Telescope
(built 1934–1948)



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

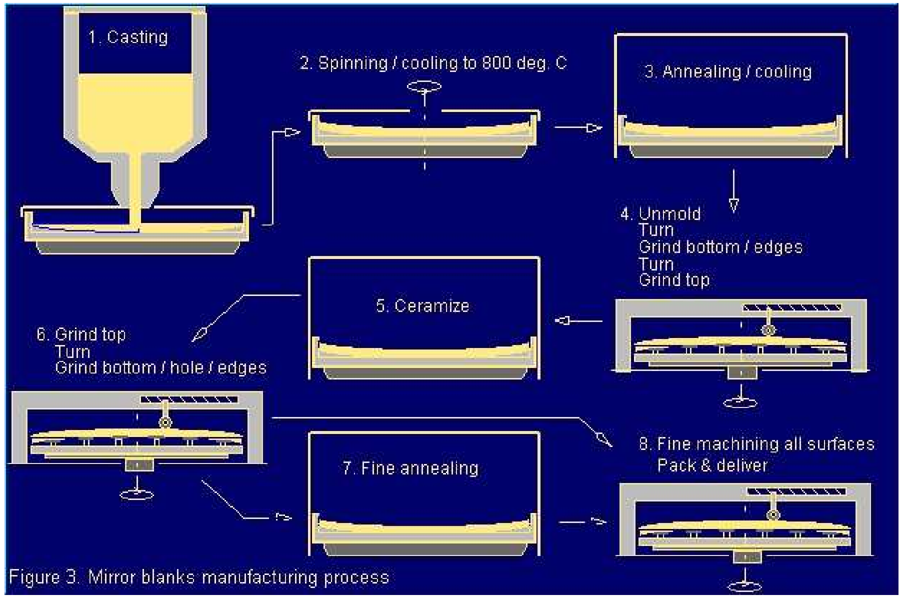
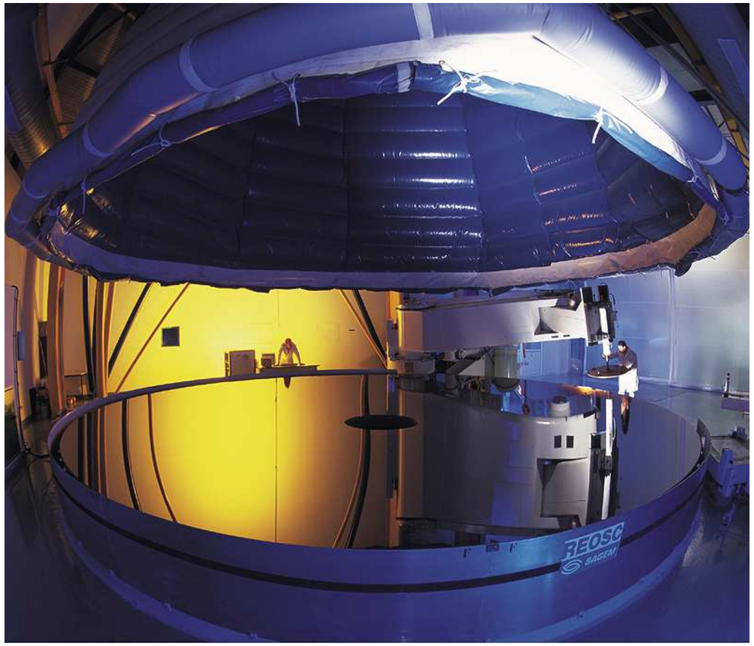


Figure 3. Mirror blanks manufacturing process

ESO



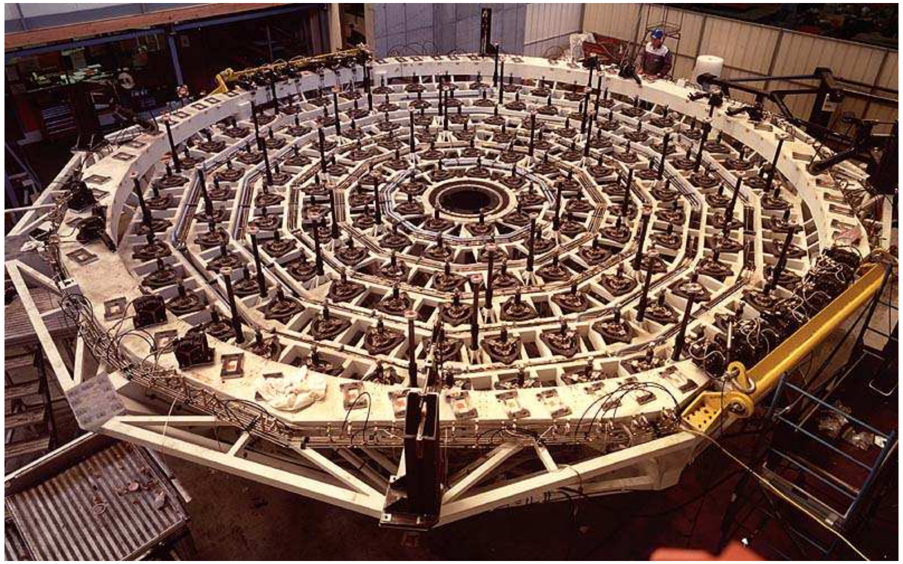
The Polished Fourth VLT 8.2-m Mirror at REOSC

Photo: SAGEM

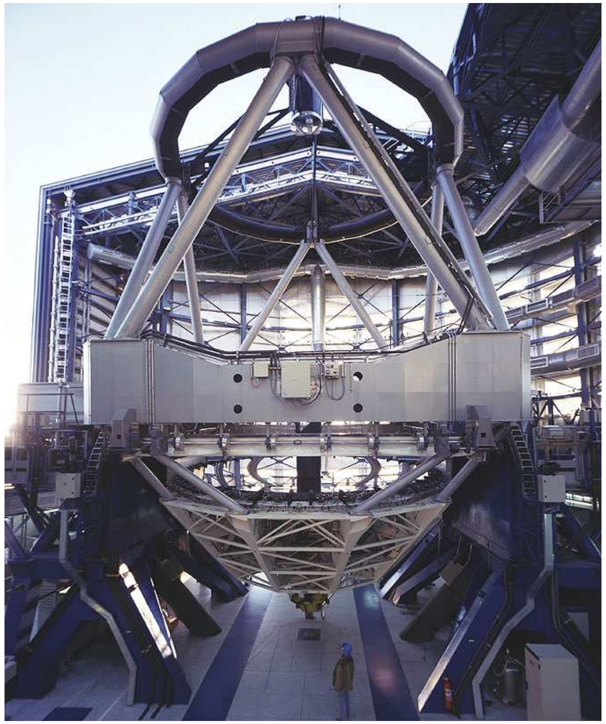
ESO PR Photo 44/99 (14 December 1999)

European Southern Observatory

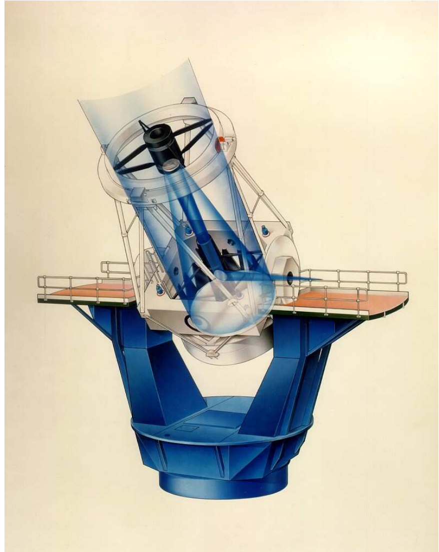
ESO



Mirror cell supporting the mirror, actuators keep mirror in shape
(“adaptive optics”, correcting all possible deformations of the mirror).



Building the VLT, VIII



Nasmyth Focus:
light reflected through axis

- ideal for modern azimutal mountings

  e.g., European Southern Observatory’s Very Large Telescope

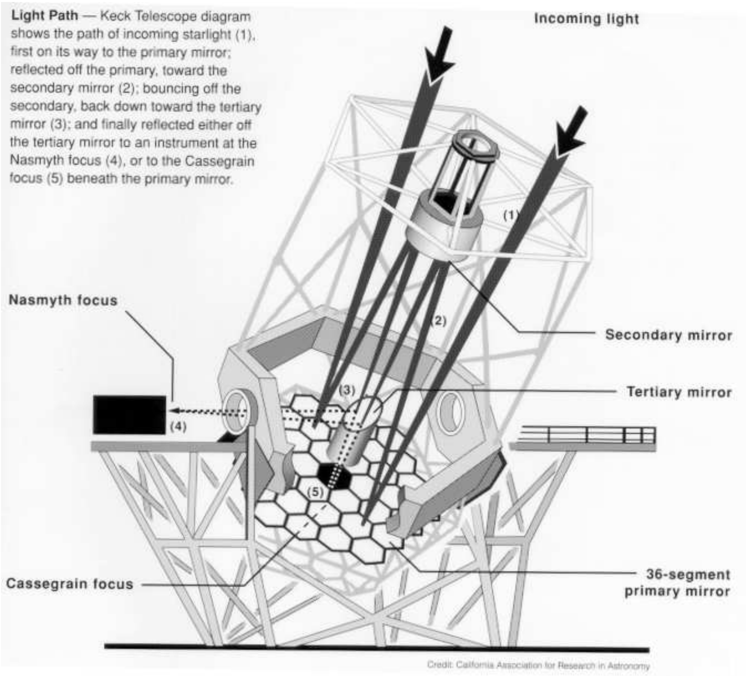
- two stationary platforms
- can host large instruments
- very stable

William Herschel Telescope, La Palma

VLT at Paranal

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

© European Southern Observatory



Keck telescopes on Hawaii

Tom Connell, WildTom Connell, Wildlife Art/Weldon-Owen, Inc./Readers Digest

IfA

Mauna Kea (4200 m above sea level): clockwise from bottom right: Subaru (8.3 m; JP), Keck (2 × 10 m), NASA IRTF (3 m), CFHT (3.6 m), Gemini North (8.1 m), UH (2.2 m), UKIRT (3.8 m)

Active Optics

From Eq. 6.10, the resolution of a telescope of diameter d is

$$\alpha = \frac{1.220\lambda}{d} = \frac{12''}{D/1\,\text{cm}} \qquad (6.10)$$

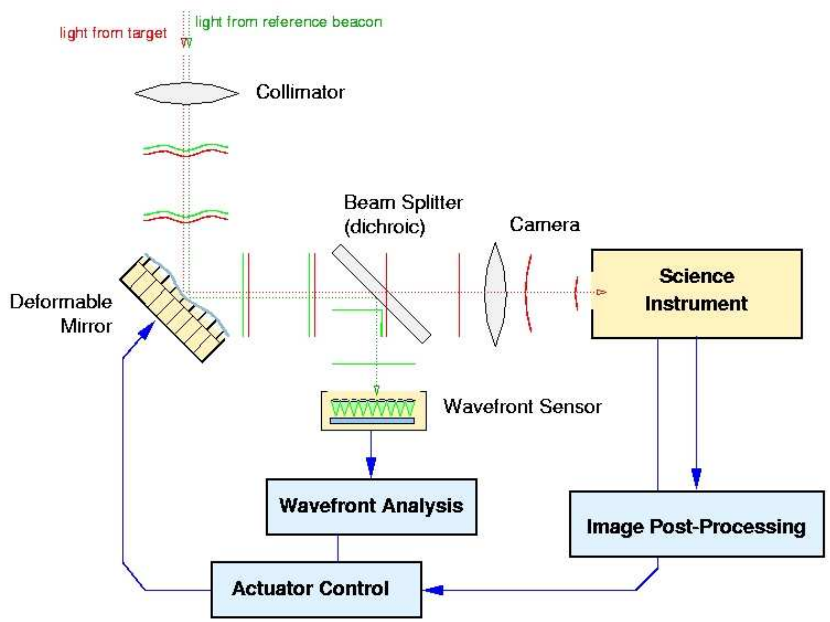
Problem: astronomical seeing

$\Longrightarrow$ 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)

The AO system of Mt. Hopkins observatory, a 30 W laser (©G. Furesz).

The AO system of Mt. Hopkins observatory, a 30 W laser (©G. Furesz).

Active Optics

Gemini North/AURA

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

Active 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!

$$\theta = 1.22\,\text{rad}\cdot\lambda/d \sim 70\,\text{mas} \quad (6.11)$$

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